

Chapter 2

Nanoelectronics and Synergistic Nanodisciplines

Abstract The fields of nanoscience and nanotechnology are introduced. The key terminology is defined. The reader is familiarized with the five fundamental inter-related nanodisciplines: nanoelectronics, nanomagnetism, nanophotonics, nanomechanics, and nanobiotechnology. Salient features of these disciplines are described. Three sub-domains of nanoelectronics known as more Moore, more-than-Moore, and beyond CMOS are explained. The association of different nanoscience disciplines with nanoelectronics is brought out. A synthetic treatment of these disciplines is stressed and the key idea of the book is elaborated.

2.1 Meaning of “Nano” and “Nanometer”

The word “nano” originates from the Greek “nanos” or Latin “nanus”, meaning “dwarf”. “Nano” is a prefix implying “very small”. It is placed before many words to form compound words, e.g., nanoplankton, nanomole, nanosecond, nanoliter, nanogram, nanowatt, nanometer, etc.

Quantitatively, “nano” means a factor of one-billionth: 1 nanometer (nm) = 10^{-9} m. A few popular examples involving comparisons of magnitudes are given below from the web to enable the curious reader to visualize how large is a nanometer [1]: (i) Thickness of human hair = 5×10^4 to 10×10^4 nm; (ii) Thickness of a sheet of newspaper = 10^5 nm; (iii) If 1 nm represents the size of a marble, then 1 m indicates the size of earth; (iv) If a sphere of diameter 1 nm is a soccer ball, then the soccer ball is comparable to the earth in size; (v) If 10^7 marks are made in a cm length, then each mark indicates a nm; (vi) In 1 s, the finger nail grows by 1 nm; (vii) 1 nm = length of 7 oxygen atoms or 3–4 water molecules placed along a line (diameter of oxygen atom = 0.155 nm, and diameter of water molecule = 0.275 nm); (ix) Diameter of a red blood cell = 7000 nm; (x) Positioning a nanometer-size structure on a 1 nm long line is equivalent to positioning a peppercorn in a distance as long as between Tokyo and Beijing.

2.2 Nanoscience

Nanoscience is the scientific study of phenomena concerning extremely small objects, materials, structures, or devices having sizes on the nanometre scale, with at least one dimension in the 1–100 nm range. It is essentially a multidisciplinary science encompassing physical and life sciences or their combinations, and dealing with the exploration of phenomena occurring in low-dimensional structures in the range of nanoscale. It also entails the manipulation of objects of these dimensions. Nanoscience extends the capabilities of existing science into the nanoscale clearly indicating what bulk phenomena happen in the same way as in the macroworld and what phenomena are distinctly different in the range of small sizes. It enunciates and elaborates the laws obeyed by the phenomena when one is dealing with these ultra-miniaturized structures. To reiterate, the nanoworld behaves in a strikingly dissimilar manner to the macroworld, and the exclusive laws of the nanoworld come under the purview of nanoscience. Although, as said above, the prefix “nano” implies 10^{-9} units, in the perspective of nanoscience, the “units” are restricted solely to nanodimensions, and not applicable to any other unit of measurement, e.g., for time, energy or power.

2.3 Nanotechnology

Nanotechnology is engaged in the maneuvering of structures or objects in the 1–100 nm size range in at least one dimension. Its aim is to develop products for potential practical applications. In nanoscience, the physical, chemical, and biological understanding of the behavior and characteristics of objects of small dimensions was acquired. The acquired knowledge is gainfully applied by nanotechnology to useful applications. The expertise thus developed appends to nanotechnology. Thus by controlling the shape and size of objects at nanoscale, nanotechnology designs, fabricates, and characterizes new materials, structures, devices, and complete systems. It continuously improves upon these prototypes to evolve better products useful for mankind.

2.4 Plurality of Nanosciences and Nanotechnologies

Nanoscience and nanotechnology, although referred in singular number, are actually a blending of several sciences and technologies. Thus, it is more correct to call them nanosciences and nanotechnologies. So the terms “nanoscience” and “nanotechnology” must be considered to imply a set of sciences and a combination of enabling technologies, instead of a single science and a single technology. They have evolved by applying nanoconcepts to a diversity of sciences and technologies.

