Asymmetric Transport due to Spin Injection into a Kondo Alloy

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Spin injection is found to have a significant effect on the transport properties of the Kondo alloy Cu(Fe). When a spin-polarized electron current flows from Co into Cu(Fe) wires through the Co/Cu(Fe) interface, the resistivity of the Cu(Fe) wire is suppressed near the interface, as distinct from the ordinary logarithmic increase in the resistivity at low temperatures. For the opposite current direction, no significant changes are observed. The asymmetry of the resistivity with respect to the current direction decays with a characteristic length of 1.5 ± 0.4 μm at 2.5 K as the distance from the interface is increased. Possible mechanisms for the asymmetry are discussed.

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Intriguing transport features associated with spin injection have been reported in artificial magnetic structures with ferromagnetic (FM)/paramagnetic (PM) interfaces [1–7]. The relevant phenomena that describe the features are spin accumulation and spin transfer. Spin accumulation is a nonequilibrium diffusive phenomenon that occurs in a dc current at a FM/PM interface. Because of a sudden change in the spin polarization of the conductivity, an excess magnetization forms near the interface similar to charge accumulation [8–11]. Spin transfer, according to Slonczewski, is associated with the relaxation of the spin current to the magnetic background. Once spin current flows through a FM/PM/FM trilayer, angular momentum may be transferred between the magnetic layers to conserve the total angular momentum [12,13]. This impinges on the arrangement of magnetic moments and induces spin waves or even magnetization switching in the magnetic layers [2–6]. In such trilayers, one of the layers is regarded as a spin aligner and the other is a detector of the spin information. Our interest in this study is what happens if we replace the detector with a Kondo alloy. A Kondo alloy is a diluted magnetic alloy in which magnetic 3*d* impurities are embedded in a host nonmagnetic metal. The resistivity of a Kondo alloy increases logarithmically with decreasing temperature because of a formation of virtual *d* bound states through the negative *s*-*d* exchange coupling between the magnetic moments and host metal [14]. The logarithmic increase—the Kondo resistivity anomaly—is quite sensitive to a magnetic field or spin arrangement of the impurity [15,16]. Therefore, provided that the spin accumulation and/or the spin transfer near the interface modifies the spin configuration of the Kondo alloy, a change in the resistivity should be anticipated. This also offers another approach to detecting spin information.

In this Letter, we present the temperature-dependent resistivity of the Kondo alloy Cu(Fe) near Co/Cu(Fe) interfaces under spin injection conditions. If a spin current flows through the Co/Cu(Fe) interface, spin accumulation in the Cu(Fe) wire could occur within the spin diffusion length Λ. Resistivity measurements within a distance Λ from the interface enable us to not only probe the spin information injected into Cu(Fe) but also get an insight into the influence of the spin injection on the electric properties of the Kondo alloy. An interesting behavior observed here is the asymmetry of the resistivity of the Cu(Fe) wire with respect to the direction of the current.

Figure 1 shows scanning electron microscopy (SEM) images of the typical device with a Co/Cu(Fe) interface fabricated on undoped Si(100) substrates by electron beam lithography and lift-off technique. Co and Cu(Fe) wires were deposited in a UHV chamber with a base pressure of $\sim 10^{-10}$ Torr. The Fe concentration of the Cu(Fe) alloy is ~0.1 at. %, showing the Kondo resistivity minimum at around 20 K. The thickness of each wire was 50 and 80 nm, respectively, where the Cu(Fe) layer covers the Co layer at the interface completely. An electron current is driven through the Co/Cu(Fe) interface from the Co into the Cu(Fe) or vice versa by changing the current direction. Voltage terminals are attached at several locations along the Cu(Fe) wire to observe the effect of spin injection as a function of distance from the Co/Cu(Fe) interface. The resistivities of several samples were measured in the temperature range 2.5 to 100 K using a four-terminal dc method and a Quantum Design Physical Property Measurement System (PPMS). Note that the resistivity in this Letter is defined by the nonlinear voltage/current relationship.

