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Coherent Spin Conduction in Multilayer Graphene

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1. Introduction

Spin transport in graphite-based materials such as carbon nanotubes [1, 2], single-layer graphene [3, 4], and multilayer graphene (MLG) has attracted considerable attention in recent years because coherent spin transport is expected over a long distance due to the weak spin-orbit and hyperfine interactions [4]. Gate control of spin conduction in such materials is of high interest from the viewpoint of realizing multi-functional spintronic devices and clarifying the underlying physics [1-3].

In this paper, we explore the gate controllability of spin conduction in MLG. In view of practical applications, we believe that MLG is superior to single-layer graphene or carbon nanotubes because the effect of sample imperfection such as ripples is smaller due to its stiffness, leading to longer mean free path l_e and spin relaxation length λ_N [5], although we need to take into account the finite screening length of the gate electric field [6]. To clarify the feasibility of the MLG-based spintronic devices, we fabricated ferromagnet (FM)/MLG/FM junctions and measured gate voltage V_g dependence of magnetoresistance (MR). Here, we report the realization of the gate-voltage dependent spin transport and show that the spin relaxation length is extremely long, significantly exceeding 8 μm.

2. Experimental

Two kinds of device structures are used: one is two-terminal configuration for local measurement (sample #1) and the other is four-terminal configuration for the non-local measurement (sample #2). Figure 1 shows device structures of samples #1 and #2. The devices were fabricated by the standard micromechanical cleavage of bulk graphite [7] followed by the electron beam lithography and metal deposition. The thickness of the MLG film was 9 nm and 2.5 nm for samples #1 and #2, respectively.

The MR at T = 4.2 K was measured with a lock-in technique. The back gate voltage was applied through the 300 nm-thick SiO_2 layer on the substrate and the in-plane magnetic field was applied parallel to the long side of the ferromagnetic electrodes.

3. Results and Discussion

Figure 2 shows MR curves of sample #1 measured for different gate voltages, V_g = -80, 0, and +80 V. The MR exhibited hysteresis corresponding to the parallel and anti-

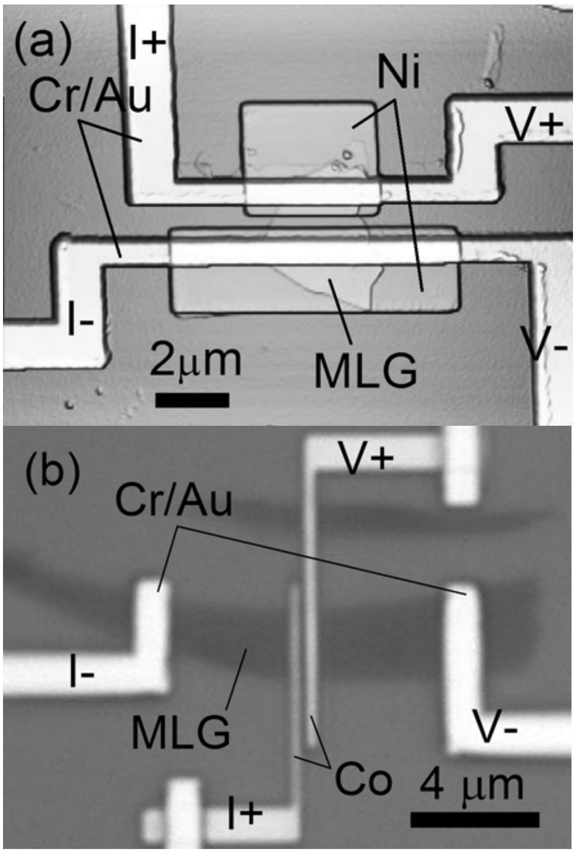

Fig. 1 (a) Atomic force micrograph of the sample #1 for local measurement and (b) optical micrograph of the sample #2 for non-local measurement. Configuration and materials of electrodes are indicated.

parallel configuration of the magnetization in FM electrodes; the magnetization is expected to be antiparallel from ~0 to ~1000 Oe in increasing magnetic field and from ~0 to ~-1000 Oe in decreasing magnetic field. However, the variation of the MR becomes obscure in comparison with the conventional MR curves presumably due to the domain structures in the wide Ni electrodes. Notice that at large gate voltages (V_g = -80 and 80 V) the MR for antiparallel configuration is smaller than that for parallel configuration, while the former is larger than the latter at V_g = 0. (Note that the behavior seen at V_g = 0 is the normal one usually observed in FM/normal metal/FM systems.) The origin of this abnormal behavior is not clear at the present moment,

