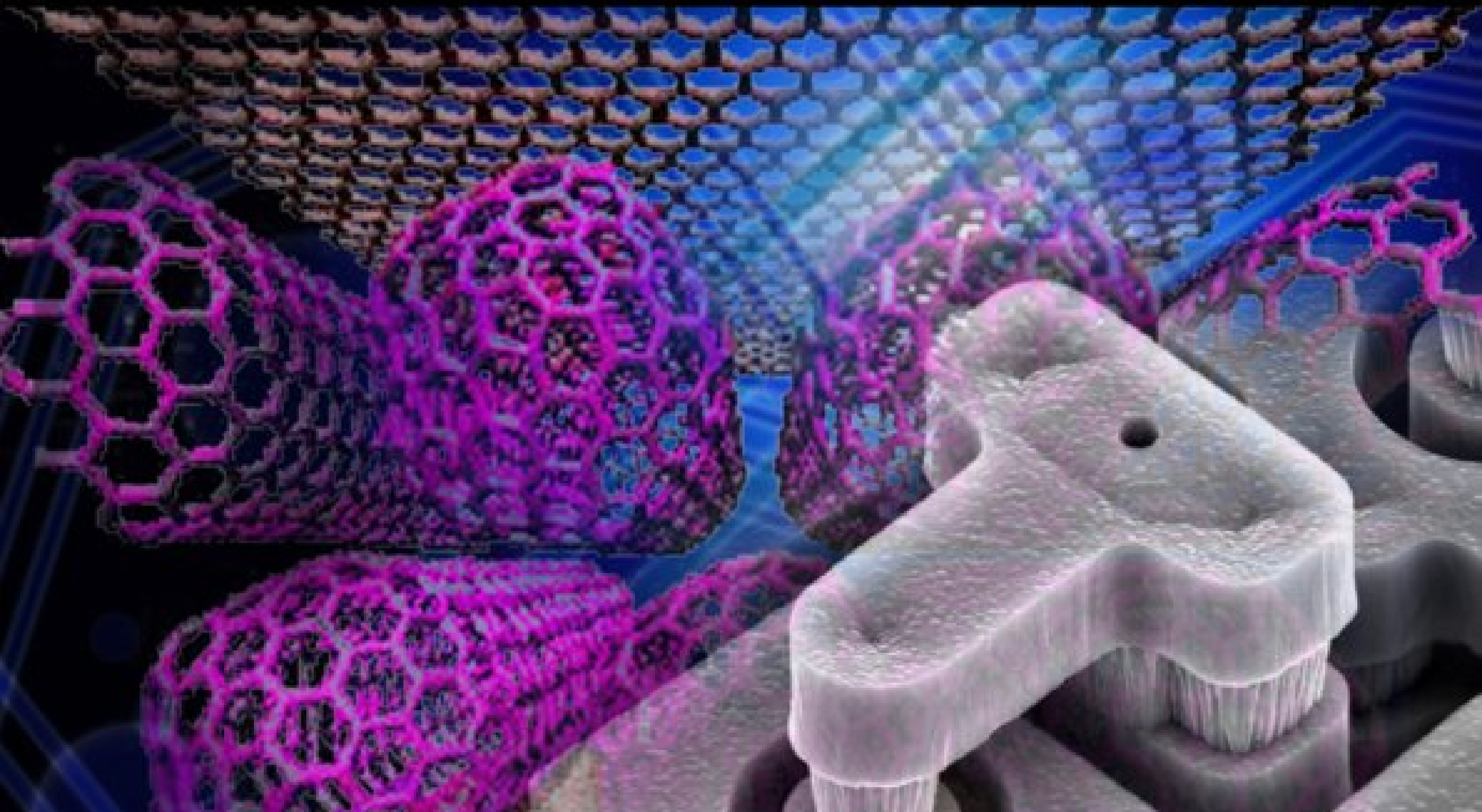
ISSN 1726-5749

SENSORS & TRANSDUCERS

10/07
Special Issue



MEMS & NEMS: Devices and Systems

International Frequency Sensor Association Publishing

Sensors & Transducers

Special Issue
October 2007

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, Vitorio, Universitá 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, Nothern 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
Djordjevich, 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
Granel, 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 Alcala, 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 Cataluna, 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
Mohammadi, 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 Lahoucin, 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 Setebal, Portugal
Petsev, Dimiter, 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, Bhbha Atomic Research Centre, Mumbai, India
Schneider, John K., Ultra-Scan Corporation, USA
Seif, Selemani, 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

Sensors & Transducers Journal (ISSN 1726-5479) is a peer review international journal published monthly online by International Frequency Sensor Association (IFSA). Available in electronic and CD-ROM. Copyright © 2007 by International Frequency Sensor Association. All rights reserved.

