

ISSN 1726-5749

SENSORS & TRANSDUCERS

7^{vol. 81}
/07



Sensor Networks and Wireless Sensor Networks

International Frequency Sensor Association Publishing





Sensors & Transducers

Volume 81
Issue 7
July 2007

www.sensorsportal.com

ISSN 1726-5479

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

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
Kanias, 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
Djordjevic, 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, Intersema 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 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
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 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, Netherlands
Yu, Haihu, Wuhan University of Technology, China
Yufra 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 81
Issue 7
July 2007

www.sensorsportal.com

ISSN 1726-5479

Editorial

SENSOR+TEST 2007: Exhibition and Conference Report

Sergey Y. Yurish I

Research Articles

Dynamic Sensor Networks

Simone GABRIELE and Paolo DI GIAMBERARDINO 1302

Simple and Low-cost Wireless Distributed Measurement System

Alessandra Flammini, Daniele Marioli, Emiliano Sisinni, Andrea Taroni 1315

Impact of Different Air Protocols on the Use of the Radio Spectrum by Radio Frequency Identification (RFID) Devices in the 860 to 960 MHz Bands

Mike Marsh 1322

Initial Results on Low Cost Microprocessor and Ethernet Controller based Data Acquisition System in Optical Tomography System

Ruzairi Abdul Rahim, Goh Chiew Loon, Mohd. Hafiz Fazalul Rahiman, Chan Kok San, Pang Jon Fea, Leong Lai Chan 1333

PC Based Linear Variable Differential Displacement Measurement Uses Optical Technique

Tapen Kumar MAITI, Prasenjit PAUL, Indrajit DAS and Soumen SAHA 1341

Resistance Based Humidity Sensing Properties of TiO₂

B. C. Yadav, Amit K. Srivastava and Preeti Sharma 1348

Al₂O₃-modified ZnO Based Thick Film Resistors for H₂-gas Sensing

D. R. Patil, L. A. Patil 1354

Effect of Residual Stress on Divergence Instability of Rectangular Microplate Subjected to Nonlinear Electrostatic Pressure

Ghader Rezazadeh, Yashar Alizadeh, Hadi Yagubizade 1364

Control of Pressure Process Using Infineon Microcontroller

A. Siddique, M. R. Jayashree, O. Muthukumar, R. Maheswari and N. Sivakumaran 1373

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>

Effect of Residual Stress on Divergence Instability of Rectangular Microplate Subjected to Nonlinear Electrostatic Pressure

¹Ghader Rezazadeh, ²Yashar Alizadeh, ³Hadi Yagubizade

^{1,3} Mech. Eng. Dept. Urmia University, Urmia, Iran,
Tel.: +98-914-145-1407,

² Mech. Eng. Dept. Arak Azad University, Arak, Iran
E-mail: g.rezazadeh@mail.urmia.ac.ir

Received: 3 June 2007 /Accepted: 16 July 2007 /Published: 23 July 2007

Abstract: In this paper, the effect of residual stress on divergence instability of a rectangular microplate subjected to a nonlinear electrostatic pressure for different geometrical properties has been presented. After deriving the governing equation and using of Step-by-Step Linearization Method (SSLM), the governing nonlinear equation has been linearized. By applying the finite difference method (FDM) to a rectangular mesh, the linearized equation has been discretized. The results show, residual stresses have considerable effects on Pull-in phenomena. Tensile residual stresses increase pull-in voltage and compressive decrease it. The effect of different geometrical properties on divergence instability has also been studied. *Copyright © 2007 IFSA.*

