Spin Injection into a Graphene Thin Film at Room Temperature

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We demonstrate spin injection into a graphene thin film with high reliability by using non-local magnetoresistance (MR) measurements, in which the electric current path is completely separated from the spin current path. Using these non-local measurements, an obvious MR effect was observed at room temperature; the MR effect was ascribed to magnetization reversal of ferromagnetic electrodes. This result is a direct demonstration of spin injection into a graphene thin film. Furthermore, this is the first report of spin injection into molecules at room temperature. [DOI: 10.1143/JJAP.46.L605]

KEYWORDS: graphene, spin injection, spin current, non-local, room temperature

Graphene,1) which is an atomically flat layer of carbon atoms densely packed into a benzene-ring structure and in which charge carriers behave as massless Dirac fermions, constitutes a new model system in condensed matter physics. A considerable number of studies on graphene has been implemented, for instance, field-effect transistors with enormously high mobilities,1) anomalous quantization of the Hall conductance,2)3) observation of bipolar supercurrent.4) Although much effort has been invested in studying charge transport in graphene, there have been no reports to date of experimental investigations focused on spin transport in graphene. Since graphene exhibits gate-voltage-controlled carrier conduction and high field-effect mobilities and it consists of only light elements (carbon atoms), which induce a small spin–orbit interaction, it has the potential to become a pivotal material for establishing a new research field of molecular spintronics in which the polarized spin current can be controlled not only by a magnetic field and a bias drain voltage but also by a gate voltage. This, however, is dependent on the ability to inject spins successfully into graphene. There are the other potential materials in non-metallic spintronics, where spin current can be controlled by applying a gate voltage, namely, dilute magnetic semiconductors5) such as GaMnAs and Si-3d metal alloys.6) However, spin injection and spin device operation at room temperature (RT) have not yet been successfully demonstrated in either system, which presents a huge obstacle to their application as spintronics materials.

Molecular spintronics has attracted considerable attention recently; in particular, spin-dependent phenomena in π-conjugated organic semiconductors have been studied.7–16) There have been several important advances in the investigation of spin-dependent phenomena in nanocarbonaceous materials, including spin-dependent transport in carbon nanotubes at low temperature,7–9) and the observation of a spin-dependent magnetoresistance (MR) effect via C60S even at RT.10–12) It is especially notable that the demonstration of spin injection into carbon nanotubes by introducing a clever experimental technique, namely a “non-local” four-terminal measurement.8) However, in the above-mentioned studies, spin injection into molecules has been definitely demonstrated only at low temperature, while the spin-dependent MR effect at RT has been observed only in C60S, where C60S behave as tunneling barriers and spins are not injected. In addition, no report of spin injection into other π-electron molecules at RT has been published, as is also the case for nanocarbonaceous materials. Thus, a demonstration of spin injection and spin-dependent transport in nanocarbonaceous materials at RT is critical for the further progress of molecular spintronics and for the development of practical applications.

In this study, we demonstrate for the first time spin injection into a graphene thin film (GTF) with high reliability by employing a “non-local” four-terminal measurement scheme. Of even greater significance, we successfully observed spin-dependent transport at RT. This result opens up the new frontier of non-metallic spintronics and also is the important step toward fabricating molecular spin devices, such as spin field-effect transistors.

Graphene spin devices were fabricated by the following process. The source material of a GTF is highly oriented pyrolytic graphite (HOPG; NT-MDT Co.). We peeled flakes of graphite off by using scotch tape,10) and then pushed these flakes onto the surface of a SiO2/Si substrate having predefined markers, in which the SiO2 layer was 200 nm thick. When the scotch tape was removed, a GTF was absorbed onto the SiO2 surface by van der Waals force. It should be noted that the absorption force between the GTF and the SiO2 was sufficiently strong that the GTF did not detach from the substrate in the course of the subsequent processes. Non-magnetic (NM) electrodes (Au/Cr = 50/10 nm) and ferromagnetic (FM) electrodes (Co = 60 nm) were then fabricated onto the GTF using electron beam lithography. The geometry of the two FM electrodes was different in order to generate different coercive forces between the two FM electrodes [see Fig. 1(a)]. Figures 1(a) and 1(b) show a schematic image and a scanning electron microscope image of our graphene spin device; the widths of the two FM electrodes were 700 and 1000 nm, the gap width between the FM electrodes was 250 nm and the contact area between the Co and the GTF was approximately 3 μm². The thickness of the GTF was estimated to be 10 nm from the atomic force microscope observations.

All MR measurements were performed at RT by using a four-terminal probing system (ST-500, JANIS) with an electromagnet. The magnetic field was swept from −40 to +40 mT in 0.2-mT steps at a sweeping rate of 0.4 mT/s. We employed a standard ac lock-in technique (maximum current = 200 μA, lock-in frequency = 216 Hz, time constant = 300 ms) to measure the MR effect. Detailed experi-
In summary, we have succeeded in injecting spins into a GTF at RT, which has not been achieved in previous molecular spintronics and semiconductor spintronics studies. The injection of spins was verified by performing non-local measurements in graphene spin devices. This result has great potential for spintronics applications.
significance for future developments in molecular spintronics and also opens a door for practical fabrication of three-terminal spin devices, in which a spin current can be modulated by applying a gate voltage.

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