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Introduction to Nanotechnology

1.1 Introduction

The word nano is from the Greek word “Nanos” meaning dwarf. It is a prefix used to describe “one billionth” of something, or 0.000 000 001; the prefix that means very, very small. Nanoscience is a part of science that studies small stuff and it is all sciences that work with the very small such as biology, chemistry, or physics. Nanotechnology is the art and science of making very small useful things, including advances in all industries, together with the electronic, chemical, and pharmaceutical.

Nanotechnology is the engineering of functional systems at the molecular scale. This covers both current work and concepts that are more advanced. Nanotechnology is sometimes referred to as a general-purpose technology. That is because in its advanced form it will have significant impact on almost all industries and all areas of society. It will offer better built, longer lasting, cleaner, safer, and smarter products for the home, for communications, for medicine, for transportation, for agriculture, and for industry in general. A key understanding of nanotechnology is that it offers not just better products but a vastly improved manufacturing process. The power of nanotechnology can be encapsulated in an apparently simple device called a personal nanofactory that may sit on your countertop or desktop. Packed with miniature chemical processors, computing, and robotics, it will produce a wide range of items quickly, cleanly, and inexpensively, building products directly from blueprints. Nowadays, nanotechnology has great impact on the development of a wide range of science and technology, including information technology (IT) that provides smaller, faster, more energy-efficient and powerful computing, and other IT-based systems; energy that provides more efficient and cost-effective technologies for energy production such as in solar cells, fuel cells, batteries, and biofuels; consumer goods that provide food and beverages for advanced packaging materials, sensors, and lab-on-chips for food quality testing, appliances and textiles for stain-proof, water-proof and wrinkle-free textiles, household and cosmetics for self-cleaning and scratch-free products, paints, and better cosmetics; and medicines that provide technology for imaging, cancer treatment, medical tools, drug delivery, diagnostic tests, and drug development [1–7].

Nanomaterials in Advanced Medicine, First Edition. Hossein Hosseinkhani.

1.2 Importance of Size in Nanotechnology

The nanoscale size effect can be summarized as follows:

- Realization of miniaturized devices and systems while providing more functionality;
- Attainment of high surface-area-to-volume ratio;
- Manifestation of novel phenomena and properties, including changes in the following:
  - Physical properties (e.g. melting point),
  - Chemical properties (e.g. reactivity),
  - Electrical properties (e.g. conductivity),
  - Mechanical properties (e.g. strength),
  - Optical properties (e.g. light emission).

For instance, when carbon is a pure solid, it is found as graphite or diamond. On the nanoscale, carbon takes on very different structures and therefore provides different properties.

1.3 Approaches in Nanotechnology

Nanofabrication aims at building nanoscale structures (0.1–100 nm), which can act as components, devices, or systems with desired properties, performance, reliability, and reproducibility, in large quantities at low cost. Nanofabrication is used in several industrial applications including the following:

- Information storage,
- Optoelectronics,
- Sensors,
- Microelectromechanical (MEM) devices,
- Power semiconductors,
- Pharmaceuticals,
- Biomedical applications,
- Microelectronics (chips).

About 10^{20} transistors (or 10 billion for every person in the world) are manufactured every year based on VLSI (very large-scale integration), ULSI (ultralarge-scale integration), and GSI (giga-scale integration). Variations of this versatile technology are used for flat-panel displays, microelectromechanical systems (*MEMS*), as well as for chips for DNA screening. More conventional applications of nanofabrication can be seen in the information storage of computers, cell phones, and digital sound and images. Nanostructures and devices can be accomplished by two approaches: top-down and bottom-up methods.

1.3.1 Top-Down Approach

In this method, large objects are modified to give smaller features. Examples are film deposition and growth, nanoimprint/lithography, etching technology, mechanical polishing. The top-down approach uses the traditional methods to pattern a bulk wafer following two processes:

- Adding a layer of material over the entire wafer and patterning that layer through photolithography;
- Patterning bulk silicon by etching away certain areas.

Problems with the top-down process are as follows:

- Cost of new machines and clean room environments grows exponentially with newer technologies.
- Physical limits of photolithography are becoming a problem.
- With smaller geometries and conventional materials, heat dissipation is a problem.

1.3.2 Bottom-Up Approach

In this method, small building blocks are produced and assembled into larger structures. Examples are chemical synthesis, laser trapping, self-assembly, colloidal aggregation, etc. It is the opposite of the top-down approach. Instead of taking material away to make structures, the bottom-up approach selectively adds atoms to create structures. Molecular assembly is like a Lego set of 90 atoms that we can use to build anything from the bottom up. You just use every atom that you want. All of the elements in the periodic table can be mixed and matched.