Sensors & Transducers Journal

Contents

Special Issue
October 2007

www.sensorsportal.com

ISSN 1726-5479

Research Articles

Foreword
Elena Gaura and James P. Brusey………………………………………………………………………… I

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

Perturbation Stochastic Finite Element Analysis of Thermoelastic Quality Factor of Micro-Resonators
Séverine Lepage and Jean-Claude Golinval.. 124

A Semi-Analytical Model for Calculating Touch-Point Pressure and Pull-in Voltage for Clamped Diaphragms with Residual Stress
Anurekha Sharma and P. J. George 131

The Development of Chemical Nanosensors
A. J. Jin, J. Li, Y. Lu.. 140

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

International Frequency Sensor Association (IFSA).

Foreword

The 10th 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

Sensors & Transducers Journal, Special Issue, October 2007, pp. 140-146

Sensors & Transducers

ISSN 1726-5479
© 2007 by IFSA
http://www.sensorsportal.com

The Development of Chemical Nanosensors

[1]A. J. JIN, [*]J. LI, [*]Y. LU
Hoda Globe Company, Engineering Division, 800 W El Camino Real,
Mountain View, CA 94042, USA.
[*]NASA, Ames Research Center, Mail Stop 230-3, Moffet Field, CA 94035, USA
Tel.: 001-650-853-3089
E-mail: aj.jin@ieee.org

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

Abstract: This paper presents a study of the chemical nanosensors (CNS) for space and environmental applications, safety alert devices, etc. The high-resolution nanosensors are applied to detect the rocket fuel hydrazine leak. The CNS detects changes in the electrical conductivity response during the chemical species presence. When the hydrazine is leaked into air, it immediately dissociates into NO_2. As a result, we are actually detecting the NO_2 gas in the trace amount from the fuel leakage. In more detail, we will discuss the sensor chips preparation and process control in terms of the resistance range control while depositing the nanomaterials on the sensors. Furthermore, there will be detailed studies of the CNS response to the dry NO_2 in the ambient conditions. The inter-digitized electrode sensors are characterized to the variables of NO_2 concentration and nanomaterials. *Copyright © 2007 IFSA.*

Keywords: Chemical nano sensors, Hydrazine, Nano technology, Nanosensor stability

---

1. Background

Nanoscience and nanotechnology, through the exploration and control of the nanomaterials at the nanometer scale, is considered as one of the key research areas for the future growth of US economy. Many sensor devices are part of our everyday life. More sensor improvements are needed for small size, great sensitivity and selectivity, fast response, minimal power consumption, and reliability demands, etc. Due to the well organized structure in atomic level of nanomaterials and their large surface-to-volume ratio, nanosensors are becoming very attractive for the next-generation of the sensing devices. Chemical nanosensors (CNS) are fabricated for space and environmental applications. For example, we can apply CNS to detect the electrical signal during the chemical species presence.

Fig. 1 is a conceptual diagram where the sensor is placed so that the physical and chemical environment can be monitored and controlled. These conditions include the total gas flow rate, chemical concentration, humidity, chemical interface, temperature, pressure, etc. When chemical gases pass by CNS, the nanomaterials in the sensor platform respond correspondingly. The sensor response by electrical conductivity change is a result of the chemical sensing. Each sensor response is monitored electronically and is recorded in the computer as a sensor signal and for further data processing.

