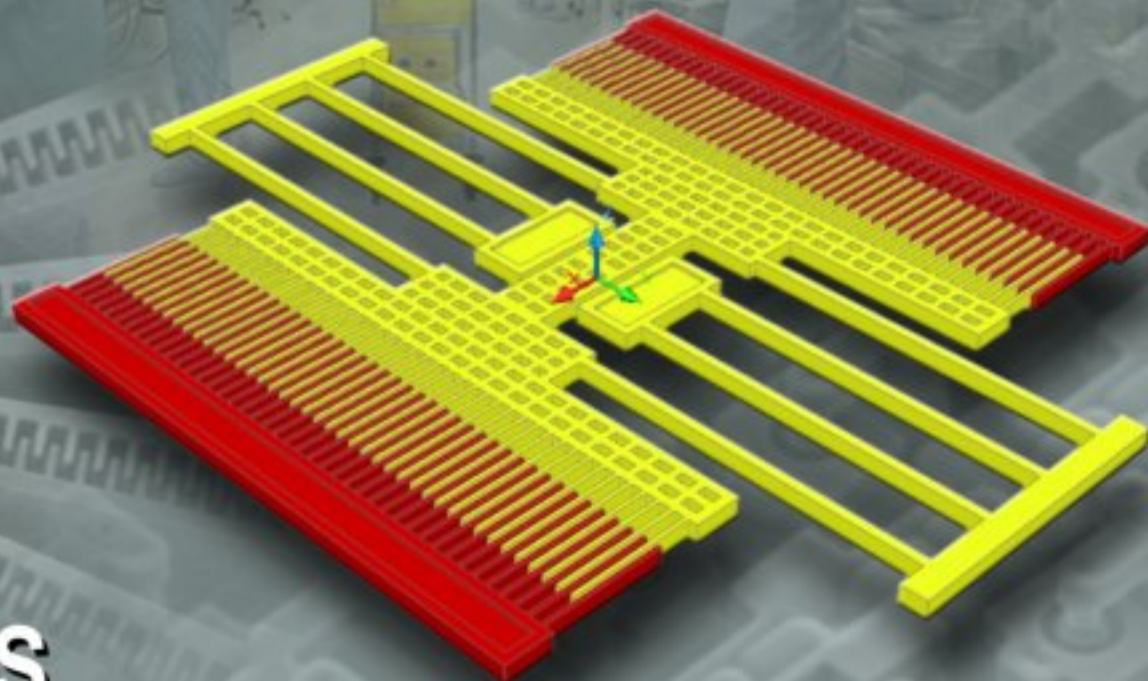


ISSN 1726-5479

SENSORS & TRANSDUCERS

vol. 103
4/09



MEMS and Modern Technologies

International Frequency Sensor Association Publishing



Editor-in-Chief: professor Sergey Y. Yurish, phone: +34 696067716, fax: +34 93 4011989, e-mail: editor@sensorsportal.com

