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K. J. Vinoy
G. K. Ananthasuresh
Rudra Pratap
S. B. Krupanidhi *Editors*

Micro and Smart Devices and Systems

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Micro and Smart Devices and Systems

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Dedicated to

Prof. Vasudev K. Aatre

for his inspiring vision, unwavering conviction, and tireless effort that have resulted in creating and nurturing a vibrant multidisciplinary research field of micro and smart systems in India

Prof. Vasudev Kalkunte Aatre was born in 1939 in Bangalore where he also spent most of his childhood and formative years. He obtained his B.E. from UVCE (then under Mysore University) in 1961, M.E. from the Indian Institute of Science (IISc), Bangalore in 1963, and Ph.D. from the University of Waterloo, Canada, in 1967, all in Electrical Engineering. He worked as Professor of Electrical Engineering at Technical University of Nova Scotia, Canada, from 1968 to 1980. He was also a Visiting Professor at IISc in 1977. In 1980 he joined the Defence Research and Development Organisation (DRDO) of India.

Prof. Aatre worked in India's Ministry of Defence in various capacities for 24 years. He started his career in DRDO as a Principal Scientific Officer (1980–1984). Subsequently, he became the Director of the Naval Physical Oceanographic Laboratory (1984–1991), the Chief Controller (1991–1999), and finally, led the organization as the Director General and Scientific Advisor to Defence Minister (1999–2004). During this long period of dedicated service, he designed and developed sonar suites for surface ships, submarines, and the air arm of the Indian Navy. He was also instrumental in the development of integrated electronic warfare systems for the Indian Army, Navy, and Air Force, and he established GaAs MMIC fabrication facility and VLSI design centers for the Ministry of Defence. Prof. Aatre is also the founding president of the Institute of Smart Structures and Systems (ISSS) and has led the national programs on smart materials and micro and smart systems.

He has published over 60 papers in the fields of active filters, digital signal processing, and defense electronics, and has two books entitled Network Theory and Filter Design and Micro and Smart Systems, both published by John Wiley & Sons. He is a Fellow of the IEEE (USA) and the National Academy of Engineering (India), a Distinguished Fellow of IETE (India) and several other societies. Dr. Aatre is the recipient of the prestigious Padma Bhushan Award of the Government of India.

Foreword

Since the dawn of civilization, Nature has been man's greatest teacher. We have learned by observing and mimicking Nature and natural phenomena with the ultimate goal of building systems as complex, efficient, and optimal as biological systems created by Nature. Such systems, if they have to mimic biological systems, need to continuously sense the environment and respond, to a degree, optimally to achieve certain objectives or perform certain tasks. Although over the centuries, especially for the last century and a half, man has developed materials, devices, and systems, which have found application in myriad fields, competing with natural systems is a dream yet to be fulfilled. The recent advances in smart, micro, and nano systems have opened up a possibility of achieving this goal.

Institute of Smart Structures and Systems (ISSS) was started by a group of scientists, technologists, and engineers in India from academic institutions, space and defense departments in 1998 to trigger research and development in potentially highly application-oriented areas of micro and smart systems. ISSS actively participated in formulating two National Programs—National Program on Smart Materials (NPSM) followed by the National Program on Micro and Smart Systems (NPMASS), both sponsored by the five Scientific Departments of the Government of India and funded by the Department of Defence, India.

While setting up infrastructural facilities such as MEMS foundries, LTCC packaging facility, and developing sensors, actuators and subsystems for aeronautical, automobile, and biomedical applications were the principal goals of NPSM and NPMASS, supporting research projects in materials, sensors, and actuators and developing human resources in this area were equally important goals of the two programs. Towards this, the two national programs sponsored several R&D projects to academic institutions and national laboratories besides establishing 65 National MEMS Design Centers (NMDCs) in institutions across the country. These institutions and centers have conducted research, trained undergraduate and postgraduate students, thus creating a large body of human resources capable of pursuing developments in the general area of micro and nano systems. This special edition gives a glimpse of the R&D work carried out in these institutions and centers.

