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**SUNDAY, JANUARY 27**

**12:00 - 18:00**    **Registration**    **Lobby (1F)**

**17:00 - 19:00**    **Welcome Reception**    **Lobby (1F)**

**MONDAY, JANUARY 28**

**07:00**    **Registration**    **Lobby (1F)**

**08:00**    **Opening Ceremony**    **Grand Ballroom 101 ~ 105 (1F)**

**PLENARY PRESENTATION I**

Session Chair:

*Shoji Takeuchi, The University of Tokyo, JAPAN*

**Grand Ballroom 101 ~ 105 (1F)**

**08:30**    **CARDIOMYOCYTES AS HIGH-POWER BUILDING BLOCKS FOR BIO-HYBRID MACHINES..... 01**  
**Kevin Kit Parker**  
*Harvard University, USA*

**Oral Session I : Micro Robots**

Session Chair:

*Franz Lärmer, Bosch, GERMANY*

**Grand Ballroom 101 ~ 105 (1F)**

**09:30**    **DESIGN OF THE FIRST SUB-MILLIGRAM FLAPPING WING AERIAL VEHICLE..... 02**  
 Palak Bhushan and Claire J. Tomlin  
*University of California, Berkeley, USA*

Here we report the first sub-milligram flapping wing vehicle which is able to mimic insect wing kinematics. Wing stroke amplitude of 90° and wing pitch amplitude of 80° is demonstrated. This is also the smallest wingspan (single wing length of 3.5mm) device reported yet and is at the same mass-scale as a fruit fly. Assembly has been made simple and requires gluing together 5 components in contrast to higher part count and intensive assembly of other milligram-scale microrobots. This increases the fabrication speed and success-rate of the fully fabricated device. Low operational voltages (70mV) makes testing further easy and will enable eventual deployment of autonomous sub-milligram aerial vehicles.

**09:45**    **A FAST-MOVING MICRO CRAWLING ROBOT WITH DIRECT ELECTROMAGNETIC DRIVING MECHANISM..... 06**  
 Xinyi Liu<sup>1</sup>, Zhiwei Liu<sup>1</sup>, Mingjing Qi<sup>1,3</sup>, Yangsheng Zhu<sup>1</sup>, Dawei Huang<sup>1</sup>, Xiaoyong Zhang<sup>1,3</sup>, Liwei Lin<sup>5</sup>,  
 and Xiaojun Yan<sup>1,2,3,4</sup>  
<sup>1</sup>*Beihang University, CHINA,*  
<sup>2</sup>*Collaborative Innovation Center of Advanced Aero-Engine, CHINA,*  
<sup>3</sup>*National Key Laboratory of Science and Technology on Aero-Engine Aero-thermodynamics, CHINA,*  
<sup>4</sup>*Beijing Key Laboratory of Aero-Engine Structure and Strength, CHINA, and*  
<sup>5</sup>*University of California, Berkeley, USA*

We present a fast-moving micro crawling robot driven directly by electromagnetically induced resonance for the first time. The forelegs of the crawling robot are glued to the resonating beams and can achieve periodical raise and recover motions to realize forward movement. Under an applied AC voltage of 4 V, the crawling robot with a total mass of 137 mg can achieve a maximum crawling speed of 232 mm/s (18.9 body lengths per second). As such, this work presents a new efficient direct driving scheme for the legged micro crawling robots.

**Oral Session I : Micro Robots(continued)**

**Grand Ballroom 101 ~ 105 (1F)**

- 10:00    3-D MICRO SWIMMING DRONE WITH MANEUVERABILITY..... 10**  
 Fang-Wei Liu and Sung Kwon Cho  
*University of Pittsburgh, USA*

Wirelessly powered and controllable microscale propulsion in 3-D space is of critical importance to micro swimming drones serving as an active and maneuverable in vivo cargo for medical uses. This article describes a 3-D micro swimming drone navigating in 3-D space, propelled by unidirectional microstreaming flow from acoustically oscillating bubbles. 3-D propulsion is enabled by multiple bubbles with different lengths embedded in different orientations inside the drone body. Each bubble generates propulsion by applying acoustic field at its resonance frequency. Therefore, 3-D propulsion in any direction is achievable by resonating bubbles individually or jointly. The drone with such a complex design was fabricated by a two-photon polymerization 3-D printer. For stable maneuverability, a non-uniform mass distribution of the drone is designed to restore the drone to the designated posture under any disturbances. The restoration mechanism is formulated by a mathematical model, predicting the restoring time and shows an excellent agreement with the experimental results. This 3-D micro swimming drone proves its robustness as a maneuverable microrobot navigating along programmable path in a 3-D space through selective and joint actuation of microbubbles.

- 10:15    Break & Exhibition Inspection**

**Oral Session II : Implantable Devices & Materials**

**Session Chair:**

**Karen Cheung, *University of British Columbia, CANADA***

**Mehmet Cagatay Tarhan, *IEMN, FRANCE***

**Grand Ballroom 101 ~ 105 (1F)**

- 10:45    SIDE-VIEW RAMAN MICROENDOSCOPE WITH MICRO STEPPING MOTOR AND ITS EX-VIVO TEST FOR REAL-TIME CANCER DETECTION..... 14**  
 Sayed Mohammad Hashem Jayhooni<sup>1</sup>, Michael Short<sup>2</sup>, Babak Assadsangabi<sup>1</sup>, Haishan Zeng<sup>2</sup>, and Kenichi Takahata<sup>1</sup>  
<sup>1</sup>*University of British Columbia, CANADA and*  
<sup>2</sup>*BC Cancer Agency Research Centre, CANADA*

This paper reports a microactuator-enabled sideview Raman microendoscope device developed for realtime, angle-resolved screening of cancers growing within narrow lumens including peripheral lung bronchi. A tubular micro stepping motor, assisted with a self-sustained ferrofluid bearing, is custom developed and integrated with a Raman spectroscopic probe via biocompatible packaging for full circumferential step scan of a probing laser beam. The performance of microfabricated prototype is assessed using reference chemicals to show the targeted function for circumferentially localized Raman data collection and analysis. *Ex-vivo* testing was successfully conducted to demonstrate intraluminal Raman analysis in animal bronchi with >99% spectral accuracy in real time.

- 11:00    ULTRA-THIN PARYLENE-C DEPOSITION ON PDMS..... 18**  
 Yaoping Liu<sup>1</sup>, Xiao Dong<sup>1</sup>, Xinyue Deng<sup>1,2</sup>, Thuan Beng Saw<sup>3</sup>, Chwee Teck Lim<sup>3</sup>, Jingquan Liu<sup>4,5</sup>, and Wei Wang<sup>1,4</sup>  
<sup>1</sup>*Peking University, CHINA,*  
<sup>2</sup>*Peking University Health Science Center, CHINA,*  
<sup>3</sup>*National University of Singapore, SINGAPORE,*  
<sup>4</sup>*National Key Laboratory of Science and Technology on Micro/Nano Fabrication, CHINA, and*  
<sup>5</sup>*Shanghai Jiao Tong University, CHINA*

This study reports the ultra-thin Parylene-C deposition on PDMS substrate for a controllable and reliable process of Parylene-C caulked PDMS (pcPDMS). This work covers the depositions on PDMS substrates with different prepolymer ratios (mass of base to curing agent, @ 10:1, 30:1 and 50:1). Stiffness could be modulated in a wide range via the proposed pcPDMS process. The prepared pcPDMS would find applications in biomedical studies, such as mechanobiology.

Oral Session II : Implantable Devices & Materials(continued)

Grand Ballroom 101 ~ 105 (1F)

**11:15 WIRELESS IMPLANTABLE INTRAOCULAR PRESSURE SENSOR WITH PARYLENE-OIL-ENCAPSULATION AND FORWARD-ANGLED RF COIL .....21**

Aubrey Shapero<sup>1</sup>, Abhinav Agarwal<sup>1</sup>, Juan Carlos Martinez<sup>2</sup>, Azita Emami<sup>1</sup>, Mark S. Humayun<sup>2</sup>, and Yu-Chong Tai<sup>1</sup>

<sup>1</sup>California Institute of Technology, USA and

<sup>2</sup>University of Southern California, USA

This paper presents a wireless and implantable intraocular pressure (IOP) sensor with parylene-oil-encapsulation packaging using a novel folded PCB architecture accomplishing practical RF coupling for power and data in a rabbit. The sensor is operated with an air gap of 5 mm between the primary coil and the animal, coupling to an on-chip coil at an input power of 32 dBm at 915 MHz, and can also be operated when the eyelid covers the sensor. Additionally, two novel results for parylene-on-oil deposition in general are presented. First, we show that the thickness of the porous layer of parylene-C (PA-C) and parylene-HT (PA-HT) deposited on silicone oils have a logarithmic decrease in porous layer thickness (PLT) versus silicone oil molecular weight (MW) over a range of 2-139 kDa. Second, we directly verify that parylene-oil-encapsulated pressure sensors retain sensitivity despite material buildup for the first time

**11:30 SELF-POWERED IMPLANTABLE BIO-MEMS: FROM EPILEPSY DIAGNOSIS TO TREATMENT AND MONITORING..... 25**

Yujia Zhang<sup>1,2</sup>, Zhitao Zhou<sup>1</sup>, and Tiger H. Tao<sup>1,2</sup>

<sup>1</sup>Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, CHINA and

<sup>2</sup>University of Chinese Academy of Sciences, CHINA

We report an implantable, biodegradable, and multifunctional system, self-powered with silk-based triboelectric nanogenerators (S-TENGs), for real time in vivo monitoring and therapeutic treatments of epileptic seizures. These S-TENGs are efficient energy harvesters with customizable in vivo operating life and biomechanical sensitivity via synergetic adjustments of silk molecular sizes, surface structuralization, and device configuration. A proof-of-principle S-TENG-based device is built with "smart" treatment triggered by specific epilepsy-induced symptoms and wirelessly mobile-device readout, exhibiting the practical potential of these S-TENGs as self-powered implantable bioelectronics and medical platforms. After completion of functions, S-TENGs are safely resorbed into the body within a programmable period, with post-operation sterilization simultaneously.

**11:45 LOW-COST, LOW-IMPEDANCE POLYIMIDE BASED MICRO-NEEDLE ARRAY (PI-MNA): A MINIMALLY INVASIVE FLEXIBLE DRY ELECTRODE FOR SURFACE BIO-POTENTIAL MONITORING ..... 28**

Junshi Li<sup>1</sup>, Zhengkun Shen<sup>1</sup>, Hancong Wang<sup>2</sup>, Dong Huang<sup>1</sup>, Yufeng Chen<sup>1</sup>, Qun Mou<sup>1</sup>, Fengyi Zheng<sup>1</sup>, Junhua Liu<sup>1</sup>, and Zhihong Li<sup>1</sup>

<sup>1</sup>Peking University, CHINA and

<sup>2</sup>University of Electronic Science and Technology of China, CHINA

In this work, we propose a minimally invasive dry flexible electrode device containing a micro-needle array entirely based on polyimide (PI-MNA) for surface bio-potential sensing and monitoring. Owing to the spiky tips, extensibility and biocompatibility, the gold-coated PI needles are able to penetrate high resistivity stratum corneum to realize low-impedance and nontoxic skin-electrode contact without tedious skin-preparation and severe invasiveness. The PI-MNA was mainly fabricated via twice of conformal moulding technique without any costly or complicated process. A specific data processing system was developed for PI-MNAs, and satisfactory bio-potentials was recorded.

**12:00 Lunch & Exhibition Inspection**

**Oral Session III : Portable Sensors**

Session Chair:

Hongyu Yu, *The Hong Kong University of Science and Technology, HONG KONG*

Jongbaeg Kim, *Yonsei University, KOREA*

Grand Ballroom 101 ~ 105 (1F)

**13:15 MICRO-/NANOFLUIDIC DIFFUSIOPHORESIS PLATFORM FOR SIMPLE CONCENTRATION AND EXTRACTION OF PARTICLES USING IONIC SOLUTIONS..... 32**

Dogyeong Ha, Sang Jin Seo, and Taesung Kim

*Ulsan National Institute of Science and Technology (UNIST), KOREA*

This paper reports a novel diffusiophoresis-based particle manipulator for the concentration and extraction on-demand using a nanochannel-integrated microfluidic channel network fabricated by the crack-photolithography. The nanochannel regulates the physiochemical environments in the microfluidic channel by suppressing convection flows, making it possible to produce a long-term and stable concentration gradient of target solutes over the microchannel. This unique feature facilitates the rapid and dynamic manipulation of chemically driven transport of particles by simply switching ionic solutions. As a result, this platform successfully achieved about 330-fold concentration of 1- $\mu$ m-polystyrene particles in 120 min and their extraction in 10 min with a 95% ratio by simply reverting the concentration gradient of the solutions without any electronic power sources and fluidic controllers.

**13:30 IN-DROPLET CELL MANIPULATION BASED ON DIELECTROPHORETIC POLARITY..... 35**

Song-I Han<sup>1</sup>, Can Huang<sup>1</sup>, Hyun Soo Kim<sup>2</sup>, and Arum Han<sup>1</sup>

<sup>1</sup>*Texas A&M University, USA and*

<sup>2</sup>*Korea Institute of Machinery and Materials, KOREA*

This paper presents a label-free cell manipulation technology within a water-in-oil emulsion droplet using different dielectrophoretic (DEP) polarity acting on cells. As the droplets containing two different types of cells (macrophages and salmonellas) flow downstream, macrophages are gradually pushed away from the edges of a tilted electrode pair by generated negative DEP (nDEP) force, resulting in cell accumulation to lower side of the droplet. While, salmonellas are attracted towards the electrode edges and follow along by generated positive DEP (pDEP) force. The asymmetric Y-junction structure results in passing droplet splitting into two daughter droplets, the lower daughter droplet that contains all or most of macrophages and the upper daughter droplet that salmonellas.

**13:45 DIELECTROPHORETIC CELL SEPARATION USING CONDUCTING SILVER PDMS MICROELECTRODES FEATURING NON-UNIFORM SIDEWALL PROFILE..... 39**

Xiaofeng Nie<sup>1</sup>, Zhongle Zhang<sup>1</sup>, Chengwu Han<sup>2</sup>, Duli Yu<sup>1,3</sup>, and Xiaoxing Xing<sup>1</sup>

<sup>1</sup>*Beijing University of Chemical Technology, CHINA,*

<sup>2</sup>*China-Japan Friendship Hospital, CHINA, and*

<sup>3</sup>*Beijing Advanced Innovation Center for Soft Matter Science and Engineering, CHINA*

This work for the first time uses silver PDMS (AgPDMS) composites to construct 3D microelectrodes featuring non-uniform sidewall profile. Such design enables an innovative dielectrophoretic (DEP) cell sorting device with electrodes and fluidic structures being molded simultaneously and completely made of AgPDMS. The interdigitated electrode digits of the device exhibit inhomogeneous two-layer structure, which projects highly non-uniform electric field that separates cells not only laterally but also vertically along the channel depth. Meanwhile, such design leads to effective focusing of cells under nDEP repulsion. The device has been showcased here for continuous-flow separation of 15  $\mu$ m from 2  $\mu$ m beads, as well as separation of human erythrocytes from similar sized 7  $\mu$ m beads with simultaneous focusing of the particles under nDEP.

Oral Session III : Portable Sensors(continued)

Grand Ballroom 101 ~ 105 (1F)

**14:00 THE COLLECTIVE TRANSPORT OF MICROPARTICLES UNDER AN ASYMMETRIC ELECTRIC FIELD ..... 43**

Masayuki Hayakawa<sup>1</sup>, Yusuke Kishino<sup>2</sup>, and Masahiro Takinoue<sup>2</sup>

<sup>1</sup>Riken Center for Biosystems Dynamics Research, JAPAN and

<sup>2</sup>Tokyo Institute of Technology, JAPAN

In this paper, we describe a collective transport of microparticles emerged in a bottom-up manner. Our transport was spontaneously realized by collision and electrostatic interaction among transported microparticles. Unlike previous technique based on a top-down manner, the microparticles collectively transported even in a condition that there were no biased external force fields. We believe that this work will contribute to the development of the transporting technique with smartness and flexibility in a device of lab-on-a-chip and micro total analysis systems (microTAS).

**14:15**

**Poster & Oral Session I**

**Poster Presentation are listed by topic category with their assigned number starting on page 28.**

**16:15**

**Break & Exhibition Inspection**

Oral Session IV : Acoustic Devices

Session Chair:

Michel Despont, CSEM, SWITZERLAND

Gwenaël Le Rhun, CEA-Leti, FRANCE

Grand Ballroom 101 ~ 105 (1F)

**16:45 PHYSICAL CLEANING TECHNOLOGY FOR SEMICONDUCTOR CHIPS USING ARRAYS OF ACOUSTICALLY OSCILLATING BUBBLES ..... 47**

Daegeun Kim, Deasung Jang, Yuna Park, and Sang Kug Chung

Myongji University, KOREA

This paper presents a new type of physical cleaning technology for removing particles and debris placed in nano/micro structures of semiconductor chips. Synthetic jets and radiation forces generated from acoustically oscillating bubbles filled in microcylinders are utilized for efficient and controllable cleaning tools. The proposed physical cleaning technology can overcome the limitation of current chemical/physical cleaning technologies with minimizing the usage of toxic chemical and the damage of fine structures in semiconductor chips.

**17:00 ACOUSTIC DROPLET EJECTION BY LAMB WAVE TRANSDUCER ARRAY ..... 49**

Yuan Ning, Hongxiang Zhang, Menglun Zhang, Buohua Liu, Xuexin Duan, and Wei Pang

Tianjin University, CHINA

This paper proposes a new regime of acoustic droplet ejection (~30 μm in diameter) without a nozzle. For the first time, the acoustic waves' interference in liquid is achieved by a Lamb Wave transducer array (LWTA). In this case, the initial velocity of droplet exceeds 5.5 m/s at an input power of 8 W. Compared with acoustic streaming effect by surface acoustic wave devices, the acoustic radiation pressure effect by LWTA is more focused and intense. Therefore, the ejected droplet is smaller and its velocity is higher. Interestingly, simulation reveals that the focusing region in liquid forms a line instead of a point.

**17:15 DEMONSTRATION OF THE FIRST SELF-SEALING AEROSOL SPRAY NOZZLE FOR MEDICAL DRUG DELIVERY ..... 53**

Torben Sebastian Last, Göran Stemme, and Niclas Roxhed

KTH Royal Institute of Technology, SWEDEN

Portable medical inhaler systems are prone to bacterial contamination and ingrowth. Here we demonstrate the first valved aerosol spray chip, a system that sprays a microjet when actuated and seals against bacterial ingrowth into the spray nozzle in the closed state by a sufficiently small gap. The sealing mechanism is realized by placing a valve seat directly underneath the spray orifices. We fabricated and characterized spray chips with and without valve mechanism and show that they have indistinguishable spray performance. Our system aims to enable the safe reuse of spray chips for multiple spray operations over an extended period, lowering the cost of treatment while increasing patient compliance.

**Oral Session IV : Acoustic Devices(continued)****Grand Ballroom 101 ~ 105 (1F)****17:30 ACOUSTIC TWEEZERS FOR TRAPPING LATE-STAGE ZEBRAFISH EMBRYOS ..... 57**

Lurui Zhao and Eun Sok Kim  
*University of Southern California, USA*

This paper reports our recent design of an immersive acoustic tweezers capable of trapping and holding large and heavy particles such as micro-particles up to 1 mm in diameter, as well as zebrafish embryos at their 24 - 36 hours post fertilization, by developing a 3-dimensional energy well in the bulk of liquid medium. The acoustic tweezer is built on a 2.03 mm thick lead zirconate titanate (PZT) substrate and operated at its thickness mode, with 18 symmetric beamforming sectors (pie shaped when viewed from top) arranged for 3 focal lengths (17.0, 18.5 and 20 mm). For a single focal length, the six beamforming sectors (with air-cavity-reflectors for eliminating out-of-phase wave interference) work together as a sectored Fresnel lens. The acoustic waves aiming at different focal lengths interfere with each other such that they produce a Bessel beam zone (with negative axial radiation force) along the center line perpendicular to the transducer surface, which works as the energy well for trapping and holding particles. The tweezers using 1.17 MHz ultrasound shows strong trapping capability and large trapping zone, and is capable of trapping and holding late-stage zebrafish embryos (0.7 - 1mm in diameter and 1.3 - 1.5 mg in weight). The fabricated acoustic tweezers has been shown to trap 24hours-postfertilization zebrafish embryos when it is placed either horizontally or vertically.

**17:45 DIRECT MODULATION PIEZOELECTRIC MICRO-MACHINED ULTRASONIC TRANSDUCER SYSTEM (DMUT) ..... 61**

Flavius V. Pop, Bernard Herrera, Cristian Cassella, and Matteo Rinaldi  
*Northeastern University, USA*

This paper demonstrates, for the first time, a new underwater communication scheme based on the Direct Modulation (DM) of an array of piezoelectric Micro-Machined Ultrasonic Transducers (MUT). The use of this new modulation scheme permits to achieve more efficient data transmission compared to what could be attained through conventional continuous waves-based (CW) driving approaches. In addition, as the received information can be extracted without the employment of mixers or amplifiers, it enables lower power consumption and low noise-figures. In this work, we report on the performance of the first dMUT-prototype. This system, which relies on a Bipolar Junction Transistor (BJT) to periodically connect and disconnect an array of pMUTs to a DC-biased filter (Fig. 1), exhibits power consumption of 140mW and enables transmitted energy-per-bit of 0:7 $\mu$ J. Such a value is two orders-of-magnitude more efficient than what attained through conventional communication approaches for underwater networks [1, 2, 3].

**18:00 Adjourn for the Day**

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**TUESDAY, JANUARY 29**

**07:00 Registration Lobby (1F)**

**08:00 IEEE Bosch Award Ceremony Grand Ballroom 101 ~ 105 (1F)**

**PLENARY PRESENTATION II**

Session Chair:

*Jun-Bo Yoon, Korea Advanced Institute of Science and Technology (KAIST), KOREA*

**Grand Ballroom 101 ~ 105 (1F)**

**08:30 SOFT AND WEARABLE TRANSDUCERS: OPPORTUNITIES AND CHALLENGES FOR DAILY USE..... 65**

**Stéphanie P. Lacour**  
*EPFL, SWITZERLAND*

**Oral Session V : Power MEMS**

Session Chair:

*David Horsley, University of California, Davis, USA*

**Grand Ballroom 101 ~ 105 (1F)**

**09:30 A SELF-POWERED PHYSICAL SENSOR USING GENETICALLY ENGINEERED SPIDER SILK PROTEINS ..... 66**

Yujia Zhang<sup>1,2</sup>, Tiger H. Tao<sup>1,2</sup>, and Zhitao Zhou<sup>1</sup>  
<sup>1</sup>*Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, CHINA and*  
<sup>2</sup>*University of Chinese Academy of Sciences, CHINA*

We report a biocompatible triboelectric material with programmable triboelectric property, multiple functionalization, large-scale fabrication capability and transcendent output performance, by genetically engineering the recombinant spider silk proteins (RSSP). Featuring totally “green” large-scale manufacturing, we introduce a water lithography (WL) technique to the RSSP triboelectric nanogenerators (RSSP-TENG) with facily adjustable surface morphologies, chemically modifiable surface properties, and controllable protein conformations. By virtue of the high electrical power, a proof-of-principle self-powered force sensor is built, showing outstanding sensitivity between input force and output voltage, simultaneously indicated with various LEDs. This work provides a novel high performance biomaterial-based TENG and extends its potential for multifunctional applications.

**09:45 NiCo<sub>2</sub>O<sub>4</sub>@MnO<sub>2</sub> DOUBLE NANOSTRUCTURES GROWN ON ETCHED NICKEL WIRE FOR FIBER-SHAPED SUPER-CAPACITORS APPLICATIONS ..... 69**

Jing Zhang and Kwang-Seok Yun  
*Sogang University, KOREA*

We report a “dual nanostructures” where MnO<sub>2</sub> nano-hairs cover NiCo<sub>2</sub>O<sub>4</sub> nano-needles forming NiCo<sub>2</sub>O<sub>4</sub>@MnO<sub>2</sub> double nanostructures. The NiCo<sub>2</sub>O<sub>4</sub>@MnO<sub>2</sub> double nanostructures were synthesized by simple two-steps hydrothermal synthesis on the etched surface of nickel (Ni) wire. These structures were applied to form high capacity of fiber-shaped super-capacitor which was fully fabricated and demonstrated in this work.

Oral Session V : Power MEMS(continued)

Grand Ballroom 101 ~ 105 (1F)

**10:00    PIEZOELECTRET MECHANOCATALYSTS FOR DIRECT WATER SPLITTING VIA ULTRASONICATION .....71**

Neil Ramirez<sup>1</sup>, Junwen Zhong<sup>1,2</sup>, and Liwei Lin<sup>1,2</sup>

<sup>1</sup>*University of California, Berkeley, USA and*

<sup>2</sup>*Tsinghua-Berkeley Shenzhen Institute, Berkeley, USA*

This work reports the first use of polymeric piezoelectret films for direct water splitting using ultrasonication as the driving mechanism. Piezoelectret devices are analogous to piezoelectret ceramic materials which produce electrical charges in response to mechanical stimulus. Water splitting has gained increasing attention as an alternative for producing renewable hydrogen energy. Hydrogen energy has high energy conversion efficiency and does not contribute to the harmful greenhouse gas effect that is responsible for various environmental hazards such as climate change, acid rain, and smog. The piezoelectret device is made of a polymer with charged microscopic dipoles that is bounded by metal electrodes. Ultrasonication is used to produce mechanical stimulus on the device which then generate a voltage on the surface of the metal electrode layers. This voltage catalyzes the water splitting reaction to produce hydrogen from water. Our process achieves water splitting without complicated thermal annealing (in contrast to previous work using piezoelectric ceramics) and does not use complicated transformer circuits. We show voltage measurements from mechanical stimulus to demonstrate that the device voltage can surpass the 1.23 V required to catalyze the water splitting reaction. Additionally, hydrogen quantification is conducted using Gas Chromatography (GC). Based on the analysis, the device has potential for passive energy harvesting of vibrational motion in liquid media such as tidal motions in the ocean.

**10:15    Break & Exhibition Inspection**

**Oral Session VI : On-Site Detection and Monitoring**

Session Chair:

*Jens Ducreé, Dublin City University, IRELAND*

*Arum Han, Texas A&M University, USA*

Grand Ballroom 101 ~ 105 (1F)

**10:45    A SMARTPHONE-BASED PORTABLE SYSTEM FOR RAPID DETECTION OF PATHOGENS ..... 75**

Yu-Dong Ma, Kuang-Hsien Li, Yi-Hong Chen, Yung-Mao Lee, Po-Chiun Huang, Hsi-Pin Ma, and Gwo-Bin Lee

*National Tsing Hua University, TAIWAN*

This study presents a smartphone-based portable system for rapid, automatic detection of pathogens (viruses and bacteria) utilizing a molecular diagnosis process. The complicated procedure including pathogen purification, isothermal nucleic acid amplification and optical detection could be carried out automatically with a smartphone on a self-driven, passive microfluidic chip utilizing a new punching-press mechanism. A lowtemperature pathogen lysis process was adopted such that flow could be precisely controlled on the passive microfluidic chip. The detection results were colorimetrically observed or could be analyzed by an integrated color sensor. This is the first time that an automated portable system was demonstrated which could perform accurate and sensitive molecular diagnosis for either viruses or bacteria within 35 min.

**11:00    ENTIRELY-3D PRINTED MICROFLUIDIC PLATFORM FOR ON-SITE DETECTION OF DRINKING WATERBORNE PATHOGENS ..... 79**

Eric Sweet, Nathaniel Liu, Juhong Chen, and Liwei Lin

*University of California, Berkeley, USA*

This work presents a novel handheld, manually-actuated microfluidic prototype designed for on-site colorimetric detection of infectious pathogens in drinking water. We have also developed a custom drop-casting protocol we use to pre-load the entirely 3D printed device, fabricated *via* ultra-high resolution additive manufacturing technology, with colorimetric enzymatic reagents and bacteria-specific nutrients, which we use to experimentally detect *Escherichia coli* (*E. coli*) bacteria in model drinking water, as well as to determine a limit of detection of 1e6 cfu/mL of *E. coli* in 6 hours. Our proposed microfluidic platform will enable entirely on-site water quality testing, eliminating the need for off-site, lab-based water sample analysis, thus significantly increasing analytical throughput. Furthermore, we have developed a design methodology for engineers to customize the number of desired on-chip pathogen detection chambers, enabling multiplexed detection of multiple pathogens.

**Oral Session VI : On-Site Detection and Monitoring(continued)**

**Grand Ballroom 101 ~ 105 (1F)**

**11:15 POINT OF CARE TESTING CHIP FOR MULTIPLE VIRUS INFECTION DETECTION USING LAMP..... 83**

Yusuke Kimura, Masashi Ikeuchi, Yoshinori Inoue, and Koji Ikuta  
*The University of Tokyo, JAPAN*

Here, we developed a portable microdevice for the simple and early detection of viral infections via the loop-mediated isothermal amplification (LAMP) method, as a point-of-care testing (POCT) method. This microdevice can simultaneously check 16 species of viral infection by observing fluorescence intensity, either by the naked eye or using a smartphone photo sensor. It requires only 1% of conventional sample amounts, and can run using a small battery. We also developed a simple system for simultaneously applying samples to 16 wells. Basic performance was verified using a dengue virus detection experiment, and the specific reaction was successfully confirmed following application of dengue virus RNA samples.

**11:30 A CONTACTLESS MICROMACHINED RESPIRATORY SENSOR USING POSITIVE TEMPERATURE COEFFICIENT MATERIAL ..... 87**

Chao-Chi Yeh, Ming-Xin Xu, and Yao-Joe Yang  
*National Taiwan University, TAIWAN*

In this work, we present an ultra-sensitive temperature sensor for non-contact real-time respiratory monitoring. The sensing element of the proposed device is an acrylate-based temperature sensing material with positive temperature coefficient (PTC) deposited on an interdigital electrode pair. The acrylate-based material exhibits an order-of-magnitude variation in resistivity over a temperature change of a few degrees, and was capable of detecting tiny temperature changes induced by exhalation air flow. The transient behaviors of the fabricated device were measured. Also, the effects on different room temperatures and positions of the sensor were measured and discussed. The fabricated device possesses the advantages such as low cost, energy efficient, and simple operation compared to common existing methods.

**11:45 MEMS 2020 Announcement**

**12:00 Lunch & Exhibition Inspection**

**Oral Session VII : Force & Pressure Sensing**

Session Chair:

**Honglong Chang, Northwestern Polytechnical University (NPU), CHINA**

**Gianluca Piazza, Carnegie Mellon University, USA**

**Grand Ballroom 101 ~ 105 (1F)**

**13:15 MAXIMIZING PERCOLATION EFFECT USING SUB-100NM NANO-VALLEY FOR HIGH PERFORMANCE WEARABLE TRANSPARENT PRESSURE SENSOR ..... 91**

Jae-Young Yoo, Min-Ho Seo, Jae-Shin Lee, Kwang-Wook Choi, Min-Seung Jo, Hyeon-Joo Song, and Jun-Bo Yoon  
*Korea Advanced Institute of Science and Technology (KAIST), KOREA*

This paper reports a high-sensitivity wearable transparent pressure sensor by maximizing the percolation effect using a sub-100 nm nano-valley. The secret to achieving high sensitivity is to make the nano-valley as narrow as possible to maximize the percolation effect (stress concentration effect). The narrow nano-valley pressure sensor showed a remarkable 400% enhancement in sensitivity compared to a sensor with no nano-valley while maintaining a high transmittance of 83%. This sensitivity value is higher than those of the previous wearable transparent pressure sensors. The fabricated sensor also showed high durability with low variation of 1.2% in repeated pressing of up to 100,000 times under 100 kPa pressure.

**Oral Session VII : Force & Pressure Sensing(continued)**

**Grand Ballroom 101 ~ 105 (1F)**

**13:30 UNDERWATER PITOT TUBE FOR SWIMMING ANIMALS ..... 95**

T. Hagiwara, H. Takahashi, T.-V. Nguyen, T. Takahata, and I. Shimoyama  
*The University of Tokyo, JAPAN*

This paper reports on an underwater Pitot tube which is designed for swimming measurement of marine animals. The tubes of the Pitot tube are filled with incompressible liquid and sealed by thin films so that the device can be used even when plunged into water. The Pitot tube has a pressure sensor inside that consists of a piezoresistive cantilever incorporated into a thin Parylene-C membrane. When a water flow is applied to the Pitot tube, the thin films at the inlets act as elastic membranes and the liquid filled in the tubes transmits the pressure to the pressure sensor. The proposed Pitot tube can be used as a water flow speedometer for biological studies of marine animals.

**13:45 POLYCRYSTALLINE SENSE LAYER FOR MAGNETIC TUNNEL JUNCTION (MTJ) AS ULTRASENSITIVE SENSING ELEMENT FOR MEMS PRESSURE SENSORS..... 99**

Akhil K Ramesh, Vaibhav Rana, Pintu Das, and Pushparaj Singh  
*Indian Institute of Technology Delhi, INDIA*

This paper reports Magnetic Tunnel Junctions (MTJ) based spintronic MEMS pressure sensor with polycrystalline magnetostrictive sense layer producing huge gauge factor. This layer of the MTJ converts the stress into the magnetic polarization. The trade-off between ferromagnetic behavior of polycrystalline thin films and magnetostriction is addressed for the first time in a MEMS pressure sensor. The sense layer behavior for MTJ with 1nm thick MgO tunnel barrier sandwiched between CoFeB thin films is discussed. TMR value is much more than 200% for polycrystalline sense layers and the analytical model shows how the increase in TMR value increases the gauge factor to 3406 in a range of 600 mbar pressure.

**14:00 NOVEL METHOD FOR SIMULTANEOUSLY IMPLEMENTING “WIRED FACE-UP AND FACE-DOWN CHIPS” ON A FILM SUBSTRATE BY USING SIMPLE SCREEN-OFFSET PRINTING ..... 103**

Yusuke Takei, Ken-ichi Nomura, Yoshinori Horii, Daniel Zymelka, Hirobumi Ushijima, and Takeshi Kobayashi  
*National Institute of Advanced Industrial Science and Technology (AIST), JAPAN*

We realized the implementation of an ultrathin piezoresistive Si chip and stretchable wires on a flexible film substrate by using simple screen-offset printing technology. This process does not require a special MEMS fabrication equipment (photolithography, etching, chip mounter etc.) and is applicable to Face-up chip where electrodes are formed on the top surface of the chip, as well as to Face-down chips where electrodes are formed on the bottom surface of the chip. This fabrication process is quite useful in the field of Flexible Hybrid Electronics (FHE) as a method for mounting and wiring electronic components. As its application, 5µm-thick piezoresistive Si chips were transferred and wired on a polyimide film tape using screen-offset printing, a bandplaster type blood pulse sensor was fabricated. We successfully demonstrated that the blood pulse can be measured with neck and wrist.

**14:15 Poster & Oral Session II  
 Poster Presentation are listed by topic category with their assigned number starting on page 28.**

**16:15 Break & Exhibition Inspection**

**Oral Session VIII : Microfluidics and Bioengineering**

Session Chair:

Hiroaki Onoe, *Keio University, JAPAN*  
 Bhaskar Choubey, *University of Siegen, GERMANY*

**Grand Ballroom 101 ~ 105 (1F)**

**16:45 SELF-ASSEMBLED NANOCHAMBER ARRAYS FOR IN-SITU TEM OBSERVATION OF LIQUID-PHASE SAMPLES ..... 105**

Kitaek Lim<sup>1</sup>, Yuna Bae<sup>2,3</sup>, Kihwan Kim<sup>1</sup>, Sungho Jeon<sup>1</sup>, Byunghyo Kim<sup>2,3</sup>, Jungwon Park<sup>2,3</sup>, and Won Chul Lee<sup>1</sup>

<sup>1</sup>*Hanyang University, KOREA,*

<sup>2</sup>*Seoul National University, KOREA, and*

<sup>3</sup>*Institute for Basic Science, KOREA*

This work presents a highly-ordered array of nanoscale chambers, capable of encapsulating liquid samples for TEM (transmission electron microscopy) imaging. The present nanochambers are formed with two layers of free-standing graphene and self-assembled nanopores in an AAO (anodic aluminum oxide) membrane, which improve a transparency for electron beam and uniformities in chamber sizes/distributions, respectively. We envision that the present work will enable us to efficiently observe nanoscale processes in liquid with high resolution TEM.

**17:00 ARTIFICIAL CELL ON A CHIP INTEGRATED WITH PROTEIN DEGRADATION .....107**

Taishi Tonooka<sup>1</sup>, Henrike Niederholtmeyer<sup>2</sup>, Lev Tsimring<sup>2</sup>, and Jeff Hasty<sup>2</sup>

<sup>1</sup>*Kyoto Institute of Technology, JAPAN and*

<sup>2</sup>*University of California, San Diego, USA*

This paper reports a microfluidic artificial cell system integrated with protein degradation. Previous artificial cells constructed in microfluidic devices only mimicked protein production. However, protein degradation is also important to reconstitute more complex cellular systems. Here, we realized, for the first time, artificial cells on a chip that can both produce and degrade proteins by adding a protein degradation system to the previous cell-free protein expression system in microchambers. Using the developed artificial cell on a chip, an oscillatory gene circuit requiring production and degradation of proteins was demonstrated.

**17:15 RECONFIGURABLE MICROFLUIDICS IN A RUBIK'S CUBE ..... 110**

Xiaochen Lai, Penghao Zhang, Xingguo Zhang, Hao Wu, Zhihua Pu, Haixia Yu, and Dachao Li

*Tianjin University, CHINA*

A Rubik's cube as a reconfigurable microfluidic system is presented in this work. Composed of physically interlocking microfluidic blocks, the microfluidic cube enables on-site design and configuration of custom microfluidics by means of turning the faces of the cube. The reconfiguration of the microfluidics could be done in the way of solving an ordinary Rubik's cube, with the help of Rubik's algorithms and computer programs. An O-ring aided strategy is used to enable self-sealing and automatic alignment of the microfluidic cube blocks. The proposed cube exhibits good reconfigurability and robustness in versatile microfluidic applications and is proved to be a promising candidate for setting up microfluidic platforms in resource-limited settings.

**Oral Session VIII : Microfluidics and Bioengineering(continued)**

**Grand Ballroom 101 ~ 105 (1F)**

**17:30     DIRECT CHEMICAL DETECTION IN A MICROCHANNEL WITH A NANONEEDLE-BASED BIOLOGICAL NANOPORE PROBE..... 114**

Kan Shoji<sup>1,2</sup>, Ryuji Kawano<sup>1</sup>, and Ryan J. White<sup>2</sup>  
<sup>1</sup>*Tokyo University of Agriculture and Technology, JAPAN and*  
<sup>2</sup>*University of Cincinnati, USA*

This paper describes the development of a spatially-resolved biological nanopore probe which pore-forming proteins are reconstituted in a bilayer lipid membrane (BLM) supported on a poly-ethylene glycol (PEG)-modified nanoneedle and the demonstration of chemical detection in an H-shaped microchannel with the probe. Recently, biological nanopore probes (BNPs) that can simultaneously measure chemical and topography information using the  $\alpha$ -hemolysin ( $\alpha$ HL) nanopore supported on a pulled-pipette probe were developed. Although BNPs have a potential to provide spatially-resolved imaging, the resolution is limited in comparison to state-of-the-art scanning probe microscopies because of the pipette size ( $\sim 30 \mu\text{m}$  O.D.). In this study, we developed a nanoneedle-based BNP which the PEG monolayer supports the BLM, the pore-forming membrane proteins are reconstituted on the tip of the nanoneedle. Furthermore, we demonstrated the detection of chemical in the microchannel using the nanoneedle-based BNP. We believe that our BNP has a potential as a living cell imaging system that can measure chemicals and topography with nanometer resolution.

**17:45     THIN LAYERED HETEROGENEOUS VASCULARIZED 3D TISSUE MODELS CONSTRUCTED WITH SEPARATED-LAYER COLLAGEN MICROTUBE..... 118**

Shun Itai and Hiroaki Onoe  
*Keio University, JAPAN*

We present an *in vitro* vascularized 3D cell co-culture, performed by a separated-layer collagen microtube device. Our device can co-culture endothelial and other cells in close position, while the collagen layers are separated into an outer support layer and an inner culture layer. The close distance between different types of cells enhances mutual cell interaction and enables us to observe the tissue structures clearly. Moreover, while collagen tubes are directly attached to silicone tubes, perfusion culture is easily performed by an external pump system. We believe that our device could help the fabrication of various vascularized tissue models in high activity, and contribute to the development of pharmacokinetic testing platforms and regenerative medicine.

