Spotlight

Interview with Mitrajit Dutta (Ph.D., 2000)

Assistant Professor
Deptartment of Mathematics and Statistic
University of New Hampshire

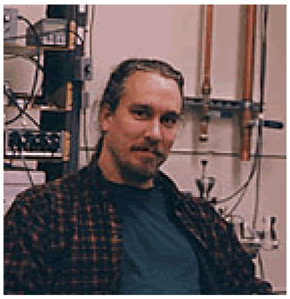
By: Karrie Sue Hawbaker, editor

I recently spoke to Dr. Mitrajit Dutta, assistant professor at the University of New Hampshire and a 2000 graduate of the University of Maryland Department of Physics. He talked to me about his journey from Maryland Physics to his current position as assistant professor in the Department of Mathematics and Statistics at the University of New Hampshire, sharing information about his current research, the lessons he's learned, advice to our student physicists and more.

Professor Dutta began his higher education career at the Indian Institute of Technology at Kanbur, where he studied physics in a program that led him directly to a masters of science degree. It was then that he came to Maryland to earn a doctoral degree. Demonstrating an interest in the field of nonlinear dynamics and chaos, Dutta seized the opportunity to study under two of the field's heavyweights, Professor Edward Ott and Professor James Yorke (who is widely credited for naming the field of Chaos). By the Spring of 2000, he had explored several ideas in chaos theory and presented a dissertation on a collection of five different problems dealing with synchronization, shadowing and border collision.

By the time he earned his Ph.D., Dutta knew that that he wanted a career dedicated to research and he recognized that the fields of academia and federal government research offer some of the best opportunities for research physicists. The fact that he is not a U.S. citizen precluded him from working for a government laboratory, so he chose to explore the world of academia. Like so many new graduates, he applied for several postdoctoral positions at universities across the U.S. However, Dr. Ott, confident in his student's abilities, advised Dutta to also apply for some faculty positions. So, when a friend told him that the University of New

Spotlight



Semiconducting Nanotubes

By: Professor Michael Fuhrer

Introduction to Carbon Nanotubes

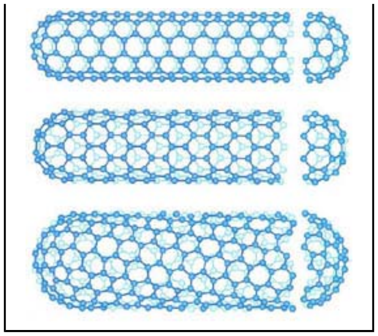
Carbon nanotubes are wires of pure carbon with nanometer diameters and lengths of many microns. A single-walled carbon nanotube (SWNT) may be thought of as a single atomic layer thick sheet of graphite (called graphene) rolled into a seamless cylinder. Multi-walled carbon nanotubes (MWNT) consist of several concentric nanotube shells.

Understanding the electronic properties of the graphene sheet helps to understand the electronic properties of carbon nanotubes. Graphene is a zero-gap semiconductor; for most directions in the graphene sheet, there is a bandgap, and electrons are not free to flow along those directions unless they are given extra energy. However, in certain special directions graphene is metallic, and electrons flow easily along those directions This property is not obvious in bulk graphite, since there is always a conducting metallic path which can connect any two points, and hence graphite conducts electricity.

However, when graphene is rolled up to make the nanotube, a special direction is selected, the direction along the axis of the nanotube. Sometimes this is a metallic direction, and sometimes it is semiconducting, so some nanotubes are metals, and others are semiconductors. Since both metals and semiconductors can be made from the same all-carbon system, nanotubes are ideal candidates for molecular electronics technologies.

In addition to their interesting electronic structure, nanotubes have a number of other useful properties. Nanotubes are incredibly stiff and tough mechanically - the world's strongest fibers. Nanotubes conduct heat as well as diamond at room temperature. Nanotubes are very sharp, and thus can be used as probe tips for scanning-probe microscopes, and field-emission electron sources for lamps and displays.