2.5 Nanomaterials

To be designated as a nanomaterial, a material must have at least one external dimension in the size range from 1–100 nm. Nanomaterials can be natural, namely, those that exist in the natural world, and artificial or engineered, viz., those that are created by human activities. Nanomaterials may be thin film coatings on surfaces with thickness <100 nm, or cylindrical structures of diameter <100 nm called nanowires and nanotubes or small objects with all three dimensions <100 nm in size, e.g., quantum dots [2]. More rigorous definitions will be introduced in Chap. 3.

Nanomaterials are finding myriads of applications in consumer products. Among the products which have benefitted maybe mentioned toothpastes, batteries, paints, and clothing. The new products seek to improve the quality of human life. The intent of using nanomaterials is to make items of everyday use cleaner, less expensive, and lighter but stronger. There is an intensive ongoing quest for highly efficient, high precision, or more aesthetic materials. Target-driven pharmaceuticals are being sought. Superior medical diagnostic tools are being manufactured. Superfast computers have been introduced. Cleaner methods of energy production are being improvised.

2.6 Uniqueness and Specialty of Nanomaterials

2.6.1 *Quantum Size Effect*

When compared with bulk materials in coarse forms but having similar chemical composition, nanomaterials are found to exhibit additional or different properties. Bulk copper is a soft, malleable, and ductile metal. Contrarily, copper particles of <50 nm diameter are ultra hard in nature. Pure bulk gold is yellow in color. But a 20-nm gold particle has a wine red color. The color of bulk silver is metallic gray. But a nanosized particle looks yellowish gray. In bulk form, platinum has a silver-white color and palladium is white. But platinum and palladium particles are black at nanolevel sizes. Moving towards the nanoscale, size-dependent properties are observed. These effects will be discussed later. Examples are quantum confinement effect in semiconductor particles, surface plasmon resonance in some metal particles, and superparamagnetism in magnetic particles.

The reason is not far to seek. The bulk properties of a material represent the averaged effects of the quantum forces for the large number of particles constituting the material. As one moves towards successively lower scales, the averaging process fails to represent the actual behavior of the material. Then individual atoms or molecules become important. What is actually observed is the result of properties of a few atoms or molecules. The properties of a small number of isolated atoms or molecules are expected to be different from those of conglomerates of a large number of these entities.