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**18:00     Adjourn for the Day**

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**WEDNESDAY, JANUARY 30**

**07:00 Registration Lobby (1F)**

**07:30 WIE Session 202 (2F)**

**PLENARY PRESENTATION III**

Session Chair:

*Shoji Takeuchi, The University of Tokyo, JAPAN*

**Grand Ballroom 101 ~ 105 (1F)**

**08:30 MEMS SENSORS FOR ROBOTS..... 120**

**Isao Shimoyama**

*The University of Tokyo, JAPAN*

**Oral Session IX : Emerging RF Applications**

Session Chair:

*Matteo Rinaldi, Northeastern University, USA*

**Grand Ballroom 101 ~ 105 (1F)**

**09:30 TOWARDS DIGITALLY ADDRESSABLE DELAY SYNTHESIS: GHZ LOW-LOSS ACOUSTIC DELAY ELEMENTS FROM 20 NS TO 900 NS..... 121**

Ruochen Lu, Tomas Manzaneque, Yansong Yang, Ming-Huang Li, and Songbin Gong  
*University of Illinois, Urbana-Champaign, USA*

We present the first group of GHz S0 mode low-loss acoustic delay lines covering a wide range of delays from 20 ns to 900 ns for digitally addressable delay synthesis. The fabricated miniature acoustic delay lines show a fractional bandwidth of 4%, a minimum insertion loss of 3.2 dB, outperforming the incumbent surface acoustic wave counterparts. Multiple acoustic delay lines with center frequencies from 0.9 to 2 GHz have been demonstrated, underscoring their great frequency scalability. The acoustic delay lines use single-phase unidirectional transducers design to launch and propagate the S0 mode in an X-cut lithium niobate thin film with large electromechanical coupling and low damping. The demonstrated acoustic delay lines can enable wide-range and high-resolution delay synthesis that is highly sought-after for the self-interference cancellation in full-duplex radios.

**09:45 WI-FI-BAND MICRO ACOUSTIC RESONANT CIRCULATOR..... 125**

Yao Yu and Matteo Rinaldi  
*Northeastern University, USA*

This paper reports on the first demonstration of a magnetic-free miniaturized micro acoustic resonant circulator showing low insertion loss (IL~3.6 dB), high isolation (IX>15 dB) and high linearity (P1dB=29.4 dBm; IIP3=37 dBm) across the entire ISM Wi-Fi band (2.4-2.5 GHz). Such an unprecedented level of performance is achieved thanks to a novel circuit architecture based on 2.4 GHz piezoelectric micro-acoustic filters periodically modulated to achieve non-reciprocity. The use of high-Q micro-acoustic filters guarantees the achievement of a large group delay and an IL significantly lower than that of circulators based on transmission lines (TLs) or acoustic delay lines [1,2], while maintaining a significantly smaller form factor, enabling strong magnetic-free non-reciprocity at the chip-scale with an ultra-low modulation frequency (12 MHz). RF switches are used as time-varying components to impart the periodic modulation. Compared to the more conventional varactors [3], the use of RF switches simplifies the modulation network, increases the modulation efficiency and significantly improves the system linearity. The demonstrated magnetic-free miniaturized circulator directly enables simultaneous transmit and receive (STAR) operation in full-duplex mode with the potential of at least doubling the data rates of existing Wi-Fi networks.

**Oral Session IX : Emerging RF Applications(continued)**

**Grand Ballroom 101 ~ 105 (1F)**

**10:00 NEMS ELECTROSTATIC RESONANT NEAR-ZERO POWER RESISTIVE CONTACT RF WAKE-UP SWITCH WITH PT FIB CONTACT ..... 129**

Alexander Ruyack, Benyamin Davaji, Leanna Pancoast, Nabil Shalabi, Alyosha Molnar, and Amit Lal  
*Cornell University, USA*

This paper reports a NEMS electrostatic RF wake-up switch capable of detection sensitivity reaching -25 dBm off resonance with sub-pW passive power consumption at less than 1.5V DC operation. The switch utilizes a multielectrode design allowing for a mechanical contact gap to be held just outside thermal oscillations and RF input to physically close the switch. This allows for operation away from pull-in and improves RF sensitivity. A focused ion beam (FIB) patterned platinum-platinum contact point enables the low DC bias requirement and improves contact resistance and longevity. The potential for on-resonance operation provides a pathway forward for improved RF sensitivity in the future.

**10:15 Break & Exhibition Inspection**

**Oral Session X : Chemical and GAS Sensors**

**Session Chair:**

*Ryan Sochol, University of Maryland, USA*

**Grand Ballroom 101 ~ 105 (1F)**

**10:45 CHIP-SCALE MEMS-CMOS MULTISPECTRAL INFRARED CHEMICAL SENSOR..... 133**

Sungho Kang, Zhenyun Qian, Vageeswar Rajaram, Sila Deniz Caliskan, and Matteo Rinaldi  
*Northeastern University, USA*

This paper reports on an ultra-miniaturized multispectral infrared (IR) chemical sensor based on an array of plasmonically-enhanced MEMS resonant IR detectors and a single multiplexed CMOS IC readout. The unique combination of such a piezoelectric-plasmonic MEMS sensing technology with a low-power CMOS read-out circuitry results in a frequency-domain IR spectrometer microsystem characterized by an ultra-miniaturized footprint (total chip area of  $\approx 1.53\text{mm}^2$ ), low power consumption ( $\approx 1.07\text{mW}$ ), and fast response ( $<100\text{ms}$  per spectral scan). Thanks to the excellent IR detection capability (noise equivalent power, NEP  $\approx 402 \text{ pW/Hz}^{1/2}$  and thermal time constant,  $\tau \sim 7.3 \text{ ms}$ ) and the plasmonic-enabled high spectral resolution ( $\lambda_0 = 3\sim 6 \mu\text{m}$ , full-width-at-half-maximum,  $FWHM < 890 \text{ nm}$ ), the CMOS-MEMS spectrometer prototype can discriminate between acetone and hexane via transmission spectroscopy. These results prove a great potential for the development of fast, accurate, and ultra-miniaturized IR spectrometer microsystems suitable for mobile IR characteristic measurements.

**11:00 STATISTICS-BASED GAS SENSOR..... 137**

Shakir-ul Haque Khan, Aishwaryadev Banerjee, Samuel Broadbent, Ashrafuzzaman Bulbul, Michelle Camilla Simmons, Kyeong Heon Kim, Carlos H. Mastrangelo, Ryan Looper, and Hanseup Kim  
*University of Utah, USA*

This paper reports a new proof-of-concept gas sensor based on statistical behavior of multiple gas molecules. The reported gas sensor, consisting of a tiny gap, provides on/off switching behavior as it captures the target gas molecules. The key innovation lies in the fact that such an on/off switching becomes statistically-reliable when multiple gaps and molecules are utilized. Such a statistics-based gas sensor was demonstrated by fabricating multiple nano-gap arrays, coating the gaps with specific chemistry linkers, and monitoring the reliability of the performance as well as other variables. The fabricated sensors in 1x1, 5x5 and 9x9 arrays showed statistics-based trends of (1) increasing decisiveness (sharper on/off slopes vs. concentrations), (2) decreasing failures (increasing repeatability) and (3) lower off-switching speed. The fabricated sensors also resulted in (4) ultra-low power of  $<1\text{nW}$  due to normally-off operation.



Oral Session X : Chemical and GAS Sensors(continued)

Grand Ballroom 101 ~ 105 (1F)

**11:15 SURFACE-ENHANCED INFRARED ABSORPTION-BASED CO<sub>2</sub> SENSOR USING PHOTONIC CRYSTAL SLAB ..... 141**

Yuhua Chang, Dihan Hasan, Bowei Dong, Jingxuan Wei, Yiming Ma, Guangya Zhou, Kah Wee Ang, and Chengkuo Lee  
National University of Singapore, SINGAPORE

Surface-enhanced infrared absorption (SEIRA) technique has been focusing on the metallic resonator structures for decades while the dissipative loss and strong heating from metal are the intrinsic drawbacks. Meanwhile, gas sensor is also challenging for SEIRA because of the small size and weak absorption of gas. This paper reports an all dielectric photonic crystal slab (PCS) platform integrated with gas selective enrichment polymer polyethylenimine (PEI) as a miniaturized gas sensor, achieving a detection limit of 20 ppm and a fast response time of 2 min in CO<sub>2</sub> sensing.

**11:30 CRUMPLED AND STRETCHABLE GRAPHENE GAS SENSOR WITH ENHANCED SENSITIVITY TO HYDROGEN ..... 145**

Zhichun Shao<sup>1</sup>, Takeshi Hayasaka<sup>1</sup>, Huiliang Liu<sup>2</sup>, Jiaming Liang<sup>2</sup>, Yichuan Wu<sup>2</sup>, and Liwei Lin<sup>1,2</sup>  
<sup>1</sup>University of California, Berkeley, USA and  
<sup>2</sup>Tsinghua-Berkeley Shenzhen Institute, Shenzhen, CHINA

We have successfully demonstrated a stretchable gas sensor with enhanced sensitivity to hydrogen based on crumpled graphene structures. Compared with the state-of-art technologies, three distinctive advancements have been achieved: (1) enhanced sensitivity to hydrogen based on the crumpled graphene at room temperature; (2) a model on the enhanced sensing mechanism on the crumpled graphene surface; and (3) stretchable gas sensor utilizing crumpled graphene with up to 200% stretchability. As such, the proposed sensing scheme and results could open up a new class of graphene-based, stretchable gas sensing systems for environmental and biological monitoring.

**11:45 ALD-RuO<sub>2</sub> FUNCTIONALIZED GRAPHENE FET WITH DISTINCTIVE GAS SENSING PATTERNS ..... 149**

Takeshi Hayasaka<sup>1</sup>, Vernalyn C. Copa<sup>1,2</sup>, Lorenzo P. Lopez Jr.<sup>1,2</sup>, Regine A. Loberternos<sup>1,2</sup>, Lauren Ida M. Ballesteros<sup>1,2</sup>, Albert Lin<sup>1</sup>, Yoshihiro Kubota<sup>1</sup>, Huiliang Liu<sup>1,3</sup>, Arnel A. Salvador<sup>2</sup>, and Liwei Lin<sup>1,3</sup>  
<sup>1</sup>University of California, Berkeley, USA,  
<sup>2</sup>University of the Philippines Diliman, PHILIPPINES, and  
<sup>3</sup>Tsinghua-Berkeley Shenzhen Institute, Tsinghua University, CHINA

This work reports distinctive gas sensing patterns for water vapor and methanol using graphene FET (Field Effect Transistors) functionalized with atomic layer deposition (ALD) RuO<sub>2</sub>. Compared with the state-of-art, three distinctive advancements have been achieved: (1) enhanced sensitivity using the scheme of electron mobility characterizations by a hybrid structure of graphene and ALD-RuO<sub>2</sub> base layer; (2) first demonstration of gas sensing by means of the 4-dimensional (4D) physical properties vectors of graphene FETs; (3) using the 16- dimensional (16D) characteristic gas sensing pattern to distinguish water vapor and methanol. As such, the device structure and the multi-dimensional physical properties vectors could offer robust gas classification schemes for gas sensing applications.

**12:00 Lunch & Exhibition Inspection**

**13:15 Poster & Oral Session III**

**Poster Presentation are listed by topic category with their assigned number starting on page 28.**

**15:15 Break & Exhibition Inspection**

**Oral Session XI : Resonators**

Session Chair:

Sheng-Shian Li, *National Tsing Hua University, TAIWAN*

Deepak Uttamchandani, *University of Strathclyde, Glasgow, UK*

**Grand Ballroom 101 ~ 102 (1F)**

**15:45 WIDELY TUNABLE 20-NM-GAP RUTHENIUM METAL SQUARE-PLATE RESONATOR ..... 153**

Alper Ozgurluk, Kieran Peleaux, and Clark T.-C. Nguyen  
*University of California, Berkeley, USA*

A capacitive-gap transduced flexural-mode square-plate resonator constructed in rapid-thermal-annealed (RTA'ed) ruthenium metal posts quality factors ( $Q$ 's) exceeding 5000 and an impressive transducer strength  $C_x/C_o$  (equivalent to  $k_t^2$ ) of up to 71% intrinsic and 36% with 55fF of bond capacitance loading, which in turn permits more than 46% voltage-controlled resonance frequency tuning (from 18.005 to 9.713MHz) with a voltage excursion from 0.5 to 2.8V. The 36%  $C_x/C_o$  is 75 times larger than the 0.48% of published AlN piezoelectric material in this HF frequency range [1]. With processing temperatures potentially below 350°C (with localized annealing), this metal resonator is amenable to integration directly over even advanced node CMOS [2], making this technology attractive for single-chip widely tunable filter and oscillator applications, e.g., for wireless communications [3].

**16:00 THERMAL PIEZORESISTIVE BACK ACTION ENHANCEMENT USING AN INNOVATIVE DESIGN OF SILICON NANOBEAM ..... 157**

Pierre Janioud<sup>1,2</sup>, Alexandra Koumela<sup>1</sup>, Christophe Poulain<sup>1</sup>, Stephan Louwers<sup>1</sup>, Carine Ladner<sup>1</sup>,  
Panagiota Morfouli<sup>2</sup>, and Guillaume Jourdan<sup>1</sup>  
<sup>1</sup>*CEA-Leti, FRANCE and*  
<sup>2</sup>*Univ. Grenoble Alpes, IMEP-LAHC, FRANCE*

Over the last few years, Thermal Piezoresistive Back Action (TPBA) in biased silicon nanobeams has demonstrated its potential to control the quality factor of resonant sensors and its ability to reach self-sustained oscillations regime. This paper reports an innovative beam geometry to improve TPBA efficiency, which consists of a thermal plate embedded in a silicon nanobeam used to implement TPBA. The plate increases the thermal inertia of the beam and consequently its thermal time constant that directly enhances TPBA. As a result, the efficiency of TPBA is considerably enhanced and the DC-Current biasing threshold, required to reach self-sustained oscillations regime, is substantially reduced saving up to one order of magnitude on energy consumption. This kind of beam can supersede regular nanobeam in most nanobeam based devices to improve TPBA efficiency with negligible changes on their mechanical and electrical behaviors.

**16:15 A TEMPERATURE-INSENSITIVE CMOS-MEMS RESONATOR UTILIZING ELECTRICAL STIFFNESS COMPENSATION ..... 161**

Jia-Ren Liu and Wei-Chang Li  
*National Taiwan University, TAIWAN*

A temperature-insensitive micromechanical resonator that utilizes an electrical stiffness compensation technique was demonstrated. In particular, a 2.92-MHz free-free beam (FF-beam) resonator based on a 0.35- $\mu$ m 2-poly-4-metal CMOS-MEMS process platform cancels the first order temperature coefficient of frequency ( $TCF_1$ ), from -70.03 ppm of an uncompensated version to +0.44 ppm, and a 22 $\times$  lower overall frequency drift from the uncompensated 2120 ppm to 95 ppm from 25°C to 55°C. In contrast to the previously demonstrated electrical stiffness compensated resonator of [1], for which the resonator consists of an *out-of-plane* overhanging temperature-compensating electrode realized by a CMOS-incompatible poly-Si surface micromachining process, this work employs an *in-plane* U-shaped compensating electrode design that allows the use of a standard CMOS-MEMS process platform for achieving the device. The FEA-derived thermal expansion of the compensating electrode is used to predict the temperature coefficient of frequency. The measured results is compared with a finite element analysis.

**Oral Session XI : Resonators(continued)**

**Grand Ballroom 101 ~ 102 (1F)**

**16:30    A SELF-SUSTAINED FREQUENCY COMB OSCILLATOR VIA TAPPING MODE COMB DRIVE RESONATOR INTEGRATED WITH A FEEDBACK ASIC ..... 165**

Ran Wei, Jaesung Lee, Tengda Mei, Yong Xie, Mohammad S. Islam, Soumyajit Mandal, and Philip X.-L. Feng  
*Case Western Reserve University, USA*

We report on the first experimental demonstration of a reconfigurable self-sustained MEMS oscillator that can generate either a stable single oscillation frequency output or a frequency comb consisting of a set of equally spaced frequency lines. The oscillator is built upon integrating a single-crystal (SC) silicon-on-insulator (SOI) comb-drive MEMS resonator with a programmable sustaining amplifier enabled by an application-specific integrated circuit (ASIC) in CMOS. The comb-drive MEMS resonator has a displacement stopper; and its first in-plane resonance mode (26.26 kHz) can be operated in linear, nonlinear, and ‘tapping’ regimes, depending on the oscillation amplitude. The reconfigurable oscillator is controlled by finely tuning the operation regime of the resonator by applying a DC polarization voltage to the resonator and via gain of the ASIC. The system can generate either a stable single oscillation frequency or controllable frequency comb output over a wide frequency range with a spacing of ~0.8 to 2.6 kHz.

**Oral Session XII : Droplet Manipulation**

**Session Chair:**

**Tianhong Cui, *University of Minnesota, USA***

**Tianzhun Wu, *Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences, CHINA***

**Grand Ballroom 103 (1F)**

**15:45    DIELECTROWETTING DRIVEN BUBBLE ELIMINATION INCORPORATED WITH ACOUSTIC EXCITATION FOR HEAT TRANSFER ENHANCEMENT ..... 169**

Youngbin Hyun, Kang Yong Lee, Seunghwan Ko, and Sang Kug Chung  
*Myongji University, KOREA*

This paper presents a new type of bubble elimination method using dielectrowetting actuation incorporated with acoustic excitation for the enhancement of boiling heat transfer demanded in various industrial fields such as microelectronics, energy, and space. The efficient control of bubbles through electric and acoustic fields is studied using microfabricated chips and experimental tools. The proposed method offers a simple actuation mechanism to be easily applied to any device but provides a highperformance bubble elimination operation.

**16:00    HYBRID ELECTRODES EFFICIENT FOR BOTH ELECTROWETTING AND DIELECTROWETTING..... 172**

Hongyao Geng and Sung Kwon Cho  
*University of Pittsburgh, USA*

This paper reports hybrid electrodes efficiently working for both electrowetting on dielectric (EWOD) and dielectrowetting. Virtually all kinds of liquid droplets, no matter which are conductive or dielectric, can be manipulated on these electrodes in an open environment without changing the electrode shape, electric signal form, or physical configuration. In addition, these electrodes are integrated with a slippery liquid infused porous surface (SLIPS) in order to minimize friction and biofouling. This electrode platform was experimentally confirmed effective for conductive liquids (water, protein solution, detergent and saline) for EWOD as well as dielectric liquids (dodecane, silicone oil, light and heavy crude oil) for dielectrowetting.

**Oral Session XII : Droplet Manipulation(continued)**

**Grand Ballroom 103 (1F)**

**16:15 ALUMINIUM NANOPARTICLE-ENHANCED OPTOELECTROWETTING DEVICE FOR EFFECTIVE LIGHT-DRIVEN DROPLET MANIPULATION ..... 176**

Si Kuan Thio and Sung-Yong Park  
*National University of Singapore, SINGAPORE*

A new concept of the single-sided continuous optoelectrowetting (SCOEW) device is presented, where light-induced electrowetting performance has been largely enhanced by simply using the layer of aluminum (Al) nanoparticles to achieve effective light-driven droplet manipulations. Previous optoelectrowetting (OEW) studies have used a low-quality photoconductive material made by titanium oxide phthalocyanine (TiOPc) and results in poor OEW modulation. In order to overcome such limitation, we propose the additional layer of Al nanoparticles that enable to improve the conductivity switching capability of the TiOPc layer and thus significantly enhance OEW performance. In this study, both numerical and experimental study results support the working principle of the light-enhanced switching performance for effective OEW modulation. Experimentally, a 2 μm thick Al nanoparticle layer at 2 wt% maximizes static contact angle modulation up to 40.7° more than regular cases, and proves a 16-fold increase in droplet actuation speed where a maximum instantaneous speed of 25.64 mm s<sup>-1</sup> has been achieved. The nanoparticle-enhanced SCOEW device can be simply fabricated via a spin-coating method as well as allow much improved OEW performance for effective light-driven 3D droplet manipulations, while offering the benefits of device simplicity, flexibility and functionality over conventional EWOD and OEW devices.

**16:30 ELECTRODEWETTING ON TRANSPARENT SUBSTRATE: DEVICE FABRICATION AND DEMONSTRATION ..... 180**

Jia Li and Chang-Jin "CJ" Kim  
*University of California, Los Angeles, USA*

Electrodewetting [1] is a newly discovered droplet manipulation mechanism that works in a manner opposite to the well-known electrowetting including electrowetting-on-dielectric (EWOD) [2]. When electrically actuated, the contact angle of a liquid on a solid surface would "increase" (i.e., electrodewetting) rather than decrease (i.e., electrowetting). This opposite effect of electrowetting allows digital microfluidic devices to work on a hydrophilic surface, i.e., free of the hydrophobic topcoat that has been the main drawback of electrowetting. In this paper, we detail the design and fabrication of electrodewetting "devices" and advance the technology to accommodate transparent substrates. To prove the feasibility of transparent devices, we achieve moving and splitting aqueous droplets along ITO electrodes on a glass wafer by electrodewetting with only ~5 V. The fabrication process is simple and compatible with today's LCD manufacturing process, indicating potential for low cost.

**Oral Session XIII : Tactile Sensors**

**Session Chair:**

**Chengkuo Lee, NUS, SINGAPORE**  
**Shuji Tanaka, Tohoku University, JAPAN**

**Grand Ballroom 104~105 (1F)**

**15:45 A MONOLITHIC FINGERPRINT-LIKE TACTILE SENSOR ARRAY REALIZING HIGH RESOLUTION IMAGING OF SPATIALLY DISTRIBUTED TACTILE INFORMATION ..... 182**

Kazuki Watatani, Kyohei Terao, Fusao Shimokawa, and Hidekuni Takao  
*Kagawa University, JAPAN*

In this study, a novel "array type" monolithic fingerprint-like tactile sensor has been developed for acquiring high resolution images of tactile information of surface. Six high resolution tactile sensors are arrayed in line at a pitch of 500μm, which is equivalent to typical pitch of human's fingerprint. Each tactile sensor can detect biaxial motion of contactor for detection of "micro surface roughness" and "local slip friction", even if it is a very soft material like clothes. As an important result obtained with the array of tactile sensors, "non-linear deformation characteristic of soft fabrics" has been acquired successfully. Moreover, distributed tactile information on "shape" and "slip friction" has been 3D visualized on a soft cloth surface at a 100μm spatial resolution for the first time.

Oral Session XIII : Tactile Sensors(continued)

**Grand Ballroom 104~105 (1F)**

**16:00    DESIGN AND FABRICATION OF A COUPLED DUAL-COIL FOR FINGERPRINT SENSOR APPLICATION ..... 186**

Shihwei Lin, Mingyu Hsieh, Yuanyuan Huang, Fuchi Shih, Zihsong Hu, and Chingfu Tsou  
*Feng Chia University, TAIWAN*

This paper presents a novel concept that uses the mutual inductance of a spiral dual-coil to identify fingerprint patterns. Unlike commercial optical and capacitive sensing technologies, this unique dual-coil design enables the measurement of a fingerprint by the effect of ridges and valleys on electrical impedance. In this study, a typical sensing chip with a 3×128 dual-coil array was fabricated by microfabrication process. The variations of coupling capacitance and mutual inductance were then used to verify the properties of different mediums. The measurement results show that the resonant frequency is produced at 8 MHz, which results in a maximum induced current of 1 mA and a phase shift of 41.3 degrees. Higher conductivity mediums cause larger phase shifts. Sample data resulting from a dual-coil array were successfully used to reconstruct a fingerprint image.

**16:15    MULTILAYERED ELECTRET/TRIBOELECTRIC GENERATOR FOR SELFPOWERED INSTANTANEOUS TACTILE IMAGING ..... 190**

Haiping Yi<sup>1</sup>, Kai Tao<sup>1</sup>, Yuxuan Gao<sup>1</sup>, Jin Wu<sup>2</sup>, and Honglong Chang<sup>1</sup>  
<sup>1</sup>*Northwestern Polytechnical University, CHINA and*  
<sup>2</sup>*Sun Yat-sen University, CHINA*

In this work, based on the principle of triboelectric/electrostatic hybrid generator, a new high-output, flexible and transparent electret power generator was fabricated by using transparent polymer materials. Moreover, thermoplastic method is proposed to shape the wavy structures perpetually. It is able to recover to previous state when pressure applied. Triggered by hand pressing, the instantaneous peak output voltage and short-circuit current can be up to 800V and 50 μA respectively, which are able to drive hundreds of commercial light-emitting diodes (LEDs). Finally, a 5\*5 pixels harvester array was constructed with instantaneous touch events for spatially mapping and motion tracking. The force is capable of recording the electroluminescent signals of the LEDs without external power sources. This work is a significant step forward in self-powered tactile-mapping visualization technology, with a wide range of potential applications in touchpad technology, personal signatures, smart wallpapers, robotics, and safety-monitoring devices.

**16:30    A TEXTILE-BASED RESISTIVE TACTILE SENSOR WITH HIGH SENSITIVITY IN A WIDE PRESSURE RANGE ..... 194**

Jaeyong Lee, Soonjae Pyo, Eunhwan Jo, and Jongbaeg Kim  
*Yonsei University, KOREA*

This paper firstly reports an all-textile tactile sensor with high sensitivity and linear response over a wide pressure range based on carbon nanotube (CNT)-coated fabric with a stacked multilayer structure. When pressure is applied, the hierarchical, porous structure of fabric with a large surface area allows the dramatic increase in the contact area between the stacked fabrics, leading to a decrease in contact resistance. The multilayer structure can improve the linearity and sensitivity owing to the effective stress distribution and the increased contact area change between the layers compared to a single-layered one. We observed a linear increase in current of the fabricated sensor under external pressure, and it exhibited high sensitivity over a broad pressure range. The proposed sensor would be an attractive candidate for flexible, highperformance tactile sensing components.

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**16:45    Break**

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**Oral Session XIV : Physical Sensors**

Session Chair:

Frank Niklaus , *KTH Royal Institute of Technology, SWEDEN*

Hanseup Kim, *University of Utah, USA*

**Grand Ballroom 101 ~ 102 (1F)**

**16:55     A HIGHLY SENSITIVE PLANER SILICON-HAIR DEVICE REPRODUCING THE FUNCTION OF HUMAN HAIR FOLLICLE..... 198**

Koki Hamamoto, Kyohei Terao, Fusao Shimokawa, and Hidekuni Takao  
*Kagawa University, JAPAN*

This is the first report of a novel silicon-hair device with the function of highly sensitive hair follicle to realize peculiar sense in hairy skin of human. The target sensitivities of our device are 10µN in force and 10nN-m in moment, since they are considered as the sensitivities of human hair follicle. A fine silicon-hair with 10µm-width and 5mm-length is monolithically integrated, and 2-axis forces and 1-axis moment applied to the silicon-hair are detected independently by tri-axis sensing structure. The fabricated device was evaluated, and the minimum detectable input was 5µN in axial force, 1µN in shear force, and 3nN-m in moment. These sensitivities are advantageous to human's hair follicle, and it is very promising to apply the device to novel measurement applications. As the first application, surface tension of liquid was precisely acquired. Absolute value of surface tensions were successfully measured at small absolute error using the highly sensitive silicon-hair device.

**17:10     HIGH-OVERTONE BULK DIFFRACTION WAVE GYROSCOPE ..... 202**

Visarute Pinrod, Benyamin Davaji, and Amit Lal  
*Cornell University, USA*

A gyroscope mechanism which utilizes Coriolis force on diffracted bulk ultrasonic waves has been realized in lithium niobate piezoelectric substrate. The operation using diffracting bulk waves eliminates the need for released spring and masses enabling operation in extreme shock and vibration. The Bulk Wave Diffraction Gyroscope (BWDG) uses interdigitated electrodes that excite thickness mode resonances in a lithium niobate substrate. The diffraction of pressure and shear waves occurs due to electrode finite aperture. The shear waves undergo Coriolis force modified reflections, with the modified waves transduced at receiver interdigitated transducers. The measured unamplified gyroscope scale is 191 µV/(deg/s), which is one of the largest scale factors reported for an all-solid-state gyroscope. Zero rate angle random walk (ARW) was 0.028deg/hr<sup>1/2</sup>, and bias fluctuation was 8 deg/hr at a power consumption of 5.3mW, operating at an overtone resonance frequency of 163 MHz.

**17:25     HIGHLY SENSITIVE ANGULAR ACCELEROMETER UTILIZING PIEZORESISTIVE CANTILEVER AND SPIRAL LIQUID CHANNEL..... 206**

Byeongwook Jo, Hidetoshi Takahashi, Tomoyuki Takahata, and Isao Shimoyama  
*The University of Tokyo, JAPAN*

This paper reports a highly sensitive angular accelerometer utilizing a piezoresistive cantilever and spiral liquid channels. The spiral structure increases the total inertial force of liquid due to angular acceleration, which leads to the sensitivity enhancement. The differential pressure between two spiral liquid channels was measured by a piezoresistive cantilever with the resolution of 0.01 Pa. The developed sensor with number of turns of the spiral with 25 achieved the sensitivity enhancement by 28.5 times, compared to the ring channel sensor.

Oral Session XIV : Physical Sensors(continued)

Grand Ballroom 101 ~ 102 (1F)

**17:40     1.5-MILLION Q-FACTOR VACUUM-PACKAGED BIRDBATH RESONATOR GYROSCOPE (BRG) .....210**

Jae Yoong Cho, J.-K. Woo, Guohong He, Donguk Yang, Christopher Boyd, Sajal Singh, Ali Darvishian, Behrouz Shiari, and Khalil Najafi  
*University of Michigan, USA*

We report a vacuum-packaged fused-silica (FS) micro birdbath shell resonator gyroscope (BRG) with near-navigation-grade in-run (evaluation duration < 1 day) bias stability of 0.0103 deg/h (at room temperature without temperature stabilization). The BRG utilizes a 5mm diameter birdbath (BB) resonator with  $n=2$  wineglass mode  $f = 10.5436$  kHz and original frequency split ( $\Delta f$ ) = 6 Hz. The BRG is encapsulated in an LCC package and has an excellent  $Q$  (1.54 million) and decay time constant ( $\tau=46$  s) after near mode matching. The performance is believed to be limited by the noise from readout-and-control circuitry. The bias stability of this device is among the best reported values for micro-scale vibratory gyroscopes today.

**17:55     A NOVEL MICROMECHANICAL MODE-LOCALIZED RESONATOR UTILIZING ANTI-RESONATING STRUCTURES .....214**

Jia-Ren Liu, Yu-Cheng Lo, and Wei-Chang Li  
*National Taiwan University, TAIWAN*

A novel micromechanical mode-localized resonator has been demonstrated. In particular, a CMOS-MEMS clamped-clamped beam resonator topped with multiple cantilevers that serve as anti-resonating tuned-mass dampers yields a resonance frequency variation of 0.14% for an equivalent mass perturbation of one picogram added on the cantilever beams, resulting in a sensitivity as high as 10× compared to that simulated without the anti-resonating structures. Additionally, the  $\mu g$ -mass perturbation yields a variation of 2.93% in the magnitude of the frequency response of the presented mode-localized sensor, whereas the regular resonator exhibits nearly zero change. Unlike typical 2-degree-of-freedom mode-localized sensors that couple two identical resonators, this approach boosts the effect of mass perturbation by miniaturizing the secondary oscillating tank, which serve as the absorbers. Via the unbalanced coupling scheme, a larger percentage change in mass for a certain mass perturbation can be achieved, thereby resulting in a higher sensitivity.

**Oral Session XV : Biomimetic and Plant Inspired Microsystems**

Session Chair:

**Beomjoon Kim, *The University of Tokyo, JAPAN***  
**Dong-Weon Lee, *Chonnam National University, KOREA***

Grand Ballroom 103 (1F)

**16:55     REALIZATION AND OPTIMIZATION OF A NEPENTHES-INSPIRED MICROSTRUCTURE EMPLOYING PR SACRIFICIAL LAYER TECHNOLOGY .....218**

Wenxi Sun<sup>1</sup>, Longjun Tang<sup>2</sup>, Wen Hong<sup>1</sup>, Bin Yang<sup>1</sup>, and Jingquan Liu<sup>1</sup>  
<sup>1</sup>*Shanghai Jiao Tong University, CHINA and*  
<sup>2</sup>*MicroPort NeuroTech Co., Ltd., CHINA*

We fabricated a bio-inspired microstructure film mimicking peristome surface microstructure of the *Nepenthes alata* and enhanced its performance by improving spreading units shape. A pioneering PR sacrificial layer technology was utilized to duplicate these complex three-dimensional structures. On account of the special micromorphology, effects of original and optimized microstructure are compared to demonstrate that liquid can achieve spontaneously spreading to one direction after optimization, even on an uphill slope. While on original structure, liquid will easily leak backward.

Oral Session XV : Biomimetic and Plant Inspired Microsystems(continued)

Grand Ballroom 103 (1F)

**17:10     A 3D PRINTED CYANOBACTERIAL LEAF FOR CARBON DIOXIDE REDUCTION..... 222**

Lin Liu and Seokheun Choi  
*State University of New York-Binghamton, USA*

This work created a self-sustainable, biological artificial leaf that dramatically reduced atmospheric carbon dioxide (CO<sub>2</sub>) and replaced it with oxygen (O<sub>2</sub>). Three-dimensionally printed photosynthetic bacteria, *Synechocystis* sp. PCC 6803, on pre-defined microfluidic reservoirs, captured solar energy to convert CO<sub>2</sub> and water into O<sub>2</sub> and carbohydrates, which they subsequently use for their respiratory reaction, re-generating water, and only about half that CO<sub>2</sub>. The artificial leaf integrated a hierarchically porous structure, mimicking biological system (i.e. plants) with the water transpiration process and the gas exchange surface, offering self-sustainable and self-maintainable features. The solar evaporation on the porous leaf surface developed suction pressure so that water/nutrients could be transported from a media reservoir to individual bacterial cells. The novel microscale approaches maximized microbial activities in a smaller group of cells with excellent control over the microenvironment.

**17:25     DECELLULARIZED PLANT LEAVES FOR 3D CELL CULTURING..... 226**

Ken Varhama, Haruka Oda, Ai Shima, and Shoji Takeuchi  
*The University of Tokyo, JAPAN*

Decellularization has become prevalent as a critical process for tissue engineering for creating large scale tissues in combination with recellularization as it paved the way to incorporate a functioning vascular system by utilizing a preexisting one. We present a rapid decellularization process of plant leaves that can be used to effectively produce cell viable perfusable scaffolds that are suited for 3D cell culturing. The leaf vein scaffolds produced using this method maintain their natural three-dimensional micro-architecture and cells can attach on to them without any coating. Despite the increased speed of production, the method yields practical leaf veins and has the potential to accelerate the development of complex large-scale tissues with further research.

**17:40     FACILE AND HIGH-EFFICIENCY MICROBEAD ARRAY BASED ON BIOMIMETIC NEPENTHES PERISTOME SURFACES..... 229**

Zhiting Peng, Tianzhun Wu, Weiliang Shu, and Yunlong Wang  
*Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences, CHINA*

For the first time, we proposed a facile method for efficiently trapping microbeads (down to 5 μm in diameter) to form static array on the biomimetic peristome surface of nepenthes with the aid of evaporation-driven Marangoni effect sitting on an inclined tepid plane. The microfabricated nepenthes peristome surfaces with oblique re-entrant microcavities in microgrooves led to directional liquid spreading. The microbeads were transported towards the receding contact line by thermocapillary flow, and trapped into microcavities under curvature-induced Laplace pressure. It can be a new universal and simple approach to capture microparticles in aqueous solution.

**17:55     WATER-ELECTROKINETIC POWER GENERATION DEVICE USING FLEXIBLE WOODY CARBON FILM ..... 233**

Seren Maeda, Hiroyuki Kuwae, Kosuke Sakamoto, Shuichi Shoji, and Jun Mizuno  
*Waseda University, JAPAN*

We developed a water-electrokinetic energy harvester using a flexible woody carbon film (FWCF). The proposed device induced streaming current/voltage by water-vapor flow and thermal-evaporation flow in natural microchannels of wood, which called tracheid. In addition, high specific area of the FWCF can improve the output. The fabricated device showed a streaming voltage of about 9.7 μV with the water-vapor flow. Moreover, the output of the device were enhanced by thermal-evaporation flow. The maximum output voltage was 421.3 μV. After stabilization, 217.8 μV was continuously observed over 30 minutes at 80 °C. These results indicate that the proposed FWCF based water-electrokinetic power generation device has a high potential in power sources for Internet of things society.



**Oral Session XVI : Micro/Nano Fabrication**

Session Chair:

Shin-ichirou Tezuka, *Yokogawa Electric Corporation, JAPAN*

Yong-Kyu Yoon, *University of Florida, USA*

**Grand Ballroom 104~105 (1F)**

**16:55    RAPID MULTI-MATERIAL DIRECT LASER WRITING ..... 237**

Andrew C. Lamont, Michael A. Restaino, and Ryan D. Sochol  
*University of Maryland, USA*

The additive manufacturing or “three-dimensional (3D) printing” technology direct laser writing (DLW) offers a level of geometric versatility at submicron scales that yields substantial benefits for fields including photonics, meta-materials, and 3D cell biology. A key limitation of DLW, however, stems from the difficulties in 3D printing micro/nanoscale structures with more than a single material. Specifically, producing multi-material components requires laborious and time-intensive protocols for manual substrate/material processing and alignment to maintain structural continuity among distinct photomaterials. To overcome these challenges, here we introduce a “rapid multi-material DLW (RMM-DLW)” strategy that enables 3D nanostructured features comprised of multiple, fully integrated photomaterials to be additively manufactured with unprecedented speed and accuracy. This approach leverages an impermanent elastomeric bonding technique to achieve temporary microchannels through which distinct photomaterials can be serially loaded, photopolymerized, and developed; the elastomer can be removed thereafter. Preliminary RMM-DLW results revealed a 74% reduction in fabrication time, with a multi-material alignment accuracy of  $0.14 \pm 0.17 \mu\text{m}$  ( $\Delta X$ ) and  $0.20 \pm 0.15 \mu\text{m}$  ( $\Delta Y$ ) – an improvement of up to one order of magnitude over conventional multi-material DLW. In combination, these results suggest a promising pathway to achieve fundamentally new classes of multi-material, and in turn, multi-functional 3D nanostructured systems.

**17:10    KIRIGAMI-LIQUID STRUCTURE FOR ELECTROLUMINESCENT ARRAY ATTACHABLE ONTO THREE-DIMENSIONAL SURFACES ..... 241**

Atsushi Takei, Shiho Tsukamoto, Yusuke Komazaki, and Manabu Yoshida  
*National Institute of Advanced Industrial Science and Technology (AIST), JAPAN*

This paper presents a new method for making electronic devices attachable onto three-dimensional surfaces. Sheets with cut patterns, kirigami structure, exhibit stretchability by deforming out-of-plane and expanding the cut patterns. Because of the stretchability, kirigami structures can be attached onto three-dimensional surfaces. However, due to openings resulting from cut patterns, kirigami cannot cover entire surfaces of three-dimensional structures. This drawback is critical especially for display devices. We fulfill openings of a kirigami structure with liquid electroluminescent (EL) elastomer, and achieve EL array attachable onto three-dimensional surfaces. The openings are fulfilled, and the resulting structure has a large device area in comparison to other kirigami devices. In this paper, we present the fabrication process and the experimental results of the EL array made with the proposed kirigami-liquid method.

**17:25    MANUFACTURING OF SUB-20 NM WIDE SINGLE NANOWIRE DEVICES USING CONVENTIONAL STEPPER LITHOGRAPHY ..... 244**

Alessandro Enrico, Valentin Dubois, Frank Niklaus, and Göran Stemme  
*KTH Royal Institute of Technology, SWEDEN*

Single nanowires have a broad range of applications in chemical and bio-sensing, photonics, and material science, but realizing individual nanowire devices in a scalable manner remains extremely challenging. This work presents a scalable and flexible method to realize single gold nanowire devices. We use conventional optical stepper lithography to generate notched beam structures, and crack lithography to obtain sub-20-nm-wide nanogaps at the notches, thereby obtaining a suitable shadow mask to define a single nanowire device. Then a gold evaporation step through the shadow mask forms the individual gold nanowires with positional and dimensional accuracy and with electrical contacts to probing pads.

Oral Session XVI : Micro/Nano Fabrication(continued)

Grand Ballroom 104~105 (1F)

**17:40     4D-PRINTING SYSTEM FOR ELASTIC MAGNETIC ACTUATORS ..... 248**  
 Seiji Azukizawa, Hayato Shinoda, and Fujio Tsumori  
*Kyushu University, JAPAN*

We propose a 4D-printing process for soft actuators. 4D-printing system can print out not only a 3-dimensional object but also deformations in the printed structure simultaneously. In this paper, we propose a new 4Dprinting system that utilizes soft resin dispersed with magnetic particles. The printed structure could be actuated by an applied magnetic field. The key in this system is magnetic anisotropy located at each portion of a structure. We show 2 demonstrations of printed actuators, and also a computational method to design the deformations of printed structures. This 4D-printing could be a powerful tool to fabricate micro soft actuators in the MEMS field.

