

Chapter 14

Nanotechnology Applications and Synthesis of Graphene as Nanomaterial for Nanoelectronics



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14.1 Introduction

At present the tremendous development in the field of integrated circuit technology (IC technology) is based on the continuous scaling of silicon-based CMOS transistor devices (Roberts 1984). The scaling helps to maintain the law proposed by Moore in 1965, which states that “the number of devices or transistor per square inch on the integrated circuit doubles every year.” The scaling in the nanometer (nm) region is posing serious problems in the integration of devices and maintaining performance of the device’s parameters (Kilby 2000; Mollick 2006). At the nanometer (nm) scale level, the effect of quantum tunneling is very much prevalent as it makes device fabrication difficult (Horowitz et al. 2005; Wu et al. 2013).

At nanometer (nm) scale region, the secondary effects come into existence. There is more power dissipation in the system along with subthreshold leakage current flow, which mainly affects the performance of the whole system. Therefore, the problem that arises due to scaling has made researchers search for alternative materials. Hence, carbon nanotubes (CNTs) and graphene are the prime contenders that can potentially replace silicon (Si) in various conventional devices. This will also be helpful in the electronics industry in the near future. The various properties of these devices include thermal, mechanical, optical, and electrical properties which are very much effected by using the nanometer designs.

In this chapter the detailed study of various properties of graphene as well as carbon nanotubes (CNTs) which are useful in the present day-to-day scenario in the nanotechnology regime has been reported. This chapter will also illustrate the implementation and the conceptualization of the term nanotechnology (nm) in numerous number

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of fields like electronics, medical, chemical, robotics, mechanical, aeronautics, and information technology along within the computers.

The term nanotechnology has its origin from the two Greek words “nano” and “technology.” The Greek prefix “nano” means “to a billionth of any entity,” and the word “technology” implicates the concept of innovation and also the art and science which thus investigate the manipulation of the matter at nanoscale (Roberts 1984; Kilby 2000; Mollick 2006). Because of which, nanotechnology or nanotech or nanoscaled technology is customarily weighed below 0.1 μm or 100 nm (so nm scale is equivalent to 10^{-9} m). Nanoscale science (or nanoscience) investigates the phantasm and properties and also measures the varied responses of materials at various scales including atomic, molecular, and macromolecular levels along with the sizes falling universally in the range of 1–100 nm.

In the current scenario which is nowadays preeminently under 5 nm, the materials properties diverge incomparably (i.e., vital role being played by quantum-scale effects) vis-a-vis a bigger particulate scale. Nanotech involves various aspects which include design, manipulation, building, production, and application, which is achieved by regulating the shape and size, formulating the properties, responses, and performance of devices and systems up to < than 100 nm.

Nanotechnology being a branch of science and technology deals with the materials having the dimensional size of the order of nanometer scale. The term nanometer means that the scale unit is having 10^{-9} m value. These materials have the size less than 100 nm. Nanotech also denotes the manipulation of the matter on supramolecular scale, atomic scale, and molecular scale (Ganji and Kachapi 2015).

Another more authenticated and generalized definition of nanotech is imparted by the National Nanotechnology Initiative (NNI) where it includes the manipulations of the element dimensions by measurably varying one of the dimensions from 1 to 100 nm. The basis of the above fact is that the quantum mechanical effects become significant in the quantum realm scale.

To conceive this idea of nanotechnology, one should observe the nail of the little finger. The dimensional width of the nail on the little finger is round about 10 million nm; another live example of the nanotechnology is the strand of human hair which is of the range 75,000–100,000 nm in diameter. This term was first coined in the late 1950s of the twentieth century especially around 1959. Being an umbrella phrase that beset all the fields of Science & Engineering at nanometer scale. Nanotech is immensely distinct and multidisciplinary field extending from the novel addendum of conventional physics devices to absolutely a new approach planted on the molecular self-assembly.

Nanotechnology being new was mainly talked by the then physicist and Nobel laureate Richard Feynman in which he stated that “There is plenty of room at the bottom” (Feynman 1992).

Nanotech being an enabling technology is expected to revolutionize the major portions of the industrial sectors. The earliest widespread description of nanotechnology was primarily focused on the particular goal of precise manipulation of atoms and molecules which is required for the fabrication of macroscopic products.

The NNI states any material to be in the nanotechnology state only if the concerned material fulfills all the conditions as [EPA, US 2007]:

- Research and technological evolution centered at the atomic, molecular, or macromolecular levels ranging approx. from 1 to 100 nm
- Creating and using systems, structures, and devices containing innovative properties and functions due their small or intermediate size
- Manipulation and control ability at atomic scale

Nanotech being an appearing technology because of feasibility of put forwarding through going materials and to forge state-of-the-art materials having utterly unique features and functionality instilled with colossal abilities for wider spectrum of applications. Supplemental to its utility in industrial arena, pioneering innovations can be forecasted in various fields like ICT, medical and allied technology, metrology, etc. (Seeman 2003).

Symbolic utilizations of nanosciences and nanoengineering field can be seen in various arenas like pharmaceuticals, cosmetic products, canned food, chemical engineering, materials with high performance, electronic items, precision mechanics, light energy models, energy generation, and environmental sciences.

Nanoscience (nanotechnology) is the most energized discipline of science and technology as it promises superior health, wealth, defense, and closing ranks between science and fiction. It has grown rapidly over the years and has already gained considerable international and national interest. It has abeyance for making enormous impact on the society, humanity, and ecology apart from their immediate uses in hardware and electronics system (Kumar 2006; Phillips 2006).

Their direct and indirect impact would be widespread, and it would give a new boost to various emerging technologies such as information technology, data storage, semiconductor technology, sensors and actuators, pharmaceutical, biomedicine, biotech, chemical industry, aerospace, and automotive industry.