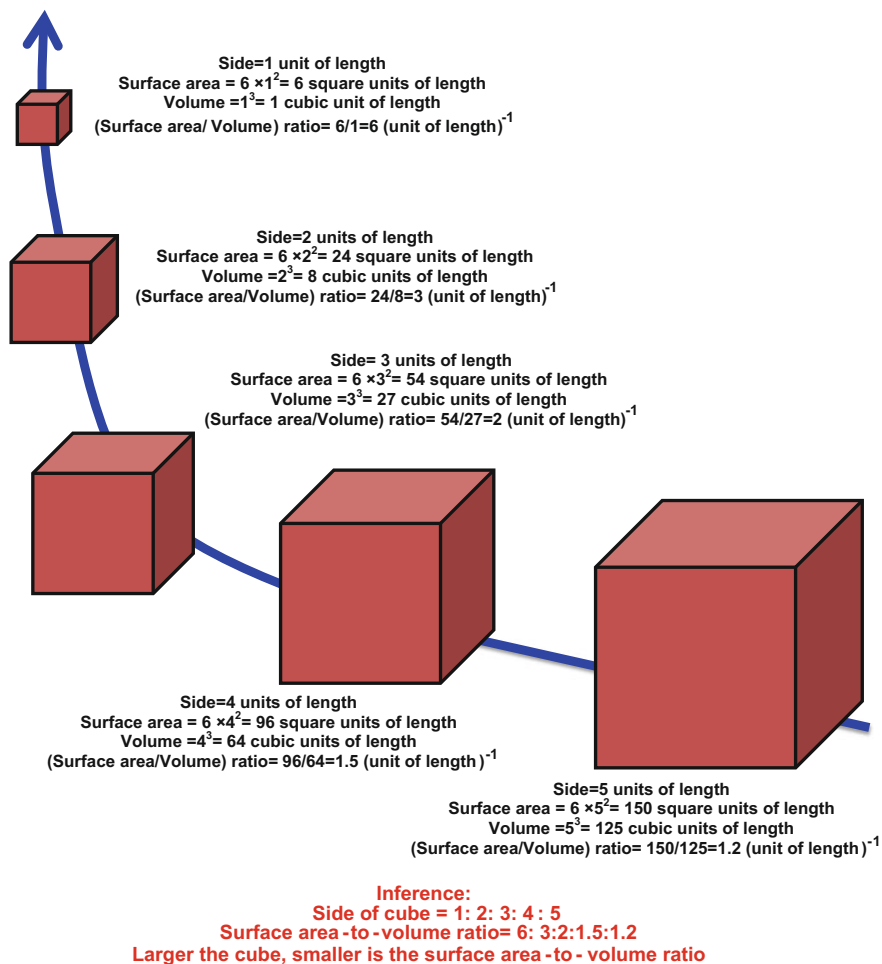


Fig. 2.1 Illustrating the impact of size of a body on the numerical value of surface area-to-volume ratio for the body

2.6.2 Surface-Area-to-Volume Ratio

Compared to the bulk form of matter, in the nanoworld, the same mass of material that has a comparatively larger surface area. To give an example (Fig. 2.1), let us consider a given mass of a material that has the shape of disk of diameter (d_1) = 1 cm and thickness (t_1) = 1 mm. Then its surface area $A_1 = \pi(d_1^2/4) = 3.14 (1^2/4) = 0.785 \text{ cm}^2$. Its volume $V_1 = \pi(d_1^2/4) t = 3.14 (1^2/4) \times 0.1 = 0.0785 \text{ cm}^3$. If now this disk is beaten to form a disk of thickness $10 \text{ nm} = 10 \times 10^{-9} \times 100 \text{ cm} = 1 \times 10^{-6} \text{ cm}$, then for the same volume, $0.0785 = \pi(d_2^2/4) t$ where d_2 is the diameter of the thin disk formed by beating.

The value of d_2 is found to be $= \sqrt{\{(0.0785 \times 4)/(3.14 \times 10 \times 10^{-9} \times 100)\}} = 316.23$ cm. The surface area of this thin disk is obtained as $A_2 = \pi(d_2^2/4) = 3.14 (316.23^2/4) = 78501.11$. Thus for the same volume 0.0785 cm^3 , the surface area increases by the factor $= 78501.11/0.785 = 100001.41$ times.

A consequence of the relatively larger surface area is that the properties of a material in nanoscale are enormously different from those in its bulk form, e.g., an inert material in bulk state may exhibit pronounced catalytic properties when reduced to nanodimensions.

2.7 Nanoelectronics

Nanoelectronics = Nano + Electronics. Electronics is concerned with: (i) controlling the flow of electrons through vacuum, inert gas ambient or a semiconductor in solid state to build devices such as diodes and transistors, and with (ii) the design and assembly of circuits using the components fabricated in step (i) for performing assigned functions in information processing, computing, communication, and power conditioning. Nanoelectronics is devoted to the application of nanoscience and nanotechnology to electronics. Briefly stated, it represents the use of nanoconcepts and methods in electronics. It entails the design, fabrication, and applications of electronic devices, circuits, and systems whose building block components are of nanoscale size (Fig. 2.2). It aims to increase the capabilities of customary electronic devices by reducing their size, weight, and power consumption. It aspires to shrink the size of transistors in integrated circuits and increase the density of memory chips with a projected density far ahead of today's systems. The purpose is to stuff the functionalities of present-day equipment such as computers into the palm of a hand. Apart from the above, display screens on electronic devices are being improved to make them comparatively thinner and lighter than they are now. Nanoelectronics is strongly pushing the miniaturization of devices to the extent of hitting their basic limitations from physics viewpoint.