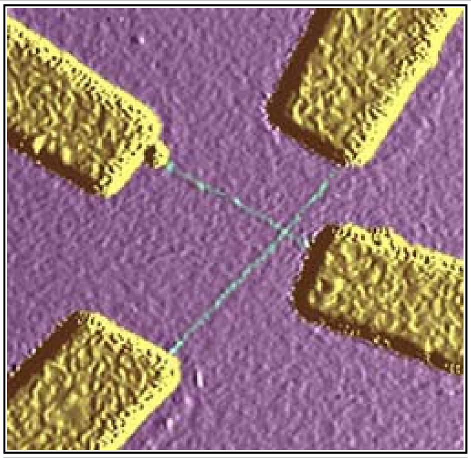
Device Fabrication



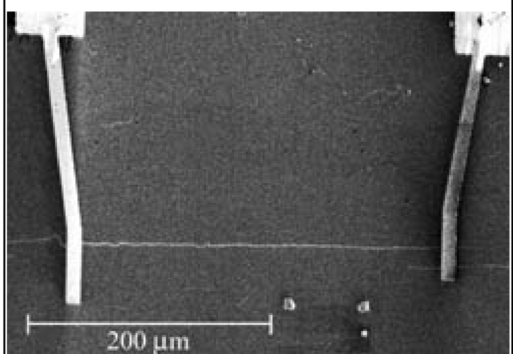
Three nanotubes of different chiralities.
(courtesy Smalley Group web site)

Find 'em and wire 'em

In the Fuhrer lab we have developed techniques for synthesizing carbon nanotubes directly on silicon substrates, locating individual nanotubes, and electrically contacting nanotubes with metallic electrodes. The general idea is to "find 'em and wire 'em", as opposed to attempting to self-assemble nanotubes in place, or deposit nanotubes or wires at random and hope to contact some nanotubes. The great advantage of the find 'em and wire 'em technique is that we can make customized devices. Some examples are below.



Atomic force microscope (AFM) image of crossed nanotubes (green) contacted by Au electrodes (yellow) using the "find 'em and wire 'em" technique. In this work, performed at UC Berkeley, the nanotubes were deposited onto the chip from solution, and located using the AFM.



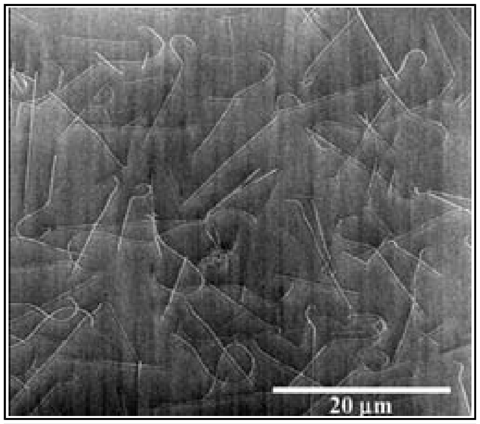
Scanning electron microscope (SEM) image of a long nanotube transistor fabricated at Maryland using the "find 'em and wire 'em" technique. The nanotube is the thin horizontal white line connecting the two gold leads (thicker vertical lines). Here the nanotubes were grown by chemical vapor deposition directly on the substrate, and located using the SEM.

The disadvantages of the find 'em and wire 'em scheme are that we are able to make only a limited number of devices, and the technique is not "scalable" - that is, making twice as many devices takes twice as much time. If nanotubes are to find electronic applications in industry, scalable fabrication techniques will be needed. However, our current techniques allow us to jump ahead and explore single nanotube devices, to see if they have the useful properties that would warrant developing techniques to mass produce devices.

