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Invited

Carbon Nanotubes: Electronic Properties and Devices

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1. Introduction

Carbon nanotubes (NT) are hollow cylinders composed of carbon atoms with diameters as small as 1 nm and lengths of several microns [1]. They can be imagined as a graphene sheet rolled into a seamless hollow cylinder. Depending on the angle at which the graphene sheet is rolled, the NT can be either a semiconductor or a metal [2]. The NTs' excellent electrical properties coupled with a high tensile strength and thermal conductivity make them ideal candidates for use in novel nanoelectronic devices.

2. Discussion

In my talk, I will discuss several aspects of nanotube behavior, transport properties, and device applications. First, I will examine the electronic structure of free nanotubes; then their interactions with their substrate and other nanotubes, as well as NT self-interactions. I will show that the strong interaction with the substrate [3] allows the manipulation with the AFM of both position and shape of individual NTs [4]. This ability to manipulate NTs allows the fabrication of simple model devices. An example of a field effect transistor (FET) using a single 1.5 nm diameter semiconducting nanotube as its channel is shown in Fig. 1. [5] The NT bridges two gold electrodes on top of a 140 nm thick gate oxide. The Si wafer itself is used as a back gate. The room temperature transfer characteristics I_{sd}-V_g for several values of V_{sd} are shown. The NT-FET behaves as a p-channel MOSFET, and V_g can modulate the current by 5 orders of magnitude. The saturation at negative V_g is related to the high contact resistance (1kΩ). The 1D hole density is ~$9x10^6/cm^{-1}$ for V_g=6V, and the hole mobilty ~20 cm^2/Vs. The high contact resistance of the nanotube can act as a tunnel barrier at low temperatures. Indeed, we have observed the transformation of an NT FET to a single electron transistor (SET) at cryogenic temperatures [6].

An interesting result of the van der Waals interaction between nanotubes is the formation of nanotube rings (loops), where the strong strain energy to bend the tubes can be more than compensated for by the bonding energy of the overlapping end segments of NT. [7] Bubble cavitation processes induced by ultrasonic irradiation of suspensions of of NTs in an aqueous environment supply the large activation energy required to bend the NTs and allow the ends to overlap. [8] There is currently strong interest in understanding the transport properties of single wall nanotubes (SWNTs). They come as close as possible to being ideal 1D electronic systems. The closed geometry of

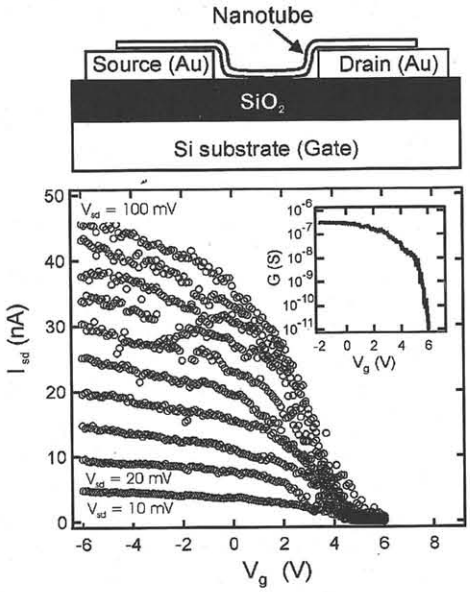

Fig. 1 Schematic and operating characteristics of a single nanotube field effect transistor.

nanotube rings (produced from SWNTs) makes magneto-resistance (MR) studies in SWNTs possible.

In Fig. 2a we show low temperature magneto-resistance measurements on a 410 nm radius NT ring. A negative MR is seen up to a field of 4 T. [9]. The MR result can be accounted for iby weak localization (WL) arising from the constructive interference of electron waves counter-propagating around the ring. [10] Fitting the MR profile to the equations of WL theory we can extract the coherence length of the electrons in the ring. The coherence length (L_φ) increases with decreasing temperature ($L_\varphi \propto T^{1/3}$) reaching a value of 520 nm at 3 K (Fig. 2b). The temperature dependence of L_φ indicates that the dominant dephasing mechanism involves electron-electron interactions [11]. When the temperature is lowered below ~1K the behavior of the ring is found to change qualitatively. The resistance now depends exponentially on temperature and the MR becomes large and shows strong side-bands. The dI/dV spectra (Fig. 3a) exhibit a resistance peak at E_F, which develops a dip at zero bias at T<0.7 K. The above behavior can be explained in terms of a transition from a weak to a strong electron localization phase. In this phase, transport is very sensitive to individual defects and leads to universal conductance fluctuations that appear as the side bands to the central magneto-resistance peak.