As commonly known, Moore's law predicts that the number of transistors/in.² in an integrated circuit doubles every year. We shall discuss more this law in later chapters. Three distinct sub-domains of nanoelectronics are identified. These are referred to as [3]: More Moore, More-than-Moore, and Beyond CMOS. The phrase "More Moore" covers the capabilities achieved as packing density of devices continues to increase in compliance with Moore's law. By "More than Moore" is meant the incorporation of additional functionalities such as sensors, RF, and power conditioning circuits, which do not scale in accordance with Moore's law. Under "Beyond CMOS" subheading fall the newer devices like single-electron transistors and molecular electronic devices, which are likely to take over from CMOS for achieving higher levels of integration than possible with CMOS.

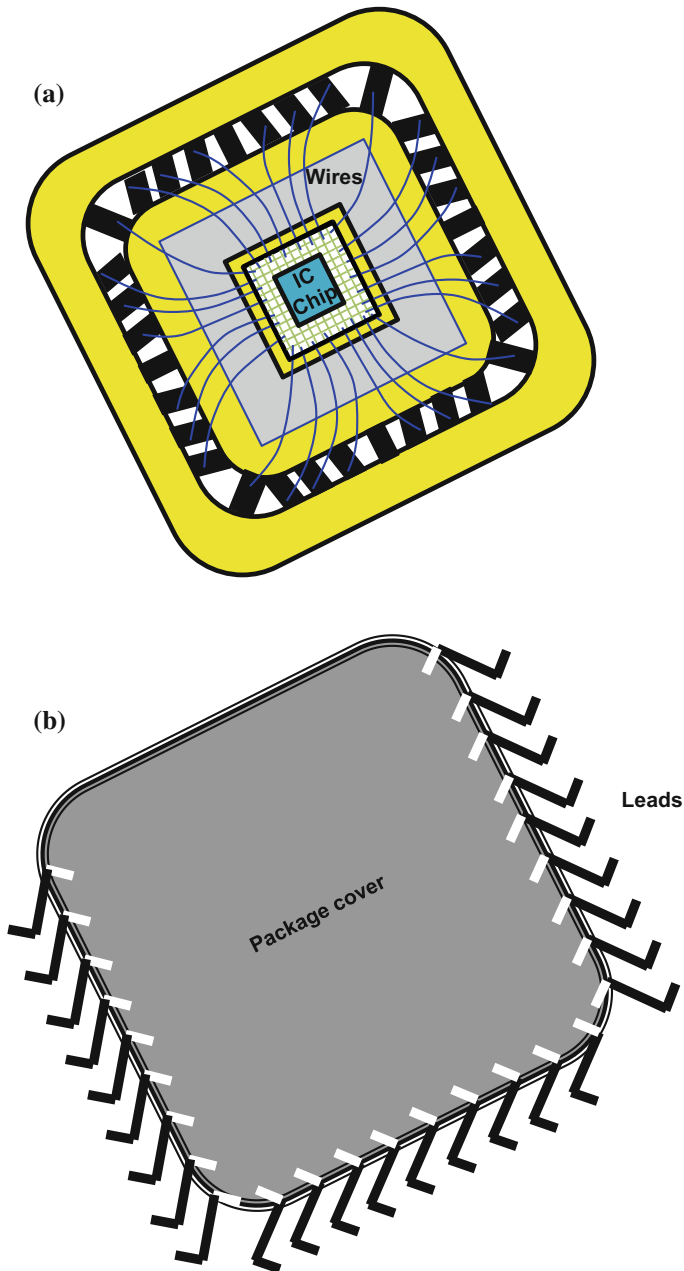


Fig. 2.2 Nanoelectronic integrated circuit (IC): **a** chip form and **b** packaged IC

2.7.1 More Moore Sub-domain

Building circuits with nanoscale components results in component counts reaching giga-scale magnitudes. Sophisticated CMOS technologies will be further improved to minimize cost per unit function. This will affect 70% of the market comprising digital logic circuits, memory, and microprocessor chips. The route leading to giga-scale complexity is the “More Moore” road.

2.7.2 More-than-Moore Sub-domain

Micro- and nanoelectronic devices of non-digital type are included. Notable devices consist of sensors and actuators for mechanical, thermal, chemical, and biological signals along with signal conditioning circuits on CMOS substrate. Other examples are micro- and nanofluidic devices and biosensors, radio frequency devices and circuits, power switching devices and circuits, light-emitting diodes and driving circuits, ultrasonic transducers and other imaging devices with associated circuitry, energy harvesters and ancillaries. Thus “more than Moore” sub-domain is essentially a technological synthesis between purely electronic devices and circuits with mechanical, and biochemical devices along with analog/RF circuits.

