Experimental Verification of Comparability between Spin-Orbit and Spin-Diffusion Lengths

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We experimentally confirmed that the spin-orbit lengths of noble metals obtained from weak anti-localization measurements are comparable to the spin diffusion lengths determined from lateral spin valve ones. Even for metals with strong spin-orbit interactions such as Pt, we verified that the two methods gave comparable values which were much larger than those obtained from recent spin torque ferromagnetic resonance measurements. To give a further evidence for the comparability between the two length scales, we measured the disorder dependence of the spin-orbit length of copper by changing the thickness of the wire. The obtained spin-orbit length nicely follows a linear law as a function of the diffusion coefficient, clearly indicating that the Elliott-Yafet mechanism is dominant as in the case of the spin diffusion length.

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Spin relaxation and spin dephasing are the central issues in the field of spintronics as they determine how long and far electrons can transfer the spin information.1,2 Owing to recent technological advancements,3–12 one can now create the spin accumulation, i.e., the electrochemical potential difference between spin-up and down electrons at the Fermi level, 10−100 times larger than that generated in conventional lateral spin valve devices or along edges of samples with spin Hall effects (SHEs). Such a large spin accumulation can induce a large pure spin current, the flow of spin angular momentum with no net charge current.13 As its magnitude scales with the spin relaxation length or the spin diffusion length (SDL), the quantitative evaluation of the SDL is of importance.

Recent reports on magnetization switching at very thin ferromagnet/nonmagnet bilayer films11,12,14 have triggered a heavy debate on the detailed mechanism. The first realization of the switching was reported by Miron et al.14 who concluded that the magnetization switching originates from the Rashba effect at the ferromagnet(Co)/nonmagnet(Pt) interface. Similar measurements were also performed by Liu et al. with a Co/Pt bilayer film11 as well as with a CoFeB/Ta bilayer one.12 They claimed that the switching is due to the perpendicularly induced spin currents via the SHE of Pt and Ta. To discuss the conversion efficiency from charge current to spin current i.e., the spin Hall (SH) angle, in their devices, they performed the spin torque induced ferromagnetic resonance (FMR) measurements and estimated the SH angle of Pt and Ta to be 0.07 and 0.15, respectively.10,12 These SH angles, however, are quite different from those obtained from the spin absorption method (0.02 for Pt and 0.004 for Ta)13. Furthermore Liu et al.10 pointed out that the overestimation of the SDLs reported in Ref.15 results in a large underestimation of the SH angles. To settle down such heavy debates, one needs another reliable way to estimate the SDL or the SH angle. In this Letter, we focus on weak anti-localization (WAL) observed in nonmagnetic metals. We first demonstrate that the spin-orbit (SO) length $L_{SO}$ obtained from the WAL curve of Ag is comparable to the SDL $L_s$ estimated from the lateral spin valve measurement. We then extend a similar discussion to a strong SO material such as Pt. In metallic systems where the elastic mean free path $l_e$ is much shorter than $L_s$, the dominant spin relaxation process is the Elliott-Yafet (EY) mechanism.17 We also confirm that the EY mechanism works very well for $L_{SO}$ by changing the diffusion coefficient $D$ of Cu wires. This experimental fact also verifies the comparability between $L_{SO}$ and $L_s$.

We prepared two types of devices, i.e., samples for WAL measurements and those for spin injection measurements. Both samples were fabricated on a thermally-oxidized silicon substrate using electron beam lithography on polymethyl-methacrylate resist and a subsequent lift-off process. For the WAL samples, we prepared ~1 mm long and 100 nm wide Ag (99.999%), Cu (99.9999%), and Pt (99.98%) wires and performed the standard 4-probe measurement using a $^3$He cryostat. In order to obtain a very small WAL signal compared to the background resistance, we used a bridge circuit.18 For the spin injection (or spin valve) measurement, we first prepared two Permalloy (Ni$_{81}$Fe$_{19}$; hereafter Py) wires, which work as spin injector and detector. To measure $L_s$ of a strong SO material such as Pt, we inverted it in between the two Py wires. The three wires were bridged by a thicker Cu wire to transfer a pure spin current generated at the Py/Cu interface. To check the reproducibility, we measured at least a few different samples on the same batch both for the WAL and spin valve measurements.