Editors for Western Europe

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

Editor South America

Costa-Felix, Rodrigo, Inmetro, Brazil

Editor for Eastern Europe

Sachenko, Anatoly, Ternopil State Economic University, Ukraine

Editors for North America

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

Editor for Asia

Ohyama, Shinji, Tokyo Institute of Technology, Japan

Editor for Asia-Pacific

Mukhopadhyay, Subhas, Massey University, New Zealand

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, Vyngantas, 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, RF Arrays Systems, India
Basu, Sukumar, Jadavpur University, India
Beck, Stephen, University of Sheffield, UK
Ben Bouzid, Sihem, Institut National de Recherche Scientifique, Tunisia
Benachaiba, Chellali, Universitaire de Bechar, Algeria
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, Jiming, Zhejiang University, China
Chen, Rongshun, National Tsing Hua University, Taiwan
Cheng, Kuo-Sheng, National Cheng Kung University, Taiwan
Chiang, Jeffrey (Cheng-Ta), Industrial Technol. Research Institute, 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 Nacional de Colombia, Colombia
Courtois, Christian, Université 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
Dickert, Franz L., Vienna University, Austria
Dieguez, Angel, University of Barcelona, Spain
Dimitropoulos, Panos, University of Thessaly, Greece
Ding, Jianning, Jiangsu Polytechnic University, China
Djordjevic, Alexander, 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
Francis, Laurent, University Catholique de Louvain, Belgium
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 Rosa, 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
Hadjloucas, Sillas, The University of Reading, UK
Hashsham, Syed, Michigan State University, USA
Hasni, Abdelhafid, Bechar University, Algeria
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
Jiang, Wei, University of Virginia, USA
Jiao, Zheng, Shanghai University, China
John, Joachim, IMEC, Belgium
Kalach, Andrew, Voronezh Institute of Ministry of Interior, Russia
Kang, Moonho, Sunmoon University, Korea South
Kaniusas, Eugenijus, Vienna University of Technology, Austria
Katake, Anup, Texas A&M University, USA
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, Kyungpook National University, 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
- 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, Saisune**, 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**, University of Oklahoma, 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
- Melnyk, Ivan**, Photon Control Inc., Canada
- 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**, Benemérita Universidad Autónoma de Puebla, Mexico
- Moradi, Majid**, University of Kerman, Iran
- Morello, Rosario**, University "Mediterranea" of Reggio Calabria, Italy
- Mounir, Ben Ali**, University of Sousse, Tunisia
- Mulla, Imtiaz Sirajuddin**, National Chemical Laboratory, Pune, India
- Neelamegam, Periasamy**, Sastra Deemed University, India
- Neshkova, Milka**, Bulgarian Academy of Sciences, Bulgaria
- Oberhammer, Joachim**, Royal Institute of Technology, Sweden
- Ould Lahoucine, Cherif**, 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
- Penza, Michele**, ENEA C.R., Italy
- 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
- Raof, Kosai**, Joseph Fourier University of Grenoble, France
- Reig, Candid**, University of Valencia, Spain
- Restivo, Maria Teresa**, University of Porto, Portugal
- Robert, Michel**, University Henri Poincare, France
- Rezazadeh, Ghader**, Urmia University, Iran
- Royo, Santiago**, Universitat Politècnica de Catalunya, Spain
- Rodriguez, Angel**, Universidad Politécnica de Catalunya, Spain
- Rothberg, Steve**, Loughborough University, UK
- Sadana, Ajit**, University of Mississippi, USA
- Sadeghian Marnani, Hamed**, TU Delft, The Netherlands
- Sandacci, Serghei**, Sensor Technology Ltd., UK
- Sapozhnikova, Ksenia**, D.I.Mendeleyev Institute for Metrology, Russia
- Saxena, Vibha**, Bhabha Atomic Research Centre, Mumbai, India
- Shneider, 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
- Shankar, B. Baliga**, General Monitors Transnational, USA
- 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
- Singh, V. R.**, National Physical Laboratory, India
- Slomovitz, Daniel**, UTE, Uruguay
- Smith, Martin**, Open University, UK
- Soleymanpour, Ahmad**, Damghan Basic Science University, Iran
- Somani, Prakash R.**, Centre for Materials for Electronics Technol., India
- Srinivas, Talabattula**, Indian Institute of Science, Bangalore, India
- Srivastava, Arvind K.**, Northwestern University, USA
- 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
- Teker, Kasif**, Frostburg State University, USA
- Thumbavanam Pad, Kartik**, Carnegie Mellon University, USA
- Tian, Gui Yun**, University of Newcastle, UK
- 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
- Vazquez, 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, Lisheng**, The Chinese University of Hong Kong, Hong Kong
- Xu, Tao**, University of California, Irvine, USA
- Yang, Dongfang**, National Research Council, Canada
- Yang, Wuqiang**, The University of Manchester, UK
- Yaping Dan**, Harvard University, USA
- Ymeti, Aurel**, University of Twente, Netherland
- Yong Zhao**, Northeastern University, China
- Yu, Haihu**, Wuhan University of Technology, China
- Yuan, Yong**, Massey University, New Zealand
- 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

Volume 103
Issue 4
April 2009

www.sensorsportal.com

ISSN 1726-5479

Research Articles

Frontiers of Nanosensor Technology <i>Vinod Kumar Khanna</i>	1
Dual Comb Unit High-g Accelerometer Based on CMOS-MEMS Technology <i>Mehrdad Mottaghi, Farzan Ghalichi, Habib B. Ghavifekr</i>	17
Modeling of Micromachined Thermopiles Powered from the Human Body for Energy Harvesting in Wearable Devices <i>Vladimir Leonov, Ziyang Wang, Paolo Fiorini and Chris Van Hoof</i>	29
Design and Development of Polysilicon-based Microhotplate for Gas Sensing Application <i>Mahanth Prasad, V. K. Khanna and Ram Gopal</i>	44
Design of a Capacitive SOI Micromachined Accelerometer <i>Wenjing Zhao, Limei Xu</i>	52
Characteristic Features of RF MEMS Switches and its Various Applications <i>B. Mishra, Z. C. Alex</i>	65
Study on the Effects of Added Mass on Mechanical Behavior of a Microbeam <i>Mohammad Fathalilou, Ghader Reza zadeh, Yashar Alizadeh, Soheil Talebian</i>	73
Titanium Hydride Formation in Current-Biased Titanium Microbolometer and Nanobolometer Devices <i>S. F. Gilmartin, K. Arshak, D. Collins, B. Lane, D. Bain, S. B. Newcomb, B. McCarthy, A. Arshak</i> .	83
Squeeze-Film Damping Effect on Dynamic Pull-in Voltage of an Electrostatically-Actuated Microbeam <i>Hadi Yagubizade, Mohammad Fathalilou, Ghader Reza zadeh, Soheil Talebian</i>	96
Porous Silicon Hydrogen Sensor at Room Temperature: the Effect of Surface Modification and Noble Metal Contacts <i>Jayita Kanungo, Hiranmay Saha, Sukumar Basu</i>	102
Design and Analyses of Electromagnetic Microgenerator <i>Nibras Awaja, Dinesh Sood, Thurai Vinay</i>	109
Dynamic Pull-in Phenomenon in the Fully Clamped Electrostatically Actuated Rectangular Microplates Considering Damping Effects <i>Ghader Reza zadeh, Soheil Talebian, Mohammad Fathalilou</i>	122
Finite Element Analysis of Static and Dynamic Pull-In Instability of a Fixed-Fixed Micro Beam Considering Damping Effects <i>Mohammad Reza Ghazavi, Ghader Reza zadeh, Saber Azizi</i>	132

