1

Introduction

Over the past 30 years, with the proposal of various micro-electromechanical systems (MEMS) and nano-electromechanical systems (NEMS), micro/nanoscale measurement techniques have rapidly become powerful, and as a result, have become an invaluable tool for investigating micro/nanoscale devices and their properties. In this chapter, we will first present the basic concepts and current state of micro/nanoscale science and technology and related measurement techniques. Subsequently, we will introduce the specific micro/nanoscale measuring techniques that lie at the core of this book and will highlight examples of important achievements in the field. We will conclude with a brief comment on the future prospects of micro/nanoscale measurement techniques.

1.1 Micro/Nanotechnology

In this book, we focus on two important issues in micro/nanotechnology: MEMS and NEMS. First, we will briefly explain how materials, mechanisms, data, sensing, and systems are integrated in micro/nanotechnology. We will also highlight how important features of micro/nanotechnology increasingly rely on the multidisciplinary advances in science and technology, and how they help to drive these advances.

1.1.1 Development of MEMS

In 1994, the Federal Ministry of Education and Research (BMBF) in Germany defined MEMS as a technology that combines computers with tiny mechanical devices such as sensors, valves, gears, mirrors, and actuators embedded in semiconductor chips. A MEMS device contains microcircuitry on a tiny silicon chip into which some mechanical device such as a mirror or a sensor has been manufactured. Such chips can be built in large quantities at low cost, making them cost-effective for many applications. They consist of sophisticated but compact sensors and actuator systems, in addition to related processing circuits, which measure and electronically process parameters such as acceleration, pressure, distance, temperature, light, and chemical concentrations. As a result, these devices have the capacity for detection, computation, and actuation. Manufacturing and processing these devices requires a combination of various cutting-edge microfabrication technologies.

Measurement Technology for Micro-Nanometer Devices, First Edition.
Wendong Zhang, Xiujian Chou, Tielin Shi, Zongmin Ma, Haifei Bao, Jing Chen,
Liguo Chen, Dachao Li and Chenyang Xue.

A typical MEMS device comprises a sensor, an actuator, a signal processing system, a control system, and a power supply. MEMS devices can transform energy, produce building blocks and signal substances for the body, generate and conduct electrical signals, and communicate with neighboring devices and more distant partners. They are also capable of repairing themselves and multiplying. MEMS devices can serve as microsensors, actuators, micromechanical optical devices, vacuum microelectronic devices, and power electronic devices. As a result, MEMS have a very broad range of potential applications in fields such as aviation, motoring, environmental monitoring, and biomedicine. Thus, the design and production of MEMS has grown into a huge industry. MEMS is believed to provide profound technological advantages to society, such as improving temperature transducers, humidity transducers, automation intelligence, and the reliability of integrated systems with built-in attitude regulation, similar to how microelectronics and computer science have brought great advantages to humans over the past few decades. MEMS technology has made electronic systems compact, more flexible, and smarter, thereby stimulating progress in the field of micro/nanotechnology.

Various types of MEMS devices, including pressure sensors, accelerators, micromachined gyroscopes, ink nozzles, and hard drive disks, are commercially available. Most industry observers predict that the global sales of MEMS devices will increase in the next five years, with an average annual increase in sales of approximately 18% (MEMS Industry Group, MIG, 2013). This will lead to opportunities as well as challenges, particularly in the fields of mechanical and electronics engineering, precision machinery and equipment, and semiconductors. The following highlights some of the expected trends in the development of the science and technology of MEMS:

1) Research scope diversification:

   MEMS-related research fields include microaccelerometers and microgyroscopes, atomic force microscope (AFM), data storage, three-dimensional microstructures, microvalves, pumps and nozzles, microflow devices, micro-optics, actuators, performance simulation of micro-electromechanical devices, fabrication processes, packaging and bonding, medical devices, device characterization and analysis of experimental results, pressure sensors, microphones, and acoustic devices. All these 16 fields have potential military and civil applications.
2) Process technology diversification:

