Physics of Multiwall Carbon Nanotubes

Christian Schönenberger and Laszlo Forró (Physics World Vol 13, No 6, 2000)

Imagine being a tailor in the nanoworld with the task of tailoring a robust drinkstraw for a virus. You might come to the idea of taking a sheet of graphite (known as graphene), cutting out a long slice which is then rolled up and stitched together to form a carbon tube. These single-wall carbon nanotubes are reality, but rather than sewing the borders together, Nature forms these tubes seamless with a typical diameter of 1-2 nm. Sumio Iijima at NEC Fundamental Research Laboratory in Tsukuba discovered these giant molecules in 1991 when he studied the soot created by a direct-current arc discharge between carbon electrodes with high resolution transmission electron microscopy. What Iijima found where nanotubes consisting of several concentrically arranged single-wall carbon tubes nested into each other like a russian doll (see Figure 1 a-b).These multishell nanotubes have outer diameters typically in the range of 10-50 nm and are now refered to as multiwall carbon nanotubes (MWNTs). Later, SWNT were discovered too and an efficient method for their production was found by Thomas Ebbesen and coworkers, also at NEC. Today, nanotubes can also efficiently be grown by catalytic decomposition of a carbon containing reaction gas (see the article of Hongjie Dai in this issue). This process has two main advantages. In the first place nanotubes are obtained at much lower temperature. This, however, at the cost of lower perfection (Figure 1 c). Secondly, the catalyst (for example iron) may be structured on the substrate which allows the selective growth of nanotubes. This has enabled the growth of structured "nanobrushes" consisting of vertically aligned nanotubes at high density (see Figure 1d). Presently nanotubes can be grown to a length exceeding 100 micrometer, yielding fibres with a very high-aspect ratio. Magically, "telefon cords" or "nanosprings" form too (Figure 1e).

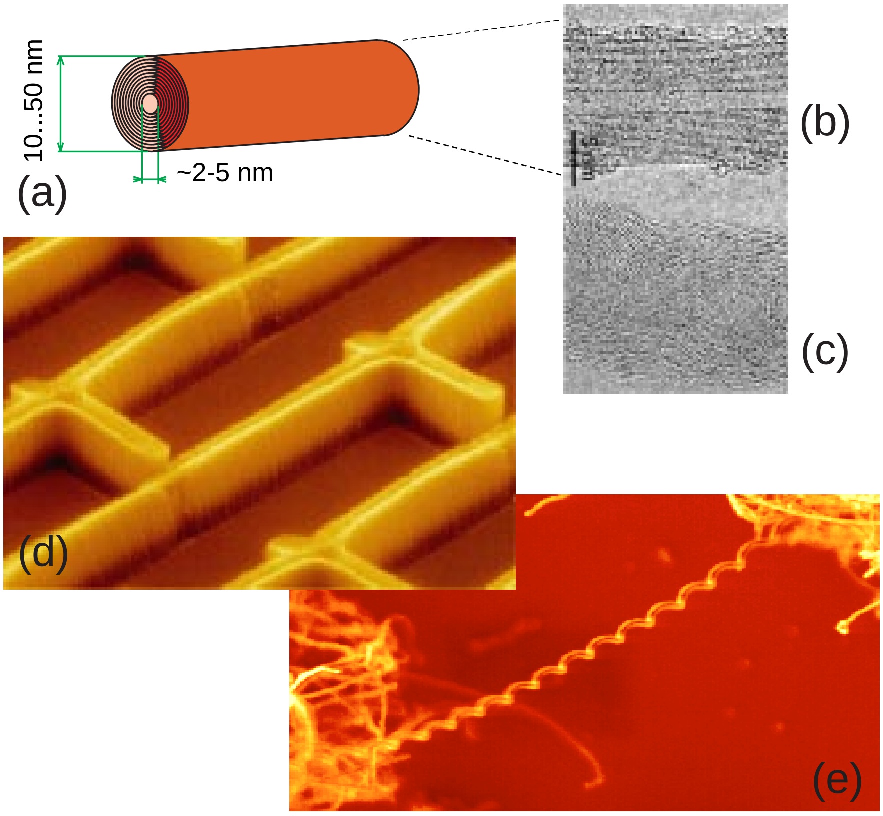

Figure 1
(a) Multiwall carbon nanotubes (MWNTs) are composed of a set of single-wall tubes concentrically stacked into each other with a typical outer diameter of 20nm. Such a structure is clearly seen in the high-resolution transmission-electron microscopy (TEM) image (b) of a well ordered MWNT grown in an arc-discharge. In contrast, (c) shows a TEM image of a highly disordered MWNT for which the idealized picture (a) does not apply. (d) shows a scanning-electron microscopy (SEM) image of a structured "brush" of vertically aligned carbon nanotubes. The structure is obtained by first printing a catalyst and subsequently growing the nanotubes selectively at the catalyst sites by thermal decomposition of a reaction gas. Depending on growth parameters, different forms of nanotubes are obtained, such as spirals (d) which are surprisingly regular. Sources: (b) and (c) Jean-Marc Bonard et al., Dep. of Physics, EPFL, Lausanne, Switzerland. (d) Hannes Kind et al. (EPFL) in collaboration with the groups of L. Forró (EPFL) and L. Schlapbach (Univ. of Fribourg). (e) Louis Schlapbach et al., Univ. of Fribourg, Switzerland.