Keywords: MEMS, Microplate, Residual stress, Divergence Instability, SSLM

1. Introduction

Due to the rapid innovation of micro- and nanoelectromechanical systems (MEMS/NEMS) technologies over the last few decades, a variety of innovative micro and nano-scale machines and sensors have been developed. MEMS/NEMS devices have therefore become key components of many systems, such as accelerometers [1], micropumps [2, 3], pressure sensors [4], chemical sensors [5], transducers [6] and etc. For this reason further advances in MEMS and NEMS design are very important and require more and deeper investigation and understanding of basic phenomena at the micro- and nanoscale devices. Electrically actuated microplates are the main component in micropumps, micromirrors, microphones, and many microsensors [7-10]. These devices have

applications in a variety of fields including biotechnology, chemical and mining industries and etc [11]. An electrically actuated microplate forms one side of a variable capacity air-gap capacitor, as shown in Fig. 1. An electrostatic field is created by applying a potential difference between the microplate and a fixed electrode. As the electrostatic force deforms the microplate, the electrostatic force itself changes with the plate deflection, resulting in coupling of the electrical and mechanical forces. The applied electrostatic load has an upper limit beyond which the mechanical restoring force of the microplate can no longer resist the electrostatic force, thereby leading to the collapse of the structure. This structural instability phenomenon is a divergence instability and in MEMS is known as 'pull-in', and the critical voltage associated with it is called the 'pull-in voltage'. The mathematical analysis of these systems started in the late 1960s with the pioneering work of H. C. Nathanson and his coworkers [12] who constructed and analyzed a mass-spring model of electrostatic actuation, and offered the first theoretical explanation of pull-in instability. At roughly the same time, G. I. Taylor [13] studied the electrostatic deflection of two oppositely charged soap films, and he predicted that when the applied voltage was increased beyond a certain critical voltage, the two soap films would touch together. While Taylor was interested in the electrostatic deflection of soap films, the small-aspect ratio model introduced in his work is the basis of many modern studies of electrostatic deflections in MEMS and NEMS. Since Nathanson and Taylor's seminal work, numerous investigators have analyzed and developed mathematical models of electrostatic actuation in attempts to understand further and control pull-in instability [14-15]. Considering the fabrication sequence of MEM actuators, the residual stress is very important and inevitable to the device. Residual stress due to the mismatch of both thermal expansion coefficient and crystal lattice period between substrate and thin film is unavoidable in surface micromachining techniques, so that accurate and reliable data of residual stress is crucial to the proper design of the MEMS devices concerned with the techniques [16]. Therefore the residual stress is an attractive research topic in the development of the microsystems technology. Effect of Residual stress has been researched on fixed-fixed micro-beams by many researches but this effect on rectangular microplate has not been researched enough. In this paper has been investigated of pull-in phenomenon considering residual stress effect on a rectangular micro-plate subjected to nonlinear electrostatic pressure. The mechanical behavior of an isotropic thin rectangular flexible micro plate under non uniform electrostatic pressure has been modeled as a thin Kirchhoff plate theory. The deflection and the pull-in phenomenon of the plate using SSM and applying FDM have been investigated. The obtained results show that the residual stress affect on pull-in parameters considerably. The different geometrical properties such as size of the plate, initial gap and plate thickness effect on pull-in voltage have also been investigated.

2. Model Description and Mathematical Modeling

As it is shown in the Fig. 1, a device with a pair of parallel rectangular plates is considered. The upper part of this device consists of a rectangular plate with thickness t , length a , width b and isotropic with Young's modulus E and with Poisson's ratio ν . that is clamped along its boundaries and the lower part that is entitled ground plate, attached to a rigid substrate. When the voltage is applied between these plates, the flexible plate is deflected toward the ground plate. For plates, t/a and t/b are usually small enough to neglect the shear deformation. So, the longitudinal displacements of the plate may be written as:

$$u(x, y) = -z \frac{\partial w(x, y)}{\partial x}, \quad (1)$$

$$v(x, y) = -z \frac{\partial w(x, y)}{\partial y}, \quad (2)$$

where $w(x, y)$ and $u(x, y)$ and $v(x, y)$ are displacements in the transverse z -direction and longitudinal x and y directions, respectively.