In order to clarify whether $L_{SO}$ from WAL measure-
ments is equivalent to \( L_s \) from spin valve ones, we first measure WAL curves of a weak SO material. Figure 1 shows typical WAL curves of a Ag wire measured at \( T = 0.4 \) and 4 K. Unlike a normal weak localization (WL) curve, the resistance increases with increasing the perpendicular magnetic field \( B \) because of the SO interaction. With decreasing temperature, the phase coherence of electrons gets longer and the WAL peak also gets sharper. The WAL peak of quasi one-dimensional (1D) wire can be fitted by the Hikami-Larkin-Nagaoka formula \[1\]:

\[
\frac{\Delta R}{R_\infty} = \frac{1}{\pi L h/e^2} \left( \frac{\frac{1}{2} \sqrt{\frac{2}{\pi} \frac{\phi}{L} + \frac{3}{2} \frac{\phi}{L_{SO} + \frac{\phi}{1_{B}}}}}{\sqrt{\frac{1}{2} \frac{\phi}{L_{SO}} + \frac{3}{2} \frac{\phi}{1_{B}}} - \sqrt{\frac{1}{2} \frac{\phi}{L_{SO}} + \frac{3}{2} \frac{\phi}{1_{B}}}} \right)
\]

where \( \Delta R, R_\infty, L, \) and \( \phi \) are respectively the WL correction factor, the resistance of the wire at high enough field, the length and width of the quasi-1D wire, \( e, h, \) and \( l_B = \sqrt{\hbar/eB} \) are respectively the electron charge, the reduced Plank constant, and the magnetic length. In Eq. (1), we have only two unknown parameters; \( L_\phi \) and \( L_{SO} \). According to the Fermi liquid theory \[20\], \( L_\phi \) does depend on temperature \( \propto T^{-1/3} \), while \( L_{SO} \) is almost constant at low temperatures \[21\]. Based on this fact, we fix \( L_{SO} \) at both temperatures to fit the WAL curves. We obtain \( L_\phi = 4.20 \) and 1.95 \( \mu \)m at \( T = 0.4 \) and 4 K, respectively, while \( L_{SO} = 800 \) nm \[22\]. The two \( L_\phi \) values meet the Fermi liquid theory \( L_\phi \propto T^{-1/3} \). We have measured 4 different Ag wires on the same batch and obtained \( L_{SO} = 760 \pm 50 \) nm.

\( L_{SO} \) should be closely related to \( L_s \). This relation has been theoretically discussed in Ref. \[1\]. The SO scattering rate \( 1/\tau_{SO} = D/L_{SO}^2 \) includes both spin-flip and spin-conserving processes, resulting in \( 1/\tau_{SO} = 3/(2\tau_{14}) \) where \( 1/\tau_{14} \) is the spin-flip scattering rate. We also note that the spin relaxation rate \( 1/\tau_s = D/L_s^2 \) is twice the spin-flip scattering rate, i.e., \( 1/\tau_s = 1/\tau_{14} + 1/\tau_{1\uparrow} \). At sufficiently low temperatures, the contribution of phonons can be neglected and one obtains

\[
L_s = \frac{\sqrt{2}}{2} L_{SO}, \quad (2)
\]

within the EY mechanism from isotropic impurity scattering. Since Ag is a monovalent metal with an almost spherical Fermi surface, one can adapt Eq. (2) to convert from \( L_{SO} \) to \( L_s \). We thus obtain \( L_s = 650 \pm 40 \) nm, which is quantitatively consistent with \( L_s \) obtained from the lateral spin valve measurements \[1\] [23].

