Impact of interface properties on spin accumulation in dual-injection lateral spin valves

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We study spin accumulation in dual-injection lateral spin valves (DLSVs) with Ni$_{80}$Fe$_{20}$/MgO/Ag or Co$_{50}$Fe$_{50}$/MgO/Ag junctions. In Ohmic NiFe/Ag junctions, there is negligible enhancement in the spin accumulation for the dual scheme compared with the conventional single scheme. In contrast, large spin valve signals of 233 and 480 mV are observed for DLSVs with NiFe/MgO/Ag and CoFe/MgO/Ag junctions, respectively. The experimental results are analyzed with a one-dimensional spin diffusion model, taking into account the junctions and their structures. The efficient generation of a pure spin current $I_S/I_C$ up to 0.55 is realized. 

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Non-local spin injection was first demonstrated in 1985 using micro-scale devices consisting a 50 μm thick Al bar with ferromagnetic junctions. This experiment yielded a tiny spin signal of a few tens of pico-volts. The experiment was revisited in 2001 using nano-scaled lateral spin valves (LSVs). This brought about an enhanced signal of about one micro-volt at room temperature, which spurred on intensive research efforts in non-local LSVs for spintronic device applications. When a current, $I_C$, is applied across a ferromagnet/non-magnet junction at the injector in LSVs, a spin current, $I_S$, is injected from the ferromagnet to the non-magnet and then diffuses toward the detector. In micro-scale non-magnets, the injected spins diffuse in all directions with a small number of them reaching to the detector. In contrast, the spin diffusion is restricted to the non-magnetic wire in nano-scale LSVs because the cross-sectional area is much smaller than the spin diffusion length, $L_S$. This reduces unwanted spin relaxation in the non-magnet, and thus the detected spin accumulation signal is dramatically improved. In light of this, removing the spin relaxation volume is an effective scheme in enhancing the spin accumulation generated in the non-magnet. Recently, Jaffrès et al. also pointed out that theoretically the spin accumulation was enhanced by confined geometries and a multi-terminal structure. Laczkowski et al. reported the experimental results for the local geometry. In order to enhance the pure spin current, it could be useful to employ simultaneous spin injection using a multi-terminal structure. Nonoguchi et al. showed multi-terminal LSVs with NiFe/Cu junctions. However, the enhancement factor of the spin accumulation in the multi-terminal scheme compared with that of a conventional structure is unclear because the spin accumulation could be reduced by increasing the number of Ohmic contacts via spin absorption effects.

In this Letter, we address the impact of the interfacial properties on the enhancement of the spin accumulation and spin injection efficiency in the non-magnets in LSVs with dual injectors (DLSVs). Although the number of injection electrodes is increased in the lateral geometry, the spin absorption effect for Ohmic NiFe/Au junctions prevents enhancement of spin accumulation in the Ag nanowire. The enhancement factor, $a$, is defined as the ratio of the spin accumulation in LSVs with dual injectors to that for a typical single injector, increases with an increase in the interface resistance and a decrease in the separation $d_{12}$ between the two injectors. We obtain the spin valve signal $\Delta R_S$ as high as 233 and 480 mΩ in DLSVs with NiFe/MgO/Ag and CoFe/MgO/Ag junctions, respectively. The efficient generation of a pure spin current $I_S/I_C$ of 0.55 is realized. LSVs with Ni$_{80}$Fe$_{20}$/MgO/Ag or Co$_{50}$Fe$_{50}$/MgO/Ag junctions were fabricated using shadow evaporation. Figure 1(a) shows a schematic diagram of LSVs in the non-local measurement scheme. The injector $X$ generates $I_S$ toward the detector $F$ and the spins that accumulated in the vicinity of $F$ are detected as a voltage. Two classes of structures are studied in this work: one is a typical LSV with a single injector and detector (LSLV), as shown in Fig. 1(b), and the other is a DLSV where the ferromagnetic wires $F_1$ and $F_2$ are used as the spin injectors and $F_3$ is used as the detector, as shown in Fig. 1(c). The width of the $F_1$ wire was 140 nm and the width of the $F_2$ wire was 250 nm.