Effect of Polyimide Variation and its Curing Temperature on CMOS Based Capacitive Humidity Sensor and Characterization of Integrated Heater <i>B. N. Baliga, D. N. Tiwari, Kamaljeet Singh, Sanjay Verma, K. Nagachenchaiah</i>	144
Sputtered Silicon as a Potential Masking Material for Glass Micromachining – A Feasibility Study <i>Abhay B. Joshi, Dhananjay Bodas, S. A. Gangal</i>	155
Thermo-Mechanical Behavior of a Bilayer Microbeam Subjected to Nonlinear Electrostatic Pressure <i>Maliheh Pashapour, Seyed-Mehdi Pesteii, Ghader Rezazadeh, Shahriyar Kouravand</i>	161
Hydrogen and Methane Response of Pd Gate MOS Sensor <i>Preeti Pandey, J. K. Srivastava, V. N. Mishra and R. Dwivedi</i>	171

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/Submission.htm>

International Frequency Sensor Association (IFSA).

Thermo-Mechanical Behavior of a Bilayer Microbeam Subjected to Nonlinear Electrostatic Pressure

¹Maliheh Pashapour, ²Seyed-Mehdi Pesteii, ^{*3}Ghader Rezazadeh, ⁴Shahriyar
Kouravand

^{1,2,3} Mech. Eng. Dept., Urmia University, Urmia, Iran

⁴ Mech. Eng. Dept., Mashhad University, Mashhad, Iran

^{*}E-mail: g.rezazadeh@urmia.ac.ir

Received: 28 February 2009 /Accepted: 20 April 2009 /Published: 27 April 2009

Abstract: In the present work mechanical behavior of a bilayer cantilever microbeam subjected to nonlinear electrostatic pressure and temperature variations has been studied. Nonlinear integro-differential thermo-electro mechanical equation based on Euler-Bernoulli beam theory has been derived and solved using Step-by-Step Linearization Method and finite difference method. The effect of temperature variations on static instability of the microbeam due to nonlinearity created by applied electrostatic forces has been investigated. In our model it has been shown that as the temperature increases, the applied voltage decreases, which in turn guides the system to an unstable condition, in other words, decreases the pull-in voltage. On the other hand, the pull-in voltage increases as the temperature decreases. Numerically obtained results for pull-in voltage and beam deflection are in good agreement with existing results in the literature. *Copyright © 2009 IFSA.*

Keywords: MEMS, Thermal, Electrical, Pull-in voltage, Static instability, Bilayer cantilever microbeam

1. Introduction

There are a number of actuation methods that can be used to excite Micro Electro Mechanical Systems (MEMS), such as piezoelectric, electromagnetic, thermal, and electrostatic mechanisms.

Study of electrostatically actuated MEMS is a branch of micromechanics whose principle is a very commonly used one on sensing or actuating devices in MEMS. The foregoing systems have found

wide applications in switches [1], micro-mirrors [2], micro-resonators [3], micro-actuators [4], micro thermo-meters [5], and tunable capacitors [6].

Boundary supported suspended microstructures, such as MEMS cantilevers, are currently used in various microengineering sensor/actuator fields. Their relatively simple geometries make them very advantageous both from a design and microfabrication point of view. A cantilever is a beam carrying loads to a strong mounting point with one end of the beam anchored, and having the other end suspended in the air. The beam forms a lever, which carries the load by being held in position by the mount, turning the loads into torque on the mount.

Due to acting of applied force, the axis of the beam deflects from its initial position. Accurate values of beam deflection are sought in many practical cases. To evaluate the value of the deflection of beams, the basic differential equation should be developed and solved. In some cases the loads applied to the beam cause the deflection of the beam to be linear. Therefore linear equation should be derived and solved by common analytical methods. But in some cases due to complexity of the nature of electrostatic forces applied on the beam, the governing equation is nonlinear and should be solved by numerical methods.

In the microscopic scale, high energy densities and large forces are available, and the electrostatic actuation may be more effective than other kinds of actuation methods. An electrostatically actuated microbeam is an elastic beam suspended above a stationary rigid plate, both made of conductive materials, and a dielectric medium filling the gap between them. An applied electric voltage between the two electrodes results in the deflection of the elastic beam and a consequent change in the MEMS capacitance. In case if the applied voltage exceeds a certain limit namely the pull-in voltage, the nonlinear electrostatic force gives rise to the well-known pull-in phenomenon that causes beam to collapse towards the stationary rigid plate. In fact as a result of the nonlinearity, stable force balance and deflection can only be achieved to one third (in lumped modeling) of the initial gap distance. Beyond this value, the stability of the displacement is lost, and the gap is sharply reduces to zero value with no further increase in the applied voltage. Determination of the pull-in voltage plays an important role in the design of MEMS devices.

Several studies have investigated this behavior of microbeams under various loading conditions. The earliest study may be found in the pioneering work of Nathanson et al. [7, 8]. In their study of a resonant gate transistor, they constructed and analyzed the mass-spring model of electrostatic actuation. Recently, some authors have used the nonlinear equation representing the idealized electrostatic structure to analyze the mechanical behavior of the MEMS devices [9, 10]. Other studies analyze the response of a microbeam to a generalized transverse excitation and with axial force using Rayleigh's energy method in order to approximate the fundamental natural frequency of the straight, undeflected beam.