CVD growth of nanotubes

Largely following research by the Dai Group at Stanford and the Lieber Group at Harvard, we are using chemical vapor deposition (CVD) to prepare our carbon nanotubes. The basic ingredients needed for CVD growth of nanotubes are a small catalyst particle (typically iron or iron/molybdenum) and a hot environment of carbon-containing gas (we use CH_4 and C_2H_4). The metal particle catalyzes the decomposition of the carbon-containing gases, and the carbon dissolves in the catalyst particle. Once the catalyst particle is supersaturated with carbon, it extrudes out the excess carbon in the form of a tube. One catalyst particle of a few nanometers in diameter can produce a nanotube millimeters in length, about 1 million times the size of the particle.

Typically we use silicon chips (pieces of flat silicon wafer from the semiconductor industry) as our substrate material, with a layer of silicon dioxide (glass) grown on top of the silicon as an insulator. The catalyst con be obtained in several ways; the easiest is to dip the silicon chip into a solution of ferric nitrate in isopropanol, and then dip the chip into hexane to cause the ferric nitrate to come out of solution. This deposits nanocrystals of ferric nitrate on the chip, which can be reduced to iron with hydrogen in the growth furnace.



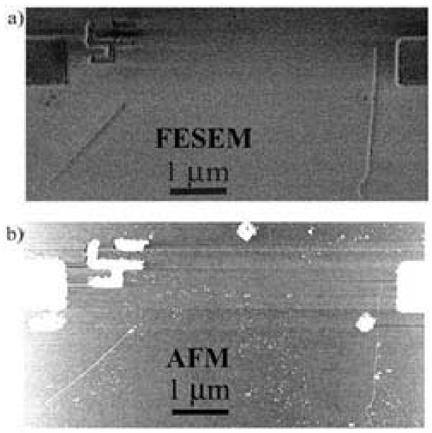
Nanotubes grown by the CVD process on a silicon dioxide covered silicon chip. The thin white lines are the nanotubes. The nanotubes here form a continuous conducting network, and thus are too dense to use for device fabrication.

Locating the nanotubes

Once the nanotubes are grown on the substrates, we need to locate them. To do this, we first deposit a pattern of alignment marks on the substrate, using a conventional lithography technique (actually we use electron-beam lithography, but optical lithography would work as well). Our original method for locating nanotubes was to use the atomic force microscope (AFM). The AFM uses a tiny needle on the end of a diving-board-like cantilever to tap on a surface as it scans over that surface. It senses the amplitude of the tapping and use that to follow the height variations in the surface, making a topographical map of the area. The AFM is very sensitive, so it is able to image the nanometer-diameter nanotubes lying on the flat substrate. However, AFM is very time consuming, taking 5 minutes or so to image a 10 x 10 micron square image.

Recently we have developed a technique to image nanotubes using the scanning electron microscope (SEM). This imaging technique relies on the fact that the nanotubes are conducting, and the substrate on which they are lying is insulating. The SEM images by scanning a high-energy beam of electrons over the sample. Secondary electrons generated by the energetic beam are collected and amplified to produce the image signal. When the SEM beam hits an insulator, some electrons stick in the insulator and it becomes negatively charged. When the beam scans over the nanotube, the electrons are free to spread out along the nanotube, and thus the area around the nanotube is less negatively charged. The less negatively charged area allows more electrons from the substrate to escape and be detected, producing a signal when the beam scans across the nanotube. Examples of SEM and AFM images of nanotubes are seen below.

Once the nanotubes are located, they may be contacted electrically using



Comparison of field-emission scanning electron microscope (FESEM) and atomic force microscope (AFM) images of nanotubes (two narrow lines) and Cr/Au alignment markers (squares and geometric shapes). The FESEM (a) images the conducting alignment marks and nanotubes, but is insensitive to the surface contamination visible in the AFM image (b). The FESEM image was acquired approximately 100 times faster than the AFM scan.

electron-beam lithogrpahy (EBL). A thin layer of resist (a polymer) is spun onto the chip, and the SEM is used again, but this time the energetic electron beam is used to write a pattern in the resist where we want the electrodes to be. The resist which has been exposed to the beam is then washed away in a solvent, and metal (such as gold) is evaporated into the holes in the resist, forming wires which contact the nanotubes. The excess metal which is on top of the resist is lifted off of the chip using a second solvent which dissolves the remaining resist. The electrodes for both the crossed nanotube device and the long nanotube device shown above were fabricated using EBL