**17:55     SOLENOID FLUXGATE CURRENT SENSOR MICROMACHINED BY WAFER-LEVEL MELT-METAL CASTING  
 TECHNIQUE ..... 252**  
 Jiebin Gu<sup>1</sup>, Xiaowei Hou<sup>2</sup>, Xiaoyuan Xia<sup>1</sup>, and Xinxin Li<sup>1</sup>  
<sup>1</sup>*Shanghai Institute of Microsystem and Information Technology, CHINA and*  
<sup>2</sup>*Ningbo CRRR Times Transducer Technology Co, LTD., CHINA*

This paper for the first time reports a practical solenoid-structure fluxgate sensor chip made by MEMS-Casting technology. The size of the sensor is only 1/3 of traditional wire-wound structure. The main progress is that wire break as a main and fatal problem of MEMS-Casting is solved. Wire break which can cause open circuit of the solenoid coils, is result of volume shrinkage during alloy solidification. Compared to previously reported SnBi alloy casted solenoid coils, the employed SnPb alloy can reduce the total resist of solenoid coil by 30%. Such a reduction on resist makes it can meet the thermal budget during practical application. MEMS-Casting method provides an alternative way to make solenoid MEMS fluxgates in addition to electroplating and wire-bonding.

Conference Banquet at Floating Island

19:00 - 21:00

**THURSDAY, JANUARY 31**

**07:00 Registration Lobby (1F)**

**PLENARY PRESENTATION IV**

**Session Chair:**

*Jun-Bo Yoon, Korea Advanced Institute of Science and Technology (KAIST), KOREA*

**Grand Ballroom 101 ~ 105 (1F)**

**08:30 SENSOR AS A SOLUTION: RECENT PROGRESS IN INTELLIGENT SENSORS DEVELOPMENT..... 256**

**Chaedeok Lee**

*LG Electronics, KOREA*

**Oral Session XVII : Carbon-based Nanomaterials**

**Session Chair:**

*Nuria Barniol, Autonomous University of Barcelona, SPAIN*

**Grand Ballroom 101 ~ 105 (1F)**

**09:30 WAFER-SCALE TRANSFER OF GRAPHENE BY ADHESIVE WAFER BONDING..... 257**

Arne Quellmalz<sup>1</sup>, Xiaojing Wang<sup>1</sup>, Stefan Wagner<sup>2</sup>, Max Lemme<sup>2,3</sup>, Kristinn B. Gylfason<sup>1</sup>,  
Niclas Roxhed<sup>1</sup>, Göran Stemme<sup>1</sup>, and Frank Niklaus<sup>1</sup>

<sup>1</sup>*KTH Royal Institute of Technology, SWEDEN,*

<sup>2</sup>*AMO GmbH, Advanced Microelectronic Center Aachen (AMICA), GERMANY, and*

<sup>3</sup>*RWTH Aachen University, GERMANY*

Graphene is an extremely promising material for emerging nanoelectromechanical systems (NEMS) and sensors, but the transfer from its growth substrate to silicon substrates remains manual and laborious. We report a novel method for the transfer of large-area chemical vapor deposited (CVD) graphene from copper foil to a target wafer by adhesive wafer bonding using bisbenzocyclobutene (BCB) as an intermediate adhesive layer. The use of conventional wafer bonding equipment enables the scalable transfer of graphene and the realization of both supported and suspended graphene devices on wafer-scale. Our method circumvents manual handling of graphene after release from its growth substrate and avoids polymeric carrier layers, a well-known source of contamination. Hence, the proposed process promises the transfer of graphene with high quality and repeatability.

**09:45 A WAFER-SCALE PROCESS FOR THE MONOLITHIC INTEGRATION OF CVD GRAPHENE AND CMOS LOGIC FOR SMART MEMS/NEMS SENSORS ..... 260**

Joost Romijn, Sten Vollebregt, Henk W. van Zeijl, and Pasqualina M. Sarro

*Delft University of Technology, NETHERLANDS*

In this paper we present, for the first time, the successful monolithic wafer-scale integration of CVD graphene with CMOS logic for highly miniaturized smart sensing structures with on-chip readout electronics. The use of a patterned CMOS compatible catalyst for pre-defined regions of CVD graphene growth, and the transfer-free process used, allows the direct implementation of patterned graphene structures between the front-end-of-line (FEOL) and back-end-offline (BEOL) processes. No significant deterioration of the graphene properties and of the CMOS logic gate performance due to the high temperature graphene growth step was observed. This is a significant leap towards industrial production of graphene-based smart MEMS/NEMS sensors.

Oral Session XVII : Carbon-based Nanomaterials(continued)

Grand Ballroom 101 ~ 105 (1F)

**10:00    FACILE IDENTIFICATION OF GRAPHENE'S CRYSTAL ORIENTATIONS BY OPTICAL MICROSCOPY OF SELF-ALIGNED MICROWIRES ..... 264**

Jimin Ham<sup>1</sup>, Yangjin Lee<sup>2</sup>, Jonghyeok Kim<sup>1</sup>, Kitaek Lim<sup>1</sup>, Sol Lee<sup>2</sup>, Sungho Jeon<sup>1</sup>, Kwanpyo Kim<sup>2</sup>, and Won Chul Lee<sup>1</sup>

<sup>1</sup>*Hanyang University, KOREA and*

<sup>2</sup>*Yonsei University, KOREA*

This work presents a facile identification method for the crystal orientations of graphene using the directional alignment between AgCN microwires and the underlying graphene. Because the microwires in the present work are visible with conventional optical microscopy, large-area graphene can be inspected with simple procedures. In the experimental study, we confirmed that the microwires can indicate graphene's crystal orientations with an acceptable accuracy as well as can be removed with a simple wet-etching process.

**10:15    Break & Exhibition Inspection**

**Oral Session XVIII : Optical MEMS**

Session Chair:

Yong-Kyu Yoon, *University of Florida, USA*

Nathan Jackson, *University of New Mexico, USA*

Grand Ballroom 101 ~ 105 (1F)

**10:45    MEMS-BASED BATTERY-LESS RFID INFRARED SENSOR TAG WITH MEMORY FUNCTION ..... 266**

Vageeswar Rajaram, Zhenyun Qian, Sungho Kang, Sila Deniz Caliskan, and Matteo Rinaldi  
*Northeastern University, Boston, USA*

In this paper we demonstrate for the first time, a battery-less radio frequency identification (RFID) infrared (IR) sensor tag capable of detecting and recording the presence of a specific IR signature associated with an event of interest. Unlike existing passive sensor tags that can only perform sensing and recording functions when wirelessly powered by a reader, the proposed IR sensor tag uses a zero-power latching micromechanical photoswitch (MP) to continuously monitor the environment and record an event occurrence without requiring any electrical power. The MP's contacts are engineered to remain latched by adhesion forces after the device is exposed to above-threshold IR irradiation, thereby forming a physical memory bit (open/closed). An integrated auto-reset functionality is also implemented to unlatch and erase the memory bit after every reading. The prototype reported here represents the first demonstration of a battery-less RFID sensor tag suitable for long-term, continuous monitoring for IR signatures indicative of failure events (e.g. overheating/fires in power infrastructure).

**11:00    A WAFER LEVEL PACKAGED FULLY INTEGRATED HYPERSPECTRAL FABRY-PEROT FILTER WITH EXTENDED OPTICAL RANGE ..... 270**

Peleg Levin<sup>1</sup>, Eli Ashkenazy<sup>1</sup>, Ariel Raz<sup>1</sup>, Miriam Hershcovitz<sup>1</sup>, Siebe Bouwstra<sup>1</sup>, David Mendlovic<sup>1,2</sup>, and Slava Krylov<sup>1,2</sup>

<sup>1</sup>*Unispectral Ltd., ISRAEL and*

<sup>2</sup>*Tel Aviv University, ISRAEL*

We report on the first demonstration of a wafer level packaged, vacuum sealed, fully integrated and cell-phone compatible tunable micromachined Fabry-Pérot filter ( $\mu$ FPF), operating within the visual and near-infrared (VIS-NIR) optical range. Implementation of a normally closed architecture combined with the electrostatic actuation enlarging, rather than closing, the optical cavity allowed unprecedented tunability of the optical gap between 600nm and down to potentially 30 nm. The ability to support such a small gap size enables, for the first time, a transparent mode to such filters. Due to the 1 mm thickness of a vertically integrated Si-on-glass (SOG) fully assembled device, manufacturability and robustness of a single crystal Si mechanical structure, and its short response time, our hyperspectral filter can be directly integrated into mobile phone camera modules, hyperspectral imagers, and remote sensors.

Oral Session XVIII : Optical MEMS(continued)

Grand Ballroom 101 ~ 105 (1F)

**11:15      RADIALLY ARRANGED DIHEDRAL CORNER REFLECTOR ARRAY FOR WIDE VIEWING ANGLE OF SEAMLESS FLOATING IMAGE ..... 274**

Yuta Yoshimizu and Eiji Iwase  
*Waseda University, JAPAN*

We proposed a new type of dihedral corner reflector array (DCRA) called "radially arranged DCRA". Our radially arranged DCRA could produce a seamless floating image with a wide viewing angle and without producing virtual images because of designed optical paths of reflected rays. We designed the arrangement of reflectors and fabricated the radially arranged DCRA by photolithography process using SU-8 3010. Using the fabricated DCRA, we measured reflection ratios of conventional and radially arranged DCRA and demonstrated floating images. The radially arranged DCRA could produce a seamless floating image with viewing angle of  $\pm 90^\circ$  and did not produce virtual images.

**11:30      HIGH RESOLUTION 3D SURFACE IMAGING USING VARIABLE STRUCTURED ILLUMINATION VIA LISSAJOUS SCANNING MEMS MIRROR MODULE ..... 278**

Yeong-Hyeon Seo, Sung-Pyo Yang, Hyunwoo Kim, Won-Kyung Lee, Kyungmin Hwang, and Ki-Hun Jeong  
*Korea Advanced Institute of Science and Technology (KAIST), KOREA*

We report a high resolution 3D imaging using variable structured illumination via Lissajous scanning MEMS mirror module. The Lissajous scanning MEMS mirror was operated at pseudo-resonant frequencies within the bandwidth. The structured illumination pattern density was controlled by selecting the greatest common divisor (GCD) of two scanning frequencies. Scanning frequency selection with high GCD provides a coarse illumination pattern. The constant pattern was obtained by modulating a laser beam at the least common multiple (LCM) of the two selected scanning frequencies. A low-Q inner mirror provides wide frequency tuning range as well as enables variable structured illumination. 3D stereoscopic image has been successfully obtained by using a variable structured illumination and stereoscopic camera. Structured illumination effectively enhances 3D imaging resolution. This structured illumination module can provide a new breakthrough for 3D MEMS imaging applications.

**11:45      RESONANT TORSIONAL MICRO-ACTUATORS USING THIN-FILM LITHIUM NIOBATE ..... 282**

Ahmed Emad<sup>1</sup>, Ruochen Lu<sup>1</sup>, Ming-Huang Li<sup>1</sup>, Yansong Yang<sup>1</sup>, Tao Wu<sup>2</sup>, and Songbin Gong<sup>1</sup>  
<sup>1</sup>*University of Illinois, Urbana Champaign, USA and*  
<sup>2</sup>*ShanghaiTech University, CHINA*

This paper reports the first torsional micro-actuator using a lithium niobate (LiNbO<sub>3</sub>, 36° Y-cut) thin film with a record-high figure of merit ( $FoM = \theta_{opt} \cdot \text{mirror-dimension} \cdot \text{frequency}$ ) of 1582 °·mm·kHz at a resonance frequency of 1.268 MHz. The large piezoelectric coefficients and high-quality factors of single crystal LiNbO<sub>3</sub> have been exploited to enable high coupling torsional actuation. The fabricated actuator has a mirror size of 22x40  $\mu\text{m}^2$ , and quality factors of 547 and 1497 in air and vacuum respectively. Moreover, the optical angle can exceed 31° ( $\theta_{opt} = 4 \cdot \theta_{mech}$ ) in both air and vacuum, leading to an FoM surpassing state-of-the-art high-frequency scanners. Our demonstration has shown great potential for scanning micro-mirrors, and light detection and ranging systems (LIDAR) applications where frequency scalability, scanning angles, and footprint are the main challenges.

**12:00      Award Ceremony, Lucky Draw & Final Remarks**

**12:30      Conference Adjourns**

POSTER/ORAL PRESENTATIONS

Hall B2 (1F)		
<b>MONDAY</b> 14:15 - 16:15	<b>TUESDAY</b> 14:15 - 16:15	<b>WEDNESDAY</b> 13:15 - 15:15

TRACK/CLASSIFICATION

Materials, Fabrication and Packaging for Generic MEMS & NEMS
Micro/Nanofluidics & Chemical Sensors
Bio & Medical MEMS
MEMS Physical Sensors
MEMS for Electromagnetics
MEMS Actuators & Power MEMS
MEMS Products

See poster floor plan on the last page of this program

Materials, Fabrication and Packaging for Generic MEMS & NEMS
Materials for MEMS & NEMS

- M-001 COUPLED PIEZORESISTIVE GRAPHENE NANO-RESONATORS..... 286**  
 Madhav Kumar<sup>1</sup>, Harish Bhaskaran<sup>1</sup>, and Bhaskar Choubey<sup>2</sup>  
<sup>1</sup>University of Oxford, UK and  
<sup>2</sup>Siegen University, GERMANY

Single atom thick graphene nanomechanical resonators can have very low mass yet high stiffness leading to the potential of very high sensitivity frequency based mass and force sensors. This sensitivity can be further enhanced by coupling two resonators using the Eigenvalues of the response. However, high Q graphene resonators are difficult to manufacture and measure. In this paper, we report the first ever coupled graphene nanoresonator system utilizing the inherent piezoresistivity of graphene. The structure offers mass sensing abilities of zeptogram level using the eigenvectors and quality factor of 1000. It also showcases the potential of making very large coupled arrays to measure more than one substance using a single sensor.

- T-002 TUNEABLE MICROPARTICLE FILTERS..... 290**  
 Emre Iseri<sup>1</sup>, Kerem Kaya<sup>1</sup>, Giacomo Di Dio<sup>1</sup>, Hiroki Yasuga<sup>2</sup>, Norihisa Miki<sup>2</sup>, and Wouter van der Wijngaart<sup>1</sup>  
<sup>1</sup>KTH Royal Institute of Technology, SWEDEN and  
<sup>2</sup>Keio University, JAPAN

We introduce microparticle filters with temperature tuneable size cut-off and surface energy. At room temperature, the filter cut-off is 164 ± 23 μm, and the filter is water-absorbing/oil-repelling (hydrophilic). At 50°C, the filter cut-off is 695 ± 31 μm, and the filter is oil-absorbing/water-repelling (hydrophobic).

- W-003 A 10NM-THICK HAFNIUM-ZIRCONIUM OXIDE PIEZOELECTRIC TRANSDUCER FOR EXTREME MINIATURIZATION OF INTEGRATED SENSORS AND ACTUATORS..... 292**  
 Mayur Ghatge, Glen Walters, Toshikazu Nishida, and Roozbeh Tabrizian  
 University of Florida, USA

This paper reports the thinnest ever-reported piezoelectric transducer for realization of extremely miniaturized nanomechanical sensors and actuators. A 10nm hafnium-zirconium-oxide (Hf<sub>0.5</sub>Zr<sub>0.5</sub>O<sub>2</sub>) (HZO) film is engineered through atomic-level stacking, capping with titanium-nitride electrodes, and proper rapid-thermal-annealing treatment to promote non-centrosymmetric orthorhombic crystallization with large piezoelectric properties. The developed 10nm HZO transducer is used for excitation of a silicon-based multi-morph nanomechanical resonator, with an overall thickness of ~350nm. The developed resonator, along with 120nm aluminum-nitride (AlN) transduced counterparts, are also used as test-vehicles to characterize the ferroelectric and piezoelectric properties of the HZO film. Benefiting from large piezoelectric coefficient ( $e_{31, HZO} \approx 2.3e_{31, AlN}$ ), fully conformal deposition, and CMOS-compatibility, ALD-deposited HZO transducer paves the way for radical miniaturization of nanosystems, realization of 3D nano-actuators, and extreme frequency scaling and monolithic integration of RF frontends for the emerging 5G wireless communication systems.

**M-004 STRETCHABLE LIQUID METAL WIRING WITH THREE-DIMENSIONAL HELICAL STRUCTURE..... 296**

Ken Matsubara and Hiroki Ota  
*Yokohama National University, JAPAN*

In this study, stretchable liquid metal(Galinstan) wiring with three-dimensional(3D) coil was developed for preventing the resistance change during device deformation. Previously, core-shell hydrogel microsprings was fabricated using a double bevel-tip nozzle[1]. In this study, liquid metal as conductive liquid was injected into core part composed of starch in the microsprings. Then, 3D coil with liquid metal was developed. In stretchable and flexible electronics, it is crucial to prevent change of electrical parameters, in particular resistance in direct current(DC) and impedance in alternating current(AC), during device deformation. The developed metal wiring maintained stable resistance (less than 1.2 % difference) during 100 % tension and stable impedance(less than 0.2%) from 1 to 100k Hz in AC. As a result, we realized liquid metal wiring which is highly stable to device deformation. This report will present an important advancement towards the realization of "liquid-state" electronic system with liquid metal.

**T-005 STUDY AND APPLICATION OF IN-SITU PHOSPHORUS DOPED THICK POLYSILICON FILMS AT LOW TEMPERATURE FOR POST CMOS MEMS INTEGRATION..... 299**

Ian Chaung, Aron Michael, and Chee Yee Kwok  
*The School of Electrical Engineering and Telecommunication, UNSW, AUSTRALIA*

This paper reports the film property and application of in-situ doped evaporated silicon films at ultra-high vacuum for temperatures ranging from 200-625°C at various doping concentrations and deposition rates. Micromachining process for the studied polysilicon film has been developed and accelerometer and comb-drives of 22µm thick have been fabricated at low temperature for the first time. Detailed studies of the film crystallinity using Raman Spectroscopy and X-TEM have been conducted. The average and gradient stresses of the films have been measured along with Young's Modulus. The result shows, for the first time, the formation of thick fully crystallized electrically active silicon films with low average stress and stress gradient by optimizing the phosphorous doping and deposition rate at temperature less than 500°C. Moreover, we have successfully fabricated an inertial sensor and comb-drive actuator using the film. The inertial sensor shows linear sensitivity of 195mV/g with a readout circuit consisting of amplifier and demodulator. The actuator moves 240nm at driving voltage of 15VDC and measures a resonance frequency of 2.1 KHz.

**W-006 STRETCHABLE FABRIC HEATER BASED ON SILVER NANOWIRE, CARBON NANOTUBE COMPOSITES ..... 303**

Junseong Ahn<sup>1,2</sup>, Jimin Gu<sup>1</sup>, Yongrok Jeong<sup>1</sup>, Kyuyoung Kim<sup>1</sup>, Junho Jeong<sup>2</sup>, and Inkyu Park<sup>1</sup>  
<sup>1</sup>*Korea Advanced Institute of Science and Technology(KAIST), KOREA and*  
<sup>2</sup>*Korea Institute of Machinery and Materials(KIMM), KOREA*

In this work, we report a novel stretchable fabric heater based on silver nanowire, carbon nanotube composites. We propose improved spray coating method to develop a stretchable fabric heater with excellent mechanical properties and electrical properties. The combination of the carbon nanotubes (CNTs) with high structural stability and silver nanowires (Ag NWs) with high conductivity could highlight the advantage of each nanomaterials. The proposed fabric heater showed a stable temperature control even in the folded and rolled states. In addition, fabric heaters were applied in commercial cotton gloves successfully.

**M-007 BIO ORIENTED NANOPOROUS MATERIALS FOR PERM-SELECTIVE ION TRANSPORTATION ..... 307**

Sungmin Park<sup>1</sup>, Seongjun Hong<sup>1</sup>, Junsuk Kim<sup>1</sup>, Hyomin Lee<sup>2</sup>, and Sung Jae Kim<sup>1</sup>  
<sup>1</sup>*Seoul National University, KOREA and*  
<sup>2</sup>*Jeju National University, KOREA*

Nanoporous structure has been actively applied for various application such as desalination, water purification, electro-chemical cell or bio applications. Recently, easy way to fabricate nanoporous membrane has been developed but it was still not applicable for bio applications because of bio-compatibility. Hydrogel was one of the known material for bio-compatible membrane, but it was hard to control. In this work, we found several candidates for bio degradable nanoporous membrane in the living organism; human nail, hen egg yolk, and albumen. The nanofluidic functionality was verified by ion concentration polarization phenomena. Surface charge of each material was estimated by conductance profile.

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- T-008    HIGHLY SENSITIVE, FOLDABLE, AND TWISTABLE GAS SENSOR BASED ON TUNGSTEN DISULFIDE-FUNCTIONALIZED CARBON NANOTUBES ON CELLULOSE PAPER .....311**  
 Woo Sung Lee and Jungwook Choi  
*Yeungnam University, KOREA*

This paper presents a WS<sub>2</sub>-functionalized carbon nanotube (CNT)-based sensitive, foldable, and twistable NO<sub>2</sub> sensor that is integrated on cellulose paper. The CNTs form percolation network on the surface of cellulose paper with NO<sub>2</sub> reactivity. Functionalization of CNTs with nanolayers of WS<sub>2</sub> significantly improves the response over 200% under 10 ppm NO<sub>2</sub> exposure. At the same time, the cellulose paper offers a high foldability and twistability needed for robust flexible sensors. All these characteristics could enable the stable and sensitive NO<sub>2</sub> detection even under heavy deformation as confirmed by bending down to 0.85 mm and twisting up to 1080°.

- W-009    FACILE FABRICATION OF A SHRINK-INDUCED ULTRASENSITIVE MICROELECTRODE ARRAYS MODIFIED WITH GRAPHENE /BI NANOPARTICLES FILM FOR TRACE LEAD IONS DETECTION .....315**  
 Zonghao Wu<sup>1</sup> and Tianhong Cui<sup>2</sup>  
<sup>1</sup>*Tsinghua University, CHINA and*  
<sup>2</sup>*University of Minnesota, USA*

For the first time, a facile and low-cost method for fabrication of ultrasensitive microelectrode arrays (MEA) lead ions sensor based on heat-shrinkable polymer and modified with graphene–bismuth nanocomposites was presented. The characterization result indicated that the electrode surface presented unique wrinkle structure by heating-shrink process. Due to the non-linear diffusion characteristic of the micro electrode, the unique micro-wrinkle structure, and excellent catalytic activity of Bi NPs, performance of the sensor had been improved greatly. The lead ions stripping peak current (Faraday current) and sensitivity increased notably, and the sensor's detection limit was achieved as 0.016 ppb. This is a very simple and low-cost but effective way to detect ultra-low concentrations lead ions and the microelectrode arrays based on heat-shrinkable film can be applied to many fields.

- M-010    HIGH-FREQUENCY HEXAGONAL BORON NITRIDE (H-BN) PHONONIC WAVEGUIDES .....319**  
 Yanan Wang<sup>1</sup>, Jaesung Lee<sup>1</sup>, Yong Xie<sup>1,2</sup>, Xu-Qian Zheng<sup>1</sup>, and Philip X.-L. Feng<sup>1</sup>  
<sup>1</sup>*Case Western Reserve University, USA and*  
<sup>2</sup>*Xidian University, CHINA*

This digest paper presents the first experimental demonstration of nanoscale phononic waveguides based on a two-dimensional (2D) layered crystalline material, namely hexagonal boron nitride (h-BN). Taking advantage of the planar geometry, the challenges in nanofabrication of 2D materials can be circumvented through a heterogeneous integration approach. Rich wave propagation characteristics of h-BN phononic waveguides are revealed in both finite element method (FEM) simulations and transmission measurements. Numerical analysis further indicates that the frequency response of the designed h-BN phononic waveguides can be finely tuned by varying the thickness or tension level of the h-BN crystals, across the high frequency (HF, 3-30MHz) to very high frequency (VHF, 30-300 MHz) bands. Manipulation and guiding of high frequency mechanical waves on integratable 2D device platforms will open new opportunities in radio-frequency (RF) signal processing and on-chip quantum information technologies.

- T-011    WATER-FLOATABLE SOFTENING PDMS BY MODIFYING PDMS ELASTOMER WITH SILICONE OIL AND MICROWAVE CURING..... 323**  
 Kai-Hao Liu, Dai-En Li, and Che-Hsin Lin  
*National Sun Yat-sen University, TAIWAN*

The density of the typical PDMS elastomer after thermal curing is 1.03 g/cm<sup>3</sup> which is higher than water. A water-floatable PDMS elastomer of the density smaller than 1.00 g/cm<sup>3</sup> is developed by mixing the commercial PDMS Sylgard 184A with low-cost silicone oil. Silicone oil is a series of short chain siloxane similar to the chemical structure of commercial PDMS elastomer and with various side functional groups such as ethyl group and aromatic groups. These functional groups are bigger than the typical methyl groups in typical PDMS such that the density and the stiffness of the polymer chains in the silicone oil modified PDMS is reduced after curing. Moreover, the viscosity of the uncured PDMS liquid is drastically reduced, which can also greatly be reduced the residual bubbles that usually observed in the conventional PDMS process. The experimental results showed that the silicone oil modified PDMS showed no significant surface properties in compared with the commercial PDMS elastomer. The newly developed PDMS process will give substantial impacts on future PDMS-based microfabrication.

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**W-012 ETHYLENE GLYCOL ASSISTED HYDROTHERMAL SYNTHESIS OF MOLYBDENUM DISULFIDE FOR MEMS HUMIDITY SENSOR..... 327**

Xiaohui Leng, Yiming Wang and Fei Wang  
Southern University of Science and Technology, CHINA

In this paper, we have realized the ethylene glycol assisted hydrothermal synthesis of molybdenum disulfide (MoS<sub>2</sub>) with tunable oxygen doping by the adjustment of reaction temperature and applied in humidity sensing with enhanced performance. The addition of ethylene glycol (EG) results in a small flake size and rich oxygen doping site in MoS<sub>2</sub>. This defect-rich structure brings benefits to the humidity sensing property. The influence of temperature is also studied and the proper temperature for the synthesis turns out to be 200°C

**M-013 TOUGH AND STRETCHABLE STRAIN SENSOR BASED ON CARBON NANOTUBE-MOLYBDENUM DISULFIDE REINFORCED SILICONE RUBBER NANOCOMPOSITES..... 331**

Youngno Seo, Vineet Kumar, Dong-Joo Lee, and Jungwook Choi  
Yeungnam University, KOREA

This work presents a silicone nanocomposite-based strain sensor that is reinforced by carbon nanotube (CNT) and molybdenum disulfide (MoS<sub>2</sub>). Incorporation of the multiwalled CNTs inside the silicone rubber matrix increases an elastic modulus and tensile strength, while the addition of MoS<sub>2</sub> nanolayers increases a fracture strain, eventually improving a tensile toughness of the nanocomposite. At the same time, percolation network is formed by the embedded nanomaterials, which can be applicable for tough and stretchable strain sensor. Experimental results demonstrate the improvement of toughness and the stable strain measurement up to 185% of tensile loading.

**T-014 HIGH GAUGE FACTOR STRAIN SENSORS BASED ON VANADIUM DOPED MOLYBDENUM DISULFIDE 2D FILMS..... 335**

Minjie Zhu, Naoki Inomata, Masaya Toda, and Takahito Ono  
Tohoku University, JAPAN

This paper reports the piezoresistive performance of two-dimensional (2D) material of vanadium (V) doped MoS<sub>2</sub> films. A novel method for forming large-area and uniform 2D film is based on sulfurization of a Mo thin film. I-V characteristics indicate that V atoms doping indeed decreases the resistivity of MoS<sub>2</sub>. Strain sensors based on V-doped MoS<sub>2</sub> resistive elements are fabricated. By using a four-point bending method, a gauge factor (GF) of ~140 for V-doped MoS<sub>2</sub> is obtained. This demonstration of substitutional doping in MoS<sub>2</sub> could help in realizing high sensitive strain sensing applications.

**Generic MEMS & NEMS Manufacturing Techniques**

**W-015 FABRICATION OF IMPLANTABLE FLEXIBLE ELECTRODES BASED ON PATTERNABLE PLATINUM NANOWIRE AND POLY DOPAMINE LAYER ..... 339**

Zhaoling Huang<sup>1,2</sup>, Qi Zeng<sup>1</sup>, Kai Xia<sup>1</sup>, Shuijie Qin<sup>2</sup>, Tianzhun Wu<sup>1,3</sup>, and Yi Zhang<sup>3</sup>  
<sup>1</sup>Institutes of Advanced Technology, Chinese Academy of Sciences, CHINA,  
<sup>2</sup>Guizhou University, CHINA, and  
<sup>3</sup>Shenzhen CAS-Envision Medical Technology CO. LTD., CHINA

A novel implantable flexible electrode array based on platinum nanowire (PtNW) was fabricated using poly dopamine (PDA) as the buffer layer and patterned by micro contact printing (μCP) technique. The biocompatible PDA film was selectively grafted on the flexible polyimide (PI) substrate patterned by μCP as the adhesive layer for the in situ electroless deposition of PtNW. As-fabricated PDA/PtNW layer can greatly reduce the impedance (1 kHz) by ~90% compared with the conventional Ti/Pt thin film deposited by sputtering. The adhesion between PDA/PtNW or Ti/Pt metal layer and PI was evaluated using ultrasonic attack and twist fatigue test. The results showed that PDA was very effective as the bioinspired adhesive layer between polymer and metal by significantly enhance the structure and impedance stability when suffering mechanical stress. These achievements can be of great interest for robust flexible electronics for implanted or wearable applications.

**M-016 LOW-COST, EFFICIENT, PHOTOLITHOGRAPHY-FREE FABRICATION OF STRETCHABLE ELECTRONICS SYSTEMS ON A VINYL CUTTER..... 343**

Renxiao Xu<sup>1</sup>, Yuanyuan Huang<sup>1</sup>, Pingsun Lee<sup>1</sup>, Pochen Yeh<sup>1</sup>, Liangjie Ren<sup>1</sup>, Aaron Togelang<sup>1</sup>, Jiaming Liang<sup>1</sup>, Yichuan Wu<sup>1</sup>, Lauren Irie<sup>1</sup>, Adam Rodgers<sup>1</sup>, Weiyu He<sup>1</sup>, Geoffrey Ding<sup>1</sup>, Mohan Sanghadasa<sup>2</sup>, and Liwei Lin<sup>1</sup>

<sup>1</sup>University of California, Berkeley, USA and

<sup>2</sup>Aviation and Missile Research Development and Engineering Center, US Army, USA

We present a new way for the fabrication of stretchable electronics systems without photolithography procedures by exploiting the through-cut, tunnel-cut, and blind-cut modes of a commercial desktop-size vinyl cutter. Compared to previous studies involving photolithography, our method produces a batch of representative devices in significantly reduced time (by ~69%) and cost (by ~73%) with similar feature sizes (100-1000µm). Our inclusion of blind-cut and tunnel-cut modes facilitates the fabrication of complex stretchable electronics systems, rather than only electrodes and interconnects. Finally, we demonstrate the capacities of our photolithography-free fabrication via a stretchable temperature-mapping patch and flexible functional electronic components.

**T-017 A SIMPLE MICRO CHECK VALVE USING PATTERNED HYDROGEL VALVE CORE..... 347**

Yingzhe Wang, Kaoru Uesugi, and Keisuke Morishima

Osaka University, JAPAN

In this paper, we present a simple in-plane micro check valve using a hydrogel valve core fabricated by photolithography. Compared to early micro check valves with multilayered structure, this simple structured valve is much easier to fabricate and operate. Experimental results show that this check valve performs better than most existing in-plane micro check valves, with nearly zero forward cracking pressure and reverse leakage. The forward fluidic resistance of the valve is easy to control by adjusting the width of valve neck. We believe this type of micro check valve could have great use of flow control in integrated microfluidic systems and generate more potentials for MEMS to be utilized in real application.

**W-018 MICROFABRICATION OF ALKALI VAPOR CELLS WITH LOWER THE OUTGASSING AND TEMPERATURE UTILIZING SILICON 3D STRUCTURE..... 350**

Katsuo Nakamura, Yuichi Kimoto, Yoshikazu Hirai, Toshiyuki Tsuchiya, and Osamu Tabata

Kyoto University, JAPAN

We report an effective Cs vapor cell fabrication at the wafer-level utilizing a novel Cs-source, that are applicable to MEMS-based atomic clocks. In this method, a microfabricated Si grooves with multiple re-entrant structures (i.e., "micro-size" scalloped patterns) is employed as a preform, and CsN<sub>3</sub> precursor is deposited on the surface. This method enables *in-situ* thermal decomposition of CsN<sub>3</sub> with high efficiency at the wafer-level. The fabricated Cs-filled cells via a combination of the Cs-source and low-temperature bonding process achieved the good atomic clock frequency stability. Furthermore, the residual gas analysis data demonstrated that the Si preform enables low residual gasses in the cell, leading to enhance long-term stability of the Cs density.

**M-019 H-LINE TRANSPARENCY ANALYSIS OF MICROLITHOGRAPHY FOR MILLIMETER SCALE HIGH-ASPECT RATIO SU-8 STRUCTURES..... 354**

Jungkwun 'JK' Kim, Hassan Al Thuwaini, and Mohammad Almuslem

Kansas State University, USA

This paper reports transparency characteristics of the h-line in the microlithography for the fabrication of ultra-tall SU-8 microstructures. Since the h-line (405 nm) in the lithography system has higher transparency to the SU-8 photoresist compared to that of the i-line (365 nm), the h-line is more suitable for fabrication of ultra-tall SU-8 microstructures for the expanded design capability of the microdevices. The transparency of the h-line through the SU-8 was experimentally verified as a function of film thickness and exposure time. Approximately 62% to the initial intensity of the h-line was observed at the 2.4 mm thick SU-8 film. The transparency of the SU-8 was also decreased by the exposure time. The h-line exposure to the 2.4 mm thick SU-8 film for 3500 seconds decreased the SU-8 transparency to the h-line by 17.7% due to the crosslinking of the SU-8. With the proposed exposure scheme, an array of 2-mm tall micropillar array and 1.5-mm long inclined micropillar array were successfully fabricated. Also, 7-mm tall micropillar was fabricated as a state-of-art microstructure. As an application, an array of 1000-µm-tall micropillars were successfully fabricated to form a 100-turn 3-D toroid inductor. The fabricated inductor showed average inductance of 950 nH in the frequency range of 0.1 to 10 MHz.

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**T-020 WATER LITHOGRAPHY: FROM PROGRAMMABLE PRINTING TO FUNCTIONAL PATTERNING..... 358**

Zhen Liu<sup>1,2</sup>, Zhitao Zhou<sup>1</sup>, Keyin Liu<sup>1</sup>, and Tiger H. Tao<sup>1,3</sup>

<sup>1</sup>*Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, CHINA,*

<sup>2</sup>*Shanghai Normal University, CHINA, and*

<sup>3</sup>*University of Chinese Academy of Sciences, CHINA*

We report a dual-mode, all-water-based, chemical-free, biopatterning method which allows rapid prototyping of functional biodevices in an extremely fast fashion and importantly in ambient conditions, on both planar and curved surfaces. Water - either pure or functionally doped - is used as the etching source and water-dissolvable silk fibroin is used as the resist. The programmable printing(including dot and line arrays, grayscale patterns) are successfully demonstrated on planar substrates and even curved surfaces. And the silk film is patterned in a “subtractive” fashion. In addition, large-scale fabrication is also achieved by using multi-row nozzles which can be controlled individually. Meanwhile, the inherent advantage of incorporating functional dopants in the aqueous ink has also been tested where the functional patterns are created by printing the fluorescein. This dual mode of manufacturing control exemplifies a generalized lithography process to produce structures with both customizable geometries and functions, which opens up new opportunities in biomedical applications.

**W-021 LEVEL SET SIMULATION OF SURFACE EVOLUTION IN ANISOTROPIC WET ETCHING OF PATTERNED SAPPHIRE SUBSTRATE ..... 361**

Jie Zhang<sup>1</sup>, Yan Xing<sup>1</sup>, Miguel A. Gosálvez<sup>2</sup>, Xiaoli Qiu<sup>1</sup>, Xiaohui Lin<sup>1</sup>, and Chibin Zhang<sup>1</sup>

<sup>1</sup>*Southeast University, CHINA and*

<sup>2</sup>*University of the Basque Country (UPV/EHU), SPAIN*

The performance of GaN-based Light Emitting Diode (LED) devices may be significantly improved by optimizing the use of maskless growth of GaN layers directly on the sidewalls of Patterned Sapphire Substrates (PSSs). In order to control the structure, arrangement, and inclination angles of the sidewalls, the use of anisotropic wet etching of sapphire needs to be clarified. To this end, this paper presents a Level Set approach to simulate the wet etching process on sapphire for the first time, thus enabling the optimization of the mask pattern for the preparation of suitable PSSs. By using the complete etch rate distribution obtained from an etched sapphire hemisphere for different concentrations and temperatures, the proposed method is expected to provide a flexible tool to determine the etched profiles of complex MEMS structures on different cuts of sapphire. In fact, the simulation results show good agreement with experiment for both transient and stable sidewalls of the trench profiles. By considering various arrays as examples, the level set algorithm is demonstrated to be applicable for simulating the fabrication of PSSs by wet etching.

**M-022 FEEDBACK-FREE ELECTROMIGRATED TUNNELING JUNCTIONS FROM CRACK-DEFINED GOLD NANOWIRES ..... 365**

Simone Pagliano, Fabrizio Gota, Shyamprasad N. Raja, Valentin Dubois, Göran Stemme, and Frank Niklaus

*KTH Royal Institute of Technology, SWEDEN*

Tunneling junctions are pairs of electrodes separated by gaps of a few nanometers (< 3 nm) that allow electrons to tunnel across the gap. Tunneling junctions are of great importance for applications such as label-free biomolecule sensing and single molecule electronics, but their fabrication remains difficult and laborious. In this paper, we present a simple 2-stage process for the fabrication of tunneling junctions consisting of electrode pairs made of gold (Au). This is achieved by combining a novel methodology for fabricating crack-defined Au nanowires at wafer-scale with a constant voltage, feedback-free electromigration procedure to form tunneling nanogaps free of debris.

**T-023 FABRICATION OF 3D MICRO ICE STRUCTURES BASED ON INKJET PRINTING..... 368**

Fengyi Zheng, Jiasheng Huang, and Zhihong Li

*Peking University, CHINA*

This study proposes a method for fabricating 3D micro structures of ice without supporting material. The inkjet printing process in a low humidity environment is employed to form ice crystals with precisely controlled direction. The pico-droplets are injected on the previously formed ice structure, and then immediately freeze into ice. Different 3D structures, with a maximum height of 2000 μm, can be formed by controlling the substrate temperature, the ejection frequency and the size of a single droplet. The branch point depends on the fall point of the droplet on the previously formed ice structure, thus a high degree of freedom is available for the 3D structure.

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- M-024 ROOM-TEMPERATURE PRINTING OF MICRONSCALE-WIDE METAL LINES FOR MICROSYSTEMS VIA ATMOSPHERIC MICROSPUTTERING..... 372**  
 Yosef Kornbluth<sup>1</sup>, Richard Mathews<sup>2</sup>, Lalitha Parameswaran<sup>2</sup>, Livia Racz<sup>2</sup>, and Luis Fernando Velásquez-García<sup>1</sup>  
<sup>1</sup>Massachusetts Institute of Technology, USA and  
<sup>2</sup>MIT Lincoln Laboratory, USA

We report a novel ion drag beam-focused, atmospheric pressure microplasma sputterer that allows, for the first time, direct-write additive manufacturing of electronics-quality conductive lines on temperature-sensitive substrates. Gold lines as narrow as 1.7 μm (i.e., on par with state-of-the-art CMOS metallization, and up to two orders of magnitude finer than reported values from competing microspattering reactors), with electrical resistivity as low as 30 μΩ-cm without annealing (i.e., half the reported resistivity value from low-temperature silver nanoparticle ink imprints), and roughness as low as 1.3 nm are reported. Smooth, conductive lines with thickness in the 30 nm to 250 nm range were successfully created.

**Packaging & Assembly**

- T-025 PROCESS DEVELOPMENT OF LOW RESISTIVE AG-BASED THROUGH SILICON VIAS USING INKJET PRINTING TECHNIQUE FOR 3D MICROSYSTEM INTEGRATION ..... 376**  
 Jia-Han Yang<sup>1,2</sup>, Kun-Lin Tsou<sup>1</sup>, Yu-Min Fu<sup>1</sup>, Yu-Ting Cheng<sup>1,2</sup>, and Yen-Fang Song<sup>2</sup>  
<sup>1</sup>National Chiao Tung University, TAIWAN and  
<sup>2</sup>National Chiao Tung University and National Synchrotron Radiation Research Center, TAIWAN

This paper presents an inkjet printing and filling process to produce 250μm deep Ag-based fully filled through silicon vias with the aspect ratio of via depth vs. diameter up to 5. With the optimization of the printing pattern, humidity control, and silver mirror reaction, the Ag TSV subjected to 400°C thermal anneal for 60 mins can exhibit a resistivity of 26μΩ-cm, the lowest resistivity and highest AR ever reported. Process simplicity and no need of metal liners make the technique with great potential for 3D microsystem integration.

