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MEMS and Nanotechnology-Based Sensors and Devices for Communications, Medical and Aerospace Applications

A.R. Jha, Ph.D.

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Dedication

This book is dedicated to my beloved parents who always encouraged me to pursue advanced research and development studies in the fields of science and latest technology for the benefits to mankind.

Foreword

One of the remarkable offshoots of the 50-year-old and yet exponentially growing silicon chip revolution has been the microelectromechanical systems (MEMS) technology. These miniaturized electromechanical devices are built on silicon substrates using well-established chip process technologies. Within these MEMS, we typically see integration, on a single silicon substrate, of not just electronic devices as on the chips, but also mechanical elements, sensors, and actuators. In addition to the commonly present materials in silicon integrated circuits (ICs), other materials such as ceramics and most recently carbon nanotube (CNT) arrays are also being incorporated into MEMS. The resulting microsystems have shown, for a variety of applications, unprecedented levels of miniaturization, reliability, and new capabilities.

Various end-user applications are based on devices that get incorporated in hybrid (MEMS and non-MEMS) systems or stand-alone MEMS. Examples include electro-optical, acoustic, and infrared (IR) sensors, RF/mm wave phase shifters, switches, tunable filters, resonators, and gyros for automobile control and safety. In addition to automobiles, the use of these subsystems in unmanned aerial vehicles (UAVs) is becoming increasingly common these days. An even faster growing application is in medical applications. These involve added technology synergies from nanobiotechnology materials. The resulting applications are concerned with advanced diagnostic tools as well as targeted deliveries of drugs to cancer cells.

This comprehensive book on MEMS and nanotechnology (NT) provides a wide-lens perspective of the field. It starts from basic design principles and current technologies for three-dimensional (3-D) MEMS with physical dimensions in the millimeter range. Fabrication processes incorporate modified silicon chip process technologies such as stress-controlled polysilicon thin films, as well as CNT arrays, and smart metal films. These are packaged in conventional as well as multichip modules (MCM) as practiced in the current state of the art. Structural material requirements for operating under harsh thermal, humid, and vibration environments are covered. The fabrication technology demands particular attention to sealing, bonding, passivation, etc. To assure compatibility, one needs to focus on coefficient of thermal expansion (CTE) match, and right choices from the available array of semiconductor technology materials from a diverse group consisting of single crystal and polycrystalline silicon, silicon oxide, silicon nitride, ceramics, glasses, polyimides, aluminum, chromium, titanium nitride, nickel, gold, etc.

There are two subsequent chapters dedicated to actuation mechanisms and integration with sensors and devices. Potential actuation mechanisms are based on electrostatic (ES), piezoelectric, electrothermal, electromagnetic, and electrochemical phenomena, which are discussed in great detail. The design trade-offs for reliability (e.g., cantilever beams), force-generating capacity, response time, and drive voltage/power requirements are covered in some depth. The mechanisms are applications specific and they must be individually customized for medical, auto, communications, and aerospace industries. A parallel-plate (PP) actuator is described in detail as a case study, because it is optimal for delivering a large output force over small displacements as needed in the case of hard-disk drives. Electrostatic (ES) rotary microactuators are also covered, as are bent-beam actuators.

Other chapters are dedicated to design, development, and performance aspects of

- RF-MEMS switches operating at microwave and mm-wave frequencies for wireless communications and electronically steerable antennas
- MEMS phase shifters, both absorption and reflection types, again for electronically steerable-phased array antennas, which offer significant reliability advantage over conventional electronics-based subsystems
- Micropumps (MPs) and microfluidic devices for chemical detection, microbiology, clinical analysis, biological detection, and heat transfer in microelectronic devices, with emphasis on process variables, reliability, and critical design parameters
- Other sensors and devices, such as varactors (tunable capacitors), accelerometers, wideband-tunable filters, and strain sensors are described.

The last chapter deals with a variety of emerging NT materials that enable special purposes of MEMS. These include quantum dots of dye-doped silica nanoparticles, zinc selenium nanocrystals, and fluorescent nanoparticles for clinical applications. Another example involves barium hexaferrite nanocomposite coatings or CNT arrays in high-temperature nanocomposites for high-performance aircraft.

This stimulating book should appeal to a wide audience consisting of design engineers, research scientists, and program managers. It contains a wealth of synergistic information and insights relating to the innovative field of MEMS and NTs. My friend, A.R. Jha, one of the most prolific writers, has covered a wide range of emerging technical fields, not yet included in the established literature. I am proud to write this foreword in support of his most recent book.

