Wireless Interconnect and the Potential for Carbon Nanotubes

Alireza Nojeh and André Ivanov
University of British Columbia

Editor's note:
Recent research has demonstrated that carbon nanotubes (CNTs) have excellent emission and absorption characteristics, leading to dipole-like radiation behavior, which makes CNTs promising alternatives for use as antennas in on-chip wireless communication. This article reviews the key characteristics of CNTs that make them so well suited for this purpose.

—Sriram Vangal, Intel

■ **WITH THE EVER-SHRINKING** dimensions of electronic devices and increasing IC densities, CMOS technology is now at a point where interconnect delay and power consumption exceed or are comparable to gate delay and power consumption. In addition to power loss, the resulting thermal issues add significant design and engineering challenges. Coupled with the increasing complexity of interconnect routing, these issues create a bottleneck to further scaling.

Researchers have been investigating several alternatives to the traditional 2D interconnect scheme. Three-dimensional ICs, where layers of devices are stacked atop one another, present a promising solution: 3D stacking substantially reduces the distance between many devices and correspondingly reduces interconnect length. This directly improves delay and power consumption and allows for more freedom in routing. The challenges of 3D integration, however, cannot be ignored. The increased integration density necessitates new approaches to thermal management. Chip fabrication presents added difficulties—for example, more alignment steps are required. Another challenge is to ensure that already-existing device layers are not damaged by some of the high-temperature steps involved in fabricating subsequent layers. Researchers are devoting considerable resources to addressing the challenges of 3D integration.

A second possible alternative to 2D interconnects involves the use of integrated photonic devices to transmit information between the various points of an IC. Optical networks-on-chip (NoCs) have emerged as one of the key alternatives to traditional interconnect designs. The advances in integrated optics provide every reason to combine its benefits with those of the CMOS world. For example, the transmission of light signals through waveguides can be achieved with a high data rate and high efficiency from the standpoint of power consumption. Optical NoCs, however, have their own challenges. Many optoelectronic components—such as integrated lasers, modulators, and detectors—are based on Group III-V semiconductor materials, and their integration with the silicon process is neither trivial nor inexpensive. Routing a chip's waveguides might pose difficulties similar to those of routing interconnect wires in regular circuits. Nonetheless, the potential benefits of optical NoCs make them another strong candidate for addressing the interconnect challenge, and research in this area is active.

New materials, new approaches

New materials are being investigated to replace traditional copper interconnect wires and interlayer dielectrics. For wires, materials that have perhaps attracted the most attention are carbon nanotubes (see the "Carbon Nanotubes: Definition and Application" sidebar for more details).

Over the past two decades, nanotubes have gained ever-increasing popularity because of their

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Carbon Nanotubes: Definition and Application

A carbon nanotube is a hollow cylindrical structure made of carbon atoms, with a nanoscale diameter and a length that can reach centimeters. It can consist of only one layer of atoms (single-walled carbon nanotube—SWNT). It can also include a number of coaxial layers with progressively larger diameters (multiwalled carbon nanotube—MWNT). Each SWNT can be thought of as graphene (one layer of graphite) rolled along a certain direction in its plane (see Figure A).

This direction is indicated by a vector called the chiral vector and represented as (*n*, *m*). The ''chirality'' and diameter of the SWNT determine its electronic properties. An intuitive way of studying the electronic band structure of a nanotube is to start with that of graphene and impose periodic boundary conditions, corresponding to the fact that the wave function of electrons should be periodic along the circumference of the nanotube. This implies that the *E*-*k* diagram (electronic dispersion curve) of the nanotube will comprise a subset of that of graphene and depend on the nanotube chirality and diameter (since these parameters affect the periodic boundary conditions). Generally, nanotubes for which the difference between *n* and *m* is a multiple of three are metallic or semimetallic; the rest are semiconducting. For a detailed analysis, please see the literature.[1]