- T-026 SELF-ASSEMBLY OF SHAPE MEMORY POLYMER PRINTED BY FUSED DEPOSITION MODELING ..... 380**  
 Akihiro Nojiri<sup>1,2</sup>, Eiji Iwase<sup>1</sup>, and Michinao Hashimoto<sup>2</sup>  
<sup>1</sup>Waseda University, JAPAN and  
<sup>2</sup>Singapore University of Technology and Design, SINGAPORE

We demonstrated the method for self-assembly of a polyurethane-based shape memory polymer (SMP) printed by a fused deposition modeling (FDM) 3D printer. SMP transfers between a rubber state and a glass state by the change of temperature, and this characteristic is usually used for memorizing a 3D shape. In this study, we used this characteristic not for shape memory but for self-assembly. When a SMP filament is printed in a rubber state by FDM, some internal stress is introduced to the printed SMP structure. Above the glass transition temperature ( $T_g$ ), the SMP structure transfers to a rubber state and releases internal stress and shrinks. Utilizing bi-layer structure with different shrink rate, we demonstrated that 2D SMP structures can transform into 3D structures. We achieved to control the rate and direction of shrinking by varying printing temperatures and patterns, which then allowed defining bending directions to form 3D structures.

**Micro/Nanofluidics & Chemical Sensors**

**Materials and Manufacturing for Micro- and Nanofluidics**

- W-027 TOWARD RAPID PROTOTYPING OF HIGH-ASPECT-RATIO SUB-100 μM PMMA MICROFLUIDIC CHANNEL: OPTIMIZATION OF PMMA CO<sub>2</sub> LASER MACHINING AND SOLVENT-ASSISTED THERMAL BONDING ..... 384**  
 Kaba Abdi Mirgissa, Woongsub Lee, and Dohyun Kim  
 Myongji University, KOREA

In this work, optimization of CO<sub>2</sub>-laser machining and solvent-assisted thermal bonding of PMMA [poly (methyl methacrylate)] sheet for rapid prototyping of microfluidic devices with sub-100-μm and high-aspect- ratio (AR) feature is reported. Design of experiments (DOE) was used to optimize the set of cutting parameters that allowed us to achieve unprecedented minimum channel width of 57.5 μm with a high AR of 3.5:1 having smooth inner surfaces in contrast to Gaussian-shaped channels with rough inner surface, cut by conventional engraving-mode laser machining.

**M-028    STACKING 2D DROPLET ARRAYS FOR 3D CONFIGURABLE DROPLET NETWORK ..... 387**  
 Hiroki Yasuga<sup>1,2</sup>, Toshihisa Osaki<sup>2,3</sup>, Koki Kamiya<sup>2</sup>, Emre Iseri<sup>4</sup>, Wouter van der Wijngaart<sup>4</sup>, Shoji Takeuchi<sup>2,3</sup>,  
 and Norihisa Miki<sup>1,2,3</sup>

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Droplet interface bilayer (DIB) networks are expected to lead to tissue-like materials that can be designed from single droplets. Although various functions, such as sensors or computing, have been implemented into DIB networks, there remains a challenge in terms of configurability of constituent droplets in three-dimensional (3D). In this paper, we construct 3D DIB networks with defined droplet positions. We prepared 2D droplet arrays in paper-like substrates based on a method that we previously reported. Vertical stacking of the 2D arrays resulted in DIB formation between layers, i.e., a 3D DIB network.

**T-029    A MASKLESS PROCESS FOR FABRICATION OF PATTERNED SURFACES WITH MICROSCALE  
 SUPERHYDROPHOBIC BORDERS FOR HIGH THROUGHPUT DROPLET MICROARRAY PRINTING..... 389**

Khuushi<sup>1</sup>, Sanjay Kumar Srinivasan<sup>1</sup>, Chandantaru Dey Modak<sup>1</sup>, Arvind Kumar<sup>1,2</sup>, Abinash Tripathy<sup>1,3</sup>,  
 and Prosenjit Sen<sup>1</sup>

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<sup>2</sup>*The University of Queensland, AUSTRALIA, and*

<sup>3</sup>*ETH Zurich, SWITZERLAND*

We demonstrate a novel and simple fabrication technique to create a 2D array of liquid capturing microregions separated by superhydrophobic borders on polydimethylsiloxane (PDMS). The pattern with microscale superhydrophobic borders was formed by transfer of nanostructures grown on a copper mesh. Our technique does not require the use of any sophisticated equipment, thus making it simple, cost-effective and easily scalable. The capturing regions defined by the superhydrophobic borders can trap droplets having volume as low as ~2.1 picolitres (*pL*) when exposed to a liquid. Trapped droplet volume depends on the dimension of the liquid capture region, which is determined by the pore opening (*L*) of the copper mesh. We demonstrate capture of various aqueous droplets of different sizes on different surfaces. These surfaces can be used in a variety of applications where cell culture in small volumes is required (e.g. cell differentiation, forming genome libraries etc.).

**W-030    A CRYSTAL-CLEAR SERS-DROPLET WITH EVENLY DISTRIBUTED 3D HOT-SPOTS ..... 392**

Ruirui Li<sup>1,2</sup>, Bo Gui<sup>1</sup>, Haiyang Mao<sup>1</sup>, Yudong Yang<sup>1</sup>, Hao Yang<sup>3</sup>, Jijun Xiong<sup>2</sup>, and Weibing Wang<sup>1</sup>

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<sup>3</sup>*Institute of Microbiology and Epidemiology, CHINA*

In this work, a crystal-clear SERS-droplet is proposed, inside of which hot-spots are evenly distributed in three-dimension. Such a droplet is prepared by rolling an aqueous droplet on a superhydrophobic SERS substrate composed of carbon nanoparticles (CNPs) and their protecting nanolayer of Parylene C (PC). Such a CNP-PC stacked SERS substrate is fabricated simply by flame deposition of CNPs, chemical vapor deposition of a PC nanolayer, and noble-metal sputtering. Due to the three-dimensional (3D) distribution of hot-spots, such a SERSdroplet is about 18.5 times more sensitive than a similar SERS substrate involving only two-dimensional hot-spots, and achieves an enhancement factor as large as  $6.6 \times 10^7$ . Besides, ascribe to even distribution of the hot-spots, the SERS-droplet has a relatively high repeatability.

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**M-031 GALLIUM OXIDE COATED FLAT SURFACE AS NON-WETTING SURFACE FOR ACTUATION OF LIQUID METAL DROPLETS..... 396**

Ziyu Chen and Jeong-Bong Lee  
*The University of Texas, Dallas, USA*

Gallium-based liquid metals are eutectic alloys that are liquid phase at room temperature. A combination of material properties such as biocompatibility, high electrical and thermal conductivity, and infinite deformability makes gallium-based liquid metal alloys (e.g., eutectic gallium indium alloy and Galinstan) excellent materials to be utilized in myriads of applications. However, liquid metal is instantly oxidized in ambient air and wets almost any surface. We report gallium oxide coating as a method for converting almost any flat surface to be non-wetting surface against naturally oxidized gallium-based liquid metal alloys. Various materials including PDMS, bare silicon wafer, SU-8 on Si, SiO<sub>2</sub> layer on Si, and glass slides were tested for their contact angles, bouncing test, and rolling test. Pneumatic actuation liquid metal droplet on gallium oxide coated flat surfaces was carried out and the speed of movement of Galinstan droplet was found to be 1.45 ~ 3.07 cm/sec. This new method does not require any micro/nano fabrication or specific nanoscale surface topology. It is markedly simple yet powerful remedy for avoiding stiction of naturally oxidized gallium-based liquid metals and is readily applicable to common microfluidic substrates to unleash full potential of gallium-based liquid metal microfluidics in various applications.

**Generic Microfluidics & Nanofluidics**

**T-032 A NOVEL SESC MICROSTRUCTURE TO REALIZE VARIOUS SPONTANEOUSLY LIQUID SPREADING PROPERTIES..... 400**

Wen Hong<sup>1</sup>, Longjun Tang<sup>1,2</sup>, Bowen Ji<sup>1</sup>, Wenxi Sun<sup>1</sup>, Bin Yang<sup>1</sup>, Xiaolin Wang<sup>1</sup>, and Jingquan Liu<sup>1</sup>  
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<sup>2</sup>*MicroPort NeuroTech (Shanghai) Co., Ltd, CHINA*

We report design and fabrication of a novel microstructure with both sharp edge and sharp corner (SESC) in its topography, which can be tailored to achieve various liquid spreading properties. The sharp edge of the SESC microstructure can hinder liquid spreading in one direction, while the sharp corner can enhance liquid spreading in another direction. By utilizing the two opposite effects of the sharp edge and the sharp corner, two different types of anisotropic wetting properties are demonstrated, including bidirectional water spreading on a 2-D SESC microstructure and unidirectional water spreading on a 3-D SESC microstructure. On the fabricated 2-D SESC microstructure, contact angle difference in parallel and perpendicular direction can reach 93.8°, which is the highest in published works.

**W-033 GENERATION OF MONODISPERSE DROPLETS FROM TENS OF µL SAMPLE VOLUME USING CENTRIFUGE-BASED MICROFLUIDIC DEVICE..... 404**

Dong-Chel Shin, Yuya Morimoto, and Shoji Takeuchi  
*The University of Tokyo, JAPAN*

We propose a centrifuge-based microfluidic device housed in a standard microtube for generation of monodisperse microdroplets from tens of µl sample volume. Centrifugation drives overpressure of a dispersed phase, thus infuses the dispersed phase into a microchannel. Because of the channel geometry for step emulsification, the infused dispersed phase is pinched off forming droplets. Then, the droplets accumulate on the bottom of the microtube by centrifugal force. We succeeded in generation of monodisperse droplets with a diameter of 130 µm (CV < 2%) by operation of centrifuge. Since the device can produce droplets in a microtube without complex experimental setup (e.g. syringe pump), it will be a powerful tool for simple generation of droplets for droplet-based applications.

**M-034 A PUMPLESS MIXER FOR EFFICIENT CAPTURING OF SMALL PARTICLES UTILIZING VIBRATION-INDUCED FLOW..... 406**

K. Kaneko<sup>1</sup>, T. Okano<sup>1</sup>, T. Hayakawa<sup>1</sup>, Y. Hasegawa<sup>2</sup>, and H. Suzuki<sup>1</sup>  
<sup>1</sup>*Chuo University, JAPAN and*  
<sup>2</sup>*The University of Tokyo, JAPAN*

We demonstrated the applicability of the vibration-induced flow, in which a mean flow is induced around a micro-pillar by applying small circulating vibration (Figure 1), for capturing small particles by larger capture beads. The current approach is advantageous in handling a small amount of liquid of down to several µL because it does not require an external pump. A set of capturing experiments implemented with a simple cylindrical pillar showed that the capturing-rate of small particles depends on the vibration parameters. Since the binding energy (affinity) of biological samples is often weak, there exists the optimal condition to achieve a high capturing rate.

**T-035 REVERSIBLE ON-DEMAND MAGNETIC LIQUID METAL MARBLE MANIPULATION BY MAGNETOWETTING: SPLIT AND MERGE, DEFORMATION AND RECOVERY ..... 409**

Jinwon Jeong<sup>1</sup>, Jeonghwa Seo<sup>2</sup>, Sang Kug Chung<sup>1</sup>, Jeong-Bong Lee<sup>3</sup>, and Daeyoung Kim<sup>4</sup>

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<sup>2</sup>*Edwards Korea Limited, KOREA,*

<sup>3</sup>*The University of Texas, Dallas, USA, and*

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This paper presents on-demand reversible split and merge, deformation and recovery of a magnetic liquid metal marble coated with iron (Fe) particles by magnetowetting. To manipulate the liquid metal by magnetic field, we coated the liquid metal surface with Fe particles using chemical reaction with diluted hydrochloric acid (HCl) solution. By applying various shapes of magnetic field, we investigated split of a magnetic liquid metal marble into 2, 3, and 4 small marbles. We investigated a split time of the magnetic liquid metal marble with the magnetic field by changing the mass of coated Fe particles. In addition, the split and merge time of liquid metal marble with diluted HCl solution and HCl vapor treatment were measured. Finally, as a proof of concept, the proposed reversible on-demand magnetic liquid metal marble manipulation was successfully demonstrated by applying diverse shapes of magnetic field. We investigated the deformability of ~0.6 ratio and the recovery time of ~9 seconds with/without magnetic field for splitted 4 liquid metal marbles.

**W-036 A MICROFLUIDIC CHIP FOR CTC WHOLE GENOME SEQUENCING .....412**

Li Ren, Jia Fei, Zhang WK, Fang ZG, Hu ZY, and Wei ZW

*National Center for Nanoscience and Technology, CHINA*

This paper developed a microfluidic chip for whole genome sequencing (WGS) of circulating tumor cells (CTC) at single-cell level. For the first time, all processing steps between collecting blood sample and feeding prepared sample to sequencer are finished in a single microfluidic chips. The microfluidic chip comprehensively performs blood filtering, CTC enrichment, CTC identification/isolation, CTC lysis and whole genome amplification (WGA) at the single cell level. The microfluidic chip was validated by clinical samples. Our results demonstrate that for the first time, the aim of “whole blood in, WGA product out” has been realized at single CTC level with clinical samples, in a microfluidic chip.

**Biological and Medical Microfluidics and Nanofluidics**

**M-037 PUMPLESS SOLUTION EXCHANGE FOR REPEATABLE NANOPORE BIOSENSOR DRIVEN BY SUPERABSORBENT POLYMER AND HYDROSTATIC PRESSURE .....416**

Tetsuya Yamada<sup>1</sup>, Koki Kamiya<sup>1</sup>, Toshihisa Osaki<sup>1</sup>, and Shoji Takeuchi<sup>1,2</sup>

<sup>1</sup>*Kanagawa Institute of Industrial Science and Technology, JAPAN and*

<sup>2</sup>*The University of Tokyo, JAPAN*

This paper reports a compact pumpless analyte exchange of a droplet based lipid bilayer. This system allows the repeatable detection. The flow in the system is caused by superabsorbent polymer and hydrostatic pressure, which realize a simple exchange system without power source. The retention time to replace the analyte could be controlled by flow rate. We succeeded in detecting nanopore signal formed by  $\alpha$ -hemolysin and observing the decreasing of blockage signal from cyclodextrin. This data indicates that the concentration of cyclodextrin in a droplet based lipid bilayer decreased. This exchange system working without external power supply is significantly simple and compact comparing with the conventional method that required two pumps.

**T-038 ON-CHIP DYNAMIC MECHANICAL MEASUREMENT .....418**

Atsushi Kirimoto, Hiroaki Ito, Mitsuhiro Horade, Toshio Takayama, Misato Chimura, Tomohito Ohtani,

Yasushi Sakata, and Makoto Kaneko

*Osaka University, JAPAN*

In this paper, we proposed a novel method of dynamic mechanical measurement of a red blood cell (RBC) in a microfluidic channel. Although dynamic mechanical measurement in a macroscopic scale provides rich information of frequency-dependent viscoelasticity, the methods for on-chip and thus high-throughput measurement in a microscopic scale have never been established. Here, using our on-chip precise position control system for a microscopic target object, we realized periodic cell motion with a specified amplitude and frequency in the microchannel, which provided the amplitude and phase difference in periodic changes of stress and deformed shape under shear flow. Through the measurements with various frequency and amplitude, we succeeded in the evaluation of RBC viscoelasticity that depends on stress frequency and amplitude.

**W-039 A MICROFLUIDIC CHIP FOR SCREENING HIGH-PRODUCING HYBRIDOMAS AT THE SINGLE CELL LEVEL ..... 422**

Wei K. Zhang<sup>1</sup>, Ren Li<sup>2</sup>, Zhi G. Fang<sup>2</sup>, Zhi Y. Hu<sup>2</sup>, Ze W. Wei<sup>2</sup>, and Qin Li<sup>1</sup>

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<sup>2</sup>*National Center for Nanoscience and Technology of China, CHINA*

Screening high-producing antibody-secreting cell from heterogeneity mammalian cell line populations is the vital procedure during the long time culture for antibody manufacture. To acquire high-producing cells, we designed a novel microfluidic chip for screening high-producing hybridomas from heterogeneous population at single cell level. All the procedures of hybridoma screening, including single cell trapping, identification, culturing and releasing, are integrated in a single chip. Compared with traditional methods based on limiting dilution, our chip realized higher monoclonal antibody (mAb) yield and shortened the screening period from 10 to 5 days with twice. It is significance that provides foundation to pharmaceutical company of rapidly screening cell lines.

**M-040 A BLOOD HEMATOCRIT TEST STRIP ..... 426**

Janosch Hauser, Göran Stemme, and Niclas Roxhed

*KTH Royal Institute of Technology, SWEDEN*

This paper reports a self-propelled microfluidic hematocrit (HCT) test that uses the correlation between blood hematocrit and wicking distance of blood in a special paper matrix. The enabling feature is a novel blood volume metering method that allows sampling from the fingertip and reliably generates a highly precise blood volume of  $47.7 \pm 1.9 \mu\text{l}$  (CV 4%) that is transferred into a porous paper matrix. A dissolvable valve ensures a relaxed time window for blood sampling, making it highly user-friendly and resilient to overfilling. The presented hematocrit test strip poses a simple, cheap, equipment-free solution for patient-centric hematocrit measurements.

**T-041 DIFFERENTIAL SODION-BASED SELF-CALIBRATED EPIDERMAL MICROFLUIDIC SYSTEM FOR CONTINUOUS GLUCOSE MONITORING ..... 429**

Zhijia Pu, Xiao Su, Haixia Yu, and Dachao Li

*Tianjin University, CHINA*

This paper reports a differential sodion-based self-calibrated epidermal microfluidic system for continuous glucose monitoring. This epidermal microfluidic system consists of an epidermal detection patch and microchannels of skin. The epidermal detection patch integrates an extraction electrode pair, an electrochemical glucose sensor and a differential sodion sensor. The extraction electrode pair is used to transdermally extract interstitial fluid (ISF) from subcutaneous tissue through the microchannels of skin. The main extracted materials are  $\text{Na}^+$  and the glucose molecules transported by  $\text{Na}^+$ . The amounts of the glucose and  $\text{Na}^+$  extracted can be detected by the glucose sensor and the sodion sensor. Here we employ the amount of extracted  $\text{Na}^+$  to indicate the amount of extracted ISF thereby to calibrate the predicted ISF glucose concentration because the  $\text{Na}^+$  concentration has quite small change in body. This method eliminates the effect of the extracted ISF volume fluctuations due to different people, different extraction positions and the permeation change as time. And the differential structure can distinguish the passive perspiration, therefore, restrains the effect of sweat.

**Integrated/Embedded Microfluidics and Nanofluidic Systems & Platforms**

**W-042 HOW TO MEASURE CELLULAR SHEAR MODULUS INSIDE A CHIP: DETAILED CORRESPONDENCE TO THE FLUID-STRUCTURE COUPLING ANALYSIS ..... 433**

Hiroaki Ito, Naoki Takeishi, Atsushi Kirimoto, Misato Chimura, Tomohito Ohtani, Yasushi Sakata,

Mitsuhiro Horade, Toshio Takayama, Shigeo Wada, and Makoto Kaneko

*Osaka University, JAPAN*

Deformability of a red blood cell (RBC) is not only a required property for microcirculation but also an important indicator for pathological changes, which can be used for potential diagnoses of various diseases such as sepsis and vascular diseases. To date, various types of microfluidic platforms have been intensively developed for high-throughput measurements of RBC stiffness. This paper reports a novel strategy to measure the shear modulus of a RBC using on-chip feedback manipulation combined with a computational analysis of shape deformation. Here, we compared the shear deformations of a RBC flowing in a microchannel to that modeled in fluid-structure coupled simulation. The strain-velocity relationships for different values of shear modulus  $G_s$  obtained in both the experiments and simulation provide the direct correspondence of experimentally observable parameters (effective strain  $\varepsilon$ , velocity  $v$ ) to a defined material constant  $G_s$ .



**M-043 STICK-TO-ANALYZE ZETA POTENTIAL MEASUREMENT CHIP WITH INTEGRATED ELECTROOSMOTIC MICROPUMP AND LIQUID FLOW SENSOR ..... 437**

Yuki Okamoto<sup>1</sup>, Koji Fujimoto<sup>2</sup>, Hiroyuki Ryoson<sup>2</sup>, Takayuki Ohba<sup>2</sup>, and Yoshio Mita<sup>1</sup>

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A novel world smallest fully-integrated zeta potential measurement sensor is realized: we fabricated, for the first time, an integrated electroosmotic flow (EOF) micro pump with micro flow sensor in an open micro-channel on an 8×8 mm<sup>2</sup> SOI chip. The sensor allows us to measure surface property (zeta potential) of planar material. Due to its noninvasive measurement, the analyzed wafer can further be MEMS-processed to realize microfluidic devices with a well-identified surface electrical property.

**T-044 INTEGRATION OF DISCRETE SENSORS AND MICROELECTRODE ARRAYS INTO OPEN MICROFLUIDIC HANGING-DROP NETWORKS..... 441**

Raziyeh Bounik<sup>1</sup>, Massimiliano Gusmaroli<sup>1</sup>, Patrick M. Misun<sup>1</sup>, Vijay Viswam<sup>1,2</sup>, Andreas Hierlemann<sup>1</sup>, and Mario M. Modena<sup>1</sup>

<sup>1</sup>*ETH Zurich, SWITZERLAND and*

<sup>2</sup>*MaxWell Biosystems AG, SWITZERLAND*

This work presents a new versatile method to integrate discrete sensor chips into open-microfluidic hanging-drop networks. As proof of concept, we integrated an electrical-impedance-spectroscopy (EIS) sensor unit into a hanging-drop platform for monitoring the size of microtissues. The fabrication and assembly method enables the integration of a large variety of silicon-based sensors, such as chemical sensors, biosensors or microelectrode arrays (MEAs), in open-microfluidic hanging-drop networks to perform studies on three-dimensional microtissues.

**W-045 ULTRA-THIN MAGNETIC MICROPUMP FOR ON-DEMAND DRUG DELIVERY ..... 445**

Cong Wang and Jungyul Park

*Sogang University, KOREA*

In this paper, we propose an ultra-thin magnetic micropump capable of on-demand drug delivery for ocular diseases. The proposed ultra-thin magnetic micropump is less than 500 μm thick and can be easily embedded in contact lens or periocular implant. Precise on-demand drug release was realized by the deflection of the magnetic membrane assembly according to the external magnetic field, and the membrane assembly consists of a thin elastic PDMS membrane and a cylindrical magnetic nanoparticle-PDMS composite block. Additionally, micro check valve composed of two PDMS layers was integrated into the micropump to realize one-directional drug delivery and prevent undesired drug diffusion.

**M-046 A MEMS REACTOR FOR OBSERVING MORPHOLOGY-EVOLUTION IN TEM AND SIMULTANEOUSLY DETECTING INVOLVED MOLECULE-NUMBER CHANGE DURING NANO-CONSTRUCTING REACTION ..... 448**

Wei Li<sup>1,2</sup>, Haitao Yu<sup>1</sup>, Fanglan Yao<sup>1,2</sup>, Xueqing Wang<sup>1,2</sup>, Pengcheng Xu<sup>1</sup>, Ming Li<sup>1</sup>, and Xinxin Li<sup>1,2</sup>

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<sup>2</sup>*University of Chinese Academy of Sciences, CHINA*

This study develops a novel MEMS reactor for *in situ* structure-property correlative characterization during nano-construction process. With the nano-reactant putting inside, the micro-reactor is installed in a transmission-electron-microscope (TEM). Nano-constructing reaction occurs after the reacting-gas of variable concentration and pressure is introduced into the reactor to react with the nano-material that is heated to desired temperature. TEM observation to the nano-structure change is enabled by integrating a 40nm-thin SiN-film window in the reactor. A resonant-cantilever gravimetric sensor is also integrated inside the reactor to load the nano-substance and detect the reaction-induced mass change via  $\Delta f_0 \propto \Delta m$ . Thus the reactor is enabled continually observing morphology-evolution and simultaneously recording the mass-change during the reaction process, thereby *in situ* building the correlation between nano-morphology and quantitative physicochemical properties. Experiment has verified that the TEM observation achieves atomic-scale resolution and the mass detection resolution gets 1 pico-gram to extract quantitative physicochemical properties. The reactor can be widely used for nano-material developments.

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**MEMS Gas and Chemical Sensors**

- T-047 CURRENT DETECTION TYPE SPR SENSOR USING AU GRATING AND BACKSIDE ILLUMINATION ..... 452**  
 Yoshiki Saito<sup>1</sup>, Yosuke Yamamoto<sup>1</sup>, Tetsuo Kan<sup>1</sup>, Takuya Tsukagoshi<sup>2</sup>, Kentaro Noda<sup>2</sup>, and Isao Shimoyama<sup>2</sup>  
<sup>1</sup>*The University of Electro-Communications, JAPAN and*  
<sup>2</sup>*The University of Tokyo, JAPAN*

In this paper, we report on miniaturization of chemical sensor using Surface Plasmon Resonance (SPR). This sensor has an Au grating on a surface of an n-Si wafer. The Au grating enables excitation SPR that can be detected electrically with the device. We demonstrated a backside illumination method to excite SPR so that the excitation light was introduced from the n-Si side, instead of the Au side. The excitation light from the backside can reach the Au grating without traveling through the sample liquid so that the unwanted attenuation of the illumination light by the sample can be avoided. The excitation light is diffracted by the grating, and the diffracted light couples to free electrons on the gold surface as SPR. Since SPR excites free electrons on the Au, they are detected as photocurrent at the Schottky junction at the Au/n-Si interface. In this study, we compared the current responses by the backside illumination method with changing the refractive index of sample using air and pure water. Depending on the change of the sample, peaks appeared at different angles in the currents response curve. We verified that the proposing device can discriminate sample species on the Au, and can perform as an SPR sensor.

- M-048 ZNO NANOSTRUCTURES FUNCTIONALIZED PIEZORESISTIVE SILICON MICROCANTILEVER PLATFORM FOR PORTABLE GAS SENSING ..... 456**  
 Jiushuai Xu<sup>1,2</sup>, Maik Bertke<sup>1,2</sup>, Andi Setiono<sup>1,2</sup>, Angelika Schmidt<sup>1,2</sup>, and Erwin Peiner<sup>1,2</sup>  
<sup>1</sup>*TU Braunschweig, GERMANY and*  
<sup>2</sup>*Laboratory for Emerging Nanometrology (LENA), GERMANY*

This paper reports a gas sensing platform composed of Si microcantilever and phase-locked loop (PLL)-based circuit, where cantilever surface was modified with ZnO nanorods and ZnO nanorods/self-assembled monolayers (SAMs). The ethanol-sensing and relative humidity-sensing characteristics were investigated. The measurements indicated that the sensors exhibited both high sensitivities and fast responses to ethanol vapor and water moisture, respectively, at room temperature. Thus, our results demonstrated the potential application of ZnO nanostructure functionalized microcantilever platform for gas sensing.

- W-049 AWARD NOMINEE\* MOLECULAR LENGTH BASED TARGET IDENTIFICATION USING A NANO-GAP SENSOR ..... 460**  
 Shakir-ul Haque Khan, Aishwaryadev Banerjee, Samuel Broadbent, Prattay Deepta Kairy, Kyeong Heon Kim, Carlos H. Mastrangelo, Ryan Looper, and Hanseup Kim  
*University of Utah, USA*

This paper reports the detection of gas molecules with an identical functional group, but in different lengths due to varying numbers of CH<sub>2</sub> backbone units, by utilizing a nano-gap gas sensor. Significance of such a gas sensor lies on its ability to distinguish molecular lengths by down to 0.15nm in this testing. The fabricated nano-gap sensor, after being functionalized by a specific linker on the surface, successfully captured all three target gas molecules of 2-CH<sub>2</sub>-diamine (0.3nm), 3-CH<sub>2</sub>-diamine (0.45nm) and 5-CH<sub>2</sub>-diamine (0.75nm). The capture of each target molecules demonstrated significant differences in both resistance and capacitances, resulting in successful identification of 2-CH<sub>2</sub>-diamine (0.3nm), 3-CH<sub>2</sub>-diamine (0.45nm) and 5-CH<sub>2</sub>-diamine (0.75nm) by producing different on/off resistance ratios of 105, 2905 and 3832 and capacitance changes of 4.45pF, 16.21pF and 26.64pF, indicating the capability of identifying multiple gas molecules in different lengths despite identical functional groups.

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**T-050    MODELLING AND EVALUATION OF BUBBLE CHROMATOGRAPHY ..... 464**  
 Ashrafuzzaman Bulbul, Kyeongheon Kim, and Hanseup Kim  
*University of Utah, USA*

This paper reports the establishment of a theoretical model of a bubble chromatography system, based on our previous experimental results [1], to investigate into characteristics and limitations in the gas-to-bubble conversion. The established model (i) utilized the gas loss mechanism into a bubble volume equation, and (ii) successfully described the phenomena of reduction in bubble diameters when a target gas was injected in comparison to those of a carrier gas. The established bubble volume model successfully predicted the volume of a *single gas* bubble that matched with the experimental measurements by considering 40.45% volumetric loss of input gases into liquid during bubble formation as confirmed by two experiments: quantitative analysis of CO<sub>2</sub> and pentane in liquid. The established bubble chromatogram model successfully predicted the volume of a *binary gas mixture* bubble with experimental data, by considering two different volumetric losses (50% and 40%) for a binary mixture of pentane target and helium carrier gas.

**W-051    WO<sub>3</sub>-MoS<sub>2</sub> MIXTURE-BASED GAS SENSOR FOR NO<sub>2</sub> DETECTION AT ROOM TEMPERATURE ..... 468**  
 Dae-Hyun Baek, GyuJun Choi, Yeunjun Kwak, Byeong-Hwa Cho, and Jongbaeg Kim  
*Yonsei University, KOREA*

We demonstrate a WO<sub>3</sub>-MoS<sub>2</sub> mixture-based gas sensor showing the response to NO<sub>2</sub> and complete recovery in air at room temperature for the first time. When n-type WO<sub>3</sub> and p-type MoS<sub>2</sub> meet, a p-n junction with an electron depletion zone is formed at the interface due to the electron transfer induced by the difference in work function. This electron depletion zone prevents MoS<sub>2</sub> from bonding directly with oxygen, thus preventing electrical instability in air that conventional MoS<sub>2</sub>-based sensors inevitably have and allowing them to respond and fully recover in air at room temperature. Here, unlike other MoS<sub>2</sub>-based sensors, the fabricated WO<sub>3</sub>-MoS<sub>2</sub> mixture-based sensors showed complete recovery after exposure to NO<sub>2</sub> in air at room temperature, which means that the fabricated sensor can be operated at low power without the heaters.

**M-052    IMPROVED PERFORMANCE OF MICRO-PRECONCENTRATOR USING MESOPOROUS SILICA WITH HIGH SPECIFIC SURFACE AREA AS A SURFACE TEMPLATE ..... 472**  
 Bin Zhao<sup>1</sup>, Fei Feng<sup>1,2</sup>, Fan Luo<sup>1</sup>, Xuelei Yang<sup>1</sup>, Haimei Zhou<sup>1</sup>, and Xinxin Li<sup>1</sup>  
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In this paper, mesoporous silica (MS) with high specific surface area was used as a surface template to improve the enrichment performance of micro-preconcentrator ( $\mu$ PC) of the volatile organic compounds (VOCs). The  $\mu$ PC was fabricated based on MEMS technology. The MS layer was deposited on the surface of the cavity of the  $\mu$ PC, and then the Tenax-TA was coated on the surface of the MS layer. The enrichment performances of the VOCs of the  $\mu$ PC with Tenax-TA and Tenax-TA using the MS layer as a surface template (MS + Tenax-TA) were respectively measured. The enrichment ratio of butyl acetate of the  $\mu$ PC with Tenax-TA was 3.08, and the  $\mu$ PC with MS + Tenax-TA was as high as 573, which has a 185 times enhancement, suggesting that the MS layer as the surface template of Tenax-TA effectively enhanced the enrichment performance of the VOCs.

**T-053    A QUASI-STATIC ELECTRICAL MEASUREMENT SCHEME FOR PROBING GAS REACTIONS ON GRAPHENE SURFACE ..... 476**  
 Huiliang Liu<sup>1,2</sup>, Yao Chu<sup>1,2</sup>, Yumeng Liu<sup>2</sup>, Takeshi Hayasaka<sup>2</sup>, Lorenzo P. Lopez Jr.<sup>2,3</sup>, Vernalyn C. Copa<sup>2,3</sup>, Xiaohao Wang<sup>1</sup>, Zheng You<sup>1</sup>, and Liwei Lin<sup>1,2</sup>  
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<sup>2</sup>*University of California, Berkeley, USA, and*  
<sup>3</sup>*University of the Philippines Diliman, PHILIPPINES*

This work marks the first use of a quasi-static electrical measurement method on graphene field effect transistors (FET) to characterize sub-ppm level of toxic gases in air at room temperature. Compared with the state-of-art technology, three distinctive advances have been achieved: (1) a quasi-static electrical measurement scheme on graphene FETs without sweeping a large range gate voltage to avoid the dipole flipping or charge trapping problem; (2) the real-time estimation of the charge neutral point ( $V_{CNP}$ ) and carrier mobility ( $\mu$ ) of graphene during the exposure to sub-ppm toxic gases in air; and (3) the demonstration of differentiable characteristics of NO<sub>2</sub> and formaldehyde by the extractions of their intrinsic charge transfer and Coulomb scattering characteristics. As such, the proposed quasi-static monitoring method can be used to sense and differentiate sub-ppm level toxic gases on graphene FETs without using an array of devices with different surface functionalization materials.

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**W-054 THE EXPLORATION OF SILICON NANOWIRES AS A STATIONARY PHASE SUPPORT FOR MICRO GAS CHROMATOGRAPHIC COLUMNS ..... 480**

Fei Feng<sup>1,2</sup>, Bin Zhao<sup>1</sup>, Fan Luo<sup>1</sup>, Xuelei Yang<sup>1</sup>, Haimei Zhou<sup>1</sup>, and Xinxin Li<sup>1</sup>

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In this paper, silicon nanowires were innovatively used as a stationary phase support for micro-fabricated gas chromatographic column ( $\mu$ GC column). The silicon nanowires were grown in-situ in the high aspect ratio microchannels of the  $\mu$ GC column, and polydimethylsiloxane (OV-101) was used as the stationary phase. It was demonstrated that the alkane mixture of C6-C10 was well separated by using the 2 m  $\mu$ GC column. The separation efficiency of the  $\mu$ GC column was as high as 23647 plates/m, which could be attributed to the large surface area of the silicon nanowires.

**M-055 REGIOSELECTIVE CONSTRUCTION OF METAL-ORGANIC FRAMEWORK (MOF) SENSING FILM ON PARYLENE-PATTERNED RESONANT MICROCANTILEVER FOR HIGHLY TOXIC MOLECULES DETECTION..... 484**

Shengran Cai<sup>1,2</sup>, Haitao Yu<sup>1</sup>, Pengcheng Xu<sup>1</sup>, and Xinxin Li<sup>1</sup>

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<sup>2</sup>University of Chinese Academy of Sciences, CHINA

In this work, Parylene-C is patterned and formed a sample reservoir on the free-end of resonant microcantilever for nano sensing material construction. The Parylene formed reservoir is suitable for corrosive precursor loading and sensing material *in-situ* construction. On the other hand, the Parylene film effectively protects the integrated elements including signal readout element and exciting heater from the damage of corrosive substances. Herein, a typical metalorganic framework (MOF) of UiO-66 film has been in-situ regioselectively constructed on microcantilevers for extremely toxic organophosphorus (OP) molecules detection. The limit of detection (LOD) to OP simulant of dimethyl methylphosphonate (DMMP) achieves 5ppb. The in-situ MOF construction method manifests satisfied reproducibility for microcantilever sensor fabrication. The DMMP sensing mechanism is identified as the specific host-guest interaction between the UiO-66 and OP molecule.

**T-056 LABEL-FREE AC SENSING BY A GRAPHENE TRANSISTOR FOR 100-PPB FORMALDEHYDE IN AIR ..... 488**

Huiliang Liu<sup>1,2</sup>, Yao Chu<sup>1,2</sup>, Yumeng Liu<sup>2</sup>, Takeshi Hayasaka<sup>2</sup>, Zhichun Shao<sup>2</sup>, Nirav Joshi<sup>2</sup>, Xiaohao Wang<sup>1</sup>, Zheng You<sup>1</sup>, and Liwei Lin<sup>1,2</sup>

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<sup>2</sup>University of California, Berkeley, USA

This work marks the first use of an AC sensing technique on a graphene transistor to realize label-free gas sensing of 100 ppb-level formaldehyde in the air at room temperature. Compared with the state-of-art technology, three distinctive advances have been achieved: (1) extraordinary sensitivity of trace amount of formaldehyde using an AC phase detection method on a single graphene transistor made of the monolayer graphene from the chemical vapor deposition (CVD) process without adding functional materials; (2) high signal stability on devices with or without artificial defects; (3) fast response time of 10 seconds and recovery time of 60 seconds with minimal baseline drifts. As such, the proposed AC sensing method can achieve fast detection of the low concentration formaldehyde in air with reproducible performances on CVD graphene with different defect densities.

**W-057 OPTIMIZED DETECTION TO ORGANOPHOSPHOROUS PESTICIDE BY SELECTING THE MOST APPROPRIATE NANO-SIZE OF SENSING NANO-MATERIAL..... 492**

Pengcheng Xu, Haitao Yu, and Xinxin Li

Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, CHINA

This paper reports an optimal sensing nanomaterial of mesoporous-silica SBA-15 for detecting residual organophosphorous (OP) pesticide by selecting appropriate wall-thickness of the amorphous-SiO<sub>2</sub> nano-channels to optimize the interaction activity of the surface  $\equiv$ Si-OH with P=O in OP molecules. With the different-sized SBA-15 nanomaterials loaded at the free ends of resonant-cantilevers, optimization for the sensing-materials can be *in situ* implemented by using the resonant-cantilevers themselves. After directly detecting OP molecules to evaluate the response curves, a novel physicochemical-parameter extraction method is developed to quantitatively obtain the value of adsorption isosteric heat ( $Q_{st}$ ) that is used as an essential criterion to select the best sensing-material with appropriate nanowall thickness. With the novel method, we have successfully obtained the optimal sensing nanomaterial for the pesticide of dichlorvos (DDVP).

**M-058 PALLADIUM HYDROGEN SENSOR WITH PERFECTLY ALIGNED AND HIGHLY UNIFORM NANOGAP ARRAYS..... 496**  
 Jae-Shin Lee, Myung-Kun Chung, Kwang-Wook Choi, Jae-Young Yoo, and Jun-Bo Yoon  
*Korea Advanced Institute of Science and Technology (KAIST), KOREA*

This paper reports a Pd hydrogen gas sensor that uses perfectly aligned uniform nanogap arrays. Depending on the nanogap size, the sensor can differentiate hydrogen concentration thanks to the volume expansion of Pd. The fabrication method of the sensor is based on conventional semiconductor processes; thus, perfectly aligned uniform nanogap arrays can be easily obtained. The standard deviation of the measured nanogap widths was less than 5nm, and this level of uniformity has not been previously demonstrated in Pd-switching-type sensors. The fabricated sensors with the uniform nanogap array showed abrupt switching characteristics when they were exposed to H<sub>2</sub> concentrations over a certain threshold level. Furthermore, based on the unprecedented high uniformity of the nanogap widths, a fine modulation of the threshold level of the H<sub>2</sub> concentrations was firstly demonstrated.

**T-059 A SAW HYDROGEN SENSOR BASED ON THE COMPOSITE OF GRAPHENE OXIDE AND PALLADIUM NANOPARTICLES ..... 500**  
 Dongsheng Li, Xianhao Le, Jintao Pang, and Jin Xie  
*Zhejiang University, CHINA*

This work proposes a surface acoustic wave (SAW) hydrogen sensor based on the decoration of graphene oxide (GO) by palladium nanoparticles on AlN/Si layered structure. A thin decoration of GO by palladium nanoparticles layer is directly coated on the sensor surface as sensing layer. The SAW hydrogen sensor shows higher sensitivity (~9.5 times) and lower cross-sensitivity towards NO<sub>2</sub> compared to those based on graphene oxide only. The hydrogen sensor has good stability and fast response (T<sub>res</sub>=6s, T<sub>rec</sub>=7s). The frequency shift of the sensor with hydrogen concentration change is described by a fitting formula.

**Other Micro- and Nanofluidics**

**W-060 A MEMS-BASED CONDENSATION PARTICLE COUNTER FOR ACCURATE AND REAL-TIME MONITORING OF AIRBORNE NANOPARTICLES AT POINTS OF INTEREST..... 504**  
 Seong Jae Yoo, Hong-Beom Kwon, Dong-Hyun Kang, Ui-Seon Hong, Kyongtae Kim, and Yong-Jun Kim  
*Yonsei University, KOREA*

Nanoparticle monitoring is very important due to their serious health hazard, while personal devices for monitoring them have not been developed yet. To accurately monitor airborne nanoparticles at points of interest on real-time basis, we developed a highperformance MEMS-based condensation particle counter (CPC). Our system could detect extremely small particles (8.6 nm) with high accuracy (deviation within 3.8 % in number concentration), showing high performance comparable to the reference CPC.

