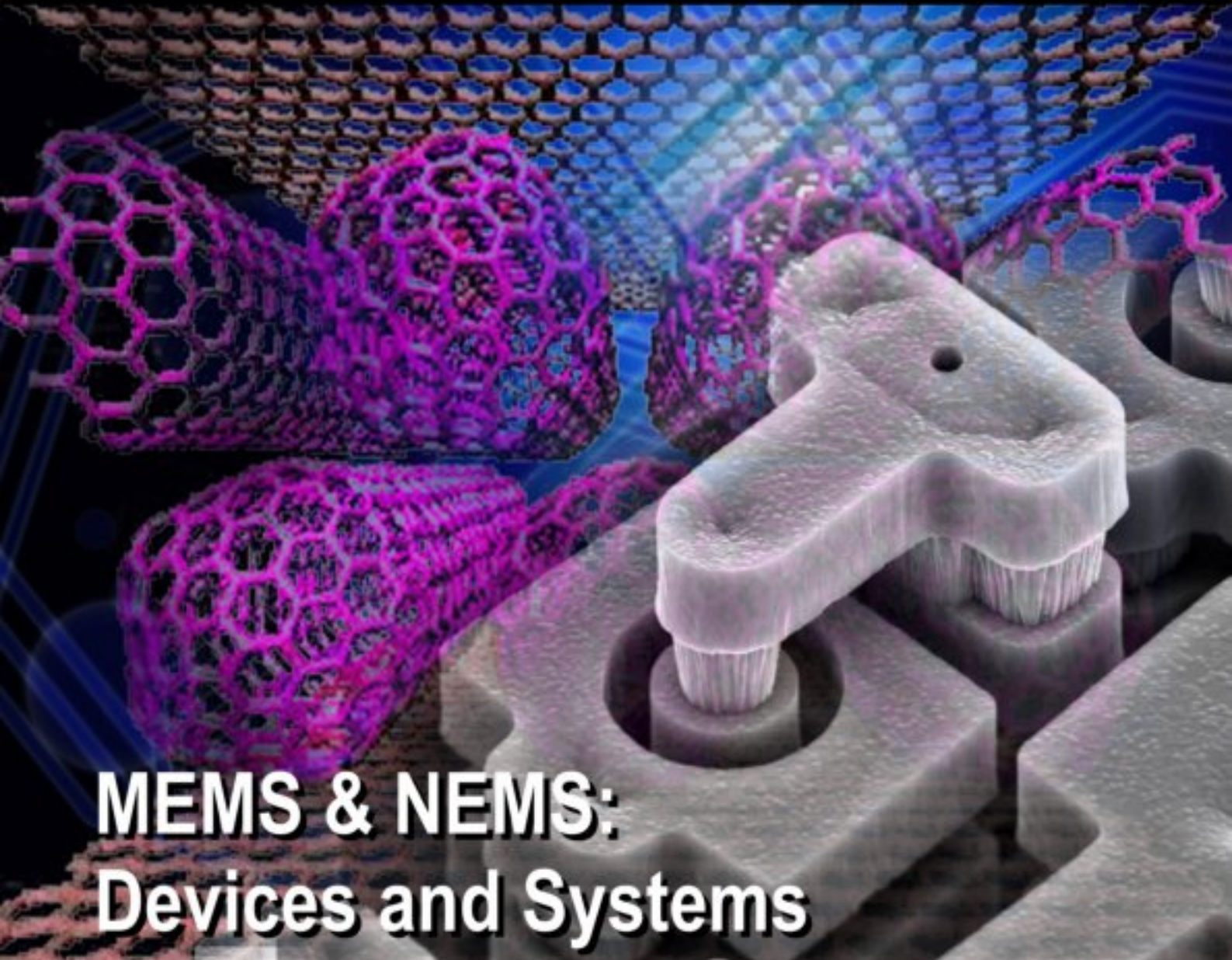


ISSN 1726-5749

# SENSORS & TRANSDUCERS

10<sup>Special  
Issue</sup>  
/07



**MEMS & NEMS:  
Devices and Systems**

International Frequency Sensor Association Publishing





# Sensors & Transducers

Special Issue  
October 2007

[www.sensorsportal.com](http://www.sensorsportal.com)

ISSN 1726-5479

**Editor-in-Chief:** Sergey Y. Yurish

**Guest Editors:** Elena Gaura and James P. Brusey

**Editors for Western Europe**

Meijer, Gerard C.M., Delft University of Technology, The Netherlands  
Ferrari, Vittorio, Università di Brescia, Italy

**Editors for North America**

Datskos, Panos G., Oak Ridge National Laboratory, USA  
Fabien, J. Josse, Marquette University, USA  
Katz, Evgeny, Clarkson University, USA

**Editor South America**

Costa-Felix, Rodrigo, Inmetro, Brazil

**Editor for Eastern Europe**

Sachenko, Anatoly, Ternopil State Economic University, Ukraine

**Editor for Asia**

Ohyama, Shinji, Tokyo Institute of Technology, Japan

## Editorial Advisory Board

**Abdul Rahim, Ruzairi**, Universiti Teknologi, Malaysia  
**Ahmad, Mohd Noor**, Northern University of Engineering, Malaysia  
**Annamalai, Karthigeyan**, National Institute of Advanced Industrial Science and Technology, Japan  
**Arcega, Francisco**, University of Zaragoza, Spain  
**Arguel, Philippe**, CNRS, France  
**Ahn, Jae-Pyoung**, Korea Institute of Science and Technology, Korea  
**Arndt, Michael**, Robert Bosch GmbH, Germany  
**Ascoli, Giorgio**, George Mason University, USA  
**Atalay, Selcuk**, Inonu University, Turkey  
**Atghiaee, Ahmad**, University of Tehran, Iran  
**Augutis, Vygantas**, Kaunas University of Technology, Lithuania  
**Avachit, Patil Lalchand**, North Maharashtra University, India  
**Ayesh, Aladdin**, De Montfort University, UK  
**Bahreyni, Behraad**, University of Manitoba, Canada  
**Baoxian, Ye**, Zhengzhou University, China  
**Barford, Lee**, Agilent Laboratories, USA  
**Barlingay, Ravindra**, Priyadarshini College of Engineering and Architecture, India  
**Basu, Sukumar**, Jadavpur University, India  
**Beck, Stephen**, University of Sheffield, UK  
**Ben Bouzid, Sihem**, Institut National de Recherche Scientifique, Tunisia  
**Binnie, T. David**, Napier University, UK  
**Bischoff, Gerlinde**, Inst. Analytical Chemistry, Germany  
**Bodas, Dhananjay**, IMTEK, Germany  
**Borges Carval, Nuno**, Universidade de Aveiro, Portugal  
**Bousbia-Salah, Mounir**, University of Annaba, Algeria  
**Bouvet, Marcel**, CNRS – UPMC, France  
**Brudzewski, Kazimierz**, Warsaw University of Technology, Poland  
**Cai, Chenxin**, Nanjing Normal University, China  
**Cai, Qingyun**, Hunan University, China  
**Campanella, Luigi**, University La Sapienza, Italy  
**Carvalho, Vitor**, Minho University, Portugal  
**Cecelja, Franjo**, Brunel University, London, UK  
**Cerda Belmonte, Judith**, Imperial College London, UK  
**Chakrabarty, Chandan Kumar**, Universiti Tenaga Nasional, Malaysia  
**Chakravorty, Dipankar**, Association for the Cultivation of Science, India  
**Changhai, Ru**, Harbin Engineering University, China  
**Chaudhari, Gajanan**, Shri Shivaji Science College, India  
**Chen, Rongshun**, National Tsing Hua University, Taiwan  
**Cheng, Kuo-Sheng**, National Cheng Kung University, Taiwan  
**Chiriac, Horia**, National Institute of Research and Development, Romania  
**Chowdhuri, Arijit**, University of Delhi, India  
**Chung, Wen-Yaw**, Chung Yuan Christian University, Taiwan  
**Corres, Jesus**, Universidad Publica de Navarra, Spain  
**Cortes, Camilo A.**, Universidad de La Salle, Colombia  
**Courtois, Christian**, Universite de Valenciennes, France  
**Cusano, Andrea**, University of Sannio, Italy  
**D'Amico, Arnaldo**, Università di Tor Vergata, Italy  
**De Stefano, Luca**, Institute for Microelectronics and Microsystem, Italy  
**Deshmukh, Kiran**, Shri Shivaji Mahavidyalaya, Barshi, India  
**Kang, Moonho**, Sunmoon University, Korea South  
**Kaniusas, Eugenijus**, Vienna University of Technology, Austria  
**Katake, Anup**, Texas A&M University, USA