2.7.3 Beyond CMOS Sub-domain

This sub-domain comprises electronics based on new state variables such as spin, molecular state, photons, etc. Examples are spintronics, molecular electronics, etc. Thus, “beyond CMOS” sub-domain will bring fundamentally new nanoscale devices into nanoelectronics.

2.7.4 Convergence of Nanosciences

Nanoelectronics can be considered as the core subject, embroidered with the nanotechnology-related ingredients contained in more Moore, more-than-Moore, and beyond-CMOS sub-domains. A closer introspection reveals that sister branches of nanomagnetism, nanophotonics, nanomechanics, and nanobiotechnology should be fused with nanoelectronics in the form of branches augmenting its capabilities (Fig. 2.3). By doing so, useful information relevant to all the above domains is unified with nanoelectronics except for the RF and power conditioning portions. Therefore, all the nanoingredients of the aforesaid sub-domains will be covered under the umbrella of nanoelectronics and complementing nanosciences. In the

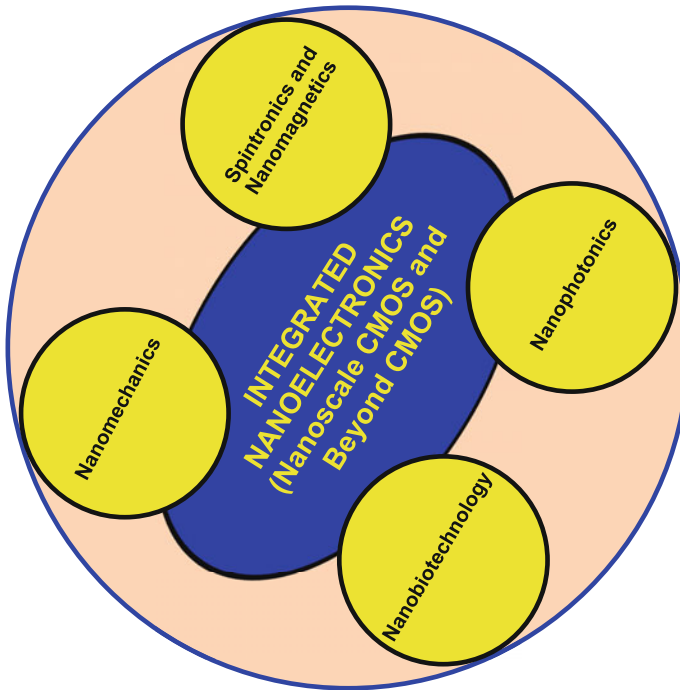


Fig. 2.3 Nanoelectronics and allied nanosciences

forthcoming subsections, we shall look at the sister branches referred to above, the so-called complementary nanosciences.

The goal is to provide a cohesive panoramic overview of an interdisciplinary field, which results from the merger of allied nanoscience disciplines, carefully appreciating their shared and unshared features. At the grass roots, all these disciplines assist each other to construct a holistic nanoscience. Instead of looking at them separately, a blended perspective is needed to understand the correct picture. An inter-diffusing perspective of the scenario will hasten progress and help in designing applications, which hitherto could not be contemplated. By cooperative interaction of the participating nanosciences, results of greater impacts will be achieved than by their individual use. This is an effort which is said to be “synergistic”.

2.8 Spintronics and Nanomagnetism

Spintronics deals with the utilization of erstwhile-ignored property of an electron, namely its spin characteristic, for information processing. It is subdivided into metallic, semiconductor, and insulator spintronics. Both spin and charge properties of electron are gainfully used in spintronics.