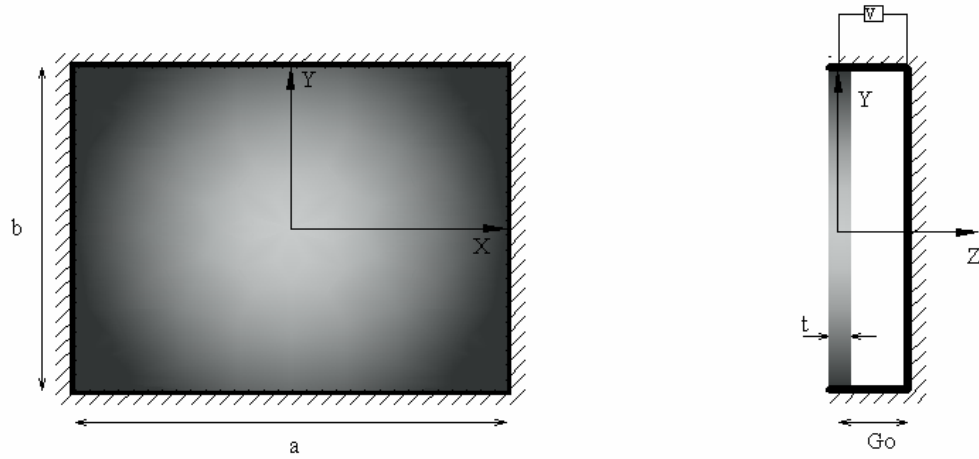


Fig. 1. Schematic view of the device.

The amplitude of the strains ε_x and ε_y , stresses σ_x and σ_y in the plate in terms of w are given [17]:

$$\varepsilon_x = -z \frac{\partial^2 w(x, y)}{\partial x^2}, \quad \varepsilon_y = -z \frac{\partial^2 w(x, y)}{\partial y^2}, \quad (3)$$

Residual stress due to the mismatch of both thermal expansion coefficient and crystal lattice period between substrate and thin film is unavoidable in surface micromachining techniques. Therefore, the total amplitude of the stresses in the thin plate considering residual stress can be written as:

$$\sigma_x = -\frac{Ez}{(1-\nu^2)} \left(\frac{\partial^2 w(x, y)}{\partial x^2} + \nu \frac{\partial^2 w(x, y)}{\partial y^2} \right) + \sigma_{rx}, \quad (4)$$

$$\sigma_y = -\frac{Ez}{(1-\nu^2)} \left(\frac{\partial^2 w(x, y)}{\partial y^2} + \nu \frac{\partial^2 w(x, y)}{\partial x^2} \right) + \sigma_{ry}, \quad (5)$$

where σ_{rx}, σ_{ry} are the residual stresses (positive for tensile stresses and negative for compressive stresses). Hence, inherent tension and compression per unit width of deformed plate:

$$\int_{-t/2}^{t/2} \left(-\frac{Ez}{(1-\nu^2)} \left(\frac{\partial^2 w(x, y)}{\partial x^2} + \nu \frac{\partial^2 w(x, y)}{\partial y^2} \right) + \sigma_{rx} \right) dz = \sigma_{rx} t = T_{rx}, \quad (6)$$

$$\int_{-t/2}^{t/2} \left(-\frac{Ez}{(1-\nu^2)} \left(\frac{\partial^2 w(x, y)}{\partial y^2} + \nu \frac{\partial^2 w(x, y)}{\partial x^2} \right) + \sigma_{ry} \right) dz = \sigma_{ry} t = T_{ry}, \quad (7)$$

The governing equation for the rectangular Microplate subjected to nonlinear electrostatic pressure considering residual stresses effect can be expressed as:

$$D \nabla^4 w - T_{rx} \frac{\partial^2 w}{\partial x^2} - T_{ry} \frac{\partial^2 w}{\partial y^2} = q(x, y), \quad (8)$$

where

$$\nabla^4 w = \frac{\partial^4 w}{\partial x^4} + 2 \frac{\partial^4 w}{\partial x^2 \partial y^2} + \frac{\partial^4 w}{\partial y^4},$$

and D is flexural rigidity and equal:

$$D = \frac{Et^3}{12(1-\nu^2)}, \quad (9)$$

The electrostatic pressure is derived from a parallel-plate approximation respect to an applied voltage. The electrostatic pressure applied per unit area of the plate can be written as:

$$q(x, y) = \frac{\varepsilon_0 V^2}{2(G_0 - w)^2}, \quad (10)$$

where V is the applied voltage between the movable and the ground plates on the fixed substrate, G_0 is the initial gap between the movable/fixed plates and ε_0 is the permittivity of air. The boundary conditions for the rectangular plate clamped at all edges are:

$$\begin{aligned} w(-a/2, y) &= w(a/2, y) = 0, \\ w(x, -b/2) &= w(x, b/2) = 0, \end{aligned} \quad (11a)$$

$$\begin{aligned} \frac{\partial w(-a/2, y)}{\partial x} &= \frac{\partial w(a/2, y)}{\partial x} = 0, \\ \frac{\partial w(x, -b/2)}{\partial y} &= \frac{\partial w(x, b/2)}{\partial y} = 0, \end{aligned} \quad (11b)$$

3. Numerical Solution

Due to the nonlinearity of the derived equation, the solution is complicated and time consuming, so in order to solve it, it is tried to linearize it. Because of considerable value of w respect to initial gap especially when the applied voltage increases, the linearizing respect to w , may causes to appear some considerable errors, therefore, to minimize the value of errors, the method of step-by-step increasing the applied voltage is proposed and the governing equation was linearized at the each step [14].

For using of SSLM, it is supposed that the w^k is the displacement of the plate due to the applied voltage V^k . Therefore, by increasing the applied voltage to a new value, the displacement can be written as:

$$w^{k+1} \rightarrow w^k + \psi(x, y), \quad (12)$$

when

$$V^{k+1} \rightarrow V^k + \delta V, \quad (13)$$

Therefore, Eq. 8 can be written as follow:

$$D \nabla^4 w^{k+1} - T_{rx} \frac{\partial^2 w^{k+1}}{\partial x^2} - T_{ry} \frac{\partial^2 w^{k+1}}{\partial y^2} = \frac{\varepsilon_0 (V^{k+1})^2}{2(G_0 - w^{k+1})^2}, \quad (14)$$

Substituting, Eq.s 12 and 13 into Eq. 14, we have:

$$D\nabla^4\psi - T_{rx}\frac{\partial^2\psi}{\partial x^2} - T_{ry}\frac{\partial^2\psi}{\partial y^2} = \frac{\varepsilon_0(V^{k+1})^2}{2(G_0 - (w^k + \psi))^2} - \frac{\varepsilon_0(V^k)^2}{2(G_0 - w^k)^2}, \quad (15)$$

By considering small value of δV , it is expected that the ψ would be small enough, hence using of calculus of variation theory and Taylor's series expansion about w^k , and applying the truncation to first order of it for suitable value of δV , it is possible to obtain desired accuracy. Hence, the linear coupled electrostatic forces can be written as:

$$\frac{\varepsilon_0(V^{k+1})^2}{2(G_0 - (w^k + \psi))^2} = \frac{\varepsilon_0(V^{k+1})^2}{2(G_0 - w^k)^2} + \frac{\varepsilon_0(V^{k+1})^2}{(G_0 - w^k)^3}\psi, \quad (16)$$

Substituting the Eq. 16 into Eq. 15, the following equation to calculate the ψ can be expressed as:

$$D\nabla^4\psi - T_{rx}\frac{\partial^2\psi}{\partial x^2} - T_{ry}\frac{\partial^2\psi}{\partial y^2} - \frac{\varepsilon_0(V^{k+1})^2}{(G_0 - w^k)^3}\psi = \frac{\varepsilon_0}{2(G_0 - w^k)^2}((V^{k+1})^2 - (V^k)^2), \quad (17)$$

Implying any numerical method and imposing the boundary conditions, the Eq. 19 may be discretized. Using central finite difference formula for a rectangular mesh with constant subdivisions Δx and Δy characteristics the foregoing equation was discretized and by solving obtained linear system of algebraic equation equations, the ψ can be calculated at a given applied voltage.

