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EDITORIAL

Charge and spin transport in carbon nanotubes

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Abstract

The basic science in quantum transport of nano-scaled 'devices' is largely based on the availability of suitable *model systems*. Nanostructures built from conventional metals are typically in the diffusive transport regime. Semiconductors, as the starting material for nanodevices, are different. Because of the low carrier density and therefore reduced screening, the Fermi energy can be tuned by electrostatic gates. Quantum dots which can be filled sequentially with electrons one by one have been realized in this material system (for a review see Kouwenhoven *et al* (2001 *Rep. Prog. Phys.* **64** 701)). Today, researchers have also started to explore the new possibilities provided by molecules (see, for example, Selzer and Allara (2006 *Ann. Rev. Phys. Chem.* **57** 593), Cuniberti *et al* (2006 *Lecture Notes in Physics* vol 680), McCreery (2004 *Chem. Mater.* **16** 4477)). A rather simple prototype 'molecule' is a carbon nanotube (CNT) (for recent reviews, see Anantram and Leonard (2006 *Rep. Prog. Phys.* **69** 507), Dresselhaus *et al* (2001 *Topics in Applied Physics* vol 80), Ebbesen (1996 *Phys. Today* **49** 26)). Charge and spin transport in CNTs have attracted a lot of attention in recent years. There are several reasons for this excitement: CNTs are almost ideal *quantum-ballistic wires*. Large electric field effects have been observed in semiconducting CNTs, potentially of interest for applications in electronics. Because a CNT is an all-surface conductor, the electrical properties are highly sensitive to the environment, which can be exploited in sensing applications. Finally, a wealth of new physics is currently appearing in experiments in which CNT-hybrid devices are used, which employ a combination of normal metal, superconducting and ferromagnetic contacts.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

There is no other element but carbon in nature that has brought about this degree of diversity. This diversity is rooted in the unique property of carbon to form single, double and even triple bonds. This fact is widely used by Mother Nature and organic chemists who are able to rationally synthesize quite complex molecules these days [2]. From the point of view of a condensed matter physicist, carbon has two basic crystallographic forms: isotropic diamond and anisotropic layered graphite, see figure 1. Whereas diamond is a large band gap insulator, graphite is a metal. With the discovery of the C_{60} bucky-ball, it became clear that other highly ordered forms of carbon exist at the nanometre scale. In 1991, Iijima *et al* observed tubular carbon structures when they examined the soot created by a direct-current arc discharge between carbon electrodes in a high resolution transmission electron microscope (TEM) [4]. This discovery was received with great interest and initiated global research activity on these novel wire-like materials [3].

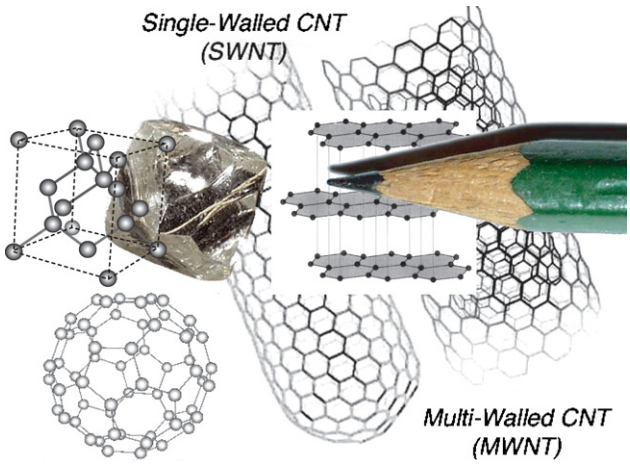

Figure 1. Different forms of carbon: a single-wall and a multi-wall carbon nanotube is shown together with diamond on the left and graphite on the right. The C_{60} buckyball is shown at the bottom left (source: adapted from P Gröning *et al* with permission, EMPA).

2. The carbon nanotube as a material

A carbon nanotube (CNT) is a seaming-less cylinder made up of one sheet of graphite. This form is also known as a single-wall carbon nanotube (SWCNT). Similar to the onion-like multi-shell structure of buckyballs, multi-shell carbon nanotubes, the so-called multi-wall carbon nanotubes (MWCNTs), also exist. In the latter form, single-wall carbon nanotubes of increasing diameter are concentrically stacked to form a larger structure. Typical diameters are 1–2 nm and 10–50 nm for SWCNTs and MWCNTs, respectively.

There are three main roots to grow carbon nanotubes: arc discharge [4, 5], laser evaporation [6] and chemical-vapour deposition (CVD) [7]. Due to its ease, flexibility and modest investment cost, the CVD process has become very popular and is now widely used. All three methods allow for the growth of SWCNTs and MWCNTs, see figure 2.

