Chapter 2

Aspects of Nanoelectronics in Materials Development

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Additional information is available at the end of the chapter

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Abstract

Nanotechnology is an enabling technology that potentially impacts all aspects of the chip-making practice from materials to devices, to circuits, and to system-level architecture. Nanoelectronics is an interdisciplinary division which refers to the use of nanotechnology in electronic components. The materials and devices used in nanoelectronics are so small that the interatomic interactions and quantum mechanical properties of such materials need to be studied extensively. Various electronic devices manufactured at nanoscale have been established: devices having negative differential resistance, switches which can be electrically configured, tunneling junctions, carbon nanotube (CNT) transistor, and unimolecular transistor. Some devices have also been linked together to form circuits proficient of performing functions such as logic functions and basic memory. Some of the widely used materials in nanoelectronics include zero-dimensional materials like quantum dots; one-dimensional materials like nanotubes and nanowires; nanoclusters and nanocomposites; carbon-based materials like carbon nanotubes (CNTs), fullerenes and graphene; etc. Plastic C nanoelectronics is also a prominent research area with collaboration between the materials science, chemistry, physics, nanotechnology, and engineering communities. As one of the most promising contenders, C nanostructures, either 2D graphene or quasi-1D CNTs, have unlocked entirely new standpoints concerning the C-based electronics. This chapter focuses on the approaches of nanotechnology toward nanoelectronics, materials used in nanoelectronics and the applications of nanoelectronics related to carbon-based materials in the field of thin-film transistors, printed electronics (PE), artificial skin and muscle, wearable electronics, flexible gas sensors, multifunctional and responsive elastomers, and plastic solar panels.

Keywords: Nanoelectronics, Semiconductors, Printed electronics, Electronic textile, Thin-film transistors

1. Introduction

In the twenty-first century, nanotechnology is evolving as cutting-edge technology and has implausible applications in physics, chemistry, biology, materials science, and medicine. The main push has been toward fabricating novel materials and investigating their properties by alteration in the particle size, shape, and distribution. This technology is an aiding technology which potentially influences nearly all aspects of the chip preparation from various kinds of materials to different devices, system-level architecture, and circuits. The technology is still in its initial phases, particularly in the field of conventional integrated circuit (IC) applications: logic computing and data storage. Examples of technologies which are engaged, presumably under molecular or quantum operations, may develop in the next 10–20 years [1].

There has been a firm growth of interest in nanoelectronics all through the past decade. It is an interdisciplinary division which talks about the use of nanotechnology in electronic components. It targets to enable the use of new approaches and materials to build electronic devices with feature sizes at the nanoscale level. The materials and devices used in nanoelectronics are so small that the interatomic contacts and quantum mechanical properties of such materials need to be considered comprehensively. Even though much of this work has a long-term explanation in the search for novel devices, most of the results are having scientific significance instead of engineering. Nanoelectronics has been considered most in the III–V semiconductors and principally in the Ga(Al)As alloy system where the construction and growth technologies are most established. Additionally, the transport properties of GaAs and the accessibility of very high-quality heterojunctions boost some potentially utilizable phenomena in a dimensional range available to high-performance lithography [2].

According to Moore's law, the computing power or the microprocessor speed has doubled up every complementary metal-oxide semiconductor (CMOS) generation or every 18 months, based on the sequential trend. This drift, which was witnessed first by examination of the past data, soon became a standard and objective for the growth of semiconductor technology and manufacturing. Yet, we have not touched the limit of computing power that is probable in the long run. Areas like advanced chip technology are concentrating on the development of nanoelectronic devices which are focused at discovering the limits to miniaturization of conventional transistors and revealing the phenomena which might lead to novel generations of devices operating on alternative principles. These miniaturized devices, beyond the Moore's law, are anticipated to be dependent on new, resourceful methods to implement spatially controlled and extremely functional nanoscale components manufactured by economical chemistry. The driving source in the last 3–4 eras of enhanced R&D efforts for advanced chip technology is the demand for computing power, along with that for data storage capacity, occasioning in improved performance and developed component packing density [3].

Nanoelectronics based on carbonaceous materials (plastic carbon nanoelectronics) is also a prominent research field with collaboration between various engineering communities and physics, chemistry, materials science, and nanotechnology. Since the advancement of plastic/organic electronics, there is a remarkable attention on the properties of the materials (based on carbon) owing to the considerable delocalization of π-electron in fullerenes and carbon nanotubes (CNTs). As one of the most promising contenders, C nanostructures, either 2D graphene [4,5] or quasi-1D CNTs [6], have unlocked entirely new standpoints concerning the C-based electronics. Through recent scientific advances in the field of nanoplastics which is a blend of the traditional plastics with emerging field of nanotechnology—many exhilarating results have established that polymers filled with carbon-based materials have exceptional properties including improved UV absorption, durability and strength, electrical conductivity, flame resistance, and reduced permeability over the last decade.