Carbon nanotubes can be viewed as giant buckyball molecules, also called fullerenes. The basic buckyball is a 60 carbon atom soccer ball. If sliced into two halves a ring of 10 atoms can be added to get a rugby-ball. Repeating this will result in cylindrical molecules capped by half a buckyball at both ends. This is in fact also true for well ordered MWNTs, for which all shells are capped. Multishell fullerenes are also known and called carbon onions. A multiwall nanotube is therefore a cylindrical onion or a carbon leek. Apart from these different shapes, the physics of carbon nanotubes depends on the direction of the tube axis relative to the lattice of the graphite sheet. There are many possible choices to roll a slice of graphene into a seamless cylinder. If bent into a nanotube the hexagons may spiral around the cylinder. Depending on this "chirality" carbon nanotubes can be metals with high electrical conductivity, or semiconductors with a relatively large band gap. Nanotubes have other remarkable properties: they are robust, very stiff with record elastic modulus, but at the same time not brittle at all. They can snap from one shape to the other if strongly compressed to finally resume their orginal perfect straightness if relaxed. These mechanical properties can, for example, be exploited for reinforcement, for nanomanipulators (tweezers) and for high-resolution scanning probe tips. Being composed of carbon only, nanotubes have a low specific weight, too. Furthermore, carbon nanotubes are hollow tubes and may be used in the future as nanopencils in which the capillary is used to deliver "ink" on the nanometer scale.

This article focuses on the physics of MWNTs. These nanotubes have for example been used as sharp tips for imaging applications in scanning-probe microscopy and as electron emitters. Electrical and mechanical properties have been studied. We intend to highlight some of these experiments in the following. Though a single-shell nanotube consitute the basic form of these molecules, multiwall nanotubes allow to study the transition from a single molecule to the behaviour of a macroscopic crystal. The later is graphite which is a layered compound consiting of an infinite stack of graphene sheets. A multiwall nanotube, that is cylindrical graphite, is a mesoscopic form, in between the single-wall nanotube molecule and planar graphite.

The carbon atoms of a single sheet of graphite are arranged in a planar honeycomb lattice in which each atom coordinates with a strong chemical bond to three neighbour atoms. The basal-plane elastic modulus of graphite is one of the largest of any known material. Graphite is therefore a very stiff material provided stress is applied within the plane. For this reason, carbon nanotubes are expected to be ultimate high-strength fibres.

In 1996 Treacy, Ebbesen and Gibson from NEC Princeton and the University of Illinois studied MWNTs, which were ridgidly supported on one side, in a transmission-electron microscope (TEM). The free ends of the nanotubes appeared considerably blured. These nanotube levers do vibrate, stimulated by thermal excitations, causing the observed bluring. From the measured vibration amplitude, an exceptionally high elastic modulus (Young's modulus E) of order E = 1 Tpa was derived. For a comparison, steel has a five times lower modulus. It is now known that for tubes with a radius larger than 1 nm, the Young's modulus should approach a value of 1.25 Tpa. This is true both for MWNT and SWNT because the modulus is mainly determined by intra-shell carbon bonds. This value has recently been confirmed. Charles Lieber and coworkers from Harvard University used a scanning-force microscope (SFM) to intentionally bend nanotubes which were dispersed on a substrate and mechanically fixed on one side. The scanning-force microscope not only allowed to image and manipulate the tubes, but could also be employed to measure the force needed to bend the tubes. Similar values for E were obtained. Another technique to explore the bending stiffness was developed by Jean-Paul Salvetat and coworkers from the EPFL in Switzerland. It involves depositing nanotubes from a suspension in liquid onto well-polished alumina ultrafiltration membranes with a pore size of about 200 nm (Figure 2a). By chance, carbon nanotubes occasionally span the pores. The deflection of these supported tubes is then deduced from atomic-force microscopy (AFM) images operating at various normal loading force (Figure 2b). The thus measured deflection is inversely proportional to the Young's modulus. Salvetat and coworkers compared the modulus of MWNTs grown by arc-discharge and catalytic decomposition of hydrocarbons. E is found to be approxiomately 1 Tpa for the former, while for the catalytic ones a much lower -- by one to two orders of magnitudes -- modulus was found. This result demonstrates that only highly ordered and well graphitized nanotubes have a stiffness comparable to graphite. In contrast, MWNTs grown by catalytic decomposition have much more defects.TEM images (Figure 1c) indeed reveal that the carbon sheets are neither continuous nor nicely parallel to the tube axis.