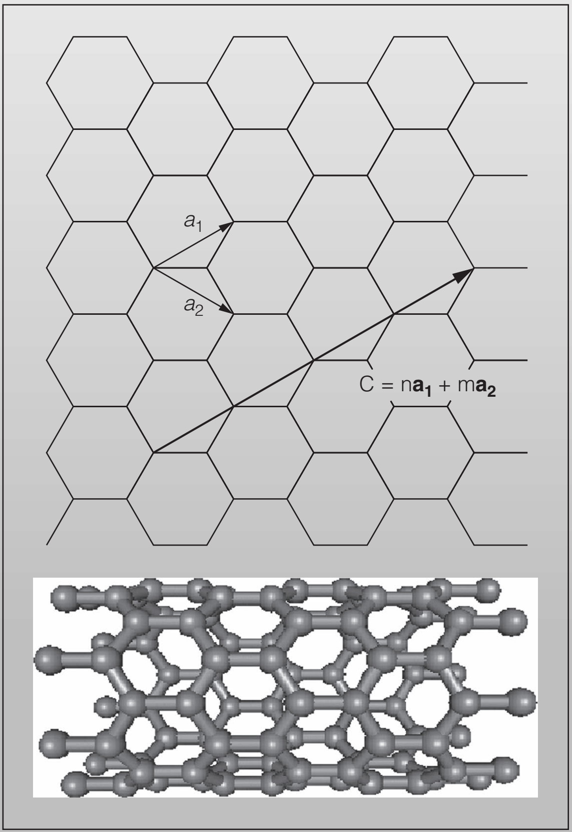

Figure A. (Top) A graphene layer showing the unit vectors and an example chiral vector. (Bottom) A single-walled carbon nanotube.

On the mechanical side, nanotubes have much to offer. Due to the sp^2 carbon-carbon bond, although nanotubes are relatively flexible in the lateral dimensions, SWNTs are extremely strong along their axis. (In MWNTs, the various layers can slide over each other relatively easily.) Together with their hollow structure, this makes them unique candidates for lightweight, ultrastrength composite materials. Nanotubes also show attractive actuation behavior and are being investigated as high-force actuators for applications such as artificial muscles. Thermal conductivity in nanotubes along their axis is very high and this makes them good candidates for heat sink structures for ICs. Due to their high surface-to-volume ratio, nanotubes can form the basis of highly sensitive chemical and biological sensors. They also have applications as high-brightness electron sources, as well as in disease treatment and hydrogen storage.

For more detail on the basic properties and potential applications of carbon nanotubes, the book by Saito and colleagues is a good start.[1]

Reference

1. R. Saito, G. Dresselhaus, and M.S. Dresselhaus, *Physical Properties of Carbon Nanotubes,* Imperial College Press, 1998.

attractive electrical, mechanical, thermal, and optical characteristics. Their unique electronic properties include the ability to carry current with densities as high as 10^9 A/cm^2, orders of magnitude higher than traditional copper and silver wires. Moreover, ballistic transport over long distances makes nanotubes ideal candidates for electric wires: a mean free path in micrometers has been observed at room temperature.

Researchers have also shown that nanotube-based field-effect transistors (FETs) have possible advantages over silicon-based devices. Because of their nanoscale diameter—which means a tight

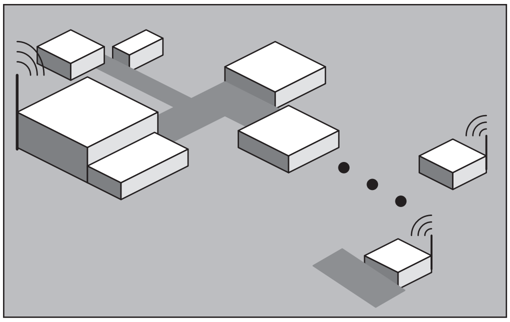

Figure 1. A futuristic schematic of an on-chip wireless interconnect network with nanoscale antennas.

confinement of electrons in the lateral dimensions—and a high aspect ratio (up to 10^7), nanotubes are virtually 1D systems, forming so-called *quantum wires.* This has important implications in the creation of novel electronic devices, such as quantum dots and single-electron transistors.