   Various processing technologies for fabricating MEMS devices have been developed over the last twenty years. These include conventional silicon bulk processing; surface sacrifice layer processing; dissolved silicon processing; deep groove etching and bond combination processing; lithography, electroforming, injection molding processing; processing of metal sacrificial layers; metal-air MOSFET; and silicon-bulk-processing-combined surface sacrificial layer processing.
3) Development of monolithic integration for MEMS devices:

   Because of the very weak (current or voltage) output signals of MEMS sensors, useful information can be completely drowned out by stray capacitance and resistance if they are connected to external circuits. Therefore, in order to obtain a high signal-to-noise ratio (SNR) for MEMS devices, the sensors and processing circuits must be integrated on a chip. For example, ADI, an American company, used monolithic integration to integrate a sensor and circuits on a single chip to produce an integrated accelerator.

4) General considerations for the fabrication and packaging of a MEMS device:
   The major difference between a MEMS device and an integrated circuit chip is that a MEMS device usually has fragile, moveable components that can get damaged during transfer of the device before packaging. Therefore, fabrication and packaging must be considered simultaneously when MEMS devices are designed. Packaging techniques are indeed one of the most important MEMS research areas and are covered in every international conference and symposium on MEMS.
5) Coexistence of commercial devices and devices for specific applications (such as for aviation, space flight, or military use):
   Depending on the context of their use, different devices might have very different demands. For example, for accelerators used in airbags in automobiles, a sensitivity of 0.5 g is required, whereas in aerospace and other high-tech fields, accelerometers with high resolutions and sensitivities of below 10^{-8} g are used.

Based on the miniaturization, intelligence, and integration features of MEMS devices, we predict that the development of MEMS will bring about a technological revolution within the society, and profoundly influence science and technology, production methods, and production qualities throughout the twenty-first century. Furthermore, we expect MEMS to accelerate the development of national science, security, and economic prosperity in China.

1.1.2 Development of NEMS

NEMS are devices that integrate electrical and mechanical functionality on the nanoscale (0.1–100 nm); they are the next logical miniaturization step after MEMS devices. Typically, NEMS integrate transistor-like nanoelectronics with mechanical actuators, pumps, or motors, and may form physical, biological, and chemical sensors. Their typical device dimensions (in nanometers) lead to low mass, high mechanical resonance frequencies, potentially large quantum mechanical effects such as zero point motion, and high surface-to-volume ratios, which are useful for surface-based sensing mechanisms. NEMS devices have been used as accelerometers or detectors of airborne chemical substances.

NEMS are expected to significantly impact many areas of technology and science, and eventually replace MEMS because of the scale on which they can function. As noted by Richard Feynman in his famous talk in 1959, "There's Plenty of Room at the Bottom," there are many potential applications of machines at smaller and smaller sizes; technology benefits by building and controlling devices at smaller scales. The expected benefits include greater efficiencies and reduced size, decreased power consumption, and lower costs of production in electromechanical systems. In 2000, the first very-large-scale integration NEMS device was demonstrated by researchers from IBM. Its premise was an array of AFM tips that can heat/sense a deformable substrate in order to function as a memory device. In 2007, the International Technical Roadmap for Semiconductors (ITRS) contained NEMS memory as a new entry in the Emerging Research Devices section (text taken from Wikipedia, the free encyclopedia, https://en.wikipedia.org/wiki/Nanoelectromechanical-systems).