3. Numerical Results and Discussion

Geometrical and material properties used in this article listed in Table 1.

Table 1. Geometrical and material properties of micro-plate.

Symbol	Parameter	Value/Unit
E	Young's modulus	169 GPa
ε_0	Dielectric of air	$8.8541878 \times 10^{-12}$
ν	Poisson ratio	0.06
t	Diaphragm thickness	$10\mu\text{ m}$
G_0	Initial gap	$1\mu\text{ m}$

Best size of steps and grid points for SSLM and FDM are calculated first with some sample step sizes with fixed number of grid points that listed in Tables 2 and 3, respectively. In all tables and figures the microplate's length and width are equal, that $a=L$ and $b=L$.

With attention to the Tables 2 and 3, the accepted results can be obtained for 0.1 (v) step size of applying voltage with 21×21 grid points.

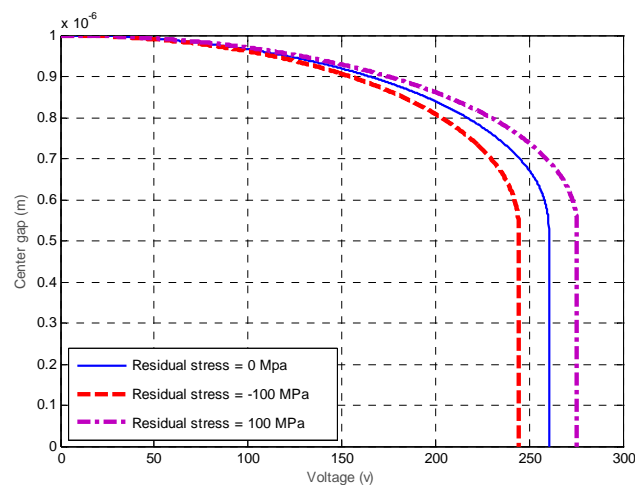
Table 2. The obtained pull-in voltage (V_p) with 31×31 grid points for different step size for applying voltage.

	Residual Stress (Mpa)	Step size for applying Voltage (v)				
		3	1	0.5	0.1	0.05
L=300 μ m	0	264.0	262.0	261.0	260.4	260.4
	-50	255.0	254.0	253.0	252.5	252.5
	50	270.0	269.0	268.5	268.0	268.0
L=200 μ m	0	588.0	587.0	586.5	585.7	585.7
	-50	582.0	579.0	578.5	577.9	577.9
	50	597.0	595.0	594.0	593.4	593.4

Table 3. The obtained pull-in voltage (V_p) with 0.1 (v) step size for applying voltage for different number of grid points for FDM.

	Residual Stress (Mpa)	Number of grid points for FDM			
		11×11	15×15	21×21	31×31
L=300 μ m	0	259.5	260.0	260.4	260.4
	-50	251.4	252.0	252.5	252.5
	50	267.5	267.8	268.0	268.0
L=200 μ m	0	583.8	584.8	585.7	585.7
	-50	575.6	576.9	577.9	577.9
	50	591.7	592.6	593.4	593.4

Results show that when the applied voltage reaches the specific value, the microplate is pulled into the fixed electrode suddenly and in fact, divergence instability or Pull-in phenomena occur. Fig. 2. shows that residual stress has considerable effect on Pull-in phenomena. Tensile residual stresses increase pull-in voltage and compressive decrease it. Effects of different dimensions of the plate and initial gaps on pull-in voltage with neglecting and considering residual stress are shown in the Figs. 3, 4, 5 and 6.