Before showing the experimental results of spin injection, it is worthwhile to estimate the spin diffusion length of the Cu(Fe) alloy used in this work. The spin diffusion length $\Lambda_{\mathrm{Cu(Fe)}}$ in the Cu(Fe) can be calculated from the spin mean-free path λ_{sf} and momentum mean-free path λ [17]: $\Lambda_{\mathrm{Cu(Fe)}} = (\lambda\lambda_{sf}/6)^{1/2}$, where $\lambda_{sf} = \tau_{sf} v_F = 1/N_I \sigma_{sf}$. τ_{sf}, v_F, N_I, and σ_{sf} are the spin relaxation time, the Fermi velocity, the impurity concentration, and the spin-flip scattering cross section, respectively. We use the

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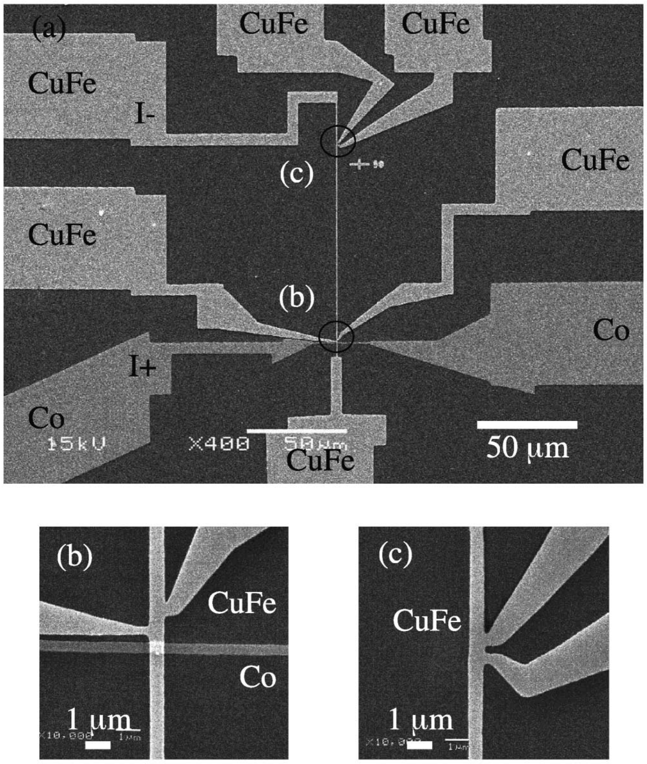

FIG. 1. SEM images of a typical spin injection device. (b) and (c) are the enlargements of the locations (b) and (c) in the image (a), respectively. No spin injection can be seen at the location (c) which is 100 μm away from the interface.

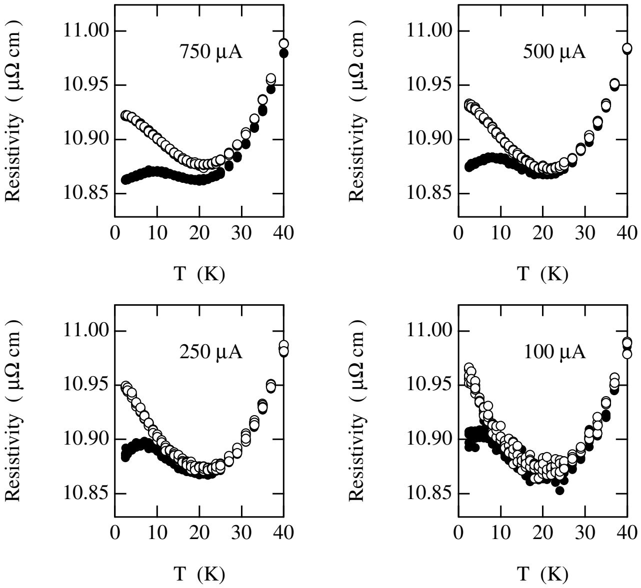

FIG. 2. Temperature-dependent resistivities of the Cu(Fe) wire in the device with a Co/Cu(Fe) interface for the electron current directions Co into Cu(Fe) and vice versa at the position of 0.5 μm away from the interface; solid and open circles correspond to the current directions from Co into Cu(Fe) and the opposite direction, respectively.

Fe concentration $N_I = 0.1$ at. %, $\sigma_{sf} = 1.8 \times 10^{-17}$ cm^2 [18], and $\lambda = 44$ nm [18,19] for the estimation, which gives the spin diffusion length $\Lambda_{\mathrm{Cu(Fe)}} = 0.2$ μm. This value is similar to the minimum distance between the interface and the voltage terminal in our devices.