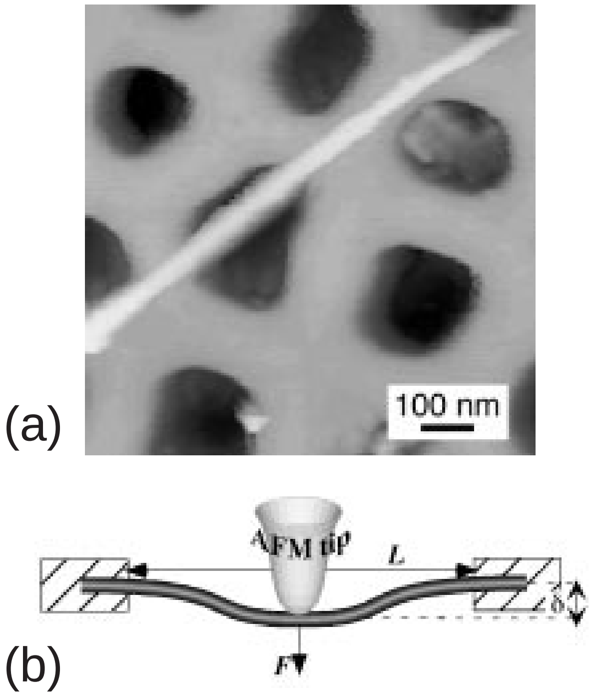

Figure 2
(a) AFM (atomic-force microscopy) image of a single MWNT adhered on the poslished surface of an ultrafiltration alumina memmbrane. Part of the nanotube is bridging over a pore (dark) of the membrane. (b) Schematic of the measurement: the AFM is used to apply a load to the nanobeam and to determine the resulting deflection. Sources: (a) Jean-Paul Salvetat et al. from EPFL, Lausanne, Switzerland. Published: Adv. Mat. 11, p161 (1999). (b) Jean-Paul Salvetat et al. from EPFL, Lausanne, Switzerland. Published: Phys. Rev. Lett. 82, p944 (1999).

Charles Lieber and coworkers not only studied the elastic behaviour of nanotubes for small deflections (linear regime) but went on to explore what happens for large deformations. They also compared carbon nanotubes with nanorods made from silicon-carbide (SiC), another very strong material. There was a surprise: Whereas the continous bending of the carbide nanorods ultimately led to fracture, MWNTs could be bent over large angles without fracturing. Instead buckling was observed. This elastic buckling has now been confirmed in several experiments, in which the nanotubes are either bent or axially compressed. Axial compression without any relaxation is possible up to limit, which has been calculated by the great mathematician Euler. Beyond this Euler-limit the initially straight tube or rod will flip into a curved form. If this experiment is performed with a drinking straw at constant load, the straw will suddenly develop kinks. These kinks are not elastic, but rather plastic deformations. The kinks remain if the load is removed. The carbon nanotubes are magic in this respect. If the force exceeds the bending strength, or the Euler limit if axially loaded, they first bend over surprisingly large angles, start to ripple and buckle to finally develop kinks as well. The amazing thing is that all these deformations are elastic and disappear completely if the load is removed. If we would apply nanotubes as mechanical springs, these springs would be very stiff for small loads, but would turn into soft ones for larger loads allowing for large excursions without breaking. Assume our cars would be made one day from carbon nanotubes alone and you would unluckiely crash with your brand new BMW into a wall. As the forces are going to exceed the limits, the tubes will strongly bend and buckle squezzing your car into something like a "VW Beetle". This happens over a relatively long length which is beneficial for an effective "crunch zone". After the crash all buckles and kinks will unfold and your car is as new as it was before! What may not be so favourable in this scenario is the fact, that your car will elastically bounce off the wall as in a billard. If combined with energy-absorbing materials, these mechanical properties of nanotubes may be usefull not only for cars but also, for example, for light bulletproof vests and earthquake-resistent buildings.

Graphite is a highly anisotropic material. It is very stiff for loads applied within the graphene planes. Because adjacent sheets are only weakly bound by Van der Waal forces, a relatively low shear strength results. Layers of graphite can easily be pealed off manually. Actually, this property of graphite allows us to write with a pencil and to sharpen it with simple tools when the pencil turns blunt. Quite in contrast, a nanotube shell cannot easily be pealed off from a MWNT, because of the tubular structure. However, it is quite possible that a single tube can be stripped off under axial stress. This has recently been observed in the following striking experiment. Ruoff and coworkers from the Washington University in St. Louis mastered to fix the ends of a MWNT to two AFM tips and measured the elongation of the nanotube while pulling until the tube broke (Figure 3). The tensile strength was found to be at least an order of magnitude lower than expected assuming a homogeneous stress distribution over all carbon shells of the multiwall tube. But because the support made only contact to the outside of the MWNT, it is the outermost shell which is mainly stressed. Ruoff and coworkers found that above the tensile limit the outermost tubes ruptures first, followed by a sudden and large elongation. From TEM images, these researchers conclude that the ruptured outer shell then slides over the inner tubes.