The optoelectronic properties of nanotubes have also been attracting attention. Researchers have demonstrated both light emitters and detectors based on carbon nanotubes. In addition, nanotubes can act as antennas for a wide range of frequencies, including optical frequencies.

Carbon nanotubes as interconnect wires

Given their high conductivity, high current-carrying capability, mechanical strength, and chemical stability, nanotubes are a natural choice for miniaturized wires and interconnect lines. An individual *single-walled nanotube* (SWNT) can allow the passage of several micro-amperes of electric current. Bundles of parallel nanotubes could be used to scale up this value. Cho et al. have compared the performance of nanotubes with that of copper/low-*k* interconnect and optics.[1] They performed an analysis for technology nodes in the 22–65-nm range and concluded that, in general, nanotubes have the lowest latency for semiglobal (~ 1 mm) interconnect levels, whereas optical interconnect technology is better for global (~ 10 mm) levels. They also found optical interconnects to be more power-efficient for longer distances at higher switching activities. Overall, nanotubes have much to offer on this front, although they may not provide a full solution. This is consistent with the 2007 *International Technology Roadmap for Semiconductors* (ITRS) prediction that materials innovation alone might not be sufficient and that new interconnect paradigms might be needed to address the increasing challenges of scaling.

Wireless interconnect

A drastically different approach to on-chip communication is a wireless interconnect scheme. This approach not only has the potential to reduce energy loss (by avoiding losses in wires) but also alleviates the routing problem. Floyd et al., for example, have demonstrated wireless interconnection on a chip over distances of 5.6 mm for a 15-GHz clock distribution using transceivers implemented in 0.18-μm CMOS technology.[2] Despite its potential advantages, on-chip RF wireless communication has potential limitations due to antenna size: because of the wavelengths in use, antennas with dimensions of a few millimeters are needed. This increases the area overhead and limits the ability to create many transceivers on a chip for communication between multiple points. In addition, interference with other RF signals in the chip environment can create difficulties. A potentially limited number of channels and the area overhead associated with the transceiver circuits are other challenges.

New scheme: Optical wireless interconnect

To overcome the problem of antenna size, a natural solution would be to use shorter wavelengths, which need smaller antennas. Using significantly shorter wavelengths as the carrier, corresponding to much higher frequencies than the rest of the on-chip signals, might also help to reduce interference. To enable wireless links to replace a large portion of interconnect lines, transceiver antenna dimensions should be in the micrometer range, corresponding to optical wavelengths. By way of analogy, under such a paradigm the IC would resemble a scaled-down version of a wireless communication network in an urban setting: instead of RF and microwave frequencies, the network uses optical frequencies. Antennas are correspondingly smaller, and the blocks of metal and dielectric on the chip are the analogous counterparts of buildings and other structures (see Figure 1). To make this all possible, however, requires efficient micro- or nanoscale antennas.

Optical properties of carbon nanotubes

Carbon nanotubes have distinctive optical properties. On one hand, nanotubes can act as antennas, and the wave nature of light is strongly manifested in their optical behavior. On the other hand, since the energy of photons in the optical domain is a few electron volts, nanotubes' absorption and emission of light involve interband transitions (excitation of electrons between various valence and conduction subbands), similar to what happens in traditional optoelectronic devices, which means that the particle nature of light is strongly apparent.

IBM researchers have performed pioneering work on optoelectronic devices based on carbon nanotubes.[3] They have demonstrated light emission due to electron-hole recombination in nanotube-based FETs. Schottky contacts connected to source and drain terminals allow for the injection of both electrons and holes in these devices without need of chemical doping. The researchers have also demonstrated that by changing the gate voltage, the location where the recombination takes place can be moved along the nanotube axis, thus moving the emission spot. The emitted light is strongly polarized along the nanotube axis. Additionally, photodetectors based on nanotube FETs were demonstrated by the IBM group, which also observed that the absorption depended on polarization, favoring light polarized along the nanotube axis.