The ideas behind the bottom-up approach are based on the following:

- Nature uses the bottom-up approach:
  - Cells,
  - Crystals,
  - Humans.
- Chemistry and biology can help assemble and control growth.

Why is Bottom-up Processing Needed?

- It allows smaller geometries than photolithography.
- Certain structures such as carbon nanotubes and Si nanowires are grown through a bottom-up process.
- New technologies such as organic semiconductors employ bottom-up processes to pattern them.
- It can make formation of films and structures much easier.
- It is more economical than top-down in that it does not waste material to etching.

Applications of bottom-up processing are as follows:

- Self-organizing deposition of silicon nanodots,
- Formation of nanowires,
- Nanotube transistor,
- Self-assembled monolayers,
- Carbon nanotube interconnects.

Ability to synthesize nanoscale building blocks with control on size and composition are under rapid development for further assembling into larger structures with designed properties that will revolutionize materials manufacturing for metals, ceramics, and polymers at exact shapes without machining as well as to be lighter, stronger, and programmable materials and have lower failure rates and reduced life-cycle costs. Also, bioinspired, multifunctional, and adaptive materials as well as self-healing materials are in concern.

Challenges ahead are as follows:

- Synthesis, large-scale processing,
- Making useful, viable composites,
- Multiscale models with predictive capability,
- Analytical instrumentation.

Self-assembly can be defined as coordinated actions of independent entities under local control of driving forces to produce large, ordered structures or to achieve a desired group effect. The driving force of self-assembly is usually based on the interplay of thermodynamics and kinetics such as chemically controlled self-assembly, physically controlled self-assembly, and flip-up principles and spacer techniques.

The future of top-down and bottom-up processing is based on many new applications and can be summarized as follows:

- Top-down processing has been and will be the dominant process in semiconductor manufacturing.
- Newer technologies such as nanotubes and organic semiconductors will require a bottom-up approach for processing.
- Self-assembly eliminates the need for photolithography.
- Bottom-up processing will become more and more prevalent in semiconductor manufacturing.

1.4 Impact of Nanotechnology

Basic advancements in science and technology come about twice a century and lead to massive wealth creation. There are incredible opportunities for nanotechnology to impact all aspects of the economic spectrum. Revolutionary forces have built commonality in railroad, auto, computer, and nanotech that all are enabling technologies.

The importance of nanotechnology is summarized here.

1.4.1 Sensors for the Automotive Industry

Automotive electronics to grow to $300 billion by 2020. The pressure to keep the cost of devices low is enormous. Sensors in use now include those monitoring wheel speed and pedal positions, oxygen sensors to check exhaust, accelerometers to detect sudden stops, and pressure and temperature sensors.

Future systems are collision avoidance; break-by-wire and steer-by-wire systems (slowing the car and guiding electrically instead of manually); and sensor systems when new fuel sources become common.

- Challenges:
  - High-temperature survival of sensors;
  - Withstanding mechanical shock, hostile environment;
  - Conditions: sever swing in T; variable humidity; road salt; noxious gases;
  - $f \sim 10$ g; ~10-year lifetime.

1.4.2 Health and Medicine

Expanding the ability to characterize genetic makeup will revolutionize the specificity of diagnostics and therapeutics. Nanodevices can make gene sequencing more efficient. Nanomedicine is very effective and less expensive health care using remote and *in vivo* devices for new formulations and routes for drug delivery as well as in optimal drug usage. It promotes more durable, rejection-resistant artificial tissues and organs. Nanosensors are widely applied for early detection and prevention.

1.4.3 Energy and Environment

Nanotechnology has the potential to impact energy efficiency, storage, and production:

- Materials of construction sensing changing conditions and in response altering their inner structure;
- Monitoring and remediation of environmental problems; curbing emissions; development of environmental friendly processing technologies.
- Some recent examples include the following:
  - Crystalline materials as catalyst support, $300 billion/yr;
  - Ordered mesoporous material by Mobil oil to remove ultrafine contaminants;
  - Nanoparticle-reinforced polymers to replace metals in automobiles to reduce gasoline consumption.

1.4.4 National Security

Some critical defense applications of nanotechnology include the following:

- Continued information dominance: collection, transmission, and protection;
- High-performance, high-strength, lightweight military platforms while reducing failure rates and life cycle costs;
- Chemical/biological/nuclear sensors; homeland protection;
- Nano- and micromechanical devices for control of nuclear and other defense systems;
- Virtual reality systems based on nanoelectronics for effective training;
- Increased use of automation and robotics.

1.5 Nanotechnology Applications

Some of the prominent applications of nanotechnologies in several fields of science and technology are summarized as follows.

1.5.1 Information Technology

Nanotechnology can make smaller, faster, more energy-efficient and powerful computing and other IT-based systems.