**Dickert, Franz L.**, Vienna University, Austria  
**Dieguez, Angel**, University of Barcelona, Spain  
**Dimitropoulos, Panos**, University of Thessaly, Greece  
**Ding Jian, Ning**, Jiangsu University, China  
**Djordjević, Alexandar**, City University of Hong Kong, Hong Kong  
**Donato, Nicola**, University of Messina, Italy  
**Donato, Patricio**, Universidad de Mar del Plata, Argentina  
**Dong, Feng**, Tianjin University, China  
**Drljaca, Predrag**, Instersema Sensoric SA, Switzerland  
**Dubey, Venketesh**, Bournemouth University, UK  
**Enderle, Stefan**, University of Ulm and KTB mechatronics GmbH, Germany  
**Erdem, Gursan K. Arzum**, Ege University, Turkey  
**Erkmen, Aydan M.**, Middle East Technical University, Turkey  
**Estelle, Patrice**, Insa Rennes, France  
**Estrada, Horacio**, University of North Carolina, USA  
**Faiz, Adil**, INSA Lyon, France  
**Fericean, Sorin**, Balluff GmbH, Germany  
**Fernandes, Joana M.**, University of Porto, Portugal  
**Francioso, Luca**, CNR-IMM Institute for Microelectronics and Microsystems, Italy  
**Fu, Weiling**, South-Western Hospital, Chongqing, China  
**Gaura, Elena**, Coventry University, UK  
**Geng, Yanfeng**, China University of Petroleum, China  
**Gole, James**, Georgia Institute of Technology, USA  
**Gong, Hao**, National University of Singapore, Singapore  
**Gonzalez de la Ros, Juan Jose**, University of Cadiz, Spain  
**Granell, Annette**, Goteborg University, Sweden  
**Graff, Mason**, The University of Texas at Arlington, USA  
**Guan, Shan**, Eastman Kodak, USA  
**Guillet, Bruno**, University of Caen, France  
**Guo, Zhen**, New Jersey Institute of Technology, USA  
**Gupta, Narendra Kumar**, Napier University, UK  
**Hadjiloucas, Sillas**, The University of Reading, UK  
**Hashsham, Syed**, Michigan State University, USA  
**Hernandez, Alvaro**, University of Alcalá, Spain  
**Hernandez, Wilmar**, Universidad Politecnica de Madrid, Spain  
**Homentcovschi, Dorel**, SUNY Binghamton, USA  
**Horstman, Tom**, U.S. Automation Group, LLC, USA  
**Hsiai, Tzung (John)**, University of Southern California, USA  
**Huang, Jeng-Sheng**, Chung Yuan Christian University, Taiwan  
**Huang, Star**, National Tsing Hua University, Taiwan  
**Huang, Wei**, PSG Design Center, USA  
**Hui, David**, University of New Orleans, USA  
**Jaffrezic-Renault, Nicole**, Ecole Centrale de Lyon, France  
**Jaime Calvo-Galleg, Jaime**, Universidad de Salamanca, Spain  
**James, Daniel**, Griffith University, Australia  
**Janting, Jakob**, DELTA Danish Electronics, Denmark  
**Jiang, Liudi**, University of Southampton, UK  
**Jiao, Zheng**, Shanghai University, China  
**John, Joachim**, IMEC, Belgium  
**Kalach, Andrew**, Voronezh Institute of Ministry of Interior, Russia  
**Rodriguez, Angel**, Universidad Politecnica de Catalunya, Spain  
**Rothberg, Steve**, Loughborough University, UK