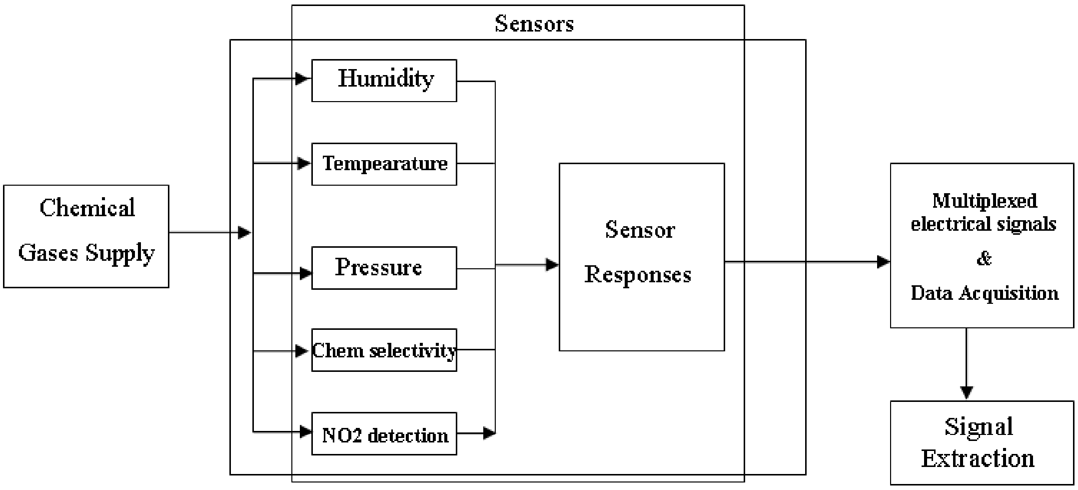


Fig.1. The schematic shows the conceptual CNS NO_2 experiments.

The purpose of our CNS project is to monitor the trace amount of NO_2 composed from the leakage of one fuel component, hydranzaine. The liquid hydrazine (N_2H_4) is an efficient rocket propellant. When the N_2H_4 is leaked into air, it immediately dissociates and produces NO_2.

As published in previous literature [1], carbon nanotubes (CNT) is very sensitive to NO_2 and it is therefore a very promising CNS to be employed as a commercial sensor product. The sensor development in this study will focus on the CNS and its NO_2 response in relationship to various NO_2 concentrations. In terms of the dry NO_2 analyte response, we will investigate the CNS on the effects of various variables such as nanomaterials and gap size, etc.

We surveyed many sensing nanomaterials, including - 1) CGNT, 2) CGNT+MPC, 3) CGNT+polymer. The nanomaterials were discussed in Section 2.2, where CGNT is the CVD grown nanotubes. The MPC is monolayer-protected gold clusters (MPC). The polymer is cellulose hydroxypropyl.

We employ the carbon nanotubes (CNT) as the base nanomaterials in the form of the CVD growth. Illustration of Fig. 2 procedures is aimed at preparing a sensor chip before its sensor application.

2. Sensor Studies and Optimization

2.1. IV Characterization

The IV characteristics of several nanomaterials are studied in the voltage windows and in the reversal voltage as well. Current and voltage characteristics are measured with a semiconductor parameter analyzer.

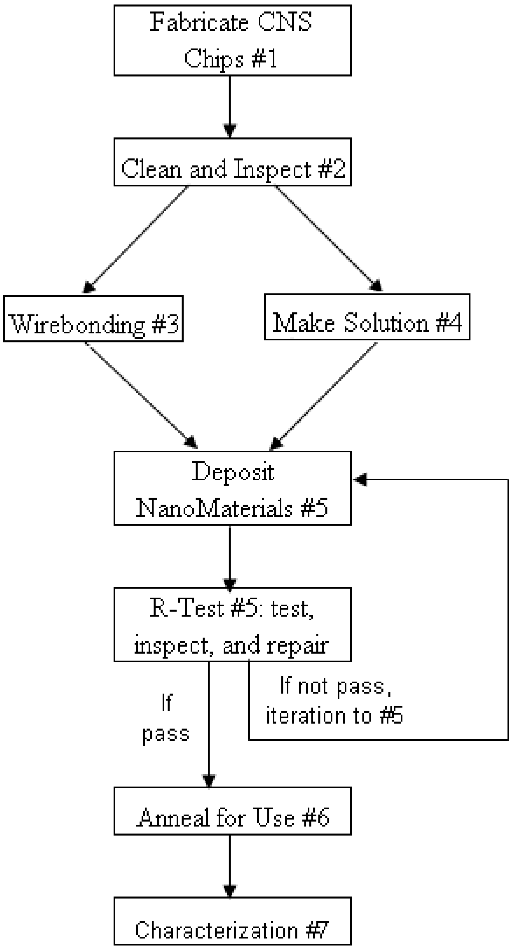


Fig. 2. The flow chart shows preparation procedures of the clean CNS chip.