**M-061 ELECTROLYTE BASED THERMAL TO ELECTRIC ENERGY CONVERSION UTILISING 10 NM DIAMETER AL<sub>2</sub>O<sub>3</sub> NANOCHANNELS ..... 507**  
 Nguyen Van Toan<sup>1</sup>, Megat Muhammad Ikhsan Megat Hasnan<sup>2</sup>, Daiki Udagawa<sup>1</sup>, Naoki Inomata<sup>1</sup>, Masaya Toda<sup>1</sup>, Suhana Mohd Said<sup>2</sup>, Mohd Faizul Mohd Sabri<sup>2</sup>, and Takahito Ono<sup>1</sup>  
<sup>1</sup>*Tohoku University, JAPAN and*  
<sup>2</sup>*University of Malaya, MALAYSIA*

This work reports the thermal to electric energy conversion based on fluidic transport in nanochannels inducted by temperature gradient. Anodized aluminum oxide (AAO) nanochannels with 10 nm-diameter and 3 μm-length are successfully fabricated by anodic oxidation process in a diluted acid electrolytic solution. Thermal to electric energy conversion using above AAO nanochannels has been demonstrated. Maximum power output of the fabricated device is found at 12.2 nW with the load resistance of 47 kΩ and temperature gradient of 17°C. The fabricated device can generate the power density of 255 μW/cm<sup>2</sup> with temperature gradient of 30°C

**Bio & Medical MEMS**

**Materials for Bio- and Medical MEMS**

**T-062 DEVELOPMENT OF GAS PERMEABLE PARYLENE HT AS A SUBSTRATE FOR CELL-CULTURE-ON-A-CHIP APPLICATIONS.....511**

Nicholas Scianmarello, Colin Cook, Kuang-Ming Shang, and Y.C. Tai  
*California Institute of Technology, USA*

Here we report on the production of highly gas permeable Parylene HT through a cryogenic deposition process. The unique combination of biological and chemical inertness of Parylene, and gas permeability of this porous variant make it interesting for cell culture and biology-on-a-chip applications. The dependence of porosity, density, and permeability on the deposition temperature allows for tunable control of material properties. Culture of HEK-293 cells on cryogenically deposited Parylene HT demonstrates viability for biological applications.

**W-063 ONE-STEP GENERATION OF DRUG-RELEASING MICROARRAY FOR HIGH-THROUGHPUT SCREENING OF SEQUENTIAL DRUG COMBINATIONS.....515**

Seo Woo Song<sup>1</sup>, Su Deok Kim<sup>1</sup>, Jiyun Kim<sup>2</sup>, and Sunghoon Kwon<sup>1</sup>  
<sup>1</sup>*Seoul National University, KOREA and*  
<sup>2</sup>*Ulsan National Institute of Science and Technology(UNIST), KOREA*

This paper reports a miniaturized platform for high-throughput, pipetting-free screening of sequential combinatorial drugs. Self-assembly of encoded drug-laden microparticles (DLPs) on the array of microwells enables the bottom-up formation of heterogeneous drug releasing microarray with a single pipetting. Face-to-face assembly of the cell chip and the drug chip allows releasing of the drug in each microwell, and simple replacement of the drug microarray achieves multi-step combinatorial drug treatment. Proposed technique does not need an automatic liquid handler for the whole procedure. For the validation, screening of sequential combination, EGFR inhibitor followed by DNA damaging agents, against TNBC was demonstrated.

**M-064 TRANSIENT MULTI-MODE SILK MEMORY DEVICES.....519**

Long Sun<sup>1,2</sup>, Zhitao Zhou<sup>1</sup>, Nan Qin<sup>1</sup>, and Tiger H. Tao<sup>1,2</sup>  
<sup>1</sup>*Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, CHINA and*  
<sup>2</sup>*University of Chinese Academy of Sciences, CHINA*

We report a programmable vanishing multi-mode memory device consisting of a silk-based resistive switching memory (operating electronically) integrated with a silk-based diffractive optical element (operating optically). The resistive switching memory (ReRAM) using silk protein as the switching layer stores electronic messages and a diffractive optical element (DOE) made of the micropatterned silk film stores the optical information. Benefiting from the superior flexibility, strength and tunable degradability of silk, this soft but robust multimode memory device is able to precisely degrade according to the preset sequence and time. The controllable disappearance of the silk-based functional microstructures leads to the transformation of the encoded information to another, thereby expanding its applications in multi-mode information encryption and anti-reverse engineering.

**T-065 FABRICATION OF 3D SILK MICROSTRUCTURES BY DIRECT TWO-PHOTON POLYMERIZATION..... 522**

Keyin Liu, Jianjuan Jiang, and Tiger H. Tao  
*Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, CHINA*

Two-photon polymerization (TPP) based on femtosecond laser (fs laser) has been renowned for its processing capability to fabricate true-3D and high-precision polymer structures such as natural proteins and photoresists. However, additional toxic photoinitiators are necessary in the conventional TPP process of natural proteins. In this work, 3D silk microstructures were achieved without any additional photoinitiator using an optimized TPP process, in which both the fs laser and silk protein were tuned. Meanwhile, conformational transition of silk protein at the focal spot of fs laser was observed using the atomic force microscope infrared spectroscopy (AFM-IR). This work will benefit the application of silkbased devices without any residual photoinitiators.

- W-066 HIGHLY CONDUCTIVE, TRANSPARENT, AND ANTI-REFLECTIVE PEDOT:PSS/ITO/AG/ITO ON PARYLENE-C WITH TUNABLE PEAK TRANSMITTANCE..... 525**  
 Weiyang Yang, Jiajia Wu, Qi Hua Fan, and Wen Li  
*Michigan State University, USA*

Transparent and flexible conductive thin films are critical components in optoelectronics, such as wearable electronics, biosensors, and displays. Traditional transparent electrodes made of a single layer of indium-tin-oxide (ITO), ultrathin metal, graphene or poly-(3, 4-ethylenedioxythiophene)/poly(styrenesulfonate) (PEDOT: PSS) hardly possess the desired combination of high transmittance, low electrical resistivity, mechanical flexibility, and biocompatibility. Although ITO/Ag/ITO multilayer thin films have been studied for solar cell applications, the deposition of high-quality ITO usually requires high-temperature processes incompatible with polymers. In this work, we successfully fabricated an ultra-flexible, conductive, transparent thin film using a PEDOT:PSS/ITO/Ag/ITO multilayer structure on Parylene C at room temperature. Compared to single-layer ITO of an equivalent thickness, the multilayer film exhibited significantly enhanced sheet conductivity, reduced electrochemical impedance, remarkable transmittance, excellent adhesion, and flexibility. The peak transmittance of the combined films can be tailored to a specific wavelength for particular applications, such as optogenetics. Besides Parylene C, our high-quality ITO/Ag films can be deposited on a wide variety of heat-sensitive substrates over large scales.

- M-067 TRACING AND RESOLVING MICROPARTICLE AQUATIC MASS MOTION AND DISTRIBUTION ON MULTIMODE SILICON CARBIDE (SiC) MICRODISK RESONATORS..... 529**  
 Hao Jia and Philip X.-L. Feng  
*Case Western Reserve University, USA*

We report on the first experimental exploration of resonant detection and spatial tracing of single microparticle in liquid using silicon carbide (SiC) microdisk resonators, by exploiting the position-dependent multimode frequency responses up to the very high frequency (VHF) band. Through integrating optical tweezers for high-resolution microparticle manipulation into a laser interferometer with ultrahigh displacement sensitivity, multimode frequency shifts in response to single microparticle loading and motion are measured, with a responsivity up to  $\sim 10\text{Hz/fg}$  in liquid. Combining finite element modeling with a neural network, we demonstrate that microscale mass locomotion can be resolved by exploiting the devices' multimode responses. These techniques hold promise for ultrasensitive detection and imaging of microscale mobile or distributed masses (e.g., cells) in liquid and may facilitate biophysical studies of cellular and sub-cellular-level behaviors (e.g., proliferation and migration).

**Manufacturing for Bio- & Medical MEMS & Microfluidics**

- T-068 ALL-METAL PLASMONIC METAMATERIALS FOR STRUCTURE COLOR AND ITS APPLICATION IN COLORIMETRIC BIOSENSOR..... 533**  
 Jia Zhu<sup>1</sup>, Guanzhou Lin<sup>1,2</sup>, Yun Huang<sup>1</sup>, Zhuojie Chen<sup>1</sup>, Xiaoyu Chen<sup>1</sup>, Peimin Liu<sup>2</sup>, and Wengang Wu<sup>1</sup>  
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<sup>2</sup>*Fuzhou University, CHINA*

Colorimetric and label-free plasmonic biosensors, relying on localized surface plasmon resonance (LSPR) on metallic subwavelength structures, have significant potential for many application areas such as clinical diagnosis and environmental monitoring detection by simple instrumentation or even naked eye. In this paper, we present a high-performance colorimetric and label-free plasmonic biosensors, consisting of an array of three-dimensional all-metal nano-cavities. The nanostructures, composed of a top array of gold disk, aluminum pillar and bottom gold reflection film, are similar to metal-insulator-metal and the insulating layer is air cavities that are easy to be filled with other gaseous or liquid dielectric. Therefore, the analytes could permeate into the nano-scale cavities and enable strong light-matter interactions there. The sensor shows significant color difference with small refraction index changes and the sensitivity reaches 683.5 nm/RIU. Moreover, when a monomolecular layer of Dithiobis(succinimidyl propionate) (DSP) was bonded to the surface of the nanostructure, the color of the metamaterials change from blue to green back. The metamaterials will offer great potential for detection and studies of binding events between the target analyte and its corresponding receptor.

**W-069 LASER-INDUCED GRAPHENE STAMP FOR HIGH PERFORMANCE ELECTROCHEMICAL SENSING APPLICATIONS..... 537**  
 Hyosang Yoon, Joongsan Nah, Jiyoung Kim, Xing Xuan, and Jaeyeong Park  
*Kwangwoon University, KOREA*

Here, we newly proposed laser-induced graphene (LIG) stamp to transfer directly it onto Au substrate from polyimide (PI) substrate. The stamped-LIG was strongly adhered by van der Waals force with Au. Unlike conventional transferred LIG electrode composed of totally carbon-based material, the proposed LIG stamp was formed with several layers of carbon on top of highly conductive Au electrode resulting in the improvement electrical and electrochemical properties. In addition, we successfully electrodeposited Pt nanoparticles (PtNPs) as catalytic material on the surface of the stamped LIG for electrochemical biosensor applications, which also resulted in highly improved redox characteristics. We characterized and compared various materials such as Au, Au/PtNPs, Au/stamped-LIG, and Au/stamped-LIG/PtNPs through cyclic voltammetry and amperometric measurement. As a result, the electrical and electrochemical redox properties were much improved. Through amperometric measurement, the developed electrochemical sensor electrode indicated  $69.33 \mu\text{A}/\text{mM}\cdot\text{cm}^2$  of the sensitivity at hydrogen peroxide concentration of 10 to  $3760 \mu\text{M}$  and limit of detection of  $2.2 \mu\text{M}$ , respectively.

**M-070 WEARABLE OPTICAL DEVICE FOR REAL-TIME MONITORING OF NEWBORN JAUNDICE..... 541**  
 Go Inamori<sup>1</sup>, Yutaka Isoda<sup>1</sup>, Zihao Song<sup>1</sup>, Azusa Uozumi<sup>2</sup>, Shuichi Ito<sup>2</sup>, and Hiroki Ota<sup>1</sup>  
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<sup>2</sup>*Yokohama City University, JAPAN*

A wearable optical device for real-time monitoring of newborn jaundice was developed (Fig. 1). Jaundice is caused by the accumulation of bilirubin in an infant's blood. Real-time monitoring of the bilirubin level in infants is required because the level can change rapidly and affect their growth. The ability of the newly developed sensor to measure bilirubin levels was comparable to that of a commercial jaundice device ( $R = 0.77$ ), indicating the sensor could successfully evaluate jaundice. This wearable sensor is an important advance in the healthcare of infants, as it provides real-time monitoring of jaundice, one of the most important medical parameters in preliminary medical screening tests for newborns.

**T-071 HIGH-SENSITIVITY PARYLENE MICROFLUIDIC CHIP CALORIMETERS FOR MEASUREMENTS OF CELLULAR METABOLIC HEAT ..... 544**  
 Jihye Kim, Sung Min Nam, Jonghyun Kim, Sumin Seo, and Wonhee Lee  
*Korea Advanced Institute of Science and Technology(KAIST), KOREA*

Chip calorimeters are promising tools for quantitative analysis of cellular metabolic rate. The measurement of cellular metabolic heat can be an excellent indicator of its physiological state and the changes in response to external stimuli such as drugs. We have developed a highly sensitive microfluidic chip calorimeter capable of maintaining cellular activity and controlling the fluid flows of biochemical stimuli around the cells. Using the chip calorimeter, we demonstrated the measurements of cellular metabolic rate by monitoring the changes in power output of a few hundred cells responding to biochemical stimuli.

**W-072 BIO-INSPIRED BARBED MICRONEEDLE FOR SKIN ADHESION WITH INTERLOCKING MECHANICS..... 547**  
 Le-Giang Tran, Thanh-Qua Nguyen, and Woo-Tae Park  
*Seoul National University of Science and Technology, KOREA*

Achieving strong adhesion to soft tissues with minimal tissue damage remains a considerable clinical challenge. In this work, we designed and fabricated a novel bio-inspired microneedle array for easy skin penetration but difficult removal. The bio-inspired microneedle has four barbs evenly distributed on two edges. This design offered distinctively less skin insertion pressure with minimal tissue damage and strong interlocking force. In order to manufacture the complex multi-barbed structure, we utilized the thermal expansion effect to form 3D two-part PDMS mold. The barbed microneedle was replicated by biodegradable and biocompatible silk fibroin, which makes it harmless and non-irritating to the skin. Performance of the barbed microneedle was tested on the paraffin membrane. The barbed microneedle array was observed to successfully insert through the paraffin membrane. During pulling the barbed microneedle out, the measured interlocking strength was up to  $11 \text{ g}/\text{needle}$  ( $107 \text{ mN}/\text{needle}$ ). The bioinspired barbed microneedle can also be used as auto breaking microneedles or tissue adhesive patches.

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**M-073 3D ELECTRON PRINTING IN GENETICALLY ENGINEERED SPIDER SILK PROTEINS AT ~ 50 NM RESOLUTION..... 551**

Nan Qin<sup>1</sup> and Tiger H. Tao<sup>1,2</sup>

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We report all-electron-based true 3d bionanofabrication, termed “3d electron printing”, to precisely produce the biomimetic, hierarchical and heterogeneous nanostructures from biologically functional genetically engineered spider silk proteins as the printing medium. The fabrication process uses only water to remove the unexposed/uncrosslinked area and eliminates the need to use and dispose of noxious chemicals. This biofriendly method offers a promising route toward fabrication of 3d functional nanodevices and nanointerfaces with unprecedented precision at ~ 50 nm resolution.

**T-074 MULTICOLOR DIFFRACTIVE OPTICAL ELEMENTS AS A DESIGNABLE BIOACTIVE PLATFORM ..... 554**

Xiaoqing Cai<sup>1,2</sup>, Zihan Gao<sup>1,3</sup>, Zhitao Zhou<sup>1</sup>, Nan Qin<sup>1</sup>, and Tiger H. Tao<sup>1,2</sup>

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<sup>3</sup>*Shanghai University, CHINA*

This work reports a set of multicolor diffractive optical elements (DOEs) that can be worked as a designable platform based on silk fibroin. The multicolor DOE based on silk fibroin that is known for its excellent biocompatibility, high transmittance and controllable degradation, can be designed to sense and process multi-level information by working at multiple wavelengths. Compared with traditional monochromatic DOE, multicolor DOE can carry out richer information that can be designed to use in more situations, such as encryption and decryption of multi-level information and cascade reaction monitoring.

**W-075 CHARACTERISATION OF MICRONEEDLE-BASED ECG ELECTRODES FABRICATED USING AN INDUSTRIAL INJECTION-MOULDING PROCESS ..... 557**

Conor O’Mahony<sup>1</sup>, Andrea Bocchino<sup>1</sup>, Michael J. Haslinger<sup>2</sup>, Daniel Fechtig<sup>2</sup>, Klaudia Schossleitner<sup>3</sup>, Paul Galvin<sup>1</sup>, and Stefan Brandstätter<sup>4</sup>

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<sup>3</sup>*Medical University Vienna, AUSTRIA, and*

<sup>4</sup>*Stratec Consumables GmbH, AUSTRIA*

This work has produced microneedle-based electrocardiography (ECG) electrodes using a commercial, high-volume fabrication process. Specifically, we have adapted industrial injection moulding (IM) techniques to replicate silicon microneedle arrays in medical-grade cyclic olefin polymers (COP) and these, to our knowledge, are the sharpest IM microneedles produced to date. The arrays are then metallised and used as ‘dry’ electrodes to record ECG signals. We also show that their performance is equivalent to that of commercial electrodes, but without the need for skin preparation or electrolytic ‘wet’ gels. This new IM process, originally developed for the mass manufacture of compact discs (CDs), has significant implications for the future viability of microneedle-based electrodes in this very cost-competitive application.

**M-076 WRINKLED MICROELECTRODE INTERFACE BASED ON OIL-PRETREATED HYPERELASTIC SUBSTRATE..... 561**

Bowen Ji<sup>1</sup>, Minghao Wang<sup>1</sup>, Zhejun Guo<sup>1</sup>, Wen Hong<sup>1</sup>, Longchun Wang<sup>1</sup>, Xiaolin Wang<sup>1</sup>, Bin Yang<sup>1</sup>, Wei Wang<sup>2</sup>, and Jingquan Liu<sup>1</sup>

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<sup>2</sup>*Peking University, CHINA*

This paper reports a unique fabrication method to obtain wrinkled microelectrodes with different surface morphologies based on different hyperelastic substrates for the first time. The wrinkle microstructures are enhanced by mixture silicone oil in the uncured poly (dimethyl siloxane) (PDMS) or Ecoflex polymer followed by oil-extraction in chloroform and depositing 5 µm Parylene-C film. The wrinkle amplitude of the oil-pretreated PDMS and Ecoflex with Parylene-C top layer show 5-fold and 125-fold increase than the unpretreated ones, respectively. Besides, the wrinkled 3D microelectrode surface distinctly exhibits greater electrochemical properties than the flat 2D one, with impedance decreases of 29.2% and 38.9% for the oil-pretreated PDMS and Ecoflex elastomer.

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**T-077 A SUPER-FLEXIBLE AND HIGH-SENSITIVE EPIDERMAL sEMG ELECTRODE PATCH FOR SILENT SPEECH RECOGNITION ..... 565**

Wei Dong, Hongmiao Zhang, Huicong Liu, Tao Chen, and Lining Sun  
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Surface electromyography (sEMG) signals generated by the muscles of the lower jaw contain corresponding voice information when talking. However, it's very hard to collect sEMG signals from the jaw because of not only the weakness of the signals but also the sharp skin curvature of this area. This paper reports a super-flexible and high-sensitive epidermal sEMG electrode patch to measure sEMG signals of the jaw from which the voice information can be extracted for speech recognition. This epidermal sEMG patch can be effectively attached to the jaw and the interconnection wire in the form of double wave can stretch more than 100%. From the characteristic of envelopes of the signals, it shows good consistency when the tester speak the same word and obvious difference can be detected when the tester speak different words. Four-layer wavelet decomposition is used to reduce noise in sEMG records and the eigenvectors are extracted from wavelet coefficients to characterize each trial. The experimental result shows that the average accuracy of the three pronunciations is about 71.7%. The accuracy of "hello" reaches up to 91%. In the future his epidermal sEMG electrode patch has great potential for the application of silent speech recognition.

**W-078 MICROFLUIDIC NEURAL PROBES WITH BURIED CHANNELS FABRICATED USING CONTINUOUS FLOW XeF<sub>2</sub> ETCHING OF SILICON ..... 569**

Kirti Sharma, Sahana Dholipet Nagendra Kumar, Oliver Paul, and Patrick Ruther  
*University of Freiburg, GERMANY*

This paper reports on the fabrication and characterization of thin silicon (Si) probes with integrated channels for minimally invasive drug delivery into the brain. Buried channels are realized in Si using plasma-free, vapor-phase, continuous-flow (cf) xenon difluoride (XeF<sub>2</sub>) etching, with the microfluidic probes subsequently thinned down to 70 μm using the etching-before-grinding approach. While plenty of data are available in literature on pulsed XeF<sub>2</sub> etching, the characteristics of cf-XeF<sub>2</sub> processing, which provides a more controlled etch process, have to date not been widely discussed. To the best of our knowledge, this is the first study that reports on the detailed characterization of cf-XeF<sub>2</sub> etching for the fabrication of micro-channels in single-crystal Si. By using etch openings of different dimensions and varying the process parameters, process characteristics such as etch rate, aperture effect, etch anisotropy, and surface roughness are investigated. Flow and mechanical fracture tests demonstrate the suitability of the fabricated probes for in vivo applications.

**Nanobiotechnology**

**M-079 MICRO-ASSEMBLY USING OPTICALLY PATTERNED MOLECULAR-MOTOR-POWERED ARTIFICIAL MUSCLES ..... 573**

Yingzhe Wang<sup>1</sup>, Yuichi Hiratsuka<sup>2</sup>, Takahiro Nitta<sup>3</sup>, Kaoru Uesugi<sup>1</sup>, and Keisuke Morishima<sup>1</sup>  
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<sup>2</sup>*Japan Advanced Institute of Science and Technology, JAPAN, and*  
<sup>3</sup>*Gifu University, JAPAN*

In this work, a novel micro-assembly method using molecular-motor-powered artificial muscles is presented. A UV scanning system was set up to fast optically pattern artificial muscles from microtubules and kinesins. With this system, micro-components could be accurately assembled by fabricated artificial muscles in microfluidic channel. The successful assemblies of hexagon micro-components have proved the feasibility of this method. We believe this new micro-assembly with simple operation and low cost has a great potential in MEMS applications.

**T-080 EXTRACELLULAR VESICLES FRACTIONATED IN DRYING DROPLET ..... 576**

Hwapyeong Jeong<sup>1</sup>, Johan Yi<sup>1</sup>, Yogesh B. Gianchandani<sup>2</sup>, and Jaesung Park<sup>1,2</sup>  
<sup>1</sup>*POSTECH, KOREA and*  
<sup>2</sup>*University of Michigan, USA*

We propose a new chromatograph using "coffee-ring effect" and Marangoni recirculation flow in microdroplets to separate extracellular vesicles spatially based on particle size. In this study, EVs were isolated spatially based on particle size in the evaporating droplet. We then find that the size of EVs is correlated with expression levels of certain tetraspanin proteins and confirmed that the possibility of this method can be used for diagnosis. Using this method, we reveal that the level of tetraspanin protein expression depends on the size of the EVs and we find that in the plasma of prostate cancer patients smaller EVs show higher expression of cancer-associated proteins and gene.

**Biosensors and Bioreactors**

**W-081 GOLD NANOSTRUCTURE DECORATED 3D POROUS CARBON ARCHITECTURES AS A NON-ENZYMATIC GLUCOSE SENSOR ..... 580**

Deepti Sharma, Jongmin Lee, and Heungjoo Shin  
*Ulsan National Institute of Science and Technology (UNIST), KOREA*

We proposed a novel non-enzymatic glucose sensor based on 3D carbon electrodes with nanoporous sponge-like networks (PC) decorated with gold particles with dendritic nanostructures (AuNs). The nanoporous carbon electrodes were fabricated by combining a simple, cost-effective, reproducible microfabrication technology known as carbon-microelectromechanical-systems (carbon-MEMS) and microwave plasma etching process. AuNs were electrodeposited on PC electrodes in a short time period. Electrochemical oxidation of glucose with AuNs/PC electrodes was examined by cyclic voltammetry. The AuNs/PC electrodes based sensor exhibits 3.8-fold high sensitivity, and 27.7-fold better limit of detection as compared to AuNs/bare carbon electrodes.

**T-083 IN SITU GLUCOSE MONITORING IN 3D-CULTURED SKELETAL MUSCLE TISSUE ..... 584**

Yuya Morimoto, Jun Sawayama, and Shoji Takeuchi  
*The University of Tokyo, JAPAN*

We propose a method for in situ continuous and dynamic glucose monitoring in cultured skeletal muscle tissue using a glucose responsive hydrogel fiber. In the skeletal muscle tissue, the fiber emits fluorescence according to glucose concentration. In addition, the skeletal muscle tissue showed contractility even in cultured with the fiber. Therefore, from measurement of the fluorescence intensity when inducing muscle contractions by applying electrical pulses, we achieved detection of increase of glucose absorption in the skeletal muscle tissue caused by its contractions. Thus, we believe that the skeletal muscle tissue containing the glucose responsive hydrogel fiber will be a useful tool for evaluation of muscle glucose absorption without tissue lysis, in contrast to conventional method needing tissue lysis.

**M-085 CONTINUOUS GLUCOSE MONITORING OF 3D TISSUE USING A PERFUSABLE DEVICE ..... 586**

Jun Sawayama, Fumisato Ozawa, and Shoji Takeuchi  
*The University of Tokyo, JAPAN*

We developed a continuous glucose monitoring (CGM) system for the monitoring of 3D tissue in vitro using a perfusable device. The system consists of perfusable cell culture unit and CGM unit that has a fluorescent-based glucose responsive hydrogel sensor, LED and a photodiode on a chip; the unit is placed under a fluidic channel. This system enables in situ observation of the glucose concentration in culture medium to control the environment of the culture systems. We confirmed that the fluorescence intensity increased depending on the glucose concentration; ranging from 0 mg/dL to 1,000 mg/dL. We successfully cultured the 3D tissue in the perfusable unit and monitored the glucose concentration of medium for 24 hours.

**T-086 DROPLET-BASED DIGITAL RATIOMETRIC FLUORESCENCE CODING FOR MULTIPLEX NUCLEIC ACID AMPLIFICATION TESTING ..... 588**

Ye Zhang, Pengfei Zhang, and Tza-Huei Wang  
*Johns Hopkins University, USA*

Multiplexed NAAT is essential for molecular diagnosis of various diseases. Currently, encoding each nucleic acid target with a specific fluorescently-labeled probe has been the most commonly employed approach for multiplexed detection. Unfortunately, this "one-color-one-target" approach is limited by spectral overlap between fluorophores and cannot achieve highly multiplexed detection. This paper proposes a novel method termed Digital Ratiometric Fluorescence Coding to expand multiplexing capacity of NAAT. We encode each nucleic acid target with a specific ratio between two standard fluorophores in single droplet via a microfluidic system, allowing multiplexed detection of targets while obviating spectral overlap restriction. For demonstration, we detected DNA targets from six sexually transmitted diseases and demonstrated the potential for further expanding the multiplexing capability of our method.

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**Biofabrication/Tissue on a chip**

- W-087 VASCULARIZED SPHEROID ARRAY IN A MICROFLUIDIC CHANNEL..... 592**  
 Keigo Nishimura, Minghao Nie, and Shoji Takeuchi  
*The University of Tokyo, JAPAN*

We propose a microfluidic device which can array multiple spheroids in an extracellular matrix (ECM) gel and locate endothelial cells (ECs) on the gel with micrometer-ordered definite distance from the arrayed spheroids. The device is composed of multiple trapping sites to array spheroids in an ECM gel and a perfusable channel adjacent to the trapping sites. On the basis of the principle of flow resistance, the trapping sites can trap spheroids in every single site. Using the device, we can array multiple spheroids and ECs with the micrometer-ordered defined distances.

- M-088 MORPHOLOGICAL CONTROL OF ENDOTHELIAL TUBE FORMATION BY THREE-DIMENSIONAL LANE-SHAPED PATTERNS..... 594**  
 Yuki Ikezawa and Hiroaki Onoe  
*Keio University, JAPAN*

This paper describes an analytical platform to control endothelial tube formation by patterning cells and extracellular matrix (ECM) within 3D lane-shaped pattern. By using PDMS groove patterns (50-250  $\mu\text{m}$  in width and height, several millimeters in length), human umbilical vein endothelial cells (HUVECs) were patterned three-dimensionally in collagen gel. The patterned HUVECs spontaneously form endothelial vascular tissues, but their morphologies can be controlled by the dimensions of patterns, cell densities, ECMs, etc. We succeeded in forming vascular tube tissues, and found that a number of branches of the vascular tissues depends on the dimensions of 3D-patterns. We believe that our culture system could be a useful tool for understanding the tube formation behavior of endothelial cells and for creating 3D-shape-controlled vascular tissues as a quantitative model *in vitro*.

- T-089 3D HEPATIC TISSUE FORMED BY iPSC-DERIVED HEPATOCYTES USING A CELL FIBER TECHNOLOGY ..... 597**  
 Shogo Nagata, Fumisato Ozawa, and Shoji Takeuchi  
*The University of Tokyo, JAPAN*

In this paper, we demonstrate that hepatocytes derived from human pluripotent stem cells (iPSCs) could promote their cell characteristics in cell-laden core-shell microfiber. The iPSC-hepatocytes are expected as cell source for regenerative medicine and chemical screening in drug development, but the cells are known to lose their properties in conventional two-dimensional (2D) culture immediately. Here we show that the iPSC-hepatocytes could be encapsulated into extracellular-matrix (ECM)-rich three-dimensional (3D) microenvironment by using microfluidic device system (named as "cell fiber technique"), and highly expressed hepatocyte-associated proteins and genes in the fibers. Furthermore, the fibers could be useful as functional grafts. These results indicate that the cell fiber can be applicable to *in vitro* construction of 3D hepatic tissue owing to spatial regulation of culture environment.

- W-090 CELL-LADEN MICROFIBER AS GROWTH FACTOR SUPPLIER ..... 599**  
 Ai Shima and Shoji Takeuchi  
*The University of Tokyo, JAPAN*

This paper demonstrated that microfiber-shaped hydrogel-encapsulated cells could be co-cultured with the target cells without cell contamination for six days and that they enhanced proliferation and differentiation of the target cells as growth factor supplier. When cultured with alginate gel-encapsulated fibroblasts, skeletal muscle cells kept proliferating without serum in the culture medium and differentiated further than were cultured in conditioned medium from the fibroblasts. Those results indicated that the secretome concurrently released from fibroblasts through the sealing hydrogel was effective as alternatives to serum or growth factors for promoting cell proliferation and differentiation in culture.

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**Medical Microsystems (Probes, Implantables, Minimally Invasive, Etc.)**

**M-091 HIERARCHICAL HYDROGEL DRUG DELIVERY SYSTEM ENABLES CONTROLLED RELEASE OF ADENO-ASSOCIATED VIRUSES FOR GENE THERAPY ..... 601**

Hideo Miyahara<sup>1</sup>, Yuta Kurashina<sup>1</sup>, Yuki Ogawa<sup>2</sup>, Ayumu Kurihara<sup>2</sup>, Tomohiko Yoshida<sup>2</sup>, Hiroataka James Okano<sup>2</sup>, Masato Fujioka<sup>1</sup>, and Hiroaki Onoe<sup>1</sup>

<sup>1</sup>*Keio University, JAPAN and*

<sup>2</sup>*The Jikei University School of Medicine, JAPAN*

This paper describes a drug delivery system (DDS) to release Adeno-associated viruses (AAVs) for gene therapy. Our system has two-level hierarchical structures made of different hydrogel materials: (i) Calcium alginate hydrogel microparticles (~100 μm in diameter) that can properly immobilize AAVs inside and release them for gene transfection triggered by enzymatic degradation, and (ii) a millimeter-scale collagen sheet that encapsulates those alginate microparticles with AAVs for stable fixation to even a tiny and complicated diseased site in our body, such as an inner ear for the treatment of hereditary hearing loss (Figure 1). We fabricated the AAVs-immobilized hydrogel microparticles and evaluated their AAV releasing functions by measured the gene transfection ratio to cultured HeLa cells. In addition, we also demonstrated that the controlled release of AAVs immobilized in the alginate microparticles embedded in the millimeter-scale collagen sheet can be externally triggered from the outside. We envision that our developed composite hydrogel DDS could be an essential and general tool for gene therapy in practical medical scenes, especially in the treatment at complicated internal sites.

**T-092 TOUGH HYDROGEL TUBE FOR LONG-TERM CELLULAR GRAFT..... 603**

Haruka Oda, Shogo Nagata, and Shoji Takeuchi

*The University of Tokyo, JAPAN*

This paper reports a fabrication of a tough hydrogel tube for implantation of the cellular graft. Poly(vinyl alcohol) (PVA) hydrogel is known for its stiffness and stability under aqueous conditions due to the crystalline crosslinking formation. This PVA hydrogel is fabricated into a tubular form with sub-hundred-micron hydrogel layer to act as an immune barrier for cellular graft implant. The strictly controlled diameter of the tube is suitable for keeping the laden cells alive for a long period of time. The PVA hydrogel tube was tough enough to induce cells though cannulation syringe, which is easily adapted by people who specialize in medicine or biology. This PVA hydrogel microtube has a great potential for long-term implantation of functional cells.

**W-093 96-COLOR MICROCONTACT PRINTING DEVICE FOR SCREENING OF TUMOR-IMAGING PROBES ON CLINICAL SAMPLES..... 605**

T. Osaki<sup>1</sup>, K. Sakamoto<sup>2</sup>, H. Onoyama<sup>2</sup>, Y. Kuriki<sup>2</sup>, M. Kamiya<sup>2</sup>, K. Kamiya<sup>1</sup>, Y. Seto<sup>2</sup>, Y. Urano<sup>2</sup>, and S. Takeuchi<sup>1,2</sup>

<sup>1</sup>*Kanagawa Institute of Industrial Science and Technology, JAPAN and*

<sup>2</sup>*The University of Tokyo, JAPAN*

This work presents a 96-color microcontact printing (μCP) device applied for screening of fluorescent probes on a clinical sample. Tumor-specific fluorescent probes have attracted attention for the diagnosis and complete resection of tumor lesions. However, intratumor heterogeneity within/between patients hinders discovery of such probes among various candidate molecules. In previous work, we therefore proposed a μCP device with a multicolored inkpad, which enabled to print a set of probes on a single sample at once. In this work, we further developed the μCP device, applicable to print 96 probes in 1cm<sup>2</sup>. Reproducibility of the printing was proved on an agarose substrate. Finally, 24 types of probes on the device were applied for a screening test on a clinical sample of a gastric cancer patient.

**M-094 MONITORING VITAL SIGNS OF RESPIRATION AND HEART BEAT SIMULTANEOUSLY VIA A SINGLE FLEXIBLE PIEZOELECTRET SENSOR..... 607**

Yao Chu<sup>1,2</sup>, Huiliang Liu<sup>1,2</sup>, Junwen Zhong<sup>2</sup>, Ying Dong<sup>1</sup>, Xiaohao Wang<sup>1</sup>, and Liwei Lin<sup>1,2</sup>

<sup>1</sup>*Tsinghua-Berkeley Shenzhen Institute, Tsinghua University, CHINA and*

<sup>2</sup>*University of California, Berkeley, USA*

This work reports a self-powered, flexible piezoelectret sensor with honeycomb structures for monitoring vital signs. Compared with the state-of-art technologies, three distinctive advancements have been achieved: (1) a self-powered and flexible pressure sensor using laser-patterned honeycomb piezoelectret structures for high sensitivity; (2) the capability to record both respiration and heart beat at the same chest location simultaneously via a single device; (3) successful extraction and separation of respiration and heart beat signals for practical applications. As such, this piezoelectret sensor could enable various health diagnostics such as asthma and cardiopulmonary arrest as well as observing the physical activity intensity levels for the training of athletes.

**T-095 HIGHLY SENSITIVE PULSE WAVE SENSOR WITH A PIEZORESISTIVE CANTILEVER INSIDE AN AIR CHAMBER.....611**

Yuya Mizuki, Thanh-Vinh Nguyen, Tomoyuki Takahata, and Isao Shimoyama

*The University of Tokyo, JAPAN*

This paper reports a sensor that can measure blood pulse waves with high sensitivity. The sensor has a piezoresistive cantilever which is designed to measure the pressure change of an air chamber covered with a thin membrane. Since the cantilever is highly sensitive to differential pressure, it can measure the pulse waves by only placing the sensor on the skin. Moreover, because the cantilever itself is able to eliminate the static pressing force physically, the effect of the pressing force on the measurement result is small. Finally, we demonstrate that the sensor can be used to measure pulse wave velocity (PWV).

**W-096 A MEMS-BASED FLEXIBLE HIGH-DENSITY BRAIN ELECTRODE FOR MULTI-MODAL NEURAL ENCODING/DECODING.....615**

Ting Xiao<sup>1,2</sup>, Shan Zhang<sup>2,3</sup>, Yu Zhou<sup>2,3</sup>, and Tiger H. Tao<sup>2,3</sup>

<sup>1</sup>*Shanghai Normal University, CHINA,*

<sup>2</sup>*Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, Shanghai, CHINA, and*

<sup>3</sup>*University of Chinese Academy of Sciences, CHINA*

We report a conformal flexible brain electrode array with 1024-recording sites within 1×1cm<sup>2</sup> through multilayer wiring for high-density and high-quality recording of neural activity. Compared with existing cortical electrode applied in clinic, our electrode array has one order of magnitude enhancement in terms of the spatial resolution. In addition, water-soluble silk film is served as the supporting layer to make the ultrathin device easier to manipulate and ensures the conformal wrapping over the curved cortex after its dissolution. Based on the fabricated electrode array, effective neural decoding has been achieved, dynamic processes of normal status, the initial status after induced epilepsy, the status of high frequency seizure, the status of remission after medication, and the succedent recovery status can be efficiently distinguished.

**M-097 INTRACOCHELEAR ELECTRIC AND ACOUSTIC STIMULATOR PROTOTYPE: AN IMPLANTABLE SOLUTION TO THE HYBRID COCHLEAR IMPLANT .....617**

Yuchen Xu, Chuan Luo, and Zheng You

*Tsinghua University, CHINA*

This paper reports an intracochlear electric and acoustic stimulator (EAS) prototype, which adopted the board-level integration of a piezoelectric micro-actuator and a thin film electrode array. The EAS prototype meets the cochlear size limitations, with its implant part having a maximum diagonal dimension of <1.5 mm, and a 21-mm-long electrode array complying with the first cochlear turn. When the electric and acoustic stimulators work simultaneously, the amplitude of the interfering stimulus' frequency component accounts for <2% of the base frequency component. Compared to the state of the art in the hybrid cochlear implant, for the first time, the prototype proved the feasibility of intracochlear hybrid stimulation with an integrated stimulator. The EAS prototype represents a promising solution to improve the patients' wearing comfort and application scenarios.

**T-098 SEWING BIOPROBE ..... 621**

Koji Yamashita<sup>1</sup>, Hirohito Sawahata<sup>1,2</sup>, Shota Yamagiwa<sup>1</sup>, Yusuke Morikawa<sup>1</sup>, Rika Numano<sup>1</sup>, Kowa Koida<sup>1</sup>, and Takeshi Kawano<sup>1</sup>

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<sup>2</sup>*National Institute of Advanced Industrial Science and Technology (AIST), JAPAN*

Referring to the conventional sewing mechanism using a sewing needle and thread, here we propose a flexible 'thread' bioprobe device, which is sewn to the biological tissue by guiding tungsten-microneedle. The thread bioprobe was fabricated by parylene-based MEMS process. The fabricated bioprobe was sewn to the mouse's muscle and platinum (Pt)-microelectrodes in the bioprobe device detected electromyography (EMG) signals. Similar to sewing the device to the muscle, the flexible bioprobe also penetrated through the mouse's brain tissue and detected light evoked neuronal activity. Compared to conventional rigid microelectrode (e.g., silicon needle), the proposed sewing bioprobe device offers i) minimization of tissue damage due to the device flexibility, ii) device (microelectrode) placement at precise position in the tissue, and iii) attachment of the device to the tissue for both acute and chronic applications.

**W-099 A SILK-ENABLED CONFORMAL BRAIN ELECTRODE FOR NEURAL RECORDING AND DISEASE TREATMENT ..... 625**

Faming Zheng<sup>1</sup>, Shan Zhang<sup>1,2</sup>, Yu Zhou<sup>1,2</sup>, Tiger H. Tao<sup>1,2</sup>

<sup>1</sup>*Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, CHINA and*

<sup>2</sup>*University of Chinese Academy of Sciences, CHINA*

We report an implantable conformal brain electrode directly on silk substrate and exploit their biomedical capabilities for neural recording and disease treatment in-vivo. A multi-layers electrode, fabricated with MEMS technology, is assembled with silk films, a dissolvable pure silk film as attaching insurance and insoluble silk film loaded with drug as function of disease treatment. This device enable real-time dynamic observation of electrocorticogram (ECoG) symptoms and spatiotemporal bioelectrical vibration across two hemispheres during epilepsy in-vivo in rat brain. The ECoG neural recording and epilepsy treatment in situ prove the great potential in multifunctional brain-machine-interface (BMI) technology for diagnosis and treatment.

**M-100 A HUMAN RESPIRATORY MONITORING SENSOR BASED ON AN ALN RESONANT MICROCANTILEVER COATED WITH GRAPHENE OXIDE ..... 628**

Yangyang Guan, Xianhao Le, and Jin Xie

*Zhejiang University, CHINA*

This paper presents a human respiratory monitoring sensor based on an AlN resonant microcantilever coated with graphene oxide (GO). The sensor shows great performance in stability and repeatability. A closed-loop respiratory measurement system with fast response, and reliability is realized. The closed-loop system increases the sensor response time by more than 3 times. The whole system can provide real-time, ambulatory human respiratory monitoring. The sensor has advantages of small size and low cost for the low dependence on large peripherals, and can be integrated on a breathing mask to form a wearable sensing system.

