A Brief Overview of Emerging Nanoelectronics

Jian Chen, 2008

Advised by Paul Ampadu, Ph.D.

Department of Electrical and Computer Engineering, University of Rochester

Current semiconductor technology is projected to reach its physical limit in about a decade.[1] To satisfy the ever-growing consumer desire for small, high-speed, low-power, and "all-in-one" devices, scientists and engineers are actively seeking solutions to continue technology trends into the future. Nanotechnology, with wide electronics applications, promises breakthroughs for the future. The fundamental principles of nanotechnology lie in nanoscience, the study of materials and phenomena at atomic scales, where macroscopic properties are no longer relevant. Nanotechnology is thus the application of nanoscience, encompassing physical, chemical and biological systems at scales up to 100 nanometers (nm), as well as integration of nanostructures into macroscopic systems.[2] Nanotechnology covers a wide range of science and engineering fields, but its current active areas of research and development can be divided into four groups—nanomaterials, nanometrology, nanoelectronics, and bio-nanotechnology. Nanomaterials have structured components with at least one dimension at the nanometer scale;[2] for example, nanoparticles are considered three-dimensional nanomaterials. Nanometrology is the science of measurement at nanometer scales. It involves the measurement and characterization of nanomaterials (i.e. size, shape, properties, etc.) as well as development of tools for measurement and characterization. It is a crucial area because it facilitates nanotechnology research and sets the standard for industrial practice. Bio-nanotechnology deals with biophysical, biochemical and biomedical mechanisms, properties, and applications at molecular scales. This paper focuses on nanoelectronics, the application of nanotechnology in electronics. Specifically, carbon nanotubes, nanowires, and quantum dots (nanocrystals) are discussed, because of their great potential for electronic systems.[2]

Basic Concepts

The energy band model, ballistic electron transport, and field-effect transistors are introduced here to aid the reader with the discussions in the next sections.

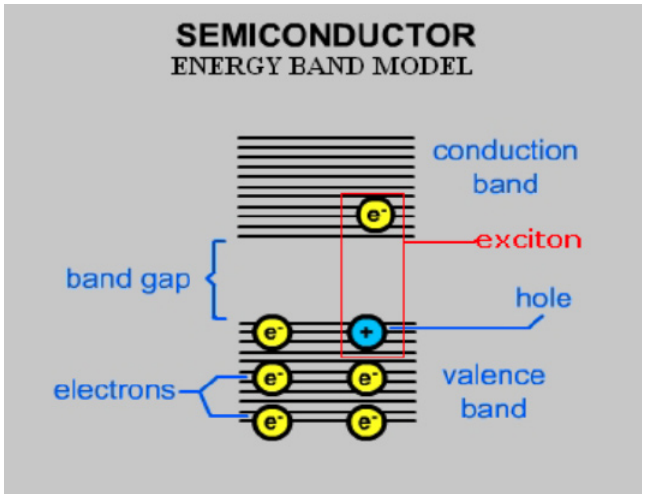
Energy Band Model

Electrons in semiconductors have a range of discrete energies. Based on the Bohr model, the electrons in an atom are limited to certain energies, which are restricted to quantized values. Hence, the electrons can be visualized as traveling in well-defined orbits, each of which may contain different numbers of electrons, representing quantized energy levels.[3] The separation between adjacent energy levels is extremely small that they can be considered a continuous band. The *bandgap* can then be pictured as a region between continuous flow of energy bands not occupied by any electrons (Fig. 1). The size of the bandgap varies depending on the material. Electrons occupying energy levels below the bandgap are described as being in the *valence band*, while those electrons occupying energy levels above the bandgap are said to be in the *conduction band.* The electrons are able to move freely in the conduction band and conduct electricity. In semiconductor materials, the majority of electrons are confined in the valence band while there are very few occupying energy levels in the conduction band. Electrons, however, can jump across the bandgap from the valence band into the conduction band when given enough energy from external stimuli, such as thermal excitation, voltage, and photon flux, leaving in the valence band some vacancies known as "holes", which are considered to be positively charged. The raised electron and the hole as a pair are called an *exciton.*[3]

Ballistic Electron Transport

Ballistic electron transport is the phenomenon of electrons traveling from one electrode to another without scattering (Fig. 2a). It is introduced here because in one-dimensional

Figure 1: Energy Band Model (Source: Evident Technologies, Inc.[43])



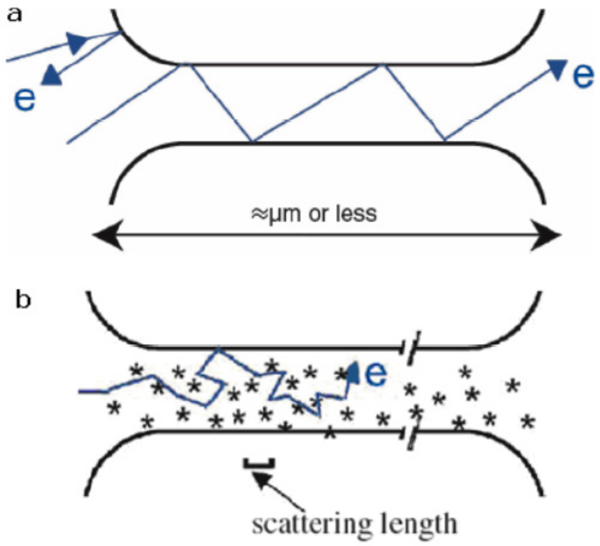


Figure 2a: Ballistic electron transport. Electrons are only backscattered at the boundary. **Figure 2b:** Diffusive Electron Transport. Numerous scattering events are visible. (Source: A.M. Song[5])