Nanotube antennas

Carbon nanotubes are a natural choice for miniaturized antennas, offering a number of potential advantages. Their high conductivity offers low resistive loss. Their perfect structure (no dangling bonds and surface states) minimizes losses arising from rough surfaces and edges, which could be present in other microstructure antennas. Their notable ability to carry current relative to their size could enable the emission of enough power to attain the necessary range of communication. Finally, their strong and stable structure yields high system reliability—namely, a long lifetime without failure or performance deterioration. Interesting work in this regard has been accomplished by Kempa et al., who investigated the scattering of light from a multiwalled nanotube (MWNT) and demonstrated that its directional radiation characteristics are similar to those of traditional radio antennas.[4] Also, in our photo-electron emission experiments from carbon nanotubes, we observed strong light absorption that could be explained by antenna effects in nanotubes (see the "Photo-electron Emission from Carbon Nanotubes" sidebar for more details).

The antenna properties of carbon nanotubes have been studied theoretically, too. For example, Hanson has presented a classical treatment of nanotube dipole antennas for the GHz-THz range of frequencies based on a quantum mechanical conductivity.[5] Burke et al. have presented a circuit model for nanotube transmission lines that considers quantum capacitance and kinetic inductance, and they have suggested that these devices could be used to interconnect the macroscopic world to nanodevices.[6] Interband transitions, which are a crucial aspect of device operation in the high-frequency region, were not considered in these works. Slepyan et al., however, have presented a theoretical framework that also included interband transitions and that researchers can use to investigate nanotube antenna properties over a wide spectral range, from terahertz to ultraviolet frequencies.[7]

The wave nature of light has also been explored in experiments on collections of nanotubes. Such collections, including nanotube arrays and bundles, could be used to make larger devices if needed, with the potential to carry more current and emit or absorb higher powers. Wang et al. have reported antenna-like behavior for visible and infrared wavelengths in arrays of carbon nanotubes.[8] Yang et al. have measured optical absorption in low-density nanotube forests and found them to be the darkest material, which means these forests could absorb light better than any other material.[9]

The optical properties of collections of nanotubes have also been investigated theoretically. For instance, García-Vidal et al. have developed a theory for the effective optical properties of aligned carbon nanotube films, namely, they have presented expressions or values for the relative permittivity of these films that take into account the electromagnetic coupling between the different nanotubes in the film.[10] Shuba et al. have investigated wave propagation and antenna effects in bundles of metallic nanotubes for terahertz to near-infrared ranges.[11] They observed that the antenna efficiency of a nanotube bundle can be much higher than that of an individual carbon nanotube.

A complete, miniaturized communication system

To show how a nanotube-based communication device might be built, we have proposed simple transmitter and receiver prototypes, as Figure 2 illustrates.

Photo-electron Emission from Carbon Nanotubes

We observed high quantum efficiency, that is, strong conversion of photons to electrons, in photo-electron emission from SWNTs. In these experiments, photons illuminate the nanotube and, as a result, electrons are emitted into vacuum (the photoelectric effect) and collected by an anode. Nanotubes exhibited a highly enhanced light absorption cross section, which we could explain based on antenna effects.[1] Figure B shows simulation results for the absorbed power as a function of nanotube length and how it is substantially higher than what would be expected without antenna resonance effects. Strong polarization dependence is also evident. In our experiments, interband transitions were also strongly present, as we used ultraviolet photons to excite electrons from the nanotube's energy levels up to the vacuum level.

Reference

1. A. Nojeh et al., "Photoemission from Single-Walled Carbon Nanotubes," *J. Applied Physics,* vol. 104, 2008, p. 054308.