The contents of this special edition clearly bring out two facts. The first and foremost is the large number of institutions involved in such R&D work and their geographical spread in India. This augurs well for the future development of this field and for the development of the required human resources thereof. The second is that the R&D activities cover the entire spectrum of the field from materials to systems and applications.

The founding members of ISSS were guided by one conviction that "India had missed the microelectronic revolution but should not miss the micro-machine and nano revolution." The happenings of the last decade and a half give great hope. I wish special editions like this were brought out once in three years to coincide with the triennial International Conference organized by ISSS.

Bangalore, March 2014 V. K. Aatre

Preface

This book covers multiple facets of micro and smart systems technologies. Miniaturization of sensors and actuators through effective use of smart materials forms the core of the book. Related aspects of material processing and characterization; modeling and simulation; and applications are also given due importance. Twenty nine chapters written by competent research teams from academia and government research labs comprise a valuable resource that gives a bird's-eye view of the state of the art of the field in India. While the technological details of the work described in this book are self-explanatory, it is pertinent to introspect on how it all happened in India not too long after the miniaturization revolution transpired elsewhere in the world.

Generous financial support and guidance from the government, vision and driving force of a leader, and a professional society that can enthuse an able workforce are perhaps three necessary factors to initiate and establish a new research area in a country. India has had all of these in the last 15 years to lay a firm foundation for micro and smart systems technologies. First, the Defence Research and Development Organisation (DRDO) and four other science and technology departments of the Government of India, initiated and ran two large research programs, namely, National Programme on Smart Materials (NPSM, 2000–2006) and National Programme on Micro and Smart Materials and Systems (NPMASS, 2007–2014), with a combined budget of nearly Rs. 270 crores ($45 M today). Second, Prof. V. K. Aatre, gave unstinted leadership and support to numerous researchers and research administrators whom he inspired and nurtured. Third, a professional society, ambitiously christened, the *Institute of Smart Structures and Systems* (ISSS) was founded in 1998 to bring together experts from multiple disciplines to create a research community in micro and smart systems in India. As a result of these efforts, India today is proud to claim its presence in the field. This edited monograph, with the exception of one chapter, is a record of the work done in India and thus it stands as a testimony to the success of a well-conceived and ably executed endeavor.

Many researchers from the academia and government research laboratories contributed to NPSM and NPMASS, which were admirably administered by the Aeronautical Development Agency (ADA) under the guidance of the Board for Smart materials Research and Technology (B-SMART). Constant support from the past and present Heads of DRDO and its higher management has helped run these programs well. Program offices of NPSM and NPMASS, which operated out of ADA, Bangalore, since 2000, did exemplary work in liaising with various arms of the programs and grantees, bringing synergy and effective program management. The chairs and members of Programme Assessment and Recommendation Committees (PARCs) looked after the technical details of the funded projects. The result of the untiring efforts of all these and many more individuals—too many to mention here—is widespread awareness of micro and smart systems technologies and engagement into research and development activities in almost all parts of India. NPSM and NPMASS have paid particular attention to human resource development by establishing more than 65 National MEMS Design Centres (NMDCs) in many states of India covering the length and breadth of the country. Hundreds of researchers have been involved in more than 150 projects funded by NPSM and NPMASS.

The most significant outcome of this concerted effort is that the spirit of multidisciplinary research in micro and smart technologies now pervades all parts of India. Most researchers began with modeling and design. Not too long ago in India, possessing a license of a microsystems simulation software meant being engaged in research in this area. But today it has changed; with the establishment of state-of-the-art well-equipped cleanrooms and characterization facilities, researchers in India are able to fabricate and even package devices and systems. All aspects of the field, development of microsensors and microactuators; material processing and characterization; fabrication; advanced modeling, design, and simulation; and systems design have all begun. Packaging and transfer of technology have also commenced. The chapters in this book are indeed organized accordingly.

The final link in this chain of events is commercialization of the developed technology. This step needs conscious effort and copious resources, perhaps an order of magnitude more than what went into creating the able research community. The time is now ripe to involve the established industries and to nurture entrepreneurship. One hopes that the same level of commitment and financial support will be given to incubating companies in micro and smart technologies in order to create a thriving industry in these areas in India.