3. Contacting single carbon nanotubes

Electrical characterization of carbon nanotubes started very early. First, macroscopic assemblies of nanotubes (the so-called nanotube mats) were studied. But it was soon realized that measuring a single nanotube would be highly desirable [8] because nanotubes were predicted to come in two distinct flavours: as semiconductors on one hand, and metals (or semimetals) on the other [9]. This was proven by Dekker and coworkers, who applied the scanning-tunnelling microscope to measure the density-of-state of single CNTs [10].

Ebbesen and coworkers were the first to contact a single carbon nanotube using microfabrication technology [11], followed by several groups worldwide (see, for example, [12, 13]), see figure 3. In the first step of the contacting procedure, carbon nanotubes are either grown directly on the substrate (in case of CVD) or they are spread from a liquid suspension over the substrate. Usually, a piece of a silicon wafer serves as a substrate. It is convenient to use highly doped and therefore conducting Si so that the substrate can be used as a gate electrode (back-gate, figure 3(*c*)). Isolation between the tubes and the back-gate is achieved by a thin top Si-oxide layer with thickness in the range of 50–500 nm. Suitable nanotubes are localized with regard to pre-structured markers using an imaging technique, such as atomic-force

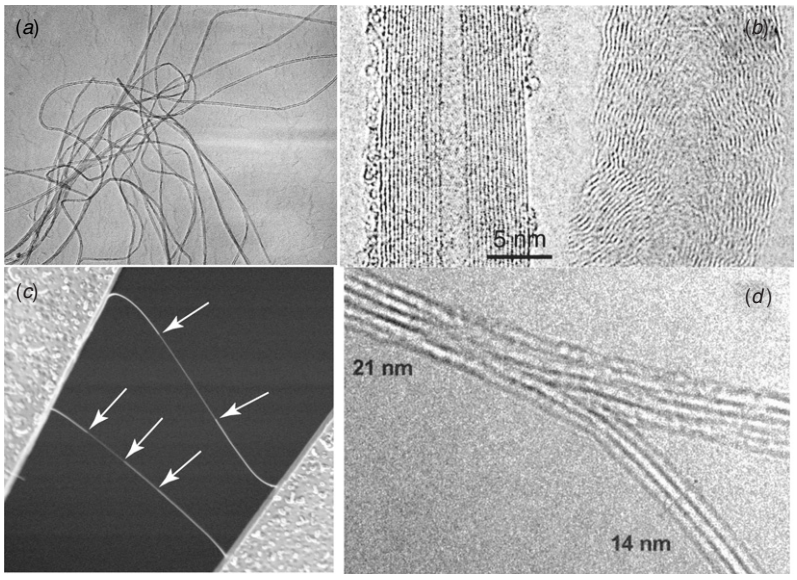

Figure 2. This figure illustrates some of the observed variability of grown carbon nanotubes: (*a*) relatively homogeneous CVD-grown SWCNTs (source: J Furer *et al*, University of Basel), (*b*) highly-graphitized arc-discharge-grown MWCNT (left) and a disordered CVD-grown MWCNT (right) (source: L Forró *et al*, EPF Lausanne), (*c*) scanning-electron microscopy image of suspended nanotubes, grown over a 3 μm slit in a Si-nitride membrane by CDV (source: B Babic *et al*, University of Basel), (*d*) TEM image of SWCNT ropes (source: M Seo *et al*, EPF Lausanne). Note that the diameter of a single tube in (*d*) is relatively large, i.e. ≈5 nm. SWCNTs obtained by laser evaporation have smaller diameters, i.e. ≈1.2 nm. The change in contrast (arrows) along the two tubes in (*c*) suggests that the structure of the nanotube is not uniform.