Regarding nanomagnetism, we recall that magnetism is the study of physical phenomena related to movement of electric charges, which produces forces of attraction or repulsion between objects, especially between iron and certain materials. Nanomagnetism = Nano + magnetism. Nanomagnetism is the scientific study pertaining to nanomagnetism, which is the branch of magnetism dealing with low-dimensional systems that have at least one dimension in the nanoscopic range. These systems exhibit different behaviors from those in the bulk, with regard to magnetic ordering, magnetic domains, magnetization reversal, etc. The differences originate from various factors such as: (i) broken translation symmetry in the nanometric regime; (ii) from the higher percentage of atoms on the surface; (iii) the comparable sizes of nanoscopic objects to some fundamental or characteristic lengths of the constituent materials. Nanomagnetism finds practical applications, encompassing fields from geology to magnetic recording, from ferrofluids (colloidal liquids that become strongly magnetized in a magnetic field) used in loudspeakers to small particles used in medicine for targeted drug delivery to specific organs and tissues [4].

2.9 Nanophotonics or Nano-optics

Nanophotonics is the combination of photonics with nanotechnology. The term “photonics” has originated from the Greek word “photo”, which means light. Photonics is the study of light whose fundamental constituent particle is the discrete packet or quantum of energy known as the photon. Photonics performs operations on light which are similar to those carried out by electrons in electronics, i.e., the role of photons in photonics is identical to that of electrons in electronics. Many tasks accomplished by photonics have their corresponding analogs in electronics, e.g., information processing, its transmission to remote locations and reception from these locations, etc.

A comprehensive field is optics. It is the branch of physics and engineering dealing with the study of the behavior and properties of light. The scope of optics includes the propagation of light, its deflection at interfaces, and interactions with different forms of matter. Optics studies light in a classical formalism as comprising rays traveling in straight lines (geometrical optics). It discusses about reflection and refraction of light. The wave theory of light is applied to explain diffraction of light. Light is treated as an electromagnetic wave. Photonics deals with quanta of light which are not considered in optics.

Nanophotonics is an offshoot, which has sprouted from a combination of photonics, optics, optical engineering, electrical engineering, and nanotechnology. It is a generic technology dealing with the study of the behavior of light on the nanometer scale, and of the interaction of light with nanoscale structures. At this scale, their structural, physical, and optical features are drastically modified relative to bulk counterparts. Nanophotonics has been extensively explored for unveiling and exploiting light-matter interactions. Of particular interest are those occurring at a scale below the diffraction limit of light, representing the boundary of conventional photonics [5]. Nanophotonics can provide high-speed and large-bandwidth, optoelectronic components of ultra-small size. Hence, it promises to revolutionize data storage, computation, telecommunications, and sensing fields.

2.10 Nanomechanics

Nanomechanics = Nano + mechanics. Mechanics is a branch of physics and mathematics. It deals with the motion or displacements of material objects, and the analysis of forces responsible for the same.

Nanomechanics is the study of the mechanical, i.e., elastic, thermal, and kinetic properties of nanostructures and nanomaterials. It involves classical mechanics, solid-state physics, statistical mechanics, materials science, and quantum chemistry. Its subbranches are: nanotribology, nanoelectromechanical systems (NEMS), and nanofluidics.

Nanotribology is the investigation of interfacial processes that take place on molecular and atomic scales. Some of the processes studied are adhesion, friction, viscous drag, scratching, wear, etc. A vital process is nanoindentation, which performs mechanical characterization of the surface by making a small notch or recess in nanometer range. Also examined is thin film lubrication at two interacting surfaces in relative motion. It may be noted that “tribology” is derived from two Greek words: “tribo” and “logy”, “tribo” meaning rubbing and “logy” knowledge. Therefore, nanotribology is the study of friction, wear, contact mechanics, and lubrication at atomic length and time scales [6]. It finds applications in magnetic storage devices such as computer hard disk drives (HDD). Another process in which it is utilized is chemical mechanical polishing (CMP) for planarization in semiconductor fabrication.

Nanoelectromechanical systems (NEMS) are scaled-down versions of microelectromechanical systems (MEMS) [7, 8]. This downscaling is done to sub-micrometer dimensions. NEMS are regarded as the logical miniaturization step succeeding MEMS. These systems are made from electromechanical devices having critical dimensions from 100 to a few nm. NEMS-based devices can have fundamental frequencies ~ 100 GHz. Their mechanical quality factors are $\sim 10^3$ to 10^5 . They can have active mass in the range of 10^{-15} g. They exhibit force

sensitivity $\sim 10^{-18}$ N and mass sensitivity $\leq 10^{-18}$ N. Heat capacities $< 10^{-24}$ cal are obtainable. Typical power consumption is $\sim 10 \times 10^{-18}$ W. Integration level in these systems approaches 10^{12} elements cm^{-2} . These systems have immense applications as force sensors, chemical sensors, biological sensors, and ultra-high frequency resonators [Ke].