All the resistivity measurements were done after saturating the magnetization of the Co wires along the wire direction to attain uniform magnetization of the Co at the Co/Cu(Fe) interface. Shown in Fig. 2 is the temperature dependence of the resistivities of the Cu(Fe) wire measured with the voltage terminals 0.5 μm away from the Co/Cu(Fe) interface. The current of 750 μA corresponds to a current density of 1.7×10^6 A/cm^2 at the interface. The resistivity exhibits a logarithmic increase below ~20 K for the electron current direction Cu(Fe) → Co. The increase is somewhat suppressed due to its unitary limit below 5 K. This is qualitatively compatible with the previous report for bulk Cu(Fe) [20]. On the other hand, the resistivity for the spin current direction of Co → Cu(Fe) deviates from that for Cu(Fe) → Co below the temperatures of the Kondo minimum. The deviation becomes significant with increasing current density. Figure 3 demonstrates the difference between the resistivities for the two current directions as a function of distance x from the Co/Cu(Fe) interface to the voltage terminals. The difference decays with increasing the distance from the interface and disappears at 5 μm. The profiles can be fitted by the exponential form $\sim \exp(-x/l_{\mathrm{ch}})$, providing an estimation of the characteristic length scale l_{ch} of 1.5 ± 0.4 μm at 2.5 K. Jedema, Filip, and van Wees reported the spin diffusion length Λ of 1.0 μm in a Cu wire using lithographically patterned devices composed of Co and Cu submicron wires [21]. Note here that the Λ in Cu wires, which were fabricated by similar processes to our experiments, is comparable to the l_{ch} in the Cu(Fe) wires in spite of additive Fe impurities, although the definition of the l_{ch} is different from the spin diffusion length.

An ambiguous voltage due to thermoelectric power in dc resistivity measurements or current-induced Ampère field can mimic the spin dependent transport feature. To carefully evaluate the extrinsic contributions, we show the resistivities of the Cu(Fe) in the device with a nonmagnetic Cu/Cu(Fe) interface instead of the Co/Cu(Fe) in Fig. 4: the inset is the difference $\delta\rho$ between the resistivities for the two current directions. The temperature dependence of the $\delta\rho$ shows a maximum around the temperature corresponding to the resistivity Kondo minimum, which is a typical behavior of the thermoelectric power of the Kondo alloy [22]. As the resistances at the interface for both the Co/Cu(Fe) and Cu/Cu(Fe) devices are similar to each other ~0.5 Ω, Joule heating at the interface should be comparable for both. Therefore, spurious effects of thermal origin are on the order of nΩ cm which are negligible in our measurements.

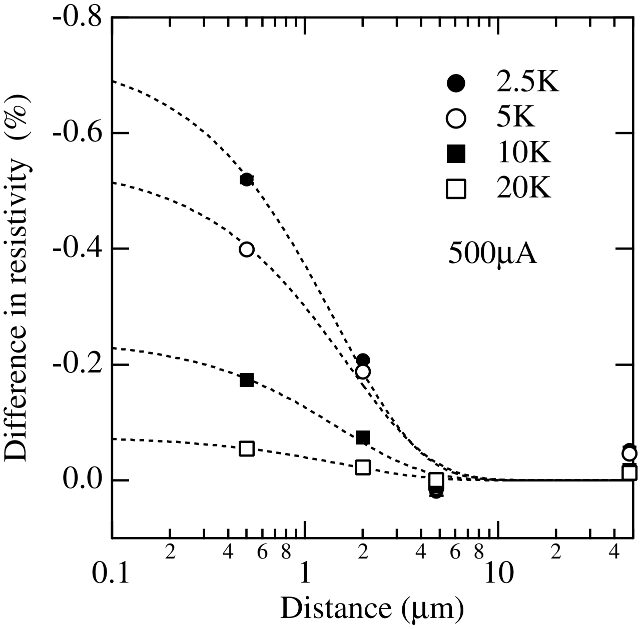

FIG. 3. Difference in the resistivities (*RD*) between the current directions as a function of the distance from the interface. The *RD* is calculated by $(\rho_{\mathrm{Co}\rightarrow\mathrm{Cu(Fe)}} - \rho_{\mathrm{Cu(Fe)}\rightarrow\mathrm{Co}})/\rho_{\mathrm{Cu(Fe)}\rightarrow\mathrm{Co}} \times 100\%$. The distance dependences are fitted by an exponential decay form (dotted curves).