**T-101 FLEXIBLE  $\mu$ LED-BASED OPTOGENETIC TOOL WITH INTEGRATED  $\mu$ -LENS ARRAY AND CONICAL CONCENTRATORS PROVIDING LIGHT EXTRACTION IMPROVEMENTS ABOVE 80% ..... 632**

Eric Klein<sup>1</sup>, Yumi Kaku<sup>1</sup>, Oliver Paul<sup>1,2</sup>, and Patrick Ruther<sup>1,2</sup>

<sup>1</sup>*IMTEK, GERMANY and*

<sup>2</sup>*University of Freiburg, GERMANY*

This paper reports on the fabrication and characterization of spherical micro-lenses ( $\mu$ -lenses) made from polydimethylsiloxane (PDMS) and their integration into optogenetic implants based on micro light-emitting diodes ( $\mu$ LEDs). The  $\mu$ -lenses are fabricated using a reusable silicon mold realized by wet chemical HNA (hydrofluoric, nitric and acetic acid) etching. It applies a masking layer with openings as small as 5  $\mu$ m and was optimized for hemispherical  $\mu$ -lens cavities of low surface roughness ( $R_a < 45$  nm). The  $\mu$ -lenses with diameters down to 10  $\mu$ m are realized by PDMS molding using a polymeric release layer (PRL) improving the  $\mu$ -lens release and enabling  $R_a$  values below 5 nm. Linear  $\mu$ -lens arrays are transferred onto the emission side of  $\mu$ LEDs comprising integrated conical concentrators (CCs). The PDMS-filled CCs improve the  $\mu$ -lens emission behavior by light reflection at the interface between the polymeric probe substrate and PDMS, without increasing the overall probe dimensions. Using  $\mu$ LEDs with integrated  $\mu$ -lens arrays in combination with CCs, the overall light extraction of the optical implants is increased by 115 % and 83 % in air and water, with the peak intensity raised by 145 % and 95 %, respectively.

**MEMS Physical Sensors**

**Materials for Physical Sensors**

**W-102    SIDEWALL TRANSFER PATTERNING-BASED NANO-CRYSTALLINE MoS<sub>2</sub> SENSING ELEMENT FOR STRESS AND OPTICAL MEMS SENSOR ..... 636**

Vaibhav Rana, Anurag Singh, Akhil Ramesh, Veerendra Dhyan, Samaresh Das, and Pushparaj Singh  
*Indian Institute of Technology, INDIA*

This paper reports patterned nano-crystalline MoS<sub>2</sub> as a sensing element for stress and electromagnetic radiation sensing. Sidewall Transfer Technique (STT) is used to pattern these nano-crystalline MoS<sub>2</sub> sensing structures without using any high-end lithography tool. All these sensing structures are realized on an SOI wafer. Four-point bending method is used to apply stress on the sensing elements, and results show the gauge factor of 74.6±6. Nano-crystalline MoS<sub>2</sub> sensing element is then irradiated by the electromagnetic radiation of wavelength 660 nm, which has doubled the current flow in the sensing element. Investigation of the, combined effects of stress and electromagnetic radiation is currently ongoing.

**M-103    ALD TITANIA SIDEWALLS ON A CMOS-MEMS RESONATOR OSCILLATOR AND EFFECTS ON RESONANT FREQUENCY DRIFT ..... 640**

Yi-Chung Lin, Metin G. Guney, and Gary K. Fedder  
*Carnegie Mellon University, Pittsburgh, USA*

A lift-off patterned atomic layer deposition (ALD) process that selectively coats CMOS MEMS sidewalls with conductive titania (TiO<sub>2</sub>) effectively eliminates the effects of dielectric sidewall charging. Charging effects are quantified through measurement of resonant frequency drift in a CMOS MEMS resonator oscillator with and without the titania coating. The coating drastically lowers the charging time constant to less than the 1 s frequency counter measurement period, compared to the long-term distributed time constant on the order of hours seen in uncoated devices and arising from trap behavior.

**Manufacturing Techniques for Physical Sensors**

**T-104    GAN/ALN HETEROSTRUCTURE MICROMECHANICAL SELF-SUSTAINED OSCILLATOR FOR MIDDLE ULTRAVIOLET (MUV) LIGHT DETECTION ..... 644**

Hailong Chen<sup>1</sup>, Hao Jia<sup>1</sup>, Pranoy Deb Shuvra<sup>2</sup>, Ji-Tzuoh Lin<sup>2</sup>, Bruce W. Alphenaar<sup>2</sup>, and Philip X.-L. Feng<sup>1</sup>  
<sup>1</sup>*Case Western Reserve University, USA and*  
<sup>2</sup>*University of Louisville, Louisville, USA*

We report on the first experimental demonstration of micromechanical feedback oscillators based on vibrating gallium nitride/aluminum nitride (GaN/AlN) hetero-structure doubly-clamped string resonators (~0.4 - 4 MHz) for real-time detection of middle ultraviolet (MUV) light. By exploiting the wide bandgap GaN/AlN hetero-structure and an optical-electrical feedback mechanism, the GaN/AlN string resonator-referenced oscillator exhibits frequency redshifts due to strong UV light absorption, with a measured responsivity of  $\mathfrak{R} = -24 \text{ Hz/nW}$  and a minimum detectable power of  $\delta P_{\min} = 6.7 \text{ nW}$ . Such GaN/AlN hetero-structure micromechanical feedback oscillators, together with the appealing GaN/AlN electromechanical and optical properties, hold promise for real-time UV photon sensing and radiation effects studies.

**W-105    HIGH POWER SI SIDEWALL HEATERS FOR FLUIDIC APPLICATIONS FABRICATED BY TRENCH-ASSISTED SURFACE CHANNEL TECHNOLOGY ..... 648**

Henk-Willem Veltkamp<sup>1</sup>, Yiyuan Zhao<sup>1</sup>, Meint J. de Boer<sup>1</sup>, Remco G.P. Sanders<sup>1</sup>, Remco J. Wiegerink<sup>1</sup>, and Joost C. Lötters<sup>1,2</sup>  
<sup>1</sup>*University of Twente, NETHERLANDS and*  
<sup>2</sup>*Bronkhorst High-Tech BV, NETHERLANDS*

We have fabricated mechanically stable, thermally isolated microfluidic channels with silicon heaters embedded in the sidewalls, using the trench-assisted surface channel technology (TASCT) [1]. Sidewall heating results in an enhanced heating uniformity while allowing high heating powers because of the relatively large cross-sectional area (20 μm by 50 μm) of the silicon heaters. In the proof-of-principle device a maximum temperature of 406 °C was reached at a heating power of 1.4 W, limited by thermal expansion of the channel. The fabrication process enables both the channels and the silicon heaters to have a rectangular cross-section with a depth defined by the device layer thickness and a variable width and length.



- T-106 COMMON FLEXIBLE CHANNEL STRUCTURE FOR INTEGRATION OF THREE-AXIS FORCE SENSOR AND SOFT MICRO ACTUATOR ..... 652**  
 Shohei Otake, Fuminari Mori, and Satoshi Konishi  
*Ritsumeikan University, JAPAN*

This paper presents integrated sensor and actuator in the same soft structure. Three-axis force sensor composed of three standing strain sensors is enabled by making the best use of its deformable flexible structure. Both force sensor and pneumatic actuator are fabricated by using common channel structures. The force sensor uses liquid metal introduced into the channel and the pneumatic actuator uses pressure supplied through the channel. We focused on the characteristic of the liquid metal strain sensor and three-axis force can be sensed by standing the strain sensors. Sensitivity of the sensor according to  $F_x$ ,  $F_y$  and  $F_z$  was calculated  $0.016 \text{ N}^{-1}$ ,  $0.019 \text{ N}^{-1}$  and  $0.035 \text{ N}^{-1}$ , respectively. The maximum generating force of integrated soft actuator was 13.3mN.

**Inertial Sensors (Gyros, Accelerometers, Resonators, Etc.)**

- M-109 STIFFNESS-MASS DECOUPLED HONEYCOMB-LIKE DISK RESONATOR GYROSCOPE..... 656**  
 Yi Xu, Qingsong Li, Xin Zhou, Kai Gao, Peng Wang, Yongmeng Zhang, Zhanqiang Hou, Xuezhong Wu, and Dingbang Xiao  
*National University of Defense Technology, CHINA*

We report, for the first time, the overall performance of a novel stiffness-mass decoupled honeycomb-like disk resonator gyroscope (HDRG). Compared with the former HDRG, this new design significantly increases the quality factor and effective mass of the resonator through hanging lumped masses on certain rings and arcs. The quality factor of the optimized resonator is 171.6k, more than twice the amount of the former design 81.1k. The bias instability of the gyroscope reaches  $0.11^\circ/\text{h}$  at room temperature without any compensation, more than eighty times smaller than the former design, exhibiting significant performance improvement. Moreover, ranging from  $-40^\circ\text{C}$  to  $60^\circ\text{C}$ , the temperature coefficient of scale factor is  $0.188\%/^\circ\text{C}$ , and the maximum variations of zero offset and bias instability over temperature are  $40^\circ/\text{h}$  and  $0.12^\circ/\text{h}$  respectively, showing good robustness to environment disturbance.

- T-110 A MEMS ACCELEROMETER BASED ON SYNCHRONIZED DETF OSCILLATORS..... 660**  
 Shudong Wang<sup>1,2</sup>, Dong Pu<sup>3</sup>, Ronghua Huan<sup>3</sup>, Zhuangde Jiang<sup>1</sup>, Yajing Shen<sup>2</sup>, and Xueyong Wei<sup>1</sup>  
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In this abstract, a novel MEMS resonant accelerometer based on synchronized double-ended tuning fork (DETF) oscillators is reported. Synchronization is recently proved to enhance the stability of coupled MEMS oscillators. In this report, synchronization was utilized to improve the performance of the resonant accelerometer. In the experimental evaluation, scale factor of the sensor proposed was 1056Hz/g. Through synchronization, the zero-bias instability of the oscillator was improved to 98ppb in an integration time of 1s, which is 2 times better than before. This design demonstrates the feasibility of resonant sensors based on synchronizing DETF oscillators and provides a new method in improving their performance.

- W-111 AN ULTRA-HIGH RESOLUTION RESONANT MEMS ACCELEROMETER ..... 664**  
 Milind Pandit<sup>1</sup>, Arif Mustafazade<sup>1</sup>, Chun Zhao<sup>1</sup>, Guillermo Sobreviela<sup>1</sup>, Xudong Zou<sup>2</sup>, Philipp Steinmann<sup>1</sup>, and Ashwin Seshia<sup>1</sup>  
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<sup>2</sup>*Institute of Electronics, Chinese Academy of Sciences, CHINA*

This paper reports initial results on the implementation of a high-resolution resonant MEMS accelerometer with a noise floor of  $17.8\text{ng}/\sqrt{\text{Hz}}$  and a bias stability of  $17.5\text{ng}$  with a differential frequency readout configuration. The differential readout scheme provides for rejection of common mode environmental effects to first order. This prototype sensor demonstrates the best bias stability and noise floor of all MEMS resonant accelerometer configurations reported till date.

**M-112 HIGH-Q 3D MICRO-SHELL RESONATOR WITH HIGH SHOCK IMMUNITY AND LOW FREQUENCY MISMATCH FOR MEMS GYROSCOPES ..... 668**  
 Sajal Singh, Ali Darvishian, Jae Yoong Cho, Behrouz Shiari, and Khalil Najafi  
*University of Michigan, USA*

In this work we report an improved design and method for fabrication of precision shell integrating (PSI) resonators for gyroscopes. PSI resonators are designed for lower thermomechanical noise and higher shock tolerance. We demonstrate fused silica (FS) micro-shell resonators with tailored sidewall thickness to tune the stiffness and mass of different regions in the resonators. PSI resonators of 10 mm diameter are demonstrated with low frequency split (1.2 Hz), high Q (7.5 million) and long ring-down time (6 minutes). The resonator's sidewall thickness is tailored to achieve large effective mass (>8 mg) and obtain  $n=2$  wine-glass mode frequency at 6-7 kHz for immunity to vibrations. The shells were successfully tested for survivability under 7000g shock. These parameters are critical in achieving near navigation-grade performance (ARW < 5 mdeg/hr, Bias Instability < 1mdeg/hr) for a MEMS gyroscope.

**T-113 STUDY ON POINT-TO-RING CORONA BASED GYROSCOPE ..... 672**  
 Ngoc Tran Van<sup>1</sup>, Tung Thanh Bui<sup>2</sup>, Canh-Dung Tran<sup>3</sup>, Thien Xuan Dinh<sup>4</sup>, Hoa Phan Thanh<sup>5</sup>,  
 Dong Pham Van<sup>5</sup>, Trinh Chu Duc<sup>2</sup>, and Van Thanh Dau<sup>6</sup>  
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<sup>5</sup>*Hanoi University of Industry, VIETNAM, and*  
<sup>6</sup>*Griffith University, AUSTRALIA*

We present for the first time a novel gyroscope using circulatory electro-hydrodynamics flow in a confined space. Three point-ring corona actuator is to generate ionic flows in three separated channels and the ionic flows then merge together at a nozzle of the main chamber to create a jet flow. The residual charge of ion winds is removed by a master-ring electrode. By the effect of angular rate, the jet flow handled by a hotwire anemometry is deflected and sensed. Results by both experiment and numerical simulation consistently show good repeatability and stability of the new configuration-based device. Since ion wind is generated by a minimum power, the device does not require any vibrating component, thus the device is robust, low cost and energy consumption.

**W-114 A TRANSFER FUNCTION APPROACH TO SHOCK DURATION COMPENSATION FOR LABORATORY EVALUATION OF ULTRA-HIGH-G VACUUM-PACKAGED MEMS ACCELEROMETERS ..... 676**  
 Kaisi Xu<sup>1</sup>, Ningli Zhu<sup>2</sup>, Fushuai Jiang<sup>3</sup>, Wei Zhang<sup>1,4,5</sup>, and Yilong Hao<sup>1,4,5</sup>  
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<sup>2</sup>*Aisino Co., Ltd., CHINA,*  
<sup>3</sup>*University of California, Davis, USA,*  
<sup>4</sup>*National Key Laboratory of Science and Technology on Micro/Nano Fabrication, CHINA, and*  
<sup>5</sup>*Innovation Center for Micro-Nano-Electronics and Integrated System, CHINA*

This paper proposes a transfer function method to estimate the performance of ultra-high-g vacuum-packaged microelectromechanical systems (MEMS) accelerometers under practical shock conditions based on test results from laboratory shock test instruments (lab instruments). As a first step to achieve the transfer function, we investigated the elastic-wave, resonant, and quasi-static responses of micro structures by time-domain analysis. The transfer function is theoretically derived from the time-domain analysis, and aims to eliminate the influence due to the difference between laboratory and practical shock durations. This enables us to obtain the mechanical responses of MEMS accelerometers under objective in-use shock loads based on laboratory shock test results, despite of the different shock durations. This transfer function method also can be adopted for the test of other types of high-g MEMS inertial sensors.

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**M-115 IN-PLANE GYROSCOPE USING A PIEZORESISTIVE BEAMS WITH SIDEWALL DOPING ..... 680**  
 Kosuke Abe, Hidetoshi Takahashi, Tomoyuki Takahata, and Isao Shimoyama  
*The University of Tokyo, JAPAN*

This paper reports a gyroscope using sidewall doped piezoresistors and vibrating mass by Lorentz force. With sidewall doped piezoresistors, in-plane deformation of the beams due to Coriolis force generated by angular motion can be detected, which was difficult with surface doped piezoresistors. The proposed gyroscope was designed so that the resonant frequencies of the driving and sensing modes were similar to each other. It was demonstrated that the developed gyroscope measured angular velocity through the resistance change of the piezoresistive beams.

**T-116 A 3-D PARALLEL-PLATE MEMS ACCELEROMETER WITH A GOLD PROOF MASS..... 684**  
 Daisuke Yamane<sup>1</sup>, Shota Otobe<sup>1</sup>, Ken Atsumi<sup>1</sup>, Tatsuya Koga<sup>1</sup>, Toshifumi Konishi<sup>2</sup>, Teruaki Safu<sup>2</sup>,  
 Shinichi Iida<sup>2</sup>, Hiroyuki Ito<sup>1</sup>, Noboru Ishihara<sup>1</sup>, Katsuyuki Machida<sup>1</sup>, and Kazuya Masu<sup>1</sup>  
<sup>1</sup>*Tokyo Institute of Technology, JAPAN and*  
<sup>2</sup>*NTT Advanced Technology Corporation, JAPAN*

This paper presents a low-noise and high-sensitivity surface-micromachined 3-axis MEMS accelerometer for sub-mG (1 G = 9.8 m/s<sup>2</sup>) sensing. 3-D parallel-plate (3D-PP) electrodes for a single high-density proof mass made of gold are proposed for the first time, and the device characteristics are experimentally evaluated. When compared with conventional devices, the Brownian noise is nearly three orders of magnitude smaller and the capacitance sensitivity is two-to-three orders of magnitude larger.

**W-117 A PIEZORESISTIVE VIBRATION SENSOR WITH LIQUID ON CORRUGATED MEMBRANE ..... 688**  
 Ryosuke Suzuki, Thanh-Vinh Nguyen, Tomoyuki Takahata, and Isao Shimoyama  
*The University of Tokyo, JAPAN*

This paper reports on a MEMS vibration sensor with a structure of liquid on a thin Parylene membrane which has a piezoresistive beam attached underneath. The proposed sensor has a high sensitivity over a wide range of frequency (from several Hz to several hundred kHz) by utilizing the inertia force of the liquid at low frequency and surface tension wave at high frequency. Most significantly, this sensor design can prevent liquid leakage which is a crucial problem in the conventional sensor which has a piezoresistive beam placed directly underneath liquid. Furthermore, sensitivity improvement using corrugated Parylene membranes was experimentally confirmed.

**M-118 OUT-OF-PLANE COMB-FINGERS FOR A LOW-NOISE, 0.12-MM<sup>2</sup> Z-AXIS ACCELEROMETER FABRICATED WITH A 3D MEMS PROCESS ..... 692**  
 F. Maspero<sup>1</sup>, S. Delachanal<sup>1</sup>, A. Berthelot<sup>1</sup>, L. Joet<sup>1</sup>, G. Langfelder<sup>2</sup>, and S. Hentz<sup>1</sup>  
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<sup>2</sup>*Politecnico di Milano, ITALY*

A z-axis accelerometer implemented with a 3-D process is presented. The device has thick inertial layer and out-of-plane differential comb-fingers. These aspects, together, allow low Brownian noise and large capacitive density. Differential static capacitance of 700fF, sub-50µg/√Hz resolution, 10kHz resonance frequency within a 0.12mm<sup>2</sup> device are shown.

**T-119 AN 8PPM/°C TEMPERATURE SENSITIVITY OF THE SCALE FACTOR IN MEMS GYROSCOPE BASED ON MULTI PARAMETERS FUSION COMPENSATION METHOD ..... 696**  
 Jian Cui, Qiancheng Zhao, Zesen Bai, and Guizhen Yan  
*Peking University, CHINA*

This paper presents a novel compensation method to improve the temperature stability of scale factor in amplitude-modulated (AM) MEMS gyroscope operating in split-mode based on multi parameters fusion compensation, which for the first time weightedly combines the resonant frequency of the primary mode, the voltage amplitude of primary mode displacement, the frequency difference between the primary mode and the sense mode together with the demodulation phase error to restrain the thermal variations of the parameters affecting the scale factor. The results show that an 8ppm/°C temperature sensitivity of the scale factor is obtained over -30°C to 70°C with the proposed compensation technique, which is considerably competitive compared with previously reported results in literatures.

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**W-120 SELF-CLOCKING ELECTRO-MECHANICAL SIGMA-DELTA MODULATOR QUADRATURE ERROR CANCELLATION FOR MEMS GYROSCOPE ..... 700**

Fang Chen<sup>1</sup>, Jiebin Gu<sup>1</sup>, Pejwaak Salimi<sup>2</sup>, Michael Kraft<sup>2</sup>, and Xinxin Li<sup>1</sup>  
<sup>1</sup>*Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, CHINA and*  
<sup>2</sup>*Catholic University of Leuven, BELGIUM*

This paper presents a novel electromechanical sigma-delta modulator (EM- $\Sigma\Delta$ M) closed-loop quadrature error cancellation technique for the sense mode of a MEMS vibratory gyroscope. The interface circuit system adopts a quadrature sigma-delta modulator structure, which allows in-phase and quadrature decomposition to efficiently realize noise shaping and quadrature error cancellation. Experimental results demonstrate that the proposed quadrature sigma-delta modulator (Q- $\Sigma\Delta$ M) control loop results in better noise and bias drift performance when compared with an EM- $\Sigma\Delta$ M single-loop architecture. Measurement results showed that the proposed quadrature EM- $\Sigma\Delta$ M gyroscope achieved -80dB quadrature error cancellation within a bandwidth of 64Hz, and an approximately 5.5-fold improvement in bias instability (decreasing the bias instability from 5°/h to 0.9°/h), compared to the same gyroscope operating in a single-loop EM- $\Sigma\Delta$ M.

**M-121 SINUSOIDAL MODULATION OF FM ACCELEROMETERS WITH INTEGRATED OSCILLATOR AND FREQUENCY DIGITIZATION..... 704**

Marco Bestetti<sup>1</sup>, Cristiano R. Marra<sup>1</sup>, Mauro Leoncini<sup>1</sup>, Alessandro Tocchio<sup>2</sup>, Francesco Rizzini<sup>2</sup>, and Giacomo Langfelder<sup>1</sup>  
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<sup>2</sup>*ST Microelectronics, ITALY*

A new operational mode of a frequency-modulated (FM) accelerometer for simultaneously improved full-scale, stability and bandwidth is presented. The system relies on a continuous sinusoidal modulation of the electro-mechanical configuration of a single resonator, which gradually reverses the sign of its frequency sensing: as a consequence, a secondary amplitude-modulation (AM) is superimposed to the primary FM effect. The following demodulations automatically cancel temperature-related drifts of the resonator frequency. The accelerometer is coupled to an integrated circuit that embeds an analog oscillator and a frequency digitization stage, with an overall consumption of 148  $\mu$ A. A sub-80- $\mu$ g/K drift coefficient and, at the same time, a sub-0.25% linearity error over 42 g of input acceleration are demonstrated. The achievable bandwidth is half of the chosen AM modulation frequency.

**T-122 ENHANCING VIBRATION ROBUSTNESS AND NOISE IN AUTOMOTIVE GYROSCOPE WITH LARGE DRIVE MOTION AND LEVERED SENSE MODE..... 708**

Leonardo Gaffuri Pagani<sup>1</sup>, Stefano Dellea<sup>1</sup>, Giulio Bursi<sup>1</sup>, Matteo Brunetto<sup>2</sup>, Luca Falorni<sup>2</sup>, and Giacomo Langfelder<sup>1</sup>  
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<sup>2</sup>*ST Microelectronics, ITALY*

The work presents a new geometry of amplitude-modulated in-plane and out-of-plane gyroscopes for improved vibration rejection in automotive applications. To this purpose, the design embeds a levered sense mode, enables to reach drive displacements as large as 13  $\mu$ m and allows complete electromechanical quadrature compensation. Under the effect of 10 g (gravity units) peak-to-peak vibrations, the sensors demonstrate 10- to 100-fold improved vibration rejection compared to previous yaw-rate geometries, holding similar characteristics for pitch-rate sensing. At the same time, noise and stability performance are 2-fold better than best-in-class automotive gyroscopes.

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**Fluidic Sensors (Flow, Pressure, Density, Viscosity, Etc.)**

**M-123 THERMAL CHARACTERIZATION OF LIQUID ANALYTES VIA PHOTOTHERMAL MODULATION OF MICROFLUIDIC RESONATORS.....712**

Yeowon Yoon<sup>1,2</sup>, Faheem Khan<sup>3</sup>, Thomas Thundat<sup>4,5</sup>, and Jungchul Lee<sup>6</sup>

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This paper reports the first thermal characterization of liquid analytes via photothermal modulation of microfluidic resonators in dynamic mode. Measurements of thermophysical properties of liquid analytes are enabled by real-time tracking of the resonance frequency shift of the microfluidic resonator while the liquid filled resonator is irradiated by a diode laser. The local irradiation induces the photothermal heating of the resonator as well as the loaded liquid sample. The volumetric thermal expansion coefficients of various liquids are correlated with resonance frequency shifts of the resonator and the ratio of specific heat to thermal conductivity tuned by varying the mole fraction of ethanol-water binary mixtures shows linear dependence on the heating time constant. In addition, a higher flexural mode displays improved sensitivity for thermal characterization of liquids via photothermal heating.

**T-124 HIGHLY SENSITIVE 2D THERMORESISTIVE MICRO CALORIMETRIC FLOW SENSOR BY USING 0.35µM CMOS MEMS TECHNOLOGY .....716**

Wei Xu<sup>1,2</sup>, Ruijie Wang<sup>2</sup>, Xiaoyi Wang<sup>2</sup>, Basant Mousa<sup>2</sup>, and Yi-Kuen Lee<sup>2</sup>

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<sup>2</sup>*Hong Kong University of Science and Technology, HONG KONG*

We report a two-dimensional (2D) Thermoresistive Micro Calorimetric Flow (TMCF) sensor by using a 0.35 µm 2P4M CMOS MEMS technology. For the nitrogen gas flow, the fabricated 2D flow sensor achieves a prominent normalized sensitivity of 60.6 mV/W/(m/s). To overcome the sensor output drifting issue due to the locally redistributed fluid flow near the bonding wires, a digital signal conditioning algorithm by using the inverse distance weighting (IDW) method, instead of the conventional fitting with sine and cosine function, was proposed. Accordingly, this 2D flow sensor system shows the excellent velocity accuracy of ±4% and the angle accuracy of ±2°. Therefore, the fabricated highly sensitive 2D TMCF sensor will be a promising flow device for the smart buildings and the meteorological monitoring system.

**M-125 GRAPHENE-BASED WIRELESS INLINE PRESSURE SENSOR FOR IN VIVO BLOOD PRESSURE MONITORING ..... 720**

Nagisa Inoue and Hiroaki Onoe

*Keio University, JAPAN*

This study describes a graphene-based wireless inline pressure sensor that can be easily inserted between an implanted microdevice and a blood vessel for *in vivo* blood pressure monitoring. Our wireless pressure sensor is simply composed of a graphene sheet (piezo-resistive sensor) attached on a microfluidic elastic tube and a coil wound up to the tube as a transmitter. The applied pressure inside the tube can be monitored wirelessly by an external receiver coil. We fabricated the sensor system applicable to monitoring the range of typical blood pressure, 10 – 18 kPa, by designing the sensitivity depending on the stiffness and the thickness of the elastic tube, the turn numbers of the coils, and the distance between the coils. Furthermore, we demonstrated to wirelessly measure the blood-pressure-mimicking pulsed inputs with our sensor that was embedded in a biological tissue. We believe that our wireless inline pressure sensor could be an effective tool for monitoring *in vivo* implanted medical devices such as microfluidic artificial kidneys.

**W-126 THE MEASUREMENT OF THE VIBRATION OF HUMAN IPS CELL-DERIVED CARDIOMYOCYTES' CONTRACTION..... 723**

Yasuaki Ishii, Takuya Tsukagoshi, Nguyen Thanh-Vinh, Kayoko Shoji Hirayama, Tomoyuki Takahata, and Isao Shimoyama

*The University of Tokyo, JAPAN*

This paper reports a direct measurement of the vibration induced by the contraction of human iPS cell-derived cardiomyocytes (hiPSC-CMs) in vitro. In our proposed method, the vibration of the cells was measured by a highly sensitive MEMS cantilever located close to (distance: several tens µm) but not in contact with the cells. As a result, the small pressure of approximately 10 mPa emitted from hiPSC-CMs' contraction was measured.

**M-127 IMPROVING STRUCTURAL STRENGTH AND STABILITY OF PARYLENE-BASED CAPACITIVE MICRO PRESSURE SENSOR USING CORRUGATED SIDEWALL ..... 727**

Tae-Bong Hur<sup>1</sup>, William W. Clark<sup>1</sup>, Youngjae Chun<sup>1</sup>, Catherine Go<sup>1</sup>, Bryan Tillman<sup>1,2</sup>, and Sung Kwon Cho<sup>1</sup>

<sup>1</sup>University of Pittsburgh, USA and

<sup>2</sup>University of Pittsburgh Medical Center, USA

This paper reports a new method to improve the structural strength and stability of parylene-based microfabricated implantable capacitive blood pressure sensor. The key idea or contribution is to introduce corrugations to the side wall of the sensor supporting the top membrane in order to effectively increase the thickness and thus stiffness of the sidewall. This design significantly reduces the possibility of membrane collapses during fabrication or operation that otherwise would commonly occur in the conventional parylene-based capacitive sensors with large diaphragm and small gap between electrodes. The fabricated sensor with corrugations shows a stable linear output behavior within the desired range of up to 200 mmHg, which is optimal for the application of the implantable real-time blood pressure monitoring system.

**T-128 A CONTINUOUS, DRIFT-COMPENSATED IMPEDIMETRIC THERMAL FLOW SENSOR FOR IN VIVO APPLICATIONS ..... 731**

Trevor Hudson, Alex Baldwin, and Ellis Meng

University of Southern California, USA

We report a liquid flow sensor developed for biomedical applications based on electrochemical impedance (EI) measurements across a constantly-biased heating element. Prior EI-based flow transduction methods were limited to periodic measurements; this novel sensing approach is amenable to real time flow monitoring and does not require curve analysis or cooling between measurements to extract EI response to flow. The use of isolated reference electrodes in the sensor layout reduces sensitivity to environmental drift in ionic concentration and temperature by over 5×. Our sensor achieved a 2σ resolution of 35 μm/sec between 0-200 μm/sec in a flexible, biocompatible form factor.

**W-129 SENSING FLUID PROPERTIES OF SUPER HIGH VISCOUS LIQUIDS USING NON-CONVENTIONAL VIBRATION MODES IN PIEZOELECTRICALLY EXCITED MEMS RESONATORS ..... 735**

Georg Pfusterschmied, Christoph Weinmann, Markus Hospodka, Bernhard Hofko, Michael Schneider, and Ulrich Schmid

TU WIEN, AUSTRIA

In this paper, reusable micro-machined piezoelectric resonators are presented, which are capable to determine the densities and viscosity values of super high viscous media with dynamic viscosities up to 64 000 mPa·s. To overcome the high viscous forces, the resonating element is designed such that the 10<sup>th</sup> order mode of a non-conventional vibration mode is excited, to provide sufficient output signal height even under such strong damping conditions. For actuation and sensing, a piezoelectric aluminium nitride thin film is used in combination with a tailored electrode design. The comparison of three different bitumen derivatives are presented in a temperature range from 75 to 150°C, demonstrating the high potential of the presented resonator concept for sensing of super high viscous liquid properties in harsh environments.

**M-130 A 2000-ATMOSPHERE BULK-TYPE PRESSURE SENSOR REALIZED ON (001) SUBSTRATE WITH SELECTIVE STRESS-FILTERING TRENCHES ..... 739**

Dequan Lin<sup>1</sup>, Elena Chan<sup>1</sup>, Zili Tang<sup>1</sup>, Lei Lu<sup>1,3</sup>, Man Wong<sup>1</sup>, and Kevin Chau<sup>1,2</sup>

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Previously reported was a bulk-type pressure sensor without fragile movable microstructure and constructed on [110]-oriented silicon substrate. Hydrostatic pressure acting on the sensor was converted to biaxial compression inside an encapsulated vacuum cavity. Two pairs of piezoresistors were used to form a Wheatstone bridge, with one pair each aligned with the [001] and [110] orientations – thus optimally utilizing the anisotropy of silicon piezoresistance on the (110) substrate. However, such anisotropy is absent on the (001) substrate because of an inherent crystal-symmetry. Presently reported is the placement of stress-filtering trenches adjacent to a selected pair of the constituent piezoresistors forming the Wheatstone bridge, thus removing the stress-symmetry by converting the local stress field from biaxial to uniaxial and allowing the construction of the bulk-type sensor on the more commonly available (001) substrate. A junction-isolated version of the pressure sensor was realized and characterized to 200 MPa (~2000 atmospheres) and 175°C, with better potential for sensor-CMOS integration.

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**T-131 A HIGH ACCURACY TRANSIT-TIME AIRFLOW VOLUMETRIC FLOWMETER BASED ON PMUTS ARRAYS ..... 743**

Xuying Chen<sup>1</sup>, Chengwei Liu<sup>1</sup>, Jinghui Xu<sup>2,3</sup>, Hong Chen<sup>1</sup>, Yong Wang<sup>1</sup>, Liang Hu<sup>1</sup>, and Jin Xie<sup>1</sup>

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<sup>3</sup>*Guangzhou Chen Fang Info Tech Ltd, CHINA*

This paper describes a high-accuracy airflow volumetric flowmeter using piezoelectric micromachined ultrasound transducers (pMUTs) arrays based on the transit-time. Two pieces of 10by10 multiplied aluminum nitride (AlN) pMUTs arrays at resonant frequency of 980kHz are employed to transmit and receive ultrasonic signals alternately. The dimension of the fabricated 10by10 array is about  $3.5 \times 3.5 \text{ mm}^2$ , so the pMUTs-based flowmeter can conveniently measure the flow rate in small pipes. Leveraging on the high signal to noise ratio (SNR, ~29 dB) of the pMUTs and good resolution (ns) of the evaluation board, the flowmeter has high accuracy. The relative errors of the correctional volumetric flow are within 3% for the reference flow rate in the range from 0-9 L/min in a pipe with a diameter of 10 mm.

**W-132 SENSITIVITY IMPROVEMENT OF MEMS THERMAL WIND SENSOR USING VERTICAL STACKING THERMISTORS ..... 747**

Zhenjun Wang, Zhenxiang Yi, Yizhou Ye, Ming Qin, and Qing-an Huang

*Southeast University, CHINA*

In this paper, a novel MEMS thermal wind sensor adopting vertical stacking thermistors is proposed for the first time. Compared with the traditional wind sensors, the novelty of this work is that eight thermistors, fabricated on two layers, can achieve improved sensitivity of wind detection. The sensor is tested in wind tunnel in calorimetric principle and the heater is supplied with constant voltage (initial power 210 mW). Experiments demonstrate that the sensitivity of the proposed sensor is double that of the traditional one without increasing the chip size. Measuring range of wind speed from 0 m/s to 33 m/s and full range (360°) of wind direction detection have been achieved.

**T-133 A NOVEL THERMOPILE-BASED GAS FLOW SENSOR FABRICATED WITH A SINGLE-WAFER-BASED FRONT-SIDED BULK-MICROMACHINING TECHNIQUE ..... 751**

Dan Xue, Zao Ni, Wei Li, Jiachou Wang, and Xinxin Li

*Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, CHINA*

This paper presents a novel p<sup>+</sup> Si/Au thermopile-based micro flow sensor, which is fabricated only from the front-side of (111) silicon wafer for high-yield and low-cost volume production. Benefited from the MIS (Micro-openings Interetch & Sealing) micromachining process and the developed patterned technique of single-crystalline silicon (SC-Si) layer under thin-film, the p<sup>+</sup> Si/Au thermocouple with significantly high Seebeck-coefficient can be employed to construct the thermopile-based gas flow sensor, and the 0.65mm×0.65mm tiny-sized MEMS gas flow sensor is achieved. The testing results show that the sensor has an ultra-high normalized sensitivity of 0.158mV/(SLM)/mW (Output without any amplification) for nitrogen gas flow and the short response time of 3.0ms. Besides, the minimum detectable flow rate is estimated at about 9.0 sccm.

**W-135 DESIGN AND CHARACTERIZATION OF A CMOS MEMS CAPACITIVE SQUEEZE-FILM PRESSURE SENSOR ..... 755**

Jason Chiu and Michael S.-C. Lu

*National Tsing Hua University, TAIWAN*

A capacitive pressure sensor operated based on the elastic squeeze-film damping effect is implemented, for the first time, in a CMOS process to provide sensor integration and sensitivity improvement. Sensor fabrication is simplified as a squeeze-film pressure sensor does not require a sealed membrane as in conventional sensors; in addition, sensitivity is significantly enhanced with the small gap achieved between capacitive plates. The sensor with a resonant plate size of  $200 \times 200 \mu\text{m}^2$  demonstrates a sensitivity of 793 Hz/kPa.

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**Sonic & Ultrasonic MEMS Transducers (Microphones, PMUTs, Etc.)**

**M-136 TRANSMITTING SENSITIVITY ENHANCEMENT OF PMUTS VIA RELEASING RESIDUAL STRESS BY V-SHAPED SPRINGS ..... 759**

Xuying Chen<sup>1</sup>, Dongyang Chen<sup>1</sup>, Jintao Pang<sup>1</sup>, Dengfei Yang<sup>1</sup>, Manjuan Huang<sup>2</sup>, Huicong Liu<sup>2</sup>, and Jin Xie<sup>1</sup>  
<sup>1</sup>Zhejiang University, CHINA and  
<sup>2</sup>Soochow University, CHINA

Residual stress can dramatically hamper the performance of piezoelectric micromachined ultrasound transducers (pMUTs), in particular the transmitting sensitivity. This paper reports a series of square pMUTs with enhanced transmitting sensitivity through V-shaped springs in different angles. The V-shaped springs can release the residual stress through self-deformation, which contributes to a flat vibrating membrane rather than a curved one. A flat vibrating membrane conduces to a large vibration amplitude. Consequently, the transmitting sensitivity of the pMUT with 150° V-shaped springs is measured as 50.9 nm/V, which is 203% higher than that of the pMUT without springs. The enhanced pMUTs have advantages in various applications of emission ultrasound.

**T-137 ACOUSTIC TWEEZERS BASED ON LINEAR FRESNEL LENS WITH AIR CAVITIES FOR LARGE VOLUME PARTICLE TRAPPING ..... 763**

Yongkui Tang and Eun Sok Kim  
 University of Southern California, USA

This paper reports a novel acoustic tweezers with multi-foci linear Fresnel lens that was designed to create a large Bessel beam zone for contactless, non-invasive object trapping in liquid. The tweezers was built on a 1- mm-thick lead zirconate titanate (PZT) substrate with rectangular air-cavity Fresnel lens having multiple focal lengths. With 25 V<sub>pp</sub> continuous 2.32 MHz sinusoidal drive, the acoustic tweezers is capable of trapping a silicon chip of 5.30×0.67×0.51 mm<sup>3</sup> in size and 3.98 mg in mass along with two 500-µm-diameter Polyethylene microspheres.

**W-138 PIEZOELECTRIC MEMS MICROSPEAKER WITH SUSPENSION SPRINGS AND DUAL ELECTRODE TO ENHANCE SOUND PRESSURE LEVEL ..... 767**

Hsu-Hsiang Cheng<sup>1</sup>, Zi-Rong Huang<sup>1</sup>, Sung-Cheng Lo<sup>1</sup>, Yi-Jia Wang<sup>1</sup>, Mingching Wu<sup>2</sup>, and Weileun Fang<sup>1</sup>  
<sup>1</sup>National Tsing Hua University, TAIWAN and  
<sup>2</sup>GlobalMEMS Co. LTD., Hsinchu, TAIWAN

This study based on piezoelectric actuating principle to design and realize a high sound pressure level (SPL) MEMS microspeaker for in-ear applications. The proposed suspension-spring design enables larger out-of-plane displacement to improve SPL and the piston movement of diaphragm to generate sound waves with better quality. Moreover, applying dual electrode pattern on the suspension springs further enhances diaphragm out of plane displacement and SPL. Measurements demonstrate the highest SPL above 100dB at 3.13kHz in a 3cm long canal. SPL higher than 70dB is obtained from 400Hz to 8.5kHz with only 2V<sub>pp</sub> driving voltage and 1.67mm<sup>2</sup> diaphragm. Furthermore, total harmonic distortion (THD) is less than 3% in most of the audio range.

**M-139 CONCENTRIC PMUT ARRAYS FOR FOCUSED ULTRASOUND AND HIGH INTENSITY APPLICATIONS .....771**

Benjamin E. Eovino<sup>1</sup>, Yue Liang<sup>2</sup>, and Liwei Lin<sup>2,3</sup>  
<sup>1</sup>Chirp Microsystems, Berkeley, USA,  
<sup>2</sup>University of California, Berkeley, USA, and  
<sup>3</sup>Tsinghua University, CHINA

This work presents an array of concentric ring-shaped piezoelectric micromachined ultrasonic transducers (PMUTs) that is capable of generating acoustic intensities in excess of 330 mW/cm<sup>2</sup> with a small 2.6 mm aperture for high intensity ultrasound applications, including catheter-based medical operations. The fabricated prototype exhibits a high output pressure of 2.8 kPa/V in standard transmission or 12.2 kPa/V with phased array focusing at 2 mm - marking the highest normalized pressure among reported PMUT arrays both with and without focusing, and the most effective acoustic focusing with a focal intensity gain of 19. The strong acoustic output is due to the high fill-factor of concentric rings compared to standard arrays of circular PMUTs, along with the improved focusing derived from the annular structure of the array.



