1. Introduction to Nanotechnology

A biological system can be exceedingly small. Many of the cells are very tiny, but they are very active; they manufacture various substances; they walk around; they wiggle; and they do all kinds of marvelous things – all on a very small scale. Also, they store information. Consider the possibility that we too can make a thing very small which does what we want – that we can manufacture an object that maneuvers at that level.

(From the talk "There's Plenty of Room at the Bottom", delivered by Richard P. Feynman at the annual meeting of the American Physical Society at the California Institute of Technology, Pasadena, CA, on December 29, 1959.)

by B. Bhushan

1.1 Background and Definition of Nanotechnology

On Dec. 29, 1959, at the California Institute of Technology, Nobel Laureate Richard P. Feynman gave a talk at the annual meeting of the American Physical Society that has become one of the twentieth century's classic science lectures, titled "There's Plenty of Room at the Bottom" [1.1]. He presented a technological vision of extreme miniaturization several years before the word "chip" became part of the lexicon. He talked about the problem of manipulating and controlling things on a small scale. Extrapolating from known physical laws, Feynman envisioned a technology using the ultimate toolbox of nature, building nanoobjects atom by atom or molecule by molecule. Since the 1980s, many inventions and discoveries in the fabrication of nanoobjects have become a testament to his vision. In recognition of this reality, the National Science and Technology Council (NSTC) of the White House created the Interagency Working Group on Nanoscience, Engineering and Technology (IWGN) in 1998. In a January 2000 speech at the same institute, former President William J. Clinton talked about the exciting promise of nanotechnology and, more generally, the importance of expanding research in nanoscale science and technology. Later that month, he announced in his State of the Union Address an ambitious $ 497 million federal, multi-agency National Nanotechnology Initiative (NNI) in the fiscal year 2001 budget, and made it a top science and technology priority [1.2, 3]. The objective of this initiative was to form a broad-based coalition in which academe, the private sector, and local, state, and federal governments would work together to push the envelope of nanoscience and nanoengineering to reap nanotechnology's potential social and economic benefits.

Nanotechnology literally means any technology performed on a nanoscale that has applications in the real world. Nanotechnology encompasses the production and application of physical, chemical, and biological systems at scales ranging from individual atoms or molecules to submicron dimensions, as well as the integration of the resulting nanostructures into larger systems. Nanotechnology is likely to have a profound impact on our economy and society in the early twenty-first century, comparable to that of semiconductor technology, information technology, or cellular and molecular biology. Science and technology research in nanotechnology promises breakthroughs in such areas as materials and manufacturing, nanoelectronics, medicine and healthcare, energy, biotechnology, information technology, and national security. It is widely felt that nanotechnology will be the next industrial revolution.

Nanometer-scale features are mainly built up from their elemental constituents. Chemical synthesis – the spontaneous self-assembly of molecular clusters (molecular self-assembly) from simple reagents in solution – or biological molecules (e.g., DNA) are used as building blocks for the production of three-dimensional nanostructures, including quantum dots (nanocrystals) of arbitrary diameter (about 10 to 10^5 atoms). A variety of vacuum deposition and nonequilibrium plasma chemistry techniques are used to produce layered nanocomposites and nanotubes. Atomically controlled structures are produced using molecular beam epitaxy and organo-metallic vapor phase epitaxy. Micro- and nanosystem components are fabricated using top-down lithographic and nonlithographic fabrication techniques and range in size from micro- to nanometers. Continued improvements in lithography for use in the production of nanocomponents have resulted in line widths as small as 10 nanometers in experimental prototypes. The nanotechnology field, in addition to the fabrication of nanosystems, provides the impetus to development of experimental and computational tools.

