Anomalous negative magnetoresistance of multi-walled carbon nanotube with $Ni_{78}Fe_{22}$ electrodes

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Abstract

Electrical transport properties of individual multi-walled carbon nanotubes in contact with the ferromagnetic electrodes, $Ni_{78}Fe_{22}$, were studied at low temperatures. The magnetoresistance curve was non-hysteretic and exhibited pronounced dip structure at the external field of 160 Oe. The magnetoresistance ratio depends strongly both on bias current and temperature.

Key words: Spin-polarized tunneling; carbon nanotube; spin coherence

1. Introduction

Recently, it has been shown that individual multi-walled carbon nanotubes (CNTs) in contact with ferromagnetic Co electrodes exhibit hysteretic magnetoresistance (MR) curve [1], attributed to the tunneling magnetoresistance (TMR) effect [2]. The observation of TMR effect in CNT-based device imply that the spin coherence of electrons injected from the ferromagnetic metal can be maintained within the CNT over an appreciable length. Since the operation of the so called *spintronic devices* critically depends on the spin coherence of the electrons injected from a ferromagnet, CNT can be a good host medium of the lateral spin injection devices [3].

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2. Results

The multi-walled CNTs synthesized by an arc discharge method were prepared on a Si substrate covered with a 500 nm-thick thermally grown SiO_2 layer. The patterns for electrical leads were generated by using electron beam lithography onto the selected CNT and then 40 nm of Py was deposited on the contact area by thermal evaporation. To form a stable ohmic contact between the CNT and the ferromagnetic metal, we have performed a rapid thermal annealing at 600 °C for 30 s [4]. Five samples (py1-py5) were studied and the diameters of multi-walled CNT were in the range of 20-40 nm.

As shown in Fig. 1, the MR curve of the sample py4 was symmetric with respect to the zero field and exhibited no hysteresis at all. Up- and down-sweep of magnetic field gave almost identical MR curves. Also, the MR curve showed pronounced dip, instead of peak, at the field intensity of ± 16 mT. All the five samples we have studied exhibited similar MR curve but with different zero-field resistance and MR ratio. If normalized by the zero-field resistance, both four- and two-

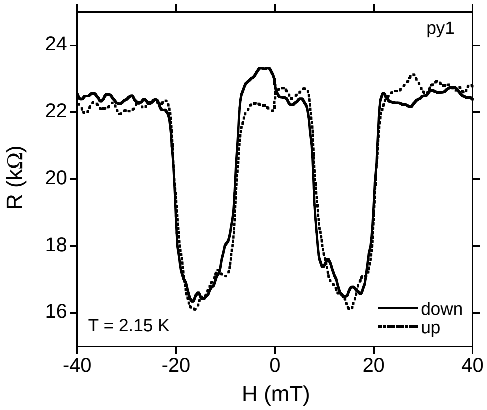

Fig. 1. The MR curve of the sample py1 at the temperature of 2.15 K. Both up- and down-field sweeps give nearly identical MR curves

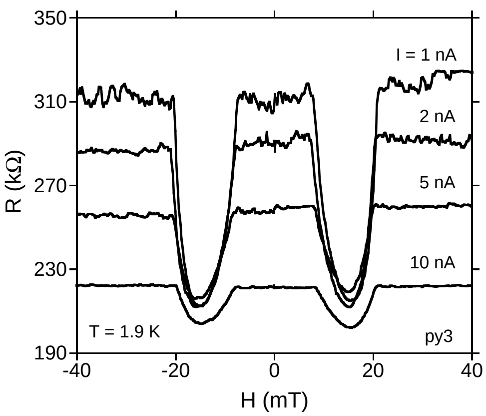

Fig. 2. The bias-dependent MR curves of the sample py3 at the temperature of 1.9 K.

probe measurements gave almost identical MR curves. The MR ratio, defined as the maximum MR change divided by zero-field resistance, was 35% at 1.5 K. The dip structure in the MR curve persists up to 10 K.

The MR curve also exhibited noticeable bias dependence, as shown in Fig. 2. With the increase of the bias current, the zero-field resistance decreases dramatically but the resistance at $H = \pm 16$ mT changes little. Strong bias dependence of the zero-field resistance means nonlinear current-voltage $(I - V)$ characteristics at zero field. The $I - V$ curve at zero field is nonlinear in the low bias region, while the $I - V$ curve at $H = 16$ mT is almost linear.

3. Discussions

No known mechanism is available for the anomalous negative MR of the CNT/Py junction but a couple of interpretations can be considered. In any case it seems certain that the spin diffusion length in a CNT is long enough at low temperatures to carry spin polarization through the CNT. First interpretation is based on the TMR effect [2]. According to this interpretation, the magnetic moments must be non-collinear in the MR dip region, 8 mT $< |H| <$ 20 mT. Unfortunately, this scenario cannot explain why the magnetic moments are not collinear only at finite field, not around zero field region for several different samples. Further, even though we admit this interpretation, the resistance should be increased where the magnetic moments become nonparallel, in normal cases.

The negative MR can be attributed to the change of the energy spectrum of the magnetic excitations. In this interpretation, the magnetic moments of the two Py electrodes are parallel to each other and are aligned to the easy axis at low field and to the field direction at high field. In the intermediate fields, the magnetic moment direction rotates continuously from the easy axis to the field direction, as the external field intensity is increased. Here we point out that the spectra of the magnetic excitations is modified significantly in the crossover region, because the two energy minimum points, the easy axis and the field direction, are almost degenerate. Collective spin excitations with denser spectra in the crossover region may result in an enhanced electron transport through the contacts. Note that similar kind of effect was addressed for tunneling spectroscopy of a ferromagnetic nanoparticle [5,6]. Further studies, both theoretical and experimental, are required.

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