Chapter 20

Engineered Nanomaterial in Electronics and Electrical Industries

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PREAMBLE

This chapter will concentrate on the current trends and changes in nanoengineered materials including noble metals, semiconductors, oxides, and alloys in electronic devices industry. These extraordinary nanomaterials have been integrated into recent consumer electronics product in which the growth potential is significant over the next decade. In electronic device industry, we have chosen to concentrate on several important developments in the main areas such as nanomaterial-based flexible, bendable and stretchable electronics, and electrophotonics applications. The content is mainly to deliver the sense of roll-up electronic displays to electronic skin thin film from the perspective of the science and technology of these nanomaterials in their current state. The brief overview of why certain materials are chosen for particular device applications is also presented. This chapter is separated into eight main sections. The first section is concerning the identification of the importance and transformations of the expanding range of novel device applications that are being discovered. The future promise in the areas of next-generation electronics is dependent on our understanding of the critical elements that influence the engineered electronic state properties and these are highlighted in the second section. This is followed by the discussion on the intense use of integrated nanophotonic devices with nanoelectronics that are controlled by the performance of photon and electron confinement at the nanoscale. Standard nanofabrication methods, employed to manufacture superconducting junctions based on quantum wires, is a key asset for 21st-century nanoelectronics in the realization of materials' nanoarchitectonics, and these are discussed in the next two subsequent sections. The chapter ends with a review of the future explosion of interest for precision-engineered nanosystems in the electrical device industry.

20.1 INTRODUCTION TO CURRENT TRENDS OF NANOENGINEERED ELECTRONIC INDUSTRY

20.1.1 Perspective on Electronic Nanoengineered Materials

In recent decades, the major technological revolutions have changed our everyday lives in so many ways for the better. The advancement of modern technology is driven considerably by the miniaturization of three-dimensional (3-D) electronic devices with embedded logic circuitry enabling myriad applications including display devices, wearable electronic devices, and biomedical devices. The incorporation of nanoengineered materials for the realization of research achievements has shown timely development with great influence in electronic industries. The primary achievement dealt with the consideration of the influence of curiosity and applied science with the interactions between materials, processes, and devices.

The efforts of nanoengineering within the industry and private sectors have shown enormous increases in the last 5 years. In 2015, nearly 900 companies were involved in some form of nanoengineered materials and nanodevice development. Based on the nanotechnology marketing record, private investment worldwide reached US$1 trillion in value, of which about US$200 billion was in the United States, for simple nanoengineered structure products (Fig. 20.1A). Over the previous years (2001–2010),