As the particle size reduces and reaches the nanoscale regime, the surface area to volume ratio of the particle rapidly increases. The number of atoms on the surface of the particle in this size range will dramatically increase compared to the atoms within the particle. A particle of 5 nm in diameter has nearly 50% of its atoms on the surface compared to the 100 nm particle where less than 5% are surface atoms. This affects the internal structure of the particle including the arrangement of atoms and the electronic configuration, and quantum effects dominate (Ferrari 2007).

In the 1980s era, two major discoveries stimulated the growth of nanotechnology in modern era:

- The first comprised of scanning via tunneling microscope discovery in the year 1981 which put forward the visualization of individual atoms along with their bonds. In year 1989 the above said technique was successfully put into action to maneuver distinctive atoms. Gerd Binnig and Heinrich Rohrer who were the developers of the microscope at IBM's research lab at Zurich got Nobel Prize in

the field of physics in 1986 (Meyyappan 2004; Novoselov et al. 2004). In the same year, the discovery of analogous atomic force microscope made by them led to the revolution in the field of nanotech.

- The second comprised of the discovery of fullerenes in 1985 by Kroto, Smalley, and Curl for which they won the Nobel Prize in the field of chemistry in 1996. C_{60} was initially not considered in the nanotech field but was then considered with the discovery of graphene tubes (called carbon nanotubes and every now and then known as the buckytubes) with numerous utilizations in the field of electronics (Meng et al. 2012).

The nanotech field during the 2000s called for upsurge in scientific, political, and commercial attention that resulted in development and controversy at the same time. The major skepticisms were related to the definitions and utilities of nanotech. In 2001 and 2003, apprehensions surfaced about the feasibility of applications forecasted by supporters of molecular nanotech, which ultimately ended up with a public discussion between Drexler and Smalley. Further the profit-oriented products started to appear with the progression of nanotech in the world. These materials are narrowed down to a wide-scale usage of these nanomaterials without the inclusion of any atomic control of matter (Wang et al. 2012).

Various instances of these encompass the usage of nanoparticles of silver as antibiotics, sunscreens composed of nanoparticle components, silica nanoparticles to strengthen carbon fiber, and clothing made of CNTs with stain resilience properties.

Governments nowadays have started promoting nanotechnology and invested funds in the research field of nanotech; for example, the USA started with the NNI that gave a size-dependent description of nanotech and facilitated monetary support for explorations and analysis on the nanoscale. Similarly the European Framework Program was established to give a boost in the development of nanotech. The mid-2000s saw the prospering of innovative and serious scientific concerns in these fields.

Various projects evolved for making nanotech road maps based on meticulous maneuvering of matter with discussions on both present and future capacities and goals.

14.1.1 Types of Nanomaterials

The nanomaterials are the foundations on which nanoscience and nanotechnology are based.

In the past few years, nanostructure science-based technology is recognized as an interdisciplinary area for researchers to collaborate. This leads to the development activity in the worldwide researcher's fraternity. Nanotechnology is having potential to revolutionize the methods in which the materials and other products are created. There are some nanomaterials that occur naturally to be utilized in various applications.

The various types of nanomaterials which have been manufactured and developed are:

- *Nanotubes*: Being a tubelike structure in nm scale, nanotubes are the kind of nanoparticles within which other smaller nanoparticles can be channeled with a property of an electric conductor as well as insulator. The various kinds of nanotubes are (Lakhtakia 2012):
 - *BCN nanotubes*
 - *Boron nitride nanotubes*
 - *CNTs*
 - *DNA nanotubes*
 - *Gallium nitride nanotubes*
 - *Silicon nanotubes*
 - *Inorganic nanotubes*
 - *Tunneling and titania nanotubes*
- *Nanorods*: Physiology here refers to branching (part of particular field) one physiology of nanoscale particle with each comprising the structural range from 1 to 100 nm after being synthesized from the metals or the semiconductors. They have standard aspect ratio to be in the range of 3–5. They are manufactured through chemical synthesis after the combination of ligands which are acting as shape-controlling agents bonding to obtain different facets of nanorods of varying strengths. They are majorly implemented in MEMS-based devices and accelerometers (Lakhtakia 2012; Respaud et al. 2016).
- *Nanocomposite*: These are the multiphase solid materials in which one phase is provided with one, two, or three dimensions of less than 100 nm. In some cases more than one phase dimensional size is in nm range, and they are thus embedded in the metal, ceramic, or polymer matrix.
- *Nanocoatings*: These are the nanosized thin films which are applied to the surface of various materials so as to enhance the various characteristic features of the materials such as the corrosion protection, protection against the degradation caused by the water and ice element, frictional minimization, antifouling and antibacterial properties, self-cleaning property, and resistance to heat and radiations along with thermal management. Nanocoatings are used for aerospace, defense, medical, oil, marine, and metallic industries (Kolyadina et al. 2016).
- *Graphenes*: They are nowadays a very attractive material for post-CMOS or silicon electronics because of their high carrier mobility and planar structure, thereby making the integration with the standard technology easier than that of CNTs. Moreover, nowadays the 2D material systems have gained a great amount of attention among various global research communities. They are majorly 2D material with only one-atom thickness (Imperiale et al. 2010).
- *Thin films*: These comprise of the layers of materials having thickness in the range of few nm to several mm.

14.1.2 Applications of Nanotechnology

Nanotechnology may be defined as the technique to manipulate matter at atomic level or molecular level. The design obtained is utilized for a particular application. The structures developed are worked in the range between 1 and 100 nm in size. This technique refers to development of structures by selection either of top-down or bottom-up design processes for individual components (Wu et al. 2008; Shahabadi et al. 2016).