Many nanoscale electronic devices have been developed till date by innumerable researchers like tunneling junctions [7–9], devices using differential resistance (negative) [10], switches which can be electrically configured [11,12], CNT transistors [13,14], and unimolecular transistors [15,16]. Some devices have also been linked together to form circuits which are capable of carrying out functions like basic memory [11,12,17] and logic functions [18–21]. Nanowire lattices with ultrahigh density and circuits with semiconductor and metal nanowires have also been documented by Heath et al. The technique was based on transforming thin-film growth thickness control into planar wire arrays [22]. Architecture of computer which is grounded on nanoelectronics (also known as nanocomputers) has also been considered [23,24], though very restricted.

This chapter focuses on the approaches of nanotechnology toward nanoelectronics, materials used in nanoelectronics and the applications of nanoelectronics related to carbon-based materials in the field of thin-film transistors, printed electronics (PE), artificial skin and muscle, wearable electronics, flexible gas sensors, multifunctional and responsive elastomers, and plastic solar panels.

2. Nanotechnology approaches for nanoelectronics

There are mainly two types of approaches for the synthesis of nanomaterials used in nanoelectronics:

1. Top-down approach
2. Bottom-up approach

Top-down approach discusses about the slicing or successive cutting of a bulk material in order to get nano-dimensional particles. Bottom-up approach refers to the stockpile of a material from the bottom: atom by atom, molecule by molecule, or cluster by cluster. Attrition or milling is a characteristic top-down method in the production of nanoparticles, while the colloidal dispersion is a good illustration of bottom-up approach in the synthesis of nanoparticles. The major difficulty with top-down approach is the defectiveness of surface structure and significant crystallographic impairment of the processed patterns. These deficiencies lead to extra challenges in the device design and construction. But this approach leads to the bulk fabrication of nanomaterial. Regardless of the flaws produced by top-down approach, they will continue to play an imperative role in the production of nanostructures. When structures plunge into a nanometer scale, there is a minute chance for top-down approach. All the tools we have possessed are too large to deal with such miniature subjects. Bottom-up approach also assures a better chance to attain nanostructures with less defects and more consistent chemical composition. On the contrary, top-down approach presumably introduces internal stress, additionally to surface defects and contaminations (see **Figure 1**).

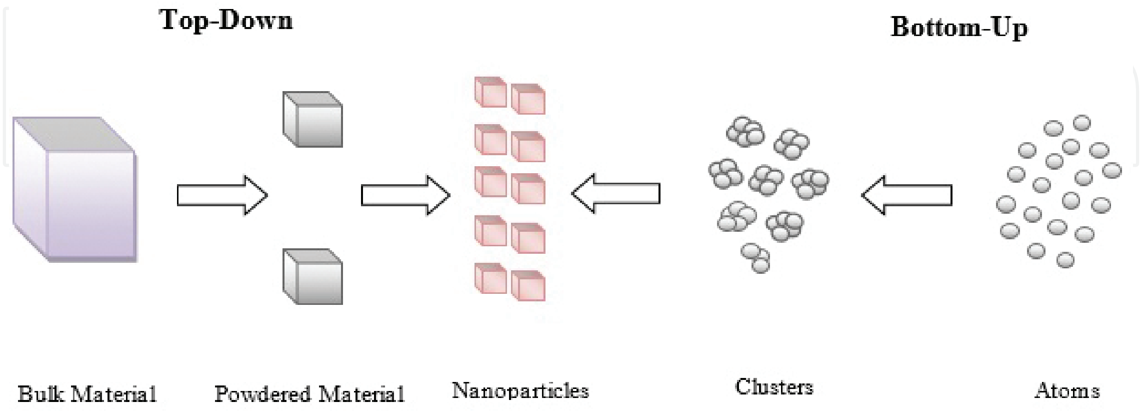

Figure 1. Approaches for the synthesis of nanomaterials.

The performance of Very Large Scale Integration circuits which are basically based on silicon has been progressively enhanced over the past few decades by scaling down the dimensions of the device, plus a virtually exponential development of microelectronics proficiencies is attained. Yet, maintaining this top-down trend for miniaturization is becoming very hard due to the basic technological and physical restrictions as well as the financial limitation. By contrast, using organic molecules as a building block for nanoscale devices has engrossed much consideration because the specifically controlled nanostructures may be formed economically by utilizing self-assembly of molecules. This bottom-up technology can possibly overcome the integral problem of the present silicon top-down technology [25].