1.5.2 Energy

Nanotechnology makes more efficient and cost-effective technologies for energy production in solar cells, fuel cells, batteries, and biofuels.

1.5.3 Medicine

Nanotechnology is effectively used in cancer treatment, bone treatment, drug delivery, appetite control, drug development, medical tools, diagnostic tests, and imaging.

1.5.4 Consumer Goods

Nanotechnology is used for foods and beverages for advanced packaging materials, sensors, and lab-on-chips for food quality testing, appliances and textiles for stain proof, water proof, and wrinkle-free textiles, and household items and cosmetics for self-cleaning and scratch-free products, paints, and better cosmetics.

1.6 Summary and Challenges

There are incredible opportunities for nanotechnology to impact all aspects of the economic spectrum. It is still very early in the game. Jitters as well as hype are not uncommon at this stage. On the wish list, more engineers are needed under the nano tent. Nanoscience will lead the discovery of novel ideas and concepts, laboratory demonstrations, nanotech products, manufacturing, reliability, and quality control. On the wish list is the need for some sanity in issuing patents. Nano has no more "scary scenarios" than does any other technology since the Stone Ages. While there is an amazing amount of research activity across the world, there are only a limited number of viable ideas with commercial potential. There is a great deal of "cool technology," but will they lead to "hot products"? In semiconductors, photonics, and other recent technologies, most new startups have been by people who left other large and small companies, those who knew what the potential customer wanted, and had some expertise in manufacturing, quality control, reliability, etc. This is not the case with nano startups; most of them are started by academics. Strong outside management and a knowledgeable board (with people from industry) are critical to compensate for the "knowledge gap" of the founder on "real-world" issues. Challenges such as the following remain:

- Recognize the nano–micro–macro hierarchy.
- There are so few engineers.
- Navigating the IP situation during the due-diligence process is not easy as various groups across the world are working on the same problems and pertinent information on IP information, priority dates, etc., are not available.
- Some opportunities are clearly very long term; one example is nanotube or molecule or DNA-based computing; several others are also in the ~15-year range.
- A great deal of nanoscience, little nanotechnology.
- Short term (<5 years):
  - Carbon-nanotube (CNT)-based displays;
  - Nanoparticles;
  - Automotive industry (body moldings, timing belts, engine covers);
  - Packaging industry;
  - CNT-based probes in semiconductor metrology;
  - Coatings;
  - Tools;
  - Catalysts (extension of existing market).
- Medium term (5–15 years)
  - Memory devices;
  - Fuel cells, batteries;
  - Biosensors (CNT, molecular, quantum dot based);
  - Advances in gene sequencing;
  - Advances in lighting.
- Long term (>15 years):
  - Nanoelectronics (CNT);
  - Molecular electronics;
  - Routine use of new composites in aerospace, automotive (risk-averse industries).
- Academia will play key role in development of nanoscience and technology:
  - Promote interdisciplinary work involving multiple departments;
  - Develop new educational programs;
  - Technology transfer to industry.
- Government laboratories will conduct mission-oriented nanotechnology research:
  - Provide large-scale facilities and infrastructure for nanotechnology Research;
  - Technology transfer to industry.
- Government funding agencies will provide research funding to academia, small business, and industry through other programs.
- Industry will invest only when products are within three to five years:
  - Maintain in-house research, sponsor precompetitive research;
  - Sponsor technology startups and spin-offs.

- Venture capital community will identify ideas with market potential and help launch startups.
- Professional societies should establish interdisciplinary forum for exchange of information; reach out to international community; offer continuing education courses.
- Advanced miniaturization, a key thrust area to enable new science and exploration missions:
  - Ultrasmall sensors, power sources, communication, navigation, and propulsion systems with very low mass, volume, and power consumption are needed.
- Revolutions in electronics and computing will allow reconfigurable, autonomous, “thinking” spacecraft.
- Nanotechnology presents a whole new spectrum of opportunities to build device components and systems for entirely new space architectures:
  - Networks of ultrasmall probes on planetary surfaces;
  - Micro-rovers that drive, hop, fly, and burrow;
  - Collection of microspacecraft making a variety of measurements.
- Barriers to nanotech entry:
  - Higher education (PhD);
  - Big capital.
- Challenges in manufacturing:
  Ability to synthesize nanoscale building blocks with control on size, composition, and further assembling into larger structures with designed properties will revolutionize materials manufacturing.
  - Manufacturing metals, ceramics, polymers, etc., in exact shapes without machining;
  - Lighter, stronger and programmable materials;
  - Lower failure rates and reduced life-cycle costs;
  - Bioinspired materials;
  - Multifunctional, adaptive materials;
  - Self-healing materials;
  - Synthesis, large scale processing;
  - Making useful, viable composites;
  - Multiscale models with predictive capability;
  - Analytical instrumentation.

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