Ashok K. Sinha
Retired Senior Vice President, Applied Materials, Inc.

Preface

Recent advancements in nanotechnology (NT) materials and growth of micro/nanotechnology have opened the door for potential applications of microelectromechanical systems (MEMS)- and NT-based sensors and devices. Such sensors and devices are best suited for communications, medical diagnosis, commercial, military, aerospace, and satellite applications. This book comes at a time when the future and well-being of Western industrial nations in the twenty-first century's global economy increasingly depend on the quality and depth of the technological innovations they can commercialize at a rapid pace. Integration of MEMS and NTs will not only improve the overall sensor or device performance including the reliability but it will also significantly reduce the sensor weight, size, power consumption, and production costs. Advancements in MEMS and NTs offer unlimited opportunities in the design and development of various electro-optics sensors, lasers, RF/mm-wave components such as phase shifters, switches, tunable filters and micromechanical (MM) resonators, acoustic and infrared (IR) sensors, photonic devices, accelerometers, gyros, automobile-based control and safety devices, unmanned aerial vehicles (UAVs) sensors capable of providing the intelligence, reconnaissance, and surveillance missions of battlefields. It is important to point out that the latest MEMS- and NT-based sensors and devices are essential to enhance tactical UAV capabilities such as surveillance, reconnaissance, detection, identification, classification, and tracking of battlefield targets. UAVs using miniaturized thermal high-resolution IR sensors incorporating NT and NT-based composite materials will significantly improve the UAV close-range attack capability and covert surveillance and reconnaissance missions in the battlefields. The defensive capability of the UAV can be converted into offensive capability incorporating NT-based tracking sensors miniaturized IR missiles and the UAV will be recognized as an unmanned combat air vehicle (UCAV).

NT can play a key role in the diagnosis and treatment of a disease. NT scientists and nanobiotechnology engineers are deeply involved in research and development activities to search for new therapies, advanced diagnostic tools, and better understanding of the cell and disease symptoms. Nanobiotechnology clinical scientists believe that correct dose of drug will be directly delivered to cancer cells to provide immediate and effective comfort to the patients.

High-resolution IR sensors and thermal high-resolution IR sensors are best suited for commercial, industrial, military, and space applications. Cryogenically cooled MEMS-based photonic, electro-optic, microwave, mm-wave, and IR devices will have significantly improved the system performance, most suitable for space surveillance and reconnaissance, premises security, missile warning, and medical diagnosis and treatment. Cryogenic cooling has demonstrated significant performance improvement of sensors deployed by the UAVs, IR search and tracking systems, radar and missile warning receivers, satellite tracking systems, and imaging sensors.

This book has been written specially for MEMS and NT design engineers, research scientists, professors, project managers, educators, clinical researchers, and program managers deeply engaged in the design, development, and research of MEMS- and NT-based sensors and devices best suited for commercial, industrial, military, medical, aerospace, and space applications. The book will be found most useful to those who wish to broaden their knowledge in the field of MEMS and NTs. The author has made every attempt to provide well-organized material using conventional nomenclature, and a consistent set of symbols and identical units for rapid comprehension by the readers with limited knowledge in the field concerned. The latest performance parameters and experimental data on MEMS- and NT-based sensors and devices are provided in this book, which are taken from various references with due credits to authors and sources. The references provided include significant contributing sources. This book consists of nine chapters, each dedicated to a specific topic and application.

Chapter 1 summarizes the current design and development activities and technological advancements in the field of MEMS and NT. Current research and development activities contributed to rapid maturity of micro/nanotechnology, which has potential applications in MM systems, (MEMS) sensors, and devices most suitable for base stations, satellite communications, cellular and mobile phones, medical diagnosis, and aerospace sensors. Design and development activities of three-dimensional (3-D) MEMS devices with physical dimensions in the millimeter range are briefly discussed. Manufacturing of MEMS components using the very large-scale integration (VLSI) process, fabrication procedure involving a modified integrated circuit (IC) technology, and incorporating a stress-controlled polysilicon process are identified. Integration of advanced technologies such as micromultiple chip module (MCM) and micro-optic (MO) in future nano/micro-spacecraft is briefly discussed. Note a nano/micro-spacecraft system can integrate several functions such as guidance, navigation, and various control functions on a chip, which are most suited for UAVs with reconnaissance and surveillance capabilities. NT-based smart materials such as nanowires (NWs), nanoparticles, carbon nanotubes (CNTs), nanocrystals, and nanostructures are briefly discussed with particular emphasis on their applications in commercial, industrial, military, and aerospace applications.