**Kausel, Wilfried**, University of Music, Vienna, Austria  
**Kavasoglu, Nese**, Mugla University, Turkey  
**Ke, Cathy**, Tyndall National Institute, Ireland  
**Khan, Asif**, Aligarh Muslim University, Aligarh, India  
**Kim, Min Young**, Koh Young Technology, Inc., Korea South  
**Ko, Sang Choon**, Electronics and Telecommunications Research Institute, Korea South  
**Kockar, Hakan**, Balikesir University, Turkey  
**Kotulska, Malgorzata**, Wroclaw University of Technology, Poland  
**Kratz, Henrik**, Uppsala University, Sweden  
**Kumar, Arun**, University of South Florida, USA  
**Kumar, Subodh**, National Physical Laboratory, India  
**Kung, Chih-Hsien**, Chang-Jung Christian University, Taiwan  
**Lacnjevac, Caslav**, University of Belgrade, Serbia  
**Laurent, Francis**, IMEC, Belgium  
**Lay-Ekuakille, Aime**, University of Lecce, Italy  
**Lee, Jang Myung**, Pusan National University, Korea South  
**Lee, Jun Su**, Amkor Technology, Inc. South Korea  
**Lei, Hua**, National Starch and Chemical Company, USA  
**Li, Genxi**, Nanjing University, China  
**Li, Hui**, Shanghai Jiaotong University, China  
**Li, Xian-Fang**, Central South University, China  
**Liang, Yuanchang**, University of Washington, USA  
**Liawruangrath, Saisunee**, Chiang Mai University, Thailand  
**Liew, Kim Meow**, City University of Hong Kong, Hong Kong  
**Lin, Hermann**, National Kaohsiung University, Taiwan  
**Lin, Paul**, Cleveland State University, USA  
**Linderholm, Pontus**, EPFL - Microsystems Laboratory, Switzerland  
**Liu, Aihua**, Michigan State University, USA  
**Liu Changgeng**, Louisiana State University, USA  
**Liu, Cheng-Hsien**, National Tsing Hua University, Taiwan  
**Liu, Songqin**, Southeast University, China  
**Lodeiro, Carlos**, Universidade NOVA de Lisboa, Portugal  
**Lorenzo, Maria Encarnacio**, Universidad Autonoma de Madrid, Spain  
**Lukaszewicz, Jerzy Pawel**, Nicholas Copernicus University, Poland  
**Ma, Zhanfang**, Northeast Normal University, China  
**Majstorovic, Vidosav**, University of Belgrade, Serbia  
**Marquez, Alfredo**, Centro de Investigacion en Materiales Avanzados, Mexico  
**Matay, Ladislav**, Slovak Academy of Sciences, Slovakia  
**Mathur, Prafull**, National Physical Laboratory, India  
**Maurya, D.K.**, Institute of Materials Research and Engineering, Singapore  
**Mekid, Samir**, University of Manchester, UK  
**Mendes, Paulo**, University of Minho, Portugal  
**Mennell, Julie**, Northumbria University, UK  
**Mi, Bin**, Boston Scientific Corporation, USA  
**Minas, Graca**, University of Minho, Portugal  
**Moghavvemi, Mahmoud**, University of Malaya, Malaysia  
**Mohammedi, Mohammad-Reza**, University of Cambridge, UK  
**Molina Flores, Esteban**, Benemirita Universidad Autonoma de Puebla, Mexico  
**Moradi, Majid**, University of Kerman, Iran  
**Morello, Rosario**, DIMET, University "Mediterranea" of Reggio Calabria, Italy  
**Mounir, Ben Ali**, University of Sousse, Tunisia  
**Mukhopadhyay, Subhas**, Massey University, New Zealand  
**Neelamegam, Periasamy**, Sastra Deemed University, India  
**Neshkova, Milka**, Bulgarian Academy of Sciences, Bulgaria  
**Oberhammer, Joachim**, Royal Institute of Technology, Sweden  
**Ould Lahoucine**, University of Guelma, Algeria  
**Pamidighanta, Sayanu**, Bharat Electronics Limited (BEL), India  
**Pan, Jisheng**, Institute of Materials Research & Engineering, Singapore  
**Park, Joon-Shik**, Korea Electronics Technology Institute, Korea South  
**Pereira, Jose Miguel**, Instituto Politecnico de Seteбал, Portugal  
**Petsev, Dimitar**, University of New Mexico, USA  
**Pogacnik, Lea**, University of Ljubljana, Slovenia  
**Post, Michael**, National Research Council, Canada  
**Prance, Robert**, University of Sussex, UK  
**Prasad, Ambika**, Gulbarga University, India  
**Prateepasen, Asa**, Kingmoungut's University of Technology, Thailand  
**Pullini, Daniele**, Centro Ricerche FIAT, Italy  
**Pumera, Martin**, National Institute for Materials Science, Japan  
**Radhakrishnan, S.**, National Chemical Laboratory, Pune, India  
**Rajanna, K.**, Indian Institute of Science, India  
**Ramadan, Qasem**, Institute of Microelectronics, Singapore  
**Rao, Basuthkar**, Tata Inst. of Fundamental Research, India  
**Reig, Candid**, University of Valencia, Spain  
**Restivo, Maria Teresa**, University of Porto, Portugal  
**Rezazadeh, Ghader**, Urmia University, Iran  
**Robert, Michel**, University Henri Poincare, France  
**Royo, Santiago**, Universitat Politecnica de Catalunya, Spain  
**Sadana, Ajit**, University of Mississippi, USA  
**Sandacci, Serghei**, Sensor Technology Ltd., UK  
**Sapozhnikova, Ksenia**, D.I.Mendeleyev Institute for Metrology, Russia  
**Saxena, Vibha**, Bhabha Atomic Research Centre, Mumbai, India  
**Schneider, John K.**, Ultra-Scan Corporation, USA  
**Seif, Selemeni**, Alabama A & M University, USA  
**Seifter, Achim**, Los Alamos National Laboratory, USA  
**Sengupta, Deepak**, Advance Bio-Photonics, India  
**Shearwood, Christopher**, Nanyang Technological University, Singapore  
**Shin, Kyuho**, Samsung Advanced Institute of Technology, Korea  
**Shmaliy, Yuriy**, Kharkiv National University of Radio Electronics, Ukraine  
**Silva Girao, Pedro**, Technical University of Lisbon Portugal  
**Slomovitz, Daniel**, UTE, Uruguay  
**Smith, Martin**, Open University, UK  
**Soleymanpour, Ahmad**, Damghan Basic Science University, Iran  
**Somani, Prakash R.**, Centre for Materials for Electronics Technology, India  
**Srinivas, Talabattula**, Indian Institute of Science, Bangalore, India  
**Srivastava, Arvind K.**, Northwestern University  
**Stefan-van Staden, Raluca-Ioana**, University of Pretoria, South Africa  
**Sumriddetchka, Sarun**, National Electronics and Computer Technology Center, Thailand  
**Sun, Chengliang**, Polytechnic University, Hong-Kong  
**Sun, Dongming**, Jilin University, China  
**Sun, Junhua**, Beijing University of Aeronautics and Astronautics, China  
**Sun, Zhiqiang**, Central South University, China  
**Suri, C. Raman**, Institute of Microbial Technology, India  
**Sysoev, Victor**, Saratov State Technical University, Russia  
**Szewczyk, Roman**, Industrial Research Institute for Automation and Measurement, Poland  
**Tan, Ooi Kiang**, Nanyang Technological University, Singapore  
**Tang, Dianping**, Southwest University, China  
**Tang, Jaw-Luen**, National Chung Cheng University, Taiwan  
**Thumbavanam Pad, Kartik**, Carnegie Mellon University, USA  
**Tsiantos, Vassilios**, Technological Educational Institute of Kaval, Greece  
**Tsigara, Anna**, National Hellenic Research Foundation, Greece  
**Twomey, Karen**, University College Cork, Ireland  
**Valente, Antonio**, University, Vila Real, - U.T.A.D., Portugal  
**Vaseashta, Ashok**, Marshall University, USA  
**Vazques, Carmen**, Carlos III University in Madrid, Spain  
**Vieira, Manuela**, Instituto Superior de Engenharia de Lisboa, Portugal  
**Vigna, Benedetto**, STMicroelectronics, Italy  
**Vrba, Radimir**, Brno University of Technology, Czech Republic  
**Wandelt, Barbara**, Technical University of Lodz, Poland  
**Wang, Jiangping**, Xi'an Shiyou University, China  
**Wang, Kedong**, Beihang University, China  
**Wang, Liang**, Advanced Micro Devices, USA  
**Wang, Mi**, University of Leeds, UK  
**Wang, Shinn-Fwu**, Ching Yun University, Taiwan  
**Wang, Wei-Chih**, University of Washington, USA  
**Wang, Wensheng**, University of Pennsylvania, USA  
**Watson, Steven**, Center for NanoSpace Technologies Inc., USA  
**Weiping, Yan**, Dalian University of Technology, China  
**Wells, Stephen**, Southern Company Services, USA  
**Wolkenberg, Andrzej**, Institute of Electron Technology, Poland  
**Woods, R. Clive**, Louisiana State University, USA  
**Wu, DerHo**, National Pingtung University of Science and Technology, Taiwan  
**Wu, Zhaoyang**, Hunan University, China  
**Xiu Tao, Ge**, Chuzhou University, China  
**Xu, Tao**, University of California, Irvine, USA  
**Yang, Dongfang**, National Research Council, Canada  
**Yang, Wuqiang**, The University of Manchester, UK  
**Ymeti, Aurel**, University of Twente, Netherland  
**Yu, Haihu**, Wuhan University of Technology, China  
**Yufera Garcia, Alberto**, Seville University, Spain  
**Zagnoni, Michele**, University of Southampton, UK  
**Zeni, Luigi**, Second University of Naples, Italy  
**Zhong, Haoxiang**, Henan Normal University, China  
**Zhang, Minglong**, Shanghai University, China  
**Zhang, Qintao**, University of California at Berkeley, USA  
**Zhang, Weiping**, Shanghai Jiao Tong University, China  
**Zhang, Wenming**, Shanghai Jiao Tong University, China  
**Zhou, Zhi-Gang**, Tsinghua University, China  
**Zorzano, Luis**, Universidad de La Rioja, Spain  
**Zourob, Mohammed**, University of Cambridge, UK

