Spin injection from a ferromagnetic metal into a nonmagnetic material

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Spin injection from a ferromagnetic metal (FM) into a nonmagnetic material, including metals, semiconductors, and superconductors, is one of the most critical issues, with a view to developing spin electronic devices. A pioneering work by Johnson *et al.* proposed a possible all-metal three terminal "Johnson spin transistor"[1]. Since the principal idea of the spin transistor relies on spin accumulation in the nonmagnetic metal base terminal, the spin accumulation phenomenon has attracted much attention so far. The spin accumulation is a diffusive process which occurs within a spin diffusion length from a FM/nonmagnetic material interface due to a sudden change in the conductivity for each spin up and down channel at the interface when spin polarized electron current flows. The spin accumulation, however, significantly reduces with increasing a conductivity mismatch between the FM and the nonmagnetic material, suggesting that nonmagnetic metals (NM) are more suitable for detecting the spin accumulation rather than semiconductor. In this seminar, I will talk about recent progress in experiments of spin injection across a FM/NM interface including our recent results of the spin injection into a Kondo alloy.

There are several reports on spin accumulation in NM. Otani *et al.* studied an anomalous Hall effect due to spin accumulation in an Al wire near a Co/Al interface in spin injection condition. More significantly, Jedema *et al.* reported spin accumulation in a pure Cu wire using a spin valve NiFe/Cu wire junction structure, where the spin diffusion length in the Cu wire was obtained to be $\sim$ 350 nm at room temperature and 1 μm at 4.2 K. We also have reported spin injection from a Co wire into the Kondo alloy Cu(Fe) wire. A Kondo alloy is a diluted magnetic alloy in which a small amount of magnetic impurity is dissolved in a host nonmagnetic metal. The temperature dependent resistivity shows a minimum at around the Kondo temperature with a logarithmic increase at low temperatures: we term this the Kondo resistivity minimum. Since the Kondo resistivity minimum is attributed to spin flip scatterings of electrons in the Kondo alloy, the resistivity below the temperature showing the Kondo resistivity minimum is very sensitive to the magnetic configuration of the impurity spins in the host metal. If spin accumulation which can occur in the Kondo alloy affects the spin arrangement of the impurity spins in the Kondo alloy, the logarithmic increase in the resistivity changes with the spin accumulation in the Kondo alloy. This feature, in turn, can give a measure of the spin accumulation by examining the change in the resistivity at low temperatures.

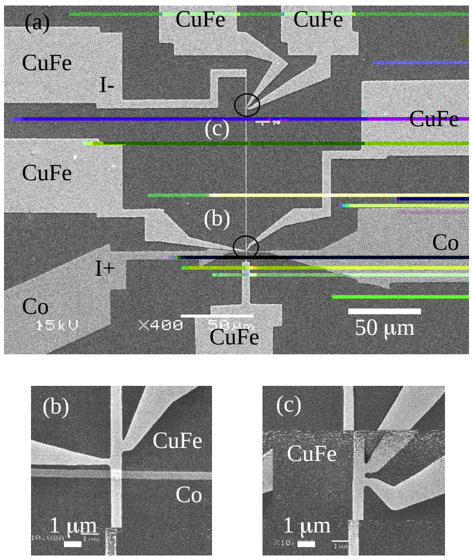

Fig.1 SEM images of the typical spin injection device with a Co/Cu(Fe) interface.

Figure 1 shows scanning electron microscope images of the typical device with a Co/Cu(Fe)

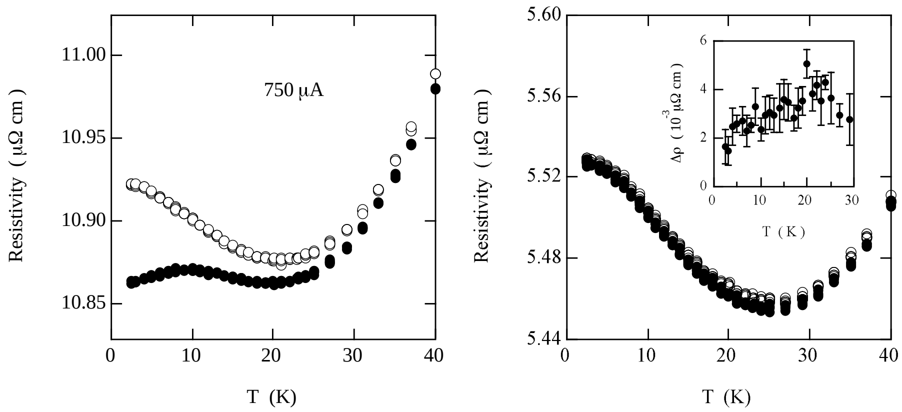

Fig. 2 Temperature dependent resistivity for two contrasting devices with a ferromagnetic Co/Cu(Fe) (left panel) or a nonmagnetic Cu/Cu(Fe) (right panel) junction. The data for closed circles are for a current direction Co→Cu(Fe), while open circles for Cu(Fe)→Co.

interface for detecting a spin accumulation effect in the Kondo alloy Cu(Fe). Two electrical terminals for measuring a voltage drop can be attached to different positions of the Cu(Fe) wire. Figure 2 shows 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 1.7×10^6A/cm^2 at the interface. The resistivity exhibits a logarithmic increase below $\sim$20 K for the electron current direction Cu(Fe)$\rightarrow$Co. The increase is somewhat suppressed due to its unitary limit below 5 K. This is qualitatively compatible with the previous report for bulk Cu(Fe). On the other hand, the resistivity for the spin current direction of Co$\rightarrow$Cu(Fe) deviates from that for Cu(Fe)$\rightarrow$Co below the temperatures of the Kondo minimum. The deviation becomes significant with increasing current density. 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$(-x/l_{ch})$, providing an estimation of the characteristic length scale l_{ch} of 1.5$\pm$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. 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. In contrast, the difference in the resistivity for the device with a nonmagnetic Cu/Cu(Fe) interface instead of the Co/Cu(Fe) is not significant as shown in Fig. 2: 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. As the resistances at the interface for both the Co/Cu(Fe) and Cu/Cu(Fe) devices are similar to each other $\sim$ 0.5 Ω, Joule heating at the interface should be comparable for both. Therefore, the contrasting results of the two separate samples clearly shows that the asymmetric features with respect to the current direction have its origin in the injection of spin polarized electrons in the Kondo alloy.

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