Charge-to-Spin Conversion and Spin Diffusion in Bi/Ag Bilayers Observed by Spin-Polarized Positron Beam

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Spintronics is promising to go beyond traditional electronics. Current-induced spin polarization (CISP) at surface and interface plays a critical role in spintronics. The spin Hall effect (SHE) and the Rashba effect are the representative phenomena producing CISP due to spin-orbit coupling (SOC). In the last fiscal year, using a spin-polarized positron beam [1], we succeeded in observing the CISP in the Bi-Ag bilayer system, which is known as a giant Rashba system, and spin diffusion in Bi and Ag layers for the first time [2].

Positrons implanted into a sample diffuse back to the surface and emitted into vacuum as positronium which is the positron-electron bound state like hydrogen. Two spin states, singlet (S=0) and triplet (S=1), are possible. These decay into two and three gamma quanta, respectively. The annihilation probability shows asymmetry upon flipping the mutual polarization vector of positrons and electrons. From this, the electron spin polarization at the outermost surface can be determined. Since two-gamma annihilation of positronium overlaps the free positron-electron annihilation, three-gamma annihilation event is used for observing the surface electron spin polarization.

Figure Fig. 1 shows the observed spin polarizations of Bi-Ag and Ag-Bi systems as functions of outer Bi and Ag thicknesses (d_{Bi} and d_{Ag}), respectively, at the input electric current density of j_c=15 A/m. The electric current flows mostly in the Ag layer since the resistivity of Bi layer (300 μΩcm) is much larger than that of Ag layer (~5 μΩcm). In the upper panel of Fig. 1, at d_{Bi}=0 nm corresponding to the Ag surface, a small but finite positive spin polarization appears. This may be due to the CISP of Ag itself. At d_{Bi}=0.3 nm, the spin polarization suddenly jumps up to +4 % and thereafter, decreases with increasing d_{Bi}. The lower panel of Fig. 1 shows that at d_{Ag}=25 nm, the spin polarization reaches -5% and decreases with increasing d_{Ag}. At d_{Ag}=0 nm corresponding to the Bi surface, the spin polarization was not observable because of very high resistivity of the Bi layer and hence difficulty in applying electric current. Thus, on Bi and Ag surfaces, an opposite sign of spin polarization appears in the same direction as electric current.

The above results suggest that the excess spins generated at the Bi/Ag interface due to the Rashba effect diffuse into both Bi and Ag layers and eventually reach their outermost surfaces. Positive spin polarization at d_{Bi}=0 nm in the Bi-Ag system is probably over compensated by larger negative spin polarization in the Ag-Bi system. Assuming a simple exponential form of $\exp(-d_{\mathrm{Bi(Ag)}}/\lambda_{\mathrm{Bi(Ag)}})$, where $\lambda_{\mathrm{Bi(Ag)}}$ is the spin diffusion length in Bi(Ag) layer, the observed decays of spin polarizations are well explained as shown by the solid curves in Fig. 1. Here, we obtained λ_{Bi}=2.1 nm and λ_{Ag}=357 nm. These values are in agreement with the previous reports.

The spin density induced by the Rashba effect is given by $\langle \delta s_y \rangle = m_e^* \alpha_R j_c/(e\hbar E_F)$, where e is the elementary charge, E_F is the Fermi energy, m_e^* is the effective electron mass, and α_R is the Rashba parameter. For the Bi/Ag[111] system, m_e^* =0.35 m_0 (m_0 is the electron rest mass), α_R=3.05×10^{-10} eVm, and E_F=0.18 eV is calculated from the Fermi wavelength k_F=0.13 Å^{-1} and m_e^*. On a metal surface, positronium is formed at the vacuum side where the electron density (n_{2D}) is low enough, typically, less than 10^{13} cm^{-2}. For the Bi surface, n_{2D}=0.5~4×10^{13} cm^{-2} at the first surface layer, which may nearly fulfill the above positronium formation condition. For the Ag surface, such a low electron density is available at a vacuum region, a few Å away from the first surface layer. Therefore, an observable spin polarization is estimated to be of the order of percent.

Thus, the spin polarization and its sign change for Bi to Ag surfaces observed here could be explained by the Rashba effect. Especially, the sign change is hardly explained in terms of the spin Hall effect and hence is the hallmark of the Rashba mechanism for the observed CISP.

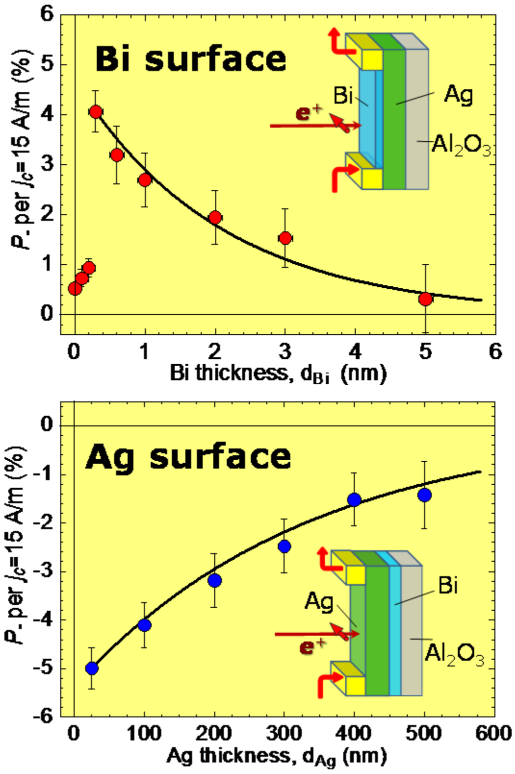

Fig. 1 Surface spin polarizations of Bi-Ag (upper panel) and Ag-Bi (lower panel) systems as functions of outer Bi and Ag thicknesses, respectively, at j_c=15 A/m. Solid lines are the fitting of an exponential function $\exp(-d_{\mathrm{Bi(Ag)}}/\lambda_{\mathrm{Bi(Ag)}})$, where $d_{\mathrm{Bi(Ag)}}$ and $\lambda_{\mathrm{Bi(Ag)}}$ are the thickness and spin diffusion length of Bi(Ag) layer, respectively.

References

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