**Fig. 2.** Center gap versus applied voltage for different residual stresses (L = 300 μ m, t=10 μ m).

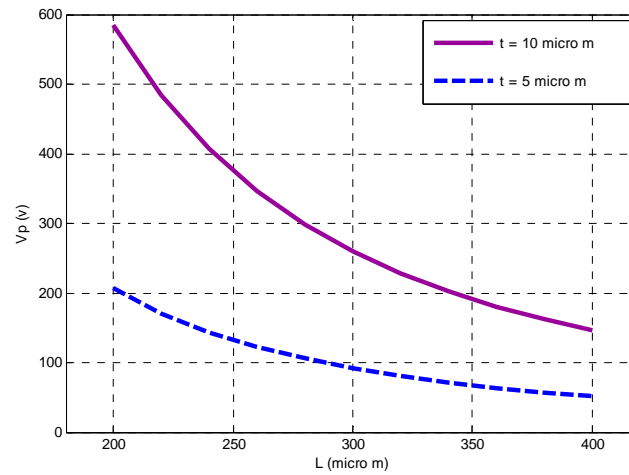


Fig. 3. Pull-in voltage versus L for different t ($\sigma_{rx} = \sigma_{ry} = 0$).

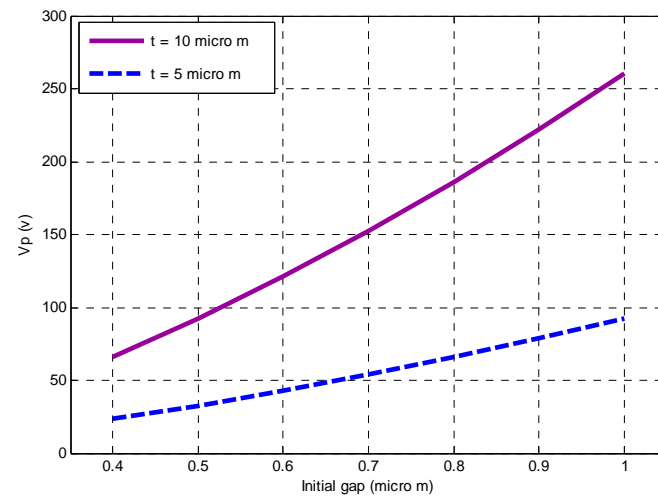


Fig. 4. Pull-in voltage versus initial gap for different thicknesses ($L = 300 \mu m$, $\sigma_{rx} = \sigma_{ry} = 0$).

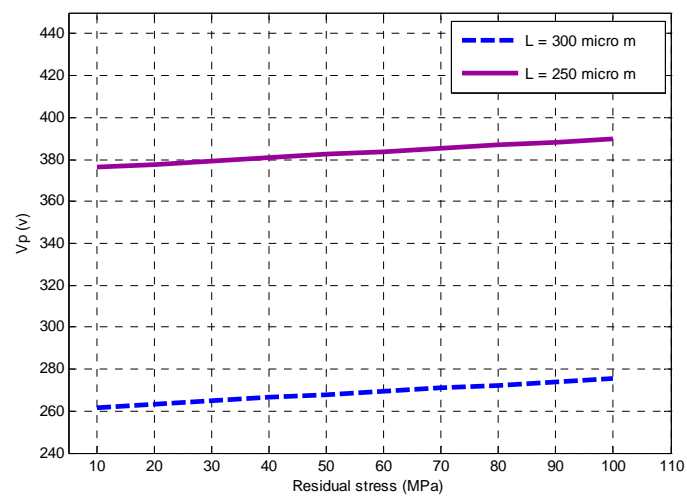


Fig. 5. Pull-in voltage versus tensile residual stress for different plate sizes.

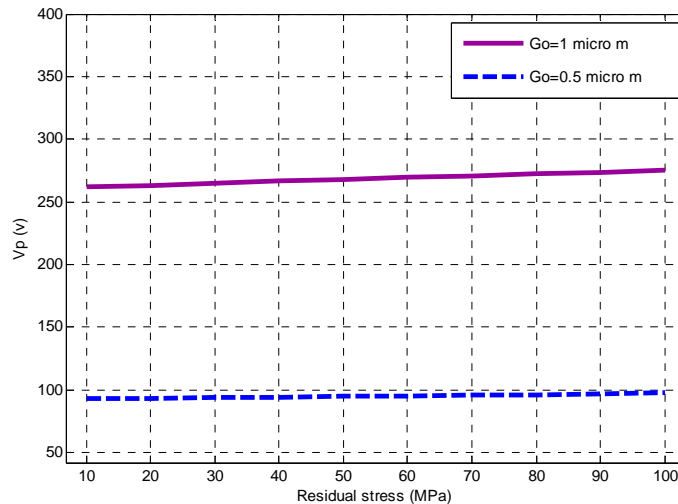


Fig.6. Pull-in voltage versus tensile residual stress for different initial gaps ($L = 300 \mu\text{m}$).