We conducted the current measurement with the DC voltage sweep from –2 V to 2 V with 0.01 V increment and employed the HP4155B semiconductor parameter analyzer. Some typical IV curves are shown in Fig. 3. For example, we investigated the IV sweep curves from typical sensors with a SWNT/MPC nanomaterial (on the left), a SWNT/cellulose nanomaterial (at middle), and the cast-SWNT nanosensors (on the right). We have plotted a variety of IV curves in Fig. 3 (a), 3 (b), and 3 (c) for the 4 µm feature gap of three typical interdigitated electrode (IDE) sensors. The non-linearity of the IV curves is also very interesting in order to identify the optimal sensors operating regime.

2.2. Bias Voltage Optimization

Moreover, we studied the bias effects by applying different DC bias values. As stated at above, the nanosensors with different nanomaterials show different IV electrical response. The electrical resistance of the CNS may be nonlinear. Therefore, we chose several different dc-bias voltages to measure the sensor response curve at various NO_2 concentrations (Fig.4).

When the gas flow is the pure air, we only detect the baseline without any signal. Then we expose a sensor by applying on a sensor the chemical/gas flow with a concentration programmed in the same total flow. The change in the electrical signal is measured and the response is extracted from the sensor. Following this step, the sensor is purged to recover.

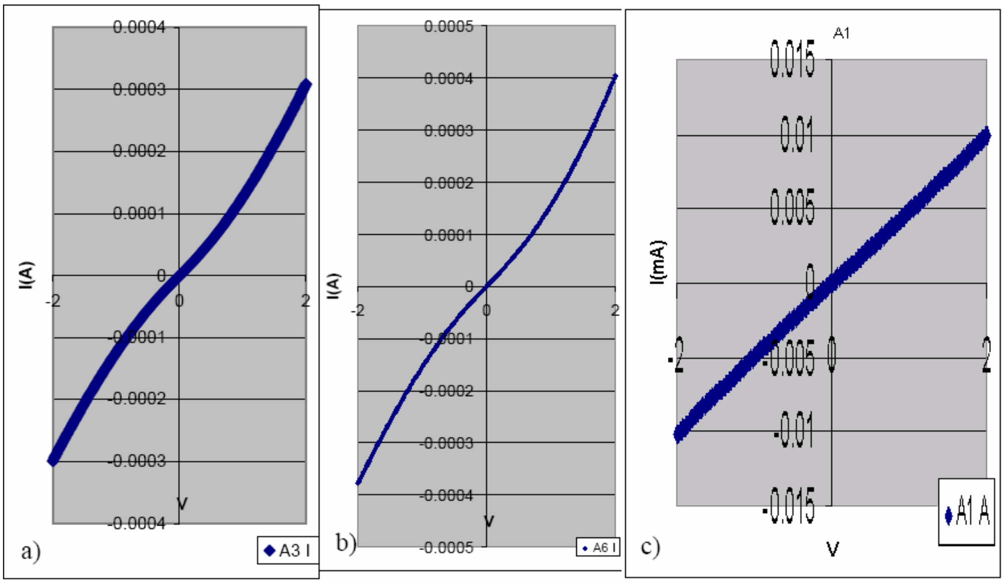


Fig.3. The IV curves of the nanosensors are characterized for three nanomaterials.
(a) CNT/MPC, (b) CNT/polymer, (c) CNT.