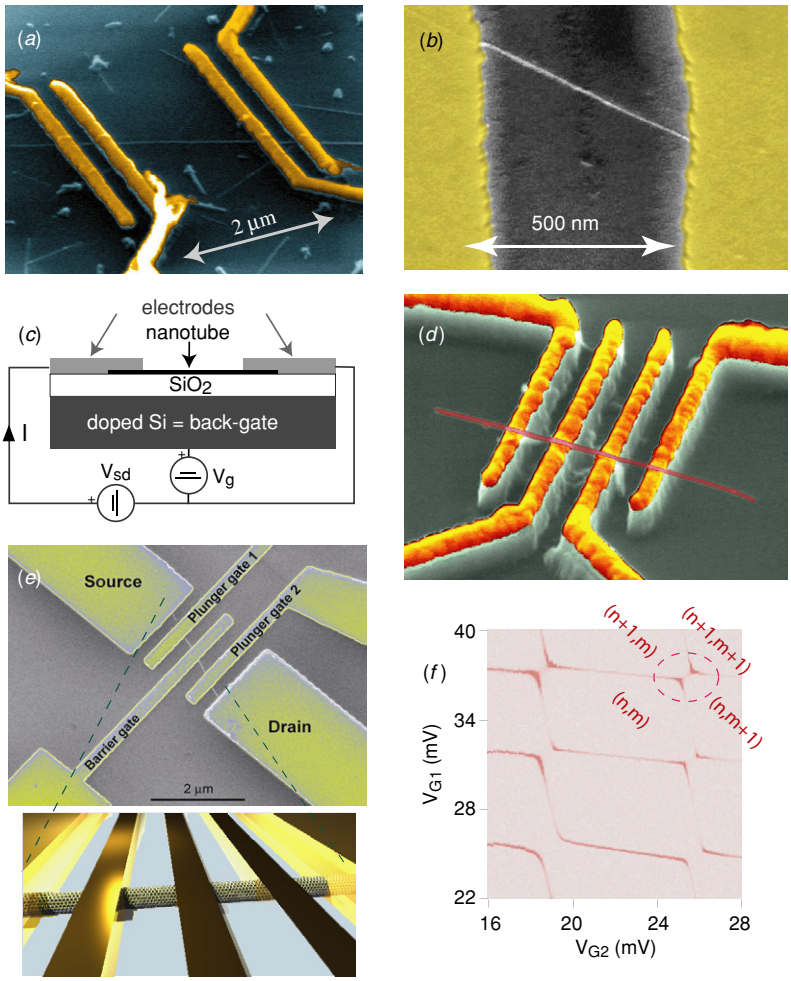

Figure 3. Top: images of single nanotube devices fabricated with electron-beam lithography. The left SEM image (*a*) shows a contacted MWCNT (source: A Bachtold *et al*, University of Basel) and the right AFM image, (*b*) a CVD-grown SWCNT (source: S Ifadir *et al*, University of Basel), (*c*) illustration of the three terminal configuration with transport voltage V_{sd} and gate voltage V_g applied to the substrate, (*d*) a nanotube device processed in reverse, i.e. the Au contact fingers were fabricated first and the nanotube was placed later on (source: A Genkinger *et al*, University of Basel). (*e*) A double quantum-dot defined in a SWCNT by three top gates. The middle gate is used to tune the barrier between the left and the right dots. The two 'plunger' gates allow us to tune the charge state of the two dots separately. A conductance measurement as a function of the two gate voltages is shown in (*f*) (source: M Gräber *et al*, University of Basel).

microscopy (AFM) or scanning-electron microscopy. Then, an electron-beam lithography step (usually a lift-off process) is applied to define contacts right over the selected tubes. As contacting materials, Au [13], Ti [14] and Pd [15] proved to yield good contacts. In this process, the electrodes are evaporated over the CNTs (figures 3(*a*), (*b*)). The opposite sequence, in which the contact structure was made first and the CNTs were placed over the contacts, was used too (figure 3(*d*)). It has even been found possible to move the CNTs by AFM onto metallic contacts. In these latter approaches, where the CNTs lie on the electrodes, contacts are usually rather high-ohmic as compared to the relatively low-ohmic contacts that can be obtained if the electrode material is grown over the CNTs. Technologically, the state-of-the art today is double quantum dots (qdots), defined on a single CNT using various gate electrodes to create tunable barriers. An example is shown in figures 3(*e*), (*f*) (also see Sapmaz *et al* and Gräber *et al* within this special issue).

It is obvious that contacting single CNTs one by one cannot be a technology for applications. It is therefore important to develop processes that allow the integration with conventional Si or GaAs-based micro-fabrication technology. An example is given by Stobbe *et al* in this special issue. In addition to the lack of mass fabrication technology, we have at present no reliable prescription to predetermine the contact resistances. We also yet do not have a full microscopic understanding of the metal nanotube contact, although there is progress [16].

The problem of the contact is inherent to small structures where details on the atomic scale matter. This problem is even more severe in the case of single molecules. Though carbon nanotubes may be viewed as giant molecules, they differ from molecules in several aspects. For example, they are quite rigid and fabricated devices are amenable to temperature-dependent measurements, which is not yet possible for real molecules.