# Contents

Special Issue  
October 2007

www.sensorsportal.com

ISSN 1726-5479

## Research Articles

### Foreword

*Elena Gaura and James P. Brusey*..... 1

### Nano-Structure or Nano-Systems: Opportunities and Pitfalls

*P. J. French and C.-K. Yang*..... 1

### New Trends on MEMS Sensor Technology for Harsh Environment Applications

*Patricia M. Nieva* ..... 10

### Healthcare for the Healthy People: Miniaturization, Sensing and Actuation Trends and Needs in Preventive and Predictive Medicine

*Alberto Sanna, Marco Nalin, Riccardo Serafin*..... 21

### Global Environmental Micro Sensors Test Operations in the Natural Environment (GEMSTONE)

*Mark Adams, John Manobianco and Matthew Buza*..... 30

### Frequency Domain Modeling of SAW Devices for Aerospace Sensors

*William Wilson, Gary Atkinson*..... 42

### Development of Materials and Sensors for the U.S. Army's Active Coatings Technology Program

*James L. Zunino III* ..... 51

### Microfabrication and Characterization of an Integrated 3-Axis CMOS-MEMS Accelerometer

*Hongwei Qu, Deyou Fang and Huikai Xie*..... 60

### Characterization and Optimization Design of the Polymer-based Capacitive Micro-arrayed Ultrasonic Transducer

*De-Yi Chiou, Mu-Yueh Chen, Hsu-Cheng Deng, Ming-Wei Chang*..... 68

### Fabry-Perot Diaphragm Fiber Optic Sensor (DFOS) for Acoustic Detection

*Yan Sun, Guanhua Feng, George Georgiou, Edip Niver, Karen Noe and Ken Chin*..... 76

### Micromechanical GaAs Hot Plates for Gas Sensors

*Jiri Jakovenko, Miroslav Husak, Tibor Lalinky, Milan Drzik*..... 84

### Integration of Microfluidics and Microacoustics Components for Miniature Flow Cytometry Systems

*Surendra K. Ravula, Darren W. Branch, Jennifer Sigman, Paul G. Clem, Igal Brener*..... 93

### Design and Characterization of MEMS Thermal Converter

*Jiri Jakovenko, Miroslav Husak, Tibor Lalinky*..... 101

### Fabrication of a Real Time Reactive Ion Etching Resonant Sensor Using a Low Temperature Sacrificial Polymer

*Bryan G. Morris, Paul J. Joseph and Gary S. May*..... 111

<b>Perturbation Stochastic Finite Element Analysis of Thermoelastic Quality Factor of Micro-Resonators</b> <i>Séverine Lepage and Jean-Claude Golinval</i> .....	124
<b>A Semi-Analytical Model for Calculating Touch-Point Pressure and Pull-in Voltage for Clamped Diaphragms with Residual Stress</b> <i>Anurekha Sharma and P. J. George</i> .....	131
<b>The Development of Chemical Nanosensors</b> <i>A. J. Jin, J. Li, Y. Lu</i> .....	140

Authors are encouraged to submit article in MS Word (doc) and Acrobat (pdf) formats by e-mail: [editor@sensorsportal.com](mailto:editor@sensorsportal.com)  
Please visit journal's webpage with preparation instructions: <http://www.sensorsportal.com/HTML/DIGEST/Submission.htm>

## Foreword

The 10<sup>th</sup> annual NSTI Nanotech Conference and Trade Show was held this year during 20-24 May at the Santa Clara Convention Center, in Santa Clara, California. The conference has grown this year to host 3000 attendees and 250 exhibitors, while the resulting proceedings boasts over 3000 pages of peer-reviewed micro and nanotechnology research.

A number of authors publishing in the Joint Electronics and Microsystems Symposia track were invited to submit a revised version of their papers to this special issue. Papers were selected from a number of symposia within the track, including: MEMS & NEMS, Sensors & Systems, Micro & Nano Fluidics, and MSM – Modeling Microsystems. These symposia brought together researchers from a number of disciplines to discuss topics ranging from theoretical developments, to design and fabrication, through to industrial applications of MEMS and NEMS sensors, devices and systems.

The joint symposia are motivated by the dream of smarter, smaller, and more complex systems that integrate micro and nano system technologies with intelligence, power and communication ability at the same micro or nano scale. The resulting increase in complexity poses an enormous challenge to engineers when designing, modeling, and fabricating such integrated micro and nano systems. The joint symposia aimed at bringing together researchers from different disciplines to exchange ideas about how to best develop such systems.

As with the joint symposia, this special issue includes papers ranging from those with a higher level focus to those covering low-level physical aspects of MEMS and NEMS devices and their modeling and fabrication. Four of the papers presented in this special issue correspond to invited talks: Sanna et al., examine miniaturization trends in preventative medicine and include some results from the EU project ANGEL; Adams et al., describe the results of the NASA funded GEMSTONE project, which involved creating and field-testing a small system of atmospheric probes; French and Yang explore the opportunities and pitfalls of scaling, whilst Nieva presents a number of new trends for using MEMS sensors in harsh environments.

We are very thankful both to the NSTI directors and Nanotech chairs (Dr. Matthew Laudon and Dr. Bart Romanovicz) and to the *Sensors & Transducers Journal* for offering the opportunity to publish this special issue.

### Guest Editors:



**Dr. Elena Gaura**

Reader in Pervasive Computing  
Director of Cogent Computing Applied Research Centre  
Faculty of Engineering and Computing  
Coventry University, UK  
e.gaura@coventry.ac.uk  
www.cogentcomputing.org



**Dr. James P. Brusey**

Senior Lecturer in Systems Engineering  
Senior Research Fellow of Cogent Computing Applied  
Research Centre  
Faculty of Engineering and Computing  
Coventry University, UK  
j.brusey@coventry.ac.uk  
www.cogentcomputing.org



## Microfabrication and Characterization of an Integrated 3-Axis CMOS-MEMS Accelerometer

<sup>1</sup>Hongwei QU, <sup>2</sup>Deyou FANG and <sup>3</sup>Huikai XIE

<sup>1</sup>Department of Electrical and Computer Engineering, Oakland University, Michigan 48309 USA

<sup>2</sup>Freescale Semiconductor, Sensors and Actuators Division, Chandler, Arizona 85224 USA

<sup>3</sup>Department of Electrical and Computer Engineering, University of Florida, Florida 32611 USA

Tel.: (1)248-370-2205

Email: qu2@oakland.edu

*Received: 17 September 2007 /Accepted: 19 September 2007 /Published: 8 October 2007*

---

**Abstract:** This paper reports the fabrication and characterization of a monolithically integrated 3-axis CMOS-MEMS accelerometer with a single proof mass. An improved microfabrication process has been developed to solve the structure overheating and particle contamination problems in the plasma etching processes of device fabrication. The whole device is made of bulk silicon except for some short thin films for electrical isolation, allowing large sensing capacitance and flat device structure. A low-noise, low-power amplifier is designed for each axis, which provides 40 dB on-chip amplification and consumes only 1 mW power. Quasi-static and dynamic characterization of the fabricated device has been performed. The measured sensitivities of the lateral- and z-axis accelerometers are 560 mV/g and 320 mV/g, respectively, which can be tuned by simply varying the amplitude of the modulation signal. The over-all noise floors of the lateral- and z-axis are 12  $\mu\text{g}/\sqrt{\text{Hz}}$  and 110  $\mu\text{g}/\sqrt{\text{Hz}}$ , respectively when tested at 200 Hz. *Copyright © 2007 IFSA.*

**Keywords:** CMOS-MEMS, Integration, Accelerometer, Microfabrication, Characterization

---

### 1. Introduction

Monolithic 3-axis accelerometers have drawn great interests from both industry and academia [1-6]. Capacitive sensing is widely employed in these accelerometers due to its high sensitivity. Most of the commercially available 3-axis accelerometers are based on thin-film microstructures and majority of them use hybrid packages, whose performances are normally limited by the structure thickness, residual stress and parasitics [1, 4-6]. The noise floors of these reported 3-axis accelerometers are normally on the order of hundreds of  $\mu\text{g}/\sqrt{\text{Hz}}$ . By using some uncommon bulk micromachining

process, some 3-axis accelerometers with high resolutions have been demonstrated [3, 7]. High cost is a major concern for these devices due to the dedicated process steps.