The micro- and nanosystems include micro/nanoelectromechanical systems (MEMS/NEMS) (e.g., sensors, actuators, and miniaturized systems comprising sensing, processing, and/or actuating functions), micromechatronics, optoelectronics, microfluidics, and systems integration. These systems can sense, control, and activate on the micro/nanoscale and function individually or in arrays to generate effects on the macroscale. The microsystems market in 2000 was about \$ 15 billion, and, with a projected 10–20 % annual growth rate, it is expected to increase to more than \$ 100 billion by the end of this decade. The nanosystems market in 2001 was about \$ 100 million and the integrated nanosystems market is expected to be more than \$ 25 billion by the end of this decade. Due to the enabling nature of these systems, and because of the significant impact they can have on the commercial and defense applications, venture capitalists, industry, as well as the federal government have taken a special interest in nurturing growth in this field. Micro- and nanosystems are likely to be the next logical step in the "silicon revolution."

1.2 Why Nano?

The discovery of novel materials, processes, and phenomena at the nanoscale, as well as the development of new experimental and theoretical techniques for research provide fresh opportunities for the development of innovative nanosystems and nanostructured materials. Nanosystems are expected to find various unique applications. Nanostructured materials can be made with unique nanostructures and properties. This field is expected to open new venues in science and technology.

1.3 Lessons from Nature

Nanotechnology is a new word, but it is not an entirely new field. Nature has many objects and processes that function on a micro- to nanoscale [1.2, 4]. The understanding of these functions can guide us in imitating and producing nanodevices and nanomaterials.

Billions of years ago, molecules began organizing themselves into the complex structures that could support life. Photosynthesis harnesses solar energy to support plant life. Molecular ensembles are present in plants, which include light harvesting molecules, such as chlorophyll, arranged within the cells on the nanometer to micrometer scales. These structures capture light energy, and convert it into the chemical energy that drives the biochemical machinery of plant cells. Live organs use chemical energy in the body. The flagella, a type of bacteria, rotates at over 10,000 RPM [1.5]. This is an example of a biological molecular machine. The flagella motor is driven by the proton flow caused by the electrochemical potential differences across the membrane. The diameter of the bearing is about 20–30 nm, with an estimated clearance of about 1 nm.

In the context of tribology, some biological systems have anti-adhesion surfaces. First, many plant leaves (such as lotus leaf) are covered by a hydrophobic cuticle, which is composed of a mixture of large hydrocarbon molecules that have a strong hydrophobia. Second, the surface is made of a unique roughness distribution [1.6, 7]. It has been reported that for some leaf surfaces, the roughness of the hydrophobic leaf surface decreases wetness, which is reflected in a greater contact angle of water droplets on such surfaces.

1.4 Applications in Different Fields

Science and technology continue to move forward in making the fabrication of micro/nanodevices and systems possible for a variety of industrial, consumer, and biomedical applications. A range of MEMS devices have been produced, some of which are commercially used [1.4, 8–12]. A variety of sensors are used in industrial, consumer, and biomedical applications. Various microstructures or microcomponents are used in micro-instruments and other industrial applications, such as micromirror arrays. Two of the largest "killer" industrial applications are accelerometers (about 85 million units in 2002) and digital micromirror devices (about $ 400 million in sales in 2001). Integrated capacitive-type, silicon accelerometers have been used in airbag deployment in automobiles since 1991 [1.13, 14]. Accelerometer technology was about a billion-dollar-a-year industry in 2001, dominated by Analog Devices followed by Motorola and Bosch. Commercial digital light processing (DLP) equipment using digital micromirror devices (DMD) were launched in 1996 by Texas Instruments for digital projection displays in portable and home theater projectors, as well as table-top and projection TVs [1.15, 16]. More than 1.5 million projectors were sold before 2002. Other major industrial applications include pressure sensors, inkjet printer heads, and optical switches. Silicon-based piezoresistive pressure sensors for manifold absolute pressure sensing for engines were launched in 1991 by NovaSensor, and their annual sales were about 25 million units in 2002. Annual sales of inkjet printer heads with microscale functional components were about 400 million units in 2002. Capacitive pressure sensors for tire pressure measurements were launched by Motorola. Other applications of MEMS devices include chemical sensors; gas sensors; infrared detectors and focal plane arrays for earth observations; space science and missile defense applications; pico-satellites for space applications; and many hydraulic, pneumatic, and other consumer products. MEMS devices are also being pursued in magnetic storage systems [1.17], where they are being developed for super-compact and ultrahigh recording-density magnetic disk drives. Several integrated head/suspension microdevices have been fabricated for contact recording applications [1.18, 19]. High-bandwidth, servo-controlled microactuators have been fabricated for ultrahigh track-density applications, which serve as the fine-position control element of a two-stage, coarse/fine servo system, coupled with a conventional actuator [1.20–23]. Millimeter-sized wobble motors and actuators for tip-based recording schemes have also been fabricated [1.24].