Two complementary approaches for the fabrication of NEMS can be found. The top-down approach uses traditional microfabrication methods, that is, optical and electron beam lithography, to manufacture devices. Although limited by the resolution of these methods, this approach allows a large degree of control over the resulting structures. Typically, devices are fabricated from metallic thin films or etched semiconductor layers. The bottom-up approach, in contrast, uses the chemical properties of single molecules to cause single-molecule components to (a) self-organize or self-assemble into some useful conformation or (b) rely on positional assembly. These approaches utilize the concepts of molecular self-assembly and/or molecular recognition. This allows fabrication of much smaller structures, albeit often at the cost of limited control over the fabrication process. Scientists have been able to find new properties of nanoscale clusters composed of dozens of atoms or molecules, through in-depth analysis of material properties. These clusters can be used to fabricate devices with specific nanotechnological functions. The main difference between nanotechnology and microelectronics is that devices manufactured via nanotechnology can have specific functions based on quantum wave theory that are achieved by controlling single atoms or molecules, whereas for microelectronic devices, and it realizes function based on the particle theory by controlling assembly of the electro.

In the following text, we will introduce briefly the principles of nanotechnology. When the dimensions of a material are in the range 0.1–100 nm, its properties can be significantly affected by the following factors:

1) Small size effect: when the size of a particle is equal to or smaller than the physical characteristic dimensions, such as the wavelength of light, the De Broglie wavelength of the conduction electrons, the coherent length of the superconducting state, or the penetration depth, then the periodic boundary conditions of the particle will break down: as a result, the acoustic, electric, magnetic, and thermodynamic characteristics of the particle will be changed.
2) Surface effect: with increasing surface area for a finite mass, the number of surface atoms becomes relatively insufficient. Therefore, surface atoms become more active because of the increasingly large surface energy. As a result, particles can more easily react with molecules adsorbed on the surface.
3) Quantum size effect: this effect is an unusual property of extremely small crystals that arises from the confinement of electrons in small regions of space in one, two, or three dimensions. This effect is seen when the size of an object is smaller than the de Broglie wavelength of electrons, and renders the classical picture of electrons trapped within hard wall boundaries unrealistic. As a result of this effect, the electronic energy levels transform from quasi-continuous to discrete, and the band gap is broadened.

Nanotechnology is a multidisciplinary field that covers many areas of research. In 1993, the International Nanotechnology Steering Committee divided nanotechnology into six branches, namely nano-electronics, nanophysics, nanochemistry, nanobiology, nanomanufacturing, and nanometrology. Nanophysics and nanochemistry are the basis of nanotechnology, whereas nano-electronics is an important application of nanotechnology. Three different definitions of nanotechnology have been proposed. One is that of "molecular nanotechnology," which was introduced in *Engines of Creation: The Coming Era of Nanotechnology* by K. Eric Drexler (with a foreword by Marvin Minsky) in the United States in 1986. The book features the concept of molecular nanotechnology, which Richard Feynman had discussed in his 1959 speech, "There's Plenty of Room at the Bottom." Drexler imagines a world where the entire Library of Congress can fit on a chip the size of a sugar cube and where universal assemblers, tiny machines that can build objects atom by atom, will be used for everything from medicinal robots that help clear capillaries to environmental scrubbers that clear pollutants from the air. In the book, Drexler first proposes the “gray goo” scenario, his prediction of what might happen if molecular nanotechnology were used to build uncontrollable self-replicating machines.

Some think that nanotechnology is a limitation of micro/nanoscale processing. In other words, a nanodevice is fabricated by the technique of processing with nanoscale resolution. Another nanotechnology definition was proposed according to developments in biology, which focus on the cell and membrane at the nanoscale.

Some predict that a material revolution, induced by nanotechnology developments in textiles, building materials, the chemical industry, oil, automobiles, and military equipment, is inevitable. In China, hundreds of companies and more than 10 production lines have been established to research nanomaterials and nanotechnology. Technological applications of nanotechnology include the creation of nanobatteries, tiny capacitors, and nearly microscopic microprocessors, which make smaller computers with even more advanced capabilities possible. Developments in this area will help decrease the replacement rate for computers that are used in advanced technological applications such as space travel, or used by everyday consumers, such as laptops. In addition, nanotechnology has produced flexible digital screens that can be bent without losing resolution, and novel plastics, nanorubbers, and nanofibers. However, there are many more applications of nanotechnology; it can be found in many objects and devices of everyday use, from wrinkle-free fabrics worn straight from the dryer to LCD screens that give us high-definition entertainment on the move, and skincare products that help keep skin cells healthy. All these use nanotechnology to make our lives better.