A single-crystal silicon (SCS) 3-axis accelerometer was developed using CMOS-MEMS technology to achieve high resolution, small size and low cost simultaneously [8]. But it has two drawbacks. First, although most of the sensing structures are made of single-crystal-silicon (SCS), the z-axis sensing still employs Al/SiO<sub>2</sub> thin-film spring beams, which has poor temperature performance. Second, the silicon undercut for electrical isolation of substrate silicon also undercuts the silicon underneath comb fingers, which increases the comb-finger gap and in turn reduces the sensitivity and signal-to-noise ratio. Recently, a new sensor design and fabrication process were proposed by Qu *et al* [9] to overcome the drawbacks in [8]. Better temperature performance was achieved by employing a torsional SCS-based z-axis spring; and the comb-finger undercut problem was much alleviated by performing the electrical isolation formation and the sensing structures etching separately.

However, there are still two significant issues in [9]. First, the isolation trenches are prone to be contaminated in the following reactive ion etch (RIE) and deep-RIE (DRIE) processes, preventing capacitive comb fingers and other microstructures from being released successfully. Second, the overheating during the dry release step severely undercuts the sensing comb fingers and springs, increasing the comb-finger gaps and even causing device failure.

In this paper, a further modified CMOS-MEMS process is developed to resolve these two remaining issues. The detailed characterization of fabricated 3-axis accelerometers is also presented.

## **2. Structure and Interface Circuit Design**

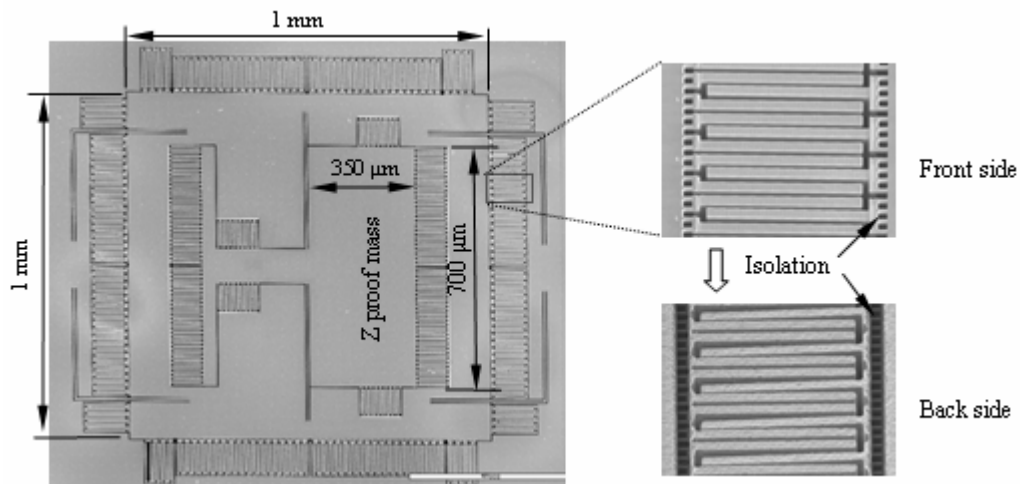
The 3-axis CMOS-MEMS accelerometer reported in this paper features a single proof mass for 3-axis sensing, in which an imbalanced torsional z-axis sensing element is embedded in the lateral proof mass [9]. A two-stage dual-chopper amplifier (DCA) is integrated with the 3-axis accelerometer for each axis as the continuous-time readout circuit [10]. Detailed structure and circuit design are reported in [9] and [10], respectively.

Fig. 1 shows an SEM micrograph of a fabricated 3-axis accelerometer, where the dimensions of the lateral- and z-axis sensing elements are also given. The thickness of all the structures is about 35  $\mu\text{m}$  and the gap for all the comb-fingers is about 2.1  $\mu\text{m}$ . The length of the lateral- and z- axis sensing comb-fingers are 85  $\mu\text{m}$  and 55  $\mu\text{m}$ , respectively, both having the same width of 4.8  $\mu\text{m}$ . The length and width of z-axis torsional mechanical springs are 400  $\mu\text{m}$  and 4  $\mu\text{m}$ , respectively. The crag-leg springs for lateral axes have the same length and width of 320  $\mu\text{m}$  and 5  $\mu\text{m}$  in both directions. The proof mass has a footprint of 1 mm  $\times$  1 mm.

## **3. Fabrication Process**

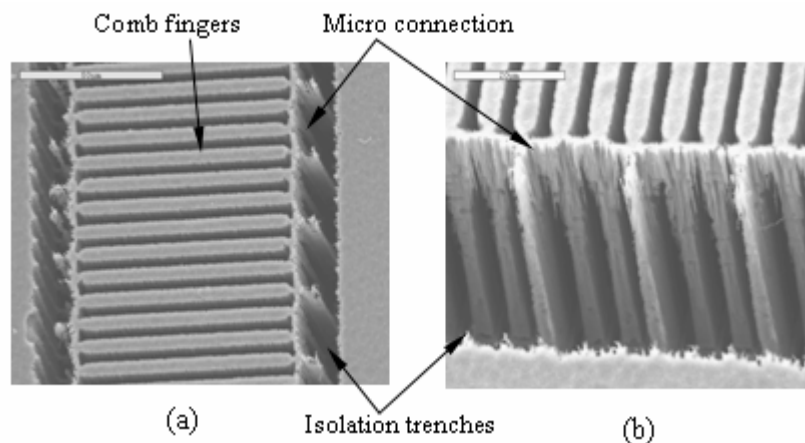
The post-CMOS microfabrication reported in [9] improves the device performance by reducing the undercut on comb fingers and mechanical springs. This is accomplished by performing the electrical isolation etch and the final release of comb fingers and mechanical springs separately. Top metal layer (M4 in TSMC 0.35 $\mu\text{m}$  CMOS process that is used in this device) is only used to pattern the electrical isolation structures. After the isolation trenches are formed, as shown in the insets of Fig. 1, M4 is removed by wet or plasma aluminum etch to expose the patterns of other structures of the accelerometer.





**Fig 1.** SEM photograph of the sensing element of the fabricated CMOS-MEMS 3-axis accelerometer. The insets show front and backside of the electrical isolation structures.

Some negative effects caused by the two-step etch process were observed. The first one is the contamination of the isolation trench formed after the first silicon DRIE. In the following plasma etching steps, including SiO<sub>2</sub> RIE and silicon DRIE, particles and polymers from assorted sources are prone to accumulate on the sidewalls of the isolation trenches. They act as micro masks in the last release DRIE step, preventing the microstructures from being completely etched through. Fig. 2 shows micro connections on the ends of sensing comb fingers. They result from the micro mask effect of the contaminants deposited on the isolation trench sidewall, and connect the rotor and stator sensing comb fingers together, making the proof mass unmovable.

