FEATURE

Electronics and Optoelectronics with Carbon Nanotubes

by Phaedon Avouris and Joerg Appenzeller

New discoveries brighten the outlook for innovative technologies

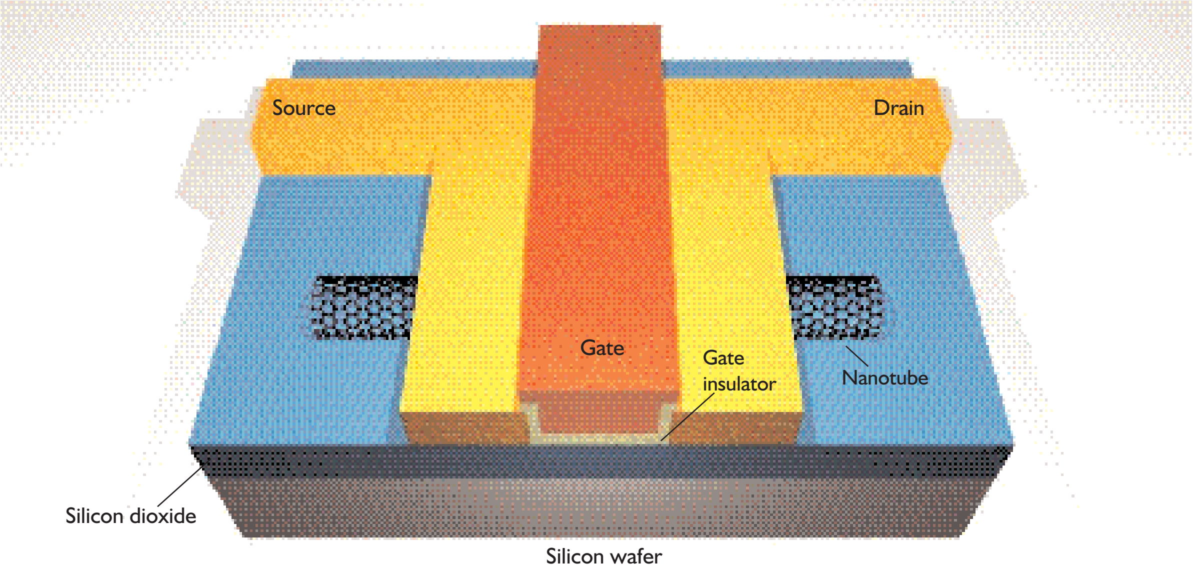

Figure 1. IBM is evaluating the potential of carbon nanotubes as the basis of a future nanoelectronics technology, as shown, for example, in this computer illustration of a top-gated field-effect transistor.

Information technology as we know it has resulted from incredibly fast advances in electronics and computing during the last few decades. One of the most important ingredients responsible for the success of integrated silicon technology is the metal oxide semiconductor field-effect transistor (MOSFET), and a major reason for its success is the MOSFET's scalability. Shrinking the dimensions of the device improves its speed and power efficiency. Today, the electronics industry is producing MOSFETs with critical dimensions of about 100 nm, and projections anticipate devices with minimum-feature sizes of around 50 nm in the year 2009.

However, the industry generally expects that within a decade or so, it will encounter critical technological barriers and fundamental physical limitations to size reduction. At the same time, there are strong financial incentives to continue the process of scaling, which has been central in the effort to increase the performance of computing systems in the past. One approach to overcoming these impending barriers involves preserving most of the existing technology, but basing it on new materials that alleviate some or most of the problems that appear in aggressively scaled silicon devices. Organic molecules and carbon nanotubes rank high among the widely pursued solutions. At IBM, we have concentrated our efforts on evaluating the potential of carbon nanotubes as the basis of a future nanoelectronics technology.

Sumio Iijima of NEC first observed carbon nanotubes (CNTs) in 1991 in electron microscope images of the soot produced by discharges between carbon electrodes. Those nanotubes consisted of several sheets of graphite (which is composed of multiple layers of carbon atoms) rolled into cylinders with one cylinder inside another, a form now referred to as multiwalled nanotubes. In 1993, Iijima and Don Bethune of IBM independently found that by adding small amounts of catalytic metals to the carbon electrodes, they could produce CNTs consisting of a single atomic layer of carbon's graphite structure—a configuration now called single-walled carbon nanotubes (SWCNTs). Since then, several different techniques have produced CNTs—most notably, laser ablation of carbon targets and metal-catalyzed chemical-vapor deposition. We have focused our attention on SWCNTs, which have proven the most useful structures for electronic applications.