BIOMEMS are increasingly used in commercial and defense applications (e.g., [1.4, 25–28]). Applications of BIOMEMS include biofluidic chips (otherwise known as microfluidic chips, bioflips, or simply biochips) for chemical and biochemical analyses (biosensors) in medical diagnostics (e.g., DNA, RNA, proteins, cells, blood pressure and assays, and toxin identification) and implantable pharmaceutical drug delivery. The biosensors, also referred to as lab-on-a-chip, integrate sample handling, separation, detection, and data analysis onto one platform. Biosensors are designed to either detect a single or class of (bio)chemicals or system-level analytical capabilities for a broad range of (bio)chemical species known as micro total analysis systems (μTAS). The chips rely on microfluidics and involve the manipulation of tiny amounts of fluids in microchannels using microvalves for various analyses. The test fluid is pumped into the chip generally using an external pump for analyses. Some chips have been designed with an integrated electrostatically actuated diaphragm-type micropump. Silicon-based, disposable blood-pressure sensor chips were introduced in the early 1990s by NovaSensor for blood pressure monitoring (about 20 million units in 2002). A variety of biosensors are manufactured by various companies, including ACLARA, Agilent Technologies, Calipertech, and I-STAT.

After the tragedy of Sept. 11, 2001, concern over biological and chemical warfare has led to the development of handheld units with bio- and chemical sensors for the detection of biological germs, chemical or nerve agents, mustard agents, and chemical precursors to protect subways, airports, the water supply, and the population [1.29].

Other BIOMEMS applications include minimal invasive surgery, such as endoscopic surgery, laser angioplasty, and microscopic surgery. Implantable artificial organs can also be produced.

Micro-instruments and micro-manipulators are used to move, position, probe, pattern, and characterize nanoscale objects and nanoscale features. Miniaturized analytical equipment includes gas chromatography and mass spectrometry. Other instruments include micro-STM, where STM stands for scanning tunneling microscope.

Examples of NEMS include nanocomponents, nanodevices, nanosystems, and nanomaterials, such as microcantilever with integrated sharp nanotips for STM and atomic force microscopy (AFM), AFM array (millipede) for data storage, AFM tips for nanolithography, dip-pen nanolithography for printing molecules, biological (DNA) motors, molecular gears, molecularly thick films (e.g., in giant magneto-resistive or GMR heads and magnetic media), nanoparticles, (e.g., nanomagnetic particles in magnetic media), nanowires, carbon nanotubes, quantum wires (QWRs), quantum boxes (QBs), and quantum transistors [1.30–34]. BIONEMS include nanobiosensors – a microarray of silicon nanowires, roughly a few nm in size, to selectively bind and detect even a single biological molecule, such as DNA or protein, by using nanoelectronics to detect the slight electrical charge caused by such binding, or a microarray of carbon nanotubes to electrically detect glucose, implantable drug-delivery devices – e.g., micro/nanoparticles with drug molecules encapsulated in functionized shells for a site-specific targeting application, and a silicon capsule with a nanoporous membrane filled with drugs for long term delivery, nanodevices for sequencing single molecules of DNA in the Human Genome Project, cellular growth using carbon nanotubes for spinal cord repair, nanotubes for nanostructured materials for various applications, such as spinal fusion devices, organ growth, and growth of artificial tissues using nanofibers.