4. Carbon nanotube field-effect transistors

From the point of view of electronics, semiconducting carbon nanotubes have proved to be very interesting systems to explore field-effect transistor (FET) action in one-dimensional channels, in which the screening of the gate field can be quite different compared to conventional FETs. In an early work by Tans *et al* and Martel *et al*, carbon nanotube FETs were found to be of a unipolar p-type [17, 18]. The p-type character was explained with charge transfer due to the different work functions between the metallic contacts and the CNT, leading to the appearance of Schottky barriers (SBs) [19] and consequently to contact resistances. In the most simple picture, the electrical resistance of such a CNT device is the series connection of two contact resistances and the channel resistance. Both contact and channel resistance will be affected by the gate voltage. The relative importance of the two parts is still being discussed. It appears though that both limiting cases are possible, i.e. the case where the SBs dominate and the one where the channel dominates. The latter is possible because the scattering mean-free path of semiconducting SWCNTs is usually small, so that a Drude-like channel resistance emerges in long CNTs [20], and secondly, highly transparent contacts have recently been realized to semiconducting nanotubes [15]. On the other hand, there is ample of evidence for the opposite limit in which the SBs at the contacts dominate. An interesting comparison between theory and experiment of this Schottky-barrier FET limit has been published by Heinze *et al* [19]. This issue of the relative importance of contact barriers, channel resistance and doping state is very important in view of applications of CNTs as active elements.

Carbon nanotubes can intentionally be n-doped using potassium [21]. Furthermore, CNTs in vacuum revealed n-type behaviour, as judged from a negative thermoelectric power [22, 23]. Combining as-grown (p-type) CNT segments with vacuum annealed or K-treated (n-type) ones allowed us to realize p–n junctions [24] and complementary FET devices [25]. In the case of potassium treatment, the n-type characteristic is due to the potassium acting as a donor. But for annealed CNTs, the situation is less clear. Importantly, there is ample of data on the environmental sensitivity of CNTs, be it reactive gases [22, 26, 27] or liquids [28–30]. A possible mechanism includes charge transfer at the metal electrode and/or CNT surface, leading to an apparent change of the electrochemical potential in the CNT and also consequently changes of the Schottky barrier. Typically, a semiconducting CNT-FET response to gas or liquid consists of a gate shift. Currently, several groups are working on testing CNT-FETs as biochemical sensors, for example, for the sensing of DNA and protein probes [31]. The contribution from Charlie Johnson addresses the sensing of DNA in this issue.

5. Carbon nanotube optics

As emphasized before, a FET is one possible application of carbon nanotubes. But as CNTs can be either metallic or semiconducting, one has to find methods to either grow one flavour exclusively (which is at present not possible) or to separate them. Moreover, the separation should ideally be possible beforehand and not only once the CNTs have already been contacted and integrated.

Progress in the separation of CNTs requires a method to distinguish metallic from semiconducting CNTs in a fast and contactless method [32]. Using optical spectroscopy, Raman, absorption and fluorescence spectroscopy, it is now not only possible to distinguish metallic from semiconducting CNTs [32], but one is even able to determine the detailed crystallographic structure of a narrow diameter CNT with certainty [33]. Though the matrix element determining the photon emission of electron-hole recombination is small, researchers have been able to detect appreciable electro-luminescence from CNTs [34]. In this issue, Balsubramanian and Burhard discuss their recent progress in photo-conductivity and electro-luminescence in CNTs.

6. Carbon nanotube quantum wires

On the basic physics side, an ideal carbon nanotube, i.e. one that has no defects and is infinite long, is a quantum wire, in which an even number of propagating one-dimensional channels are occupied. Hence, one therefore predicts the following characteristic features. (1) Sharp peaks should appear in the energy-resolved density-of-states due to the one-dimensional nature of the conductor. (2) Because there are no defects, charge transfer is ballistic *within* the CNT and consequently the electrochemical potential should be constant along the tube. (3) The conductance (at zero temperature) is quantized and either zero (semiconducting tube) or $4e^2/h$ (metallic tube) for an ideal and charge-neutral nanotube device. And finally, let me also mention the 'trivial' statement: (4) nanotubes are *tubular* one-dimensional conductors. As physicists, we are used to the fact that nature is not perfect, or more precisely that our models are usually too simple and too naive. In view of this, it is quite remarkable that all four facts have been confirmed.

In a seminal paper, Dekker and coworkers have proved statement (1) [10]. Using scanning-tunnelling microscopy, they could image CNTs with atomic resolution and correlate the structure with the measured density-of-states. Bachtold *et al* measured the potential drop along CNTs over a length of $L \approx 1\ \mu$m and confirmed that the voltage drops predominately over the contacts in SWCNTs [35]. Hence, back-scattering is to a great extent absent in (metallic) SWCNTs. As expected, statement (3) (quantized conductance) is the most tricky one. There are many accounts in the literature where the measured conductance G of single CNT devices is much smaller than $G_0 = 2e^2/h$. However, in recent years, high conductance values have been reported too. See, for example, the work by Liang [36] and Babic [37]. Finally, the fact that nanotubes are indeed tubular structures was also confirmed in electrical measurements [38]. Because they are hollow, a magnetic flux threading the interior changes the periodic boundary condition through a Aharonov–Bohm phase. The periodic modulation in G was analysed in MWCNTs and found to be in agreement with the tubular structure.