Bangalore, April 2014

K. J. Vinoy
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Bangalore, April 2014

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Abbreviations

ADC	Analog-to-digital converter
AFE	Antiferroelectric
AFE-FE	Antiferroelectric to ferroelectric switching
AFP	Amplifying fluorescent polymer
A-IgG	Anti-immunoglobulin G
APA	Amplified piezo actuator
ASME	American society for mechanical Engineers
ASSURED	Affordable, sensitive, specific, user-friendly, rapid and robust, equipment-free, and delivered to those who need it
ASTM	American society for testing and materials
at.%	Atom percentage
ATS	Alkyltricholrosilane
Bo	Bond number
CA	Contact angle
CBP	Cardiac biopotentials
CFRP	Carbon fiber reinforced plastics
CMOS	Complementary metal oxide semiconductor
CNT	Carbon nanotubes
CSIR	Council of scientific and industrial research, India
CVD	Cardiovascular diseases
CVI	C for virtual instrumentation
DAC	Digital-to-analog converter
DAQ	Data acquisition
DC	Direct current
DI	De-ionized
DNA	Deoxy-ribonucleic acid
DNT	2,4-Dinitrotoluene
DoS	Department of Space, India
DRDO	Defence Research and Development Organization, India
DRIE	Deep reactive ion etching
DSC	Differential scanning calorimeter
DST	Department of Science and Technology, India
EC	Electrocaloric
ECG	Electrocardiograph

EDC	*N*-(3-Dimethylaminopropyl)-*N*′ Ethyl-carbodiimide Hydrochloride
EESSs	Electrical energy storage systems
EGFET	Extended-gate field-effect transistor
EMI	Electro magnetic interference
FE	Ferroelectric
FEA	Finite element analysis
FE-AFE	Ferroelectric to antiferroelectric switching
FEM	Finite element method
FGA	Forming gas anneal
FITC	Fluorescein Isothiocyanate
FSO	Full scale output
FWHM	Full width at half maxima
GFRP	Glass fiber reinforced plastics
GPa	Giga Pascal
GPRS	General packet radio service
HMX	High melting explosive (Octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine)
ICAF	International Committee for Aeronautical Fatigue
ICCMS	International Congress on Computational mechanics and Simulation
IDE	Inter Digited electrode
IgG	Immunoglobulin G
IPA	Iso-propylalcohol
ISFET	Ion-sensitive field-effect transistor
KMF	Kotagiri Mission Fellowship Hospital
KOH	Potassium hydroxide
LCD	Liquid crystal display
LED	Light emitting diode
LPCVD	Low-pressure chemical vapor deposition
LSCO	Lanthanum strontium cobaltate
LTCC	Low-temperature co-fired ceramic
LUMO	Lowest unoccupied molecular orbital
MEMS	Micro electro mechanical systems
ML	Multi-layered
MOSFET	Metal-oxide semiconductor field-effect-transistor
MuA	11-Mercapto-undecanoic acid
MWCNT	Multi-wall carbon nanotubes
NDE	Non destructive evaluation
NHS	*N*-Hydroxysuccimide
Ni	Nickel
NiTi	Nickel Titanium
NPMASS	National Programme on Micro and Smart Systems
NPSM	National Programme on Smart Materials
Op-Amp	Operational amplifier
OTS	Octadecyltrichlorosilane
PANP	Polyaniline nanoparticles