Next we discuss the SDL of a strong SO material such as Pt which is the most standard SHE material. As mentioned in the introduction, this is one of the causes of the big debates, i.e., \( L_s = 11 \) nm from the spin absorption measurements \[15\] and \( L_s = 1.4 \) nm from the spin torque FMR measurements \[14\]. To solve the problem, here we perform two different measurements to obtain \( L_{SO} \) or \( L_s \) of Pt; WAL and spin absorption in the lateral spin valve devices. Note that the Pt wires for the WAL and spin absorption measurements were prepared at the same time. Figure 2(a) shows a typical WAL curve of Pt. The field scale is 20 times larger than that for Ag wires, which indicates that \( L_{SO} \) is much shorter. We observe maxima of the WAL curve at around \( \pm 0.9 \) T. From the best fit of Eq. (1), we obtain \( L_{SO} = 12 \) nm. We have performed similar measurements for 5 different samples and using Eq. (2) we have determined \( L_s \) of Pt to be \( 10 \pm 2 \) nm \[24\].

The spin absorption measurement into the Pt wire is shown in Fig. 2(b). For comparison, Py middle-wire devices were prepared since the SDL of Py is well-known from other experiments \[25\]. We have performed nonlocal spin valve (NLSV) measurements with and without the middle wires \[8, 9, 15\]. The in-plane magnetic field \( B_t \) is applied parallel to the two Py wires [see the inset of Fig. 2(b)]. A pure spin current generated from Py1 is absorbed perpendicularly into the middle wire because of the strong SO interaction of Pt (or Py). As shown in Fig. 2(b), the NLSV signal detected at Py2 is reduced by inserting the Pt or Py wire compared to the one without any middle wire. To extract the SDLs of Pt and Py, we first use the 1D analytical model based on the Takahashi-Maekawa formula \[13\]. In this model, the normalized NLSV signal \( \Delta R_{S_{\text{with}}}^2 / \Delta R_{S_{\text{without}}}^2 \) can be expressed as follows \[8, 9\]:

\[
\frac{\Delta R_{S_{\text{with}}}}{\Delta R_{S_{\text{without}}}} \approx \frac{2R_M \sinh(d/L_{Cu}^C)}{R_{Cu} \{ \cosh(d/L_{Cu}^C) - 1 \} + 2R_M \sinh(d/L_{Cu}^C)} \quad (3)
\]

where \( R_{Cu} \) and \( R_M \) are the spin resistances of Cu and the middle wire (Pt or Py), respectively. The spin resistance \( R_X \) of material “X” is defined as \( \rho_X L_X^X/(1-\rho_X^2) \) \( A_X \times \rho_X \). \( L_{Cu}^C, p_{Cu} \) and \( A_X \) are respectively the electrical resistivity, the SDL, the spin polarization, and the effective

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FIG. 1: (Color online) WAL curves of Ag wire measured at \( T = 0.4 \) and 4 K. The broken lines are the best fits of Eq. (1). The inset shows a scanning electron micrograph of the Ag wire.
cross sectional area involved in the equations of the 1D spin diffusion model \[8, 9\]. \(d\) is the distance between the two Py wires, in the present case \(d = 700\) nm. Although the spin absorption rate \(\Delta R_S^{\text{with}}/\Delta R_S^{\text{without}}\) is almost the same for the Pt and Py middle wires, the obtained \(L_s\) from Eq. \(3\) are \(11(\pm 2)\) nm for Pt and \(5(\pm 1)\) nm for Py. This is because the resistivity of Pt is nearly half of Py. The SDL of Pt coincides well with that from our WAL measurement and the SDL of Py is also consistent with other experimental results \[22\].

We have also used the three-dimensional (3D) spin diffusion model based on the Valet-Fert formalism \[29\] to obtain \(L_s\) of Pt. This has been done in order to refute the claim made by Liu et al. that \(L_s\) of Pt extracted from the 1D model might be overestimated \[16\]. As detailed in Ref. \[9\], SDLs obtained from the two methods do not differ significantly when the SDLs are comparable or smaller than the thickness of the middle wire. In fact, we have confirmed that the 3D analysis for the Pt middle wire gives almost the same value as the 1D model. We thus conclude that the SDL of Pt itself is not of the order of 1 nm but about 10 nm.

