Spin-dependent boundary resistance in the lateral spin-valve structure

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We report the detection of clear spin-valve signal without any spurious magnetoresistive signal in a lateral spin-valve structure consisting of Cu/Ni–Fe ohmic junction using local current injection. The obtained spin-valve signal is much larger than that of the nonlocal spin-valve configuration because of the efficient spin accumulation. The local current injection experiments with different probe configurations proved that the spin-valve signal is caused by the spin-dependent boundary resistance at the interface between the ferromagnetic voltage probe and the spin-polarized nonmagnetic wire. © 2004 American Institute of Physics. [DOI: 10.1063/1.1805698]

Spin injection can induce the effective magnetic field in the nonmagnet due to spin accumulation, and also control the magnetization of ferromagnet. Thus, this behavior may provide a possible method to manipulate the magnetization direction instead of applying the external magnetic field. In order to detect efficiently the spin accumulation signal, most of the experiments have been carried out in the vertical configuration called current perpendicular to plane structure. It is however difficult to fabricate multi-terminal devices with vertical structures, where one can only obtain limited information about a series resistance of the magnetic multilayers. On the contrary, lateral configurations can realize complex ferro/nonmagnetic hybrid devices which have great potenti-alities for developing a new class of spintronic devices such as a spin transistor, spin battery, etc. However, it has been difficult to detect spin-dependent signals in lateral structures because the spurious magnetoresistance effect smeared intrinsic signals.

Recently, the nonlocal probe configuration to extract only spin current from the spin-polarized charge current has been demonstrated by Jedema et al. They succeeded in detecting a clear spin-accumulation signal in the ferro-/nonmagnetic metal planar junction by the nonlocal spin-valve (NLSV) measurement even at room temperature. According to Ref. 5 in the local spin-valve (LSV) measurement, the signal was dominated by large anisotropic magnetoresistance (AMR) from the ferromagnetic electrode, which makes it nearly impossible to observe the spin valve effect. In their later report, they succeeded in detecting spin-accumulation signal in the LSV measurement for low temperature measurement. However, the signal still includes AMR contributions from the ferromagnetic electrode. Here, we report the detection of the clear spin-valve signal in the LSV measurement without any spurious magnetoresistance signal by using specially designed ferromagnetic electrode for room temperature measurement. We also discuss the role of the ferromagnetic voltage probe using different configurations.

A lateral spin-valve device consisting of two Ni–Fe wires bridged by a Cu probe was fabricated by means of electron beam lithography and lift-off technique. Figures 1(a) and 1(b) show scanning-electron-microscope (SEM) images of the final device. First, we fabricated two Ni–Fe wires with different widths, 100 and 200 nm, spaced by a distance of 200 nm. Ni–Fe wires 30 nm in thickness were grown using an electron beam evaporator with a base pressure of $2 \times 10^{-9}$ Torr. Then, the Cu wire was fabricated across the Ni–Fe wires by the lithographer and a resistance heating evaporator with a base pressure of $3 \times 10^{-8}$ Torr. The interface between the Ni–Fe and the Cu wires was well cleaned by the Ar-ion milling prior to the Cu deposition. The contact resistance of the interface was ohmic and very low, meaning a transparent contact. The resistivities of Ni–Fe and Cu wires are, respectively, 26.8 and 2.08 $\mu\Omega$ cm at room tem-

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FIG. 1. (a) SEM image of the fabricated lateral spin-valve device and (b) magnified image around junction.
temperature, and 18.2 and 1.04 $\mu$m at 4 K. The measurement was performed at room temperature and 4 K in the magnetic field along the wire by using conventional lock-in technique. Parallel or antiparallel magnetic states of Ni–Fe wires can be adjusted by varying the magnetic field with respect to different switching fields of two Ni–Fe wires.

The magnetization reversal in narrow magnetic wires is in general governed by nucleation and propagation processes of a domain wall. As shown in Fig. 1(a), both ends of ferromagnetic wires are connected to large ferromagnetic pad. In such structures, the large pad facilitates the nucleation of the domain wall. This results in a switching field lower than that of the simple wire without the pad. In the simple ferromagnetic wire, even 100 nm in width, a small contribution of AMR is observed in longitudinal magnetoresistance during magnetization reversal because the magnetization tends to tilt slightly from the wire axis (current flowing direction) in association with the domain wall nucleation. On the contrary, in the wire with pads, the magnetization direction is well defined either parallel or antiparallel to the current because the domain wall nucleation takes place only in the pad which does not affect the magnetization distribution in the wire. In this way we can suppress the AMR contribution in the LSV configuration.

First, we performed the NLSV measurement with the probe configuration shown in the inset of Fig. 2(a). The NLSV curve exhibits the clear spin-valve signal corresponding to either parallel (high) or antiparallel (low) state as in Fig. 2(a). The resistance change due to spin accumulation is 0.4 m$\Omega$ at room temperature. Then, we measured the magnetoresistance with the LSV configuration shown in the inset of Fig. 2(b). It is clearly seen that the LSV measurement exhibits the clear spin-valve signal without any spurious signal from ferromagnetic wire. This implies that the present structure can significantly suppress the AMR contribution.

