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Graphene Spintronics

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1. Introduction

After the first success of fabricating multi-layer graphene and its field effect transistors (FETs) in 2004 [1], a tremendous number of studies has been implemented in order to clarify attractive physical features of single-layer and multi-layer graphene (SLG and MLG). Integer Hall Effect up to room temperature (RT) [2-4], extraordinarily high mobility [5], proximity effect [6] and band-gap engineering [7] have been so far reported, which induces much interest for graphene electronics.

In 2007, introduction of a spin degree freedom to graphene electronics (graphene spintronics) was successfully achieved by several groups, including our group, individually [8-10], where spins were injected, a pure spin current was generated and the spins were manipulated in SLG and MLG up to RT. It should be noted that although there were reports on spin injection into organic semiconductors, spin coherence and spin manipulation have never been successfully measured, which provides direct proof of spin injection and shows a fact that the measurements were reliable. In this sense, it may be said that the spin injection into graphene was the first steadfast success of spin injection into molecular materials. The reason why people are attracted by spin injection into carbonaceous molecules is based on facts that the low atomic mass of carbon can induce the weak spin-orbit interaction and that 99% of the carbon isotopes has no nuclear spin and therefore hyperfine interaction between nuclei and electronic spins should be weak.

In this talk, I introduce the detail of our first observation of spin injection and pure spin current in graphene-based spin valve devices and also unprecedented robust bias-voltage dependence of spin polarization of injected spins, which could be an important breakthrough for expanding device designing for realization of spin MOS FETs [11].

2. Experimental

The starting materials used for preparation of the MLG spin valves were highly oriented pyrolytic graphite (HOPG, NT-MDT Co.) and polyimide-oriented highly oriented graphite (Super graphite, Kaneka Co.). MLG flakes were peeled from these materials using adhesive tape. The flakes were then pushed onto the surface of a SiO_2/Si substrate (SiO_2 thickness=300 nm). The typical thickness of MLG that provided observable spin injection signals in a spin valve structure was 2-40 nm. The non-magnetic and ferromagnetic electrodes used were Au/Cr (=40/5 nm) and Co (=50 nm), respectively, and were patterned using an electron beam lithography technique. The width of the Co electrodes, Co1 and Co2, were the same, but Co2 possessed a pad structure in order to weaken the coercive force, and the gap width of the Co electrodes was 1.5 μm. All measurements of magnetoresistance (MR) effects were performed at RT. We introduced a non-local scheme in addition to a conventional local scheme for excluding spurious signals. The spin injection was investigated using a four terminal probe system (ST-500, Janis Research Company Inc.) with an electromagnet. The magnetic field was swept from -400 Oe to +400 Oe in steps of 8 Oe. A source-meter (Keithley Instruments Inc., KH2400) and a multi-meter (Keithley Instruments Inc., KH2010) were used to detect spin injection signals.

3. Results and discussion

Figure 2 shows comparison between results on “non-local” and “local” schemes at RT. The injection electric current was set to be -1 mA. Although anisotropic MR effect was observed in the "local" measurement, positive MR signals can be seen in the same external magnetic field where "non-local" resistance hysteresis was observed. This fact unambiguously indicates that spin injection into MLG was succeeded in both measurements at RT.

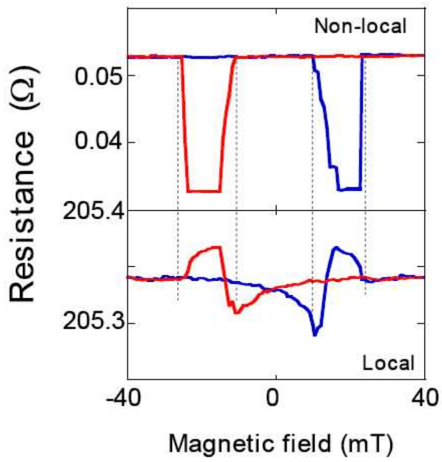

Fig. 2 Comparison between results on "non-local" and "local" MR effects.

Hanle-type spin precession was observed by using "non-local" scheme, and it was found that the spin diffusion constant, spin flip length, spin coherent time and spin polarization were estimated to be 2.1×10^{-2} m^2/s,1.6 μm, 120 ps, and 0.09, respectively. These values are very close to those observed in single layer graphene [9].

Finally, I briefly introduce the latest finding of robustness of spin polarization. It is widely known that MR ratio monotonously decreases as bias voltage increases, which is thought to be attributed to decrease of spin polarization of injected spins. However, it was found that spin polarization of injected spins into MLG did not decrease up to +2.7 V at RT [11]. This finding is probably due to an ideal interface formation between Co and MLG because the "local" spin injection signal intensity was almost double of that of the "local" spin injection signal intensity, which was theoretically predicted and experimentally realized in metallic spin valves [12].

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