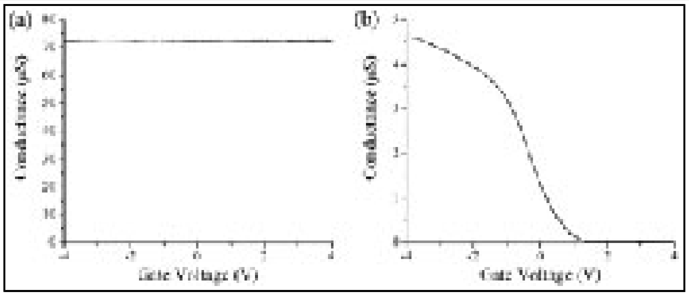
Electrical measurements

The wires on the chip are much bigger than the nanotube, but still fairly small - typically the largest parts of the wires on the chip are one or two tenths of a millimeter across. We make contact to the wires on the chip under a microscope, either by using a wire bonder which can attach larger wires to the chip to connect it to a rigid chip holder, or by using a probe station, which has sharp needles that can be used to temporarily make contact to the wires on the chip.

Once electrical contacts are made to the nanotubes, we can test their electrical properties. The simplest nanotube device has just two electrode, one at each end of the nanotube. There is actually a third electrode, called the gate, which is the silicon substrate underneath the nanotube. This electrode is not in electrical contact with the nanotube, since it is separated from the nanotube by an insulator (typically silicon dioxide). However, the capacitor formed by the nanotube and the gate can be charged by applying a voltage between nanotube and gate. This way we can change the amount of charge on the nanotube.

When we change the gate voltage (changing the amount of charge on the nanotube) and measure the conductance between the two contacts on the nanotube (conductance is the inverse of resistance) we see one of two types of behavior. Either the conductance stays constant as we change the gate voltage, or it drops dramatically as we make the gate voltage more positive (see below). We identify the first type of behavior with the metallic nanotubes - changing the charge on a metal does not change its conductance. The second type of behavior we associate with the semiconducting nanotubes - unless they are "doped", semiconductors don't have any charges which can carry current. The gate voltage allows us to add charge to the nanotube and make it conduct. Negative gate voltage adds "holes" (positive charges corresponding to the absence of an electron) to the nanotube, and it conducts better.

Around zero gate voltage there are no holes, and the nanotube stops conducting. (The nanotube should conduct again at a positive enough voltage which would add negatively charged electrons to the nanotube, but it doesn't for reasons related to a barrier at the metal-nanotube interface.)



Conductance as a function of gate voltage for (a) a metallic nanotube, and (b) a semiconducting nanotube.

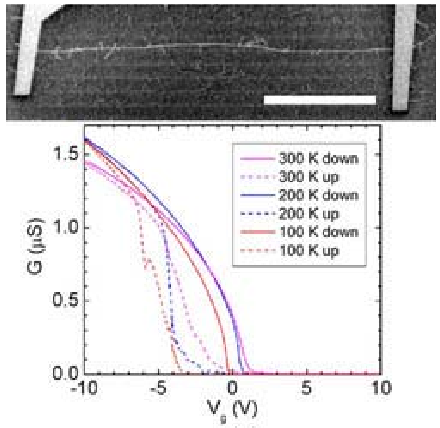
Conductance and Mobility

Recently, much of our research has focused on semiconducting nanotubes, because of their utility for devices. Since the conductance of the semiconducting nanotube can be changed by the voltage on a third electrode (the gate), the nanotube acts like a switch. This type of switch is called a field-effect transistor (FET), and forms the basis of most computer chips used today. We are very interested in determining how well nanotubes perform as field-effect transistors, in order to gauge their prospects for future electronics applications.