Integrated circuit (IC) technology also utilizes the top-down methodology in which the interconnects and devices are prepared by procedures such as thin-film deposition, etching, photolithography, and metallization. Although the fabrication tool competencies keep refining with each technology generation, the complications rise histrionically as the dimensions of the components approach nanometer scale in which various physical effects would stop the tools from operating properly. These restrictions set the ultimate scaling barrier of silicon CMOS, irrespective of the great technological impetus built up over the last three decades. Bottom-up methodology employs chemistry which is not so expensive, to stimulate self-assembly of multifarious mesoscopic structures. There are some fundamental advantages related to bottom-up approach in nanotechnology, like extremely low-power dissipation, rich functionality, and high component packing density, which would fall perfectly on the trend of technological demand but unattainable by the top-down approach [1].

The fundamental differences between the traditional top-down semiconductor nanoscale technology and futuristic bottom-up molecular nanotechnology are listed in **Table 1**.

Top-down approach for semiconductor nanoscale technology	**Bottom-up approach for molecular nanotechnology**
Approach is from larger (bulk wafer) to smaller (chip)	Approach is from small (self-assembled structure) to large (chip)
Methods employed are pattern and etch	Methods employed are synthesis and self-assembly
Production cost is high	Production cost is low
Accessibility for material/device is less	Accessibility is more
Selection of material is stubborn	Selection of material is malleable
Design tool/infrastructure is developed	Design tool/infrastructure is open

Table 1. Comparison between two approaches in nanoelectronics.

Overall, considering the advantages of bottom-up approach over the top-down approach, it can be said that bottom-up technology is better than the top-down technology for the fabrication of various materials used in nanoelectronics.

3. Materials used in nanoelectronics

The nanoscale components used in nanoelectronics fall into two major categories:

1. Inorganic nanocrystals

2. Organic molecular components

1. Inorganic nanocrystals such as nanotubes and nanowires, named after their physical shape determined through the use of growth kinetics, are typically low-dimensional (up to nanoscale) structures. Substantial progress has been made on carbon nanotube (CNT) from the time of its discovery in the early 1990s [26]. Yet, hindrances such as difficulty in separating nanotubes, having different chiralities and properties, and process compatibility inhibit CNT from being readily used for chip applications, though advancement has been made in display [27], and sensing and thermal conducting applications. Li et al. [28] have developed a nanoelectrode assay grounded on vertically aligned multi-walled carbon nanotubes (MWCNTs) rooted in SiO_2 which is used for ultrasensitive DNA recognition. The use of aligned MWCNTs delivered a new bottom-up arrangement for fabricating trustworthy nanoelectrode arrays. Li et al. [29] have fabricated a gas sensor by the simple molding of single-walled carbon nanotubes (SWCNTs) on an interdigitated electrode (IDE) and offered for gas and organic vapor recognition at room temperature. The electrical response indicated well-defined and reproducible linear performance and a detection limit of <44 ppb for NO_2 and 262 ppb for nitrotoluene. Thermal contact conductance properties of CNF-Cu composite materials have also been established by Li and coworkers [30]. The composite material CNF-Cu had been verified at a variety of powers and pressures, yielding reasonable trends specifying the viability of their usage as a thermal interface material in both IC packaging and equipment-cooling applications. 1D semiconductor nanowires may find a number of uses in chip technology due to

exceptional compatibility of the process with the facilities of silicon fabrication, deterministic electrical properties, and variability of material selections.

2. Molecular components (organic) like molecular wires, single molecule, molecular monolayers, and supramolecules with different schemes are the contenders from other classes. Organic molecular components are prepared by amalgamation, and therefore less variation is probable in chemical composition and structural parameters. There are a large number of molecular species prevailing, possibly personalized for various device applications using surface molecular engineering. Single or a few electron transports or transfers include extremely low-energy logic switching or data storage. Molecular nanocomponents have great prospective in manufacturing low-power, ultradense, and low-cost computing chips [1].

These components primarily form self-assembled nanostructures which are having wide range of applications in nanochip technology (see **Figure 2**).

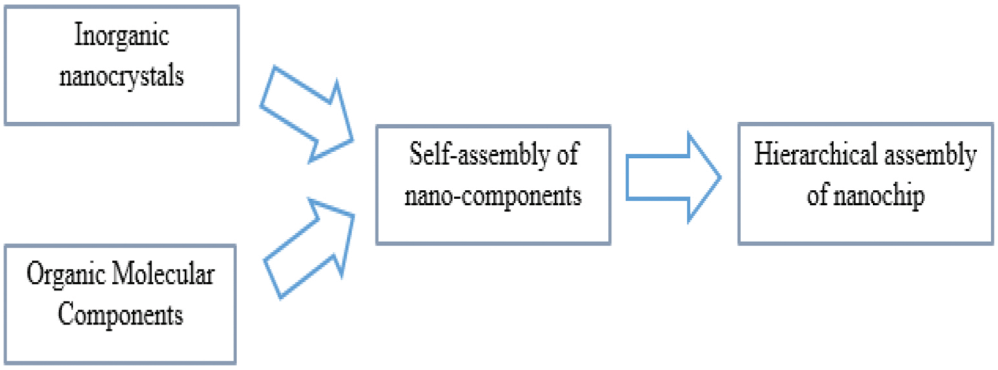

Figure 2. Nanoscale components for next-generation nanochips.