The reason why \(L_s\) of Pt reported in Ref. \[16\] is much shorter than ours is that in the FMR measurement, the ferromagnet/nonmagnet bilayer is always used. In such a bilayer system, one cannot avoid the contribution from the magnetic damping effect \[16, 27, 28\]. As a result, the real SDL of nonmagnet can be modulated by the FMR, which results in a much shorter SDL. Thus, such a shorter SDL cannot be adapted to the case of the spin absorption method and the SH angle of Pt should be about a few percent \[15\].

Recently, Kondou et al. \[29\] measured the SH angle of Pt using the same method as Liu et al. \[10, 12, 16\] but they carefully studied the thickness dependence of ferromagnet and nonmagnet. They found that the symmetric part of FMR spectra, from which the SH angle is extracted, does depend on the thickness of ferromagnet and one should take the zero-limit to avoid any effects from the ferromagnet \[29\]. The extrapolated SH angle is 0.022 for Pt, which is quantitatively consistent with that in Ref. \[17\].

To further support the comparability between \(L_{SO}\) and \(L_s\), we study the disorder effect on \(L_{SO}\). In metallic systems where \(l_e < L_s\), the EY mechanism is dominant for the spin relaxation process. If Eq. \(2\) is valid in metallic systems, \(L_{SO}\) should also follows the EY mechanism.

In Fig. 3(b) we plot \(L_{SO}\) of Cu as a function of \(D\). Note that \(D\) is determined from the Einstein relation \(D = 1/(\epsilon^2 \rho N)\) where \(N\) is the density of state at the Fermi level \[30\]. \(L_{SO}\) nicely follows a linear law down to 20 nm thick Cu wires. According to the EY mechanism, \(\tau_e\) consists of the phonon and impurity contributions as follows: \(1/\tau_e = 1/\tau_e^{\text{imp}} + 1/\tau_e^{\text{ph}}\). Since we focus on the low temperature part, we can neglect the phonon contribution \[21\] and concentrate on the discussion only about the spin relaxation from impurities, which makes the analysis much simpler \[31\]. In addition, the impurity contribution can be expressed as \(\tau_e^{\text{imp}} = \tau_e/\epsilon_{\text{imp}}\) where \(\tau_e\) and \(\epsilon_{\text{imp}}\) are the elastic scattering time and the probability of spin-flip scattering, respectively \[32\]. Thus, one obtains the following equation:

\[
L_{SO} = \frac{2}{\sqrt{3}} L_s = \frac{2D}{v_F \sqrt{\epsilon_{\text{imp}}}} = \frac{2l_e}{3 \sqrt{\epsilon_{\text{imp}}}}
\]  

where \(v_F\) is the Fermi velocity. As can be seen in
the SDL has not been focused on in those reports. As far as the lateral spin valve structure, the disorder dependence of experimental works to determine the SDL \([4, 6, 32]\) in the present system is perfectly diffusive and there is no specular scattering from the surface [13]. In this case, the surface scattering can be regarded as a kind of impurity or defect, and thus Eq. \([\big]\) works down to our lowest \(D\).

In conclusion, we have experimentally verified the comparability between the SO lengths and the SDLs of noble metals using the WAL and spin absorption methods. This comparability works not only for weak SO materials but also for strong SO materials such as Pt. We have also studied the disorder effect on the SO lengths of Cu by changing the thickness of wires. The obtained SO length nicely follows a linear law as a function of \(D\), which clearly verifies the EY mechanism in the present system.

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The Debye temperature of Ag (Cu) is about 220 (320) K. In the present situation ($T \leq 4$ K), the phonon contribution to $L_{SO}$ is negligibly small.

Strictly speaking, the prefactor in Eq. (2) would not be correct for Pt since Pt is not a simple monovalent metal. However, it should not be so different from $\sqrt{3}/2$.

$N = 2.51 \times 10^{22}$ states/eV/cm$^3$ for Cu.