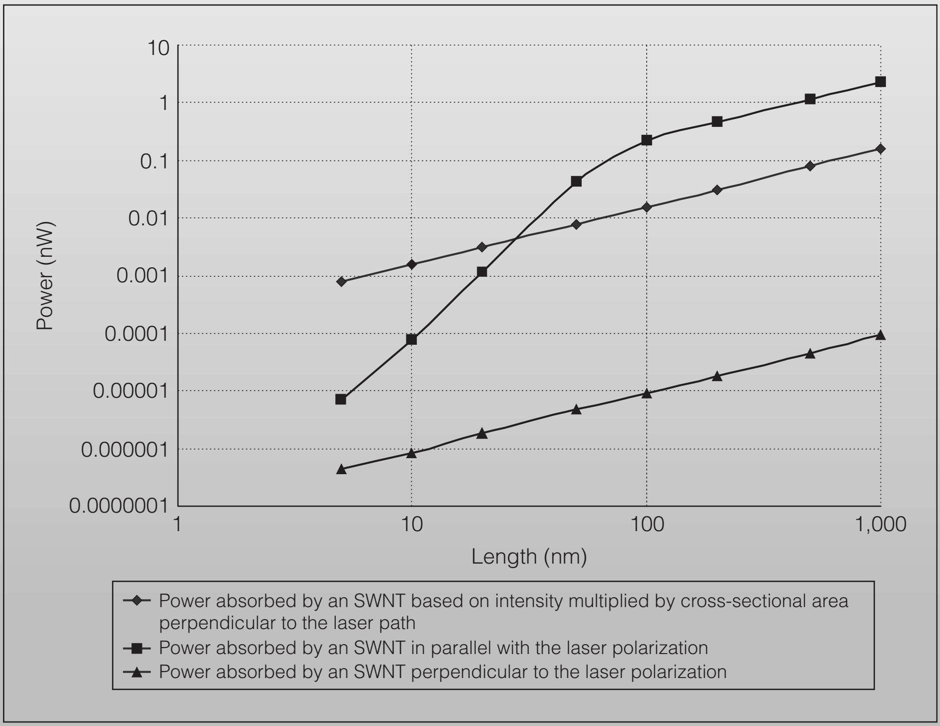

Figure B. Power absorbed in an SWNT as a function of its length for photons with a wavelength of 266 nm. The actual absorbed power is higher than what one expects purely based on the geometrical cross-section of the nanotube. Dependence on polarization is also apparent. (Reprinted with permission from A. Nojeh et al., "Photoemission from Single-Walled Carbon Nanotubes," *J. Applied Physics,* vol. 104, 2008, p. 054308. © 2008, Am. Inst. of Physics.)

A typical transmitter consists of a signal generator and an antenna. For optical signals (10^{14}–10^{15} Hz), it is not possible to generate such frequencies using a standard CMOS oscillator circuit. A major potential advantage of using nanotube antennas is that in the transmitters, signals can also be generated by the antenna itself. As Avouris and Chen have explained,[3] light can be generated when a constant voltage is applied across an SWNT connected between two metal electrodes with thin Schottky barriers. The light's wavelength is primarily determined by the nanotube energy band gap (which is determined by the nanotube chirality, as discussed in the "Carbon Nanotubes: Definition and Application" sidebar) and which, typically being around 1 eV or a fraction of an eV, leads to infrared emission (a wavelength of ~ 1–2 μm).

Accordingly, the transmitter circuit needs only to apply a constant voltage to the nanotube for the duration of each pulse corresponding to a 1 bit.

In the receiver, which has a structure similar to the transmitter (see Figure 2), the nanotube acts as a photo detector, in which electron-hole pair generation due to the incident photons creates a current pulse for the duration of the incoming light pulse, corresponding to the information bit sent by the transmitter. When the nanotube's length is chosen properly, current resonance and antenna effects should enhance the amount of light absorption and the generated current. A low-noise CMOS trans-resistance amplifier circuit creates the output voltage signal. Central to both devices is the nanotube: in the transmitter, the nanotube is both the modulator and the antenna; in the receiver, the nanotube is both the antenna and the demodulator. The CMOS circuitry will add some area overhead, which could be roughly a few tens of square micrometers in state-of-the-art technologies. However, this is expected to be less than the corresponding area occupied by transceivers in RF wireless communication, because extra oscillator and demodulation circuits are not needed. To examine what type of communication network could potentially be enabled using this scheme, we developed a highly simplified (and highly speculative) estimate of the power loss behavior and number of communication channels that this system might make available.