From the definition, it acts on the emerging technologies associated with the novel classes of therapeutics. Using the improved technology of nanotechnology, it may be possible to improve upon targeted drug delivery (Hu et al. 2012), detection (Goenka et al. 2014), medical instrumentation (Goenka et al. 2014), and other specific areas. Many materials will be acted upon where the nanomaterial being used has a large surface area to volume ratio and is size dependable for many applications as stated above. Before extensively discussing about the advantages of the Nanotechnology, there should be discussion about why the nanotech is becoming the most favored technology among the researchers. The nanotech is the most widely illustrated field because of the following:

- *Engineers*: Development of processes and techniques to handle materials at nanoscale and fabrication of devices
- *Electronics*: Development of new types of semiconductor materials having enhanced features

14.1.3 Advantages of Nanotechnology

Among the engineers it is most widely privileged because of the following factors:

- Materials manufactured are stronger, lighter, cheaper, durable, and precise.
- With the help of nanotech, the computers manufactured can become billion times faster and million times smaller. The manufacturing cost is also negligible.
- Nanotechnology is having great impact on various electronics products; thus they refashion/remodel their procedures and applications. The areas which are benefitted most include diodes, nanotransistors, OLED, quantum computers, plasma displays, etc. (Yeole and Padole 2015).
- Nanotech is also profitable for the energy sector. With the advancement of smaller and energy-efficient products, especially the energy-absorbing and the energy-storing devices, the energy consumption and wastage have been reduced dramatically. Production of solar cells, fuel cells, and hot solar cells has revolutionized the energy sector.
- Materials like nanotubes, aerogels, nanoparticles, etc. are very much stronger, durable, and lighter than some of the conventional tools and equipment like steel, aluminum, and other heavy earth metals (Prokhorov and Botsula 2010).

- With the advent of nanotech in the medical sector, smart drugs have been created for faster, side effect-free, and effective treatment of human ailments like diabetes and cancer and for tissue regeneration along with bone repair (Jelicic et al. 2015).
- In the defense sector, this technology is mainly useful for the development of weapons of mass destruction with ease and with less cost.

14.2 Graphene as Nanotechnology Material

The demand for fast response time devices is increasing tremendously in the past few decades. With the reduction in the area of devices, the conventional semiconductor devices are not suitable because they tend to exhibit the second-order effects. This leads to the technology scaling of the devices. This leads to shift in the technology and made researchers to search for alternative materials to be used in electronics industry. Out of many materials, graphene and CNT have commanding presence in the electronics industry.

There are several areas for applications of graphene due to its properties such as high conductivity. Its large surface area makes it a promising material for batteries and for energy storage applications (Bae et al. 2010), while its transparency, conductivity, and flexibility make it an interesting material for flexible displays and touch screens (Novoselov et al. 2004). Other applications include the use of graphene as a conductive ink, chemical sensor, barrier layer, or heat spreader. Yet, the initial interest in graphene was sparked by its potential for post-silicon optical and electronic applications, due to its high intrinsic mobility, scalability, and observed electric field effect (Novoselov et al. 2004; Schwierz 2010).

There is limitation while looking forward for miniaturization of the devices there is limitation for scaling of device technology while following the Moores law (Schaller 1997). The time limit for reaching the limit has been postponed with more innovations in structures and architectures utilized by researchers throughout the world. The limit is about to reach its full restriction when the length of the transistors becomes less than 10 nm.

At this duration the potential of graphene as electronic material can be utilized. Thus the research on improving and modifying various techniques related to graphene need to be improved. Since the last decade, there is tremendous research related to problems associated with graphene-based electronics reported by researchers across the globe. There is definitely some more time requirement in the future to fully develop graphene-based transistors so as to replace silicon-based electronics.

The structures developed using graphene for logic transistors are probably different than the contemporary MOS structure. This is attributed to the difference in properties of graphene and silicon.

Because of its high mobility, graphene is considered to be an important material for devices that require ultrahigh speed such as analog and digital logic circuits. Use of devices in RF applications with graphene is nowadays very much prevalent. As graphene possesses remarkable optical property of linear dispersion. This property of Dirac electrons drives the use of graphene-based optoelectronic devices in broadband applications. Graphene is known to exhibit high optical damage threshold, and high third-order optical nonlinearities of graphene devices are also implemented in photonic devices. The application of graphene can be further extended to interconnect and to achieve that there is requirement of techniques so as to realize various applications as reviewed. Graphene being an extraordinary material used in the channel of devices is very much useful in high-frequency RF applications. On the basis of available facts, it can be clearly stated that graphene possess ultrahigh mobility that leads to ballistic transport at mm scale, along with large saturation velocity. In addition to high-frequency applications, they are also used in the design of LNA (low-noise amplifier). As it is well known fact that the RF transistors have maximum frequency of oscillation (f_{max}) and the cutoff frequency (f_T). Currently the highest reported cutoff frequency for graphene MOSFET is 427 GHz, and the maximum f_T is 45 GHz (Wu et al. 2016). Figure 14.1 describes the cutoff frequency for graphene transistors and other competing transistor types.

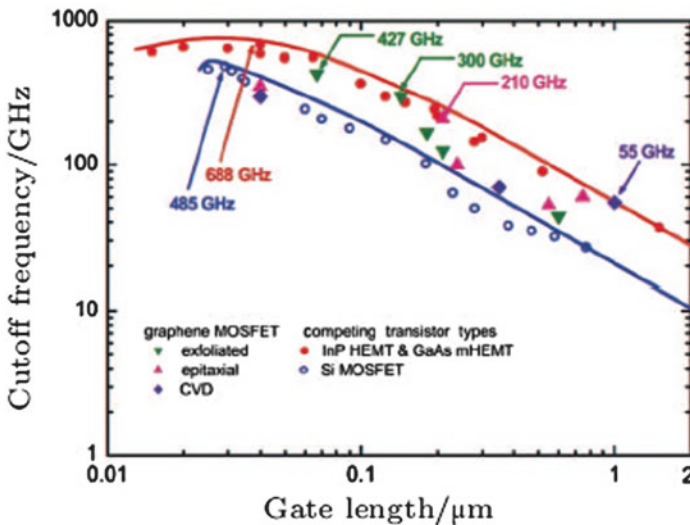


Fig. 14.1 Cutoff frequency of graphene MOSFETs, Si MOSFETs, and III-V HEMTs versus gate length in μm (Schwierz 2011)