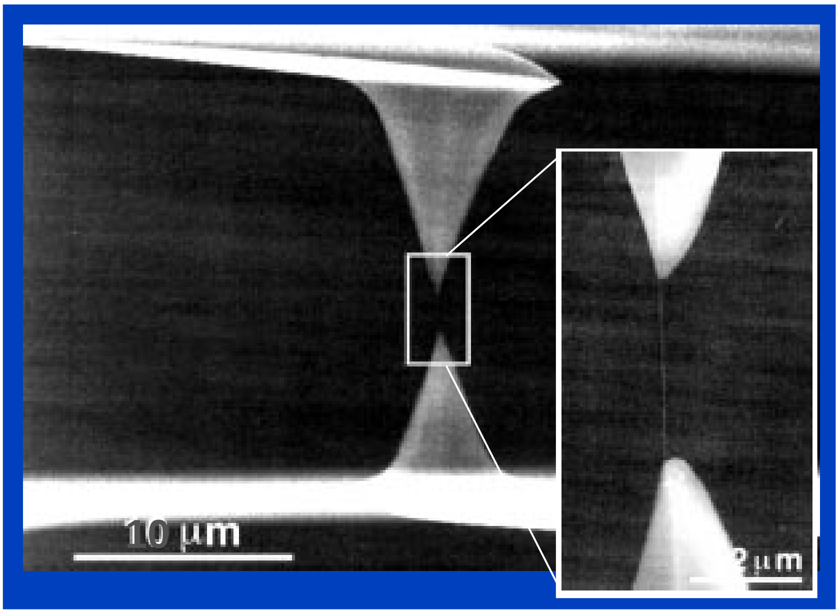

Figure 3
An SEM image of two AFM tips holding a MWNT, which is attached at both ends on the AFM silicon tip by electron-beam deposition of carbonaceous material. Inset: High magnification of the inner portion. Source: Min-Feng Yu et al. in the group of Rodney S. Ruoff from Washington Univ., St. Louis, USA. Published: Science 287, p637 (2000).

The high strength of carbon nanotubes makes them promising candidates in reinforcement applications. There are many outstanding problems to be overcome before composite materials can be fabricated, which reflect the exceptional mechanical properties of the individual nanotubes. As well as optimizing the material properties of the individual tubes, the tubes must be bonded to a surrounding matrix in an efficient way to enable load transfer from the matrix to the tubes. In addition, efficient load bearing within the tubes themselves needs to be accomplished in such a way that shearing is prevented.

Carbon nanotubes are giant molecular wires in which the electrons can freely propagate, as in an ordinary metal. This strongly contrasts with conventional "conducting" polymers (like, for example, polythiophene) where the electrons localize. These molecules are actually insulators and become conductors only if heavily doped. Furthermore, conducting polymers have considerably shorter conjugation lengths. Each carbon atom of the graphene honycomb lattice has four valence electrons of which three are strongly bound to neighbours giving graphene its in-plane rigidity. The fourth electron is delocalized and shared by all the atoms allowing for electrons to conduct. However, it turns out that a single sheet of graphite (graphene) is electronically a hybrid: it is neither a semiconductor, nor a metal. Graphene is a semimetal or a "zero-gap" semiconductor. This peculiarity renders the electronic states very sensitive to additional boundary conditions, as the periodic boundary condition along the circumference of a carbon nanotube. A stationary electron wave can only develop, if the circumference of the tube is a mutliple of the electron wavelength. This condition removes the peculiarity of graphene and turns nanotubes into either true metals or semiconductors. That two sorts of nanotubes exist have experimentally been confirmed in SWNTs (see the article by Paul McEuen in this issue). For MWNTs one expects a more complicated and richer dependence, because of a possible additional electronic coupling between adjacent shells. Combining different nanotubes and sublementing these with gate electrodes a large variety of electronic components ranging from wires, bipolar devices to field-effect transistors can be embodied in nanotubes. On the fundamental side, a perfect metallic nanotube is supposed to be a ballistic conductor. A ballistic conductor is the best (normal electron) conductor an engineer can dream of, only beaten by a superconductor. If an electron is injected from a contact into a ballistic wire with ideal contacts, the electron will end at the drain contact with certainty. There is no back-scattering in the wire, which is the source of intrinsic electric resistance and leads to Ohm's law. A defectless carbon nanotube is like an optical fibre. Fibres with large cores are called multi-mode fibres because several eigenmodes are allowed to propagate (usually at different speed) along the fibre. For data transmission, so called single-mode fibres are prefered because they allow for higher data rates. A single-wall nanotube is almost a single-mode fibre for electrons. Theory predicts not one, but the existence of two propagating eigenmodes independent of the diameter. The electric conductance (the inverse of the resistance) is then expected to be twice the fundamental conductance unit G_0 ($G_0=2e^2/h$). Note, that the resistance is not zero as it would be for a superconductor. But quite in contrast to classical resistors and to Ohm's law, the resistance is independent of the length of the wire. The electronic properties of one-dimensional (1d) conductors have generated a lot of interest. The reason for this excitement lies in the very rich phase diagram and the prediction that in a 1d system Coulomb interaction should lead to a strongly correlated electron gas, called a Luttinger liquid, instead of the usual quasi-particles described by a Fermi-liquid. Here, we will concentrate on two interesting recent experiments that address the question of whether MWNTs are ballistic or diffusive conductors.