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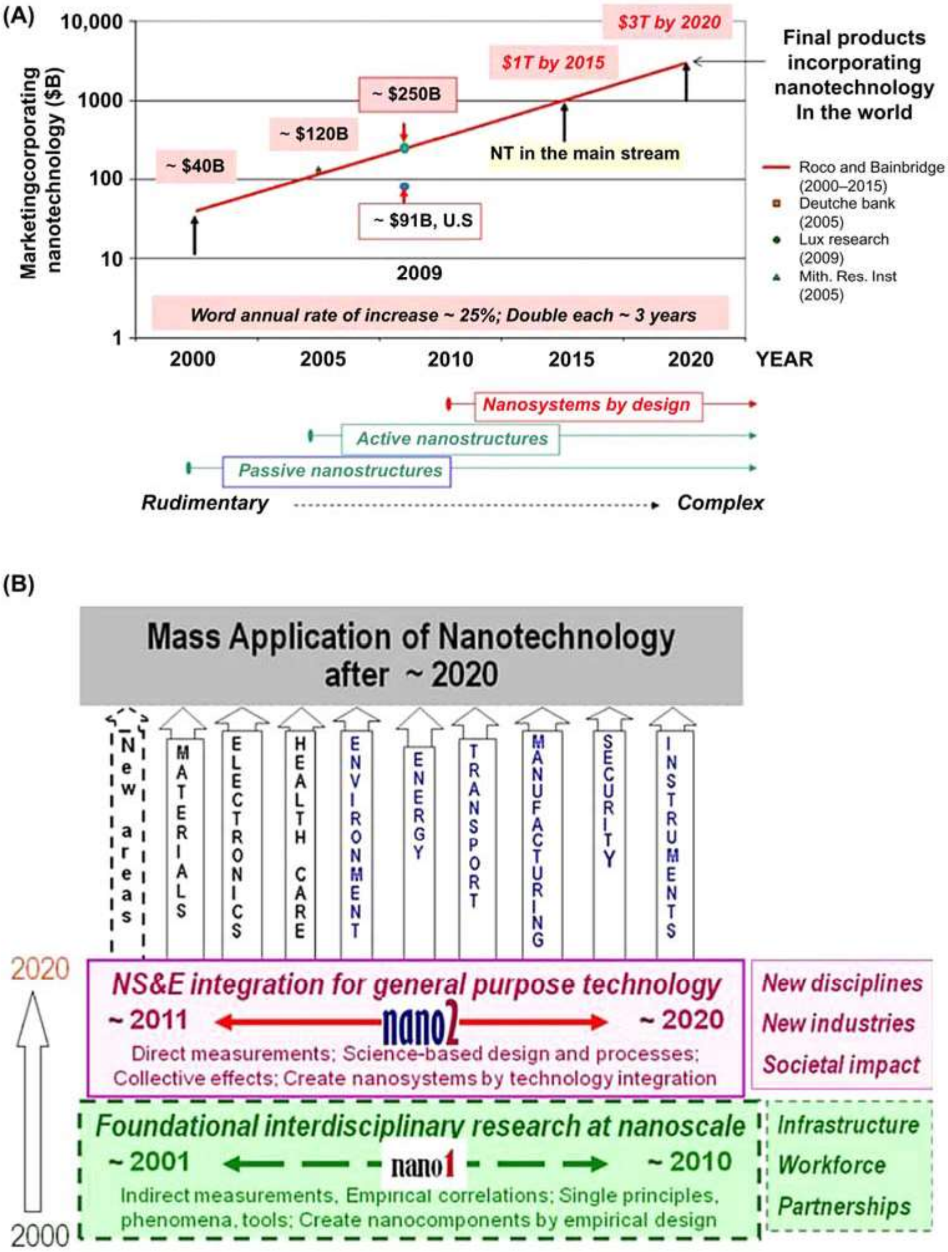
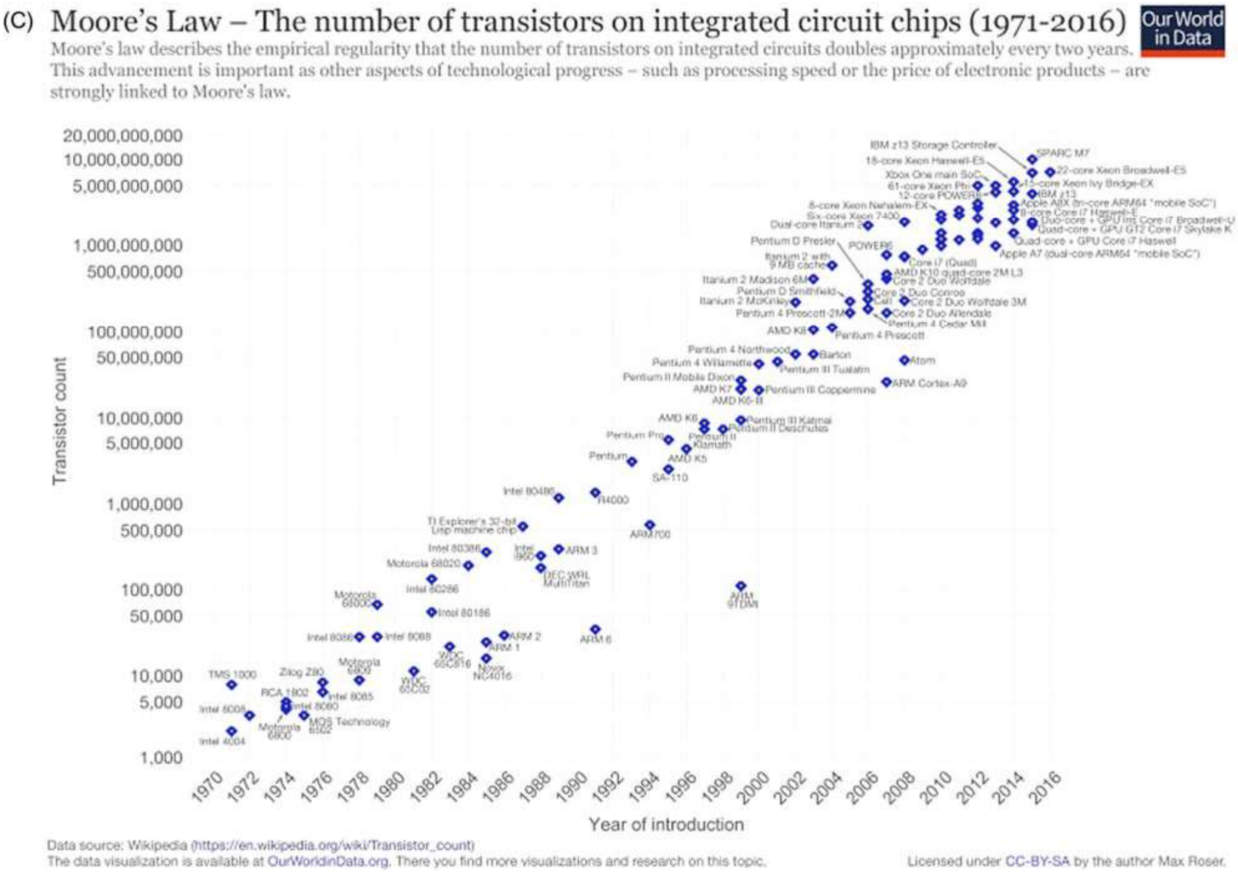