A temperature change is one of the basic actuation parameter that can tune the system directly. Thermal actuation is known for its capability in producing a large and linear displacement with respect to a heating power. This mechanism usually is derived using the known bilayers (multilayers) including different thermal expansion coefficients. In microcapacitive thermal sensors and thermal tunable capacitors, the used bilayer microbeam is not only subjected to the electrostatic force but also to thermal bending moment. In addition, the all of micro actuators and micro sensors exhibit to temperature changes.

By applying simultaneously effect of electrostatic force and thermal moment, the pull-in parameters can change. But there are no enough studies in the effect of temperature changes on the stability of electrostatically actuated microstructures. In the present work, a bilayer microbeam, which is loaded by nonlinear electrostatic force and thermal bending moment, is studied. The static behavior of the

microbeam and its static instability (pull-in phenomenon) are investigated. Numerical obtained results for pull-in voltage and cantilever deflection are in good agreement with results existing in the literature.

2. Design and Modeling

Fig. 1 shows a schematic of the proposed model. It consists of a deformable bilayer cantilever microbeam separated from a fixed ground plate as a substrate by an air gap g_0 .

A dc voltage source, V , between the capacitor electrodes is used to create electrostatic force along the microbeam.

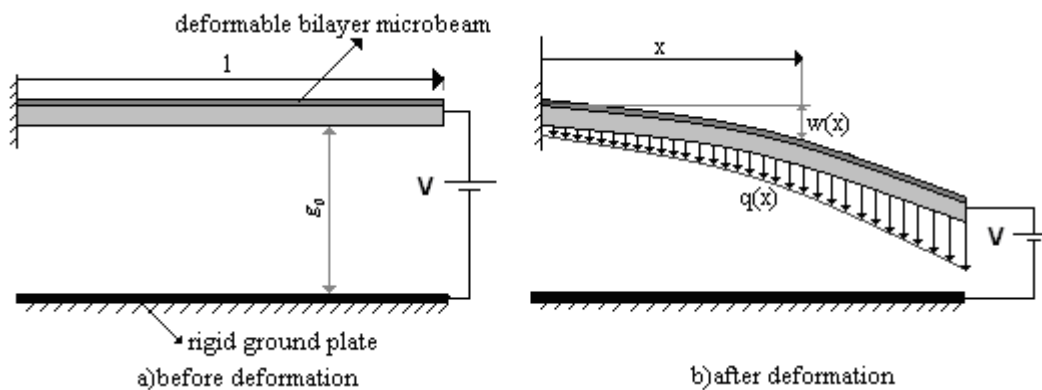


Fig. 1. A Schematic view of a bilayer cantilever microbeam subjected to electrostatic force and thermal moment: a) before deformation; b) after deformation.

In this work the following reasons can cause the deflection of the microbeam:

- Temperature changes (Different expansion coefficients of two selected materials cause the deflection of the microbeam as a result of temperature changes)
- Electrostatic force resulted from applied voltage

The temperature changes and externally electrostatic force applied to the movable microbeam cause the microbeam to move downward which in turn leads the air gap between the movable microbeam and the fixed ground plane to decrease, therefore increase the capacitance between them.

3. Mathematical Modeling

Fig. 2 shows an element of bilayer cantilever microbeam. Assume a microbeam with length l , thickness t , width b , expansion coefficient α , cross sectional area A , and isotropic with Young's modulus E , whereas for upper microbeam subscript 1 and for the lower one 2 is used. $w(x)$ is the deflection of the microbeam. Let that x be the coordinate along the microbeam with its origin at the left end, and z be the coordinate along the cross section with its origin at the mid plane of the microbeam or neutral axis of the cross section when there are no temperature changes.

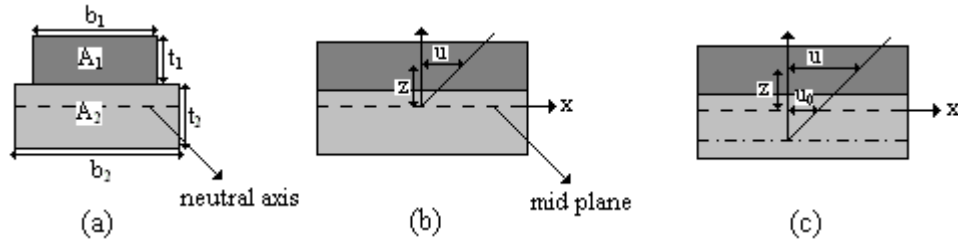


Fig. 2. An element of the bilayer cantilever microbeam: a) section view; b) side view when there are no temperature changes; c) side view in the presence of temperature changes.

As a result of temperature variations in the system, the mid plane is stretched while u_0 is the displacement or extension of the mid plane in x direction. u is the total extension along x axis of a layer located at a given distance z due to temperature changes and electrostatic force.