nanostructures, which will be discussed later, the electron transport is often observed to be ballistic. One important concept leading to ballistic electron transport is the *electron mean free path* (l_e), which is known as the average distance electrons can travel ballistically before encountering any random scatterers.[5] The significance of this concept is that, when the device is miniaturized to scales equal to or smaller than the mean free path, electron transport in the conduction channel becomes ballistic. When the transport is not ballistic, it is termed diffusive; in this regime, electrons traveling in the conduction channel encounter numerous scattering events (Fig. 2b). In contrast to ballistic transport, diffusive transport can often be observed at macroscopic scales. However, under ballistic transport, where electrons are often only backscattered at the boundaries of the conduction channel, the concept of ohmic resistance is no longer relevant.[5] Because of the small scale dimensions at which ballistic transport occurs, quantum confinement effects play a significant role, and therefore conductance G of the material can be defined by the Landauer-Buttiker formula:[7,8,9]

$$G = N(2e^2/h)T \qquad (1)$$

where e is the electron charge, h is Planck's constant, N is the number of the occupied quantum confinement modes by electrons in the channel, and T is the transmission coefficient of the ballistic electrons going from one electrode to another.[5] One of the advantages that ballistic transport offers is higher operating speeds, since electrons do not encounter random scattering in the channel. Because of the absence of scattering, fewer electrons are required in the channel to pass the signal, leading to less power consumption.

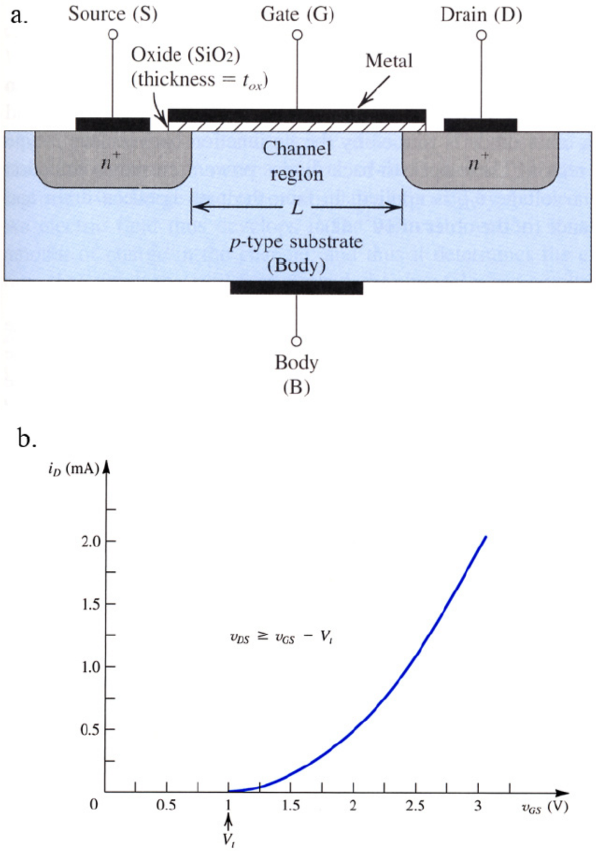
Field-effect Transistors (FETs)

FETs are fundamental building blocks commonly found in modern semiconductor electronics. They are devices that have three electrode terminals known as *source*, *drain* and *gate*. The current can flow in between the source and drain through the *channel*, with the gate controlling the current flow. The channel is insulated from the gate to prevent electrons from tunneling through the gate (Fig. 3a). There are n-type and p-type FETs. In the n-type device, the current will start flowing from the source to drain when a positive voltage, greater than a threshold V_t, is applied to the gate (Fig. 3b); in the p-type the current flows when the gate voltage is negative.

Carbon Nanotubes

Carbon nanotubes (CNTs), as the name suggests, are tubes with diameters in nanometer (nm). A CNT can be pictured as a honeycomb-structured sheet of graphene, which is a single atomic layer of graphite, wrapped up to form a cylindrical tube. The CNTs can be open on both ends, or bounded in one or both ends. There are two main types of CNTs—single-walled nanotubes (SWNT) and multi-walled nanotubes (MWNT). The MWNTs are several concentric SWNTs of different diameters nested together. Typical diameters of carbon nanotubes range from 1 nm to 5 nm. However, the length of the nanotubes can range from hundreds of nanometers to several centimeters long. Researchers at the New Jersey Institute of Technology have reported self-assembled 10-foot-long hollow thin steel tubing SWNT.[26] This extremely large length-to-diameter ratio makes the CNTs perhaps the most ideal one-dimensional structure in real world practice.[1] In contrast, given the same length, objects like regular metal wires may have much larger diameters and therefore are commonly considered 3-D structures. Ever since its first discovery in the early 1990s by Sumio Iijima,[10,11] currently a senior researcher at the NEC Corporation in Tsukuba, Japan; CNTs have generated great interest among nanotechnology researchers worldwide, and they have been hailed as the most promising candidate for the development of nanoelectronics. CNTs, especially single-

Figure 3a: Physical structure of a N-type transistor. **Figure 3b:** The i_D–v_{GS}, drain current vs. gate voltage, characteristic for an N-type transistor in saturation (V_t= 1V). (Source: Sedra and Smith.[6])



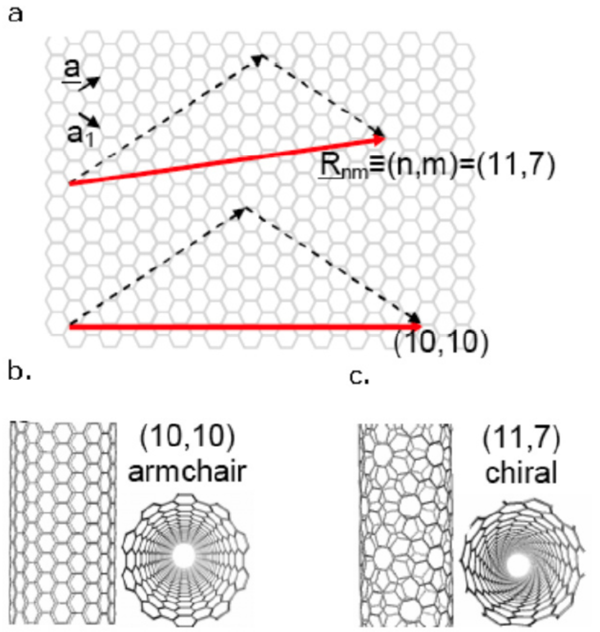


Figure 4a: The wrapping methods. **Figure 4b:** Metallic "armchair" structure. **Figure 4c:** Semiconducting "chiral" structure. (Source: Javey and Dai.[1])

walled nanotubes, possess unique electrical properties that may enable the delivery of superb performance and extremely low power consumption. Moreover, carbon nanotubes have been used to produce several prototype devices (e.g., novel top-gated transistor prototype[12]) in laboratories worldwide. These devices were observed to deliver better performance in some technical aspects, such as transconductance and current density, than current silicon technology.[12,13,14,19,21]

