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Spin electronics using carbon nanotubes

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Abstract

We use ferromagnetic contacts to inject and detect spin-polarized electrons in multi-walled carbon nanotubes. The small diameter of the nanotube allows us to probe individual magnetic domains. As the alignment of the magnetizations within a pair of contacts switches from parallel to antiparallel, the nanotube resistance switches from a low to a high resistance state. This result is a first step towards the possibility of carbon nanotube-based spin electronics.

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Spin-polarized electrons can be injected from a ferromagnet into non-ferromagnetic materials [1–3], and also through oxide tunnel barriers [2,4,5]. Here, we investigate spin injection into carbon nanotubes, and observe direct evidence for spin coherent transport. We measure a hysteretic magnetoresistance in a number of ferromagnetically contacted multi-walled carbon nanotubes, with a maximum resistance change of 9%. From this we estimate the nanotube spin-flip scattering length to be at least 130 nm.

Fig. 1 is an electron micrograph of one of our ferromagnetically contacted nanotube devices. We use crude multi-wall carbon nanotubes (MWNTs) synthesized from graphite rods by the arc discharge evaporation method [6]. The nanotubes are dispersed onto a SiO_2/Si substrate, and subsequently located with respect to Pt/Au alignment marks using a scanning electron microscope. Ferromagnetic cobalt (Co) contacts are thermally evaporated at a pressure of 4×10^{-7} Torr. Magnetoresistance measurements are performed at 4.2 K with B directed in the plane of the substrate. Fig. 2 shows the two-terminal differential resistance of a Co-contacted nanotube as a function of magnetic field. The field is swept first from -100 to 100 mT (solid line) and then back to -100 mT (dashed line). A resistance peak appears as the magnetic field moves through 0 T. The width of the resistance peak is approximately 50 mT, which is commensurate with the coercive field strength for a thin Co film [7]. There is also

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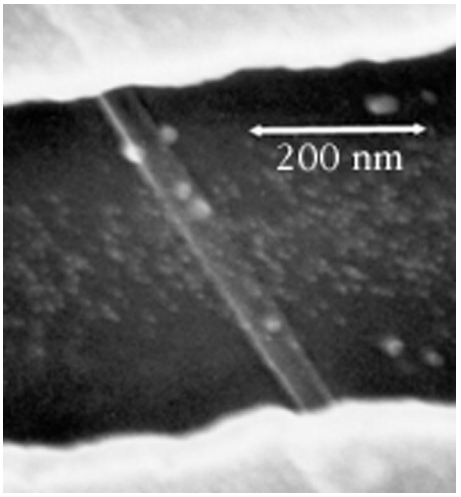

Fig. 1. Electron beam micrograph of a typical Co-contacted multi-walled nanotube. The Co contacts lie on top of the nanotube. The diameter of this particular nanotube is 40 nm; nanotube diameters ranged between 10 and 50 nm.

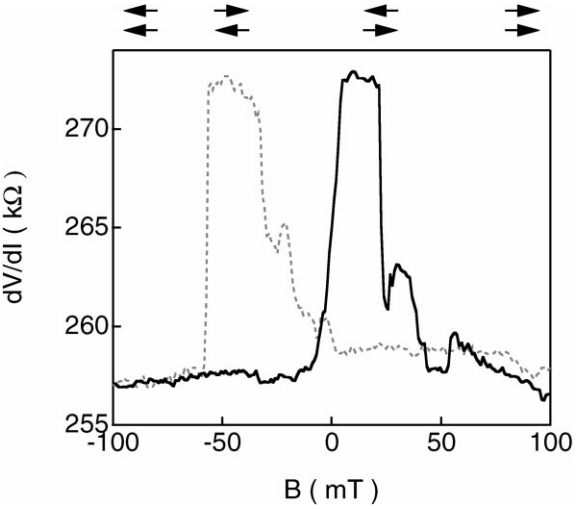

Fig. 2. Two-terminal differential resistance as a function of magnetic field for a Co-contacted MWNT. The magnetic field is directed parallel to the substrate, and the temperature is 4.2 K. The solid (dashed) trace corresponds to the positive (negative) sweep direction. The magnetization direction of the left and right contacts is represented by the arrows at the top of the figure.

a large hysteresis in the peak position ($\approx \pm 50$ mT) between positive and negative sweep directions, indicating the probable influence of the contact magnetization.

Similar hysteretic magnetoresistance has been observed in magnetic tunnel junctions, and has been attributed to spin-polarized electron tunneling [4,5,8]. The conduction electrons within a ferromagnet such as Co have a preferred spin direction, which is determined by the local magnetization. In the absence of spin-scattering, the tunnel resistance between two ferromagnetic contacts depends on their relative spin orientation. In the anti-parallel state the majority spin states are out of alignment and the junction resistance is higher than in the parallel state in which the majority spin states are aligned.

The observed peak in the nanotube resistance in Fig. 2 suggests that the contact magnetizations, which are aligned parallel with the magnetic field at $B = \pm 100$ mT, become misaligned as the field is swept through $B = 0$ T. The misalignment may be caused by magnetization fluctuations that occur locally, on the scale of the nanotube diameter (30 nm). The average Co domain size (50 nm) [7] is on the order of the width of the nanotube so that the nanotube contacts only a small number of magnetic domains. The coercivity of each domain varies, and depends on its geometry and the local energy conditions.