Table 14.1 Advent of high-frequency GFET devices (Hua-Qiang et al. 2013; Lin et al. 2010)

Achievement	F_T /GHz	Gate length/nm
Field effect in graphene	–	–
1st top-gated GFET	–	500
1st GHz GFET	14.7	500
1st GFET (submicrometer gate length)	26	150
1st epitaxial (GFET on SiC)	4.4	2000
1st 100GHz (epitaxial GFET on SiC)	100	240
1st nanowire gate GFET	300	144
1st CVD GFET with deep-submicrometer gate length	155	40
1st 427 GHz GFET with transferred gate stacks	427	67

Table 14.2 Comparison of different material characteristics

Characteristics	Si	SiC	InAlAs/ InGaAs	AlGaAs/ InGaAs	AlGaN/ GaN	Graphene
Peak electron velocity ($\times 10^7$ cm/s)	1.0	2.0	1.0	1.3	1.3	5–7
Electron mobility at 300 K ($\text{cm}^2/\text{V}\cdot\text{s}$)	1500	700	5400	8500	1500–2200	>100,000
Thermal conductivity (W/cm-K)	1.5	4.5	0.7	0.5	>1.5	48.4–53

The various improvements in the cutoff frequency are depicted in Table 14.1.

The comparison analysis of various characteristics is shown in Table 14.2.

Another material that has also found numerous applications in the field of electronics is carbon nanotubes (CNTs). Because of the rapid scaling of electronic devices, the energy consumption is a major cause of concern for researchers (Lin et al. 2011). Most of the researchers are now focusing their concern onto the ultralow-power sensors. Out of most of the sensors, gas sensors for air quality detection consume maximum power when used, so CNTs are used instead for energy-saving process. CNT-based gas sensor devices can detect NO_2 with power consumption of less than 50 nW. CNTs are innovative devices with good transistor scalability with growth in performance, and CNTFETs have outstanding current capability. CNTFETs have been extensively used at 32 nm technology and also below 28 nm. As it is well-known that the modern-day wireless receivers have to support a variety of wireless standards working at different frequency bands, thus there is an immediate requirement of power conservation devices. The perfect solution to these problems is the CNTFETs which have transit frequency (f_T) in the range of terahertz (THz). The CNT model parameter description is illustrated in Fig. 14.2.

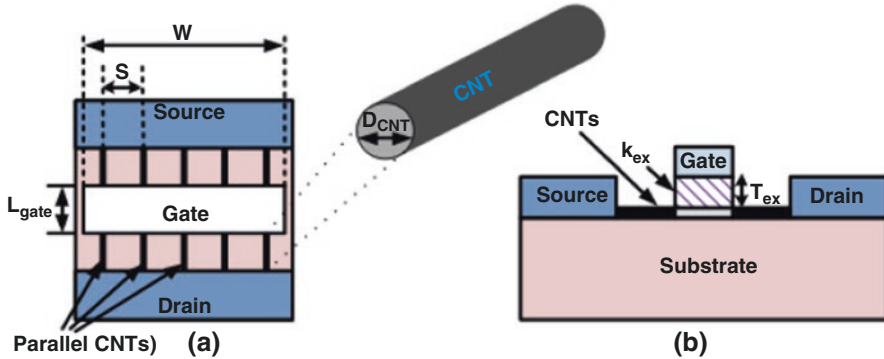


Fig. 14.2 (a) CNTFET as Channel (b) CNTFET structure

14.3 Graphene and Its Future Aspects

The structure of graphene can be described as a 2D honeycomb lattice of carbon atoms having thickness of one atom. Graphene being an allotropic form of carbon is 2D (two-dimensional). It has a hexagonal lattice packing at the atomic scale. Its structure is similar to other allotropes of carbon, namely, CNTs, graphite, charcoal, and fullerenes (C_{60} buckminsterfullerene). The aromatic molecule is considered to be of indefinitely large size. The combination of the words graphite and “ene” was first coined by scientist Hanns-Peter Boehm in 1962. It was discovered by Konstantin Novoselov and Andre Geim in 2004 at the University of Manchester (Hancock 2011). Graphene is a layered material with single-atom-thick layer of graphite (McClure 1956; Slonczewski et al. 1958; Wallace 1947). Although its existence is theoretically known for many years, single-atom layer is considered as thermodynamically unstable.

Novoselov et al. were the initial researchers who experimentally identified the single-atomic-layer structure of graphene. The findings are not in contradiction to the theory as the layer was well supported on the substrate (Novoselov et al. 2004). Also demonstration of high mobility is done experimentally during examination of electrical properties.

In 2010, Nobel Prize in physics was awarded for revolutionary experiments on 2D graphene materials. Graphene is a flat monolayer of carbon atoms which are tightly packed in order to achieve honeycomb structural lattice. One carbon atom is covalently bonded with three adjacent carbon atoms as shown in Fig. 14.3 through sp^2 hybridization, while the rest of the p_z carbon orbitals form an extended electron system (Thakur and Thakur 2015). Due to the unique electronic state of graphene, it possesses appreciable electrical properties.

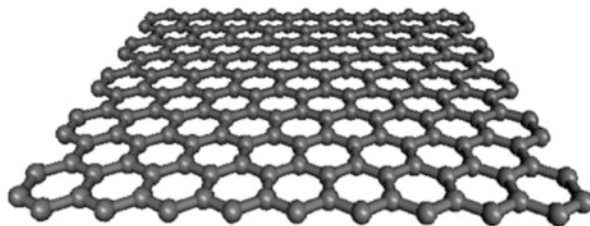


Fig. 14.3 Graphene atomic structure

Graphene has been known for excellent properties that include high mobility ($10^5 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ at room temperature), high current density (10^9 A/cm^2), high thermal conductivity, and good mechanical properties.