Structure of Single-Walled Carbon Nanotubes

As previously mentioned, carbon nanotubes are two-dimensional (2-D) graphene sheets rolled up to become essentially 1-D tubes. It has been theoretically and experimentally shown that the electrical properties of the SWNTs can be altered by wrapping up the graphene sheets in different ways. The various "wrapping methods" and the resulting types of SWNTs are generally described using a sheet of honeycomb structured graphene, presented in Fig. 4.

The two vectors $\mathbf{a}$ and $\mathbf{a}_1$ in the hexagon (Fig. 4a) are known as unit vectors of graphene in real space, and the pair of integers (n,m) indicates the number of unit vectors along two directions of the hexagonal lattice, and the chiral vector, along which the graphene sheet is rolled up, is the vector sum of the two unit vectors multiplied by the indices, or mathematically

$$\mathbf{R}_{\mathbf{nm}} = n\mathbf{a}_1 + m\mathbf{a}_2 \qquad (2)$$

If $n = m$, the resulting nanotube is known as the "armchair" structure (Fig. 4b), which is experimentally equivalent to a metal. When $n - m \neq 3j$, the nanotube is semiconducting, and known as the "chiral" structure (Fig. 4c).[1,13] *McEuen* et al.[12] state that in an SWNT, the momentum of the electrons moving around the circumference of the nanotube is quantized, and such quantization results in tubes that are either one-dimensional metals or semiconductors.

Synthesis of Carbon Nanotubes

Several synthesis methods have already been developed to date, though virtually none of them are mature enough to be cost-efficiently exploited for mass commercial purpose. The synthesis method introduced here, known as catalyst chemical vapor deposition (CCVD), is a gaseous carbon source-based synthesis that is relatively more efficient than other currently available methods (such as laser ablation[4]). The CCVD allows the nanotube growth to directly take place on a silicon wafer that has catalyst material such as iron placed on its surface. The wafer is then exposed to a flow of carbon source gas, such as methane (CH_4), in a standard furnace, which provides heating at 660°C ~ 1000 °C. The carbon atoms from the decomposed methane gas can then condense on the cooler substrate, resulting in the growth of carbon nanotubes from the catalyst seeds that were previously placed on the substrate. The CCVD yields larger quantities of carbon nanotubes and offers more flexible control over the properties of the nanotubes in terms of engineering the properties of the catalyst and adjusting the growth conditions.[12] Therefore the CCVD method is more favorable to large scale manufacturing of carbon nanotubes. Yet, some technical difficulties (e.g. growth of uniform CNTs) need to be solved before CCVD can become a reliable, cost-effective synthesis method for commercial and industrial CNTs.

Electrical Properties of Carbon Nanotubes

Although study of the electrical properties of CNTs is still ongoing, some significant discoveries have been made and important theories have been established. The unique electrical properties are largely derived from the 1-D characteristic and the peculiar electronic structure of graphite.[19] Further two factors determine the conductivity (metallic or semiconducting) of a CNT—chirality (ways of wrapping) and the diameter of the tube.

Generally, the conductance of a carbon nanotube is measured by attaching each end of the tube to an electrode, and varying the gate voltage (V_g) applied to the nanotube from a third terminal. If the conductance is relatively independent of V_g, the tube is considered metallic; if apparent variation of the conductance in response to V_g is observed, then the tube is semiconducting. The conductance G of a carbon nanotube is given by equation (2). *McEuen* et al.[12] point out that $N = 4$ for a SWNT at low doping levels such that only one transverse sub-band is occupied, and thus the conductance of a ballistic SWNT with perfect contacts ($T = 1$) between the tube and the electrodes is $4e^2/h = 155$ µS. This gives a corresponding resistance of 6.5 kΩ, which is the unavoidable fundamental contact resistance. Imperfect contacts additionally cause a resistance $\mathbf{R}_c$, while the presence of scatters (e.g. defects in the nanotube) that give a mean free path le for backscattering (electrons colliding with defect and consequently bounce

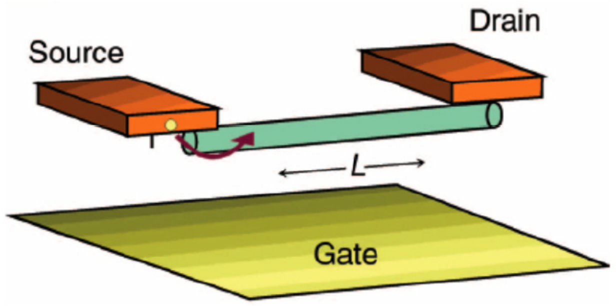


Figure 5: Measuring the conductance of a carbon nanotube. (Source: P. McEuen and J. Park.[14])

backwards) contributes an ohmic resistance denoted as

$$\mathbf{R}_t = (h/4e^2)L/\boldsymbol{l}_e \qquad (3)$$

where L is the length of the nanotube.[12] Therefore the total resistance is given by the sum of the three:[12,14]

$$\mathbf{R} = h/4e^2+\mathbf{R}_c+\mathbf{R}_t \qquad (4)$$

In semiconducting nanotubes, the diameter of the tube affects conductivity through the bandgap, because of quantum mechanical effects. The bandgap of semiconducting CNTs is given by

$$E_g = 0.9\text{eV}/d \qquad (5)$$

where d is the diameter of the tube in nanometers.[14] This indicates that the bandgap can be changed by controlling the diameter of the nanotube. The larger the tube diameter, the smaller the bandgap. Compared to those of silicon and gallium arsenide (GaAs), which have values of 1.12 eV and 1.42 eV respectively, a semiconducting CNT has a smaller bandgap and hence requires less external energy, such as thermal excitation, to be made conducting. By increasing the diameter, the bandgap energy of CNT can be reduced to a level comparable to that of germanium, which is 0.66 eV.[3]