PBS	Phosphate buffer saline
PCB	Printed circuit board
PDE	Partial differential equation
PDMS	Polydimethylsiloxane
PDMS	Poly-dimethyl Siloxane
PE	Paraelectric
PECVD	Plasma enhanced chemical vapor deposition
PEDOT	PSS:poly (3,4-ethylenedioxythiophene) poly(styrenesulfonate)
PETN	Penta erythritol tetra nitrate
pHpzc	pH at the point of zero charge
PLD	Pulsed laser deposition
PLZT	Lead lanthanum zirconate titanate
PMN	Lead magnesium niobate
pMUTs	Piezoelectric micromachined ultrasonic transducers
POC	Point-of-care
PT	Lead tiatanate
PTFE	Poly-tetrafluoro ethylene
PVDF	Polyvinylidene fluoride
PZ	Lead zirconate
PZT	Lead zirconate titanate
RC	Resistance capacitance network
RCA	Radio Corporation of America
RDX	Research Department Explosive (1,3,5-Trinitro-1,3,5-triazacyclohexane)
REFET	Reference field-effect transistor
RF	Radio Frequency
RIE	Reactive ion etching
RIU	Refractive index unit
SAMs	Self assembled monolayers
SEM	Scanning electron microscopy
SHM	Structural health monitoring
SIF	Stress intensity factor
SMA	Shape memory alloys
SOI	Silicon on insulator
SPR	Surface plasmon resonance
SPW	Surface plasmon wave
SWCNT	Single walled carbon nanotubes
TCAD	Technology computer-aided design
TEM	Transmission electron microscopy
Ti	Titanium
TM	Transverse magnetic
TMAH	Tetra-methyl ammonium hydroxide
TNT	2,4,6-Trinitrotoluene
T-NT	Titanium-rich nickel titanium
UART	Universal asynchronous receiver/transmitter

UTM	Universal testing machine
VCG	Vectorcardiograph
WCA	Water contact angle
XRD	X-ray diffraction

Part I
Microsensors

Design, Development, Fabrication, Packaging, and Testing of MEMS Pressure Sensors for Aerospace Applications

K. N. Bhat, M. M. Nayak, Vijay Kumar, Linet Thomas, S. Manish, Vijay Thyagarajan, Pandian, Jeyabal, Shyam Gaurav, Gurudat, Navakanta Bhat and Rudra Pratap

Abstract In this chapter we present the design, fabrication, packaging, and calibration of silicon micro machined piezo-resistive pressure sensors for operation in the pressure range of 1.2–400 bar. Based on the detailed Finite Element Analysis (FEA), the diaphragm dimensions and the optimized locations for the piezo-resistors are designed, to achieve the best performance parameters over a wide range of pressures, with minimum nonlinearity and adequate burst pressure. The process parameters are optimized and the pressure sensors fabricated in the Centre for Nano Science and Engineering (CeNSE) at IISc. The wafers are diced, the devices mounted on headers, wire bonded and packaged suitably, tested, and calibrated at the cell level to determine the adequacy of the performance parameters of the sensors for different pressure ranges. The results achieved on the pressure transducer assembly with Active Temperature Compensation and the offset compensation using electronics and EMI filters in a single package are presented. Excellent linearity within 0.5 % in the output voltage versus pressure is demonstrated, over the specified pressure ranges (i) $0-1.2$ bar and (ii) $0-400$ bar, and over the temperature range of -40°C to $+80$°C.

Keywords Pressure sensors · Microfabrication · Packaging · Aerospace applications · Finite element analysis · Pressure sensor calibration

1 Introduction

Pressure sensors cater to about 60 % of the MEMS market. Among the various types of pressure sensors, piezo-resistive pressure sensors are easy to design to suit a wide range of pressure ranges. They are simple to fabricate with a suitably

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designed diaphragm acting as the sensing element and piezo-resistors serving as transducers. Miniaturization and batch processing of this device is achieved with great precision using the silicon micromachining technique for realizing the diaphragm [1–3]. The piezo-resistors and the interconnections are achieved using photolithography, diffusion, ion implantation, and thin film deposition, which are well established in the microelectronics technology. All the finer aspects of design, fabrication, packaging, characterization, and calibration of silicon micro machined piezo-resistive pressure sensors ranging from 1.2 (0.12) to 400 bar (40 MPa) fabricated at the National Nano Fabrication Centre (NNFC) of the Centre for Nano Science and Engineering (CeNSE) at the Indian Institute of Science, Bangalore in India are presented in the following sections of this chapter. The analysis and the experimental results on the devices fabricated have shown that the best results in terms of sensitivity and accuracy can be achieved by appropriately laying out the resistors either inside or outside the diaphragm, depending on the diaphragm dimensions and aspect ratios, which are decided by the maximum pressure range of operation. The chapter also brings out the various critical issues encountered during packaging and calibrating the pressure sensors.