MEMS- and NT-based sensors will be most attractive for aerospace, military, and space applications, where weight, size, power consumption, and reliability are the critical design requirements.

Chapter 2 identifies and describes various actuation mechanisms, their performance capabilities, limitations, and potential applications. Integration of MEMS technology with next-generation sensors and devices is briefly mentioned. Potential actuation mechanisms such as ES, piezoelectric, electrothermal, electromagnetic, electrodynamic, and electrochemical are discussed in great detail with emphasis on cantilever beam reliability, force-generating capacity, response time, design complexity, and drive voltage and power requirements. An RF-MEMS switch design is briefly described to understand the critical roles played by each element of the actuation mechanism deployed. Design requirements for a freely movable microstructural flexible membrane known as an armature or beam are identified. The mechanical displacement is provided by the microactuator using the force generated by an appropriate actuation mechanism. Plots of mechanical force generated by each actuation mechanism as a function of air gap, spring constant of the beam, beam geometrical parameters, and mechanical properties of materials involved are provided for the benefits of MEMS designers, students, and research scientists. Design requirements for electrodes, cantilever beams, contact surfaces, and passivation layers are identified. Pull-in and sticking problems generally experienced by some microactuators, which can affect the actuator reliability, are briefly mentioned. Actuation mechanisms most suited for communications, medical diagnosis, aerospace, and auto-safety applications are identified. Actuation mechanisms most suitable for RF-MEMS switches, mm-wave phase shifters, micropumps (MPs), health-monitoring devices, and chemical and biological threat-detecting sensors are recommended with emphasis on reliability, cost, actuation voltage, and design aspects.

Chapter 3 describes the latest version of actuation mechanisms capable of providing higher actuation forces to achieve displacements in rectangular dimensions. Performance capabilities of actuation mechanisms described in this chapter are not possible from the mechanisms discussed in Chapter 2. Current microactuators such as the ES rotary microactuator, bent-beam electrothermal microactuator, vertical comb array microactuator (VCAM), and electrochemical microactuator using CNTs are described with major emphasis on enhanced performance capabilities, operational benefits, design simplicity, fabrication aspects, and reliability. Optimum design configurations of electrodes capable of providing uniform and reliable actuation force for the actuators are identified with emphasis on enhanced force-generating capability and higher tracking accuracy over a wide bandwidth. A parallel-plate (PP) actuator configuration is described in great detail, because it is best suited for applications demanding a large output force over small displacements as in the case of hard-disk drives. The design aspects of ES rotary microactuator, which is considered most ideal for the dual-stage servomechanism, are briefly discussed. Design requirements for the critical elements of a rotary microactuator are identified. Computed values of static displacements and power consumption as a function of actuator beam geometrical dimensions and actuation voltages are summarized. Computerized data on ES force generated by the conventional and tilted configurations of rotary microactuator as a function of clearance and tilt angle is provided in a tabular format. Major drawbacks of the bent-beam actuator, namely, the long response time and thermal time constant, which is much higher than the electrical and mechanical time constants, are identified. Plots of generating force as a function of beam dimensions, air gap, and actuation voltages for various actuators are provided. Normalized torque plots as a function of normalized angular displacement and normalized capacitive gap are presented for a rotary microactuator with optimum shaped electrodes. Calculations and plots of displacement and mechanical resonance frequency as a function of piggyback microactuator dimensions, number of electrodes, and structural material parameters are provided for the benefits of the MEMS engineers, graduate students, and research scientists. Performance comparison data on vertical and lateral comb array microactuators is summarized with emphasis on drive voltage and electrical power requirements.