For selected microbeam, t/l is usually small enough to neglect the shear deformation and strain definition is used. Total strain at x direction at a given cross section of the microbeam is the sum of thermal strain (ε_T) and mechanical strain (ε_m) based on Euler-Bernoulli beam theory. Thus it can be written as [11]:

$$\varepsilon_{x\text{ total}} = \varepsilon_T + \varepsilon_m = \frac{du}{dx} = \frac{du_0}{dx} - z \frac{d^2w}{dx^2}, \quad \varepsilon_T = \alpha \theta \quad ; \theta = T - T_0, \quad (1)$$

where θ is the temperature change, measured with respect to initial temperature T_0 . Using Hook's law and equation 1, the relationship between the stress, strain and temperature changes for Euler-Bernoulli beam in a cross section area of upper and lower microbeam can be expressed as below:

$$\begin{aligned} \sigma_x^{(1)} &= E_1 \frac{du_0}{dx} - E_1 z \frac{d^2w}{dx^2} - E_1 \alpha_1 \theta \\ \sigma_x^{(2)} &= E_2 \frac{du_0}{dx} - E_2 z \frac{d^2w}{dx^2} - E_2 \alpha_2 \theta \end{aligned} \quad (2)$$

Considering that the axial force with respect to free end along the x axis is zero, the equation of bilayer microbeam deflection can be expressed as [11]:

$$-(EI)_{eq} \frac{d^2w}{dx^2} = M(x) + M^T, \quad (3)$$

where

$$(EI)_{eq} = \left(E_1 \int_{A_1} z^2 dA + E_2 \int_{A_2} z^2 dA \right), \quad M^T = \left(E_1 \alpha_1 \int_{A_1} z dA + E_2 \alpha_2 \int_{A_2} z dA \right) \theta = \Omega \theta \quad (4)$$

M^T is the thermal moment and $M(x)$ is the external bending moment in a given section resulted from electrostatic pressure acting along the microbeam. With respect to Fig. 3:

$$M(x) = \int_x^l q(\xi)(\xi - x) d\xi, \quad (5)$$

where $q(\xi)$ is the electrostatic force per unit length of the microbeam and is defined as below [1]:

$$q(\xi) = \frac{\varepsilon_0 b_2 V^2}{2(g_0 - w(\xi))^2}, \quad (6)$$

where ε_0 , V and g_0 are the permittivity of air, applied voltage and initial gap between the microbeam and ground plate, respectively.

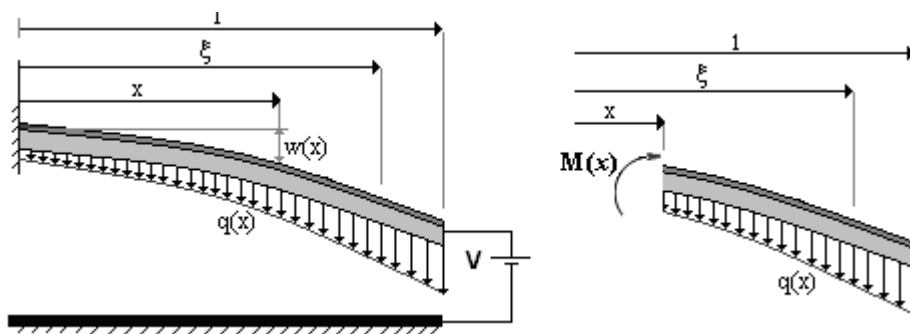


Fig. 3. Moment and electrostatic pressure in the model.

4. Numerical Solution

Solution of nonlinear integro-differential equation 3, due to its nonlinear nature, is more complex and time consuming. In order to overcome the complexity, it is common to linearize it. Since the deflection of the microbeam (w) is high enough as compared to initial gap, the linearization of equation 3 with respect to w of initial position causes considerable errors in results. Due to step by step applying voltage and temperature a method namely Step-by-Step Linearization Method (SSLM) is proposed for linearization [4], while linearizes the nonlinear equation in each step with respect to the previous one. At last a linear equation in terms of the difference of the deflection of the microbeam between two successive steps ($\psi(x)$) is derived and solved by Finite Difference Method (FDM).

Selection of the small step sizes of applied voltage and temperature causes $\psi(x)$ is small, so the generated errors by this method are surly neglected.

To perceive abovementioned method more, assume T_i and V_i be the temperature and the applied voltage in i^{th} step which cause to the deflection of the microbeam $w_i(x)$.

$$T_{i+1} \rightarrow T_i + \delta T \quad \& \quad V_{i+1} = V_i + \delta V \quad \Rightarrow \quad w_{i+1} \rightarrow w_i + \delta w = w_i + \psi(x), \quad i = 1, 2, \dots, N, \quad (7)$$

where δT and δV are the temperature and the voltage changes between two successive steps, respectively. Rewriting equation 3 for $(i+1)^{th}$ step, the following equation is obtained:

$$-(EI)_{eq} \frac{d^2(w_i + \psi(x))}{dx^2} - M_{i+1}^T = M_{i+1}(x) \quad (8)$$

whereas:

$$M_{i+1}(x) = \int_x^l \frac{\varepsilon_0 b_2 V_{i+1}^2}{2(g_0 - w_i(\xi) - \psi(\xi))^2} (\xi - x) d\xi, \quad M_{i+1}^T = \Omega \theta_{i+1} \quad (9)$$

Based on Calculus of variation theory and using Taylor's series expansion, $M_{i+1}(x)$ can be written as:

$$M_{i+1}(x) = M_i(x) + \left. \frac{\partial M}{\partial w} \right|_{(w_i, V_i)} \delta w + \left. \frac{\partial M}{\partial V} \right|_{(w_i, V_i)} \delta V, \quad (10)$$

The higher order of the Taylor's series can be neglected due to small value of δV . Considering that $w_i(x)$ and $w_{i+1}(x)$ satisfy the differential equation of the microbeam deflection, the linear equation for $\psi(x)$ can be expressed as:

$$-(EI)_{eq} \frac{d^2 \psi(x)}{dx^2} - \int_x^l \frac{\varepsilon_0 b_2 V_i^2}{(g_0 - w_i(\xi))^3} \psi(\xi) (\xi - x) d\xi = \int_x^l \frac{\varepsilon_0 b_2 V_i \delta V}{(g_0 - w_i(\xi))^2} (\xi - x) d\xi + \delta M^T, \quad (11)$$

For a cantilever microbeam, the corresponding boundary conditions are zero displacement and zero slope in the fixed end of the microbeam. The unknown function $\psi(x)$ also satisfies the same boundary conditions.