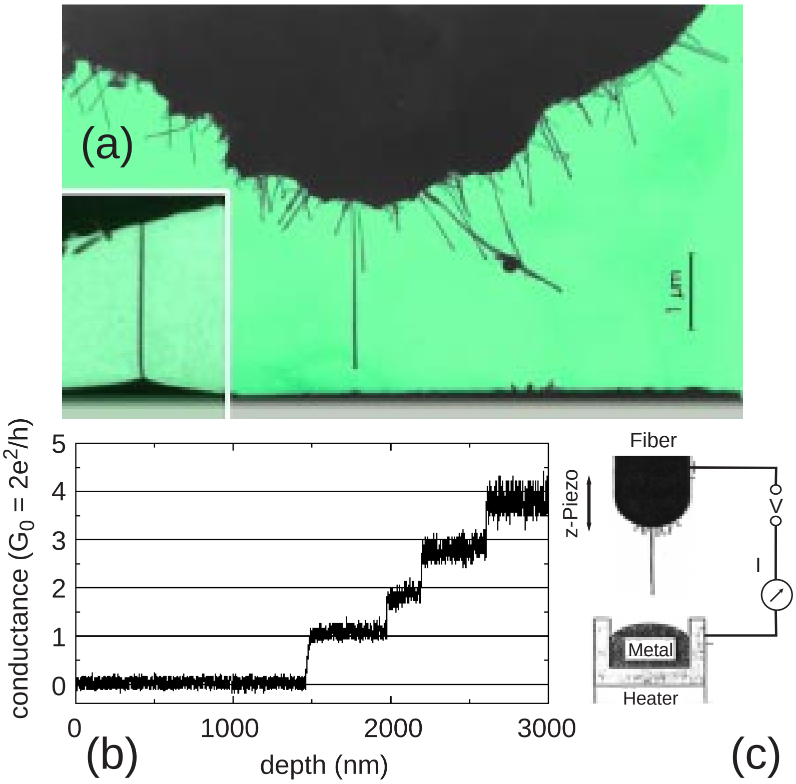

Figure 4
(a) TEM image of the apex of a macrobundle of MWNTs. Several individual nanotubes are seen to stick out from the bundle. Electric characterization of single nanotubes is realized by lowering the bundle into a liquid metal acting as an electric contact (c). A single MWNT immersed into the liquid is seen in the inset of (a). The electric measurement (b) shows the conductance as a function of depth of immersion. The steps are caused by additional nanotubes which subsequently immerse into the liquid metal. The universial step-height, which is close to the quantum conductance, suggests that the nanotubes are ideal waveguides for electrons, so-called quantum wires. Sources: Walt A. de Heer et al., School of Physics, Georgia Inst. of Tech., Atlanta, USA. (a) is appeared in the review article of Cees Dekker, Physics Today, May 1999, p25. (b) Walt de Heer et al., unpublished. (c) S. Frank et al. Science 280, p1744 (1998).

In 1998 Walt de Heer and his colleagues from the Georgia Institute of Technology invented an ingeneous way for measuring the electrical conductance of single MWNTs. A macroscopic fibre of MWNTs was fixed on a manipulator which allowed to steer the fibre above a drop of liquid metal (for example mercury), see Figure 4. Because individual MWNTs stick out from the fibre, a single MWNT can now easily be contacted by gently lowering the fibre into the conducting liquid. By dipping the nanotubes to different depths it is possible to determine the resistance per unit length, which should be zero in an ideal ballistic wire. This method of contacting a nanotube is very different to, for example, the structuring of metal electrodes to nanotubes using high-resolution sub-micron fabrication technology (an example is shown in Figure 5). Reasonably low-ohmic contacts, both for multiwall- and single-wall nanotubes, were very difficult to achieve in previous experiments. It is important to emphasize that the quantized conductance can only be observed if ideal contacts are realized. These early experiments showed that MWNTs are far from being ballistic. In contrast, strong evidence was found that electrons scatter in nanotubes, so that transport is more appropriately characterized as diffusive. Taken these early experiments the results of de Heer and coworkers were very surprising. First, these researchers showed that all MWNTs have nearly the same conductance corresponding to one conductance quantum. Secondly, the length dependent resistance was found to be very low. These two results suggest that MWNTs are ballistic conductors, despite the many shells that may be expected to interact. Moreover, another important observation was made. A large electrical current could be passed through a single MWNT corresponding to current densities exceeding 10^7 A/cm^2. If the associated power would be dissipated along the nanotube, that is if the nanotube would be a classical resistor, the temperature would exceed thousands of Kelvins. This is impossible, since the tube should have been vaporized before. Nanotubes can carry exceptionally large electrical currents, and this, virtually dissipation-less. While the first two observations strongly suggest ballistic transport, this third result tells us that electrons in nanotubes are strongly decoupled from the lattice. "Hot" electrons are therefore not converted into lattice vibrations in the first place (this is what would destroy the tube), but are efficiently removed by the liquid metal contact.

