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Characteristics of a Carbon Nanotube-based Tunnel Magnetoresistance Device

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Tunnel magnetoresistive devices using an individual multi-walled carbon nanotube were fabricated and their low-temperature electrical transport propertiers were investigated. With the ferromagnetic Co electrodes, the multi-walled carbon nanotube exhibited hysteretic magnetoresistance curve at low temperatures. Depending on the temperature and the bias current, the magnetoresistance ratio can be as high as 16% at the temperature of 2.2 K. Such high magnetoresistance ratio indicates a long diffusion length of the multi-walled carbon nanotube.

Key words : carbon nanotube, magnetic tunnel junction, spin injection, spintronic device

1. Introduction

Since discovery, a variety of carbon nanotube (CNT)-based electronic devices, such as field effect transistor [1-3], single electron transistor [4], hetero-junction [5-7], and crossed junction [8], have been proposed and realized. Most of the CNT-based devices, however, exploit charge degree of freedom without considering the spin degree of freedom of electron. Recently, it has been shown that individual multi-walled CNTs in contact with ferromagnetic metal electrodes exhibits hysteretic magneto-resistance (MR) curve [9], attributed to the tunnel magneto-resistance (TMR) effect [10-13]. The electrical current flowing through a magnetic tunnel junction, consisting of two ferromagnets separated by insulating layer, is affected by relative orientation of the magnetic moments of the ferromagnetic layers [10].

Since the change of magnetoresistance in an MR device depends critically on the spin coherence of the electrons injected from a ferromagnet, the spin information of the electrons injected from a ferromagnet must be transferred to the other ferromagnet through interface and the host medium. The key issue of the MR devices is then to reduce the spin-flip scattering of electrons at the interface and inside the host medium. In these respects, CNT can be a good candidate for the host medium of a lateral spin injection devices [14]. Due to its perfect crystallinity, CNT is expected to have a large spin diffusion length. In Tsukagoshi, Alphenaar, and Ago's experiment, the spin diffusion length was estimated to be greater than 130 nm [9].

In this paper we report the electrical transport properties of multi-walled CNTs in contact with the ferromagnetic Co electrodes. At temperatures below 10 K, the Co/CNT junction exhibited hysteretic MR curve with the resistance peaks at the field intensity of about 0.3 T, a typical behavior of a magnetic tunnel junction. The MR ratio increases with the decrease of the temperature, becoming as high as 16% at 2.2 K.

2. Experiments and 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-thick Co film was deposited on the contact area by thermal or e-beam evaporation. To form a stable ohmic contact between the CNT and the Co film, we have performed a rapid thermal annealing at 400~600 °C for 30 s [12].

Figure 1 shows the scanning electron micrograph of the sample. Atomic force microscope study revealed that the diameter of multi-walled CNT was about 20~30 nm. The Co electrodes in the contact region are 200~400 nm wide and are 300~500 nm apart from each other.

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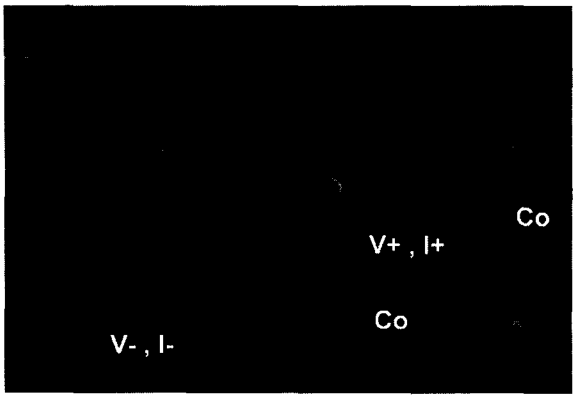

Fig. 1. Scanning electron micrograph of a CNT-based magnetoresistance device.

The sample resistance was measured in two-probe configuration by using a lock-in preamplifier. Figure 2 shows the temperature-dependent MR curves of the sample. Clear hysteresis was observed in addition to the large background negative MR. Such negative MR was typically observed in a multi-walled carbon nanotube and was attributed to the localization effect [15]. Though we have not shown here, single-walled carbon nanotube did not exhibit background negative MR [16].

The hysteresis in the magnetoresistance curve indicates that an appreciable percentage of spin-polarized electrons injected from a Co electrode to the multi-walled CNT arrived at the other Co electrode without spin-flip scattering. Following Julliere's model [10], the maximum MR ratio for a magnetic tunnel junction (MTJ), consisted of two ferromagnets with spin polarization P_1 and P_2, is given by

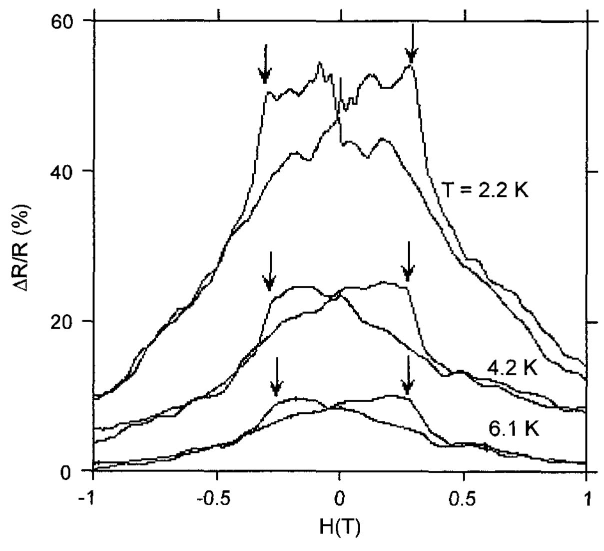

Fig. 2. The Temperature dependence MR curves of the sample.

$$\frac{\Delta R}{R} \equiv \frac{R_a - R_p}{R_p} = \frac{2P_1P_2}{1 + P_1P_2},$$

where R_a and R_p are the resistance with the anti-parallel and parallel configurations of the magnetic moments of the two consisting ferromagnetic layers. Since $P_1 = P_2 = 0.34$ for the Co films, theoretically predicted maximum MR ratio is 21%. The MR ratio we have observed was 16% at 2.2 K, close to the maximum MR ratio, indicating that most of spin-polarized electrons injected from one electrode arrived at the other electrode without losing spin information. The spin diffusion length can be comparable to or longer than the electrode distance, several hundreds of nanometers. This is expected result, considering the perfect crystalline nature of the CNT.

3. Summary

We have fabricated and investigated a CNT-based magnetoresistive device. Clear hysteresis in the magnetoresistance curves were observed. The MR ratio increased fast with the decrease of the temperature. At the temperature of 2.2 K, the MR ratio was as high as 16%, comparable to the maximum MR ratio theoretically predicted, 21%. Our observation revealed that the CNT had a long spin diffusion length and was an ideal material for a lateral spin injection device.

Acknowledgements

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