Hence the nonlinear equation 3 is converted to the linear equation 11 in terms of $\psi(x)$, therefore using FDM and imposing the boundary conditions, equation 11 can be solved easily.

5. Numerical Results and Discussion

In order to validate the achieved equation, the pull-in results for single and bilayer cantilever microbeam using SSLM and FDM are now presented.

5.1. Single Layer Microbeam

The physical and geometrical properties of the cantilever single layer microbeam are shown in Table 1.

Table 1. Geometrical and physical properties of the single layer cantilever microbeam.

Design variable	Value [12]
E	$155.8 \times 10^9 \text{ Nm}^{-2}$
b	5 mm
t	$57 \text{ }\mu\text{m}$
l	20 mm
ε_0	8.85 pFm^{-1}
g_0	$92 \text{ }\mu\text{m}$

Before getting results to compare, it is necessary to find the best step size for applying voltage and number of grid points for FDM. The convergence of the results is listed in Table 2. As declared in Table 2 the best results can be 0.15 volt for step size of applying voltage and 50 grid points for finite-difference method.

Table 2. Obtained pull-in voltages for single layer microbeam with different grid points and step sizes for applying voltages.

Number of grid points	Different steps for bias voltages				
	0.25	0.22	0.20	0.17	0.15
35	70.2	70.0	69.9	69.7	69.6
40	70.0	69.9	69.8	69.5	69.4
45	69.9	69.7	69.6	69.4	69.3
50	69.8	69.7	69.5	69.4	69.2
55	69.8	69.6	69.4	69.2	69.2

Table 3 shows the calculated tip gap versus different applied voltages, which are compared with the results of reference [12]. The calculated pull-in voltage for this model using SSLM is 69.2 volt and it agrees very well with the results in [12].

Table 3. Tip gap versus applied voltage.

Applied voltage (volt)	Tip gap in proposed model (μm)	Tip gap (μm) [12]	Experiment (μm) [12]	$\Delta\%$
20	90.3	90.2	90.5	0.2
40	84.5	84.3	84.6	0.1
60	70.7	71.5	70.0	0.01
65	63.2	67.2	64.0	0.01

$$\Delta(\%) = \frac{ABS(\text{obtained results in proposed model} - \text{experimental results}[12])}{\text{experimental results}[12]} \times 100$$

5.2. Bilayer Microbeam

For proposed bilayer model the geometrical and physical properties, assuming $t_1 = t_2 = t$ and $b_1 = b_2 = b$, are shown in Table 4. To have more sensitivity and large deflection, two materials with high difference in their thermal expansion coefficients are considered (Gold and Silicon). The convergency of the results for a bilayer microbeam is listed in Table 5. Based on results given in the Table 5 the best step size for voltage application is 0.15 V and the best number of the grid points is 50.

The pull-in voltage for cantilever bilayer microbeam is 10.1 volt, when there are no temperature changes.

Table 4. Geometrical and physical properties of the proposed bilayer model.

Design variable	Value
(Au) α_1	$14.3 \times 10^{-6} \text{ k}^{-1}$
(Si) α_2	$2.6 \times 10^{-6} \text{ k}^{-1}$
E_1	$80 \times 10^9 \text{ Nm}^{-2}$
E_2	$122 \times 10^9 \text{ Nm}^{-2}$
b	$90 \mu\text{m}$
t	$3 \mu\text{m}$
l	$500 \mu\text{m}$
ε_0	8.85 pFm^{-1}
g_0	$2 \mu\text{m}$

Table 5. Obtained pull-in voltages for proposed bilayer cantilever microbeam with different grid points and step sizes for applying voltages ($\theta = 0$).

Number of grid points	Different steps for bias voltages				
	0.25	0.23	0.20	0.18	0.15
20	10.6	10.6	10.4	10.4	10.4
30	10.5	10.4	10.4	10.3	10.2
40	10.4	10.4	10.3	10.3	10.2
50	10.4	10.4	10.2	10.2	10.1
90	10.3	10.3	10.2	10.1	10.1
120	10.3	10.3	10.2	10.1	10.1

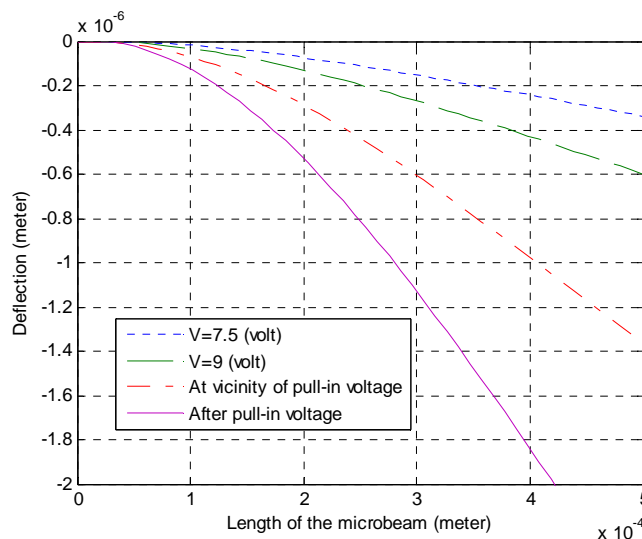


Fig. 4. Deflection of the bilayer cantilever microbeam versus microbeam length for different applied voltages ($\theta = 0$).