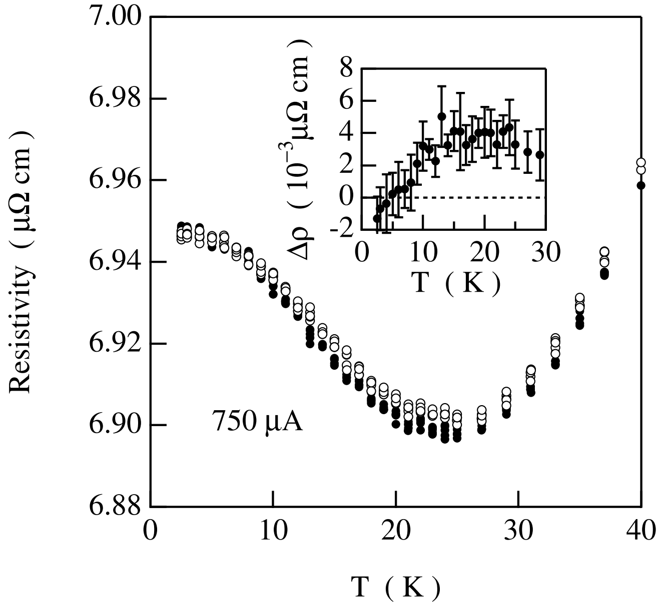

FIG. 4. Temperature-dependent resistivities of the Cu(Fe) wire at the position of 0.5 μm away from the Cu/Cu(Fe) interface for both current directions. Open circles are for the current direction of Cu(Fe) → Cu and solid circles are for Cu → Cu(Fe). The difference between the resistivities for the current directions is shown in the inset as a function of temperature.

The suppression of the resistivity at low temperatures is reminiscent of the field effect in the Kondo alloy [15,16,20]. The quasibound states of conduction electrons and localized moments are broken up in the presence of magnetic fields, causing suppression of the logarithmic increase in resistivity. We tentatively attribute the asymmetry of the resistivity to a nonequilibrium magnetization that is efficiently induced for the spin current direction of Co → Cu(Fe). The difference in the induced magnetic field ΔH between the two current directions can be estimated based on the magnetoresistance data of the Cu(Fe) wire without junction shown in Fig. 5. The ΔH is ~5 kOe at 2.5 K at a current density $j = 1.7 \times 10^6$ A/cm^2, corresponding to the Zeeman splitting of 2.9×10^{-5} eV.

When a current flows through a FM/PM interface, the conductivity polarization suddenly changes but the spin current should be continuous, resulting in a split of the chemical potential between spin-up and spin-down electrons [9–11]. We deduce the difference in the chemical potential $\Delta\mu = \mu_\uparrow - \mu_\downarrow$ at the interface of Co/Cu(Fe) using the expression given by van Son, van Kempen, and Wyder [9]:

$$\Delta\mu = eJ_e \frac{2(2\alpha - 1)(\sigma_{\mathrm{Cu(Fe)}}^{-1}\Lambda_{\mathrm{Cu(Fe)}})(\sigma_{\mathrm{Co}}^{-1}\Lambda_{\mathrm{Co}})}{(\sigma_{\mathrm{Co}}^{-1}\Lambda_{\mathrm{Co}}) + 4\alpha(1-\alpha)(\sigma_{\mathrm{Cu(Fe)}}^{-1}\Lambda_{\mathrm{Cu(Fe)}})}, \quad (1)$$

