Spin-injection properties from mesoscopic Co electrodes to single-walled carbon nanotube

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Abstract

We have studied the spin-dependent transport properties of single-walled carbon nanotubes having the mesoscopic ferromagnetic Co electrodes. The resistances of Co contacted single-walled nanotubes with the voltage probe length of 1.5 μm change hysteretically as a function of the magnetic field, with the magnetoresistance change of 3.4 % at low temperatures, exhibiting the spin-polarized electron transport. The estimated spin-flip scattering length was about 1 μm at 4.2 K.

Key words: Carbon nanotube; spin injection; tunnel magneto-resistance

1. Introduction

There have been intensive studies on the transport and injection properties of the spin-polarized electrons from ferromagnetic to non-magnetic materials, open a new class of devices [1]. The spin-polarized electrons can be injected to the various materials, such as metal and semiconductor through a tunnel barrier. The electron scatterings at interfaces and inside of material will generally reduce the spin coherence length, which play a critical role on the proper action of spin devices[2] [3].

The proper choice of materials having the long spin coherence length and good contact barrier enables us to have the coherent spin injection from the ferromagnetic material into nano-sized non-magnetic spin mediator. The carbon naotubes (CNTs) are considered as one of the promising spin mediators because of their ballistic nature of conduction and relatively long spin scattering length [4]. Coherent spin transport has been observed in multi-walled CNT system with Co electrodes. The maximum magnetoresistance (MR) change of 9 % was observed in multi-walled CNT at 4.2 K [5].

However, there has been no detailed experimental study until now on spin-dependent transport properties of the single-walled CNT with ferromagnetic contacts. We have contacted the ferromagnetic Co electrodes to the single-walled CNTs and studied their spin-dependent transport properties.

2. Results and discussion

The individual single-walled CNT was prepared on a Si substrate with a 500 nm-thick thermally-grown SiO_2 layer. The patterns for ferromagnetic Co contacts were generated by using electron beam lithography onto the selected CNTs and then 40 nm of Co was deposited directly on the contact area by thermal evaporation. The diameter of CNT is about 3 nm. The distance between the two Co electrodes is about 1.5 μm.

Figure 1 shows the MR change as a function of magnetic field between the two Co electrodes at various temperatures. The two-probe resistance increases from 1.3 MΩ to 4.3 MΩ as the temperature is lowered from 8.2 K to 0.1 K at a zero magnetic field. The observed MRs show the typical hysteretic behaviors

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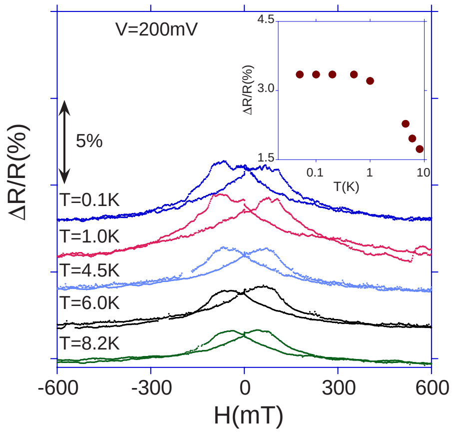

Fig. 1. The MR change as a function of magnetic field between the two Co electrodes of the length, $L \approx 1.5$ μm at various temperatures. Inset: The MR ratio as a function of temperature.

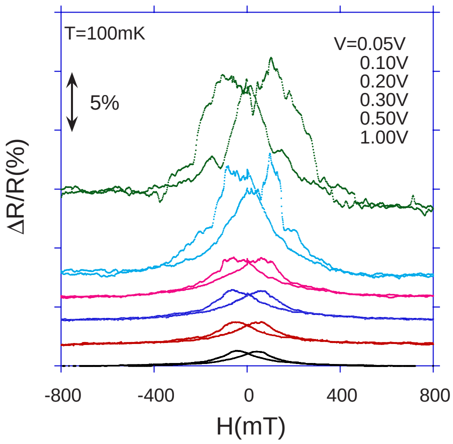

Fig. 2. The MR curves at 100 mK with varying the bias voltage.

of tunnel magneto-resistance devices. The width of the hysteretic resistance peak is about 200-300 mT. Compared to the MR curves in the multi-walled CNT, the switching of spin direction is not abrupt and MR changes rather smoothly as the magnetic field swept from a high field region. The coersive field in our case is about ten times larger than that of multi-walled CNT, which might be the smaller size of Co grains due to the thermal annealing process. The hysteretic MR in Co/CNT/Co is known to originate from the local magnetization fluctuations of individual domains on the scale of CNT diameter. Since the average size of Co magnetic domain is comparable to that of the diameter of the CNT, CNT may contact several magnetic domains with the different coercive fields, which gives the hysteretic MR peaks [5].

As the temperature is lowered, the MR ratio increases from 1.6 % at 8.2 K to 3.4 % below 0.8 K at the bias voltage, $V=$ 200 mV. The measured MR ratio is rather smaller than that of multi-walled CNT, which is about 9 % at 4.2 K. The small MR ratio in our single-walled CNT might be related with the disorders such as defects, twists, and bendings along the tube and non-ideal interfaces between the nanotube and Co contacts. In this system, spin-flip scatterings may occur more frequently within our nanotube and at interfaces than in the straight multi-walled CNT with good ohmic contacts.

Inset of Fig. 1 shows the change of MR ratio as a function of temperature. With decreasing the temperature from 8.2 K, the MR ratio increases slightly and becomes saturated below 0.8 K. The spin-flip scattering length, l_s, can be estimated by assuming the exponential decay of l_s within the tube as $\exp(-l/l_s)$. 10.8 % (MR ratio=2.3 % at 4.2 K) of spin-polarized electrons travel 1.5 μm without spin-flip scatterings and survive at the other electrode. Then the estimated, l_s is about 1μm at 4.2 K.

Figure 2 shows the MR measurements at 100 mK with varying the bias voltage. Note that the MR ratio increases with lowering bias voltage. As a bias voltage level was lowered from 1.00 V to 0.05 V, the MR ratio increases from 1.1 % to 10.4 % by a factor of about 10. Since our CNT has the Coulomb charging gap due to disorder-induced dots at low temperatures, the bias-dependent enhancement of MR ratio would be related with the Coulomb blockade effect. The enhancement of MR ratio in the Coulomb blockade regime might be reasonably explained by co-tunnelling effect of electrons via virtual charged state of the island [6].

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