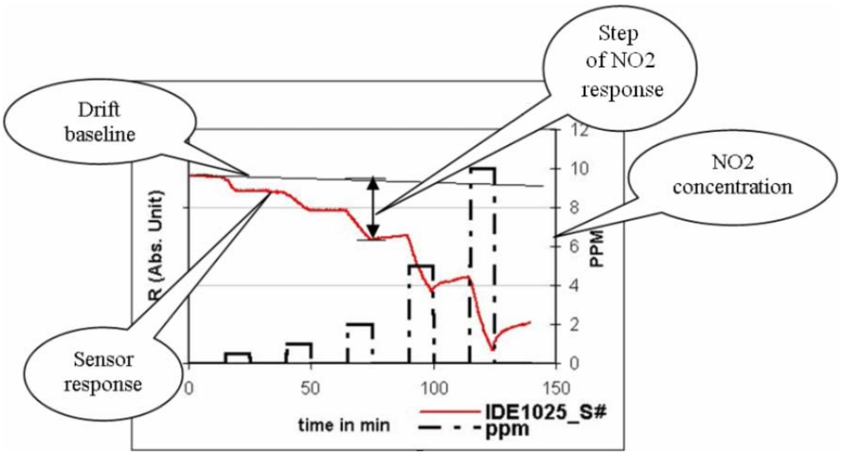


Fig.4. Typical data trace of the CNS response to the dry NO_2 chemical at various concentrations. The influence of the various environmental factors will be discussed later.

After having enough purge time, go back and iterate the exposure-purge steps until the sensing process finish. Here is a typical recipe where different gas flow is sequentially applied to the sensor:

15’ Air →10’ Exposing_x (x = 0.5-, 1-, 2-, 5-, or 10-ppm) →15’ Air… where the time unit is minutes, and the unit of exposure concentration is ppm or parts per million. A typical recipe may contain many exposure-purge cycles by iterating through a given set of concentrations.

Fig. 5 is a typical KAC31 run, where the chip KAC31 is a sensor chip with nanomaterials of CGNT-only, CGNT and MPC composite, and CGNT and polymer composite, respectively. Sixteen sensors are shown to have strong response. We analyzed the data and the relationship between the resistance change and the chemical flow as follows:

1) Make a linear fit to the drift baseline (on the initial 15’ conditioning);
2) The baseline resistance is taken near the end of the recipe step-1 that is the end of the initial conditioning;

3) Using linear regression method, extrapolate the baseline as a function of time;
4) The response dR is calculated as the difference between the resistance signal and the baseline at the time immediately after the exposure step. As shown in Fig. 3.2a, the CNS response steps are extracted for every concentration.

Furthermore, the analysis yields the dR and dR/R0 dependence upon NO_2 concentration.

By extracting dR/noise ratio for every sensor at all concentrations, we calculate the sensitivity function and plot this function in Fig. 5 versus the sensors. As a remark, the sensor's resolution in terms of the sensitivity limit, S/N, can also be derived by an extrapolation method.

Table 1. Tabulated is a typical recipe of the dry NO_2 chemical sampling. The sensors chip is conditioned and tested by this recipe. The standard flow rate in total is 400CCM for the most tests. Note that every concentration is diluted by pure air.

Step number	1	2	3	4	5	6	7	8	9	10	11
Mode (F-flow, C-concentration)	F	C	F	C	F	C	F	C	F	C	F
Time (minutes)	15'	10'	15'	10'	15'	10'	15'	10'	15'	10'	15'
NO2 (ppm)	0	0.5	0	1	0	2	0	5	0	10	0