Besides their excellent feature of controllable conductivity, there are several other electrical properties that make CNTs attractive. For example, CNTs have extremely low electrical resistance. Resistance stems from collisions between electrons and defects in the crystal structure of the material in which the electrons are traveling. However, for electrons traveling in the nanotubes, the 1-D structure of the CNT limits propagation path to one-directional , eliminating any other angles for electron scattering (such as occurs in 3-D conductors), and thus greatly increasing the efficiency of electron transport. Electrical resistance in CNTs may occur under the circumstance of backscattering, in which the direction of electron motion changes abruptly from forward to backward. However, backscattering requires strong collisions under higher voltage bias[12,19] and hence is less likely to happen. In addition, the ballistic electron transport range is fairly long compared to high-quality compound semiconductors (e.g. GaAs)—a few micrometers in metallic CNTs and several hundred nanometers in semiconducting ones.[5,19] Low resistance enables faster current flow (thus faster operating speeds) and lower power consumption. In metal wires, the resistance is inversely proportional to the cross-section area of the wire, leading to increasing power consumption with device down-scaling. Heat generated as a result of high power consumption can also possibly melt the metal wires. On the other hand, in addition to low resistance, CNTs (metallic) are capable of withstanding extremely high current densities (up to ~ 10^9A/cm^2, > 1000 times greater than metals like copper and silver)[13] and conducting heat very well,[4] making them perfect candidates for interconnects and heat sinks in electronic circuits.

The last remarkable electrical property to be discussed is the surface state of CNTs. The type of chemical bonds that atoms can make varies, depending on the chemical element. In the case of silicon (Si), the material widely used in modern electronics, each atom in the interior crystal bonds with four other nearby atoms. However, on the surface, there exist atoms that are not fully bonded. These atoms can trap wandering electrons, resulting in unwanted charged sites that may eventually degrade the device function. To solve this problem, one current technique is to expose the silicon surface to oxygen, which bonds with the silicon atoms to form an oxide thin film. However, the carbon atoms in nanotubes don't have any unbonded atoms, and thus eliminate the need to grow a thin film on the surface or limit the options of gate insulator to only silicon oxide. This is significant because other superior materials can be chosen that help minimize the possibility of electrons tunneling into the gate, which can consequently degrade the device performance.[19]

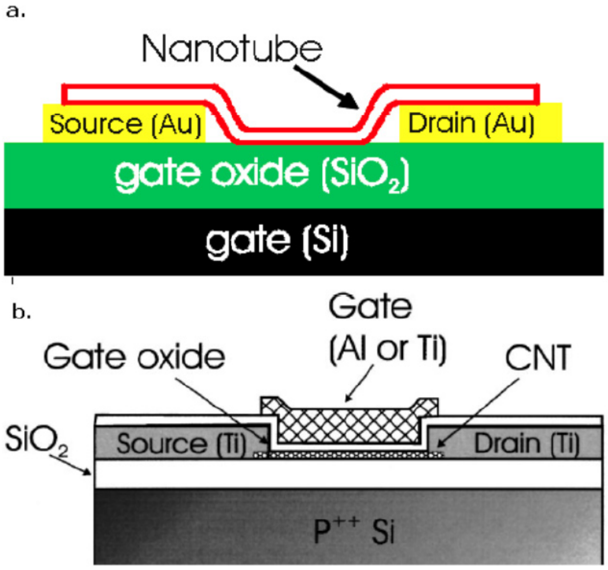


Figure 6a: Back–gated CNT-FET prototype. **Figure 6b:** Top–gated CNT-FET prototype. (Source: (a) IBM[15] (b) *S.J. Wind* et al.[16])

Technological Applications of Carbon Nanotubes

Given their unique electrical properties, robust mechanical strength, and excellent thermal conductivity, CNTs have wide applications in current and future technologies. In 2002, researchers demonstrated the top-gated, CNT-based FET (Fig. 6b) that offered more flexible control on the operation of individual devices compared to an earlier, conventional back-gated transistor prototype (Fig. 6a).[16] This device has further shown to have significantly better transconductance (the measure of the change in channel current with respect to gate voltage change) than current-generation MOSFETs. Combined with other technical aspects of the device, such as turn-on voltage and I_{on}/I_{off} ratio, the researchers concluded that performance potential of the CNT-FETs may rival, if not exceed, that of state-of-the-art silicon-based MOSFETs.[12,17,18]

Besides their use as devices, carbon nanotubes have other applications. A few typical, electronics-related applications are listed below:

Field Emission: Field Emission can be described as the emission of electrons from the ends of a nanotube when a small electric field is applied parallel to its axis.[4] An attractive application of this effect of the carbon nanotubes is flat-panel displays. Motorola reported that the method they developed can be used to produce a 50 inch display that is superior in brightness and power consumption and cheaper than other types of flat-panel displays such as LCD and plasma.[25]

Chemical sensors (CNT transistor-based): Although the high-performance processors that demand uniform, high-quality carbon nanotubes won't be available soon, CNT-FETs can be used to produce highly sensitive chemical sensors that can work with a mix of different nanotubes. Because of their high sensitivity of conductance to local chemical environment, CNT-FETs are unique as detectors of various chemical gases.[22]