FIG. 1. (a) Schematic diagram of the measurement configuration of non-local spin injection. Scanning microscope images of (b) a conventional SLSV, and (c) a DLSV.

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F2, F3, and Ag wires were all 100 nm wide. The separation $d_{12}$ between F1 and F2 was 350 nm, whereas the separation $L$ between F2 and F3 varied from 300–4500 nm in order to characterize the spin diffusion in both the DLSV and SLSV. The details on the fabrication process have been reported in previous studies.12,13 The switching fields in the F wires were controlled either by the width or the domain wall pad attached to the edge of the wire.

The non-local spin injection measurements were performed on LSVs using a conventional current-bias lock-in technique with an applied current of 0.15 mA and a frequency of 79 Hz. The magnetic field was applied parallel to the F wires for the spin valve measurements. The field dependence of the spin valve signal for DLSV with Ohmic NiFe/Ag junctions (Ohmic-DLSV) and $L = 500$ nm is shown in Fig. 2(a). In the full hysteresis loop, the six leaps of non-local resistance are clearly observed, corresponding to the magnetization reversals in the three F wires. The magnetic configurations are indicated with arrows in Fig. 2(a). Since the current directions are opposite to each other for the F1/Ag and F2/Ag junctions, spin accumulation in the Ag wire is maximized when the magnetization configurations of F1 and F2 are anti-parallel. $\Delta R_S$ is defined as the overall change in the non-local resistance, which is observed to be 11.5 mΩ. The contributions of each injector, F1 and F2, to $\Delta R_S$ are estimated to be $\Delta R_{F1} = 1.8$ mΩ and $\Delta R_{F2} = 9.7$ mΩ, respectively, as depicted in Fig. 2(a). The low value of $\Delta R_{F1}/\Delta R_{F2} = 0.19$ suggests that F1 is not working efficiently in enhancing the spin accumulation at the detector. In contrast, $\Delta R_S$ of DLSVs with NiFe/MgO/Ag junctions (NiFe/MgO-DLSV) and $L = 500$ nm is as large as 233 mΩ, as shown in Fig. 2(b). The contributions from each injector to the signal are estimated to be $\Delta R_{F1} = 104$ mΩ and $\Delta R_{F2} = 129$ mΩ with $\Delta R_{F1}/\Delta R_{F2} = 0.806$, implying that both the F1 and F2 injectors work equivalently in NiFe/MgO-DLSVs.

Figure 3 shows $\Delta R_S$ as a function of $L$ for the DLSVs. $\Delta R_S$ decreases with an increasing $L$, caused by spin relaxation in the Ag nanowire. Clear enhancement of the $\Delta R_S$ is observed for NiFe/MgO-DLSVs, while the $\Delta R_S$ in Ohmic-DLSVs is slightly enhanced in comparison with that in Ohmic-SLSVs. To gain insight into the differences in $\Delta R_S$ for the junctions, we performed fitting of $\Delta R_S$, based on the one dimensional spin-diffusion equation.14,15 The equations obtained for $\Delta R_S$ for DLSVs and SLSVs are

\[
\Delta R_{S_{\text{DLSV}}} = R_N(P_{F2/F1} + P_{F3/F1})e^{-L/\xi_S}
\times \frac{(2 + r_{F1} + r_{F2})(P_{I2/F1} + P_{F2/F2}) + 2e^{-d_{12}/\xi_S}(r_{F2} + r_{F2})(P_{P1}r_{F1} + P_{F1}r_{F1}) + e^{-2d_{12}/\xi_S}(-2 + r_{F1} + r_{F2})(P_{P2}r_{F2} + P_{F2}r_{F2})}{(2 + r_{F1} + r_{F2})(1 + r_{F2} + r_{F2})(1 + r_{F1} + r_{F1}) - e^{-2L/\xi_S}} + e^{-2d_{12}/\xi_S}(-2 + r_{F1} + r_{F2})(1 + r_{F2} + r_{F2})(1 + r_{F1} + r_{F1}) - e^{-2L/\xi_S}(-1 + r_{F2} + r_{F2}) + (1 + r_{F1} + r_{F1}) - e^{-2L/\xi_S}(-1 + r_{F2} + r_{F2}) + (1 + r_{F1} + r_{F1}) - e^{-2L/\xi_S}(-1 + r_{F2} + r_{F2}) + (1 + r_{F1} + r_{F1}) - e^{-2L/\xi_S}}
\]