2 FEM Analysis and Diaphragm Design Considerations

Based on the theory of plates [4], which assumes that the diaphragm is anchored all around its edges (as shown in Fig. 1a), the location of the maximum stress is usually identified to be at the center of the edge of the diaphragm and hence the piezo-resistors are conventionally embedded on the inner side of the diaphragm edge. However, for the silicon micro machined diaphragms, realized either by Deep Reactive Ion Etching (DRIE) or wet chemical anisotropic etching, the physical location of the anchor position is on the backside of the chip as shown in Fig. 1b and c. Hence, the maximum stress position with respect to the diaphragm and the positions of piezoresitors on the chip need to be assessed.

A rigorous 3D FEM-based COMSOL [5, 6] simulation of these bulk micro machined diaphragms has indeed shown that the position of the longitudinal peak stress component, estimated along the line XX' (marked in Fig. 1d) lies outside the diaphragm edge at a distance *Xp* (marked in Fig. 1b and c), when the aspect ratio, length/height (*L*/*h*), of the diaphragm is low. In Fig. 2 we show the typical result obtained for the case of a DRIE etched diaphragm having thickness $h = 200$ μm and lateral dimension $L = 750$ μm, for different magnitudes of pressure applied on this DRIE diaphragm as shown in the inset. For this case, the *L*/*h* ratio is 3.75 and the location of the peak stress lies outside the diaphragm edge at a distance $X_p = 75$ μm. It is also interesting to note that the position of the peak stress remains the same irrespective of the magnitude of the pressure applied.

The effects of aspect ratio (*L*/*h*) on the position X_p of the peak longitudinal stress, for an applied pressure $P = 100$ bar is studied using the FEM simulation tool, considering *L*/*h* ratios ranging from 2.5 to 8.5 by varying *L* from 500 to

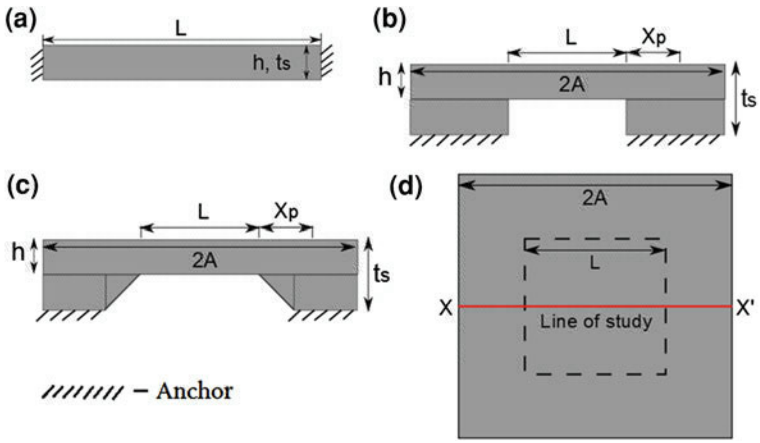

Fig. 1 Cross-section of the diaphragm **a** anchored on all *sides* (as in the theory of plates) **b** and **c** anchored on the *backside* (as obtained in the DRIE and KOH etched silicon). **d** *Top view* of the chip showing the *square* diaphragm of side length L (= 2a) by *dashed line*. The side length of the *square* chip is shown as 2A