Technical Challenges in Carbon Nanotubes

Several technical challenges must be addressed before carbon nanotubes can become a viable technology for the electronic industry. These challenges, to a large extent, stem from manufacturing issues. Due to the extremely close connection between the geometric structure of CNTs and their properties (electrical properties in particular), a much more detailed, mature understanding of CNT growth mechanism is highly desired. Current challenges in carbon nanotubes (for use in electronics) include lack of precise control of the synthesis process to produce CNTs with desired diameter and chirality,[24] high synthesis temperature (incompatible with many other standard silicon processes),[14] inefficient method of sorting of bundles of nanotubes, immature ability of precise positioning of nanotubes on silicon wafer, and high resistance contact between source/drain electrodes and the CNTs. Current synthesis methods for producing CNTs in larger quantities often result in producing a mix of metallic and semiconducting CNTs that tend to bundle up together. It is necessary to be able to efficiently separate CNTs of different metallicities as well as keep them from sticking together. The problem of precisely positioning large number of nanotubes in between corresponding source/drain electrodes on the silicon wafer also needs to be solved. Lower contact resistance between the metal electrodes and the CNTs is desired as well (researchers are currently proposing using metallic CNTs as source/drain electrodes). Nonetheless, significant improvements have been made world-wide, for example, a novel vertical CNT growth method has been developed at Purdue University;[27] a device produced at Rice University sorts CNTs by size and conductivity;[28] a method developed at IBM T.J Watson Research Center can accurately position a certain number of CNTs;[23] a lower temperature (350°C) growth technique for single-walled nanotubes has been developed at the University of Cambridge, England.[29] The efforts devoted to tackling these challenges are succeeding in improving the field dramatically.

Nanowires (NWs)

Nanowires are another novel class of nanostructures with excellent prospects for future nanoelectronics development. They can be constructed from a variety of materials, used primarily to determine their electrical conductivity. Thus, nanowires can be classified based on the material of which they are made; for example, metallic (Au, Ni, Pt, etc.), semiconducting (Si, GaN, InP, etc.), and insulating (SiO_2, TiO_2, etc.). Although the diameter of nanowires, like that of carbon nanotubes, is one of the factors that determine their electrical transport property, this "conductivity by material" characteristic of nanowires is certainly an advantage over the carbon nanotubes, whose conductivity is determined by their chirality (recall that chirality demands more precise control during synthesis). This advantage becomes more significant especially when using nanowires as transistors, owing to the manufacturing convenience.[30]

Physical Structure of Nanowires

Nanowires, in many cases, are considered one-dimensional (1-D) nanostructures just like carbon nanotubes; although, their length-to-diameter ratio (sometimes called aspect ratio) may not be as large as that of CNTs because of their larger diameter. The diameter of nanowires could range from 10 nm to 70nm, and their lengths could be at micron to centimeter scales. This gives nanowires typical length-to-diameter ratios of 1000 or larger. Unlike SWNTs, nanowires in most cases do not have hollow interior space, and their surfaces are also not structured like the carbon crystal lattice of graphene and therefore may cause surface scattering of electrons. Nanowires made of semiconducting materials can also be doped, i.e. their electrical properties may be altered by adding impurities to their chemical structure.[30]

Electrical Transport Properties of Nanowires

As the size of a nanowire becomes sufficiently small, quantum confinement effects play a significant role in electrical transport phenomena. As another class of 1-D nanostructure, nanowires are capable of exhibiting ballistic electron transport as their lengths L are reduced to equal or smaller than the electron mean free path $\boldsymbol{l_e}$,[30,32] and electrical conductance of nanowires with N conduction channels is defined by equation (2):

$$G = N(2e^2/h)T$$

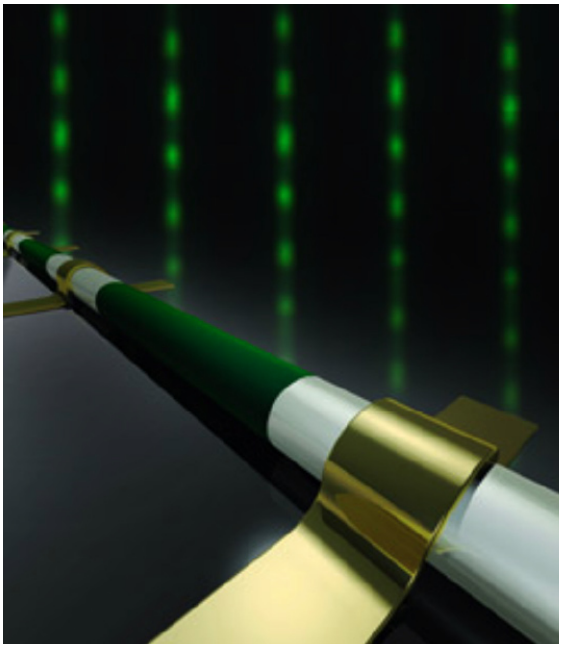
On the other hand, when a nanowire has a length greater than the electron mean free path, its electrical transport is diffusive.

Technological Applications of Nanowires

Nanowires have a wide range of potential applications in electronics, optoelectronics and (biochemical) sensor systems, owing to their small structure and unique properties. A small list of nanowire applications is presented below:

Electronics: In nanowire-based FETs, nanowires are typically deposited on an insulating substrate (e.g. SiO_2) and connected to the source and drain, then either a bottom or top gate configuration is added as the third terminal electrode to form the FET. Although it remains unclear whether NW-FETs can outperform the current state-of-the-art MOSFETs, several techniques have been developed, such as thermal annealing to improve source/drain-to-nanowire contacts and the novel

Figure 7: NiSi/Si nanowire heterostructures devices (Source: Lieber Research Group, Harvard University[31])



Germanium core/silicon shell nanowire heterostructures, and the NW-FETs exploiting these techniques have been shown to have improved performance in some technical aspects (i.e. transconductance, on-current, and carrier mobility) that are three to four times better than their current silicon MOSFET counterparts.[33] Nanowires can also be used to produce wire arrays that serve as interconnect in the circuitry.[34,35,37]