MWCNTs are also interesting systems because of their strong anisotropy. It has been found that for small applied voltages, the current may flow to a large extent in the outermost shell only. This is because the external electrodes only make

contact with the outermost shell [38]. However, if a large bias is applied, electrons may also hop into inner shells. Together with inelastic scattering, such as the emission of phonons, the large bias regime reveals interesting nonlinear current–voltage characteristics, which are highlighted in the paper by Bourlon *et al* in this special issue.

7. Carbon nanotubes and disorder

No carbon nanotube is ideal. There is a random potential along the CNT due to adsorbates, defects and inhomogeneous substrate interaction, all leading to a finite probability for back-scattering. The question is rather: how long can the scattering mean-free path l_{mfp} be? As a comparison, whereas l_{mfp} can exceed 100 μm in high-mobility GaAs-based heterostructures, it is rather of order $l_{\mathrm{mfp}} \sim 1$ μm in carbon nanotubes. It is generally longer in metallic CNTs and shorter in semiconducting ones.

However, one has to be careful in reading through the literature because all sorts of materials exist. There have been reports on two-dimensional-like diffusive transport in multi-wall carbon nanotubes in which l_{mfp} was of order 1 nm only [8]. Clear evidence for quasi-ballistic transport, interpolating between one and two dimensions, was also observed [39]. This work has been extended by Strunk and coworkers and is reported in this issue. By using a strong-coupling gate, they were able to tune the Fermi energy over several subbands and study the effect on quantum interference.

An interesting and universal observation is the robustness of the metallic state of carbon nanotubes. Although only a few channels participate in transport, the expected 'strong' localization of the conductor into an insulating state driven by quantum coherence at low temperature has not been observed. The robustness of the metallic state makes nanotubes rather special conductors. Since a high electrical conductivity also implies a high thermal conductivity, carbon nanotubes may also be used as efficient and robust heat conductors in the future.

8. Carbon nanotubes and Coulomb interaction

As compared to the 'ideal' carbon nanotube, a real CNT not only contains inevitably a certain degree of disorder, but the electrons in CNTs are also expected to 'strongly' interact. In low-dimensional conductors, one expects the electron–electron interaction to have a dramatic effect on the nature of the elementary excitations. In one dimension, the Luttinger liquid (LL) theory predicts that no long-lived quasi-particle exists near the Fermi level. Instead, collective charge excitations are predicted. Their density as a function of energy vanishes with a power-law dependence at the Fermi energy. The exponent of this power law is non-universal and depends on the Coulomb interaction. In a tunnelling experiment, this manifests itself by a zero-bias anomaly, displaying a scaling behaviour as a function of voltage and temperature.

In tunnelling to CNTs pronounced zero-bias anomalies were found. Because of the power-law suppression in the observed tunnelling density-of-state, these anomalies were interpreted as a signature for Luttinger liquid behaviour [40, 41]. Interestingly, similar zero-bias anomalies were also measured in a doped multi-wall carbon nanotube, in which as much as 20 channels were occupied [42]. Because these latter results could also be interpreted within the framework of environmental Coulomb blockade [43], it questions the previous interpretation of zero-bias anomalies in terms of the LL behaviour.

The key prediction of the LL theory is spin-charge separation. Because of the repulsive interaction, the charge excitations are stiffer and therefore propagate faster than the spin excitations. To my knowledge, there is no experiment in which different velocities have been directly measured. One should also stress that the clean disorder-free CNT is in fact the 'trivial' case. This also holds true for both non-interacting and interacting cases. Much more interesting is the question of the effect of disorder on resistance in a strongly interacting wire. In this issue, Mora *et al* present their theoretical work on the cross-over of the interaction correction from the ballistic to the diffusive regime, i.e. from the Luttinger liquid to the Altshuler–Aronov interaction corrections.

