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Effect of the interface resistance in non-local Hanle measurements

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We use lateral spin valves with varying interface resistance to measure non-local Hanle effect in order to extract the spin-diffusion length of the non-magnetic channel. A general expression that describes spin injection and transport, taking into account the influence of the interface resistance, is used to fit our results. Whereas the fitted spin-diffusion length value is in agreement with the one obtained from standard non-local measurements in the case of a finite interface resistance, in the case of transparent contacts a clear disagreement is observed. The use of a corrected expression, recently proposed to account for the anisotropy of the spin absorption at the ferromagnetic electrodes, still yields a deviation of the fitted spin-diffusion length which increases for shorter channel distances. This deviation shows how sensitive the non-local Hanle fittings are, evidencing the complexity of obtaining spin transport information from such type of measurements. © 2015 AIP Publishing LLC.

I. INTRODUCTION

Pure spin currents are a key ingredient in the field of spintronics, which takes advantage not only of the charge of the electron but also of its spin as an alternative to transport information. Lateral spin valves (LSVs), consisting of two ferromagnetic (FM) electrodes bridged by a non-magnetic (NM) channel (see Fig. 1(a)), are widely used to electrically create pure spin currents due to their non-local geometry, in which a spin-polarized current is injected from one of the FM electrodes (the injector) into the NM channel, and the pure spin current at the second FM electrode (the detector) is measured.

Hanle effect is based on the precession of spins under a perpendicular magnetic field. Due to the diffusive nature of the spin transport through the NM, there is dispersion on the time that spins need to travel from the FM injector to the detector, which in turn originates an angular dispersion on the orientation of the spins arriving at the FM detector. This causes the measured spin current at the FM detector to be zero for high enough magnetic fields. In addition to being an effective tool for spin manipulation, it presents an important advantage in the study of the spin-injection and spin-transport mechanisms, because it permits to obtain the spin polarization of the FM (PF), of the FM/NM interface (Pf), and the spin-diffusion length of the NM (kNL) by using a single LSV, as opposed to the conventional non-local spin valve (NLSV) method, which needs several LSVs with different distances (L) between the FM electrodes in order to obtain these parameters. However, Hanle measurements are very sensitive to different device details such as the interface resistance or the finite length of the NM channel. The used model has also been widely discussed in terms of the liability of the obtained information. It has been suggested that it is not possible to measure Hanle effect with transparent interfaces or that, if doing so, the equation needs to be carefully chosen.

In the present work, we analyze the validity of the general expression for the study of spin injection and transport in LSVs with any FM/NM interface resistance, presented from Ref. 5. We do so by fitting the equation to measurements of the Hanle effect in LSVs with different interface resistances and comparing the obtained parameters to those obtained from the fitting of the NLSV measurements as a function of L in the very same devices. Whereas in the presence of a contact resistance both methods are in good agreement, we observe an anomalous behaviour for the case with transparent contacts, where there is a clear mismatch between both methods. While, for L larger than kNL, this disagreement can be solved by taking into account the recently proposed spin absorption anisotropy at the FM electrodes, it is still present when L is shorter than kNL, evidencing that an additional effect is influencing the spin precession. Our analysis shows the complexity of an accurate fitting of non-local Hanle measurements, a widely used technique to extract relevant spin-transport parameters.

II. EXPERIMENTAL DETAILS

The LSVs employed in this work were fabricated by a two-step electron-beam lithography, ultra-high-vacuum (base pressure of ≤1 × 10^-8 mbar) evaporation, and lift-off process. In the first step, FM electrodes were patterned in PMMA resist on top of a Si/SiO2 substrate and 35 nm of permalloy (Py) or cobalt (Co) was evaporated. Different widths of the FM electrodes were chosen, wF1 ~ 85 nm and wF2 ~ 140 nm, in order to obtain different switching magnetic fields. In the second step, the NM channel with a width of wN ~ 190 nm was patterned and Cu was thermally evaporated with a thickness of t ~ 150 nm. Ar-ion milling was performed prior to the Cu deposition in order to remove resist left-overs. The reason for choosing different materials as FM electrodes is the need of different FM/NM interface properties.