5. Conclusions

Correct modeling of a microplate with electrostatic actuation is an important step in design of MEMS/NEMS devices. The governing equation considering residual stress terms on a rectangular microplate was modeled. The nonlinear governing equation was linearized using SSLM successively and was showed that by using this method can be achieved results with desired accuracy. The results showed that the tensile residual stresses stiffen microplates but conversely the compressive residual stresses soften them, so residual stresses have considerable effects on divergence instability. The obtained results can be used as design tools to improve performance of MEMS/NEMS devices that consist of microplate in future designs.

References

- [1]. M. Bao and W. Wang, Future of Microelectromechanical Systems (MEMS), *Sens. and Act. A*, 56, 1996, pp. 135-141.
- [2]. M.T.A. Saif, B.E. Alaca and H. Sehitoglu, Analytical Modeling of Electrostatic membrane Actuator Micro Pumps, *IEEE J. of MEMS*, 8, 1999, pp. 335-344.
- [3]. Pouria Soleymani, Hamed Sadeghian, Ahmadali Tahmasebi and Ghader Rezazadeh, Pull-in Instability Investigation of Circular Micro Pump Subjected to Nonlinear Electrostatic Force, *Sensors & Transducers Journal*, 69, 7, 2006, pp. 622-628.
- [4]. Adel Nabian, Ghader Rezazadeh, Mohammadali Haddad-Derafshi and Ahmadali Tahmasebi, Investigation of Pull-in phenomena of Rectangular Micro-Plate Subjected to Nonlinear Electrostatic Pressure, *Sensors & Transducers Journal*, 73, 11, 2006, pp. 810-818.
- [5]. J. A. Pelesko and D. H. Bernstein, Modeling MEMS and NEMS, Chapman Hall and CRC Press, 2002.
- [6]. M. J. Anderson, J. A. Hill, C. M. Fortunko, N. S. Dogan, and R. D. Moore, BroadBand Electrostatic Transducer, Modeling and Experiments, *J. Acoust. Soc.*, Am 97, 1995, pp. 262-272.
- [7]. Zengerle R, Richter A and Sandmaier H, A micro membrane pump with electrostatic actuation, In *Proceedings of the Conference on 'Micro Electro Mechanical System (1992)'*, Travemunde, Germany.
- [8]. X. M. Zhang, F. S. Chau, C. Quan, Y. L. Lam and A. Q. Liu, A study of the static characteristics of a torsional micro mirror, *Sensors Actuator A*, 90, 2001, pp. 73-81.
- [9]. P P. C. Hsu, C. H. Mastrangelo and K. D. Wise, A high sensitivity polysilicon diaphragm condenser microphone, In *Proceedings of the Conference on 'MEMS (1998)'*, Heidelberg, Germany.