(1)

\[
\Delta R_{S_{\text{SLSV}}} = R_Ne^{-L/\xi_S} \times \frac{(P_{F2}r_{F2} + P_{I2}r_{F1})(P_{F3}r_{F3} + P_{F3}r_{F3})}{(1 + r_{F2} + r_{F2})(1 + r_{F3} + r_{F3}) - e^{-2L/\xi_S}}.
\]

(2)
where \( r_{fj} = [2/(1 - P_{fj}^2)] R_{fj}/R_N \) and \( r_{ij} = [2/(1 - P_{ij}^2)] R_{ij}/R_N \) are the normalized spin resistances of F and the normalized interface resistance, respectively. \( P_{fj} \) and \( P_{ij} \) are the spin polarizations of the j-th F and the interface, respectively. \( R_N = \rho_N \bar{\lambda}_N/N \) and \( R_F = \rho_F \bar{\lambda}_F/A \) are the spin resistances of N and F, respectively. \( R_{ij} \) is the j-th junction resistance and \( \rho \) is the resistivity.

For the NiFe/MgO/Ag junctions, the interfacial resistance-area product \( R_N A = 0.1 \Omega(\mu m)^2 \) was much larger than \( R_N A = 8.0 \times 10^{-3} \Omega(\mu m)^2 \), implying that the spin absorption from Ag to NiFe was mostly suppressed. The experimental data are fitted using a one dimensional model with fitting parameters \( P_1 = 0.37 \) and \( \lambda_{Ag} = 930 \) nm as can be seen in Fig. 3. The enhancement factor of the spin accumulation in DLSVs, compared with that in SLSVs, is estimated to be \( x \equiv \Delta R_S/DLSV/\Delta R_S/SLSV \). The analytical expression obtained for \( x \) is

\[
\begin{align*}
\Delta R_S &= 1 + 2\exp(-d_{12}/\lambda_N) + \exp(-2d_{12}/\lambda_N) \\
&= 1 + \frac{R_{F1}}{R_{F2}} \Delta R_{F1} + (1 + \exp(-2d_{12}/\lambda_N)),
\end{align*}
\]

from Eqs. (1) and (2) in the interfacial spin polarization dominated regime, i.e., \( R_{ij} \gg R_N \). For the NiFe/Ag junctions, the interface parameters \( P_{ij} \) and \( R_{ij} \) were neglected. The experimental data were fitted by adjusting \( P_{NiFe} \) and \( \lambda_{Ag} \) and setting \( \lambda_{NiFe} = 5 \) nm, reported by Dubois et al.\(^{11}\) We obtained \( P_{NiFe} = 0.37 \) and \( \lambda_{Ag} = 970 \) nm, giving \( x = 1.2 \). This analytical model supports the small enhancement of \( \Delta R_S \) in Ohmic-DLSVs.

In order to discuss the origin of the different \( x \) in DLSVs, the spin absorption process is examined in more detail, following the model that led to Eqs. (1) and (2). First we consider the spin current injected from the F1/Ag junction. The contribution to \( \Delta R_S \), namely, \( \Delta R_{F1} \), is characterized as a function of an interface parameter, \( x_2 \equiv r_{f2} + r_{i2} \), which determines the magnitude of spin absorption in F2. From Eq. (1) one can obtain \( \Delta R_{F1} \propto x_2/\beta (x_2 + \gamma) \), where \( \beta \) and \( \gamma \) are coefficients independent of \( x_2 \), derived from Eq. (1). As a result, \( \Delta R_{F1} \) increases with \( x_2 \) because of the suppression of the spin absorption effect. \( \Delta R_{F1} \) of the Ohmic-DLSV is quantitatively evaluated to give 2.1 mΩ from Eq. (1) with the fitting parameters mentioned above, which is in good agreement with the experimental value shown in Fig. 2(a). Second, we analyze the spin current injected from the F2/Ag junction in the same manner. From Eq. (1), one can obtain \( \Delta R_{F2} \propto (x_1 + \delta)/(\varepsilon x_1 + \phi) \), where \( \delta, \varepsilon, \) and \( \phi \) are \( x_1 \)-independent coefficients derived from Eq. (1) and \( x_1 \equiv r_{f1} + r_{i1} \) can determine the spin absorption in F1. \( \Delta R_{F2} \) of the Ohmic-DLSV is 8.6 mΩ, which is much larger than that of \( \Delta R_{F1} \), implying that the spin accumulation is less influenced by the spin absorption effects in F1 compared with that of F2. This is caused by the difference in the path travelled by the injected spin current: spins injected from F2 diffuse toward F1 and F3 with some spins passing through the Ag wire at the F1/Ag interface to reach the detector, whereas, all of the spins injected from F1 pass through the Ag wire at the F2/Ag interface before reaching the detector.