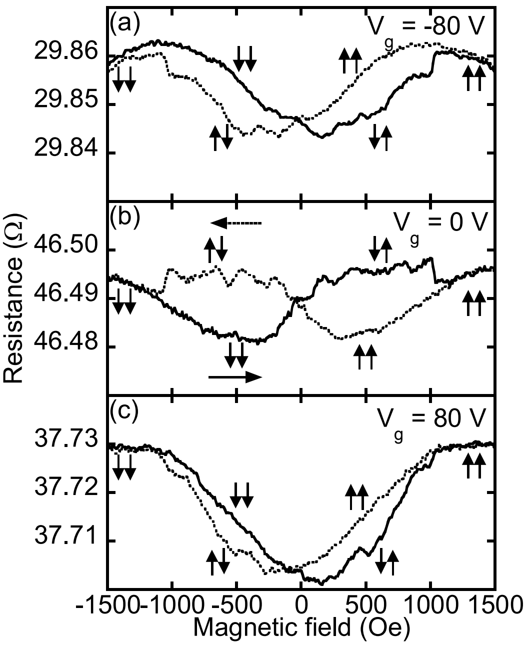

Fig 2. MR of sample #1 measured at V_g = -80, 0, 80 V from top to bottom. Solid (dashed) lines are MR in increasing (decreasing) magnetic field. Arrows indicate the magnetization configurations of FM electrodes.

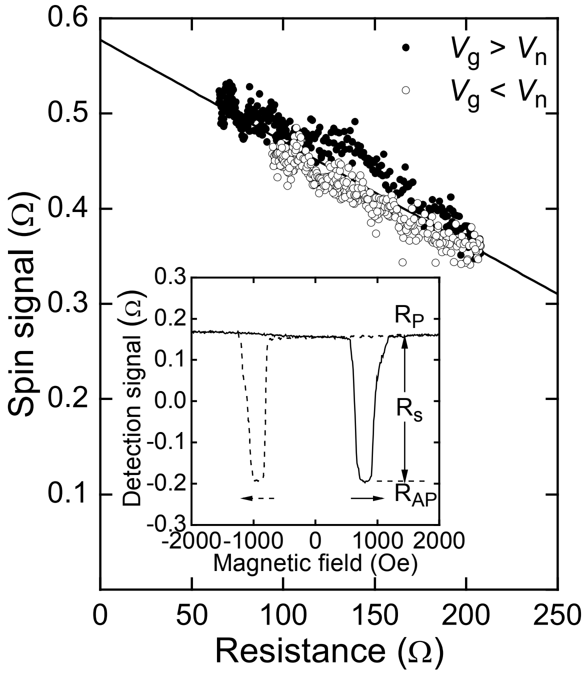

Fig 3. Linear relation between spin signal and resistance of sample #2. The solid (open) symbols correspond to the data obtained at $V_g > V_n$ ($V_g < V_n$), where V_n = 1.5 V is the charge neutrality point. Inset: Non-local detection signal as a function of the applied magnetic field at V_g = 0. Arrows indicate the sweep direction.

however, it is usually attributed to the Fabry-Perot type interference of electrons in the non-magnetic material [2,3] (MLG in our case). This indicates that the electrons and spins transport coherently in MLG, with l_e and λ_N substantially longer than the electrode spacing (~0.3 μm).

To investigate the spin transport in MLG in more detail, the non-local measurement was performed. The arrangement of current and voltage leads are shown in Fig. 1(b). The advantage of this method is that the voltage is insensitive to non-essential background magnetoresistances, such as the anisotropic magnetoresistance and the Hall effect, due to the voltage detection circuit separated from the current loop. The detection signal V/I is shown in the inset of Fig. 3. Sharp transition between a positive value R_P and a negative value R_{AP} were observed, corresponding to the parallel and antiparallel configuration of magnetization in the Co electrodes. This bipolar behavior confirms the spin injection from the Co electrode and the spin accumulation in the MLG. Here, we define the spin signal as $R_s = R_P - R_{AP}$. The main panel of Fig. 3 shows the spin signal as a function of the resistance R of the MLG, obtained by changing the gate voltage. It is clear that R_s is a monotonically decreasing linear function of R, which has never seen in conventional FM/normal metal/FM systems.

According to the general theory [8], such linear relation is attained only when the contact resistance between MLG and FM satisfies some special conditions [8,9], which gives a lower limit to λ_N: λ_N >> 8.4 μm [9]. Note that the obtained spin relaxation length is longer than those of conventional metals such as Al and Cu and even than that of graphene: λ_N = 1.5-2 μm.

4. Conclusion

We confirmed the V_g dependent spin transport in MLG by the local and non-local measurements. The both results indicate the long spin relaxation length in MLG. The gate tuning of MR opens the new possibility of graphite-based spintronic devices and MLG is a promising material for its realization.

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