Nanofluidics is the examination and application of fluid flow in and nearby objects of nanoscale sizes [9]. The transport of fluid in and around objects with at least one characteristic dimension below 100 nm facilitates the occurrence of unusual, distinctive phenomena. Such phenomena are not observed at macrofluidic or microfluidic size scales [10].

Nanofluidic structures are used in circumstances where the specimens must be handled in tremendously small quantities. Nanofluidics is used in clinical diagnostics in lab-on-a-chip devices. It is also applied to nano-optics. Tunable microlens array is thereby made.

2.11 Nanobiotechnology

Nanobiotechnology = Nano + biotechnology. Biotechnology is the exploitation of living organisms, processes, and systems in industrial plants to manufacture products for upgrading the quality of human life. Nanobiotechnology applies nanotechnology to biological sciences to unify the design of materials and devices with the inimitable specificity afforded by biomolecules. In this way, new biomaterials are designed. Sensors working on the changes in conformation of biomolecules are fabricated. More effective particles for drug delivery are produced.

The difference between nanobiotechnology and bionanotechnology must be emphasized. Nanobiotechnology exploits the advancements in nanotechnology for improving biotechnology. Bionanotechnology utilizes the advantages of natural or biomimetic systems. It designs and produces novel nanoscale structures. An intense bilateral exchange of expertise across the precincts of these fields is taking place. It is focused around new materials and tools, predominantly from the physical sciences. It employs new phenomena, largely from the biological sciences. In these negotiations, the physical sciences put forward tools for synthesis and fabrication of devices. These tools are used for characterization of cells, subcellular components, and materials used in cellular and molecular biology. In turn, the biological sciences display the elegant group of prevailing functional nanostructures [11].

2.12 Discussion and Conclusions

Preliminary terms of nanoscience and nanotechnology were defined in this chapter. The vast scope of the subject of the book was introduced. The book seeks to develop the central theme of nanoelectronics aided by complementary nanosciences

of nanomagnetism, nanophotonics, nanomechanics, and nanobiotechnology. The roles of different nanosciences were described in terms of the sub-domains defined according to Moore's law. With this notion of burgeoning nanoelectronics tree and its branches, the reader will be taken to further journey in this escalating field.

Review Exercises

- 2.1 Explain the meaning of the word "nano". What is a nanometer? Give two examples, which will help in imagining how large is a nanometer?
- 2.2 Define nanoscience and nanotechnology. In these definitions, can the prefix "nano" be assigned to any physical parameter? If not, what is the restriction?
- 2.3 Define nanomaterial. Give two examples of nanomaterials and cite two applications of these materials.
- 2.4 Why are properties of nanomaterials different from those of bulk matter? Give two examples in which a difference of properties is observed as one goes to nano dimensions.
- 2.5 Correct the statement: As one moves to the nanoscale, copper particles become soft, gold particles look green, and silver particles appear blue in color.
- 2.6 A cube of side 1 cm is beaten to form a sheet of thickness 1 nm. By what factor will its surface area increase?
- 2.7 What is the difference between electronics and nanoelectronics? What are the advantages gained in moving to the nanoscale in electronics?
- 2.8 Explain the concepts of the sub-domains: (i) More Moore, (ii) More-than-Moore and (iii) Beyond CMOS.
- 2.9 What property of an electron is utilized in spintronics besides its electrical charge?
- 2.10 What is nanomagnetism? What are its applications?
- 2.11 How does photonics differ from optics? Define nanophotonics. What are its applications?
- 2.12 What is nanomechanics? Name its sub-branches.
- 2.13 What kinds of processes are studied in nanotribology? Where is nanotribology used?
- 2.14 Explain the following terms and give their applications: (i) nanoelectromechanical systems and (ii) nanofluidics.
- 2.15 What is nanobiotechnology? How does nanobiotechnology differ from nanotechnology?

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