Any change in the nanotube magnetoresistance due to spin-injection requires that a sufficiently small amount of spin-scattering occurs both within the nanotube, and at the interfaces between the nanotube and the contacts. The difference between the tunnel resistance in the parallel (R_p) and antiparallel (R_a) states [4] is given by

$$\Delta R/R_a = (R_a - R_p)/R_a = 2P_1P_2/(1 + P_1P_2).$$

Here, P_1 and P_2 are the percentage of conduction electrons polarized in the majority spin band in the ferromagnetic contacts 1 and 2. For Co, the polarization has been determined to be 34% [9] giving a maximum resistance change of 21%. In Fig. 2, $\Delta R/R_a$ is 9% so that approximately 14% of the spin-polarized electrons travel the 250 nm through the nanotube without spin-flipping. The spin-scattering length, l_s, can then be estimated by assuming that the spin polarization drops off as $\exp(-l/l_s)$ within the nanotube. This gives $l_s = 130$ nm. Although fairly long, this is probably an underestimation. Because of the low atomic number of carbon, spin–orbit scattering in the nanotube should

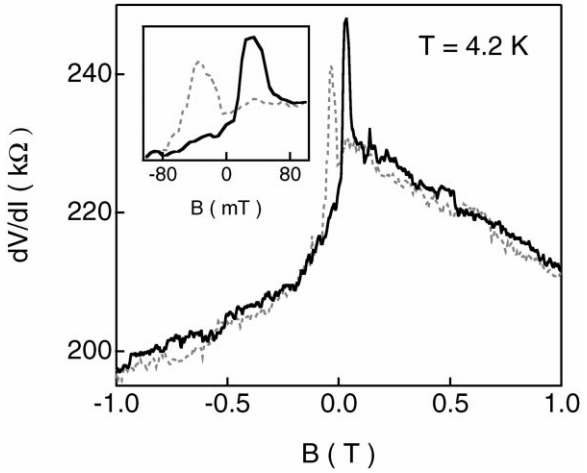

Fig. 3. Magnetoresistance of a second Co-contacted MWNT, showing the behaviour at high-magnetic field. The solid (dashed) line corresponds to the positive (negative) sweep direction. The inset details the region near zero field.

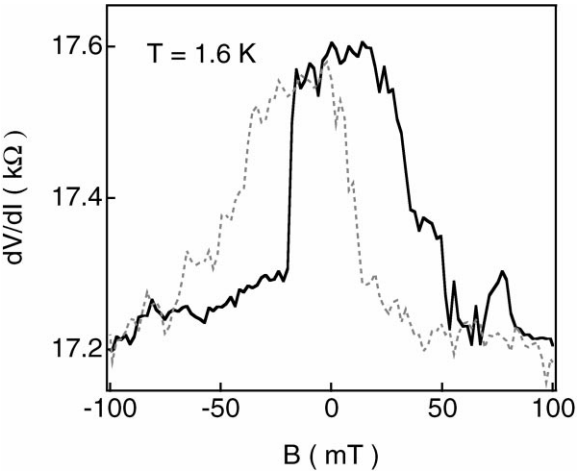

Fig. 4. Magnetoresistance of a MWNT contacted with two different ferromagnetic materials: Co and NiFe. The device is fabricated using a shadow evaporation technique. The solid (dashed) line corresponds to the positive (negative) sweep direction.

be negligible, while a large amount of spin-scattering is expected at the nanotube/ferromagnetic interface. In addition, the local spin-polarization will depend on the interface quality, and could be appreciably lower than 34%. We expect that spin coherent effects should be observable in carbon nanotubes over much longer distances and higher temperatures if improvements in the interface quality can be achieved.

Fig. 3 shows the high-field magnetoresistance of a second Co-contacted nanotube device, measured between ± 1 T. A hysteretic magnetoresistance peak is again observed around zero field (see inset for detail). The resistance drops substantially as the magnetic field increase to higher values. A similar decrease in the high-field resistance has been observed in non-magnetically contacted nanotube devices, and attributed to the quenching of weak localization among current pathways through the nanotube [10]. What is unusual in our device, however, is that the magnetoresistance is asymmetric in B ($R(B) \neq R(-B)$). This is in conflict with the reciprocity theorem for a two-terminal resistance measurement [11]. It is possible that the local domain configuration is different in the two field directions, thus altering the contact resistances. Further work is necessary to understand this effect.

In Fig. 4 we show the magnetoresistance of a MWNT fabricated using a shadow evaporation technique, which allows the two contacts to be made from different magnetic materials. NiFe is evaporated from one side of the substrate, followed by Co evaporation from the other side. A gold capping layer is then evaporated from directly above the substrate to protect the magnetic surface. Fig. 4 shows that hysteretic magnetoresistance is also observed for the NiFe/MWNT/Co device; however, the absolute resistance and the resistance change are smaller than in the Co-contacted samples. The exact reason for this difference is unknown – perhaps the shadow evaporation technique improves the continuity of the magnetic film and reduces the contact resistance in comparison with the single-layer Co devices.

Our results are consistent with recent experiments that show that the electron path lengths within MWNTs are extremely long. The phase coherence length is found to be 250 nm and the elastic scattering length 60 nm [10]. Further work indicates that MWNTs behave as ballistic conductors, even at room temperature [12]. We expect the spin-flip scattering in the nanotubes should also be highly suppressed. Consider for example that the spin scattering length in a metal [3] or a semiconductor [13] is typically

much longer than the phase coherence length or the elastic scattering length. Carbon nanotubes have already been considered as potentially useful electronic devices because of their low dimensionality and relatively high conductivity [14,15]. Our observations of clear spin-dependent phenomena show that the nanotube is also a strong candidate to form the basis of new spin-electronic devices.

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