Chapter 4 deals with the packaging, structural material, and fabrication requirements vital for the design, development, and testing of MEMS- and NT-based sensors and devices. In addition, this chapter briefly discusses structural material requirements best suited for MEMS devices capable of operating under harsh thermal, humid, and vibration environments. Thermal, structural, mechanical, electrical, optical, and RF/microwave properties of the materials required in the fabrication, packaging, and bonding for MEMS sensors and devices are summarized. Important characteristics of soft and hard substrates, piezoelectric, and ferromagnetic materials needed for the fabrication of MEMS devices are discussed with emphasis on reliability and device longevity under harsh operating environments. Sealing material requirements are identified with particular emphasis on coefficient of thermal expansion (CTE) match, mechanical integrity, and MEMS device reliability over extended periods. Traditional semiconductors, alloys, and metal materials such as single crystal, polysilicon, silicon oxide, silicon nitride, ceramics, glassed, polymers, polyimides, aluminum, chromium, nickel, gold, and controlled expansion (CE) alloys are briefly discussed. Important properties of zero-level and first-level packaging, sealing, bonding, contact pads, passivation layers, and low-loss electroplating materials are summarized with emphasis on retaining optimum performance over extended periods and under severe operating environments. Properties of alumina, quartz, and fused silica best suited for mm-wave MEMS switches and phase shifters are discussed with major emphasis on dimensional stability, heat dissipation capability, insertion loss, isolation, structural integrity, and strength-to-weight ratio.

Chapter 5 exclusively focuses on the design and development aspects and performance capabilities and limitations of RF-MEMS switches operating at microwave and mm-wave frequencies most suited for wireless communications applications and electronically steerable antennas. Two types of RF-MEMS switch configurations, namely, series and shunt configurations, are discussed in great detail. Advantages of MEMS-based direct-contact switches over the conventional semiconductor RF switches are summarized with emphasis on reliability, power consumption, and control voltage requirements. Critical elements for both the RF-MEMS switches and the RF/microwave phase shifters are described. Performance capabilities and limitations of RF-MEMS shunt and series switches are summarized. Techniques to reduce insertion loss and to enhance isolation, switching speed, power-handling capability, and reliability are outlined. Effects of packaging environments on the functionality and performance of RF-MEMS switches are summarized with emphasis on reliability. Techniques to eliminate failure mechanisms in RF switches are recommended. Benefits of low actuation mechanisms are summarized. In the case of RF-MEMS switches, the nonlinear effects such as signal distortions and intermodulation products generated by the upstate bridge capacitance are mentioned.

Chapter 6 is dedicated to the MEMS phase shifters operating at microwave and mm-wave frequencies. Two categories of phase shifters, namely, absorption types and reflection types, are discussed. It is important to mention that the phase shifter is the most critical component of electronically steerable-phased array antennas, which are widely deployed in electronic warfare (EW) systems, missile tracking radar, forward looking radar used by fighter/bomber aircraft, covert communications systems, and space-based surveillance and reconnaissance sensors. Phase shifters using conventional field-effect transistors (FETs) and PIN-diodes suffer from high insertion loss, excessive power consumption, and poor reliability. However, integration of MEMS switches, MEMS tuning capacitors, and air gap, 3 dB couplers using coplanar waveguide (CPW) technology will lead to design and development of microwave and mm-wave phase shifters with low insertion loss, high isolation, negligible power consumption, enhanced reliability, and significantly reduced intermodulation products and signal distortions. MEMS-based phase shifters are best suited for reconnaissance satellite, missile seeker receivers, and UAVs where weight, size, power consumption, and reliability are the principal design requirements. Optimum design parameters such as Bragg frequency, center conductor width of CPW transmission line, spacing between the MEMS bridges and electrode geometry and dimensions are specified to achieve minimum insertion loss per bit, low-voltage standing wave ratios (VSWRs), reduced phase errors, and high isolation over wideband operations. Optimum design configurations for 2-bit, 3-bit, and 4-bit MEMS-based phase shifters capable of operating wideband in mm-wave regions are identified. Performance capabilities and limitations for MEMS-based true-time-delay (TTD) phase shifters operating in X-band, K-band, V-band, and W-band are summarized.

Chapter 7 concentrates on the design requirements, performance capabilities, and limitations of MPs and microfluidic devices and their potential applications in various disciplines. Note that microfluidics is an important branch of MEMS technology best suited for chemical detection, microbiology, clinical analysis, biological detection, and heat transfer in microelectronic devices. The MP is the critical component of a self-contained microfluidic system or sensor. Performance capabilities of passive MP designs, namely, floating-wall check valves or cantilever-beam "flapper valves," widely known as pneumatic valves, are summarized with emphasis on reliability. Design aspects of MPs using fixed valves involving no moving parts are described with emphasis on flow rate, pressure, and reliability over extended periods.