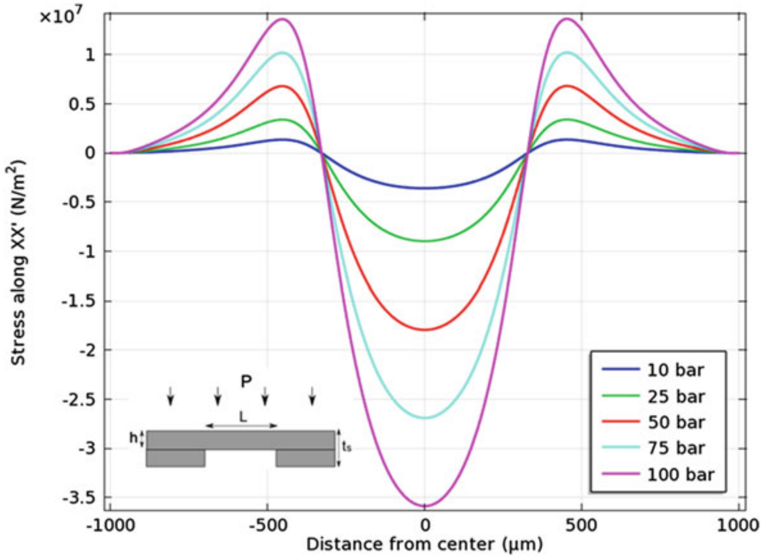

Fig. 2 FEM analysis results showing the stress distribution along XX' for different magnitudes of pressure P (in bars) = 10, 25, 50, 75, and 100 applied on a DRIE diaphragm having $h = 200$ µm and $L = 750$ µm, and a *square* chip having the side length 2A = 2 mm, $t_s = 400$ µm

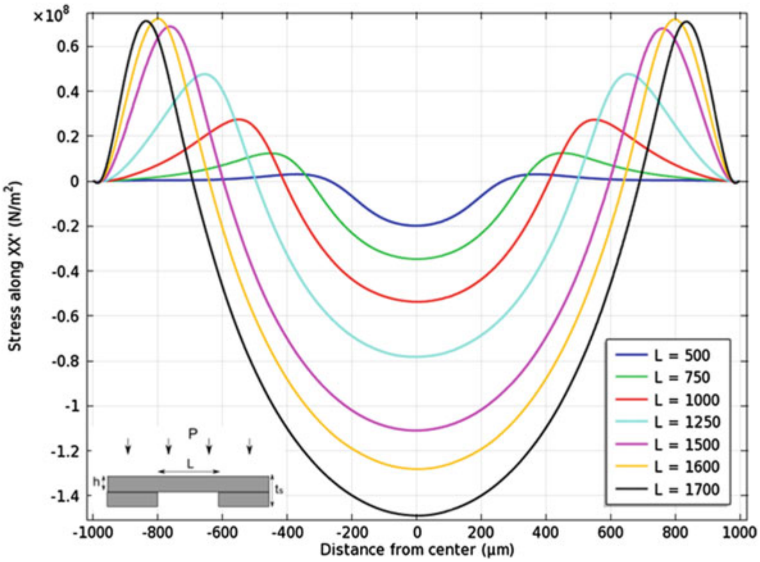

Fig. 3 FEM analysis results showing the variation of stress along XX' for a 200 μm thick DRIE etched diaphragm, for different diaphragm side lengths (*L*) as running parameter, when a pressure of 100 bar is applied

1700 μm and keeping the DRIE etched diaphragm thickness fixed at $h = 200$ μm. The results are shown in Fig. 3. The distance (*Xp*) between the edge of the diaphragm and the position of peak as a function of *L*/*h* ratio determined for the cases having $h = 200$ μm and $h = 20$ μm are shown in Table 1a and b.

We also determined the effect of the diaphragm lateral length *L* on the position of the peak stress (*Xp*), with a fixed diaphragm thickness, $h = 100$ μm, considering both DRIE etched and KOH etched diaphragms with crosssection shown in Fig. 1b, c. The results obtained from all the simulation studies involving various thicknesses and *L*/*h* ratios are shown in Fig. 4, where *Xp* is plotted versus *L*/*h* ratio. It can be seen that in general, *Xp* is positive when the aspect ratio is below eight indicating that the peak stress lies outside the diaphragm portion for these cases. As it can be seen from Fig. 4, in the case of thick diaphragms with $h = 200$ μm that are used for high-pressure applications, the location of peak stress lies at $Xp = +50$ μm outside the diaphragm edge when *L*/*h* ratio is equal to 5, corresponding to $L = 1000$ μm. On the other hand when $L/h > 8$, corresponding to the cases $L > 1600$ μm, with $h = 200$ μm, *Xp* becomes negative showing that the location of the peak stress shifts onto the diaphragm surface. In this situation as the diaphragm is too large the pressure range of operation decreases. In the case of thin diaphragms of the order of 20 μm thickness, $Xp = 0$ or very small ($Xp = +1$ to $+3$ μm). Thus, in situations where the diaphragm is thin, the theory of plates holds good with the maximum stress occurring at the diaphragm edge.