Among these kinds of materials, carbon-based materials such as CNTs, fullerenes, and graphene are gaining much consideration because of the ability of carbon to form bond with other elements which can easily be changed by physical interactions and chemical reactions.

4. Applications of nanoelectronics related to carbon-based materials

4.1. Thin-film transistors

In recent times, the performance of flexible thin film transistors (fTFTs) has been enhanced extraordinarily. CNTs have been used by numerous researchers for the fabrication of thin-film transistors (TFTs). As soon as the CNTs have been purified, solubilized, possibly functionalized, and finally deposited by one of the selective depositions or self-assembly methods, they can be associated in a device geometry which lets the study of their electronic properties. The attention in CNTs, especially SWCNTs, is because of their extraordinary electrical and structural properties [31]. The random linkage of SWCNTs is easily designed by drop, spin, and spray-coating methods. Although the SWCNTs having semiconducting properties show unipolar p-type behavior in an ambient environment in general [32,33], the random network of SWCNTs has revealed that this network can function as a semiconducting channel and conduction lane in the TFT device, as a result of dominant semiconductor and minimal density metallic tubes [34,35] (see **Figure 3**).

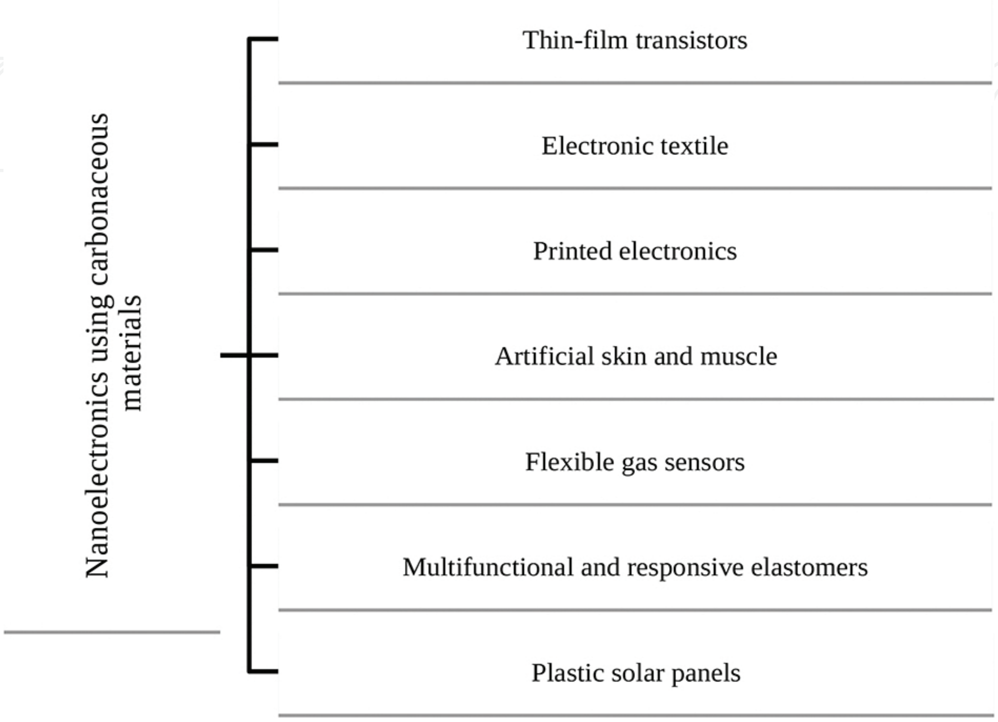

Figure 3. Applications of nanoelectronics in different fields.

Thin-film transistors based on controllable electrostatic self-assembled monolayer SWCNT network have been prepared by varying the density of nanotubes on the substrate made up of silicon. The densities of SWCNT network have been examined as a function of concentration and assembly time. It has been detected that the density of SWCNT network increases from 0.6 mm^2 to 2.1 mm^2, as the average on-state current (Ion) increases from 0.5 mA to 1.47 mA [36].

Organic thin-film transistors (OTFTs) with a spun cross-linked poly-4-vinylphenol (PVP) dielectric have been produced on a flexible substrate made up of polyethersulphone (PES). In order of increasing the electrical performance of OTFTs, a random network of SWCNTs was engaged as an underlay for carrier transfer devoid of sacrificing the flexibility of the TFTs [37].