- [10].H. A. Tilmans and R. Legtenberg, Electrostatically driven vacuum-encapsulated polysilicon resonators: part II, Theory and performance, *Sensors Actuators A*, 45, 1994, pp. 67-84.
- [11].Xiaopeng Zhao, Eihab M Abdel-Rahman and Ali H Nayfeh, A reduced-order model for electrically actuated microplates, *Journal of Micromechanics and Microengineering*, 14, 2006, pp. 900-906.
- [12].H. C. Nathanson, W. E. Newell, R. A. Wickstrom, and J. R. Davis, The Resonant Gate Transistor, *IEEE Trans. on Elect. Devices*, 14, 1967, pp. 117-133.
- [13].G. I. Taylor. The coalescence of closely spaced drops when they are at different electric potentials, *Proc. Roy. Soc A*, 306, 1968, pp. 423-434.
- [14].Gh. Rezazadeh, A. Tahmasebi and Mikhail Zubtsov, Application of Piezoelectric Layers in Electrostatic MEM Actuators: Controlling of Pull-in Voltage, *Journal of Microsystem Technologies*, 12, 12, 2006, pp. 1163-1170.
- [15].Rezazadeh Ghader and Tahmasebi Ahmadali, Eliminating of the Residual Stresses Effect in the Fixed-Fixed End Type MEM Switches by Piezoelectric Layers, *Sensors & Transducer Journal*, 66, 4, 2006, pp. 534-542.
- [16].Mukherjee T., Fedder G.K., White J., Emerging simulation approaches for micromachined devices, *IEEE Trans comput Aided Des Integr Circuits Syst*, 19, 2000, pp. 1572-1589.
- [17].S. Timoshenko and S. Woinowski-Krieger, Theory of Plates and Shells, McGraw-Hill, 2nd ed., 1959.

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

Sensors & Transducers Journal (ISSN 1726-5479)

Open access, peer review
international journal devoted to research,
development and applications of sensors,
transducers and sensor systems.

Published monthly by
International Frequency Sensor Association (IFSA)



<http://www.sensorsportal.com/HTML/DIGEST/Submission.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.

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 4-12 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.

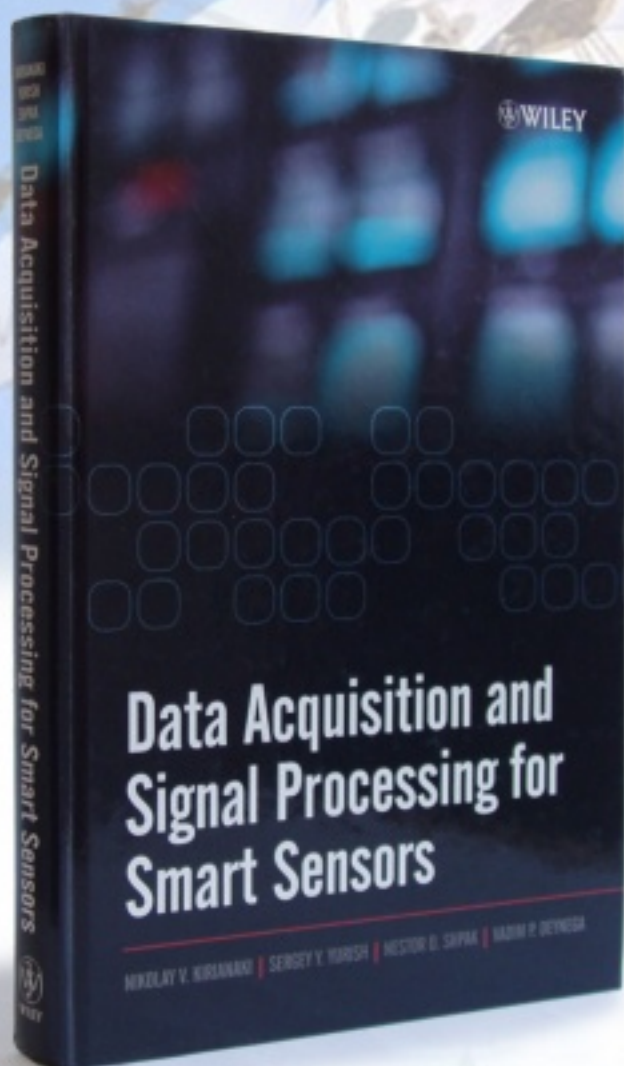
Advertising Information

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



WILEY
1807-2007

KNOWLEDGE FOR GENERATIONS



'This book provides a good basis for anyone entering or studying the field of smart sensors not only for the inexperienced but also very useful to those with some experience'

(from IEEE Instrumentation & Measurement Magazine review)

Order online:

http://www.sensorsportal.com/HTML/BOOKSTORE/DAQ_SP.htm

www.sensorsportal.com