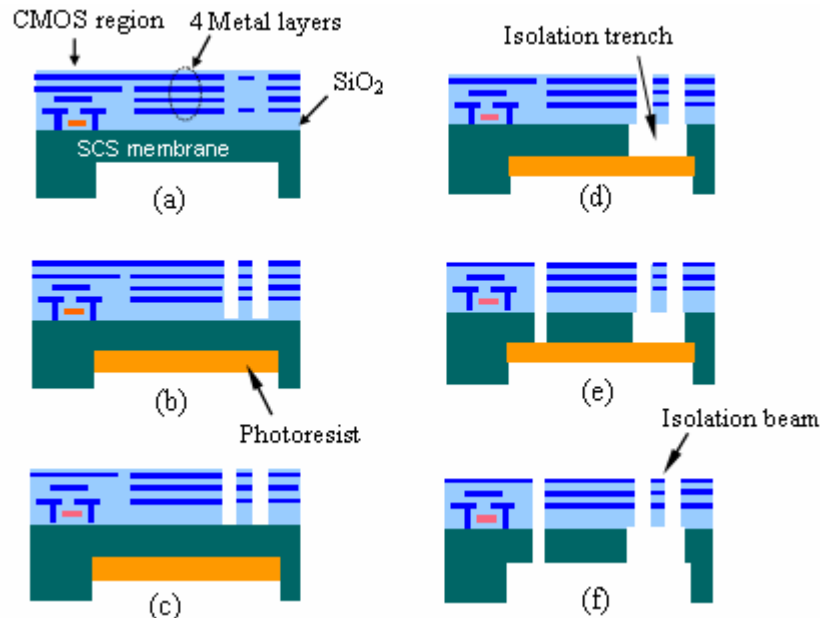


**Fig. 2.** SEM micrographs showing the micro connections caused by the contamination of the isolation trench in plasma etch steps. (a) top view; (b) side.

The second negative effect is the rapid silicon undercut of comb fingers and mechanical springs due to the overheating of these fine structures during the plasma etch. This undercut happens within a very short over-etch after the accelerometer is released. The reason for the severe undercut is the reduced thermal conductance from the comb fingers to the substrate. The heat generated from chemical reaction and ion bombardment in silicon DRIE can not be dissipated effectively, which consequently raises the temperature of the suspended microstructures. This positive feedback eventually leads to

high etching rate and the comb fingers will be undercut very quickly. The same effect was also observed on the z-axis sensing element where the heat can only be transferred through the two long torsional springs.

An improved process, as illustrated in Fig. 3, has been developed to overcome the above two effects.

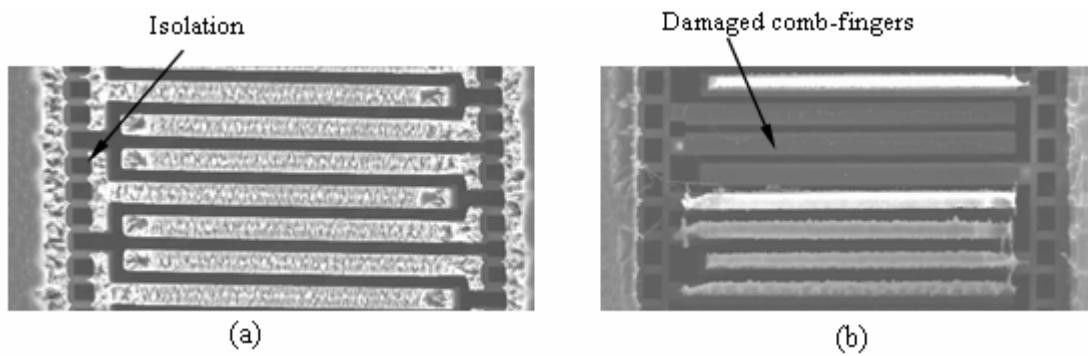


**Fig. 3.** Post-CMOS microfabrication process flow. (a) Backside etch. (b) Backside PR coating followed by front side anisotropic SiO<sub>2</sub> etch. (c) Top Al etch. (d) Deep Si etch and undercut to form isolation structures. (e) Anisotropic SiO<sub>2</sub> etch and DRIE Si etch for comb fingers and mechanical springs. (f) PR ashing for final release.

There is only one slight modification to the CMOS-MEMS process used in [9]. After the backside etch that produces a silicon membrane and defines the structure thickness (Fig. 3(a)), a thick sacrificial photoresist (PR) layer ( $\sim 50\mu\text{m}$ ) is applied on the back of the silicon membrane (Fig. 3(b)). After the isolation etching is completed (Fig. 3(c)-3(d)), this PR layer functions as a thermal path during the DRIE silicon etch that forms the entire microstructure (Fig. 3(e)). Finally, the PR is removed by oxygen plasma ashing to release the device (Fig. 3(f)). In Fig. 4, a comparison is made between sensing comb fingers fabricated with and without backside photoresist coating. The undercut of the silicon on comb fingers is greatly reduced and the finger damage is completely avoided by using the modified process (Fig. 4(a)). In contrast, without the PR layer as thermal path, electrical isolation trenches greatly reduce thermal flow from comb fingers to substrate. Consequently comb fingers are overheated and seriously undercut (Fig. 4(b)).

Furthermore, the PR layer helps reducing the backside contamination caused by back scattering. It also helps in tuning the isolation trench profile and relocating the contaminants on the sidewalls. As a consequence, microstructures can be completely released without the micro connections caused by the contaminant particles. This can also be observed in Fig. 4(a).

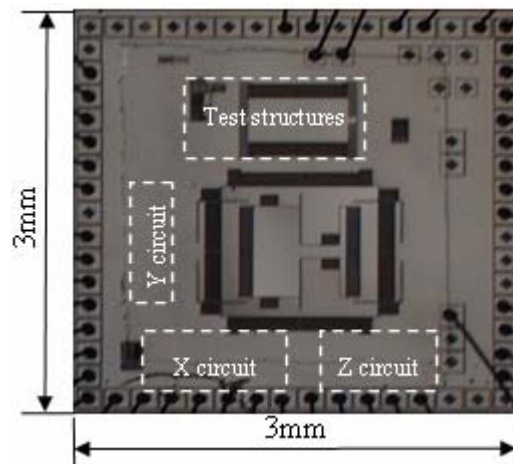
It should be noted that the thermal effect and the modified process described above are valid to many other MEMS devices with structures similar to this 3-axis accelerometer. A proper device design also helps in reducing the thermal problem described above. By considering the aspect-ratio dependent etching effect (ARDE), we can design the device in such a way that the etch-through sequence for different structures can be well controlled.



**Fig. 4.** Comparison of microstructures fabricated with and without backside PR coating. (a) With PR coating, the comb fingers are completely released with slight footing effect; (b) without coating, some comb fingers are completely damaged due to the heating effect.

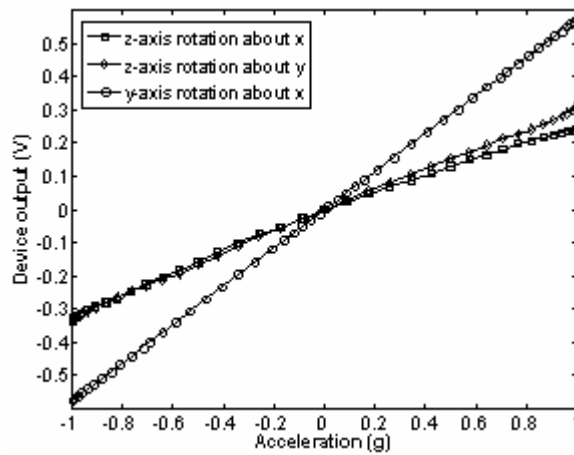
#### 4. Device Characterization

Fig. 5 is the photograph of a wire bonded die showing the locations of the 3-axis sensor and interface circuits. A dummy on-chip interface circuit was tested with an overall gain of 40 dB and a 16 nV/ $\sqrt{\text{Hz}}$  electronic noise floor was measured.