SWCNT network (SWCNTN)-based thin-film transistors (TFTs) have been fabricated using roll-to-roll (R2R) gravure and inkjet on plastic foils to demonstrate the integrability in point of mass production with a low budget [38]. CNT-polyethylene terephthalate (PET) transistors have also been established by means of as-measured current gain cut-off frequency fT of 1 GHz and constant transconductance as high as 6 GHz [39].

It is worth observing that the greater mobility in combination with disappearing band gap means that graphene will be having less application for logic transistors which must be turned off, but it will be more suitable for high-frequency analog RF transistors where fTs in the order of 50 GHz are already probable. It has also been detected that at the nanoscale, the role of electrical contacts in electronic devices turns out to be increasingly important since they become an intrinsic part of the functional unit.

4.2. Artificial skin and muscle

The skin is the human body's largest organ which shields the body from disease and physical damage and helps to control body temperature. People with third-degree burns have to face a huge number of problems. They lose a huge proportion of their skin layers, for big wounds along with cases of venous ulceration. These are conditions where self-healing property of the skin lost normally [40–42]. Artificial skin and muscles are of great support in such kind of situations. Till now, the solitary other approach of covering up these parts is skin grafting, where the skin is taken from a different body part of the patient himself or from the donor's skin and grafted in the affected part. Such process is an expensive proposition and also involves a lot of uneasiness and pain. Scars are left on the treated wound and also the part from where the skin is taken. There is also the concern about the refusal of skin transplants from some other body parts. Bio-mimicking of artificial muscles or skins prepared from thin layers of polymers and CNTs is currently being fabricated by various scientific groups.

A rubberlike stretchable active matrix has been developed by means of elastic conductors [43] in which an ionic liquid of 1-butyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide was used and homogeneously distributed on single-walled carbon nanotubes (SWCNTs) as chemically unchanging dopants in a vinylidene fluoride-hexafluoropropylene copolymer matrix to produce a composite film. The active matrix sheet can be stretched biaxially and uniaxially by 70 % without mechanical or electrical damage. The elastic conductor helps in the production of electronic integrated circuits, which can be attached anywhere else, comprising random curved surfaces and movable portions, like the joints of a robot's arm.

High-resolution thin-film device has been synthesized to sense texture by means of touch. By using metal and semiconducting nanoparticles, a 100-nm-thick, large-area thin-film device was self-assembled such that the change in current density through the film and the light intensity (electroluminescent) was linearly proportionate to the local stress [44].

It is also extensively acknowledged that skin sensitivity is a significant concern for future robots used by humans in daily life for housekeeping and entertainment determinations. In spite of such fact, comparatively less progress has been made in the area dealing with pressure recognition compared to the areas of voice and sight recognition, primarily because good electronic artificial skin with mechanical flexibility and a large area is not yet obtainable. The construction of a delicate skin made up of thousands of pressure sensors involves a flexible switching matrix which cannot be realized with present silicon-based electronics. Within this perception, Someya and coworkers [43,45,46] have presented the incorporation of organic field-effect transistors and rubber pressure sensors, both of which being manufactured by low-cost processing technology such as large-area printing technology that can provide a perfect solution to realize a practical artificial skin.

4.3. Printed electronics (PE)

Printing is a multipurpose aiding technology for electronic products that cannot be prepared with the distinctive Si microelectronics technology. Polycrystalline and amorphous Si can make large-area products but have little carrier mobility and are stereotypically restricted to a rigid substrate. The printing of semiconductor and metals, conversely, permits the creation of large-area electronics on flexible substrates and allows high-volume scale economies. It is supposed that printed electronics will modernize our standard of living within the next two decades just as Si microelectronics has done in the past decades. The biggest segment of the total printed electronics manufacturing will be printed transistors and memory.

The PE printing technologies generally can be classified as either "mixed subtractive-additive" (where the processing steps include subtractive steps, such as etching or lift-off [47,48]) or "fully additive" (where the processing steps stringently include deposition only, devoid of etching or lift-off) methods. Printed electronics is generally based on polymers or organic molecules that are inexpensive and can be assembled into devices using room temperature fabrication methods. In recent times, a different conception, using nanoscale materials and solution-based deposition methods, is making inroads into the technological and profit-making sectors.

The impact of printed electronics on the recyclability of paper has been proved, and a case study has been done for smart envelopes in the field of courier and postal services [49]. The smart-printed envelope comprises of an amalgamation of both conventional (thin flexible batteries and resistors) and printed electronic constituents (conductive track layout based on nanosilver ink). For this purpose, a comparison among envelopes with and without these constituents (batteries, resistors, and conductive track layouts) was carried out through pilot-scale paper reprocessing tests. The generation of rejects in the course of the reprocessing process as well as the final quality of the recycled paper (mechanical and optical properties) were established and quantitatively assessed.