FIGURE 20.1 (A) The projection for the worldwide market of nanoengineered products for 20 years. The estimation was based on several companies related to research and development of nanoengineering products in the United States, Japan, and Europe. The market estimation shows the doubling increment trend for every 3 years as an outcome of the successive development of nanoengineered materials. (B) The nanotechnology research directions for industrial needs until 2020 with the transition from Nano-1 to Nano-2. (C) The Moore's Law observation indicates the exponential progress in the number of transistors on integrated circuits. In 2016, the astonishing regularity was found to be true. However, the shrunk usage of conventional transistors becomes more in-demand. *Reproduced from M.C. Roco, The long view of nanotechnology development: the national nanotechnology initiative at 10 years, in: Nanotechnology Research Directions for Societal Needs in 2020: Retrospective and Outlook, Springer, Netherlands, Dordrecht, 2011, pp. 1—28 with permission from Springer Link and reproduced from online resources M. Roser, Technological progress. Available from: ⟨https://ourworldindata.org/technological-progress/⟩, 2016.*

the research field focused on the discovery of unique properties, new phenomenon, and outstanding functional properties of nanoengineered materials, the synthesis of nanomaterials building blocks for a particular application, improvement, and advancement from the incorporation of simple nanoengineered components in existing products. The field domination is considered as a science-centric ecosystem which is also known as a Nano-1 decade


(C) Moore's Law – The number of transistors on integrated circuit chips (1971-2016)

Moore's law describes the empirical regularity that the number of transistors on integrated circuits doubles approximately every two years. This advancement is important as other aspects of technological progress – such as processing speed or the price of electronic products – are strongly linked to Moore's law.

Data source: Wikipedia (https://en.wikipedia.org/wiki/Transistor_count)
The data visualization is available at OurWorldinData.org. There you find more visualizations and research on this topic.

FIGURE 20.1 (Continued).

(Fig. 20.1B) [1]. In the year 2017, the socioeconomic consideration took place and is considered as a Nano-2 decade. Within this phase, the focus is toward the science-based design of new products and the mass-use of nanoengineered materials.

In the same way, the improvements of many crucial applications including optoelectronics and high-speed electronics are better equipped to perform. The remarkable performance of the nanoelectronic device is not only just because of the tiny stack of compound layers and brilliant functions of the design itself but the initial wonderment that everything works at all. New-generation devices such as bendable high-speed electronic storage that go beyond microprocessing contain millions of nanostructure "transistors" and will influence the life of 21st-century devices to an incalculable extent. The sophistication in the development of the electronic devices industry mandated more researchers and engineers to exceptionally research the state-of-the-art gates of subnanometer size to achieve sustainable and longer performance devices. The additional characteristics of next-generation devices have to have high portability and flexibility, nondestructive read-out characteristics, easily integrating structure, and a single device system [2–4]. For example, the application of nanoengineered structures in the inversion layer typically found in the improvised version of metal oxide semiconductor field-effect transistor (MOSFET) with a reduced density below tolerable levels is very competent compared to the conventional transistor [5–7]. In fact, most integrated devices manufactured today are based on the first MOSFET transistor technologies which are distinct from the bipolar device used in the first chips but still date from the 1960s. In 2017, the replacement of choice to conventional MOSFET are the organic field-effect transistor (OFET) which have incorporated a distinct charge-storage layer for electrical function with nanoengineered materials and the nanofloating gate dielectric. The development has been considered as a promising path for high-performance electronic devices due to the enhanced molecular makeup and potential charge trapping site efficacy [8].