Power loss behavior

An individual SWNT can typically tolerate a current of a few microamperes under an applied voltage of just a few volts. This corresponds to a power dissipation on the order of 10 μW. Only a fraction of this power will be converted to optical power. The communication range that this enables will be strongly affected by the environment and the relative positioning of the transmitter and receiver antennas. One way to increase coverage would be to build the antennas on top of microtowers to emulate the construction used in conventional wireless communications.

Consider a single transmitter and receiver pair at the same frequency and polarization. The power at the receiving antenna varies inversely with the square of the distance between the pairs, *r*, if there is only a line-of-sight communication channel. Considering the effect of ground reflections, the received power degrades much faster if the distance is greater than a critical value given by $r_0 = 2\pi h^2/\lambda$, where h is the height of the antennas and λ is the wavelength. (This gives a pessimistic estimate by assuming a perfectly reflective ground plane; for lower reflectivity, this distance will be longer.) A design rule for our proposed nanotube-based system would be to ensure that the longest distance between communicating source and destination pairs is less than r_0.

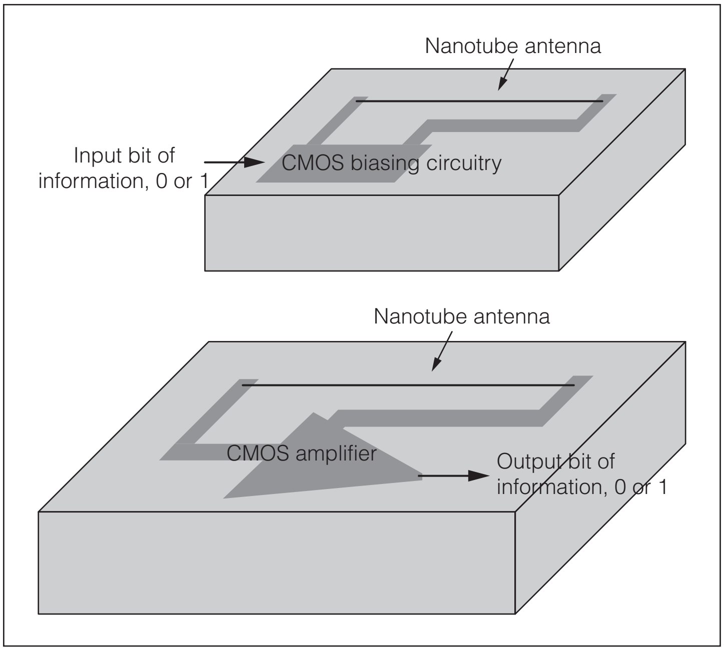

Figure 2. Schematic representation of nanotube-based transmitter and receiver modules. In the transmitter (top), the nanotube acts as modulator and antenna. In the receiver (bottom), it acts as antenna and demodulator. (Source: A. Nojeh et al., "Reliability of Wireless On-chip Interconnects Based on Carbon Nanotube Antennas," *Proc. 14th IEEE Int'l Mixed-Signals, Sensors and Systems Test Workshop,* IEEE Press, 2008, pp. 1-6.)

If the antennas are placed on microtowers with a height of 50 μm, assuming the nanotubes with the lowest band gap in the batch of nanotubes utilized have a band gap of around 0.5 eV (corresponding to a maximum wavelength of 2.48 μm), r_0 will be greater than 6 mm. This means that we could still be operating within the inverse-square power loss region in an on-chip wireless network. Nonetheless, it may turn out that the power generated by the nanotube will not be enough to enable an adequate range. Using collections of parallel nanotubes to increase the transmitted or received power could provide a potential solution, as well as allow for more directionality. Another possibility might be to use a separate "oscillator"—that is, light source (which could be an on-chip light-emitting diode or laser)—with enough power to excite the transmitting nanotube, and to use the nanotube only as the antenna, which is conceptually similar to conventional radiofrequency circuits.