**T-140 IMPLEMENTATION OF TWO-POLY DIFFERENTIAL MEMS MICROPHONES FOR SNR AND SENSING RANGE ENHANCEMENT..... 775**

Sung-Cheng Lo<sup>1</sup>, Chun-Kai Chan<sup>1</sup>, Ya-chu Lee<sup>1</sup>, Mingching Wu<sup>2</sup>, and Weileun Fang<sup>1</sup>

<sup>1</sup>National Tsing Hua University, TAIWAN and

<sup>2</sup>GlobalMEMS Co. LTD., TAIWAN

This study designs and implements the differential MEMS microphone (Fig.1) to improve its signal-to-noise ratio (SNR) and sensing range using MOSBE process [1]. The microphone has three major merits: (1) achieve Differential MEMS Microphone using top/bottom diaphragm and top/bottom back-plate formed by two poly-Si layers (Fig.1b); (2) reduce Low Frequency Acoustic Loss by removing release holes and adding surrounding mesa for diaphragm (Fig.1b); (3) improve Sensing Area and Sensitivity through parallel plate gap-closing capacitance sensing enabled by rigid diaphragm with flexible U-shaped springs (Fig.1c); and one minor merits: single sacrificial layer to define differential sensing gaps to reduce process induced thickness variation. Measurements indicate microphone of 800µm “diameter” diaphragm: acoustic differential sensitivity is -40.5dB (Ref: 1V/1Pa) at 1kHz; ±3dB bandwidth ranges 50-20kHz; and the SNR is over 57.8dB.

**W-141 PIEZOELECTRIC MICROMACHINED ULTRASONIC TRANSDUCER WITH A UNIVERSAL BOTTOM-UP FABRICATION APPROACH IMPLEMENTED ON A FOIL AS DOPPLER RADAR FOR GESTURE RECOGNITION ..... 779**

Guo-Hua Feng, Hua-Jin Liu, and Gui-Rong Lai

National Chung Cheng University, TAIWAN

This paper presents a state-of-the-art piezoelectric micromachined ultrasonic transducer (PMUT) array fabricated on a 10 µm thick metal foil. Using a bottom-up micromachining technique, the PMUTs of electrode/ piezoelectric film/ electrode sandwiched structures with versatile patterns can be implemented on a large-area foil with thickness even thinner than a hair. The proposed microfabrication easily allows the PMUT to generate ultrasonic waves with demanded resonances. The higher-order resonances of PMUT are functionally operated due to self-released residual stress fabrication. The developed PMUT array foil can be attached to the surface/substrate of arbitrary curvature. The integrated stereolithographic process can tune the operation frequencies of processed PMUTs. We successfully demonstrated the developed PMUT as a ranging transmitter and a Doppler radar to perform the hand gesture recognition.

**M-142 MONITORING VOLCANIC ACTIVITY WITH HIGH SENSITIVE INFRASOUND SENSOR USING A PIEZORESISTIVE CANTILEVER ..... 783**

Jumpei Shimatani, Hidetoshi Takahashi, Mie Ichihara, Tomoyuki Takahata, and Isao Shimoyama

The University of Tokyo, JAPAN

In this paper, we propose a high sensitive monitoring method of infrasound evoked by a volcano eruption. The sensor unit is composed of two differential pressure sensors and an air chamber. The pressure resolution of the developed sensor is approximately 0.01 Pa, which is sufficiently small to detect the tiny infrasound. The measurable frequency range is from 0.3 Hz, which is sufficiently low for the infrasound. The sensor units were set at the foot of volcano, *Sakurajima, Kagoshima*, Japan. It was confirmed that the sensors kept the high sensitive monitoring performance for a month.

**T-143 HIGH-PRESSURE OUTPUT 40 kHz AIR-COUPLED PIEZOELECTRIC MICROMACHINED ULTRASONIC TRANSDUCERS ..... 787**

Guo-Lun Luo, Yuri Kusano, Matthew N. Roberto, and David A. Horsley

University of California, Davis, USA

This paper presents air-coupled piezoelectric micromachined ultrasonic transducers (PMUTs) fabricated from single-crystal PZT, enabling very high sound pressure level (SPL) output of 100.3 dB at 33 cm distance. The single-crystal PZT deposited via PVD has low permittivity, enabling the highest figure of merit (FOM,  $e_{31}^2/\epsilon_r\epsilon_0$ ) PMUTs to date. The PMUTs operate at a low resonant frequency of 40 kHz, which results in lower acoustic absorption loss and therefore longer operating distance, and have 10X greater mechanical displacement and SPL output compared to prior-art AlN PMUTs. Comparing to prior PZT PMUTs, the single-crystal PZT used here has low permittivity ( $\epsilon_r = 308$ ) and high piezoelectric coefficients ( $e_{31} \sim 24.5$ ), resulting in low insertion loss. Acoustic experiments conducted with commercial ultrasonic transducers and reference microphones show that a 2x2 array PMUTs has 1.91 mV/Pa (-74.3dB) receive sensitivity, demonstrating much higher efficiency per unit transducer volume compared to conventional transducers.

**W-144 PINNED BOUNDARY PIEZOELECTRIC MICROMACHINED ULTRASONIC TRANSDUCERS..... 791**

Yue Liang<sup>1</sup>, Benjamin E. Eovino<sup>2</sup>, and Liwei Lin<sup>1</sup>  
<sup>1</sup>*University of California, Berkeley, USA and*  
<sup>2</sup>*TDK-Chirp Microsystems, USA*

This work reports a piezoelectric micromachined ultrasonic transducer (pMUT) with a pinned boundary for enhanced vibrational deformation and emission pressure. In contrast to the state-of-art large-scale piezoelectric ultrasonic transducers, pMUTs have limited output ranges/amplitudes due to their physical sizes which constrains their various potential applications. Using the pinned boundary design instead of the traditionally clamped structure, we demonstrate drastic performance enhancements without any added fabrication complexity. Experimental results show that the operational mode shape matches with simulations and produces a measured 2.5× improvement in displacement and an estimated 3.3× higher pressure output per volt at resonance.

**M-145 WIDEBAND ULTRASONIC TRANSDUCER BASED ON MODIFIED SPACE-FILLING CURVES..... 795**

W. Purcell<sup>1</sup>, S. Islam<sup>1</sup>, S. Rhee<sup>1</sup>, A. Nguyen<sup>1</sup>, S. H. Song<sup>2</sup>, F. Ahmad<sup>1</sup>, and A. Kim<sup>1</sup>  
<sup>1</sup>*Temple University, Philadelphia, USA and*  
<sup>2</sup>*Sookmyung Women's University, KOREA*

In this paper, a wideband ultrasonic transducer designed by space-filling curves is reported. The transducer is based on the Hilbert space-filling curve, which incorporates some modifications such that a series of identical holes are cut from the piezoelectric membrane. The modification is achieved by relocating one or two segments to form a closed shape. Four ultrasonic transducers (one through four iterations of Hilbert curves) are proposed and compared in terms of resonant frequency, bandwidth, and acoustic intensity response. The fabricated ultrasonic transducers using polyvinylidene fluoride (PVDF) had the resonant frequency around 11.6 MHz with an increasing trend in 3dB bandwidth as iteration order increases (averaging 11.5% improvement per order increment).

**T-146 BROADBAND AND FAST RESPONSE THERMOPHONE USING GRAPHENE NANOFILM..... 799**

Wei Huang, Peng Li, Xianhao Le, Xiaodong Zhang, Chao Gao, Zhen Xu, and Jin Xie  
*Zhejiang University, CHINA*

This paper reports a high performance thermal sound generator based on the nano-sized graphene. Sound pressure is related to heat to explore the relationship between thermal fluctuations and SPL. We study the effect of power, distance, substrate and thickness on acoustic pressure. The graphene loudspeaker demonstrates a high performance with wide-band sound generation from 3 to 40 kHz and low drive voltage due to the excellent property of the material. Such thin-film loudspeaker has stable property and has great potential in many applications.

**Force & Displacement Sensors (Tactile, Force, Torque, Stress & Strain Sensor)**

**W-147 AN MRI-COMPATIBLE FORCE SENSOR WITH ENCLOSED AIR USING PRESSURE TRANSMISSION..... 803**

Daiki Akutagawa<sup>1</sup>, Tomohiko Izumizaki<sup>1</sup>, Masataka Hori<sup>1</sup>, Tetsuji Dohi<sup>1</sup>, Hidetoshi Takahashi<sup>2</sup>,  
 and Isao Shimoyama<sup>2</sup>  
<sup>1</sup>*Chuo University, JAPAN and*  
<sup>2</sup>*The University of Tokyo, JAPAN*

We fabricated an MRI-compatible force sensor with enclosed air using pressure transmission. The fabricated force sensor consists of a contact portion, sensing portions, and connecting pipes. When force was applied to the contact portion, the internal air pressure increased with a deformation of the contact portion, and is transmitted to the sensing portion through the connecting pipes. In the sensing portion, the change in air pressure is detected by a change in the resistance of a piezoresistive cantilever. Since using this air pressure transmission, the sensing portion can be placed away from the magnet of the MRI. Therefore, the force sensor does not interfere with the magnetic field, and it can be used in the magnet of an MRI.

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**M-148 PDMS CANTILEVER INTEGRATED WITH METAL WRINKLES TO MEASURE CONTRACTILE BEHAVIOURS OF MATURED CARDIAC CELLS..... 807**  
 Nomin-Erdene Oyunbaatar and Dong-Weon Lee  
*Chonnam National University, KOREA*

The surface topography plays crucial role for controlling the variety of cell growing behavior, including corneal, epithelial and skeletal and cardiac muscle cells. In this paper, we describe a new idea to form regular microgrooves patterns (wrinkles) on a highly flexible PDMS cantilever using a mechanical stress of metallic thin films. The geometric dimensions and direction of metal wrinkles on the cantilever were optimized by controlling of process conditions (pre-stretching and deposition). The displacement of the PDMS cantilever was greatly improved due to the alignment of the cardiac cells growing along the wrinkles. Based on the basic experiments, we confirmed that the highly sensitive cantilever-based sensor can accurately monitor the changes in cardiac contractility and beating duration with various concentration of drugs. The suggested strategy is effectively reducing process steps in the cantilever fabrication and it is excellent route for analysis of mechanical response of cardiac cell with preliminary drug toxicity screening.

**T-149 DEVELOPMENT OF A HIGHLY STRETCHABLE STRAIN SENSOR BASED ON PATTERNED AND ROLLED CARBON NANOTUBES .....811**  
 Jaeyong Lee, Soonjae Pyo, Eunhwan Jo, and Jongbaeg Kim  
*Yonsei University, KOREA*

This paper reports a highly stretchable strain sensor consisting of patterned and rolled carbon nanotubes (CNTs) embedded in an elastomer. To form overlapped lines of CNTs on the elastomer, vertically aligned CNTs (VACNTs) are grown on the patterned catalytic sites and rolled out by a roller. In the initial unloaded state, these lines of CNTs are overlapped with each other. Under loading, the flexible substrate is extended, and the overlapped CNT lines are slid and separated, increasing the electrical resistance. The fabricated sensor showed excellent sensing performances including broad sensing range (>500% strain), high sensitivity (gauge factor >28), high repeatability, and durability. In addition, since the shape of the CNT lines determines the resistance through the deformed lines of CNTs under applied strain, the performance of the sensor can be further improved by optimizing the pattern design. Therefore, the sensor would be an attractive candidate for diverse applications of strain sensors.

**W-150 A PAPER-BASED DISPOSABLE STRAIN SENSOR BY DIRECT LASER PRINTING .....815**  
 Yu Long<sup>1</sup>, Xining Zang<sup>2</sup>, Junwen Zhong<sup>1</sup>, Renxiao Xu<sup>1</sup>, Takeshi Hayasaka<sup>1</sup>, and Liwei Lin<sup>1</sup>  
<sup>1</sup>*University of California, Berkeley, USA and*  
<sup>2</sup>*Massachusetts Institute of Technology, USA*

A paper-based, disposable strain sensor by means of a direct laser printing process with high sensitivity has been developed and demonstrated. Commercially-available printing papers are first soaked with the gelatin-Mo<sup>5+</sup>ink and ablated by a CO<sub>2</sub> laser to convert molybdenum ions into conductive MoC and graphene nanocomposite flakes for disposable paper electronics. The strain sensor made of continuous MoC flakes has the capability of detecting and distinguishing both tensile and compressive strain. It is found that the stability of the sensor is preserved when there are defects in the device as well as in environments with heavy humidity for potential applications in wearable devices.

**M-151 130-MHz OPTOMECHANICAL VIBRATING SENSOR: TOWARDS HIGH BANDWIDTH / ULTRASENSITIVE MEASUREMENTS.....819**  
 Lucien Schwab<sup>1</sup>, Pierre-Etienne Allain<sup>2</sup>, Louise Banniard<sup>3</sup>, Nicolas Maurant<sup>1</sup>, Denis Lagrange<sup>1</sup>, Alexandre Fafin<sup>3</sup>, Marc Gely<sup>3</sup>, Maxime Hermouet<sup>3</sup>, Guillaume Jourdan<sup>3</sup>, Sébastien Hentz<sup>3</sup>, Ivan Favero<sup>2</sup>, and Bernard Legrand<sup>1</sup>  
<sup>1</sup>*University of Toulouse, FRANCE,*  
<sup>2</sup>*Université Paris Diderot, FRANCE, and*  
<sup>3</sup>*Université Grenoble Alpes, FRANCE*

We show all-optical operation of a VLSI optomechanical micro-resonator designed for high resolution sensing applications. Mechanical resonance frequency is above 100 MHz with Q-factor of 1000 in air, yielding measurement bandwidth above 100 kHz. We demonstrate low thermomechanical noise floor resolved with exquisite motion detection limit down to 4.10<sup>-16</sup> m.Hz<sup>0.5</sup>. This performance, enabled by optomechanical transduction, paves the way for very high-speed and ultra-sensitive sensing applications.

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**T-152 EVALUATION OF GROUND SLIPPERINESS DURING COLLISION USING MEMS LOCAL SLIP SENSOR..... 823**

Taiyu Okatani and Isao Shimoyama  
*The University of Tokyo, JAPAN*

In this paper, we propose a method to evaluate slipperiness of a place where a foot of a legged robot collides. This method will enable the robot to prevent a slip even if the slipperiness is unexpected, whereas conventional robots have no choice but to presume the slipperiness. We show a MEMS local slip sensor is applicable to not only static situations but also dynamic situations like collision. We tested the sensor by dropping it vertically against three types of surfaces which varied in slipperiness. The results show the three surfaces can be distinguished during the collision by monitoring the sensor response.

**W-153 MONOLITHIC/VERTICAL INTEGRATION OF PIEZO-RESISTIVE TACTILE SENSOR AND INDUCTIVE PROXIMITY SENSOR USING CMOS-MEMS TECHNOLOGY ..... 826**

Jia-Horng Lee, Sheng-Kai Yeh, and Weileun Fang  
*National Tsing Hua University, TAIWAN*

This study demonstrates the monolithic/vertical integration of piezo-resistive tactile and inductive proximity sensing units using standard TSMC CMOS process (Fig.1). Before contact, the proximity sensing of object is achieved by inductance change of spiral coil; after contact, the tactile load from object is detected by resistance change of bent piezo-resistors (Fig.1b). The proposed sensor design to offer the proximity/tactile sensing capabilities has four merits: (1) tactile and proximity sensing units can be vertically implemented and integrated on one chip, (2) no interference between two sensing mechanisms to enable sensing units working independently, (3) simultaneous detection for proximity/tactile is achieved to enable continuous object monitoring before/after contact, (4) footprint reduction of sensing chip due to vertical-integrated design. Measurements indicate the sensitivity of tactile unit is 0.73mV/N (loading range: 0-2N), sensing distance of proximity unit is 2.5mm for stainless steel object, and simultaneous/continuous detection for tactile and proximity are also demonstrated.

**M-154 FLEXIBLE PRESSURE SENSOR BASED ON POROUS DIELECTRIC ELASTOMER CONTAINING CONDUCTIVE FILLER ..... 830**

Jungrak Choi<sup>1</sup>, Kyuyoung Kim<sup>1</sup>, Yongsuk Oh<sup>2</sup>, and Inkyu Park<sup>1</sup>  
<sup>1</sup>*Korea Advanced Institute of Science and Technology (KAIST), KOREA and*  
<sup>2</sup>*Northwestern University, USA*

In this work, we report a highly sensitive and flexible capacitive pressure sensor based on a porous dielectric matrix containing multi-walled carbon nanotubes (MWNTs) as conductive fillers. Porous dielectric matrix containing conductive fillers has a high resolution because the conductive fillers increase dielectric constant of the matrix and make big difference of dielectric constant between micro-pore in the matrix and matrix itself. This difference leads to a high sensitivity. Additionally the output signal of the pressure sensor shows little variation under different environment disturbances, such as dynamic pressure inputs, temperatures, and different air humidity levels. Furthermore, a robot-arm system, with the ability to move a soft material, is constructed to demonstrate the practical applications of the pressure sensor by using a pressure feedback control.

**T-155 FLIP-CHIP INTEGRATION OF INDUCTIVE CMOS TACTILE SENSOR WITH SI CAVITY FOR POLYMER-FILLER/METAL-BALL SENSING INTERFACE ..... 833**

Sheng-Kai Yeh and Weileun Fang  
*National Tsing Hua University, TAIWAN*

This study presents a flip-chip integrated CMOS chip with polymer-filler and metal-ball in backside Si cavity for inductive tactile sensor (Figs.1a-b). By using the polymer-filler and chrome-steel ball as force/sensing interface, the proposed inductive tactile sensor has several merits : (1) cavity on backside Si-substrate for polymer molding and chrome-steel ball housing, (2) dual-stage polymer molding to define polymer-spring and to fix the chrome-steel ball, (3) flip-chip bonding to replace the wire bonding for the electrical connection, and (4) sensing-chip backside loading design for flip-chip bonding. The presented design is implemented using the standard TSMC 0.35µm 2P4M CMOS process and in-house post-CMOS processes. Measurements indicate the sensitivity of tactile sensor is 3.2nH/N within loading range of 0-2N, and the monolithically integrated thermometer with TCR of 0.1%/ °C is also demonstrated.

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**Other Physical Sensors**

**W-156 ENERGY TRANSFER CONTROL OF MODE COOLING INDUCED BY CAPACITIVE NONLINEAR COUPLING IN MEMS RESONATOR ..... 837**

Tongqiao Miao, Xin Zhou, Fenlan Ou, Kuo Lu, Yongmeng Zhang, Xuezhong Wu, and Dingbang Xiao  
*National University of Defense Technology, CHINA*

This paper reports a novel method of the mode cooling by the capacitive nonlinear coupling in MEMS resonators. Through the anti-Stokes sideband by activating the parametric pump, the phonon manipulation can be realized by the capacitive nonlinear coupling in the typical MEMS torsional resonator. It is demonstrated that the energy transfer of MEMS harmonic oscillators can be easily controlled by the mode cooling. Also, it is found that the  $A-f$  effect of nonlinear vibration can be influenced by the mode cooling, which provides a new method of controlling nonlinear vibration in MEMS resonators. Moreover, it is found that the ratio of quality factors between two modes ( $Q_2/Q_1$ ) has a huge impact on the strength and the smoothness of the cooling effect, which provides a novel method of reducing the high voltage used to produce the strong coupling effect and increasing the cooling smoothness by optimizing the mechanical design.

**M-157 LOW-COST MICRO PREDICTIVE MEAN VOTE (PMV) SENSOR AND ITS APPLICATION FOR SMART PERSONAL VENTILATION SYSTEMS ..... 841**

Izhar<sup>1</sup>, Wei Xu<sup>1,2</sup>, Xiaoyi Wang<sup>1</sup>, Ruijie Wang<sup>1</sup>, and Yi-Kuen Lee<sup>1</sup>  
<sup>1</sup>*Hong Kong University of Science and Technology, HONG KONG and*  
<sup>2</sup>*Shenzhen University, CHINA*

We report a low-cost micro Predictive Mean Vote (PMV) sensor system for human thermal comfort with the improvement of measurement accuracy. The PMV sensor system consists of a Thermoresistive Micro Calorimetric Flow (TMCF) sensor, commercial temperature/relative humidity (RH) sensors and an MCU which can implement the PMV calculation based on ASHRAE Standard 55. Thanks to the excellent resolution (6 mm/s) and high accuracy ( $\pm 27$  mm/s) of the integrated TMCF sensor, the experimental results indicate that the accuracy of our PMV sensor ( $\pm 0.03$ ) is better than that of the commercial PMV meter ( $\pm 0.04$ ). Furthermore, a smart personal ventilation system (sPVS) is developed by using our proposed PMV sensor and a PID controlled cooling fan. By regulating the local airflow velocity, it is clear that our sPVS can provide both optimized thermal comfort and energy saving.

**T-158 MEASUREMENT OF FRICTION FORCE BETWEEN DIRECTLY INTEGRATED CARBON NANOTUBE BUNDLES IN TIP-TO-TIP CONTACT USING MEMS TRIBOMETER PLATFORM ..... 845**

Wondo Kim<sup>1</sup>, Eunhwan Jo<sup>1</sup>, Jae-Ik Lee<sup>2</sup>, and Jongbaeg Kim<sup>1</sup>  
<sup>1</sup>*Yonsei University, KOREA and*  
<sup>2</sup>*Massachusetts General Hospital, Harvard Medical School, USA*

In this paper, by using MEMS tribometer platform, we measured static and dynamic friction force between carbon nanotube (CNT) bundles in tip-to-tip contact. The MEMS tribometer platform consists of two shuttles which can have tangential motion relative to the reference shuttle and two comb-drive actuators that can apply normal and tangential force, respectively. Vertically aligned and self-adjusted CNT bundles were directly grown on a designated location in MEMS tribometer platform forming a uniform contact area. By gradually increasing tangential force while observing displacement of each shuttle, we were able to differentiate between static and dynamic friction regime and calculate corresponding friction forces.

**W-159 A MICRO RESONANT DC ELECTRIC FIELD SENSOR BASED ON MODE LOCALIZATION PHENOMENON ..... 849**

Zimu Yan, Jiaju Liang, Yongcun Hao and Honglong Chang  
*Northwestern Polytechnical University, CHINA*

This paper for the first time reports a resonant DC electric field sensor (EFS) based on the mode localization phenomenon. The sensor uses a 3-degrees-of-freedom (DoF) weakly coupled resonator (WCR) as the mechanical sensing element, with comb capacitors on both sides for converting electric field to stiffness perturbation. The perturbation causes a drastic change in the mode shape owing to the mode localization phenomenon. Then we use the amplitude ratio (AR) instead of the frequency as the readout metric, and the sensitivity based on the AR is 1720 times higher than that based on the frequency. Just under the open-loop test, the resolution of the sensor reaches  $20.4\text{V/m}\sqrt{\text{Hz}}$  in the range of 7 kV.

- M-160 WEARABLE SOFT MICROFLUIDIC PRESSURE SENSOR USING 3D-PRINTED MOLD FOR HEALTH MONITORING ..... 853**  
 Kyuyoung Kim<sup>1</sup>, Jungrak Choi<sup>1</sup>, Yongrok Jeong<sup>1</sup>, Minseong Kim<sup>1</sup>, Jaeho Park<sup>1</sup>, Yongsuk Oh<sup>2</sup>, and Inkyu Park<sup>1</sup>  
<sup>1</sup>*Korea Advanced Institute of Science and Technology (KAIST), KOREA and*  
<sup>2</sup>*Northwestern University, USA*

In this research, we introduce a wearable soft microfluidic pressure sensor using 3D-printed microbumps and liquid metal and its potential applications in health monitoring. Our pressure sensor fabricated with elastomer and liquid metal which provide stretchability has an enhanced sensitivity (0.3 kPa<sup>-1</sup>@100kPa) compared to other reported microfluidic pressure sensors [1] and a good recovery characteristic in pressure range to 100 kPa. It has an enough sensitivity to be applied in pressure monitoring applications. Blood pressure could be estimated through monitoring pulse rate and electrocardiogram (ECG) data simultaneously. Also, human body pressure distribution was monitored using multiple pressure sensors attached on the clothes when lying on the bed. Biosignals and human body pressure data achieved through the proposed pressure sensor would be applied to early diagnosis and prevention of diseases such as diabetes and bedsores.

- T-161 A MICRO AEROSOL SENSOR FOR PM1 CONCENTRATION DETECTION BASED ON 3D PRINTED VIRTUAL IMPACTOR AND SAW SENSOR ..... 856**  
 Yong Wang, Yinshen Wang, Weixin Liu, Dongyang Chen, Yangyang Guan, Changju Wu, and Jin Xie  
*Zhejiang University, CHINA*

This paper reports a micro aerosol sensor for PM1 concentration detection based on three-dimensional (3D) printing virtual impactor (VI) and surface acoustic wave (SAW) sensor. The VI structure has been optimized by computational fluid dynamics (CFD) simulation to realize flow distribution for classifying particles. And when the air flow distribution ratio between the major flow and minor flow is 9:1, the VI presents a good classification performance. The performance of the aerosol sensor is characterized through classification and detection of silicon oxide particles with diameter ranging from 0.1 to 4µm. The results show that particles smaller than 1 µm are successfully classified by the VI and the resonant frequency of the SAW sensor decreases linearly with the particles mass increment.

**MEMS for Electromagnetics**  
**Materials and Manufacturing for Electromagnetic Transducers**

- W-162 NIR AND MIR ABSORPTION OF ULTRA-BLACK SILICON (UBS). APPLICATION TO HIGH EMISSIVITY, ALL-SILICON, LIGHT SOURCE ..... 860**  
 Sreyash Sarkar<sup>1</sup>, Ahmed A. Elsayed<sup>1,2</sup>, Elyes Nefzaoui<sup>1</sup>, Jérémie Drévilion<sup>3</sup>, Philippe Basset<sup>1</sup>, Frédéric Marty<sup>1</sup>, Momen Anwar<sup>2</sup>, Yiting Yu<sup>4</sup>, Jiancun Zhao<sup>4</sup>, Xichen Yuan<sup>4</sup>, ZhongZhu Liang<sup>5</sup>, Diaa Khalil<sup>2,6</sup>, Yasser M. Sabry<sup>2,6</sup>, and Tarik Bourouina<sup>1,6</sup>  
<sup>1</sup>*Université Paris-Est, FRANCE,*  
<sup>2</sup>*Ain Shams University, EGYPT,*  
<sup>3</sup>*Université de Poitiers, FRANCE,*  
<sup>4</sup>*Northwestern Polytechnical University, CHINA,*  
<sup>5</sup>*Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, CHINA, and*  
<sup>6</sup>*Si-Ware Systems, EGYPT*

We present the Near-Infra-Red (NIR) and Mid-Infrared (MIR) absorption properties of Ultra-Black Silicon obtained by wafer-level cryogenic plasma processing. We found that when using highly-doped silicon, the spectral range of near-unity full absorption of light is extended from the visible range till a wavelength of 10 µm. This MIR wavelength range coincides with that of the maximum of black-body radiation from room temperature up to a few thousand Kelvin. Therefore, according to Kirchhoff's Law, we take advantage of the enhanced properties of black silicon to realize ultra-compact light-sources of high efficiency, which are operated in combination with a MEMS-FTIR spectrometer.

**M-163 FABRICATION OF A TUNABLE CAPACITOR WITH A NON-PLANAR PLATE BY USING TITANIUM AND POLYIMIDE AS SACRIFICIAL LAYERS ..... 863**

Huiliang Liu<sup>1</sup>, Xin Guo<sup>2</sup>, Zheng You<sup>1</sup>, and Zewen Liu<sup>2</sup>  
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<sup>2</sup>*Tsinghua University, CHINA*

This work marks the first use of titanium (Ti) and polyimide (PI) sacrificial layers to realize the fabrication of the non-planar plate for a MEMS variable capacitor. Compared with the state-of-art technology, three distinctive advances have been achieved: (a) first demonstration of Ti and PI sacrificial layers to realize a 300 nm-thick gap between source electrodes and 3 μm-thick gap between drive electrodes for the non-planar plate with a single electroplating process; (b) a controllable Ti etching process with HF-free solution; and (c) a MEMS variable capacitor with a stable tuning ratio greater than 10 by the non-planar top plate and weight-balanced structure.

**RF MEMS Components & Systems**

**T-164 X-CUT LITHIUM NIOBATE SERIES-PARALLEL RESONATOR CONFIGURATION BOOSTS PASSIVE VOLTAGE AMPLIFICATION FOR WAKE-UP RECEIVERS TO 46 V/V ..... 867**

Luca Colombo, Abhay Kochhar, Gabriel Vidal-Álvarez, and Gianluca Piazza  
*Carnegie Mellon University, USA*

This work reports on the use of X-cut Lithium Niobate (LN) microelectromechanical resonators in a series-parallel configuration (L-network) to boost passive voltage amplification in asynchronous Wake-Up Radio Receivers (WuRx) to 46 V/V – the highest passive voltage gain ever attained for WuRx with large capacitive input impedance ( $C_{load}$ ) –. We harness the quality factor ( $Q_s > 4000$  at 50 MHz) and electromechanical coupling ( $k_t^2 > 30\%$ ) of X-cut LN resonators and configure them in a series-parallel network to provide passive voltage amplification when driving a capacitive load (e.g. the input impedance of an envelope detector). The use of this L-network is disruptive over the conventional use of a single series resonator and provides more than 30% gain improvement. The proposed technique requires two identical resonators and is robust against frequency variations. Finally, it requires the use of smaller resonators for a given capacitive load, making it further immune to gain variations experienced when using large parallel arrays of resonators.

**W-165 HIGHLY LINEAR MAGNETIC-FREE ISOLATOR BASED ON A TIME-MODULATED DIFFERENTIAL RF MEMS LATTICE FILTER ..... 871**

Piotr Kulik, Yao Yu, Guofeng Chen, and Matteo Rinaldi  
*Northeastern University, USA*

This paper experimentally demonstrates the first time varying magnetic-free RF MEMS isolator. For the first time, magnetic-free non-reciprocity is achieved by periodic modulation of an individual differential Aluminum Nitride (AlN) thin-film bulk acoustic resonator (FBAR) based lattice filter. The fabricated FBAR lattice filter is used as an ultra- compact and low-loss frequency selective delay network and it is periodically modulated by RF switches. By taking advantage of the differential nature of the designed lattice architecture, only one MEMS filter is required to achieve non-reciprocity, significantly reducing the system complexity. Due to the high figure of merit (FoM) of the FBARs, large group delay (30 ns) is achieved with low insertion loss (IL) leading to the demonstration of a miniaturized RF isolator characterized simultaneously by low IL (5.8 dB), strong isolation ( $IX > 20$  dB), broad bandwidth (20 dB isolation bandwidth ~20 MHz), and with an ultra-low modulation frequency (4.5 MHz). This modulation frequency is significantly lower compared to conventional magnetic-free non-reciprocal networks based on transmission lines and lumped elements. Furthermore, such a low modulation frequency allows the use of GaAs SPDT RF switches with large power handling performances, resulting in an isolator with the highest power handling performance and highest linearity (P1dB=27.8 dBm; IIP3=51 dBm) ever demonstrated among time-modulated magnetic-free non-reciprocal networks.

**M-166 A 1.65 GHz LITHIUM NIOBATE A1 RESONATOR WITH ELECTROMECHANICAL COUPLING OF 11.4% AND Q OF 3112 ..... 875**  
 Yansong Yang, Ruochen Lu, and Songbin Gong  
*University of Illinois, Urbana-Champaign, USA*

This paper reports on the demonstration of a 1.65 GHz A1 mode lithium niobate resonator with a high electro-mechanical coupling ( $k_t^2$ ) of 14%, a high-quality factor (Q) of 3112, and a near spurious-free response. The 1.65 GHz resonance has been achieved by exploiting the high phase velocity of the first-order antisymmetric (A1) Lamb wave mode in a Y-cut lithium niobate (LiNbO<sub>3</sub>) thin film, while spurious mode suppression is accomplished with electrode optimization. The performance demonstrated herein marks the first time that a new resonator technology outperforms surface acoustic wave (SAW) resonators and thin-film bulk acoustic resonators (FBARs) regarding the figure of merit (FoM) in the 1-6 GHz frequency range. Thus, the A1 mode lithium niobate resonator in this work promises a new platform for the fifth-generation (5G) front-end filtering.

**T-167 AlN PIEZOELECTRIC NANO-ELECTROMECHANICAL ISOLATOR VIA PARAMETRIC FREQUENCY CONVERSION AND AMPLIFICATION..... 879**  
 Jaesung Lee<sup>1</sup>, Matthew H. Matheny<sup>2</sup>, Michael L. Roukes<sup>2</sup>, and Philip X.-L. Feng<sup>1</sup>  
<sup>1</sup>Case Western Reserve University, USA and  
<sup>2</sup>California Institute of Technology, USA

We report on a novel aluminum nitride (AlN) resonant nanoelectromechanical systems (NEMS) approach to realizing an electrically tunable nonreciprocal isolator by exploiting nonlinear parametric frequency conversion and efficient mechanical amplification in a radio-frequency (RF) AlN membrane NEMS resonator. The isolator is constructed by combining frequency conversion enabled by the NEMS resonator's strong parametric effect, and tandem band-pass filtering, so that the signal can be transmitted or blocked according to its propagation direction and frequency. In the band of the isolator that is set by the NEMS resonance, it exhibits up to ~60dB signal isolation between measured  $S_{21}$  and  $S_{12}$  transmission. Further, the isolation band frequency and width can be tuned via a dc polarization voltage.

**W-168 BOOSTING QS OF ALN RESONATORS BY REDEFINING ACOUSTIC BOUNDARIES ..... 883**  
 Anming Gao<sup>1</sup>, Martin Winterkorn<sup>2</sup>, Yansong Yang<sup>1</sup>, Ruochen Lu<sup>1</sup>, J. Provine<sup>2</sup>, and Songbin Gong<sup>1</sup>  
<sup>1</sup>University of Illinois, Urbana-Champaign, USA and  
<sup>2</sup>Stanford University, USA

This paper reports on a quality factor (Q)-boosting technique for aluminum nitride (AlN) Lamb wave resonators by lithographically defining their acoustic boundaries. The technique has been demonstrated to enhance resonator Q from 980 to 3000 without compromising the electromechanical coupling ( $k_t^2=1.75\%$ ), consequently resulting in a high figure of merit of 52.25 (FoM= $k_t^2 \cdot Q$ ). Our approach derives from our quantitative analysis of the reflection coefficient at the acoustic boundaries of a conventional Lamb wave AlN resonator, which suggests inadequate energy confinement from a reflection coefficient of only 0.47. A two-prong approach, which involves first defining the release regions lithographically and then adding a Pt layer regionally over the anchors, is adopted to create a more significant impedance mismatch at the acoustic boundaries and reduce energy leakage to the surrounding.

**M-169 A CHIP-SCALE RF MEMS GYRATOR VIA HYBRIDIZING LORENTZ-FORCE AND PIEZOELECTRIC TRANSDUCTIONS ..... 887**  
 Tao Wu<sup>1</sup>, Ruochen Lu<sup>2</sup>, Anming Gao<sup>2</sup>, Cheng Tu<sup>3</sup>, Tomás Manzaneque<sup>4</sup>, and Songbin Gong<sup>2</sup>  
<sup>1</sup>ShanghaiTech University, CHINA,  
<sup>2</sup>University of Illinois, Urbana-Champaign, USA,  
<sup>3</sup>Northeastern University, USA, and  
<sup>4</sup>Delft University of Technology, NETHERLANDS

This paper presents the design and experimental results of the first chip-scale radio frequency MEMS gyrator based on hybridizing Lorentz-force and piezoelectric transduction. The MEMS gyrator has a non-reciprocal phase response of 180° and can be used as the building blocks for synthesizing complex non-reciprocal networks. The equivalent circuit and measured performance of a fabricated MEMS gyrator are presented, both showing the anticipated 180° phase difference. The demonstration marks the first time that non-reciprocity is attained at radio frequencies with an entirely passive chip-scale mechanical device. Various challenges in achieving strong coupling and low insertion loss for the designed devices will be discussed.



**T-170 RF MEMS THERMISTOR POWER SENSOR BASED ON WHEATSTONE FULL-BRIDGE STRUCTURE..... 891**  
 Chenlei Chu, Xiaoping Liao, Hao Yan, and Zhenxiang Yi  
*Southeast University, CHINA*

In this paper, we have first proposed a RF MEMS thermistor power sensor based on Wheatstone full-bridge structure. The proposed RF MEMS thermistor power sensor is fabricated using GaAs MMIC (monolithic microwave integrated circuit) technology. In this device, two parallel low TCR (temperature coefficient of resistance) heaters are employed to keep the impedance match stable. And a Wheatstone full-bridge formed by four identical thermistors is used for the unknown RF power measurement. To improve the sensitivity of the sensor, a MEMS substrate membrane is fabricated beneath the hot area to suppress longitudinal heat loss by back etching process. The whole structure is integrated with CPW transmission line, which has the potential of high integration density. Compared with traditional thermistor power sensor, this device has both advantages of stable impedance match and high sensitivity.

**MEMS for Timing & Frequency Control**

**W-171 A MONOLITHIC FBAR OSCILLATOR BASED ON HETEROGENEOUS SYSTEM-ON-CHIP INTEGRATION ..... 895**  
 Chuanhai Gao, Menglun Zhang, Yuan Jiang, Buohua Liu, and Wei Pang  
*Tianjin University, CHINA*

We demonstrate a heterogeneous system-on-chip (SoC) integration strategy for a 2-GHz FBAR-based oscillator. The CMOS IC and above-IC film bulk acoustic resonator (FBAR) were fabricated on their respective silicon substrates, and then the FBAR thin-film structure was transferred on the top of IC chip, followed by short on-chip metal connections. An SU-8 thin film structure serves as an adhesive layer and provides an air cavity for the FBAR. This heterogeneous SoC integration strategy endows the chip with minimized space occupation and short interconnections, providing potential high electrical performance and eliminating process incompatibilities (e.g. high temperature deposition or bonding) in otherwise integration strategies.

**M-172 INTERFACE CIRCUIT DESIGN TO ENABLE MINIATURIZATION OF CMOS-MEMS THERMAL-PIEZORESISTIVE OSCILLATORS FOR MASS SENSING APPLICATIONS..... 899**  
 Chiao-An Sung, Ting-Yuan Liu, Anurag A. Zope, Ming-Huang Li, and Sheng-Shian Li  
*National Tsing Hua University, TAIWAN*

This work focuses on the integrated circuit design for CMOS-MEMS-based thermal-piezoresistive oscillators (TPOs). Conventional TPOs necessitate bulky discrete circuit components, which impedes integration and miniaturization of the microsystems. The proposed circuit implemented using TSMC 0.18  $\mu\text{m}$  CMOS technology serves as sustaining amplifier and biasing circuit for our previously developed CMOS-MEMS thermal- piezoresistive resonators (TPRs), thus achieving TPOs with small form factor, targeted for mass/particle sensing applications. The previous version using commercial PCB electronics consumes 2.73 W while the proposed design greatly reduces the power consumption down to 15 mW. In addition, no harmonics have been found in oscillator output power spectrum while reaching 0 dBm (i.e., 1 mW). The far-from-carrier phase noise is demonstrated with -73.85 dBc/Hz and -80.06 dBc/Hz at 1 kHz and 100 kHz offsets respectively at a carrier frequency of 814.49 kHz in ambient pressure; as a result it is suitable for sensor applications. The miniaturized CMOS-MEMS TPO system features a frequency resolution of 65.9 Hz, thus corresponding to a mass resolution of 33.9 pg, which would potentially serve as aerosol ( $\text{PM}_{2.5}$ ) sensors.

**T-173 A FULLY-DIFFERENTIAL CMOS-MEMS DETF RESONATOR DESIGN WITH EXTENDED MASS AND ELECTRODES TO ENABLE HIGH POWER HANDLING ..... 903**  
 Jhe-Ru Guo, Anurag A. Zope, Chao-Yu Chen, Ming-Huang Li, Mei-Feng Lai, and Sheng-Shian Li  
*National Tsing Hua University, TAIWAN*

We propose a novel differential drive and sense double-ended tuning fork (DETF) with wing electrodes to reduce the motional resistance ( $R_m$ ) while achieving excellent power handling. The devices are fabricated using back end of line (BEOL) materials of 0.18 $\mu\text{m}$  1P6M CMOS process. The wing electrodes are added to the high-velocity region to achieve high transduction efficiency. This increases the device mass ( $m$ ), which requires increased stiffness ( $k$ ) to maintain the same resonance frequency. The proposed design has resonance at 1 MHz in vacuum under a dc bias ( $V_p$ ) of 30V with  $R_m$  of 250 k $\Omega$  for a Q of 2,300. The device can sustain the input power of 438 nW delivered to the resonator, corresponding to -5 dBm of the drive power from the network analyzer (NA), which is around 2000X higher as compared to traditional capacitive MEMS resonator design.