14.3.1 Properties of Graphene

Graphene falls under the category of zero-gap semiconductors having high electrical conductance. The charge carriers in these materials consisting of several layers are confined naturally in plane. This results in a weak van der Waals interaction between the nanomaterial and its surroundings (Mas-Balleste et al. 2011).

Due to this reason, 2D nanomaterials are sometimes classified as van der Waals materials. This weak interaction of graphene aids in the isolation of single-layer materials, with thickness of single atomic layer. The single-layer thickness of 2D nanomaterials like graphene makes them a suitable option to help meet the scaling demand requirement of future technology scenarios. These unique properties of graphene have attracted researcher's interest throughout the research community, thus elevating graphene's status to that of a true wonder material.

Graphene is being considered as a wonder material nowadays because of its exhibition of remarkable properties (Burtcher 2005):

- *Electronic properties:* Electron mobility possessed by graphene materials is surprisingly very high; the value of mobility reported at room temperature is noted to be around $15,000 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$.
- *Optical properties:* Graphene possess high value of opacity in the case of atomic monolayer; in the initial stages, it is capable of absorption with $\pi\alpha \approx 2.3\%$ fraction of white light, the portion which is incident on its surface.
- *Thermal properties:* The thermal conductivity of graphene at room temperature is in the range of $4.84 \pm 0.44 \times 10^3$ to $5.30 \pm 0.48 \times 10^3 \text{ Wm}^{-1} \text{ K}^{-1}$ (Burtcher 2005).
- *Mechanical properties:* The breaking strength of graphene as compared to that of steel is 200 times more, with a reported tensile modulus (stiffness) of 1 TPa (150,000,000 psi).

- Graphene is lighter, harder, stronger, and more flexible than steel. Graphene can also be recycled and is considered a sustainable, eco-friendly, cost-effective product.
- Containing single-layer carbon atoms, graphene is the thinnest material known and is stronger than diamond.
- Used for storing H₂ gas used as fuel cells in powered cars.
- Being highly chemically sensitive material, it is capable of detecting explosives.
- Containing nanometer-sized particles, graphene is helpful in removing ions in the desalination of water.

14.3.2 Different Types of Nanostructures and Methods of Graphene Preparation

Researchers have to deal with very fine structures during synthesis of nanomaterials. This characteristic of nanomaterials led researchers to come up with approaches for its synthesis. The two approaches used for the synthesis of nanomaterials can be bottom up or top down. In these approaches, atoms are either assembled together or disassembled. Bulk solids can be converted into finer pieces till there are few atoms remaining. The various techniques for the fabrication of different types of nanostructures are (Prokhorov and Botsula 2010):

- *Nanoprocessing*
- *Nanotooling*
- *Nanomachining*
- *Surface engineering*

In the field of electronics, the various materials fabricated are (Kolyadina et al. 2016; Yeole and Padole 2015; Prokhorov and Botsula 2010):

- *NEMS and MEMS devices*: These are basically the sensor and actuator circuits implanted at the nano- and microscale, thus offering opportunity for integration into application that requires high performance as well as high precision but at the same time containing some space constraints.
- *Nanosensors, actuators, and displays*: CNTs are used for the design of actuators, thereby leading to greater strength. SWNTs (single-walled nanotubes) are used for sensor applications as well as for the development of FED (field emission displays).
- *Double electron layer tunneling transistors (DELTTs)*: The most influencing quantum effect in transistor-like devices is tunneling which signifies that the particle plunges into the barrier which would not have been possible in the real world. They are built with a planar process using conventional semiconductor deposition. DELTT has an insulating barrier between two 2D walls. In this device

the operation is accomplished by the modulation of 2D-to-2D tunneling between the two coupled quantum wells and doesn't require lateral depletion or lateral gating.

- *Resonance tunneling devices (RTDs)*: These devices are specifically two-terminal devices comprising very high switching speed. RTDs for logic applications include resonant tunneling diode and hybrid devices in which resonant tunneling diodes are incorporated with single- or multi-FETs (RTD-FETs). Although they are not strictly transistor devices as they don't have a third terminal, these devices are used in addition with transistors to increase the performance of conventional circuits.
- *Single-electron transistors (SETs)*: These devices are three-terminal switching devices that transfer the electrons from source to drain. SETs include quantum dots, small conducting materials, as basic building material.
- *Spin logic devices (SLDs)*: The category includes a novel device, spin metal-oxide-semiconductor field-effect transistor (spin MOSFET). The device possesses a MOS gate structure and contacts having half metallic ferromagnetic (HMF) property for the source and drain. The other variations of the device include property called spin-torque transistor which provides new devices that include spin gain transistor (SGT) and magnetoresistive element (MRE) hybrid hall effect (HHE) devices (Hua-Qiang et al. 2013).
- *Hybrid hall effect (HHE) devices*: This particular class of devices includes single- or multiple-input wires passing over a region consisting of ferromagnetic material. The magnitude of the current in the direction of the input wire is large, and the magnetic field thus generated results in the magnetization of the ferromagnetic element, in right- or left-hand side direction. This direction absolutely depends on the direction of the current flow.
- *CNT-based field emission devices (FEDs)*: Field emission devices are basically electron emitters, which emit electrons on application of high electric field. Conventional cathode-ray tube and other electron emitters employ thermionic emission process. In the preceding process, the electron overcomes the work function barrier by thermally heating the cathode. But the field emission is different from the thermionic emission as in this process a very high electric field is applied at the tip of the emitter due to which the surface potential becomes very narrow and the electron tunnels through the barrier potential (Yeole and Padole 2015).