Optoelectronic: It has been demonstrated that nanowires can be predictably synthesized as n- or p-type. They can be assembled into cross-wire p-n junctions, which emit light strongly and have been said to be the smallest light-emitting diodes (LEDs) ever made. Such LEDs are potential candidates for optoelectronic applications.[36]

Biochemical sensing system: Through chemical modification on nanowire-based sensors, a group of receptors that are sensitive to specific biochemical matters are linked to the surface of nanowire connected between the source and drain electrodes on a p-type NW-FET. Upon the binding event between the receptors and the biochemical molecules (e.g. protein), the increased positive charges on the NW surface decrease the conductance of the p-type NW-FET. This serves as an electrical signal to be processed.[38,39]

Limitations and Challenges in Nanowires:

The conductivity of nanowires is expected to be less than that of carbon nanotubes. This problem largely arises from nanowires' surface condition. Unlike carbon nanotubes, nanowires are made from a variety of materials, and their surfaces may have unbonded atoms. These atoms can potentially become sites of defects that trap excessive charges, which negatively affect the conductance of the nanowire. Such edge effects can grow more severe as nanowires shrink in size and their surface-to-volume ratios become larger. Moreover, as discussed, ballistic electrical transport can occur only when the wire length is reduced to the scale of the carrier mean free path. Nanowires that do not meet this requirement will experience numerous electron scattering events.

Some other challenges include manufacturing cost and integration difficulty. Precise control over nanowire growth has been achieved in laboratory. However, according to Lieber, currently the cost of developing large-scale manufacturing would probably not be justified by a 4 to 5 times improvement in performance over current technology.[42] For the integration into nanosystem circuitry using nanowire arrays as interconnects or building blocks, the challenge lies in finding effective processes for building contact structures. Researchers at the California Nanosystems Institute claimed that wire arrays they created are far smaller than the resolution obtainable with electron-beam lithography, so integrating them into semiconductor processes will be difficult.[40]

Quantum Dots

Quantum dots, also known as semiconductor nanocrystals, are a special class of semiconductor nanostructure. Since they are capable of emitting electromagnetic radiation (especially visible light) when given external stimulus, quantum dots are also known as fluorescent semiconductor nanoparticles. Their unique optical tunability and photovoltaic characteristics enable a wide range of current and potential applications in optoelectronics and other fields such as life science.

Structure of Quantum Dots

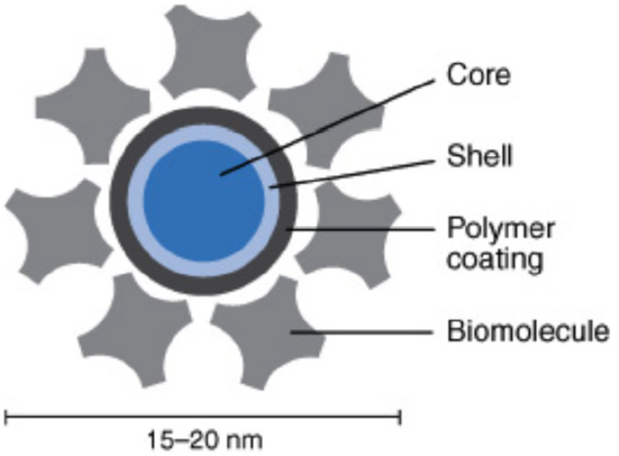


Figure 8: Structure of a quantum dot produced at Quantum Dot Corporation (Source: Quantum Dot Corporation[44])

Quantum dots have typical diameters ranging from 2 to 10 nanometers. The overall structure of a quantum dot consists of a core, a shell, an outer coating, and may have bio-molecules attached to the surface of the coating. The core of the QD is enclosed within the shell, whose outer surface is entirely occupied by the polymer coating, with bio-molecules as external attachments.[44] QDs produced at Evident Technologies have structures that consist of only cores and shells.

Properties of Quantum Dots

The uniqueness and usefulness of QDs stem from their tunable optoelectronic properties. The fluorescent nature of QDs enables them to absorb external stimulus (e.g. thermal excitation, voltage, and laser flux) and re-emit light of various wavelengths. As mentioned, when given enough energy, a number of electrons can jump across the bandgap into the conduction band momentarily. While falling across the bandgap back to the valence band, depending on the size of the bandgap and the energy they lose during the transition, the electrons emit electromagnetic radiations of different wavelengths. The emission wavelength is fixed in bulk semiconductor materials because of their fixed bandgap. On the other hand, the tunability of the QDs is made possible through the precise control of QDs' sizes, which in turn determine the size of the bandgap and peak emission frequency of the electrons. As a QD becomes sufficiently small, the size of its semiconductor crystal decreases to equal or smaller than the Exciton Bohr Radius, known as the separation distance between the electron and the hole in single exciton pair,[45] and consequently the energy levels become more discrete and the bandgap increases. As a result, the energy electrons lose when falling across the bandgap becomes larger, and the emitted wavelengths become shorter, leading to "blue-shifted" light (more towards the blue end of spectrum). The light emitted, therefore, appears to be redder for QDs of larger sizes.[43]

Applications of Quantum Dots

The tunable optical property grants QDs a variety of optoelectronic applications, such as light-emitting diodes (LEDs) and quantum dot lasers. Researchers at Vanderbilt University, for example, have discovered that CdSe quantum dots are able to emit white light when excited with an ultraviolet laser. Moreover, QDs can also be used in solar cells. In 2004, scientists at Los Alamos National Laboratory demonstrated that impact ionization in PbSe quantum dots could occur at very high efficiency, which may lead to considerable increase in power conservation efficiency of QD-based solar cells.[49,50,51,52]