1.2 Development of Micro/Nanoscale Measurements

Micro/nanoscale measurements are used to investigate the characteristics and functions of micro/subnanometer-scale devices, and to evaluate microscale and surface/interface effects. These measurements form the foundation of the processing and testing of micro/nanoscale devices; they are an important way to qualitatively and quantitatively evaluate micro/nanoscale manufacturing and to ensure that such devices work with high precision.

Micro/nanoscale measurement techniques mainly include measuring physical, chemical, and mechanical properties of devices at the micro/nanoscale. Features of such measurements include measurement traceability and error evaluation, investigation of mechanical properties of structural components, investigation of device geometries, investigation of physical parameters, such as electronic properties, forces, magnetism, light, acoustics, multiple-domain coupling effects, and parametric device characterization.

1.2.1 Significance

Theoretical and experimental methods are used when trying to explore and reveal the physical laws of the world. The reliability of theoretical results should be quantitatively verified by experiment, and new theoretical results should be based on the analysis of experimental data. As a result, measurement techniques are very important, both theoretically and experimentally.

Micro/nanoscale measurements are critical for the design, simulation, quality control, and performance evaluation of MEMS and NEMS. However, because of their low stability, yield, and reliability, micro/nanoscale measurements are currently a key limiting factor in the development of MEMS and NEMS. The main limitations of such techniques are as follows:

1) The theories and techniques of micro/nanoscale measurements for MEMS and NEMS are not sufficiently well developed.
2) The available online measurement systems are not good enough, which means that problems that occur during the processing of MEMS/NEMS devices cannot be detected immediately.

These factors significantly limit the reliability of MEMS/NEMS and limit their potential for use in industrial and commercial applications.

1.2.2 Types of Micro/Nanoscale Measurements

Depending on the stage of the device fabrication process at which they are performed, micro/nanoscale measurements can be divided into three categories: wafer, chip, and device measurements.

Wafer measurements are used to check for conformity between a design and the processed structure, and to check for consistency and reproducible results among different microstructures or wafers. Chip measurements are mainly used to measure yields before packaging. Device measurements are mainly used to test the packaging quality and reliability of a finished device.

Wafer measurements include online tests of geometrical, mechanical, and material properties of micro/nanoscale structures such as films, beams, sheets, combs, and helical springs. Therefore, they are the basis of chip and device measurements. These measurements have been investigated by Tianjin University, Huazhong University of Science and Technology, Shanghai Institute of Microsystem and Information Technology, Harbin Institute of Technology, and North University of China, during the Tenth Five Year Plan of China. As a result, many machines used for morphology, stress, and mechanical measurements have been developed and online testing processing lines have been set up. Thus, challenges related to static geometry parameters, characteristics of periodic or aperiodic motion, microstresses, and elasticity in the context of MEMS/NEMS structures have been solved.

However, there are still some challenges with respect to wafer measurements. Firstly, for some microstructures, measurements are limited to planes (two dimensions) and are not accessible in three dimensions. For example, some parameters of high height/width ratio structures cannot be measured because of this limitation. Secondly, although the mechanical parameters of some MEMS can be measured, those of other devices, such as microfluidic MEMS or the surface characteristics of Bio-MEMS and the electromagnetic characteristics of RF-MEMS, cannot be measured. The transformation of measurement from prototype to equipment has to be completed. For example, equipment for stress detection is important in wafer measurements because low cost, online, multi-position, rapid measurements are urgently needed. The same problem exists for equipment used in morphology measurements of flash frequency interference.