An effective and simplistic approach has been utilized to successfully synthesize approximately uniform silver nanoparticles (AgNPs) with particle size <10 nm, and the sintering of AgNPs has been demonstrated at room temperature for inkjet-printed flexible electronics [50].

Thin-film supercapacitors have been fabricated by means of materials which are printable to create devices having flexibility on plastic. The dynamic electrodes were prepared using sprayed SWCNTs' networks aiding as both charge collectors and electrodes. Using an aqueous gel electrolyte (printable) along with a liquid electrolyte (organic), the devices' performances illustrate very high energy and power densities (6 W h/kg for both the electrolytes and 23 and 70 kW/kg for aqueous gel electrolyte and organic electrolyte, respectively) which are analogous to presentation in other supercapacitor devices based on SWCNTs fabricated via different techniques [51].

In the field of flexible nanotube electronics, it has been revealed that polymer-supported network transistors show electronic properties that are similar to those of more orthodox, silicon-supported nanotube devices and are bendable and economical. Likewise, it is also demonstrated that nanotube networks could be made up as metallic networks by increasing the nanotube density. These could serve as economical, solution-treated contacts and interconnects [52].

4.4. Electronic textile

Electronic textile materials in the field of Nanoelectronics can be demarcated as fabrics where functions, interconnections, and electronics are intertwined into them. Electronic textiles give the conventional textile industry a novel additional value characterized by the possibility of making healthier everyday life, harmless and satisfied, conveying technological accomplishments closer to the people, through the apprehension of interfaces which are easy to use between humans and devices [53]. Clothings can now transform into various colors on command, give you a checkup, and connect by Wi-Fi. The first outcomes by now have appeared on store shelves, e.g., snowboarding jacket aimed to play MP3 music files with the assistance of controls stitched onto the jacket.

The main concern in this area is to assimilate flexible wires into textile substrate, connect them to electronics that can endure bending, twisting, and stretching, and power the whole ensemble. The requisite of upholding the textiles' mechanical flexibility lessens the possible technologies and materials appropriate for the objectives of the assignment: electrical conductivity along with its modulation cannot be attained through traditional semiconductors (like inorganic and silicon semiconductors). Certainly, a need for materials is there, whose mechanical properties do not fluctuate much from those of the textile substrates. Conductive polymers and CNTs, presently explored in the area of molecular electronics, are the unsurpassed contenders for undertaking such needs.

Flexible and wearable wire-shaped micro-supercapacitors have been designed which are based on highly aligned titania and carbon nanotubes [54]. A titanium wire has been used sheathed with outwardly aligned titania nanotubes as one of the electrodes to create all-solid-state micro-supercapacitors, in which the second electrode is carbon nanotube fiber or sheet. The capacitance of the subsequent micro-supercapacitor with a CNT sheet electrode was about three times of that for the analogous device with the second electrode based on a single CNT yarn. The exclusive wire-shaped structure made it promising for the wire-shaped micro-supercapacitors to be woven into various textiles and associated in series or parallel to meet a large variety of explicit energy demands.

A scalable nonliquid-crystal spinning procedure has been developed by researchers for the fabrication of continuous graphene fibers with tailored assembly for high-performance wearable supercapacitors [55]. These fibers infatuate surfaces with bark-like fine microstructure and differently designed cross sections with locally aligned dense pores, depending on the jet stretch ratio (R) throughout spinning. This nonliquid-crystal spinning approach could be stretched to the assembly of other two-dimensional nanomaterials into macroscopic fibers for uses in micro-devices, wearable electronics, and smart textile.

CNT-based interconnects could be fabricated by a number of methods. Two carbon nanotube (CNT) network fabrication procedures have been proposed, the normal spin rate coating (NR) and the slow spin rate coating (SR), and two interconnect assemblies, the single-layer structure

(SL) and the double-layer structure (DL), have been to make CNT interconnects [56]. A novel method has also been developed to produce nanocomposite textiles made from carbon nanotubes (CNTs) with improved sensing competencies [57]. Catering to the always increasing demand of upgraded sensors, this work deliberates the electrospinning fabrication scheme that has been engaged to cultivate novel CNT-based piezoelectric strain sensors. When these new piezopolymer composites which are based on CNTs were electro-spun into smart textiles, the ability of strain sensing (measured by voltage through the sensor) can be increased by 35 times, from 2.4 to 84.5 mV for the nanotubes with 0.05 wt%. The leading principle accountable for such enhancement was found to be the dipolar orientation in the piezoelectric material.