Two flavors

SWCNTs are materials with unique properties. They have diameters of typically 1–3 nm, but they are also long—up to several millimeters in length, and, undoubtedly, much longer tubes can be produced. Taking into account their small diameter and their huge aspect ratio, SWCNTs are close to an ideal one-dimensional system. They are incredibly strong (with a tensile strength many times that of carbon steel), and because they are strongly bonded covalent materials, they typically show few defects. SWCNTs are also thermally stable at temperatures of more than 1,000 °C, and have a thermal conductivity similar to diamond.

One of the amazing properties of carbon nanotubes is that they come in two flavors—metallic or semiconducting. Because of their extremely small diameter, quantum-mechanical effects determine the electronic structure of a carbon nanotube. This means that the quantization conditions along the nanotube perimeter determine whether a nanotube acts as a metal or a semiconductor. Rolling up a piece of graphite and creating a hollow, seamless cylinder can be done in different ways. As a result, the tubes differ in their diameters and by how the carbon atoms are arranged relative to the tube axis (see *The Industrial Physicist*, February/March 2004, pp. 24–27).

Certain ways of creating nanotubes yield a finite density of states at the Fermi level (a metallic nanotube) and others produce tubes with a vanishing density of states (semiconducting tubes), with typical bandgaps in the range of 1 eV, or a fraction of an electron volt. The existence of both electrical types of SWCNTs has raised hopes for the future development of an all-carbon-based nanoelectronic technology in which active devices are made of semiconducting SWCNTs and the electrical wiring (the interconnects) consists of metallic SWCNTs.

Field-effect transistors

Several types of devices can be made using SWCNTs instead of conventional semiconductors such as silicon. However, because the field-effect transistor (FET) has turned out to be the most valuable conventional electronic device, the emphasis of our group has been on CNT field-effect transistors (CNTFETs). To understand the promise of CNTFETs, we need to first consider some of the factors that limit the ultimate scaling of conventional MOSFETs.

Phenomena such as quantum-mechanical tunneling become extremely important as the length of the transistor channel and the thickness of the gate insulator (currently ~1.5 nm) decrease, as required by the scaling rules. The resulting large leakage currents undermine the function of the transistor as a switch. Moreover, because leakage currents imply a substantial standby and leakage power, they add to the already high power consumption of strongly scaled devices. As part of the scaling process, the width of the metallic wiring should also be reduced. However, that reduction leads to an increased resistance, a slowing of system performance, and greater degradation of the metallic wires by electromigration, which results from the force exerted by the high current density.

Why nanotubes?

SWCNTs, which are one-dimensional systems, do not allow the small-angle scattering of electrons or holes by defects or phonons that occurs in a three-dimensional system because carriers in them have only two directions of propagation, forward or backward. Backscattering that leads to electrical resistance requires a reversal of the momentum of the carrier, and the probability of such reversals is small. Because of the reduced phase space for scattering, SWCNTs exhibit a lower resistivity than conventional three-dimensional structures.

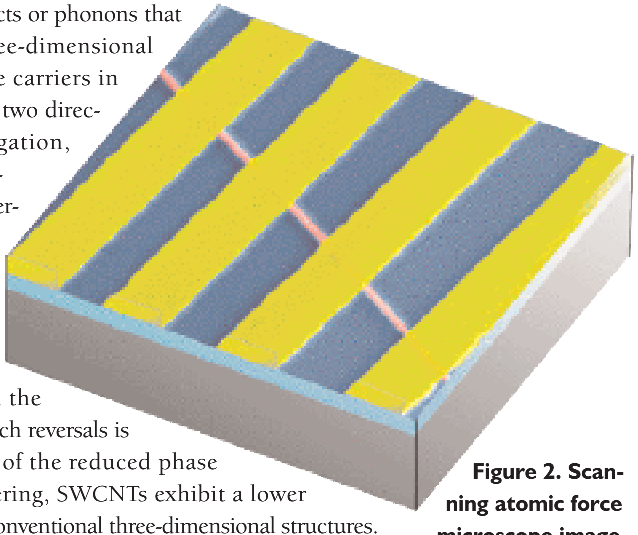

Figure 2. Scanning atomic force microscope image of a multiwalled carbon nanotube with gold electrodes on top.

Electrical transport in good-quality metallic nanotubes is ballistic, that is, the electrons do not suffer from any scattering event over a few micrometers, even at room temperature. Semiconducting SWCNTs are also ballistic on a length scale of at least a few hundred nanometers, more than is needed to fabricate CNTFETs. Therefore, the energy dissipation in the body of SWCNTs is minimal, and the issue of dissipated power density in the transistor channel is reduced. There is also no electromigration, and metallic nanotubes carry current densities 2–3 orders of magnitude higher than metals such as copper or aluminum—materials currently used in electronic chips.