Chip measurements mainly involve evaluation of the whole manufacturing process and the measurement of the performance of the microstructure with its accessories. The main problem for chip measurement is how to standardize the measurements and set up standardization guidelines. The main problem in doing this is the lack of measuring standards for the new metrology technologies that are being developed. Comparing chip measurements of MEMS/NEMS and microelectronics devices, for microelectronics measurements, we found that the focus is only on the detection of basic qualities such as resistance and capacitance of diodes and triodes. In contrast, chip measurements of MEMS/NEMS devices are more complicated and standardized measurements are needed to evaluate the whole process. For instance, it is necessary to measure the standard microcantilever built into a piezoresistive device in order to characterize the performance of the entire chip.

Device measurement mainly includes detection and evaluation of the quality of packaging and bonding, and that of usage reliability. During the Tenth Five Year Plan of China, the Harbin Institute of Technology developed equipment for bonding quality evaluation, and North University of China investigated measurements for micro-accelerators and pressure devices in various environments such as different temperatures, humidity, pressures, and vibrational environments. At present, the main problem for device measurement is that, firstly, inward version capability, such as wire bonding quality, chip-shell connection quality, and air-tightness, is needed for the microdevice after packaging. Secondly, for the reliability evaluation of microdevices, a standard and authoritative base for system measurement is needed. At present, such measurement equipment is scattered across many research centers, and it is hard to obtain raw data to establish comprehensive microdevice reliability evaluations.

With the rapid development of science and technology, we have a clearer understanding of the fields of micro/nanotechnology, and the need for more advanced micro/nanoscale measurement techniques with greater precision and resolution. Although the development of nanoscale science and nanotechnology has placed increasing challenges on the requirements of nanoscale measuring techniques, it simultaneously provides increased opportunities to develop novel nanoscale measuring techniques. We believe that breakthroughs in nanoscale measurements will accelerate the development of nanoscale science and technology.

1.2.3 Conclusion and Outlook

Demand for standardized measurement systems is becoming more urgent with the increasing commercialization of MEMS/NEMS devices and their application in a wide range of fields. Continued advances in MEMS technology have led to development of many of new devices. Thereinto, integration and packaging is becoming the main obstacles for their applications. Current trend in MEMS/NEMS is to produce ever smaller, lighter and more capable devices at a lower cost than ever before. In addition, the whole systems have to operate at very low power and in very adverse conditions while assuring durable and reliable performance. This editorial presents pertinent aspects in development of MEMS including, but not limited to, design, analysis, fabrication, characterization, packaging, and testing. The development of nanotechnology brings plenty of new challenges and responsibilities to NEMS, especially with the frontier engineering technology from mechanical engineering to intelligent nanosystems, from microelectronic engineering to nano, spin electronics and photonics. [1, 2]

In China, significant progress has been made in MEMS, thanks to support from the National High-tech R&D Program of China (863 Program). For example, many open platforms and research centers have been developed, and research has been performed into inertia sensors, RF-MEMS, Bio-MEMS, OPTIC-MEMS, POWER-MEMS, microfluidic MEMS, and electromagnetic MEMS. Furthermore, great progress has been made with respect to the theory and applications of MEMS/NEMS techniques. However, because of poor processing stability, low yields, and reliability issues, the industrialization of MEMS/NEMS is still in its infancy. Key factors that limit this are inadequate MEMS/NEMS techniques, and the fact that online measurement cannot be performed, which means that problems during manufacturing, packaging, and usage cannot be found and detected in real-time. In addition, they restrict the ability to maintain the consistency of the manufacturing process and device quality.