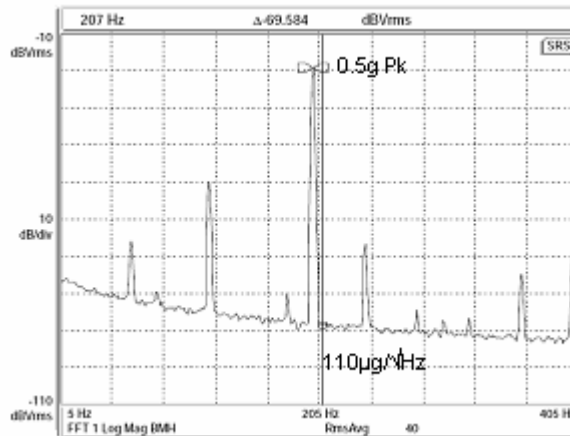


**Fig. 5.** Photograph of the wire bonded die.

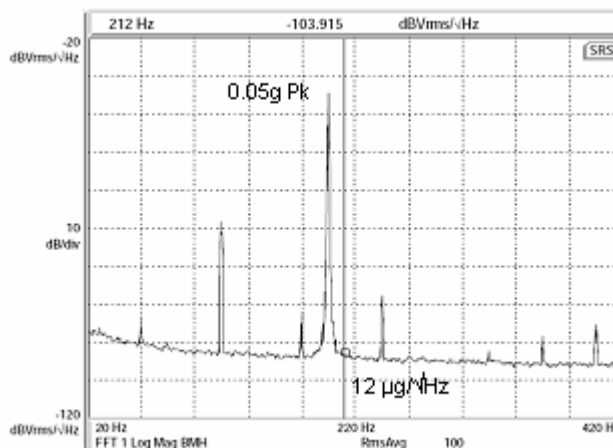
The sensitivities in the lateral axes and z-axis were measured as 560 mV/g and 320 mV/g, respectively, at a 1.5 V modulation signal, by using a quasi-static rotation stage. The resonant frequency of z-axis was measured as 1.5 kHz using a Polytech laser vibrometer. It's about 15% lower than the simulated results, reflecting a remaining slight undercut to the mechanical springs in the plasma etch process. The resonant frequencies of lateral axes are still under test. Due to the asymmetry of the z-axis proof mass, the z-axis sensing element has relatively high cross-axis sensitivities which were measured to be 2.1% from the x-axis and 4.7% from the y-axis, as shown in Fig. 6. The noise measurement was conducted using a LDS shake table and SRS network spectrum analyzer. The spectral response of the z-axis output at a 200 Hz, 0.5-g external acceleration is shown in Fig. 7. The overall noise floor of the z element is 110  $\mu\text{g}/\sqrt{\text{Hz}}$ . Although both x- and y-axis have the same number of identical sensing comb-fingers, there is a slight sensitivity difference between these two lateral axes due to the arrangement of the mechanical springs. The spectrum of y-axis output under a 200 Hz, 0.05-g acceleration is shown in Fig. 8. A noise floor of 12  $\mu\text{g}/\sqrt{\text{Hz}}$  is demonstrated.



**Fig. 6.** Static test results of the z- and y- axis using a precision rotary stage.



**Fig. 7.** The spectrum of the z-axis output under 0.5g at 200 Hz (RBW = 1Hz).



**Fig. 8.** The spectrum of the y-axis output under 0.05g at 200 Hz (RBW = 1Hz).

An overall temperature coefficient of sensitivity (TCS) of approximately 0.28%/°C was measured, which is mainly caused by the gain drifting of the first open-loop amplification stage of the on-chip

amplifier. This is verified by circuit simulation, and a temperature insensitive amplifier is under design. In order to measure the temperature-dependent curling of the sensing comb drives, a band heater was taped on the back of the PLCC-52 sensor package, and the sensor temperature was measured by a spot thermocouple. The vertical curling of the sensing comb fingers was measured using a Wyko optical profilometer. A maximum negative 0.533  $\mu\text{m}$  net curling at the free end of the comb-fingers was measured in a temperature range from room temperature to 96°C. Since the sensor structure thickness is about 50  $\mu\text{m}$ , the corresponding change of the electrode engaged area was approximately 0.23%. Based on these data, a positive 304 ppm/°C temperature coefficient of sensitivity (TCS) of the lateral-axis sensing was derived. Due to the complete SCS structure, temperature-induced structure curling was not observed on the z-axis sensing element.

The measured performance of the device is summarized in Table 1. As a comparison, the performance of ADXL330, a 3-axis accelerometer from ADI, is included.

**Table 1.** Performance summary of the reported device and comparison with ADXL330 from ADI [1].

Parameters	Measured values	
	This work	ADXL330
Chip size (mm × mm)	3×3	4×4 (package)
Lateral axes sensitivity (mV/g)	560	300
Z axis sensitivity (mV/g)	320	300
Circuit noise floor (nV/ $\sqrt{\text{Hz}}$ )	16	-
Power consumption of each axis (mW)	1	0.64~1.15
Lateral axes noise floor ( $\mu\text{g}/\sqrt{\text{Hz}}$ )	12	170
Z axis noise floor ( $\mu\text{g}/\sqrt{\text{Hz}}$ )	110	350
Sensitivity temperature drift (%/°C)	0.28	0.01

## 5. Conclusion

A 3-axis CMOS-MEMS accelerometer with a single proof mass has been demonstrated in this work. The single-crystal silicon incorporated in the device ensures robust sensor structures and high resolution. Low-power consumption (1 mW for each axis) and low-noise floors in all three axes are achieved simultaneously with a compact device size. Compared to the previous processes, this modified post-CMOS microfabrication process has greatly increased the release yield by removing and relocating the contaminants generated in the plasma etching process. It also has increased the process tolerances by providing additional thermal path to the suspended microstructures in plasma etching processes. Though only photoresist was used in this work, there exist many other more suitable materials for the additional heat dissipation. This method can be widely used in micromachining MEMS devices with similar suspended structures. Due to its small size, low power consumption and high resolution, this 3-axis accelerometer has a variety of applications including health monitoring, video games and infrastructure securities.

## Acknowledgements

This project is partially supported by the NASA/UCF-UF Space Research Initiative and University of Florida Startup Fund. The CMOS chip fabrication was supported by MOSIS through its Educational Program.