9. Carbon nanotube quantum dots

Strong localization has not been observed in metallic carbon nanotubes with source and drain contacts separated by typically $\sim$1 μm. This shows that wavefunctions can extend from source to drain, at least over this distance. As the contacts between the CNT and the metallic electrodes are far from being adiabatic, back-scattering is expected at the CNT-metal contact (see section 4). This situation is illustrated in figure 4(*a*). Contacting a CNT turns it into a finite length object, and length quantization needs to be considered. The energy scale for an electron propagating back and forth with velocity v_{F} in a one-dimensional wire with length L is given by $\delta E = hv_{\mathrm{F}}/L$, where h is Planck's constant. Expressed in temperature, δE amounts to $T_{\delta E} \approx 40$ K for a device 1 μm in length. Though this is lower than room temperature, it is a relatively large energy scale (for low-temperature physicists for sure). Hence, at low (actually not too low) temperature, the one-dimensional CNT turns into a zero-dimensional quantum dot. It is quantum-dot physics in carbon nanotubes, which brought about the most exciting results recently.

As sketched in figure 4(*a*), a quantum dot can, in the simplest possible model, be described by three parameters: the level-spacing δE between the discrete eigenstates (orbitals) of the dot, the coupling strength between the orbitals in the CNT and the left and right electrodes, expressed by Γ, and the parameter U, describing the Coulomb interaction. U is the single-electron charging energy, which needs to be paid if the CNT gets charged by one additional electron. In metallic CNTs, this parameter is to a good accuracy constant and can be expressed by a capacitor as shown in figure 4. Note that this capacitor is the sum of the gate, source and drain capacitance, and usually the latter two dominate. It turns out that U is of the same size than δE in typical carbon nanotube quantum dots. There is some room to tune this: for example, strong screening with gates placed tightly all over the CNT will not only increase the gate coupling, but also lower U quite a bit. Now let us assume that δE is much larger and the temperature much smaller than both U and Γ. Then, one can now distinguish three regimes: weak ($\Gamma \ll U$), intermediate ($\Gamma \sim U$) and

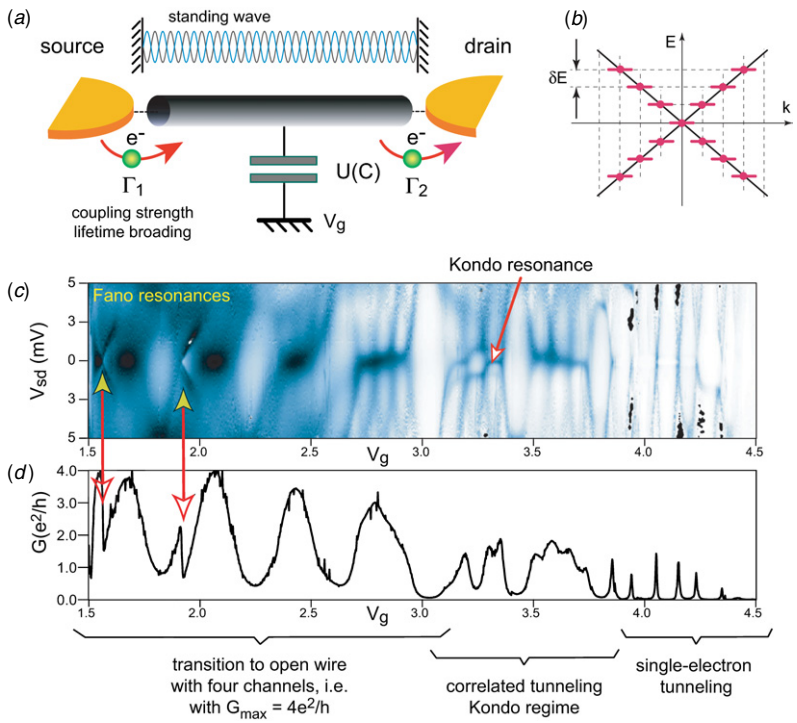

Figure 4. These schematics (*a*), (*b*) illustrate the formation of zero-dimensional (quantum-dot) eigenstates. The continuous energy spectrum of a one-dimensional wire is transformed into discrete energy values (ideally), equidistantly spaced by the level spacing δE. (*c*) An example of a measurement of the differential conductance as a function of source-drain voltage V_{sd} (vertical) and gate voltage V_g (horizontal). In (*d*) the zero-bias conductance is shown as a graph. Due to the strong dependence on V_g of the tunnelling coupling from this CNT to the leads, several physical phenomena are observed together. These are from right to left: Coulomb blockade, the Kondo effect and Fano resonances, corresponding to the regimes of low, intermediate and high tunnelling coupling. (Parts (*c*) and (*d*) reprinted (figure 2) with permission from Babic and Schönenberger 2004 *Phys. Rev.* B **70** 195408. Copyright (2004) by the American Physical Society.)