According to the one-dimensional spin diffusion model, the obtained spin-valve signal in the NLSV configuration should be a half of that in the SV configuration. However, in the present case, we observe the spin-valve signal in the LSV configuration 2.5 times larger than that in the NLSV configuration. This is due to the difference in the spatial distribution of the spin current between the NLSV and LSV configurations. In the NLSV configuration, the spin current density in the left-side edge of the Cu/Ni–Fe junction located opposite to the spin detector is larger than that of the right-side edge due to the inhomogeneous spin current density. The similar relation of spin signals between the NLSV and LSV measurements was reported by Jedema et al. However, in their device, the spin current distributions around the spin-injecting junction in both configurations are the same. Therefore, this does not apply for the explanation for the origin of a factor 2.5.

We next compared the spin valve signals obtained by choosing a different pair of voltage probes among two Ni–Fe wires and both ends of Cu wire. In this study the current is always applied between Ni–Fe 1 and Ni–Fe 2 as shown in Fig. 2(b). This thus keeps the same charge current distribution regardless of the magnetic alignment of Ni–Fe wires.

There are four ways to choose a pair of voltage probes. The first one is the LSV configuration where two voltage probes are Ni–Fe 1 and Ni–Fe 2. When the current $I$ is injected from the ferromagnet to the nonmagnet, the difference in equilibrated potential is given by $R_{SB} I$ where $R_{SB}$ is the boundary resistance as in Fig. 3(a). When the spin splitting at the interface is denoted as $\Delta \mu$, the boundary resistance $R_{SB}$ is expressed as

![FIG. 2. Resistance changes as a function of the external magnetic field measured in (a) the nonlocal configuration and (b) the local configuration at room temperature. The insets show the probe configuration for the measurement. (c) corresponds to the spin-valve signal in the local current injection at 4.1 K.](Image)

![FIG. 3. (a) Schematic electro-chemical potential distribution in the structure. The black and dashed lines, respectively, correspond to the distribution in ferromagnet and nonmagnet. Schematic distribution of the electro-chemical potential in the Ni–Fe 1/Cu/Ni–Fe 2 structure in (b) parallel and (c) antiparallel states.](Image)
The second one is the configuration where Ni–Fe 1 and Cu wires are the voltage probes. The spin boundary resistance is generated only by the single interface. Therefore, the obtained spin signal is $R_{SB}(AP) - R_{SB}(P)$. The third one with Cu and Ni–Fe wires is the same as that of the second one. The last one corresponds to Cu and Cu wires. There is obviously no spin boundary resistance expected except for the constant resistance $R_0$ of Cu wire.

The magnetoresistance curve with selecting Ni–Fe 1 and Cu wires as the voltage probe is shown in Fig. 4(a). As we described earlier, the obtained spin signal is 0.5 mΩ, half the value measured in the LSV. The obtained spin signal with selecting Cu and Ni–Fe 2 wires as the voltage probe was also 0.5 mΩ as shown in Fig. 4(b). The magnetoresistance curve with selecting two Cu wires as the voltage probe shown in Fig. 4(c) showed no field dependence. Thus, we conclude that the obtained spin valve signal is caused only by the spin-boundary resistance between the Ni–Fe/Cu interface.

In conclusion, we succeeded in suppressing spurious magnetoresistance to measure the clear spin valve signal using both nonlocal and local probe configurations. The obtained spin signal of the LSV is much larger than that of the NLSV because of the efficiently induced difference in spin accumulation between parallel and antiparallel magnetic states. We also experimentally checked that the spin signal originates from the boundary resistance between the ferromagnetic voltage probe and the spin-polarized Cu wire.

FIG. 4. Resistance changes as a function of external magnetic field measured with (a) Ni–Fe 1 and Cu voltage probes, (b) Ni–Fe 2 and Cu voltage probes and (c) two Cu probes. The insets show the probe configuration for the measurement.

$$R_{SB} = \frac{\Delta \mu (\sigma_1 - \sigma_2)}{2 e I (\sigma_1 + \sigma_2)},$$

where $\sigma_1$ and $\sigma_2$ are, respectively, conductivities for up and down spin in the ferromagnetic layer and $I$ is a charge current. The value of $R_{SB}$ in the parallel configuration $R_{SB}(P)$ should be smaller than that in the antiparallel configuration $R_{SB}(AP)$ because the value of $\Delta \mu$ in the antiparallel state is larger than that in the parallel state. Therefore, in the LSV configuration, the detected resistance originates from $R_{SB}$ at Ni–Fe 1/Cu, Ni–Fe 2/Cu interfaces and the ohmic resistance $R_0$ of the Cu wire, as shown in Figs. 3(b) and 3(c). In this case, the obtained spin signal corresponding to the difference in the resistance between parallel and antiparallel states is given by $2(R_{SB}(AP) - R_{SB}(P))$.