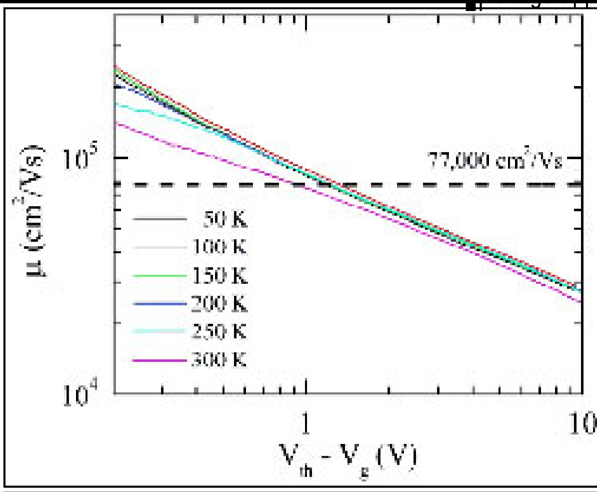
The first question one might ask is: How well do semiconducting nanotubes conduct? The figure below shows the conductance of a very long nanotube (about 1/3 of a millimeter long) as a function of gate voltage. The highest conductance observed is 1.6 micro-Siemens, which corresponds to a resistance of around 600 kilo-Ohms. How does this compare to other materials? In order to compare, we need to consider the conductivity, conductance x length/area. This takes into account the fact that we expect a long, thin wire to have lower conductance than a short, fat wire. The conductivity of the nanotube is around 2.6 micro-Ohm-centimeters. This is comparable to good metals like copper (1.6 micro-Ohm-centimeters), which is very surprising. This means that this nanotube switch can be tuned from insulating, to conducting as well as copper, simply by changing the gate voltage!

The above analysis also hints that conductivity isn't the best number to use when comparing one semiconductor to another, since the conductivity changes with charge density (in this case with gate voltage). It's fine for metals, like copper, where the charge density is very high and doesn't change much. The number that's used to indicate how well one semiconductor conducts compared to another is mobility. Mobility is the conductance divided by the density of charge carriers, so it can be used to compare the conductance of semiconductor samples with different amounts of charge to carry the current.

We know the charge density in our nanotube devices, because we know the capacitance C between the nanotube and the gate electrode that is producing the charge. The charge Q is proportional to the capacitance and to the amount of gate voltage V we have applied: $Q = CV$. So we know everything we need to find the mobility. The mobility of one of our long nanotube transistors is shown below.



The top panel shows an SEM image of a long semiconducting carbon nanotube spanning between two gold electrodes (scale bar is 100 micrometers). The bottom graph shows the conductance of this nanotube as a function of the voltage applied to the back gate (silicon substrate) …ures of 300, 200, and 100 Kelvins.



Mobility as a function of gate voltage for a semiconducting carbon nanotube. At low gate voltage (low charge carrier density) the mobility exceeds that of InSb (77,000 cm2/Vs), the previous highest-known mobility at room temperature.

The mobility is higher than 100,000 cm2/Vs at room temperature, higher than any other known semiconductor. (The previous record, for InSb, was 77,000 cm2/Vs, set in 1955.) The mobility is a function of the gate voltage, and is higher when the gate voltage is low, i.e. when there are fewer charges in the devices. We don't know why this is yet, but we are studying this. The mobility is also rather independent of temperature, suggesting that the thermal vibrations of the lattice, called phonons, don't play much of a role in scattering the electrons.

Why is the mobility so high? Part of the reason is that graphite itself is a good conductor of electricity. The mobility of charges in graphite is around 20,000 cm2/Vs at room temperature. Graphite also has other excellent properties - it's strong, lightweight, and an excellent conductor of heat. But graphite isn't a semiconductor - it doesn't have a bandgap - so it can't be used to make semiconductor devices like transistors. The nanotube can be thought of as a way to engineer a bandgap in graphite so we can use it for semiconductor devices (see Introduction to Carbon Nanotubes above). The mobility in nanotubes turns out to be even higher than in graphite. Part of the reason for this may lie in the one-dimensional nature of the nanotube - it's harder to scatter electrons in one-dimension, because they can only go forward or backward, not to the sides.