Graphene being a wonder material can be manufactured with the help of well-equipped and highly advanced environment instilled with the world's most advanced technology. The synthesis and application of graphene oxide nanosheets for the removal of toxicants from water is as shown below (Khurana et al. 2018):

From the above method shown in Fig. 14.4 for the formation of the graphene material, we define the following steps:

Step 1: Take some amount of graphite which is a composite of carbon, and add a few ml of sulfuric acid, i.e., H_2SO_4 . A little amount of nitric acid, i.e., HNO_3 , is also added to the mixture.

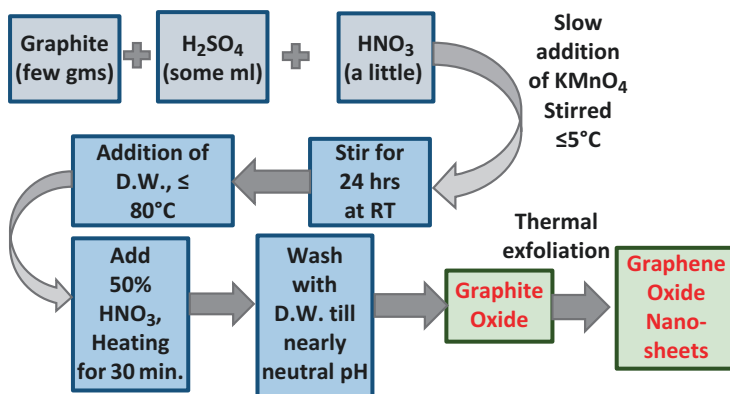


Fig. 14.4 Preparation method for graphene formation (Khurana et al. 2018)

Step 2: Afterward the slow addition of potassium permanganate, i.e., KMnO_4 , in the mixture is accomplished which is followed by stirring done at a temperature less than 5°C , i.e., $\text{temp} \leq 5^\circ\text{C}$.

Step 3: Continuously stir the mixture for 24 hours at room temperature, and then add 140 ml of distilled water at a temperature of less than 80°C .

Step 4: Add 50% of HNO_3 and subsequently heat for 30 min or half an hour.

Step 5: The mixture thus obtained is washed with D.W. till the pH returns to its neutral value of 7. This then leads to the formation of graphite oxide.

Step 6: After the formation of the graphite oxide by performing thermal exfoliation, graphene oxide nanosheets can be formed.

Outcome of the process yields 15 g/batch with optimization and ease.

14.3.3 Characterization of Graphene Material

The characterization of graphene material is a vital part of graphene research, and it involves measurements that are based on various spectroscopic and microscopic techniques. The process of characterization is required for the determination of layers and chemical purity of sample. The entire information is obtained by getting information about the absence and presence of defects. The simplest and most effective method that is mostly used for the identification of the number of graphene layers is optical contrast method. Characterization of the graphene material can be described through FTIR response (Fig. 14.5), Raman shift (Fig. 14.6), and X-ray diffraction (Fig. 14.7).

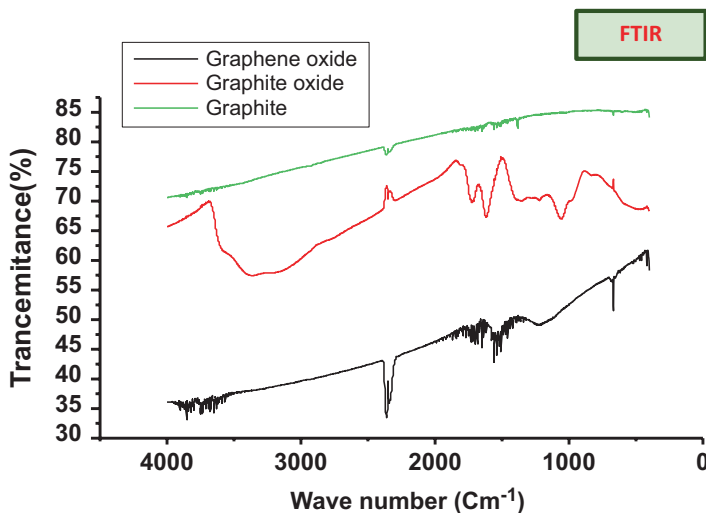


Fig. 14.5 FTIR response of graphene (Khurana et al. 2018)

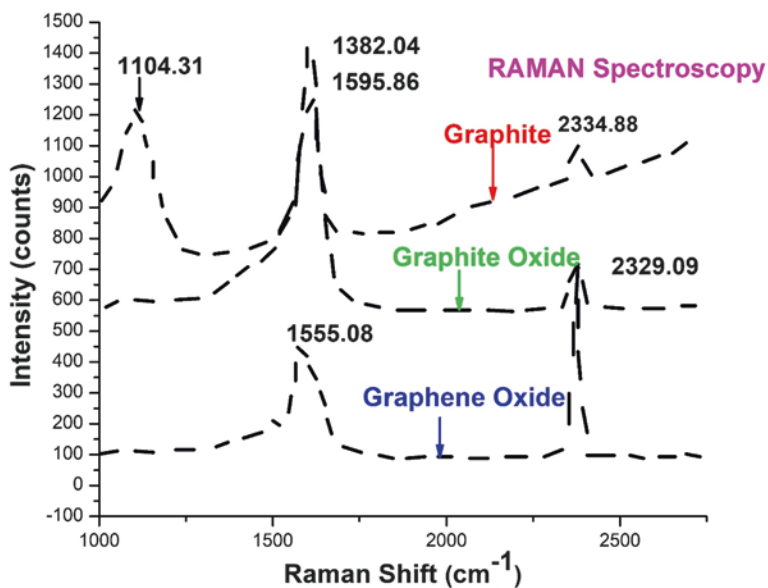


Fig. 14.6 Raman shift vs intensity in graphene using Raman spectroscopy (Khurana et al. 2018)