Challenges

The challenge to date for QDs is the cost of manufacture, with the majority of it originating from the synthesis solvent used to produce quantum dots. One gram of CdSe QDs produced at Evident Technologies Inc. cost $6399 (as of January 2005), while the same quantity of CdSe QDs made at NN-Labs Inc. cost $2100-$3375 (as of March 2005). The research team led by Professor Michael Wong at Rice University have recently reported a method of using heat transfer fluids as synthesis solvent instead of conventional octadecene can help cut the cost down by 80%. The next step according to him is to develop a continuous-flow system for making quantum dots in kilogram amounts.[46,47]

Summary

In this paper, the structure, properties, applications, and technical challenges of carbon nanotubes, nanowires, and quantum dots were discussed in detail. In addition, the synthesis of carbon nanotubes was also covered. Since quantum effects play a predominant role in the properties of these nanostructures, the energy band model was presented to help the reader understand fundamental concepts. Since the electron transport properties in larger materials differ significantly from those of nanostructures, concepts of ballistic electron transport and conductance of one-dimensional nanostructures (i.e. carbon nanotubes and nanowires) were also discussed in detail. On the other hand, the unique electrical properties of quantum dots as three-dimensional nanostructures reside in their tunability, enabling them to be promising candidates for optoelectronics applications. However, by observing the technological challenges, one can reasonably claim that research and development of nanotechnology applications in electronics are still at the early stage, and nanotechnology is not very likely to replace the current semiconductor technology as a predominant force in electronics industry soon. Owing to decades of development, semiconductor technology has the maturity that current nanotechnology does not have. Nonetheless, superior properties of novel nanostructures have been shown. While the challenges are still being overcome, one can take advantage of the superiorities of these nanostructures and use them as "components", such as building circuit interconnects with CNTs or nanowires, which are incorporated into semiconductor technology to extend its physical limit. Moreover, the advantages of nanotechnology and other competing semiconductor-based technologies can also be possibly combined to create better devices. As design, testing, and manufacturing techniques of nanotechnology gradually mature, it can undoubtedly become a leading force that has ubiquitous influence in the electronics industry.

Acknowledgement

The author would like to give special thanks to his faculty advisor, Professor Paul Ampadu from the University of Rochester Department of Electrical and Computer Engineering. In addition, many thanks to the ECE graduate students David Wolpert, Qiaoyan Yu, and Bo Fu. Their helpful discussion, generous advice and support are invaluable.

References

1. A. Javey, H. Dai. "Carbon nanotube electronics." *Proceedings of the 19th IEEE International Conference on VLSI Design*, pp.6, January 2006
2. Dowling et al. "Nanoscience and Nanotechnologies: opportunities and uncertainties." *Nanoscience and Nanotechnologies*, Royal Academy of Science and Royal Academy of Engineering, pp.5-26, July, 2004.
3. R.F. Pierret. *Semiconductor Fundamentals*. Vol. 1, 2nd Edition, Addison-Wesley Publishing Company, Chapter 2, pp. 19-35, 1989
4. P. Poole and F.J. Owens. *Introduction to nanotechnology*. John Wiley & Sons, Inc., Chapter 5, pp.114-130 2003.
5. A.M. Song. "Room-Temperature Ballistic Nanodevices." *ENN*, American Scientific Publishers, Vol. 9, pp.371-389, 2004
6. A.S. Sedra and K.C. Smith. *Microelectronic Circuits*. Oxford University Press, Chapter 4, pp. 237-252, 2004.
7. R. Landauer. "Electrical resistance of disordered one-dimensional lattices." *Philos. Mag.* Vol.21, No. 172, pp.863-867 (1970).
8. M. Büttiker. "Four-Terminal Phase-Coherent Conductance." *Phys. Rev. Lett.* Vol. 57, pp.1761–1764, 1986
9. B.J. van Wees et al. "Quantized conductance of point contacts in a two-dimensional electron gas." *Phys. Rev. Lett.* Vol. 60, pp. 848–850, 1988
10. S. Iijima. "Helical microtubules of graphitic carbon." *Nature*, Vol.357, pp.56-58, 7 November 1991
11. S. Iijima and T. Ichihashi. "Single-shell carbon nanotubes of 1-nm diameter." *Nature*, Vol. 363, pp.603-605, 17 June 1993
12. P.L. McEuen, M.S. Fuhrer, and H. Park. "Single-walled carbon nanotube electronics." *IEEE Trans. Nanotech*, Vol. 1, No. 1, pp.78, March 2002
13. P. Avouris. "Carbon nanotube electronics and optoelectronics." *MRS Bulletin*, Vol.29, No.6, pp.403, June 2004
14. P.L. McEuen and J-Y. Park. "Electron transport in single-walled carbon nanotubes." *MRS Bulletin*, Vol.29, No.4, pp.272, April 2004
15. IBM Corporation. "Nanotube field-effect transistor." http://www.research.ibm.com/nanoscience/fet.html
16. S.J. Wind, J. Appenzeller, R. Martel, V. Derycke, and P. Avouris. "Vertical scaling of carbon nanotube field-effect transistors using top gate electrodes." *Appl. Phys. Lett.*, Vol. 80, No.20, pp3817-3819, May 2002
17. S.J. Wind et al. "Carbon nanotube devices for future nanoelectronics." *IEEE-NANO*, Vol.1, pp236, August 2003
18. J. Appenzeller et al. "Carbon nanotube electronics." *IEEE Trans. Nanotech.* Vol.1, No.4, December 2002
19. P. Avouris. "Supertubes." *IEEE Spectrum*, Vol.41, No.8, pp40-45, August 2004
20. Bachtold, P. Hadley, T. Nakanishi, and C. Dekker. "Logic circuits with carbon nanotube transistors." *Science*, Vol.294, pp1317-1320, November 2001
21. A. Javey, J. Guo, Q. Wang, M. Lundstrom, and H. Dai. "Ballistic carbon nanotube field-effect transistors." *Nature*, Vol. 424, pp.645-657 August 2003
22. K. Bullis. "Carbon nanotube computers." *Technology Review*, 26 May 2006 http://www.technologyreview.com/read_article.aspx?id=16931&ch=nanotech
23. C. Klinke, J. Hannon, A. Afzali, and P. Avouris. "Field-effect transistors assembled from functionalized carbon nanotubes." *Nano Lett.* Vol.6, No.5, pp.906-910, April 2006
24. M.S. Dresselhaus and H. Dai. "Carbon nanotubes: continued innovations and challenges." *MRS Bulletin*, Vol.29, No.4, pp237-239, April 2004
25. W.A. de Heer. "Nanotubes and the pursuit of applications." *MRS Bulletin*, Vol.29, No.4, pp281-285, April 2004
26. M. Karwa et al. "Selective Self-assembly of Single-Walled Carbon Nanotubes in Long Steel Tubing for Chemical Separations." *Journal of Materials Chemistry*, No. 16, pp. 2890-2895, 2006
27. M.R. Maschmann et al. "Vertical single- and double-walled carbon nanotubes grown from modified porous anodic alumina templates." IOP Publishing, *Nanotechnology* 17, pp. 3925-3929, July 2006
28. T. Simonite. "Gadget sorts nanotubes by size." *New Scientist Tech*, June 2006. http://www.newscientisttech.com/article/dn9419.html
29. Editor of EE Times Europe. "Carbon nanotubes grown at lower temperatures." *EE Times Europe*, 9 August 2006. http://www.eetimes.eu/semi/191900052
30. Bhushan (editor). *Springer Handbook of Nanotechnology*. Springer-Verlag Berlin Heidelberg, Part A 3-4, pp. 39-138, 2004
31. C.M. Lieber. *NiSi/Si Nanowire Heterostructure Devices*. Lieber Research Group, Harvard University, 2004. http://cmliris.harvard.edu/gallery/index.php
32. K. Takayanagi. "Suspended gold nanowires: ballistic transport of electrons." *JSAP International*, No.3, pp.3-8, January 2001