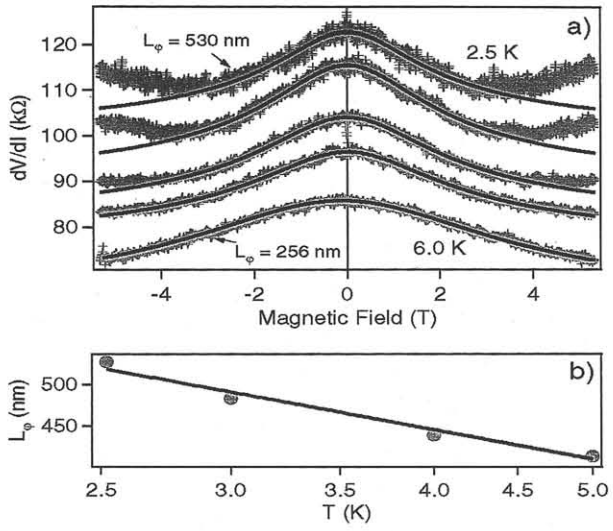

Fig. 2. (a) Low temperature magnetoresistance of a SWNT ring. (b) Temperature dependence of the coherence length.

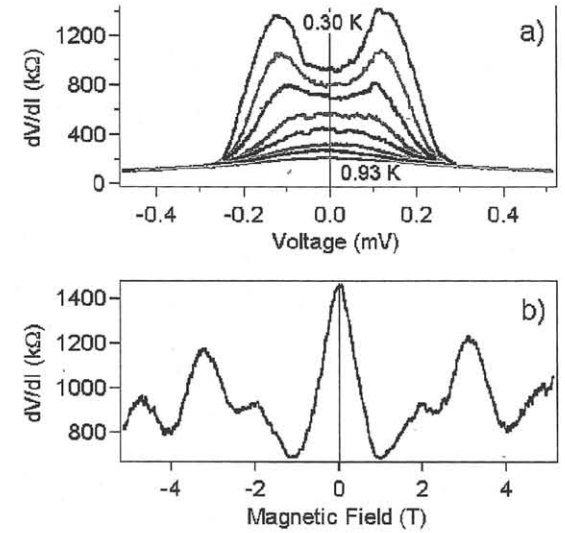

Fig. 3 (a). Differential resistance of the nanotube ring, taken, from top to bottom, at 0.3K, 0.4K, 0.50K, 0.63K, 0.70K, 0.81K and 0.93K. (b) Magnetoresistance of the ring at 0.4K.

Unlike conventional metal conductors, NTs are covalent materials in which the carriers participating in chemical bonds. As a result, structural distortions of NTs may lead to significant changes in their transport properties. I will discuss the effects of two types of NT deformations: NT bending and NT twisting.

Bending is widely observed in NTs on solid substrates. The strong adhesion forces between NTs and the substrate on which they are placed bend the NT so that they conform to the substrate topography [3]. We have explored theoretically the effects of bending on the NT electronic structure. We found that the most important change involves an increased mixing between σ and π electrons. This mixing introduces new, rehybridized states near E_F [12]. Calculations of the conductance using a Green's function approach show that significant changes in the conductance take place at large bending angles when kinks start appearing in the NT structure [13].

Twisting leads to more drastic changes in the NT transport properties. Armchair (n,n) NTs are metallic. However, twisting destroys their symmetry and opens up a band-gap, turning them into semiconductors. Green's function calculations for a (6,6) NT show that the band-gap scales linearly with twist angle θ_T up to θ_T=12°/nm. Above that angle, the NT structure collapses into a twisted ribbon, and the band-gap remains constant. [14] In this respect we note that all large diameter (D) multi-wall NTs behave at room temperature as metals because the band-gap scales as $1/D^2$. Indeed, we have not been able to gate multi-wall NTs. However, when twisted, they could be gated and act as FETs [5].

3. References

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