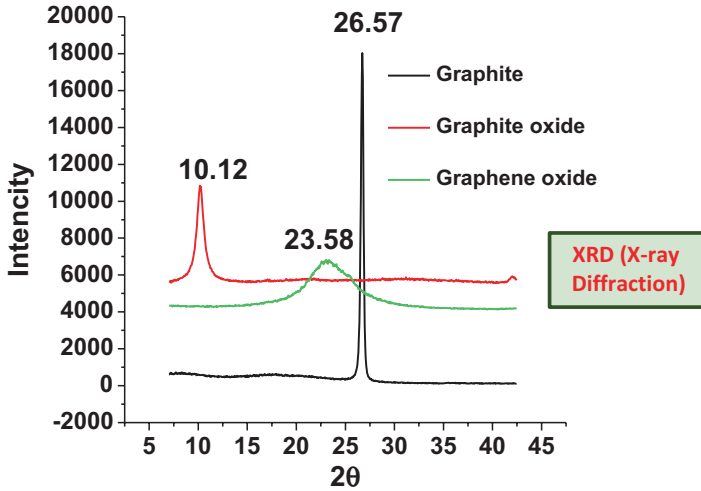


Fig. 14.7 X-ray diffraction method (Khurana et al. 2018)

14.3.4 Potential Applications of Graphene (Hua-Qiang et al. 2013; Awano 2009; Lam and Liang 2011)

- Single-molecule gas detection
- Sensors/solar cell
- Room temperature distillation of ethanol for fuel and human consumption
- Graphene nanoribbons
- Graphene optical modulator
- Graphene transistors
- Integrated circuits
- Electrochromic devices
- Transparent conducting electrodes
- Ultra-capacitors

14.4 CNT and Its Growing Demand

A number of nanomaterials are being developed for structural application; out of those nanomaterials, CNTs have been extensively researched around the world. They have numerous remarkable properties such as exceptionally high specific mechanical properties and physical strength with remarkable thermal properties (Dai 2001).

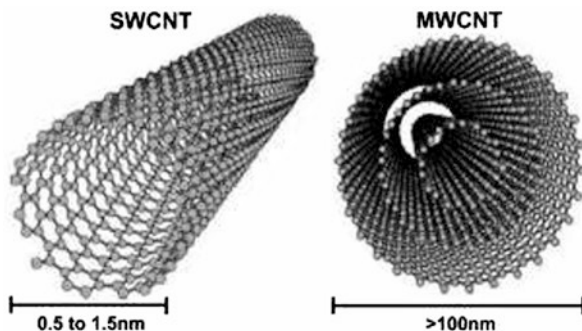


Fig. 14.8 Single-walled and multi-walled CNTs (Dai 2001; Saito et al. 1998)

The various types of CNTs (shown in Fig. 14.8) are:

- *Single-walled carbon nanotubes (SWCNTs)*: CNTs exist as single-walled (SWCNTs) or multi-walled structures (MWCNTs) which are composed of the concentric SWCNTs. Single-walled carbon nanotubes can be shown as a sheet of graphene rolled onto a cylindrical tube with the ends closed by the hemispheres of fullerene. In other words they can be considered as a structure obtained by elongating fullerenes along one axis. The strength and the stiffness of CNTs are derived from the C-C SP^3 bond, the strongest bond in nature. The result is the strongest and the stiffest material ever known. The diameters of SWNTs range from 0.5 to 3 nm (Dai 2001; Saito et al. 1998).
- *Multi-walled carbon nanotubes (MWCNTs)*: They are made up of concentric SWCNTs with different diameters. The equilibrium separation distance between them is considered to be equal to that of the equilibrium separation distance of graphene sheets which is 0.342 nm. The diameter of MWCNTs ranges from approximately 2–20 nm with the upper bound poorly defined. While MWCNTs are as stiff as SWCNTs, they are not as strong as SWCNTs due to the defects produced during the growth of the outer cylinder.

14.5 Conclusion

Nanotechnology because of its smaller size and unique properties has immense potential in the field of electronics, health care, and many other branches of science and technology. Nanotech being an emerging technology has a vast variety of futuristic applications in the day-to-day scenario of human life. It brings new aspects of various inert materials by modifying various optical, chemical, mechanical, and electronic properties at nanoscale. The degree of influence of nanotech on the daily lifestyle of humans depends on the humans entirely. Nanotech is the unavoidable future of humanity. Various nano-by-products such as graphene and CNTs are analyzed; these are wonder materials that have revolutionized entirely the electronics industry.