4.5. Flexible gas sensors

Sensing of gases signifies an essential subject in a huge variety of technological fields like processing in industries, storage, fuel cells, and separation. Conventional sensors for gases are made up, generally on substrates which are inorganic in nature, e.g., quartz, glass, and silicon wafers. The rigidity of such sensors related with the use of rigid substrates might restrict their use in a number of novel areas, e.g., aerospace science and portable devices, which demand lightweight and flexible sensing components. Flexible multi-sensors which support humidity, temperature, and detection of gas can be mass-produced at lesser cost and can consequently be incorporated onto Radio Frequency Identification tags or in smart textiles for logistic applications. CNTs which provide many sites where gasses can react, due to their extraordinary surface area and nanoscale assembly, set up a class of capable building blocks for manufacturing flexible chemical sensors on organic substrates.

Flexible vapor sensors using single-walled carbon nanotubes have been fabricated via the line-patterning technique [58]. Thin, strongly adhering films of single-walled carbon nanotube (SWCNT) bundles on flexible substrates such as polyethylene terephthalate (PET) have been used for sensing various kinds of vapors (hexane, toluene, acetone, chloroform, acetonitrile, methanol, water, etc.). These PET patterns are covered with films of electronically conductive SWCNT bundles (1–2 μm thick) by dip coating in aqueous surfactant-supported dispersions and attached in glass chambers fortified for sensing vapors. Flexible carbon nanotube sensors have also been developed for nerve agent simulators for the nerve agents sarin (diisopropyl methylphosphonate, DIMP) and soman (dimethyl methylphosphonate, DMMP) [59].

The fabrication of density-controlled single-walled carbon nanotube (SWCNT) thin films on poly(dimethylsiloxane) (PDMS) substrates has been reported by vacuum filtration and PDMS direct molding [60]. The flexible thin film of SWCNT indicates high stability (mechanically) with insignificant changes in conductance after twisting by 180°. This can be made known that conductance of SWCNT thin-film has high sensitivity to NH_3 gas partial pressure. It is also observed that the lesser the density of SWCNTs, the greater would be the sensitivity. The outcomes indicate that the flexible thin films of SWCNTs might be valid to future mobile sensors having high sensitivity.

High-performance hydrogen sensors have been manufactured with outstanding mechanical flexibility and durability on thin plastic sheets with the use of high-quality semiconducting single-walled carbon nanotubes adorned with discrete Pd nanoparticles [61]. The response times are normally less than 15 s for 1 % hydrogen, and the sensors are entirely recovered within 5 min in the air devoid of hydrogen. The flexible sensors can sense hydrogen with concentrations as low as 100 ppm (0.01 %). These flexible hydrogen sensors can find direct applications for sensing hydrogen leakage in various systems with demanding lightweight, mechanical flexibility, and high sensitivity.

A transparent and flexible glucose biosensor has also been reported on which multi-walled carbon nanotubes (MWCNTs) and glucose oxidase (GOx) are layer-by-layer (LBL) self-assembled onto a polymer-based substrate [62]. Biosensor exhibited a response range (linear) of 0.02–2.2 mM with a low detection limit of 10 μM. This significant act, pooled with the large-area preparation procedure, proves that this multilayer biosensor based on CNT is compatible for marketable applications.

The fabrication of flexible NO_2 sensors has also been done by layer-by-layer self-assembly of multi-walled carbon nanotubes and to study their gas-sensing properties [63]. First, a charged substrate (negative) is arranged by the construction of a monolayer which is organic (3-mercapto-1-propanesulfonic acid sodium salt; MPS) on a substrate of polyester with a pair of Au electrodes (comb-like). Afterward, two-cycle poly(4-styrene sulfonic acid-co-maleic acid)/ poly(allylamine hydrochloride) (PSSMA/PAH) bilayers are placed on an MPS-modified substrate. Finally, multilayers of MWCNTs are designed as interchanging layers of cationic PAH and MWCNTs (negatively charged) on the modified substrate.

4.6. Multifunctional and responsive elastomers

The development in the field of nanoelectronics in the future relies on the multipurpose devices which can help in overcoming form-factor restrictions related with systems that only offer flexibility in combination with optical, electrical, and chemical properties. In that respect, polymer/CNT composites are among the maximum quoted contenders for nanoelectronics, a leading locus which stems mostly from their inherent electronic and structural properties.

The volume fraction-resolved, time-resolved, and frequency-resolved spectra of carbon black (CB) have been investigated at room temperature which is well above the glass transition temperature of the matrix-effective complex permittivity of well-characterized CB-filled ethylene butylacrylate copolymer samples which are surrendered to a uniaxial tension [64]. At low strain, the temporal evolution of permittivity while aging under stress showed a logarithmic growth phase followed by a logarithmic decay phase, whereas for sufficiently large strain, the permittivity behaviors overlap with those observed below the percolation threshold. An inspection of these materials using the surface and volume morphological evolutions under the act of a mechanical stress at the microscale by scanning electron microscopy (SEM) and atomic force microscopy (AFM) directed that aging during a few hundred hours, at a rational strain, generates cracks and voids that are aligned alongside the stretching direction.