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**W-174 ACTIVE BOOST IN THE QUALITY FACTOR OF AN ALN MEMS RESONATOR UP TO 165,000..... 907**

Changting Xu<sup>1</sup> and Gianluca Piazza<sup>2</sup>  
<sup>1</sup>Qualcomm Technologies, Inc., USA and  
<sup>2</sup>Carnegie Mellon University, USA

This work reports a method to boost the quality factor ( $Q$ , defined as the ratio of the resonant frequency to the 3-dB bandwidth) of a 55 MHz AlN MEMS contour-mode resonator (CMR) from  $\sim 1,000$  to  $>165,000$ . The resulting resonator exhibits an  $f$ - $Q$  product of  $8.8 \times 10^{12}$  Hz, comparable to quartz crystals ( $\sim 3 \times 10^{13}$  Hz). This significant progress is accomplished by pumping energy into the resonator through an externally applied force that has a specific phase relationship with respect to the driving voltage source. This method overcomes the fundamental limit of AlN  $f$ - $Q$  product using a finite amount of external power. We further validated this concept and showed more than 12 dB improvement in phase noise of an oscillator built using the  $Q$ -boosted resonator. Comparing with other active  $Q$ -boosting methods, this technique has the advantage that it intrinsically avoids self-oscillations. We demonstrated an interesting approach to improve the performance of AlN CMRs for timing applications.

**M-175 POWER-EFFICIENT OVENIZED LITHIUM NIOBATE SHO RESONATOR ARRAYS WITH PASSIVE TEMPERATURE COMPENSATION.....911**

Ming-Huang Li<sup>1</sup>, Chao-Yu Chen<sup>2</sup>, Ruochen Lu<sup>1</sup>, Yansong Yang<sup>1</sup>, Tao Wu<sup>3</sup>, and Songbin Gong<sup>1</sup>  
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<sup>2</sup>National Tsing Hua University, TAIWAN, and  
<sup>3</sup>ShanghaiTech University, CHINA

In this work, we demonstrate, for the first time, a micro-oven-integrated 170 MHz microelectromechanical systems (MEMS) resonator array implemented in a  $36^\circ$ -rotated-Y-Cut lithium niobate on silicon oxide (LN-OX) platform using the fundamental shear horizontal (SH0) mode. The array not only attains a high heating efficiency of 33 K/mW but also exhibits a promising electromechanical coupling coefficient ( $k_t^2$ ) of 9.6%, a quality factor ( $Q$ ) of 1360, a resulting figure of merit ( $\text{FoM} = k_t^2 \cdot Q$ ) of 130, and a passively-compensated temperature coefficient of frequency (TCF) of 13.8 ppm/K. The design of the individual resonator in the array, namely a weighted 3-electrode resonator with embedded heaters on the suspended busbars, is the key to achieving the high heating efficiency while mitigating spurious modes across a wide frequency span (100–300 MHz).

**T-176 A REFLECTION-TYPE VAPOR CELL FOR MICRO ATOMIC CLOCK.....915**

Hitoshi Nishino<sup>1</sup>, Masaya Toda<sup>1</sup>, Yoshiaki Kanamori<sup>1</sup>, Yuichiro Yano<sup>2</sup>, Masatoshi Kajita<sup>2</sup>, Tetsuya Ido<sup>2</sup>, Motoaki Hara<sup>2</sup>, and Takahito Ono<sup>1</sup>  
<sup>1</sup>Tohoku University, JAPAN and  
<sup>2</sup>National Institute of Information and Communications Technology, JAPAN

This paper reports the design, fabrication and evaluation of a reflection-type Rb vapor cell with a Glass/Si/Glass structure for chip-scale micro atomic clocks. To miniaturize the cell and obtain a Rb resonance signal with a high sensitivity, long laser light traveling pass on the horizontal plane is required in the vapor cell. The horizontal Rb vapor cell with integrated mirrors are proposed and developed. A (100)-oriented Si wafer with cut off  $9.74^\circ$  toward [011] direction was used to make  $45^\circ$  mirrors by using anisotropic wet etching. Also,  $90^\circ$  mirrors were fabricated by Si deep RIE (Reactive Ion Etching) and  $\text{H}_2$  annealing. Absorption line of Rb was confirmed and CPT (Coherent Population Trapping) resonance was demonstrated in the fabricated devices.

**Photonic Components & Systems**

**W-177 LOW-LOSS MEMS PHASE SHIFTER FOR LARGE SCALE RECONFIGURABLE SILICON PHOTONICS.....919**

Pierre Edinger, Carlos Errando-Herranz, and Kristinn B. Gylfason  
 KTH Royal Institute of Technology, SWEDEN

We experimentally demonstrate a silicon MEMS phase shifter achieving more than  $\pi$  phase shift with sub-dB insertion loss (IL). The phase is tuned by reducing the gap between a static suspended waveguide and a free silicon beam, via comb-drive actuation. Our device reaches  $1.2\pi$  phase shift at only 20 V, with only 0.3 dB insertion loss – an order of magnitude improvement over previously reported MEMS devices. The device has a small footprint of  $50 \times 70 \mu\text{m}^2$  and its power consumption is 5 orders of magnitude lower than that of traditional thermal phase shifters. Our new phase shifter is a fundamental building block of the next-generation large scale reconfigurable photonic circuits which will find applications in datacenter interconnects, artificial intelligence (AI), and quantum computing.

**M-178 DUAL MODE MID-INFRARED CHEMICAL SENSOR USING BRAGG WAVELENGTH IN SUBWAVELENGTH GRATING INCORPORATED BROADBAND DIRECTIONAL COUPLER..... 922**

Bowei Dong<sup>1,2,3</sup>, Ting Hu<sup>2</sup>, Yuhua Chang<sup>1,3</sup>, Dim-Lee Kwong<sup>2</sup>, and Chengkuo Lee<sup>1,3</sup>

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In this paper, we present a broadband directional coupler (DC) based dual mode chemical sensor for the mid-infrared (MIR). For the first time, we propose chemical sensing based on refractive index (RI) change in a compact DC by incorporating a subwavelength grating (SWG) structure into conventional DC that introduces a sharp Bragg wavelength. Meanwhile, the SWG structure can also engineer the dispersion in the DC to achieve broadband operation so that the device can operate in a wide wavelength range that benefits spectrum analysis in the MIR. Fivefold enhancement in the operation bandwidth compared to conventional DCs has been achieved for 100% coupling efficiency experimentally. The sensing capability of the device for dichloromethane (CH<sub>2</sub>Cl<sub>2</sub>) detection in ethanol (C<sub>2</sub>H<sub>5</sub>OH) is investigated by simulation. A sensitivity of -0.47% self-normalized transmitted power change per percentage of CH<sub>2</sub>Cl<sub>2</sub> concentration is revealed in the RI sensing mode while 0.12% change in the total integrated output power is realized in the absorption sensing mode.

**T-179 A COMPACT MEMS-BASED INFRARED SPECTROMETER FOR MULTI-GASES MEASUREMENT..... 926**

Shaoda Zhang<sup>1,2</sup>, Wu Bin<sup>3</sup>, Xingyu Zheng<sup>3</sup>, Haisheng San<sup>1,2</sup>, and Werner Hofmann<sup>1</sup>

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A microspectrometer based on a middle-infrared (Mid-IR) linear variable optical filters (LVOF) and a MEMS-based infrared thermopile detector array has been developed for multi-gases sensing in the indoor and industrial environments. The designs, fabrications, and characterizations of LVOF and thermopile detector are presented. Experimentally, the LVOF exhibits a mean FWHM of ~400 nm and mean peak transmittance of ~70% at the central wavelength of the operating spectrum of 2.5 ~ 5μm. The thermopile detectors used *p*- and *n*- polysilicon/Al metal as thermocouple materials, exhibiting a resistance temperature coefficient of 0.08 %/°C and a responsivity of 112 V/W. The LVOF can be regarded as a narrow-band filter array that is installed above the thermopile detector array to form a portable and inexpensive Mid-IR spectrometer for multi-gases sensing.

**W-180 ENGINEERING AND TUNING OF SLOW LIGHT IN MID-INFRARED SILICON-ON-INSULATOR PHOTONIC CRYSTAL WAVEGUIDES..... 930**

Yiming Ma<sup>1,2</sup>, Bowei Dong<sup>1</sup>, Bo Li<sup>1</sup>, and Chengkuo Lee<sup>1,2</sup>

<sup>1</sup>National University of Singapore, SINGAPORE and

<sup>2</sup>NUS Suzhou Research Institute (NUSRI), CHINA

We design, fabricate, and characterize slow light devices based on photonic crystal waveguides (PhCWs) in the mid-infrared wavelength range of 3.9-3.98 μm. Lattice shifting and thermo-optic tuning methods are employed to manipulate the slow light region for potential spectroscopy sensing applications. Up to 20 nm wavelength shift of the slow light band edge is demonstrated. Normalized delay-bandwidth products as high as 0.084-0.112 are obtained thanks to dispersion engineering. The slow light enhancement effect of thermo-optic tuning efficiency is verified by the proportional relationship between the phase shift and the group index. This work serves as a proof-of-concept that slow light effect can strengthen light-matter interaction and thereby improve device performance in sensing and nonlinearity applications.

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**Free Space Optical Components & Systems (Displays, Lenses, Detectors)**

**M-181 DIVERSIFIED AND PRECISE PLASMONIC COLOR TUNING BY THREE-DIMENSIONAL AIR-GAP NANOCAVITIES ..... 934**

Yun Huang<sup>1</sup>, Jia Zhu<sup>1</sup>, Zhuojie Chen<sup>1</sup>, Xiaoyu Chen<sup>1</sup>, Tian Kang<sup>1</sup>, Guanzhou Lin<sup>1,2</sup>, Rui Zhu<sup>1</sup>, Wengang Wu<sup>1</sup>, and Peimin Lu<sup>2</sup>  
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<sup>2</sup>*Fuzhou University, CHINA*

We report a new arrayed three-dimensional (3D) air-gap nanocavities with multiple tunable geometrical parameters. Light is tightly confined into the nanocavities and strong surface-plasmon coupling is introduced, realizing narrow band resonance. Vivid plasmonic colors are generated, and can be tuned by multiple geometrical parameters of the 3D nanocavities, including shapes, separations, and heights. What's more, the surface-plasmon coupling resonance has different dependence on different variable geometrical parameters. So, multi-dimensional color tuning with different spectral sensitivities is realized by proper and precise structural design, leading to both broad gamut and sophisticated plasmonic color printing at the optical diffraction limit.

**T-182 ULTRA-FAST AND COMPACT VARIFOCAL LENS ..... 938**

Matthias C Wapler and Ulrike Wallrabe  
*University of Freiburg, GERMANY*

We present the, to our knowledge, so far fastest deformable lens, with a response time of 100 to 200 μs and a clear aperture of 7.6 mm at 9 mm outer diameter (84%). This is achieved using transparent compliant elastomer structures with an index-matched optical fluid and an actuator covering just 11% of the diameter that we bond in a two-stage gluing process using a gas phase curing agent.

**W-183 ULTRATHIN COMPOUND EYE CAMERA FOR SUPER-RESOLUTION FAR-FIELD IMAGING USING LIGHT ABSORBING MULTIPLE LAYERS ..... 942**

Kisoo Kim, Kyung-Won Jang, and Ki-Hun Jeong  
*Korea Advanced Institute of Science and Technology (KAIST), KOREA*

This work reports an ultrathin compound eye camera with monolithic light absorbing layers for super-resolution far field imaging. The structure of our camera system features microlens arrays (MLA) formed an inverted direction, multiple block layers (MBL) to block optical crosstalk around the lenses, spacers and a CMOS image sensor array (ISA). Also, the monolithic MBL structure were used to reduce the total thickness of the lens with spacers to 740 μm and clear array images were obtained using the packaged camera. The modulation transfer function (MTF) 50% representing the quality of an image was improved by about 1.5 times using super-resolution far field imaging. This ultrathin compound eye camera can help in reducing the overall thickness of devices with embedded imaging components such as smartphones.

**MEMS Actuators & Power MEMS**

**Materials and Manufacturing for Actuators & Power MEMS**

**M-184 A NOVEL STRATEGY FOR LITHIUM-ION BATTERY ANODE WITH ENHANCED CYCLING PERFORMANCE: SILICON PARTICLES ENCLOSED IN SHELL-LIKE MXENES/CNTS NANOSTRUCTURE ..... 946**

Bingmeng Hu<sup>1,2</sup>, Xuanlin Kuang<sup>1,2</sup>, Sixing Xu<sup>1,2</sup>, and Xiaohong Wang<sup>1,2</sup>  
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<sup>2</sup>*Tsinghua National Laboratory for Information Science and Technology, CHINA*

We report a strategy for lithium-ion battery anode based on high-capacity silicon nanoparticles (SiNPs) encapsulated in modified shell-like Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> layers, which are one of the typical 2D transition metal carbides (MXenes), supported by the frame of carbon nanotubes (CNTs). The structure provides enough space for the volume expansion of the SiNPs during lithiation and delithiation, while the solid electrolyte interface (SEI) films form stably on the surface of the structure to prevent electrolyte consumption. Moreover, the intrinsically high electrical conductivity of MXenes and CNTs improves the electrode dynamics and provides conductive channels, which can greatly enhance the cycle performance of lithium-ion battery. This work has demonstrated that the MXenes/CNTs/SiNPs nanostructure with extraordinary conductivity, stability and adaptability can be used in anodes for the first time, and a high specific recyclability of 591.56 mAh g<sup>-1</sup> after 30 cycles has been achieved in the half cell test.

- T-185 STAMP-ASSISTED GRAVURE PRINTING OF MICRO-SUPERCAPACITORS WITH GENERAL FLEXIBLE SUBSTRATES ..... 950**  
 Haobin Wang, Yu Song, Liming Miao, Ji Wan, Xuexian Chen, Xiaoliang Cheng, Hang Guo, and Haixia Zhang  
*Peking University, CHINA*

In this paper, we present a scalable and general fabrication for micro-supercapacitors (MSCs) among various flexible substrates assisted by the stamp, which combines the conductive polymer composites with gravure printing process. Compared with the traditional transferring techniques, this method greatly simplifies the process and mitigates the mechanical damage during the preparation. Profiting from the composites of carbon nanotubes (CNTs) and polydimethylsiloxane (PDMS) as the printing inks, the MSCs exhibit elegant areal capacitance ( $10.491 \mu\text{F}/\text{cm}^2$ ) on the paper substrate. Meanwhile, optimizing the ratio of matrix and curing agent of PDMS, the interaction between ink and substrate is effectively enhanced. Therefore, such novel fabrication technology significantly improves the production efficiency as well as broadens the applications.

- W-186 3D PRINTED FLEXIBLE TRIBOELECTRIC ENERGY HARVESTERS VIA CONFORMAL COATING OF PARYLENE AF4 ..... 954**  
 Ilbey Karakurt, Junwen Zhong, and Liwei Lin  
*University of California, Berkeley, USA*

For the first time, a 3D-printed flexible and wearable triboelectric energy harvester (TEH) is presented based on the 3D printing of polymeric material, polyurethane (PU), and a post conformal coating process using Parylene AF<sub>4</sub>. The key advancements of this work include: (1) the usage of the stereolithographic (SL) 3D printing process for the prototype of a multiple-layer energy harvester to increase the active surface area; (2) the deposition of high surface charge density material, Parylene AF<sub>4</sub>, with a conformal coating process to act as the active layer. The experimental results for a prototype triple-layer device show a peak short circuit current (SCC) of 390nA and a peak power density of  $5.5\mu\text{W}/\text{cm}^2$ . As such, this work can potentially open up a new class of energy harvesters based on 3D printing technologies for arbitrary geometries for applications such as shoe soles.

- M-187 GOLD-DECORATED CARBON NANOTUBE NETWORK AS CONTACT SURFACE OF MEM SWITCH FOR EXTENDED LIFETIME..... 958**  
 Eunhwan Jo<sup>1</sup>, Yong-Bok Lee<sup>2</sup>, Jaeyong Lee<sup>1</sup>, Su-Bon Kim<sup>2</sup>, Wondo Kim<sup>1</sup>, Min-Ho Seo<sup>2</sup>, Jun-Bo Yoon<sup>2</sup>, and Jongbaeg Kim<sup>1</sup>  
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<sup>2</sup>*Korea Advanced Institute of Science and Technology (KAIST), KOREA*

This work demonstrates a highly reliable microelectromechanical (MEM) switch with high switching performance by integrating gold (Au)-decorated carbon nanotube (CNT) network in the contact area. By decorating the CNTs with Au nanoparticles (Au-NPs), we obtained several times extension in the lifetime of the MEM switch with low contact resistance. We verified that the extended lifetime and the low contact resistance originate from the deformable CNTs under mechanical load and the Au NPs with high conductivity at the contact-interface. Our switch also revealed low adhesion force at the contact-interface, which results in highly repeatable and stable actuation voltages at both turn-on and off, whereas typical MEM switches with high adhesion force show irreversible stiction or unstable turn-off voltage. The proposed switch exhibited 1.9 times longer lifetime under hot-switching conditions, compared to previously studied MEM switches based on Au-Au contact.

- T-188 HIGH WORK DENSITY GETE MECHANICAL PHASE CHANGE ACTUATOR ..... 962**  
 James Best and Gianluca Piazza  
*Carnegie Mellon University, USA*

This paper reports on the fabrication and testing of a new class of non-volatile MEMS actuator based on GeTe phase change material. The demonstrated actuator is capable of unidirectional strain up to 7%, which can be related to an intrinsic work density of  $\sim 200 \text{ J}/\text{cm}^3$ — one order of magnitude beyond any other semiconductor-based actuation material. GeTe is a phase change material that has been reported to exhibit a large volume change when switched between the amorphous (larger) and crystalline (smaller) states [1]-[4]. We confine these changes in a small geometry ideal for the making of micro/nanoscale vertical displacement actuators and toggle the GeTe states by thermal cycling the material using a tungsten heater. Both amorphous and crystalline states are stable at room temperature, making the actuator non-volatile. An average 14 nm thickness difference was measured between amorphous and crystalline states for a 200 nm thick GeTe actuator, ideal for example for closing/opening a contact in NEMS relays. More broadly, given the high work density of this material, we expect it to have a significant impact on micro/nanoscale actuators when arranged in other geometries.

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**W-189 FLEXIBLE AND SCALABLE BIOCHEMICAL ENERGY HARVESTING: A YARN-BASED BIOBATTERY ..... 966**

Yang Gao, Lin Liu, Jonghyun Cho, and Seokheun Choi  
*State University of New York-Binghamton, USA*

We demonstrated an innovative, flexible yarn-based biobattery that generates green electricity from bacterial respiration. The battery can be easily scaled up by controlling the length of the yarn of a single battery or connecting multiple yarns in series. Bacterial cells in the yarn break down the organic fuels (e.g. glucose and lactic acid) and transfer the produced electrons to the electrode, providing power for external applications. The yarn-based biobattery was knotted into a bracelet by connecting three battery units in series, generating the current density of 329.95 A/m<sup>3</sup>. Furthermore, this proposed biobattery can be woven or embroidered into a large smart fabric, potentially providing hundreds of milliamperes for powering actual wearable electronics.

**Actuator Components & Systems**

**M-190 MULTI KILOVOLT LITHIUM NIOBATE PYROELECTRIC CANTILEVER SWITCHED POWER SUPPLY ..... 970**

Di Ni, K. B. Vinayakumar, Visarute Pinrod, and Amit Lal  
*Cornell University, USA*

High voltage actuators used in micro-robotics can require several kilovolts for sufficient displacements. A high voltage electronics driving system is required for functional robotics so that it can be integrated within the microrobot with minimal impacts on robot size and weight. Here we report a proof-of-concept Pyroelectric High Voltage Generator (PHVG) combined with a cantilever electrostatic switch used in pull-in mode, which demonstrated actuations of a piezoelectric actuator. The use of an electrostatic switch with pyroelectric LiNbO<sub>3</sub> generator provides a pathway to generate high voltages from very small battery voltages and the capability to turn them on with small size and weight. We have demonstrated output voltages up to 1900V from PHVG in the ambient with a 15V input voltage at a temperature change of 2-3°C. The high-voltage generated is measured using the pull-in voltage of the cantilever switch. Scaling of the structure can lead to the development of low-SWAP high-voltage sources in the 10-20 kV range.

**T-191 FREQUENCY AGILE PMUT-BASED ULTRASONIC COMMUNICATION LINKS..... 974**

Bernard Herrera, Flavius Pop, Cristian Cassella, and Matteo Rinaldi  
*Northeastern University, USA*

The present work reports on the generation of distinct ultrasonic communication frequency bands by using a single Piezoelectric Micro-Machined Ultrasonic Transducer (PMUT) array. In contrast to the common use of these transducers within their resonance band, off-band operation is enabled through the use of specially designed broadband matching networks. By harnessing the capacitive nature of a fabricated PMUT array and its good matching with the medium, transmission improvements of up to 15 dB over 0.2 fractional bandwidths around 2 and 3 MHz center frequencies were achieved on a transducer resonating at 1.1 MHz. The resulting sharp roll-off and good off-band rejection for the acoustic channels are crucial features for the implementation of intra-body networks with multiple, simultaneously transmitting nodes with different bandwidth requirements (fig. 1).

**M-193 HETEROGENEOUS INTEGRATED MEMS INERTIAL SWITCH WITH ELECTROSTATIC LOCKING AND COMPLIANT CANTILEVER STATIONARY ELECTRODE FOR HOLDING STABLE 'ON'-STATE ..... 978**

Xiaojing Zhang<sup>1</sup>, Jianhao Shi<sup>1</sup>, Xi Zhu<sup>2</sup>, Yipin Wang<sup>1</sup>, Jiaming Chen<sup>1</sup>, Guifu Ding<sup>1</sup>, and Zhuoqing Yang<sup>1</sup>  
<sup>1</sup>*Shanghai Jiao Tong University, CHINA and*  
<sup>2</sup>*University of Technology Sydney, AUSTRALIA*

This paper presents a novel MEMS inertial switch that can hold a stable 'on'-state by electrostatic force locking. The compliant stationary electrode is designed as a micro-cantilevers array to weaken the collision intensity during the pull-in process, which can significantly reduce the contact bouncing. The simulation result shows that the designed switch can hold a stable 'on'-state under the acceleration of 52g at 24V electrostatic voltage. The silicon dry etching, multilayer metal electroplating and Au-Sn eutectic bonding are combined to fabricate the heterogeneous integrated switch. The test result confirms that the fabricated switch can realize a stable 'on'-state locking state under 48g shock acceleration with 27V electrostatic pull-in voltage.

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**T-194 A CLOSED-LOOP CONTROLLED CMOS MEMS BIAxIAL SCANNING MIRROR FOR PROJECTION DISPLAY..... 982**

Cho-Chuan Tsai and Michael S.-C. Lu  
*National Tsing Hua University, TAIWAN*

This work presents a bi-axial electromagnetically-driven piezoresistively sensed scanning mirror with a  $\theta_{opt} \cdot D \cdot f_{r,fast}$  product over 2400 deg-mm-kHz, showing the capability to achieve HD720 (720 × 1280) display resolution. Both driving and sensing capabilities are conveniently realized by CMOS MEMS technologies. The transduction mechanism provides a more linear response than capacitively transduced scanning mirrors. Based on the open-loop characterization of the driving and sensing performance, closed-loop control of slow-axis motion is designed and demonstrated.

**W-195 A RESTORING FORCE BOOSTING STRUCTURE WITH FLEXIBLE STICTION RECOVERY ELECTRODE FOR MEMS RELAYS/SWITCHES..... 986**

Wei Bian<sup>1,2,3</sup>, Jiahao Zhao<sup>1,2,3</sup>, Zheng You<sup>1,2,3</sup>, and Xiangzheng Sun<sup>1,2,3</sup>  
<sup>1</sup>*Tsinghua University, CHINA,*  
<sup>2</sup>*Innovation Center for Future Chips, CHINA, and*  
<sup>3</sup>*State Key Laboratory of Precision Measurement Technology and Instruments, CHINA*

A restoring force boosting structure for latching MEMS relays/switches was introduced in this paper. Experimental results have shown that the restoring force was multiplied with the novel structure, compared to the traditional structures. To obtain high restoring force, a flexible Stiction Recovery Electrode (SRE) was adopted in this work. The flexible-SRE curves if the voltage was applied between it and the micro cantilever. Restoring force of the novel structure was two times higher than the structures with the fixed-SRE, and an order of magnitude higher than that of actuators without the SRE. Besides the experiment results, theory and simulation results were also introduced in this paper.

**M-196 LOW VOLTAGE HAPTIC SLIDER BUILT USING SOL-GEL THIN-FILM PZT ACTUATORS REPORTED ON GLASS..... 990**

Fabrice Casset, Gwenael Le Rhun, Baptiste Neff, Brigitte Desloges, Christel Dieppedale, and Stéphane Fanget  
*CEA-Leti, FRANCE*

This paper reports on the development of a unique haptic solution based on thin-film Pb(Zr0.52,Ti0.48)O3 (PZT) actuators reported on glass substrate, allowing the feeling of textured surfaces playing with the variable friction between a finger and the plate resonator, induced by ultrasonic vibration. The integration of PZT actuators on glass substrate leads to a plate displacement amplitude multiplied by more than a factor 7 compared to the displacement amplitude induced by thin-film AlN actuators that are classically deposited on glass substrate. It opens the way to low voltage and high performances haptic devices.

**T-197 A NOVEL APPROACH TO SWIMMER ACTUATION VIA LEAKY SURFACE ACOUSTIC WAVE ..... 994**

Deqing Kong, Kazuki Nishio, and Minoru Kuribayashi Kurosawa  
*Tokyo Institute of Technology, JAPAN*

A novel approach to the swimmer actuation via leaky surface acoustic wave (LSAW) is proposed in this paper. The propulsion system of the swimmer is simple without tails and propellers because the acoustic propulsion of swimmer is derived from acoustic jet. In this study, the acoustic jet from the cavity is generated by the radiated longitudinal wave via LSAW, based on 128° y-rotated x-propagation lithium niobate substrate. Furthermore, the simple structure and low cost mass production of the SAW devices can be fulfilled. The device dimension can be miniaturized by the higher driving frequency; at 1 GHz, the dimension of U-IDT actuator are one-hundreds, namely, less than 0.3 mm. Because of the miniaturization and high power density, the novel swimmer with the LSAW actuator can be expected for the small robot in the human blood vessel. Particularly, small size swimmer is attempt to be a drug carrier or fixer inside the human body.

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- W-198 A GEOMETRICALLY PREDETERMINED EIGHTH ORDER NONLINEAR FLEXURE FOR EXTENDING THE STABLE TRAVEL RANGE OF THE ELECTROSTATIC ACTUATOR..... 998**  
 Xiaojian Xiang, Xuhan Dai, Kai Kang, Shi Sun, and Guifu Ding  
*Shanghai Jiao Tong University, CHINA*

In this paper, we designed and fabricated a highly nonlinear suspension flexure with geometrically predetermined eighth order force-displacement relation for extension of the stable travel range of electrostatic actuator. Its strong nonlinearity is obtained by a rolling slide between a customized curved trajectory and a ball at the tip of the mandril. The customized nonlinear behavior can be adjusted and dominated by a geometrically predetermined trajectory. The experimental result illustrates that the restoring force of the fabricated nonlinear flexure is proportional to the eighth power of the electrode displacement approximately, and the stable travel of the electrostatic actuator with this flexure is extended to at least 63% of the nominal gap. The proposed scheme can also be implemented to other systems where the nonlinearity is needed, such as energy harvesting and the damper in the micro-scale.

**Power MEMS Components & Systems**

- M-199 ALL SOLID-STATE FLEXIBLE MICRO-SUPERCAPACITOR BASED ON HYBRID ELECTRODES FOR POWER APPLICATION ..... 1002**  
 Swati J. Patil, Jong Sung Park, and Dong Weon Lee  
*Chonnam National University, KOREA*

In the present work, we have fabricated a flexible and efficient micro-supercapacitor for future advanced electronic applications. A simple time saving, eco-friendly electrodeposition method was employed for nanostructured thin film materials formation on a micropattern flexible polyethylene terephthalate (PET) substrate, and the resulting outcome shows that its promising applications in miniaturized power electronics devices. The nanostructures-based flexible microsupercapacitor can deliver areal capacitance of 0.253 mF/cm<sup>2</sup> at a current density of 0.03 mA/cm<sup>2</sup>. The maximum power and energy densities of the fabricated flexible asymmetric micro-supercapacitor are estimated to be 30 mW/cm<sup>2</sup> and 0.056 mWh/cm<sup>2</sup>, respectively.

- T-200 THE METHODOLOGY TO MAKE SMART CONTACT LENS BECOME A SEMI-PASSIVE SYSTEM..... 1006**  
 Jin-Chern Chiou, Cheng-En Shieh, Kuan-Ting Yeh, and Shun-Hsi Hsu  
*National Chiao Tung University, TAIWAN*

This paper, for the first time, reports a thin-film supercapacitor as an energy storage component for smart contact lens applications. By using previously developed 3D packaging technology, the proposed supercapacitor with 130 μm thickness can be packaged into a standard hydrogel contact lens with smooth wrinkle-free surface. Based on experiments, the proposed thin-film supercapacitor can work in saline solution and shows the future vision and eye disease related applications. Note that the previous developed radio frequency identification (RFID) based smart contact lens can now be changed from passive system to semi-passive system with the aid of proposed supercapacitor.

- W-201 HIGH PERFORMANCE FLEXIBLE THERMOELECTRIC DEVICE INCLUDED RIGID MATERIAL ..... 1010**  
 Makoto Kashiwagi, Tomoya Koshi, and Eiji Iwase  
*Waseda University, JAPAN*

A Thermoelectric device (TE-device) is promising way to achieve energy harvesting from wasted heat. For energy harvesting, flexibility and stretchability are necessary since a heat source surface has complex shape such as free-form surface. We realized high performance flexible TE-device which combining rigid BiTe-based thermoelectric elements (TE-elements) and flexible structures such as stretchable substrate and expandable electrical wirings. In this device, the BiTe-based TE-elements ensures thermoelectric performance and the flexible structures ensures flexibility. By designing as that, the device has high thermoelectric conversion performance which is comparable with conventional TE-device while having flexibility.

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- M-202 ELECTRET BASED VIBRATION ENERGY HARVESTER WITH SELF-HEALABLE SURFACE CHARGE..... 1013**  
Yulong Zhang, Yushen Hu, Meihua Wang, and Fei Wang  
*Southern University of Science and Technology, CHINA*

In this paper, we propose an electrostatic vibration energy harvester (e-VEH) with self-healable surface charge of electret. The device is made of a sandwich structure with out-of-the-plane gap closing scheme. Nine tungsten corona tips with tip diameter of 5  $\mu\text{m}$  are assembled into the device. With a corona charging setup self-powered by the part of the harvested energy of the e-VEH, the electret can be charged/recharged, which would solve the charge decay problem for application in harsh environment. The surface potential of the electret is tested after self-healing, and an improved power output of e-VEH has been achieved with good reliability.

- T-203 A DOUBLE-DECK STRUCTURED MEMS ELECTROSTATIC VIBRATIONAL ENERGY HARVESTER FOR MINIMAL FOOTPRINT ..... 1017**  
Hiroaki Honma and Hiroshi Toshiyoshi  
*The University of Tokyo, JAPAN*

This paper presents electrostatic vibrational energy harvesters which use double-deck structures for minimal footprint. The double-deck structure allocates the suspensions and the comb-electrodes in different layers of an SOI wafer. For electrical interconnection between the both layers, a stiction bar is used to bring the SOI structure to the same potential as the substrate. With an input acceleration of 0.18 G at 521 Hz, output power of 13.2  $\mu\text{W}$  is obtained from the double-deck type, where the chip size of the equivalent device performance is reduced to 62% of the previous models.

- W-204 BIPOLAR MICRO ELECTRET POWER GENERATOR ..... 1021**  
Kai Tao<sup>1</sup>, Binqiao Wang<sup>1</sup>, Yixin Chen<sup>1</sup>, Lihua Tang<sup>2</sup>, Jin Wu<sup>3</sup>, and Honglong Chang<sup>1</sup>  
<sup>1</sup>*Northwestern Polytechnical University, CHINA,*  
<sup>2</sup>*University of Auckland, NEW ZEALAND, and*  
<sup>3</sup>*Sun Yat-sen University, CHINA*

Inspired by electromagnetic hydropower station that contains reverse polarized magnet, this paper reports a novel micro electrostatic rotary energy harvester (e-REH) that integrates both positive and negative charged electrets into single rotational energy conversion system. It is the first time successfully demonstrating the feasibility and viability of micro-patterning bipolar charge into single electret sheet for boosting rotary energy harvesting effectiveness. Selectively localized corona charging method with rotational shadow mask is invented to pattern the predefined area with microscale opposite types of charges. With the fabricated prototype, the experimental results show the superior performance of the proposed bipolar e-REH: the output voltage increases over 200% compared to the positive alone and negative alone configurations.

- M-205 A MEMS VIBRATORY ENERGY HARVESTER CHARGED BY AN OFF-CHIP ELECTRET ..... 1025**  
Daisuke Yamane<sup>1,2</sup>, Hiroaki Honma<sup>3</sup>, and Hiroshi Toshiyoshi<sup>3</sup>  
<sup>1</sup>*Tokyo Institute of Technology, JAPAN,*  
<sup>2</sup>*JST, JAPAN, and*  
<sup>3</sup>*The University of Tokyo, JAPAN*

This paper reports a MEMS vibratory energy harvester using an off-chip electret source. The proposed device allows, for the first time, to physically separate MEMS tunable capacitors and electret charge source in a MEMS electret energy harvester, which enables us to enhance the design and fabrication flexibility of both MEMS structures and electret. A proof-of-concept device is fabricated, and its performance is experimentally evaluated. The results confirm the energy harvesting operation of the proposed device architecture.

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- T-206    TRANSFORMING LATERAL LIMBS MOVEMENT TO VERTICAL FREQUENCY-UP-CONVERSION (FUC) RESONANCE FOR WEARABLE ENERGY HARVESTERS..... 1029**  
 Ruofeng Han<sup>1</sup>, Keli Li<sup>1</sup>, Nianying Wang<sup>1</sup>, Qisheng He<sup>1</sup>, Dacheng Xu<sup>2</sup>, and Xinxin Li<sup>1</sup>  
<sup>1</sup>*Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, CHINA and*  
<sup>2</sup>*Soochow University, CHINA*

This paper reports a novel wearable energy-harvester to generate electric-power from human-joint rotation induced lateral stretch/rebound of the flexible substrate. The energy harvester integrates micro-plated nickel cantilever with the piezoelectric film and fixes them to the flexible substrate. By using the magnetic coupled frequency-up-conversion (FUC) between the ferromagnetic nickel cantilever and the magnet on the substrate, the low-frequency lateral human limbs movement is converted into high-frequency vertical (perpendicular to the substrate) resonant power generation of the piezoelectric cantilever, thereby effectively generating stable electric energy. Within the whole elbow/knee movement in the frequency-range of 0.5Hz~5.0Hz, the electric-energy generated in one movement cycle always stably keeps within 0.56μJ~0.69μJ. Body kinetic energy-harvesting experiments under limbs movements like squat, walking, jogging and fast running have verified the device to be promising in various wearable applications.

**Other Actuators & Power MEMS**

- W-207    THERMOMAGNETIC MICRO-TRACKS-GUIDED MAGNETIC BEAD MANIPULATION: A DEMONSTRATION OF MOVING BEAD ACROSS DIFFERENT TRACKS ENABLED BY NOVEL EMBEDDED ON-CHIP MICRO HEATING WIRES..... 1033**  
 Lin-Huei Fang, Hao Duan, Chin-Chung Chen, Chin-Cheng Cheng, and Tien-Kan Chung  
*National Chiao Tung University, TAIWAN*

In this paper, we show a demonstration of moving bead across different tracks enabled by novel embedded on-chip micro heating wires for thermomagnetic micro-tracks-guided magnetic bead manipulation. The demonstration includes a magnetic-bead-manipulation chip (which consists of thermomagnetic NiCu micro-disk tracks deposited on top of on-chip platinum micro heating wires fabricated on top of a silicon substrate), a magnetic bead, a thermoelectric generator (TEG), a pulse-generation circuit, and four external electromagnets. Because curie temperature of the track is approximate in room-temperature range, when we apply a pulse current to the heating wires to individually heat the track higher than room temperature, the magnetic property of the track is switched to paramagnetic. Oppositely, when we apply a current to TEG to cool the track lower than room temperature, the track is switched to ferromagnetic. By sequentially/selectively heating or cooling the tracks to switch the tracks to paramagnetic or ferromagnetic, together with applying directional magnetic field, we can achieve moving bead across different NiCu micro-disk tracks. This is an important and significant progress for conventional thermomagnetic micro-tracks-guided magnetic bead manipulation which cannot demonstrate moving bead across different tracks. Therefore, our approach provides a new and complete thermomagnetic micro-tracks-guided magnetic bead manipulation for lab-on-chip micro systems and biomedical MEMS/NEMS.

- M-208    CHAOTIC SIGNAL GENERATION IN THE MHz RANGE WITH A MONOLITHIC CMOS-MEMS MICROBEAM RESONATOR ..... 1037**  
 Joan Barceló, Ivan de Paul, Sebastià Bota, Jaume Segura, and Jaume Verd  
*University of the Balearic Islands, SPAIN*

For the first time, chaotic signal generation with a simple and straight clamped-clamped beam resonator has been experimentally measured. The submicrometric MHz resonator and the readout circuit have been fabricated and monolithically integrated using a commercial 0.35-μm CMOS technology. Extensive homoclinic chaotic motion has been obtained from the bistable cc-beam resonator and validated by means of a positive Lyapunov exponent.

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**T-209    MANIPULATING THE MOVING TRAJECTORIES OF INSECT-SCALE PIEZOELECTRIC SOFT ROBOT BY FREQUENCY ..... 1041**

Jiaming Liang<sup>1,2</sup>, Yichuan Wu<sup>1,2</sup>, Zhichun Shao<sup>2</sup>, Justin K. Yim<sup>2</sup>, Renxiao Xu<sup>2</sup>, Yi Song<sup>2</sup>, Mingjing Qi<sup>3</sup>, Junwen Zhong<sup>2</sup>, Min Zhang<sup>4</sup>, Xiaohao Wang<sup>1,4</sup>, and Liwei Lin<sup>1,2</sup>

<sup>1</sup>*Tsinghua Berkeley Shenzhen Institute, Tsinghua University, CHINA,*

<sup>2</sup>*University of California, Berkeley, USA,*

<sup>3</sup>*Beihang University, CHINA, and*

<sup>4</sup>*Tsinghua University, CHINA*

This paper reports the control and manipulation of the moving trajectories of insect-scale soft robots by the applied driving electrical voltage frequency utilizing the asymmetric structural design of the actuating mechanism. Three distinctive advancements have been achieved: (1) a simple asymmetric structural design to create uneven responses on the legs of artificial insects to realize motion controls; (2) the capability of moving forward, leftward and rightward by adjusting the applied driving frequency; and (3) a demonstration of recording the ethanol concentration map around an area in real time by carrying a gas sensor on top of the robot on a controlled path bypassing the existing obstacles. As such, this work can advance the state-of-art technologies on wirelessly controlled, unmanned robots for various potential applications.

**MEMS Products**

**Calibration and Measurement Methods for MEMS Products**

**W-210    SEALED CAVITY PRESSURE EVALUATION FROM 1 PA TO OVER 10 KPA USING THIN DIAPHRAGM FOR MEMS VACUUM PACKAGING ..... 1045**

Muhammad Salman Al Farisi, Hideki Hirano, and Shuji Tanaka

*Tohoku University, JAPAN*

This article reports a wide range vacuum evaluation system for a sealed cavity of packaged micro-devices. The measurement is based on the zero-balance method, which encompasses the measurement from its resolution to near the atmospheric pressure. The key improvement for high vacuum evaluation is the use of an intentionally tensile stressed thin Si diaphragm using high concentration boron doping to minimize the initial deflection of the diaphragm. During the pressure change operation of the zero-balance method, no diaphragm buckling which prevents high accuracy vacuum measurement is confirmed, because the flat diaphragm has a single zero-balance point, i.e. mono-stable. Such feature results in single digit Pa measurement accuracy.

**M-211    ULTRATHIN RADIATION COATING ENABLING HIGH ACUCRACY AND HIGH RESOLUTION REAL-TIME INFRARED IMAGING OF THERMAL MEMS DEVICES ..... 1049**

Yipin Wang, Qi Liu, Yunna Sun, Xiaojing Zhang, Jiaming Chen, Zhuoqing Yang, and Guifu Ding

*Shanghai Jiao Tong University, CHINA*

An ultrathin radiation coating is invented to modify the surface of MEMS devices for the real-time extraction of high-accuracy and high-resolution infrared (IR) thermography. A testing device is designed and fabricated to identify the accuracy of thermography. The maximum deviation of measured temperature calibrated by thin film sensor is 60°C without radiation coating. In stark contrast, the corresponding error is reduced to less than 1°C with the radiation coating. Meanwhile, this method enables accurate thermography to be obtained in real time, and the feature with a smallest width of 10 µm can be clearly visible in the thermography.