Prior to the development in the performance of the nanoelectronic device phase, the improved potential of the electronic devices is measured based on the logarithmic scale of the transistor employment for a particular sustained period. The embodiment of Moore's Law is mainly used to predict the rate of the continued usage of transistors in devices, and the estimation would progress until at least 10 years ahead from current years (Fig. 20.1C) [9]. The continuous miniaturization dimension of electronic device circuit component is primarily related to the reduction in the thickness of the OFET gate insulator. The trend continuation patterns are considered as more of a self-fulfilling prophecy. Most of the massive industrial bodies follow the logarithmically scaled for static scaling until 2016 where the number of fabricated transistor per year and the numbers incorporated of on a single chip increases. Nonetheless, the continual cramping of transistors onto chips based on Moore's Law has been the feedstock of exuberant innovation in electronic devices. Perhaps, the empirical data measured by Moore's law-driven roadmap has not long been the baseline as further scale-off devices become significant. For example, in 2016, the improvements have been made by switching the 10 nm chip with the Cannonlake processor by Intel and that consequently has shrunk the use of the conventional transistor [10]. The focus on the use of nanoengineered processor takes a different approach which has also been described as "More than Moore" [11]. The diverse array of nanoengineering-based sensors and processors have now not only undertake logic and cache but have also shown promise and offer much higher switching speeds at much lower power than conventional transistor's material. However, scaling is not off the roadmap entirely. Perhaps, looking toward 2020, the "gate all around" incorporates nanoengineered materials with different quantum effects with a significant boost to reinvigorate the demand for a processor that is just plain faster but yet smaller with more power.

Nanoengineered materials and nanotechnology are considered as a general-purpose technology by 2020 especially in the electronic industry, encompassing new-generation products with increasing structural and dynamic complexity that includes passive nanostructures, active nanostructures, nanosystems, and molecular nanosystems in better comprehension and conservation of nature. Nanostructured materials have unique characteristics due to their small size, which can impact functions that are distinct from those of their bulk counterparts. Research in nanoengineered materials has crossed many opportunities including modeling, design, fabrication, processing, characterization, and analysis of nanostructures properties of devices and systems. Therefore, research in nanoengineered materials has an extraordinary range of possibilities based on the fact that the properties of materials' changes takes place when the size approaches a few tens or hundreds of atoms. The purpose of nanoengineered materials is to build and engineer more materials with novel, useful, and tailorable properties. The integrated nanoengineered materials within this scope are considered as tiny particles or nanowires (NWs) of metals, semiconductors, and magnetic structures consisting of hundreds to a few thousand atoms each. Fundamental to the success of the nanoengineered materials is the ability to control electron transport across molecular components. The replacement of rigid electronic materials with nanoengineered materials enhances the electronic properties (the same as rigid electronic materials), but with better unique features (e.g., bendability, foldability, and wearability) owing to the reduced thickness [12].

In this case, the complementary systems that incorporated nanoengineered materials in the nanoelectronic device applications derive from many attractive attributions. These include cadmium selenide nanocrystals for flexible electronic circuits, silicon nanophotonic component in complementary metal-oxide-semiconductor (CMOS) integrated circuits, nanomagnets as switches, silver nanoparticles ink in circuit boards, nanopatterned silicon surface lasers, carbon nanotube (CNT) transistors in integrated circuits, copper nanoparticles, single-atom thick graphene film for high speed transistors, CNT as nanoemissive display panels, magnetic quantum dots (QDs) in spintronic semiconductor devices, and organic nanoglue thin film increases thermal conductance in computer chips. The promising strategies through replacing the rigid electronic materials (e.g., a silicon wafer) with nanoengineered materials have helped resolve seminal challenges and offer distinct advantages incomparable with conventional means in the various field of science and engineering. The major research thrust in nanoengineered materials is the fabrication of conjugated nanostructures that can be in different and similar types of metallic nanoparticles (silver and copper) as well as heterogeneous nanostructures such as semiconductor nanocrystals and metal NWs. In fact, today's proven strategy is to procure better low-cost materials in the combination of different nanoengineered materials [13–17]. This synergistically and controllably associates the advantages of properties from each constituent to fulfill better functionalities and does indeed show significant improvements in device performance [17,18]. The high performance and multifunctionality of hybrids of nanoengineered materials substantially offer to optimize physical, mechanical, optical, chemical, and magnetic properties as compared to their pure individual states. By integrating an advanced form of different functional nanoengineered materials, the realization goal in fabricating optimizes size, thickness, and concentration of the nanomaterials can be designed.