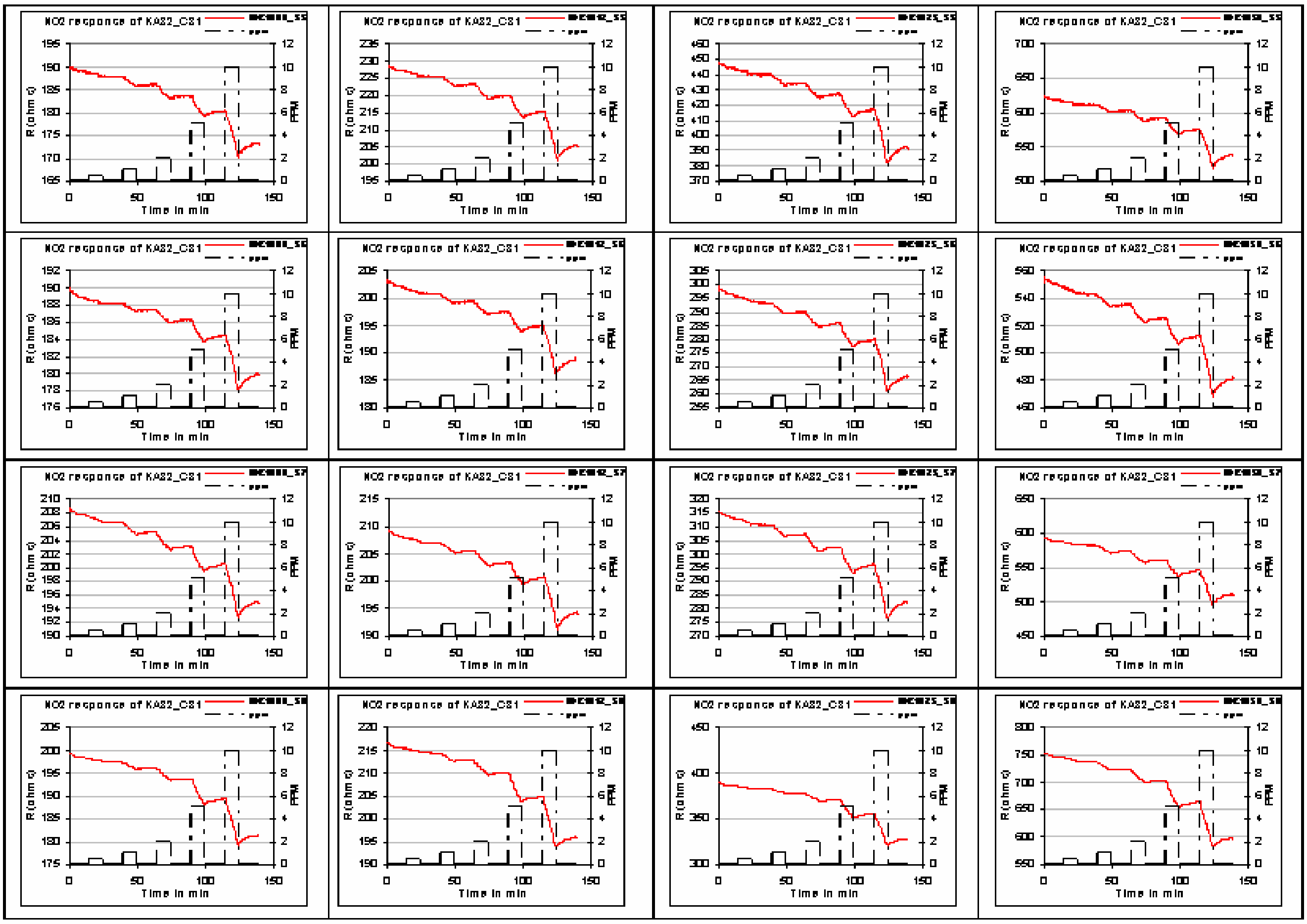


Fig.5. Every trace at above shows an individual sensor of KAC31 chip to the NO_2 chemical diluted in air at 400 CCM total flow rate and at ambient conditions. The sensors are labeled. The coordinates are at below: x-axis is the minutes of time; y-axis at left is the electrical signal; the secondary y-axis at right indicates NO_2 levels at 0-, 0.5-, 1-, 2-, 5-, 10-ppm concentrations.

Furthermore, the analysis yields the dR and dR/R0 dependence upon NO_2 concentration. By extracting the dR/noise ratio for every sensor at all concentrations, we calculate the sensitivity function and plot this function in Fig. 5 versus both the sensor and the NO_2 concentration.