where $\alpha = (\sigma_\uparrow - \sigma_\downarrow)/(\sigma_\uparrow + \sigma_\downarrow)$ is the conductivity polarization of Co, $\sigma_\uparrow$ ($\sigma_\downarrow$) is the spin-up (down) conductivity in Co, σ_{Co} ($\sigma_{\mathrm{Cu(Fe)}}$) is the total conductivity of Co [Cu(Fe)], $\Lambda_{\mathrm{Co[Cu(Fe)]}}$ is the spin diffusion length in Co [Cu(Fe)], and J_e is the current density. Choosing realistic parameters, $\alpha = 0.38$, $\sigma_{\mathrm{Cu(Fe)}}^{-1} = 2 \times 10^{-8}\ \Omega$m, $\sigma_{\mathrm{Co}}^{-1} = 5 \times 10^{-8}\Omega$m, and $\Lambda_{\mathrm{Cu(Fe)}} = 10\Lambda_{\mathrm{Co}} = 1 \times 10^{-6}$ m, we find $\Delta\mu = 3.4 \times 10^{-5}$ eV, which is in good agreement with the Zeeman spin splitting obtained from the experiments above [23]. From these results, we remark that the suppression of the resistivity is primarily due to spin accumulation near the interface.

In linear response theories, however, a reversal of the current does not change the splitting of the chemical potentials, i.e., spin accumulation, but just reverses the sign for spin-up and spin-down channels [9–11]. This indicates that further mechanisms which explain the smaller spin accumulation and/or shorter spin diffusion length for the current direction of Cu(Fe) → Co are required for understanding the asymmetry with respect to the current direction. Heide's recent calculation claimed that the misalignment of the spin accumulation with the background magnetization makes a correction to the spin diffusion length [10]. The correction is caused by a higher scattering rate for nonaligned moments. If there exists a thin Cu(Fe) layer where Fe moments are partially spin polarized towards the Co moments by an exchange interaction at the Co/Cu(Fe) interface [24], the orientation of the spin accumulation alternately changes from parallel to antiparallel with respect to the Fe moments at the

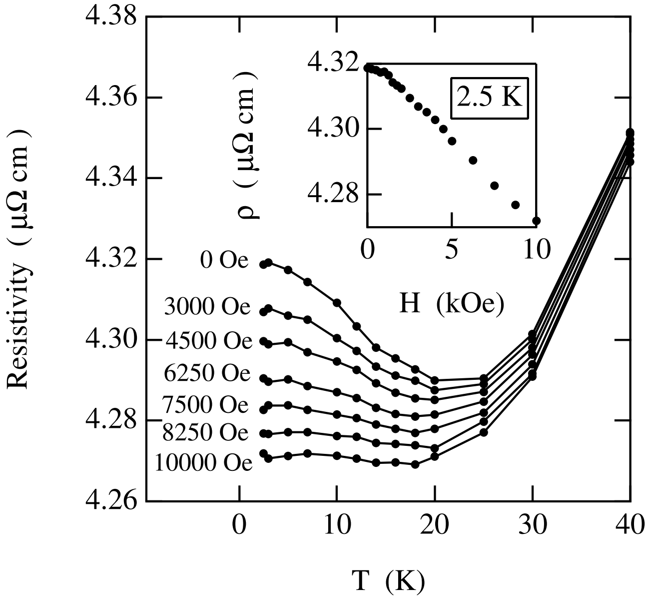

FIG. 5. Temperature-dependent resistivities of the Cu(Fe) wire without a Co/Cu(Fe) interface in various magnetic fields. The inset shows the magnetoresistance of the Cu(Fe) wire measured at 2.5 K.

interface by reversing the current direction. Accordingly, the spin diffusion length may become shorter for the current direction of Cu(Fe) → Co than Co→Cu(Fe) due to antiparallel alignment of the spin accumulation to the Fe moments near the interface. It should be also noted that the Heide effects should be efficient in highly spin-polarized materials such as half-metals, suggesting that the interface might be just a source of rapid relaxation during the spin injection process for the current direction of Cu(Fe) → Co. Although the details are not yet fully understood, we believe that these kinds of interface effects should be associated with the lack of spin accumulation for the current direction of Cu(Fe) → Co.

We have given the first demonstration of spin injection into a Kondo alloy and shown the asymmetry of the resistivity with respect to the current direction near the Co/Cu(Fe) interface. An excess magnetic field of ~5 kOe was obtained for the electron current direction of Co→Cu(Fe). This is consistent with the magnitude of the splitting of the chemical potential for spin-up and spin-down electrons at the interface deduced from a simple spin accumulation model. The understanding, nevertheless, is not adequate since the linear response theory cannot explain the asymmetric feature. Further studies for the spin injection into the Kondo alloys are required for a complete understanding.

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