strong ($\Gamma \gg U$) coupling. In the weak-coupling regime transport is dominated by Coulomb interactions [12]. Electrons can only be transferred sequentially from source to drain, one by one [1]. For a small applied bias, this is however prohibited by Coulomb interaction, except for special values of the gate voltage for which the Coulomb blockade is lifted. In the opposite limit of strong coupling, the system behaves as a non-interacting resonant tunnelling device whose transmission can be described by a Breit–Wigner energy dependence [36]. In particular, if the eigenstate lies in the vicinity of the Fermi energies of source and drain, the maximum (quantized) conductance is observed. In CNTs it is not $2e^2/h$, but twice as much: $4e^2/h$. This doubling is due to a peculiar two-fold orbital degeneracy which can be traced back to the band-structure of graphene. Most interesting is, however, the intermediate regime. Here, the quantum dot is an interacting object, but because of the relatively large Γ second-order (the so-called co-tunnelling) and higher-order processes participate in transport [44]. This may lead to the appearance of Kondo physics.

Unfortunately, we are not yet able to determine Γ in CNTs, the most important parameter, intentionally and in advance. Nonetheless, it has become possible to explore charge transport in carbon nanotubes in all three regimes. Sometimes even the contacts are such that they change their transparency with the applied back-gate voltage. In these cases, all three regimes are present in one device [37]. An example is shown in figures 4(*c*), (*d*). The nanotube is in the single-electron tunnelling regime (weak coupling) at large gate voltages V_g to the right. In contrast, it is in the strong-coupling regime at low V_g to the left. A Kondo resonance is indicated by an arrow. Due to the two-fold orbital degeneracy (in addition to spin), the Kondo problem is an interesting one in these quantum dots. First, if one electron is added, the ground state has spin $s = 1/2$ and a Kondo resonance form. However, the degeneracy of the $N = 1$ ground state is not two, as is the case in a usual spin-1/2 Kondo system, but rather four, enhancing the Kondo effect [45]. Interesting is the case at half-filling, i.e. if two electrons are added. The ground state can be either a paired-electron state, a singlet or a triplet state, depending on the 'level mismatch' and on the exchange energy. It may even be that a pronounced Kondo resonance appears at $N = 2$. This is the case if all states overlap leading to a large ground-state degeneracy [46]. If the conductance between source and drain approaches $4e^2/h$, the (broadened) quantum-dot eigenstates are imaged in the differential conductance plots. These Breit–Wigner resonances were also termed Fabry Perot resonances [36]. In addition to these, pronounced *Fano resonances* may appear at large coupling (figures 4(*c*), (*d*)) [46].

In this special issue, three contributions highlight the recent results in quantum-dot physics of carbon nanotubes. First, Sapmaz *et al* present a nice review including the results on unconventional Kondo physics, double quantum dots and suspended quantum dots. Secondly, Gräber *et al* focus exclusively on double quantum dots, whereas Buitelaar *et al* discuss their recent results on charge pumping in surface acoustic-wave-driven carbon nanotubes.

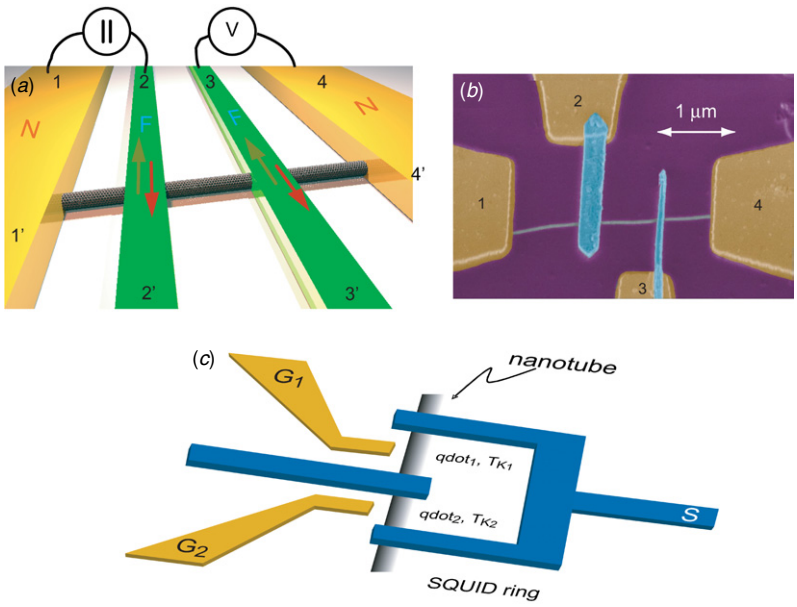

Figure 5. Example (*a*) of a carbon nanotube hybrid device, consisting of two normal metal (N) and two ferromagentic (F) contacts arranged in the order N-F-F-N and (*b*) an actual realization. In a non-local measurement of spin accumulation [48], current is driven between one N-F pair, here between contacts 1 and 2, while the voltage is measured between the other N-F pair, i.e. between contacts 3 and 4. (*c*) A sketch of the carbon-nanotube SQUID experiment which has in each arm a gate-tunable quantum dot. This amazing device has just been realized [49].