Nanoelectronics can be used to build computer memory, using individual molecules or nanotubes to store bits of information, as well as molecular switches, molecular or nanotube transistors, nanotube flat-panel displays, nanotube integrated circuits, fast logic gates, switches, nanoscopic lasers, and nanotubes as electrodes in fuel cells.

1.5 Reliability Issues of MEMS/NEMS

There is an increasing need for a multidisciplinary, system-oriented approach to manufacturing micro/nanodevices that function reliably. This can only be achieved through the cross-fertilization of ideas from different disciplines and the systematic flow of information and people among research groups. Common potential failure mechanisms for MEMS/NEMS that need to be addressed in order to increase reliability are: adhesion, friction, wear, fracture, fatigue, and contamination. Surface micro/nanomachined structures often include smooth and chemically active surfaces. Due to the large surface area to volume ratio in MEMS/NEMS, they are particularly prone to stiction (high static friction) as part of normal operation. Fracture occurs when the load on a microdevice is greater than the strength of the material. Fracture is a serious reliability concern, particularly for the brittle materials used in the construction of these components, since it can immediately, or eventually, lead to catastrophic failures. Additionally, debris can be formed from the fracturing of microstructures, leading to other failure processes. For less brittle materials, repeated loading over a long period causes fatigue that would also lead to the breaking and fracturing of the device. In principle, this failure mode is relatively easy to observe and simple to predict. However, the materials properties of thin films are often not known, making fatigue predictions prone to error.

Many MEMS/NEMS devices operate near their thermal dissipation limit. They may encounter hot spots that can cause failures, particularly in weak structures such as diaphragms or cantilevers. Thermal stressing and relaxation caused by thermal variations can create material delamination and fatigue in cantilevers. In large temperature changes, as experienced in the space environment, bimetallic beams will also experience warping due to mismatched coefficients of thermal expansion. Packaging has been a big problem. The contamination, which probably happens in packaging and during storage, can also strongly influence the reliability of MEMS/NEMS. For example, a particulate dust landed on one of the electrodes of a comb drive can cause catastrophic failure. There are no MEMS/NEMS fabrication standards, which makes it difficult to transfer fabrication steps in MEMS/NEMS between foundaries.

Obviously, studies of determination and suppression of active failure mechanisms affecting this new and promising technology are critical to the high reliability of MEMS/NEMS and are determining factors in successful practical application.

Mechanical properties are known to exhibit a dependence on specimen size. Mechanical property evaluation of nanometer-scaled structures is carried out to help design reliable systems, since good mechanical properties are of critical importance in such applications. Some of the properties of interest are: Young's modulus of elasticity, hardness, bending strength, fracture toughness, and fatigue life. Finite element modeling is carried out to study the effects of surface roughness and scratches on stresses in nanostructures. When nanostructures are smaller than a fundamental physical length scale, conventional theory may no longer apply, and new phenomena may emerge. Molecular mechanics is used to simulate the behavior of a nano-object.

1.6 Organization of the Handbook

The handbook integrates knowledge from the fabrication, mechanics, materials science, and reliability points of view. Organization of the book is straightforward. The handbook is divided into six parts. This first part introduces the nanotechnology field, including an introduction to nanostructures, micro/nanofabrication and, micro/nanodevices. The second part introduces scanning probe microscopy. The third part provides an overview of nanotribology and nanomechanics, which will prepare the reader to understand the tribology and mechanics of industrial applications. The fourth part provides an overview of molecularly thick films for lubrication. The fifth part focuses on industrial applications and microdevice reliability. And the last part focuses on the social and ethical implications of nanotechnology.

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