Fig. 4 indicates the deflection of the bilayer cantilever microbeam at vicinity of pull-in voltage, two voltages smaller than the pull-in voltage and either after the pull-in phenomenon happens. As shown in Fig. 4, bending stiffness of the microbeam decreases while its deflection increases, as the voltage

increases. As a result of applying δV , the microbeam experiences a greater δw compared to its former state as approaching the pull-in voltage while at the pull-in voltage entirely loses its stiffness and collapses towards the rigid plate, in other words buckling phenomenon occurs.

Here system behavior is investigated applying temperature and voltage simultaneously. It is obvious that the sequence of applying these two actuators in turn is of main importance in determining the microbeam response.

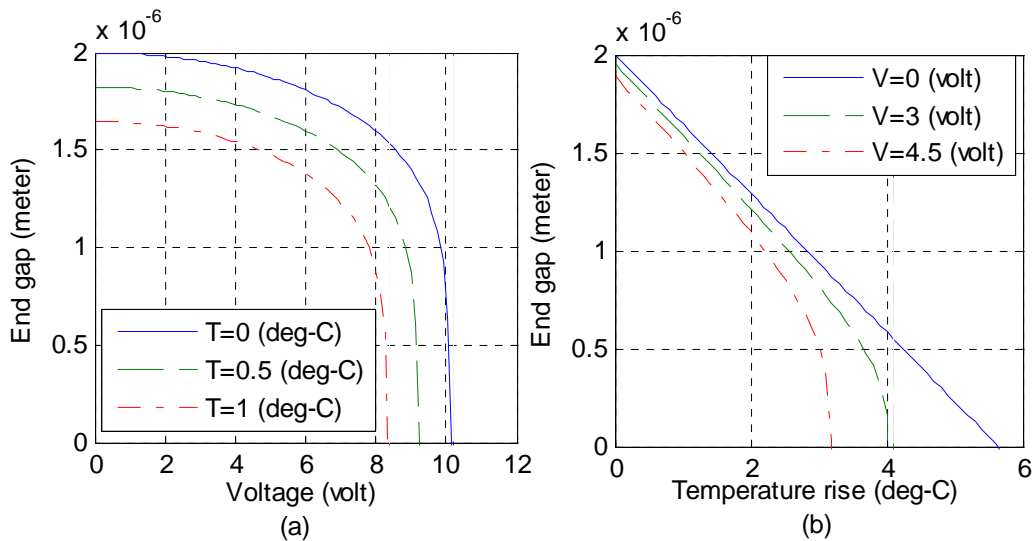


Fig. 5. (a) Tip gap of the microbeam versus voltage;
(b) Tip gap of the microbeam versus temperature changes θ .

Fig. 5(a) shows the tip gap of the microbeam versus applied voltage for different temperature changes. As shown when the microbeam heats up, a pull-in phenomenon happens earlier than when there is no temperature rises. It means that the pull-in voltage will decrease as the temperature rise increases.

Fig. 5(b) shows the tip gap of the microbeam versus the temperature rise when the microbeam deflects due to a given applied voltage and then the temperature rise causes the microbeam to increase deflection up to the pull-in temperature. When there is no applied voltage and microbeam deflects by temperature changes only, there is no nonlinearity and the tip gap varies linearly with the temperature and the system keeps its stability and it solely contacts with the ground plate.

6. Conclusion

In the present work, a bilayer cantilever microbeam subjected to nonlinear electrostatic pressure and temperature changes was studied. Nonlinear integro-differential thermo electro mechanical equation based on Euler-Bernoulli beam theory was derived and linearized using Step-by-Step Linearization Method and solved by applying Finite Difference Method. The static instability of the bilayer microbeam was studied. The results illustrated that due to nonlinear nature and displacement dependency of the electrostatic force, increasing the applied voltage guides the structure to an unstable state. In the lack of the electrostatic forces increasing the temperature variations does not have any influence on the stability, but when the structure is subjected to a bias voltage, due to displacement dependency of the electrostatic force, the temperature changes guides the structure to an instable state.