10. Carbon nanotube hybrids

One may rightly argue that many (if not all) of the studied transport phenomena (e.g. Coulomb blockade, Kondo effect and Fano resonances) have also been, or are being, studied in semiconductor-based quantum dots, in which similar transport regimes can be realized. There are differences in terms of the interaction strength, a measure of which is the ratio $r_S := \delta E/U$. These differences are however not large if we compare the CNTs with the semiconductor quantum dots. Even more so, the interaction parameter can be tuned in semiconductors via the carrier density, something which is only indirectly possible in the CNTs (screening by a proper choice of the gate structure). In addition, the transparency to the contacts can easily be controlled in semiconductor quantum dots because split gates can be used to precisely control the opening from the tunnelling regime up to the transparency one. Hence, all these favours semiconductor-based quantum dots. However, there are opportunities for basic physics for which the CNTs are clearly superior (or even the only possible choice at present).

In the first place, a freely *suspended CNT quantum dot* is relatively easy to fabricate and provides a quantum dot which has an addition mechanical degree-of freedom (a vibrating quantum dot) [47]. Even more important are *hybrid* nano-systems in which normal metals (N), superconductors (S) and ferromagnets (F) are combined on the nanometre scale. Hybrids, such as S-N-S devices, have been realized using metallic nanowires which are diffusive multichannel systems and, more recently, also in single atom contacts. However, only with the CNTs it has been possible to explore the zero-dimensional regime, for example, a quantum dot with superconducting leads [50]. An enhanced Josephson current has been reported in S-contacted CNTs with highly transparent contacts [51]. In the regime of intermediate coupling, the interplay between superconductivity and Kondo physics has been studied [50] as well as the multiple-Andreev reflection in a quantum dot [52]. The zero-bias Kondo resonance at odd dot filling, for which the differential conductance ($\mathrm{d}I/\mathrm{d}V$) is close to the quantized conductance in the normal state, is either enhanced or suppressed in the superconducting state depending on the ratio of the Kondo temperature to the superconducting order parameter [50, 53]. Very recently, gate tunability of the supercurrent [54] and even a tunable nano-SQUID along the schematics of figure 5(*c*) were demonstrated [49]. In addition, there are reports on intrinsic superconductivity in the CNTs [55].

Comparing the demonstrated possibilities in zero dimension, the N-qdot-N case is typically being studied in semiconductor-based quantum dots. Using metallic colloids (grains), the S-qdot-S case is also accessible, but in a quite distinct transport regime (very small level spacing as compared to charging energy). With the CNTs, all of the following five possible cases (in addition to N-qdot-N) can be realized: S-qdot-S, S-qdot-N, S-qdot-F, F-qdot-N and F-qdot-F.

As already mentioned, ground-breaking results have been obtained with superconducting contacts. Though more difficult to realize, ferromagnetic contacts using Co, Fe and PdNi alloys have been demonstrated [56, 57]. In particular, the latter ferromagnetic Pd_{1-x} Ni_x alloy [57] could provide two-terminal resistances as small as 5.6 kΩ, proving that highly transparent ferromagnetic contacts can be realized. Most excitingly, the observation of a gate-tunable magneto-resistance effect, which can be seen as a kind of spin-interference field effect, has shown that there are still interesting new effects to be discovered [58]. Carbon nanotubes are well suited for spin transport because of the low spin–orbit interaction which should render the spin a good

quantum number for a long time. Two contributions in this issue focus on the emergent field of spin transport in CNTs, the one from Cottet *et al* and the one from Krompiewski.

11. Outlook

During recent years, we have learnt that a fully conjugated pi-electron system can be a truly metallic wire at lengths as large as 1 μm or even beyond. This demonstrates that there is no principle obstacle for good electrical conduction in molecular systems. There are many challenges ahead for carbon nanotubes (and even more so for organic molecules) to (ever) seriously become a part of electronics. But unlike the expectations expressed only a few years ago, it is very remarkable how active and vivid this field has evolved and how many new and beautiful papers on the physics of charge and spin transport have appeared recently. If this goes on like this, it is wonderful. But we also have to see that new low-dimensional systems have entered the scene: the semiconducting nanowires (see, for example, [59]) and monolayers of graphene (see, for example, [60]). While the latter extend the unique possibilities of CNT to two dimensions, it will be interesting to compare the 'performance' of the former with the CNTs.

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