With respect to FETs, nanotubes do not have surface dangling bonds, as silicon does, and so there is no need to mainly use silicon dioxide (SiO_2) as the gate insulator. Other crystalline or amorphous insulators with higher dielectric constants can be used instead. This implies that one can get higher performance in CNTFETs without having to use ultrathin SiO_2 gate insulating films. In addition, CNTFETs may make new applications possible. For example, semiconducting SWCNTs, unlike silicon, are direct-gap materials and, as such, they directly absorb

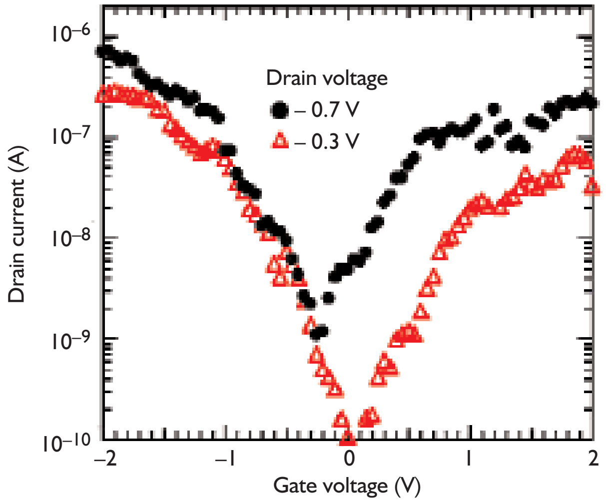

Figure 3. With a thin gate insulator, carbon nanotube field-effect transistors become ambipolar, conducting electrons when a positive bias is applied to the gate and holes when a negative bias is applied.

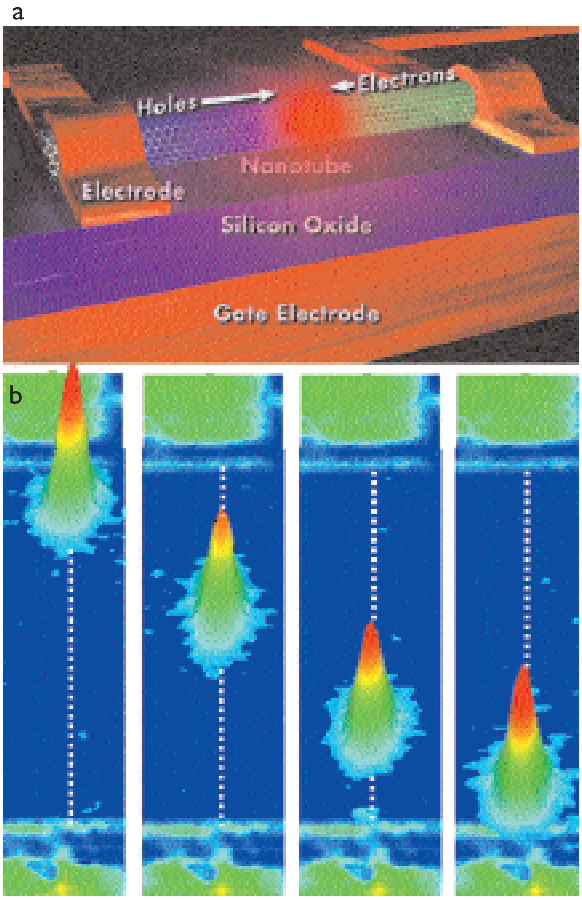

Figure 4. Electrons and holes can be injected from opposite ends of a carbon nanotube to create a single-molecule, electrically controlled light source (a). The light emission can be translated between the two metal electrodes (b) by varying the gate voltage because this is an undoped system. The same device can function as a switch, a light emitter, or a light detector.

and emit light, thus possibly enabling a future optoelectronics technology based on SWCNTs.

Because of the technological barriers that face aggressively scaled silicon devices, researchers must consider two points—the difficulty of fabricating commercial devices with dimensions smaller than the current limits of optical lithography and the increasing fluctuations in nanoscale device parameters. Fluctuations in threshold voltages and output currents, for example, become more prominent as devices are scaled down in size. In SWCNTs, on the other hand, the critical dimension that most affects their parameters is the diameter, which is determined by the chemical synthesis.

In this context, novel technologies for the fabrication of nanostructures are expected to allow good control over critical device dimensions in the future. Although one can envision the transistor width being controlled through chemistry, SWCNTs do not necessarily allow the fabrication of extremely small-length devices because limitations such as those imposed by quantum tunneling will also be present in CNTFETs, and lithography will likely be used to define the channel lengths of CNTFETs. It is expected, however, that carbon nanotubes will allow a simpler fabrication of devices with superior performance at about the same length as their scaled silicon counterparts.