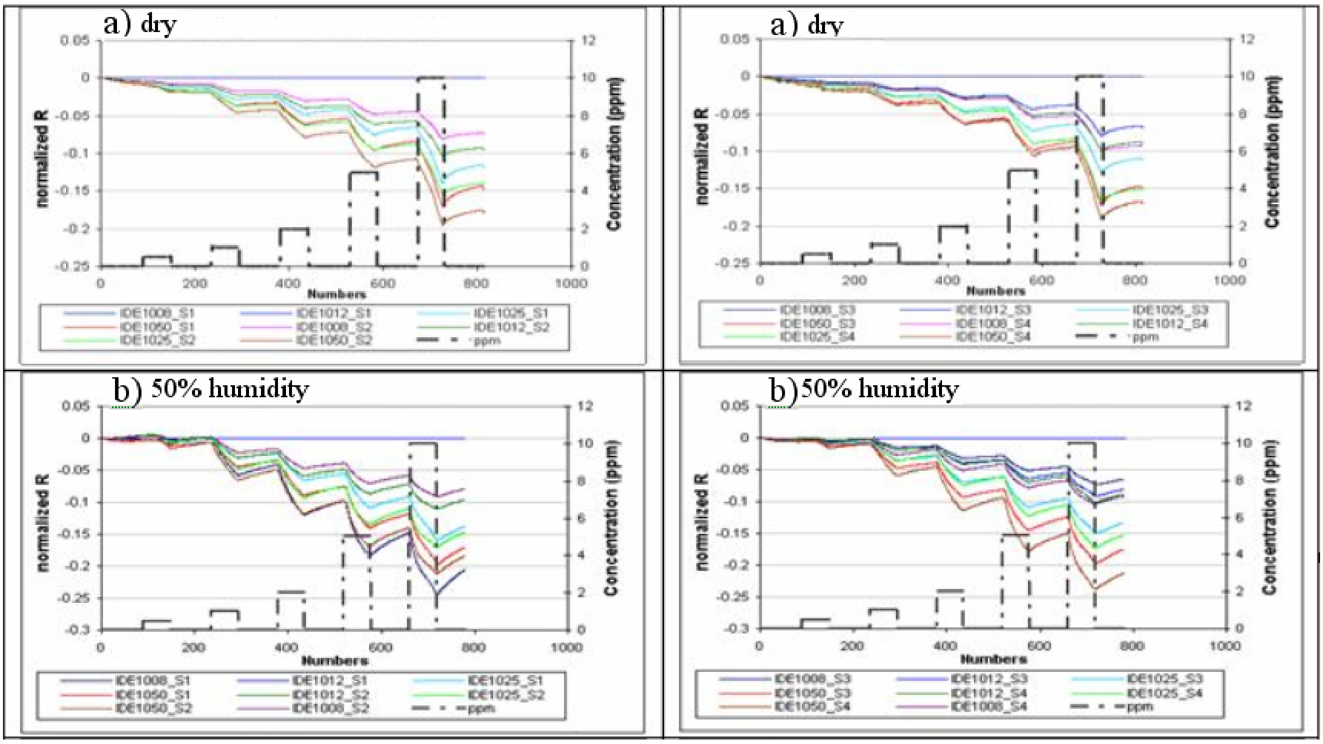


Fig.6. These charts show the relative response traces of the KAC31 chip with two RH levels: (a) 0% or dry, (b) 50%. The NO_2 concentration varies as shown at 0.5-, 1-, 2-, 5-, and 10-ppm.

We have studied the sensor's responses at various humidity values. The humidity tests were set up with the CNS characterization system. The humidifier was calibrated by the factory. We observed that, for the response at low humidity range of 0 % to 30 % RH, the relative sensor response shows that the humidity in this range has quite small effects on the nanosensor response. The NO_2 response increases with the increasing at a humidity level of 50 % and greater.

3. Conclusion

In summary, the CNS has significantly high resolution. We have studied the trace concentration of NO_2 in sub 1-ppm regime. Further studies are in the progress to characterize the life-expectance of CNS and the effect of temperature, pressure, etc.

Acknowledgment

The author is indebted to discussions with Dr. Pedro Medelius from ASRC at Kennedy Space Center, Florida, USA.

References

[1]. J. Li, Y. Lu, Q. Ye, M. Cinke, J. Han, and M. Meyyapan, *NanoLett.*, 3, 2003, p.929.

[2]. J. Li, Y. Lu, Q. Ye, and L. Delzeit, *Electrochemical and Solid-State Letters*, 8 _11_ H100-H102 _2005.

[3]. P. Young, Y. Lu, R. Terrill, and J. Li, *Journal of Nanoscience and Nanotechnology*, 5, 2005, p.1.

[4]. L. Delzeit, I. McAninch, B.A. Cruden, D. Hash, B. Chen, J. Han, M. Meyyapan, *J. Appl. Phys.*, 91, 2002, p. 6027.

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

Sensors & Transducers Journal

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 additional, 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 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/Submition.htm Authors must follow the instructions strictly when submitting their manuscripts.

Advertising Information

Advertising orders and enquires may be sent to sales@sensorsportal.com Please download also our media kit: 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

www.sensorsportal.com