References

- [1]. H. Sadeghian, Gh. Rezaadeh, P. Osterberg, Application of the Generalized Differential Quadrature Method to the Study of Pull-In Phenomena of MEMS Switches, *J. of Microelectromechanical System IEEE/ASME*, Vol. 16, No. 6, 2007, pp. 1334-1340.
- [2]. Gh. Rezaadeh, F. Khatami, A. Tahmasebi, Investigation of the Torsion and Bending effects on Static Stability of Electrostatic Torsional Micromirrors, *J. Microsystem Technologies*, Vol. 13, No. 7, 2007, pp. 715-722.
- [3]. V. Sazonova, A Tunable Carbon Nanotube Resonator, *Ph. D. Thesis*, Cornell University, 2006.
- [4]. Gh. Rezaadeh, A. Tahmasebi, M. Zubtsov, Application of Piezoelectric Layers in Electrostatic MEM Actuators: Controlling of Pull-in Voltage, *J. Microsystem Technologies*, Vol. 12, No. 12, 2006, pp. 1163-1170.
- [5]. Y. Zhang, T. Ikehara, J. Lu, T. Kobayashi, M. Ichiki, T. Itoh, R. Maeda, Novel MEMS-based Thermometer with Low Power Consumption for Health-Monitoring Network Application, *SPIE*, Vol. 6800, 2008, pp. 6800 1V.
- [6]. A. Mehdaoui, M. B. Pisani, D. Tsamados, F. Casset, P. Ancey, A. M. Ionescu, MEMS Tunable Capacitors with Fragmented Electrodes and Rotational Electro-Thermal Drive, *J. Microsystem Technologies*, Vol. 13, No. 11, 2007, pp. 1589- 1594.
- [7]. H. C. Nathanson, W. E. Newell, R. A. Wickstrom, J. R. Davis, The Resonant Gate Transistor, *J. IEEE Transactions on Electronics Devices*, Vol. 14, No. 3, 1967, pp. 117-133.
- [8]. W. Newell, Miniaturization of Tuning Forks, *Science*, Vol. 161, No. 3848, 1968, pp. 1320-1326.
- [9]. G. Flores, G. A. Mercado, J. A. Pelesko, Dynamics and Touchdown in Electrostatic MEMS, *ICMENS2003*, 2003.
- [10]. E. M. Abdel-Rahman, M. I. Younis, A. H. Nayfeh, Characterization of the Mechanical Behavior of an Electrically Actuated Microbeam, *J. Micromechanics and Microengineering*, Vol. 12, No. 6, 2002, pp. 759-766(8).
- [11]. S. Timoshenko, Strength of material, Part1, *Van Nostrand*, New York, 1930.
- [12]. Y. C. Hu, C. M. Chang, S. C. Huang, Some Design Consideration on the Electrostatically Actuated Microstructures, *J. Sensors and Actuators*, Vol. 112, No. 1, 2004, pp. 155-161.

2009 Copyright ©, International Frequency Sensor Association (IFSA). All rights reserved.
(<http://www.sensorsportal.com>)



**Universal Frequency-to-Digital Converter
(UFDC-1 and UFDC-1M-16)
in MLF (5 x 5 x 1 mm) package**

**SMALL WORLD -
BIG FEATURES**

SWP, Inc., Toronto, Ontario, Canada,
Tel. +34 696067716, fax: +34 93 4011989, e-mail: sales@sensorsportal.com
http://www.sensorsportal.com/HTML/E-SHOP/PRODUCTS_4/UFDC_1.htm

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. *Sensors & Transducers Journal* is indexed and abstracted very quickly by Chemical Abstracts, IndexCopernicus Journals Master List, Open J-Gate, Google Scholar, etc.

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 8-14 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 Please download also our media kit: http://www.sensorsportal.com/DOWNLOADS/Media_Kit_2009.pdf

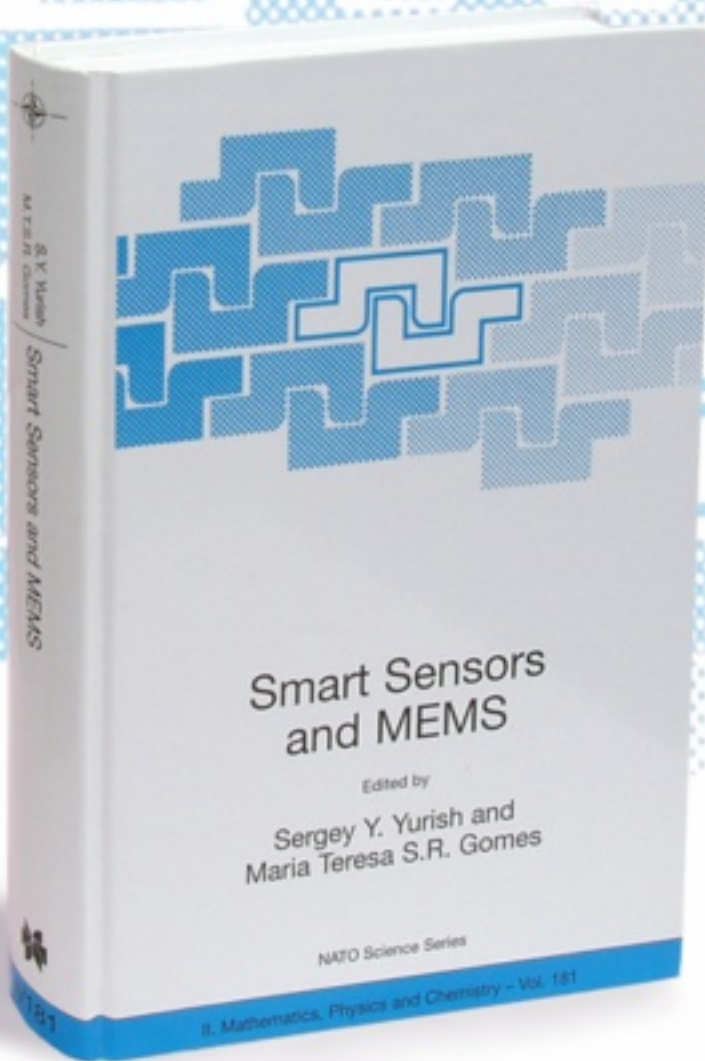
Smart Sensors and MEMS

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