Dr. Michael Fuhrer is an assistant professor here in the Department of Physics at the University of Maryland. A member of our nanotechnology initiative, Professor Fuhrer specializes in carbon nanotube electronics, single molecule electronics and nanopatches. For more information, he can be reached at mfuhrer@physics.umd.edu.

Hampshire was conducting a search for an assistant professor, he applied. Fortunately, he was soon offered a position in the Department of Mathematics and Statistics at the University of New Hampshire, which he accepted.

Since then, he and his UNH colleagues have been exploring several topics that are either extensions of or related to his thesis, including:

· Synchronization of Chaos
· Communication with Chaos
· Controlling Chaos
· The Breakdown of Shadowing in Chaotic Systems
· Algorithms for Generating Shadowing Trajectories
· Algorithms for Estimating Model Parameters for Chaotic Systems
· Border Collisions and Multiple Attractor Bifurcations
· Quantum Mechanical Properties of Fractal Systems
· Connections Between Chaos and Information Theory

Dutta and his team are also exploring interdisciplinary research with several other scientists at the University of New Hampshire, including those in the departments of biology and mathematics.

Though Dutta is principally interested in research rather than teaching, he has also been quite successful enlightening both undergraduate and graduate students on the principles of mathematics and physics, especially in the area of chaos. In the last four years, he has repeatedly received positive feedback from his students.

He partly attributes his success in this area to the experience he gained as a teaching assistant here at Maryland Physics and the Department's teaching assistant orientation program. Dutta was a TA for both undergraduate courses and for graduate classes in advanced statistical mechanics and chaotic dynamics. While he didn't always find life as a TA one hundred percent rewarding, he feels that he learned several important lessons from the experience. He learned to quickly read where the students were academically and to adjust his teaching accordingly. He learned a careful balance of teaching material that was demanding enough that it did not bore the students, but not so demanding that its difficulty only led them to frustration. And he learned valuable communication or "people" skills. In fact, he noticed a dramatic improvement in these skills after merely one semester. He also found that, as someone coming to the University from another culture, working as a teaching assistant gave him interactions with people that helped him learn about the American perspective.

Professor Dutta's career in academia has taught him several important lessons, including:

· **Patience.** Patience is important in everything from research to teaching -- and especially when you are teaching undergraduates the day after a football game!
· **Diligence.** A career in physics, just like so many others, requires hard work and diligence.
· **Persistence.** Often, your first approach to a problem will be one that someone else

has already tried. And often, on the first try, you will fail. It is important to be persistent and try another way, never losing your sense of optimism.

Professor Dutta also offers some advice to our Maryland Physics students.

· Don't be afraid to try something new or off the beaten path. One needs to be resourceful and creative in this field.
· Don't turn away from an idea just because its unconventional - sometimes they are the only ones that work.
· Take advantage of the cultural and entertainment opportunities in the D.C. area - especially those Kennedy Center student discounts!
· Enjoy it while it lasts! Take the time to enjoy both the excitement of exploring many different research ideas and the camaraderie with your faculty and fellow students. Integrating your research into lunches and dinners is a great way to enjoy both the exciting science and the social relationships that make higher education such a great adventure.

As someone still in the early stages of his career, Dutta has set many goals for himself. On the short term, he is working toward becoming a tenured professor. However, on the longer term, his ultimate goal is to do good science.

The University of Maryland Department of Physics is very proud of Professor Dutta for his accomplishments and wishes him the best of success in his future endeavors!

If you would like to find out more about Professor Mitrajit Dutta and his work, please visit his Web site at www.math.unh.edu/~dutta. If you have questions for him, please feel free to email me at karrie@physics.umd.edu with "Question for Dr. Dutta" in the subject line. I will be happy to pass the inquiry along to him.

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