## References

- [1]. Analog Device, Inc., ADXL330 low-power, 3-axis accelerometer, *Datasheet, Rev. PrA.*, Oct. 2005.
- [2]. M. Lemkin and B. E. Boser, A three-axis micromachined accelerometer with a CMOS position-sense interface and digital offset-trim electronics, *IEEE Journal of Solid-State Circuits*, Vol. 34, 4, 1999, pp. 456-468.
- [3]. J. Chae, H. Kulah, and K. Najafi, A monolithic three-axis micro-g micromachined silicon capacitive accelerometer, *Journal of Microelectromechanical Systems*, Vol. 14, 2, 2005, pp. 235-242.
- [4]. Freescale Semiconductor, *MMA7260Q Datasheet, Rev. 2.*, Mar. 2006.
- [5]. Bosch Sensortec GmbH, *SMB360 Accelerometer Datasheet*, Ver. 1.0-112005, May 2005.
- [6]. ST Microelectronics, LIS3L02AQ3 MEMS linear inertial sensor, May 2005.
- [7]. H. Takao, H. Fukumoto, and M. Ishida, A CMOS integrated three-axis accelerometer fabricated with commercial submicrometer CMOS technology and bulk-micromachining, *IEEE Transactions on Electron Devices*, vol. 48, 9, 2001, pp. 1961-1968.
- [8]. H. Xie, Z. Pan, W. Frey, and G. Fedder, Design and Fabrication of an Integrated CMOS-MEMS 3-Axis Accelerometer, *The 2003 Nanotechnology Conference*, San Francisco, CA, Feb. 23-27, 2003, pp.292-295.
- [9]. H. Qu, D. Fang, and H. Xie, A single-crystal silicon 3-axis CMOS-MEMS accelerometer, *Proceedings of IEEE Sensors 2004*, Vienna, Austria, Oct. 24-27, 2004, pp.661-664.
- [10]. D. Fang, H. Qu, and H. Xie, A 1mW Dual-Chopper Amplifier for a 50- $\mu\text{g}/\sqrt{\text{Hz}}$  Monolithic CMOS-MEMS Capacitive Accelerometer, *Technical Paper Digests of 2006 Symposium on VLSI Circuits*, Honolulu, HI, Jun. 15-17, 2006, pp.59-60.

---

2007 Copyright ©, International Frequency Sensor Association (IFSA). All rights reserved.  
(<http://www.sensorsportal.com>)

# FIRST MEDITERRANEAN PHOTONICS CONFERENCE

*Jolly Hotel, Ischia  
25-28 June 2008*

**A European Optical Society Topical Meeting  
Organized by Italian Optics and Photonics Society**

**General chairman: Prof. Antonello Cutolo  
Co-chairs: Prof. Mario Armenise, Prof.ssa Roberta Ramponi**

## **Preliminary list of topics**

Polymers, carbon nanotubes and metamaterials  
for photonics  
Post silicon materials, devices and technology  
Micro and nanophotonics devices  
Photonic crystals  
Optical fibers, guided and integrated optics

## ***And their applications to***

Telecommunications  
Non linear optics  
Optical sensors  
Optical contactless characterization techniques  
High precision measurements  
Industrial applications  
Aeronautics and aerospace  
Underwater applications  
Structural and environment monitoring  
Biosensors  
Homeland security



**Deadline for submitting a four page summary: March 31st 2008  
Acceptance notification by April 30<sup>th</sup> 2008  
To receive further informations, please, contact:  
[paola.ambrosino@unisannio.it](mailto:paola.ambrosino@unisannio.it)**

## Guide for Contributors

---

### Aims and Scope

*Sensors & Transducers Journal* (ISSN 1726- 5479) provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because it is an open access, peer review international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per annual by International Frequency Association (IFSA). In addition, some special sponsored and conference issues published annually.

### Topics Covered

Contributions are invited on all aspects of research, development and application of the science and technology of sensors, transducers and sensor instrumentations. Topics include, but are not restricted to:

- Physical, chemical and biosensors;
- Digital, frequency, period, duty-cycle, time interval, PWM, pulse number output sensors and transducers;
- Theory, principles, effects, design, standardization and modeling;
- Smart sensors and systems;
- Sensor instrumentation;
- Virtual instruments;
- Sensors interfaces, buses and networks;
- Signal processing;
- Frequency (period, duty-cycle)-to-digital converters, ADC;
- Technologies and materials;
- Nanosensors;
- Microsystems;
- Applications.

### Submission of papers

Articles should be written in English. Authors are invited to submit by e-mail [editor@sensorsportal.com](mailto:editor@sensorsportal.com) 6-14 pages article (including abstract, illustrations (color or grayscale), photos and references) in both: MS Word (doc) and Acrobat (pdf) formats. Detailed preparation instructions, paper example and template of manuscript are available from the journal's webpage: <http://www.sensorsportal.com/HTML/DIGEST/Submission.htm> Authors must follow the instructions strictly when submitting their manuscripts.

### Advertising Information

Advertising orders and enquires may be sent to [sales@sensorsportal.com](mailto:sales@sensorsportal.com) Please download also our media kit: [http://www.sensorsportal.com/DOWNLOADS/Media\\_Kit\\_2007.PDF](http://www.sensorsportal.com/DOWNLOADS/Media_Kit_2007.PDF)

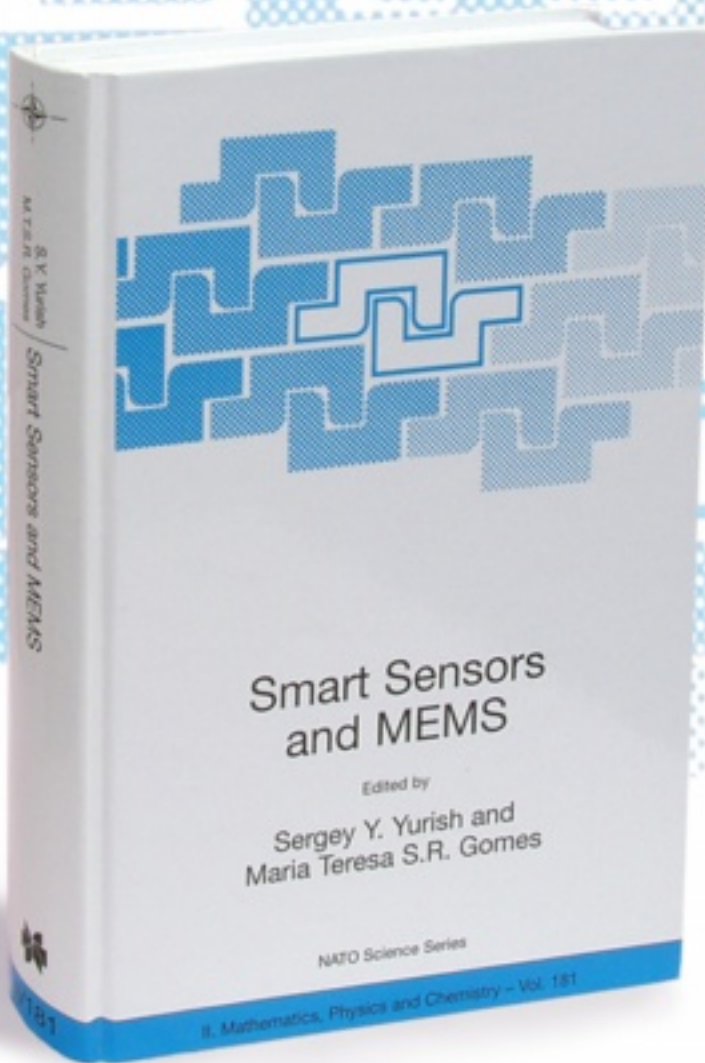
# Smart Sensors and MEMS

Edited by

Sergey Y. Yurish and  
Maria Teresa S.R. Gomes

The book provides an unique collection of contributions on latest achievements in sensors area and technologies that have made by eleven internationally recognized leading experts ...and gives an excellent opportunity to provide a systematic, in-depth treatment of the new and rapidly developing field of smart sensors and MEMS.

The volume is an excellent guide for practicing engineers, researchers and students interested in this crucial aspect of actual smart sensor design.



**Kluwer Academic Publishers**

Order online:

[www.sensorsportal.com/HTML/BOOKSTORE/Smart\\_Sensors\\_and\\_MEMS.htm](http://www.sensorsportal.com/HTML/BOOKSTORE/Smart_Sensors_and_MEMS.htm)

[www.sensorsportal.com](http://www.sensorsportal.com)