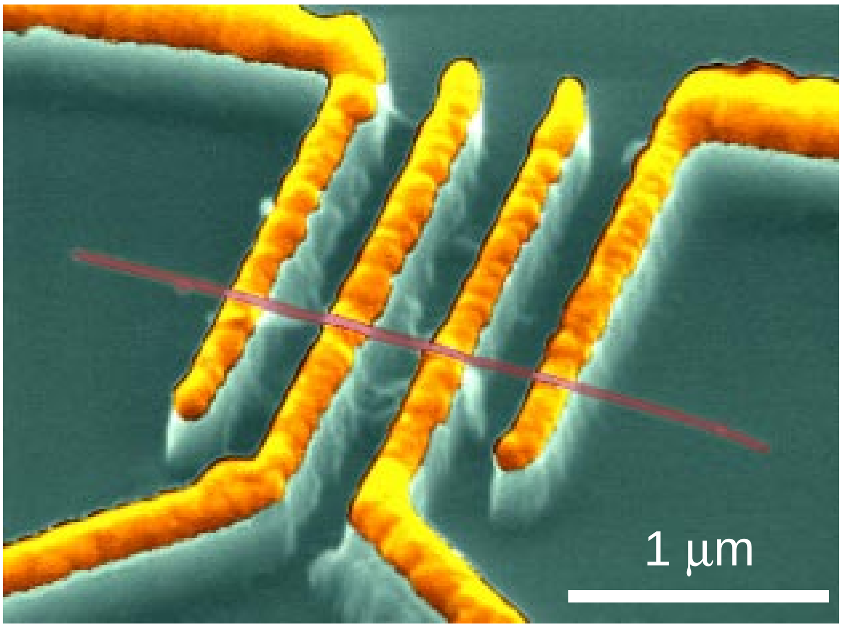

Figure 5
SEM image of a MWNT lying across four Au elctrodes, which were fabricated by state-of-the art electron-beam lithography prior to the deposition of the nanotube. Source: C. Schönenberger and Adrian Bachtold, Inst. of Physics, Univ. Basel, Switzerland unpublished.

Because MWNTs consist of several concentrically arranged SWNTs, one would expect that MWNTs do not qualify as one-dimensional conductors. If adjacent carbon shells interact as in graphite, electrons may not be confined to one shell only. The results of de Heer and coworkers suggest however that the current mainly flows through the outermost shell only. Our own investigation has proven that this is indeed the case. In this respect, studying electric transport in MWNTs is somewhat similar to studying transport in a large diameter SWNT. The nanotube core soley acts as a mechanical support for the electrically active outermost shell. Note, that is this is no longer true, if we would found a way to contact the bulk, or even were able to selectively address inner shells. MWNTs have certain specific advantages over SWNTs: their large diameter favour low-ohmic contacts, because of the larger contact area. Arc-discharge grown MWNTs do not contain magnetic impurties, which is important for spintronics, in which the spin of the electrons is used for magnetic-sensing or switching applications or even for computation. Their large diameter enable to investigate quantum-interference phenomena in magnetic field. The most profound quantum-intereference effect is the Aharonov-Bohm (AB) effect. The illustration of Figure 6a shows what happens if an electron beam is split into two partial beams following different paths, but merge together on a screen on which the electron intensity is measured. One observes an intensity modulation in the form of a periodic stripe pattern. Such a pattern is called interference pattern. Its observation demonstrates that in this experiment a single electron does not choose either path but behaves as an extended wave which has amplitude on both paths simultaneously. The two paths form a closed loop threaded by a magnetic flux. Though electrons need never come in "contact" with the magnetic field, the interference pattern changes periodically with flux with a period given by the magnetic-flux quantum $\phi_0 = h/e$. This is the Aharonov-Bohm effect. Now imaging a carbon nanotubes (a single wall for symplicity) placed in a magnetic field parallel to the tube axis (Figure 6b). Since nanotubes are cylindrical conductors the electrons that propagate on the cylinder can circle around the tube in either the clockwise or counter-clockwise direction (see Figure 6c).These two "pathes" interfere, as in the example discussed before, resulting in a periodic modulation of the electrical resistance with magnetic flux through the hollow. In this case the period is half the flux-quantum. This effect is relatively robust and can even be observed if transport in nanotube is diffusive. For an ideal ballistic nanotube, a much more dramatic effect is expected. Whether a nanotube is a semiconductor or a metal depends only on the relative phase of the wavefunction around the tube circumference. Since the magnetic flux changes the phase, a metallic NT should continously evolve into a semiconducting one and vice versa. We have placed single electrically contacted MWNTs in a parallel field and studied both the temperature and flux dependence of the electrical resistance (collaboration between the University of Basel and the Ecole Polytechnique de Lausanne). Figure 6d displays the main result. There is a resistance peak at zero magnetic field. This peak reappears at approximately +/- 8.5 Tesla, although with reduced amplitude. If this increase is caused by the AB effect, resistance peaks should appear equidistantly. The additional resistance increase at the highest field of 15 Tesla agrees with this expectation. The magnetic field at the peak position can be related to the diameter of the nanotube, which turns out to be equal to the geometric outer diameter of the NT measured independently. This demonstrate unambigiously, that the electric current is carried by the outermost tube only. We would like to mention here, that in order to observe the first peak in a similar experiment with SWNTs would require a magnetic field of 1000 Tesla because of the small tube radius. The peak separation in Figure 6d corresponds to half ϕ_0 suggesting that transport is not ballistic in our MWNTs. If it were ballistic a much larger effect should have been observed, since the metallic NT would be turned into a semiconductor with a gap much larger than the measuring temperature. This and other magneto-resistance measurements have allowed to deduce the scattering length and the length dependent resistance. We found that transport is diffusive. A large variation in scattering length have been deduced, ranging from 3 nm (very diffusive) to 100 nm (quasi-ballistic, i.e. intermediate between diffusive and ballistic). That the observed metal-to-semiconductor transition has not been observed is a puzzle which needs to be solved, as we have to find an explanation for the large variation in scattering length, from near infinity (de Heer et al.) to a couple of nanometers. Although transport in our MWNTs is best characterized as diffusive, large electric currents (up to 1mA) can be passed through the nanotubes, demonstrating that the electrons couple only weakly, if at all, to the lattice. All magnetoresistance measurements can very well be understood in the Fermi liquid framework assuming two-dimensional diffusive transport. However, recent measurements of the tunneling DOS in MWNTs have revealed anomalies quite similar to feature seen in SWNT which were assigned to Luttinger liquid behaviour (see article by Paul McEuen in this series).