Performance parameters of various types of MPs such as piezoelectric valve-free (PEVF) MP, electrohydrodynamic (EHD) ion-drag MP, and ferrofluidic magnetic (FM) MP are summarized with emphasis on flow rate, pressure head, and reliability over extended durations. Design aspects for an MP using ES actuation mechanism are identified with emphasis on cost and performance. MPs using ES actuation methods are best suited for drug delivery applications. MPs with fixed-valve designs most ideal for transport of particle-laden fluids are described in great detail. Design, fabrication, and testing of fixed-valve pumps are briefly discussed. Low-order linear model capable of identifying design parameters for optimum performance and predicting resonance behavior is described. Benefits of low-order linear modeling and dynamic nonlinear modeling of MPs are briefly discussed. Numerical computations for resonance frequency, spring constant, pressure gradient, and equivalent mass for a piezoelectric valve-free MP are provided for the benefit of the readers. Curves illustrating the flow rates as a function of natural frequency and differential pressure are provided for the benefit of MEMS-based MP designers.

Chapter 8 describes the performance capabilities of selected MEMS and NT-based sensors and devices best suited for commercial, industrial, health monitoring, military, and aerospace applications. Discussions will be limited to sensors and devices not described previously. Performance capabilities of unique MEMS- and NT-based sensors and devices such as MEMS varactors or tunable capacitors, wideband-tunable filters, accelerometers, NT-based tower actuators using multiwall carbon nanotubes (MWCNTs), biosensors incorporating CNTs, strain sensors using smart materials, and MEMS sensors using smart materials to monitor health of structures, weapon systems, and battlefield environments are summarized. Potential applications and benefits of micro-heat pipes, photovoltaic cells, NT-based radar-absorbing materials, photonic detectors, lithium-ion microbatteries (MBs), and microminiaturized deformable mirrors are discussed identifying their unique performance capabilities. Applications of NWs, nanotubes, nanocrystals, nanorods and nanoparticles in commercial, military, medical, and aerospace disciplines are identified. Timoshenko and Euler–Bernoulli equations are used to compare the computational accuracy of the resonance frequency associated with beams used by various micro-resonators. Potential applications of MEMS varactors in wideband-tunable filters, phase shifters, RF synthesizers, and reconfigurable RF amplifiers are discussed with emphasis on reliability and stable RF performance over extended periods.

Chapter 9 summarizes materials and their important properties critical in the design and development of MEMS- and NT-based sensors, photonic components, and the new generation of MEMS devices for possible applications in aerospace, automobile, clinical research, cancer diagnosis/treatment, and drug delivery. Applications of photonic bandgap devices and photonic bandgap fibers are identified. High temperature stability, frequency stability, and lowest phase noise of optoelectronic-oscillators (OEOs) operating at 10 GHz and beyond are specified. Potential applications of quantum dots dye-doped silica nanoparticles and zinc selenium nanocrystals are identified for clinical research, cancer therapy, and biosensor technology. Benefits of fluorescent nanoparticles capable of providing high-resolution images superior to those obtainable from current magnetic resonance imaging (MRI) and computerized tomography technologies are identified for cancer research and diagnosis. Potential applications of barium hexaferrite nanocomposite coatings vital in the development of stealth technology are briefly discussed with particular application in high-performance fighter or reconnaissance aircraft to avoid detection by enemy radar. Important thermal, mechanical, and electrical properties of bulk and microscale materials best suited for fabrication and packaging of MEMS- and NT-based sensors and microsystems are summarized. Materials and their properties widely used in the design of MEMS- and NT-based sensors and devices such as acoustic sensors; CNT-based transistors; multijunction, high-efficiency photovoltaic cells using organic thin-films; and smart sensors to monitor weapon health, battlefield environments, and chemical/biological/toxic agents are briefly summarized. Applications of CNT arrays in multifunctional, high-temperature nanocomposites best suited for rocket motors and warheads, high-current density electron emitters with cold cathodes, MEMS biosensors, electrochemical actuators, and electrodes for MBs are discussed in great detail with emphasis on reliability and performance parameters not possible with other technologies.

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Author

A.R. Jha, BSc (engineering), MS (electronics), MS (mechanics), and PhD (electronics), technical director, Jha Technical Consulting Service, has design, development, and research experience of more than 35 years in the fields of radar, electronic warfare, lasers, phased array antennas, solid-state mm-wave components, cellular/mobile/satellite communication, receivers, MEMS devices, and IR sensors. Dr. Jha has published more than 75 technical papers (including eight invited papers) and authored eight high-technology books and holds a U.S. patent on a mm-wave terrestrial communication antenna.

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