The evolution of the absorption spectra for plastoferrites and carbon black-filled ethylene butylacrylate copolymer composites subjected to a uniaxial tension has been executed which is dependent on frequency and measured using a network analyzer (vector) as a function of the ratio of elongation over the frequency range (0.3–5 GHz) and at room temperature [65].

Loading a random network of SWCNT on a substrate (elastomeric) affords a two-terminal stretchable resistor having the capability to lodge strains more than 20 %. Such kind of strain leads to the distortion of individual SWCNTs within the whole network, in this manner varying their electronic properties in a reversible manner, because of the deviations either in the SWCNT-SWCNT contacts and/or band gaps [66,67]. This property can be used to make strain sensors with piezo-resistance gage factor, which can be defined as resistance modulation per strain, equivalent to those of the orthodox metal-strain gages.

4.7. Plastic solar panels

As the natural resources of the world are declining, the requirement of cheap and novel energy sources is developing. The sun is one such source which produces heat as well as light which can be harnessed and used for people's benefit. Solar cell designs are conventionally based on crystalline silicon, but not only that such material has been in short supply, the process of silicon solar is comparatively expensive too. As the solar industry struggles in order to reduce the cost to make it a feasible substitute of fossil fuels, many are now focusing toward plastic panels. In this viewpoint, photovoltaic devices which are flexible, e.g., polyimide solar cells, have recently been made up.

The photoelectrical properties of p-n junction organic solar cells have been investigated which are grounded on Cm and phthalocyanines mainly oxotitanium (IV) phthalocyanine (OTiPc) [68]. The Al/C and OTiPc/indium tin oxide (ITO) cells disclose relatively high-energy conversion efficiencies at 720 nm (10 p W cm^{-2}) due to the creation of a p-n junction between Cm and OTiPc. When ITO is used as the front electrode instead of Al, the stability of cells gets extraordinarily enhanced, so that the photocurrents remain unaffected for a long period of time even on white light illumination at high light intensity.

A pure carbon counter electrode (CE) has been manufactured for dye-sensitized solar cells (DSCs), by means of a substrate (industrial flexible graphite sheet) and activated carbon as the catalyst [69]. The CE presents series resistance (R_s) and charge-transfer resistance (R_{ct}) which are very low by merging the flexible graphite's high conductivity with the activated carbon's high catalytic property. The R_s and R_{ct} for the counter electrode are correspondingly only a quarter and two-thirds of those for a platinized tin oxide glass doped with fluorine (Pt/FTO). DSCs having cell areas of 0.15 and 1 cm^2 made up with this CE exhibit higher solar-to-electricity conversion efficiencies. The respective values are 6.46 % and 5 %, matching with 6.37 % and 2.91 % for the Pt/FTO-based devices.

The photovoltaic properties of indium tin oxide (ITO)/C_{60}/H_2 (pc), (pc = phthalocyanine)/Au-sandwiched solar cells have also been investigated [70]. The cell's photocurrent action spectra show that photocurrent which is generated at C_{60}/H_2 (pc) interface because of the diffusion of C60 excitons is due to the excited state of C60 that has a comparatively longer lifespan, while the cell made at a lower vacuum (331,025 torr) reveals a much lesser photocurrent (JSC51.4 $\mu A\ cm^{-2}$) since oxygen in C60 acts as carrier traps and increases the resistance of C60.

5. Conclusion

This chapter deals with the various approaches of nanotechnology toward nanoelectronics, viz., top-down and bottom-up technology in which bottom-up technology was found to be having superiority over the top-down approach for the fabrication of materials, circuits, etc. used in nanoelectronics. Further, this chapter shows the materials which can be used in nanoelectronics. Among the various materials used, carbon-based materials such as CNTs, fullerenes, and graphene are gaining much consideration because of the ability of carbon to form bond with other elements which can easily be changed by physical interactions and chemical reactions. Further, the recent advancements of C-filled plastics for uses in diverse types of optoelectronic, electronic, and sensor systems have been reviewed. Devices which are based on the plastic C/organic nanoelectronics are twistable, stretchable, and deformable into curvilinear shapes, in that way assisting the applications that would not be possible to achieve by using the brittle, rigid, and planar nature of electronics of today, e.g., Si or III–Vs. In order to build such robust and flexible electromechanical devices, multiple components with specific electrochemical and interfacial properties need to be incorporated into solo units. The chapter focuses on the application of carbon-based materials in various fields of nanoelectronics, viz., thin-film transistors, printed electronics, artificial skin and muscle, wearable electronics, flexible gas sensors, multifunctional and responsive elastomers, and plastic solar panels.

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