Communication channels

The wavelength and frequency of the light generated through electron-hole recombination in the transmitter depend on the nanotube's electronic structure. Based on the IBM research, the full width at half maximum (FWHM) of the emission and absorption spectra are in the 0.1-eV order of magnitude.[3] Using a conservative 0.15 eV for frequency channel width, and given that SWNTs have band gaps of up to around 1.5 eV, this leads to the possibility of approximately 10 different frequency channels using different nanotube types.

Light emitted by the nanotube is polarized along the axis, and absorption is also polarization dependent. This might provide an additional means of separating channels by using antennas positioned in various directions with respect to each other. The simplest way to exploit this property is to double the number of channels, as we have discussed, by using nanotubes in horizontal and vertical directions. Whether, in practice, polarization can be used to create additional channels will depend on the nature of the propagation environment. In any case, a limited number of channels are available, and we must develop appropriate coding schemes and communication protocols to enable a large number of communicating devices on a chip to share the limited number of channels.

Fabrication challenges and opportunities

For a given application, an important question is whether the current nanotube fabrication methods provide enough control over nanotube properties including chirality, diameter, length, and orientation. Variations in these can significantly impact device performance (see the "Device-to-Device Variations" sidebar). Carbon nanotubes can be fabricated by a variety of processes, including arc discharge, laser ablation, and chemical vapor deposition (CVD). To use nanotubes for electronic device applications, we typically use one of two approaches. The first consists of growing a collection of nanotubes, subsequently purifying and/or sorting them and finally depositing individual or collections of nanotubes where needed. The deposition typically takes place from a solution containing dispersed nanotubes, either randomly or using a method such as dielectrophoresis. Nanotubes can also be directly grown in predefined locations using catalytic CVD, where the location of catalyst islands determines where nanotube growth starts.

The methods we have described have allowed researchers to make individual or small sets of nanotube-based electronic devices. However, the controllable fabrication of a large number of nanotubes in a repeatable, scalable manner has proven to be a tremendous challenge and remains a major obstacle to nanotubes' becoming a commercial reality for applications such as integrated electronics. Even if controlled fabrication were to become a reality, nanotube integration with CMOS circuits would still present challenges. For example, the high-temperature CVD growth of nanotubes could damage existing CMOS circuitry on the substrate.

Controlled fabrication is an active research area involving both academia and industry, and various research groups report advances regularly. For instance, centrifugation-based techniques have been developed to sort nanotubes based on electronic and optical properties. The application of an electric field, using CVD gas flow direction or taking advantage of pre-defined patterns on a substrate surface, can help align nanotubes in desired directions. Moreover, ways exist to modify nanotube properties after fabrication. The device length can be determined by depositing electrodes after the growth of nanotubes on a surface or by using a focused ion beam to selectively cut sections of nanotubes. Mechanical deformation can affect nanotubes' electronic properties; by applying pressure to a given metallic nanotube, we could change its electronic structure to semiconducting and vice versa.

Are nanotube antennas really a solution?

The exact amount of optical power absorption in nanotubes and the maximum achievable efficiency in converting it to electric power remain open questions. Whether nanotube optical antenna devices will indeed enable wireless on-chip communication at reasonable distances (mid- to long-range interconnect) is still unknown. As we have mentioned, experiments point at efficient light absorption in nanotubes,

Device-to-Device Variations

Given that light absorption directly depends on the electronic structure of the material, in nanotubes there is a strong dependence of light absorption on the chirality and diameter. Bachilo et al. measured distinct absorption and emission transitions for a wide variety of semiconducting nanotubes.[1] Dukovic et al. used two-photon excitation spectroscopy to investigate the dependence of exciton binding energies and band gap on nanotube structure and found these quantities to scale inversely with diameter.[2]

Researchers are also studying optical absorption in nanotubes theoretically, for example, by calculating the transition dipole moments based on the tight-binding approximation for the electronic structure of nanotubes.[3] We earlier proposed a simple structure for nanotube-based transmitters and receivers[4] and, based on a classical approach, estimated that optical absorption in nanotubes can be very sensitive to their diameter.[4] Figure C shows that a change of diameter from 1 nm to 3 nm can change the absorbed power by almost an order of magnitude. Therefore, for such nanotube-based circuits, the design of robust and reliable circuits or systems based on components with large random variations becomes a crucial aspect of the research.