33. J. Xiang, W. Lu, Y. Hu, Y. Wu, H. Yan, and C.M. Lieber. "Ge/Si nanowire heterostructures as high-performance field-effect transistors." *Nature*, Vol.441, pp.489-493, 25 May 2006
34. Y. Cui, Z. Zhong, D. Wang, W.U. Wang, and C.M. Lieber. "High performance silicon nanowire field-effect transistors." *Nano.Lett.*, Vol.3, No.2, pp.149-152, January 2003
35. Y. Huang, X. Duan, Y. Cui, and C.M. Lieber. "Gallium nitride nanowire nanodevices." *Nano.Lett.*, Vol.2, No.2, pp.101-104, January 2002
36. X. Duan, Y. Huang, Y. Cui, J. Wang, and C.M. Lieber. "Indium phosphide nanowires as building blocks for nanoscale electronic and optoelectronic devices." *Nature*, Vol.409, pp.66-69, 4 January 2001
37. Y. Huang, X. Duan, Y. Cui, L.J. Lauhon, K. Kim, and C.M Lieber. "Logic gates and computation from assembled nanowire building blocks." *Science*, Vol.294, pp.1313-1317, 9 November 2001
38. F. Patolsky and C.M. Lieber. "Nanowire nanosensors." *Materials Today*, pp.20-28, April 2005
39. F. Patolsky, G. Zheng, and C.M. Lieber. "Nanowire-based biosensors." *A.C.S. Analytical Chem.*, pp.4261-4269, 1 July 2006
40. C. Brown. "Nanowire array manufacturing becoming a 'Snap'." *EE Times*, 04/23/2003, http://www.eetimes.com/showArticle.jhtml?articleID=18308245
41. C.M. Lieber. "The Incredible Shrinking Circuit." *Scientific American*, 285 No.3, pp58-65, 2001
42. K. Bullis. "Nanowire transistors faster than silicon." *Technology Review*, 20 June 2006. http://www.technologyreview.com/read_article.aspx?id=17008&ch=nanotech
43. Evident Technologies. "How quantum dots work." http://www.evidenttech.com/qdot-definition/quantum-dot-introduction.php
44. Quantum Dot Corporation. "Qdot nanocrystal technology." http://probes.invitrogen.com/products/qdot/overview.html
45. W. Buhro and V.L. Colvin. "Semiconductor nanocrystals: shape matters." *Nature materials*, Vol.2, pp.138-139, March 2003
46. G.P. Collins. "Cheaper Dots." *Scientific American*, 5 December 2005 http://www.sciam.com/article.cfm?chanID=sa004&articleID=00052124-A8B8-137B-A7A583414B7F0000
47. S. Asokan et al. "The use of heat transfer fluids in the synthesis of high-quality CdSe quantum dots, core/shell quantum dots, and quantum rods." IOP Publishing, *Nanotechnology* 16, pp.2000-2011, 2005
48. Z.A. Peng and X. Peng. "Formation of high-quality CdTe, CdSe, and CdS nanocrystals using CdO as precursor." *J. Am. Chem. Soc.*, Vol.123, No. 1, pp.183-184, 2001
49. C. Wang, M. Shim, and P. Guyot-Sionnest. "Electrochromic nanocrystal quantum dots." *Science*, Vol. 291, pp.2390-2392, 23 March 2001
50. M.J. Bowers II, J.R. McBride, and S.J. Rosenthal. "White-light emission from magic-sized cadmium selenide nanocrystals." *J. Am. Chem. Soc*. Vol. 127, No. 44, pp. 15378-15379, 2005
51. S. Strauf et al. "Self-tuned quantum dot gain in photonic crystal lasers." *Phys. Rev. Lett*. 96.127404 , 31 March 2006
52. R.D. Schaller and V.I. Klimov. "High efficiency carrier multiplication in PbSe nanocrystals: implications for solar energy conversion." *Phys. Rev. Lett.*, Vol.92, No.18, 186601(4), 7 May 2004