There are two main reasons for the backward in the development for technique of MEMS/NEMS. Firstly, the available measurement platforms are inadequate; MEMS are mostly designed, manufactured, and tested using Si-based microelectronics equipment. However, MEMS devices are significantly different from microelectronics devices because they often have movable microstructures. Furthermore, MEMS devices is varieties, small quantities at present, the well-directed technique of measurements call for the general measurement platform. Secondly, MEMS devices are not simply miniaturized versions of macro-electromechanical systems, and thus, traditional measurement techniques cannot fulfill their requirements. As a result of these shortcomings, research into micro/nanoscale testing in recent years has included extensive work into the measurement of multi-domain coupling parameters at the microscale, precision measurements at the multiscale and also at the sub-nano scale, and explorations of new measuring principles and methods.

Some of the major progress in these fields has been related to the following:

1) Improvement of measurement precision and fields: In the second half of the twentieth century, machinery precision has been improved from 0.1 mm to 0.001 mm and geometric precision from 0.01 μm to 0.001 μm. The measurement precision for equipment is typically three orders of magnitude higher, with this trend expected to continue. In addition, with the improvement of the fabrication and installation of large and mega-mechanical systems (such as power stations and aerospace manufacturing), and with the expansion of the research area, the measurement scale has greatly increased from the macro- to the microscale. At present, the range is from 10^{-15} to 10^{25}, a difference of 40 orders of magnitude. Similarly, for force measurements, the difference is about 14 orders; and for temperature measurements the difference is about 12 orders.
2) Dynamic measurements for analyzing various states of motion, physical, and chemical reactions, and for analyzing the evolution of processes are becoming popular. They also allow new characteristics to enter into design philosophy and manufacturing. Furthermore, they allow online and real-time measurements (rather than the traditional off-line ones).

3) Single-channel to multi-channel information acquisition: in traditional measurement methods, problems related to obtaining information were relatively simple, which are rather complicated in modern measurement systems. For example, modern methods often involve various types of information, and face issues with data reliability because of the huge amount of information. Furthermore, there are challenges related to quick transmission of data, efficient data management, and elimination of crosstalk. Therefore, the development of so-called multi-information fusion techniques promises to be an important new field.
4) Integration of geometrics and non-geometrics.
5) Complication of measurement objects and extramalization of the conditions: currently, some measurements show trends of complication and extramalization. Sometimes, a whole machine or piece of equipment needs to be measured, leading to diverse parameters and complex definitions. Also, sometimes, such measurements need to be performed under high temperature, high pressure, high speed, or high-risk situations, and make it become extramalization.
6) The wide application of virtual instrument technology.

At present, the research on measurements at micro/nano scale has attracted increasing number of researchers. Using micro/nano technology, the principle or change in the nature at atomic or molecular scales can be investigated. The development of micro/nanoscale technology is closely related to developments in the available equipment. Micro/nanoscale geometrical and topographical measurements are well developed. For example, the HP5528 has a double-frequency laser interferometer measurement system (with a resolution of 10 nm) and an optical stylus profile scanning system with a resolution of 1 nm. Scanning probe microscopy (SPM), which includes scanning tunneling microscopy (STM) and atomic force microscopy (AFM), can directly observe atomic structures and lattices on sample surfaces, and manipulate, assemble, and nanoprint atoms or molecules. This ability represents a significant success. The family of SPM techniques, which involves the use of cantilevers and tips, scanners and controllers, and data acquisition systems, enables people to observe the physical and chemical properties of atoms on sample surfaces.

In this book, we focus on measurement techniques for micro/nanoscale devices, including their methods and the equipment that they require. We summarize the development of this technology and emphasize on micro/nanoscale measurement techniques, including geometry testing, dynamic test technology, mechanical measurements, MEMS online testing, and reliability test of principles, method and equipment. We also discuss the specific characteristics of pressure sensors and accelerometers, which are widely used in this field.

References

1 Pryputniewicz RJ, Merriam KG. Challenges in MEMS technology. Strain. 2007;8:00407.
2 Guo W, Xie H, Zheng Q. Current trends of micro- and nanomechanics. Acta Mechanica Solida Sinica. 2009;22:6, I-III.