First devices

A CNTFET is the analogue of a silicon MOSFET in which SWCNTs replace the silicon channel. The first crude devices, created independently at Delft University of Technology in The Netherlands and IBM, appeared in 1998, and their performance and our understanding of their operation have improved steadily since then. In the first prototypes, a thick SiO_2 film covered a silicon wafer, and noble metal electrodes were fabricated on it using lithography and lift-off processes. A SWCNT was then positioned to bridge two of these electrodes, which acted as the source and drain of the transistor, while the SWCNT played the role of the transistor channel. The heavily doped wafer served as the gate electrode, isolated from the channel by the thick oxide used as a gate dielectric (Figure 2).

These initial structures were functional switches with a current flow about 100,000 times greater in the on-state than when they were turned off. However, they had high contact resistance and low on-currents. In addition, all devices on a chip had to be on or off in unison. Subsequent efforts improved the metal–CNT contacts and increased the gate coupling in the nanotube channel region. By 2001, CNTFET structures were produced whose performance characteristics, such as the drive current and transconductance, proved superior to state-of-the-art MOSFETS. Advances in top-gated devices with thin SiO_2 gate films or high-dielectric-constant materials permitted controlling each device on a chip individually, and several combinations of metals and ways to fabricate the metal–SWCNT contacts have significantly reduced the contact resistance (Figure 1).

The early CNTFETs with thick gate oxides proved to be p-type, that is, current transport was mediated by holes. The demonstrated advantage of complementary metal oxide semiconductor (CMOS) technology suggested the need to have both p- and electron-mediated n-type transistors. SWCNTs are ideal for CMOS applications because of the symmetric structure of their valence and conduction bands; electrons and holes have essentially the same band structure and, consequently, nearly the same effective mass. N-type FETs were produced by doping of the p-type FETs, and CMOS-based logic gates (inverters, for example) were demonstrated. Two types of such circuits were realized. Besides using the conventional approach of wiring together individual FETs, our group has built novel intrananotube devices—the first intramolecular logic circuits—which are fabricated along the length of a single SWCNT.

Unusual behavior

To optimize SWCNT devices, researchers have adopted the scaling process perfected for fabricating silicon devices. The improvements obtained, however, have not agreed with the anticipated scaling behavior. Examining this difference, we came to realize that, in general, potential barriers at the source–SWCNT and drain–SWCNT contacts controlled the operation of the devices, and, thus, the bulk switching mechanism that describes silicon devices did not apply to SWCNT devices. These barriers stem from the band-bending that results from the charge-transfer process at the metal–SWCNT interfaces and can be considered as one-dimensional Schottky barriers (SBs) analogous to those formed at a metal–three-dimensional semiconductor interface.

However, unlike the three-dimensional SBs, one-dimensional SBs can be much narrower, even without doping the semiconductor, and they can easily be thinned by the gate field such that tunneling through them results in a substantial current contribution. In effect, SB CNTFETs are novel tunneling devices. Decreasing the thickness of the gate insulator also demonstrated a drastic change in the character of the CNTFETs; they become ambipolar. Typical current–voltage curves of an ambipolar transistor are shown in Figure 3. Such a device conducts electrons when a positive bias is applied to the gate, and holes when a negative bias is applied. Under certain biasing conditions, electrons and holes can be simultaneously injected from opposite ends of the CNT channel. This ambipolar behavior is unwelcome in devices because it increases the leakage current. We resolved this by using asymmetric gates.

Optoelectronic applications

Ambipolar behavior, however, has valuable optoelectronic applications. The injected electrons and holes are confined in the nanotube structure, and when they meet, they are neutralized. If their net momentum is zero and they have opposite spin, they can recombine and give off the recombination energy in the form of light. We have recently demonstrated that, indeed, this mode of recombination takes place, and we have produced a single-molecule, electrically controlled light source (Figure 4).

Unlike conventional light-emitting diodes, which involve fixed p-n junctions produced by doping, the SWCNT light source is a three-terminal device that involves no doping and also allows control of the emission intensity and the position of the emitting spot along the length of the CNT. The diameter of the CNT defines the wavelength of the emitted light, typically in the infrared range. The reverse process of photocurrent generation with a significant yield by photoexcitation of a CNTFET device has also been demonstrated. This single CNT device can function as an electrical switch, a light emitter, or a light detector, depending on the biasing.

Despite the spectacular properties of SWCNTs, researchers must overcome many serious hurdles before a SWCNT-based electronic nanotechnology can be implemented. The main difficulty involves the synthesis of a homogeneous SWCNT material. Currently used techniques produce a mixture of different-diameter semiconducting and metallic SWCNTs. Recently, however, significant progress has been made toward a more selective synthesis, while simultaneously, techniques for the separation of the different SWCNTs have advanced. Although major tasks need to be addressed, taking into account the amazing rate of progress in this field, one can envision an optimistic future for SWCNT-based electronics.

Further reading

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BIOGRAPHY

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