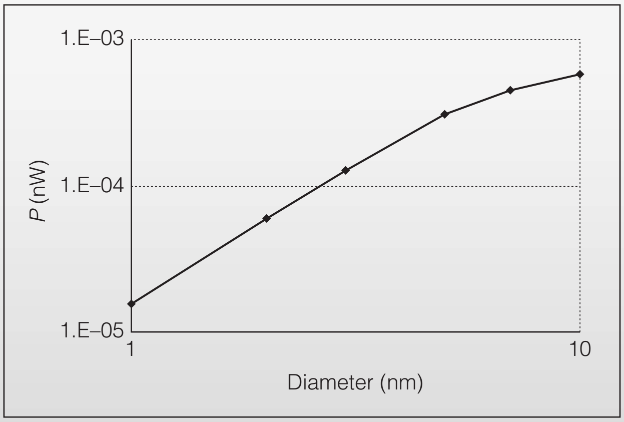

Figure C. Effect of diameter on power absorption in a nanotube receiver antenna. (Source: A. Nojeh et al., "Reliability of Wireless On-chip Interconnects Based on Carbon Nanotube Antennas," *Proc. 14th IEEE Int'l Mixed-Signals, Sensors and Systems Test Workshop,* IEEE Press, 2008, pp. 1-6.)

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yet researchers are working on the use of nanotubes as transparent electrodes for applications in solar cells on the premise that nanotubes will not absorb much of the incoming light. The key to reconcile this seeming contradiction is in realizing that whether nanotubes have high absorption or transparency depends on how a collection of nanotubes is used to form a particular structure, as well as on the nanotubes' electronic structure. Also, depending on the application, the definition of what is a good or poor absorber of light can vary. For instance, for a given thickness, a nanotube layer might absorb more light than a similar layer made of other materials. Due to nanotubes' high conductivity, however, a single layer of well-ordered nanotubes could provide a good level of conduction for application as a solar cell electrode. To achieve the same level of conductivity with another material would require a higher thickness, with correspondingly higher optical absorption.

OVERALL, NANOTUBES ARE seemingly good absorbers of light relative to their dimensions. Further investigation is necessary before a strong claim can be made on their usefulness for applications such as small-scale wireless communications. In particular, communication between a nanotube emitter and receiver pair working at optical frequencies is yet to be demonstrated. Recent experiments by Gabor et al. provide more hope for ultra-efficient light-to-electricity conversion in nanotubes.[12] They have demonstrated that multiple electron-hole pairs can be generated as a result of the absorption of only one photon, which has direct implications for the application we have discussed. Similarly, Mueller et al. have recently demonstrated nanotube light emitters with improved light generation efficiency.[13] These important works suggest that we could be closer to having a nanotube-based on-chip communication system than we think. ■

Acknowledgments

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Alireza Nojeh is an assistant professor of electrical and computer engineering at the University of British Columbia. His research interests include the fabrication, characterization, and modeling of nanodevices, in particular based on carbon nanotubes. He has a PhD in electrical engineering from Stanford University and is a member of IEEE.

André Ivanov is a professor and head of the Department of Electrical and Computer Engineering at the University of British Columbia. His research interests include the design, test, and reliability of integrated circuits and systems. He has a PhD in electrical engineering from McGill University. He is a Fellow of the IEEE and a Professional Engineer of British Columbia.

■ Direct questions and comments about this article to Alireza Nojeh and Andre Ivanov, Dept. of Electrical and Computer Engineering, University of British Columbia, Vancouver BC, V6T 1Z4, Canada; anojeh@ece.ubc.ca and ivanov@ece.ubc.ca.