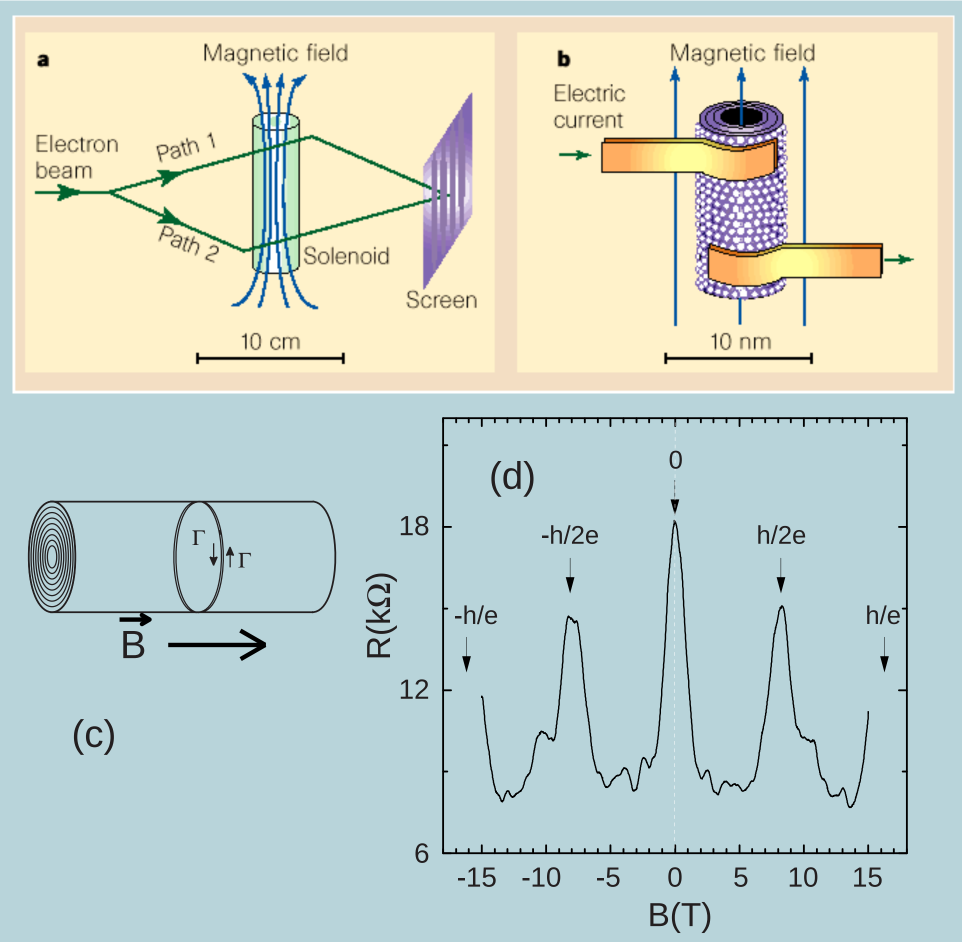

Figure 6
(a) Illustration of the Aharonov-Bohm (AB) effect. The flux through the solenoid changes the relative phase of the electron-waves in path 1 and path 2 of this two-beam electron interferometer. This affects the intensity modulation on the screen (the interference pattern). Similarly, the electron waves in a carbon nanotube are modified by the magnetic flux threading the interior of the tube (b). The change in interference pattern in (a) translates into a change of the electric resistance in (b). The illustration in (c) highlights the main interference contribution observed in the experiment which is due to closed-electron trajectories encircling the nanotube clockwise and counter-clockwise. (d) shows the measured resistance R as a function of parallel magnetic field. The arrows point to multiple flux-quanta h/2e. Sources: Illustrations (a-b) are by David Cobden; appeared in Nature, Vol. 397 (1999) to highlight the article by Adrian Bachtold et al. Nature 397 , p673 (1999). (c) unpublished, (d) C. Schönenberger et al. Appl. Phys. A 69, 283 (1999).

Finally we would like to mention that spin transport has recently been demonstrated by Kazuhito Tsukagoshi (RIKEN), Bruce Alphenaar (Hitachi Cambridge) and Hiroki Ago (Cavendish, Cambridge). This team used cobalt layers, a ferromagnet, to contact a single MWNT. The measured nanotube resistance depends on the relativ orientation of the magnetization in the two contacts. These researchers thereby realized the first wire-based planar magnetic switch. A carbon-based wire is an interesting candidate for transporting magnetic information carried by a single spin, because very large spin coherence length are expected.

The small diameter and high aspect ratio of carbon nanotubes is very favourable for the electric field emission of electrons. Already for moderate voltages, a strong electric field develops at the free end of supported nanotubes because of their sharpness. This has been realized by de Heer, Chatelain and Urgate already in 1995. They also immediately realized that these field emitters must be superior than conventional sources and may find their way into all kind of applications, most importantly into flat-panel displays (see the article by de Heer and Martel in this issue). Here, we will focus on a recent comparison between the yield of electron emission from different