References

- Awano Y (2009) Graphene for VLSI: FET and interconnect applications. In: Electron devices meeting (IEDM), 2009 IEEE international. IEEE, pp. 1–4
- Bae S, Kim H, Lee Y et al (2010) Roll-to-roll production of 30-inch-graphene films for transparent electrodes. *Nat Nanotechnol* 5(8):574–578
- Burtscher L (2005) Electrical and mechanical properties of carbon nanotubes
- Dai H (2001) Carbon nanotubes: synthesis, structure, properties, and applications. In: Topics in applied physics, vol 80. Springer, Berlin
- EPA, US (2007) Nanotechnology white paper. SP Council
- Ferrari AC (2007) Raman spectroscopy of graphene and graphite: disorder, electron–phonon coupling, doping and nonadiabatic effects. *Solid State Commun* 143(1–2):47–57
- Feynman RP (1992) There’s plenty of room at the bottom. *J Microelectromech Syst* 1(1):60–66
- Ganji DD, Kachapi SHH (2015) Introduction to nanotechnology, nanomechanics, micromechanics, and nanofluid
- Goenka S, Sant V, Sant S (2014) Graphene-based nanomaterials for drug delivery and tissue engineering. *J Control Release* 173:75–88
- Hancock Y (2011) The 2010 Nobel Prize in physics—ground-breaking experiments on graphene. *J Phys D Appl Phys* 44(47):473001
- Horowitz M, Alon E, Patil D, Naffziger S, Kumar R, Bernstein K (2005) Scaling, power, and the future of CMOS. In: Electron devices meeting. IEDM technical digest. IEEE international. IEEE, p 7
- Hu Y, Li F, Han D et al (2012) Simple and label-free electrochemical assay for signal-on DNA hybridization directly at undecorated graphene oxide. *Anal Chim Acta* 753:82–89
- Hua-Qiang W et al (2013) Graphene applications in electronic and optoelectronic devices and circuits. *Chin Phy B* 22(9):098106
- Imperiale I, Bonsignore S et al (2010) Computational study of graphene nanoribbon FETs for RF applications. In: Electron devices meeting (IEDM), 2010 IEEE international. IEEE, pp 32–33
- Jelicic V, Magno M et al (2015). Towards Internet of Things for event-driven low-power gas sensing using carbon nanotubes. In: Advances in sensors and interfaces (IWASI), 2015 6th IEEE international workshop on. IEEE, pp 271–276
- Khurana I, Shaw AK, Saxena A, Khurana JM, Rai PK (2018) Removal of trinitrotoluene with nano zerovalent iron impregnated graphene oxide. *Water Air Soil Pollut* 229(1):17
- Kilby JS (2000) The integrated circuit’s early history. *Proc IEEE* 88(1):109–111
- Kolyadina EY, Matveeva LA et al (2016) Nanotechnology, features of surfaces and interfaces in the nanostructures with C 60 fullerenes and carbon composite films. In: Nanomaterials: application & properties (NAP), International conference on. IEEE, p 01PCSI03-1
- Kumar V (2006) Alchemy at the nanoscale: magic heteroatom clusters and assemblies. *Comput Mater Sci* 36(1–2):1–11
- Lakhtakia A (2012) Nanotechnology and metamaterials: conceptualization and intersection for new opportunities. In: Semiconductor electronics (ICSE), 2012 10th IEEE international conference on. IEEE, p A1
- Lam KT, Liang G (2011) Electronic structure of bilayer graphene nanoribbon and its device application: a computational study. In: Graphene nanoelectronics. Springer, Berlin, Heidelberg, pp 509–527
- Lin YM et al (2010) *Science* 327:662. See also Supporting Online Material, available online
- Lin YM, Valdes-Garcia A et al (2011) Wafer-scale graphene integrated circuit. *Science* 332(6035):1294–1297
- Mas-Balleste R, Gomez-Navarro C, Gomez-Herrero J, Zamora F (2011) 2D materials: to graphene and beyond. *Nanoscale* 3(1):20–30
- McClure JW (1956) Diamagnetism of graphite. *Phys Rev* 104(3):666
- Meng L, Zhang X, Lu Q, Fei Z, Dyson PJ (2012) Single walled carbon nanotubes as drug delivery vehicles: targeting doxorubicin to tumors. *Biomaterials* 33(6):1689–1698

- Meyyappan M (2004) Carbon nanotubes: science and applications. CRC Press, Boca Raton
- Mollick E (2006) Establishing Moore's law. *IEEE Ann Hist Comput* 28(3):62–75
- Novoselov KS, Geim AK et al (2004) Electric field effect in atomically thin carbon films. *Science* 306(5696):666–669
- Phillips JM (2006) Up close: nanoscale science research centers. *MRS Bull* 31(1):45–49
- Prokhorov ED, Botsula OV (2010) Negative differential conductivity of semiconductor diode with resonance-tunnel border. In: *Physics and engineering of microwaves, millimeter and submillimeter waves (MSMW), 2010 international Kharkov symposium on*. IEEE, pp 1–3
- Respaud M, Tap H, Grisolia C et al (2016) Nanotechnology practical teaching at school and university. In: *2016 IEEE nanotechnology materials and devices conference (NMDC)*. IEEE, pp 1–2
- Roberts DH (1984) Silicon integrated circuits: a personal view of the first 25 years. *Electr Pow* 30(4):282–284
- Saito R, Dresselhaus G, Dresselhaus MS (1998) Physical properties of carbon nanotubes. Imperial College Press, London
- Schaller RR (1997) Moore's law: past, present and future. *IEEE Spectr* 34(6):52–59
- Schwierz F (2010) Graphene transistors. *Nat Nanotechnol* 5(7):487–496
- Schwierz F (2011) VLSI technology, systems and applications (VLSI-TSA)
- Seeman NC (2003) DNA in a material world. *Nature* 421(6921):427
- Shahabadi N, Jamshidbeigi M, Falsafi M (2016) Functionalization of Fe₃O₄@ SiO₂ magnetic nanoparticles with nicotinamide and in vitro DNA interaction. *J Mol Liq* 224:227–233
- Slonczewski JC et al (1958) Band structure of graphite. *Phys Rev* 109(2):272
- Thakur VK, Thakur MK (2015) Carbon allotropes and fascinated nanostructures: the high-impact engineering materials of the millennium. In: *Chemical functionalization of carbon nanomaterials*. CRC Press, Boca Raton, pp 25–50
- Wallace PR (1947) The band theory of graphite. *Phys Rev* 71(9):622
- Wang X, Wang C et al (2012) Noble metal coated single-walled carbon nanotubes for applications in surface enhanced Raman scattering imaging and photothermal therapy. *J Am Chem Soc* 134(17):7414–7422
- Wu W, He Q, Jiang C (2008) Magnetic iron oxide nanoparticles: synthesis and surface functionalization strategies. *Nanoscale Res Lett* 3(11):397
- Wu J, Shen YL, Reinhardt K, Szu H, Dong B (2013) A nanotechnology enhancement to Moore's law. *Appl Comput Intell Soft Comput* 2013:2
- Wu Y, Zou X, Sun M et al (2016) 200 GHz maximum oscillation frequency in CVD graphene radio frequency transistors. *ACS Appl Mater Interfaces* 8(39):25645–25649
- Yeole P, Padole DV (2015) Design of basic logic gates using carbon nano tube field effect transistor and calculation of figure of merit. In: *Emerging trends in engineering and technology (ICETET), 2015 7th international conference on*. IEEE, pp 28–33