The interface layer is critical in enhancing the spin accumulation in DLSVs, and in SLSVs. The NiFe ferromagnetic layer has been used in our past studies.\(^{12,13,15,16}\) However, a higher spin polarization is expected for CoFe and CoFe\(_2\).\(^{18-21}\) Therefore, we fabricated LSVs with CoFe and CoFe\(_2\) and measured the Hanle effect signal for the SLSV, as shown in Fig. 4(a). The magnetic field was applied perpendicular to the substrate. The analytical expression for \( \Delta R_S \) is expressed as

\[
\Delta R_S = P_T \Delta R_N \text{Re} \left( \frac{i \omega_L}{\omega} \exp \left( -\frac{L}{\lambda_N} \right) \right),
\]

where \( \omega_L = g \mu_B B/\hbar \) is the Larmor frequency, \( g \) is the g-factor, \( \mu_B \) is the Bohr magneton and \( \tau_{sf} \) is the spin relaxation time. \( P_1 = 0.52 \) and \( \lambda_{Ag} = 780 \) nm are obtained by fitting Eq. (4) to the experimental data with \( L = 4.5 \) mμ. Figure 4(b) shows the spin valve signal for a DLSV with CoFe/MgO/Ag. Large \( \Delta R_S \) of 230 and 480 mΩ are observed at 300 K and 10 K, respectively, whereas for SLSVs \( \Delta R_S \) are 135 and 230 mΩ. We note that the relation between the enhancement of the detected spin accumulation and the efficiency of the generation of the pure spin current is not trivial. However, the one-dimensional spin diffusion model revealed the same enhancement factor, \( x \), between them for SLSVs with F/MgO/Ag. The \( x \) is enhanced up to 4 in the small \( d_{12}/\lambda_N \) limit, suggesting that \( \lambda_{Ag} = 2P_1/2 = 0.44 \) (\( P_1 = 0.37 \) and \( x = 2.4 \) for NiFe) and \( x = 11.5 \) (\( P_1 = 0.52 \) and \( x = 2.1 \) for CoFe) can be further improved by optimizing \( \lambda_{Ag} \) and \( d_{12} \). This could be useful for the development of a variety of spintronic devices using pure spin current and spin accumulation.

In summary, we have investigated the enhancement of the spin accumulation in DLSVs. The spin accumulation was enhanced by a factor \( x \) for the dual scheme compared with the

![Fig. 4. (a) Hanle effect of SLSV with CoFe (14 nm)/MgO (7.0 nm)/Ag (50 nm) junctions. Black and red dots show the Hanle signals with parallel and anti-parallel magnetic configurations of injector and detector, respectively. The diffusion constant of Ag was 0.056 m²/s. (b) Non-local spin signal as a function of magnetic field for DLSV with CoFe/MgO/Ag junctions with L = 300 nm.](image-url)
conventional single scheme; $z$ was 2.4 and 1.2 for the NiFe/MgO/Ag and NiFe/Ag junctions, respectively. Analysis based on the one-dimensional spin diffusion model revealed that the spin absorption effect in the middle of the NiFe/Ag junction strongly suppresses the enhancement of the spin accumulation in Ohmic-DLSVs. We found that $z$ reaches 4 in the present device structure with a small $d_{1/2}/k_N$ and without spin absorption. Large spin signals of 233 and 480 m$\mu$ were obtained for DLSVs with NiFe/MgO/Ag and CoFe/MgO/Ag, respectively.

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