kind of nanotubes. To realize a field-emission source with one nanotube only, single MWNTs were mounted on a supporting gold wire that was etched into a tip. No adhesive was used; the tubes were solely held by Van der Waals forces. MWNTs with closed and open tips have been compared (see Figure 7a). Arc-discharge grown nanotubes are normally closed, but can be opened by either applying a very large electric field or by an oxygen treatment at high temperature. Most single MWNT emitters, closed as well as opened, are capable of emitting over a large current range with an incredibly large maximum of 0.1 mA. This represents a tremendous current density for such a small object. Figure 6b compares the emission current for closed and opened MWNTs. Closed nanotubes are much more efficient as opened once. This is remarkable, because opened ones are expected to have a smaller effective curvature giving rise to a larger field amplification. It is most likely that the free dangling bonds are saturated by other species (such as oxygen) resulting in localized states. These states lie far below the Fermi energy and can therefore not participate in the electron emission. For closed nanotubes localized states at the tip have been predicted too, but these states couple to the nanotube pi-orbital and effectively enhance the emission and narrows the energy ditsribution. This narrowing is of particular importance for electron microscopy, where a monochromatic source is required to further improve the image resolution.

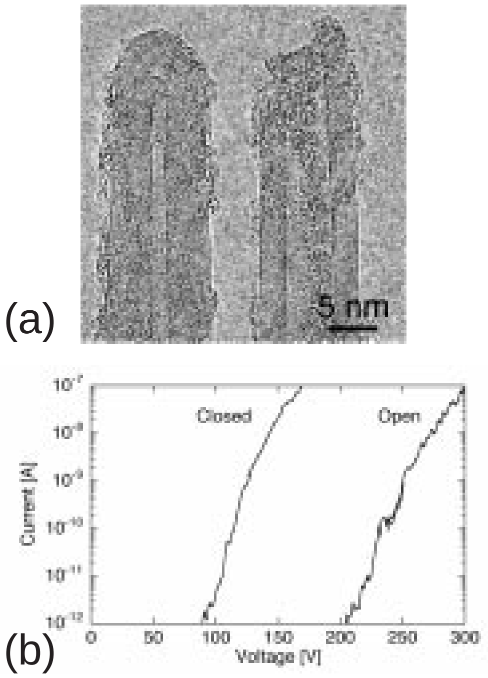

Figure 7
(a) TEM images of MWNT-tips used in studies of field-emission of electrons. The left tip is closed and the right open. (b) Current-voltage characteristics for a single closed and open MWNT. Source: Published: Jean-Marc Bonard et al. Appl. Phys. A 69, 245 (1999).

Carbon nanotubes have shown a wealth of phenomena. Some results we firmly understand already, others are controversials today. Nanotubes are great molecules and good conductors with a wide range of interesting properties useful for applications. The future for nanotube looks very bright: Nanotubes are interesting model systems for fundamental studies of one-dimensional systems, but they are equally well (or even more) attractive to applied reserachers and industries due to the large variety of potential applications.

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