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resistances. Py has given us high-quality transparent interfaces with a high spin polarization,\textsuperscript{13,14} whereas Co is easily oxidized allowing the fabrication of an interface with a non-zero resistance.\textsuperscript{15} The interface resistance ($R_I$) was measured in all samples, where a cross-shaped junction was fabricated in addition to the regular LSVs. Several samples were fabricated and measured (all of them containing LSVs with different $L$). Since the obtained results are reproducible,\textsuperscript{16} only two samples will be compared in this paper. Sample #1, containing Co/Cu LSVs, has an $R_I \times A_I$ product ($A_I$ is the contact area) of $2.8 \times 10^{-5} \ \Omega \ \mu m^2$ (the $R_I$'s has values of $R_I = 1.6 \ \Omega$ and $R_I = 1 \ \Omega$, which falls in the intermediate regime, i.e., they are not transparent interfaces but they cannot be considered to be in the fully tunneling regime\textsuperscript{17}). The measured $R_I$ at the Py/Cu junctions of sample #2 is negative, meaning that $R_I$ is of the order or lower than the resistance of the electrodes and $R_1 \times A_1 \leq 10^{-3} \ \Omega \ \mu m^2$.\textsuperscript{14,18,19} Therefore, sample #2 is in the transparent regime.\textsuperscript{14,17}

All measurements were performed in a liquid He cryostat at 10K, applying a magnetic field $B$ and using a “DC-reversal” technique.\textsuperscript{11} The voltage $V$, normalized to the applied current $I$, is defined as the non-local resistance $R_{NL} = V/I$ (see Fig. 1(a) for a scheme of the measurement).

This magnitude is positive [negative] when the magnetization of the electrodes is parallel (P) [antiparallel (AP)], depending on the value of $B$. Two types of measurements have been performed: (i) $R_{NL}$ as a function of the in-plane magnetic field along the FM electrodes ($B_{P}$) from Fig. 1(a)), so-called NLSV measurements, and (ii) $R_{NL}$ as a function of the out-of-plane magnetic field ($B_{Z}$) from Fig. 1(a)), so-called Hanle measurements. In the case of NLSV measurements, the absolute value of $R_{NL}$ does not vary, only its sign does change when the magnetizations of the FM electrodes change from P to AP. The difference between the positive and the negative values of $R_{NL}$ is the spin signal, $\Delta R_{NL} = 2 \times R_{NL}$, which is proportional to the spin accumulation at the FM detector (see lower inset of Fig. 1(b)). In the case of Hanle measurements, the magnitude of the measured $R_{NL}$ gradually changes from positive to negative (or vice versa) due to the precession of the spins. In addition, a reduction in $R_{NL}$ with $B_{Z}$ is superimposed, due to the angular dispersion of the orientation of the spins.\textsuperscript{6}

The expression used for fitting the Hanle measurements, obtained by solving the Bloch-type equation with an added one-dimensional spin-diffusion term applied to the LSV geometry,\textsuperscript{3,5,10,20} is the following:

$$\Delta R_{NL} = 2 \Delta R_{N} \left[ \frac{P_{I} R_{1} + P_{F} R_{F}}{1 - P_{I}^2 R_{N} + 1 - P_{F}^2 R_{N}} \right] = 2 \Delta R_{N} \left[ \frac{P_{I} R_{1} + P_{F} R_{F}}{1 - P_{I}^2 R_{N} + 1 - P_{F}^2 R_{N}} \right] \left( \frac{R_{NL}^{\Delta N} e^{-t_{s}/\lambda_{N}}}{R_{NL}^{\Delta N} e^{-t_{s}/\lambda_{N}}} \right)^{2} \left( \frac{R_{NL}^{\Delta N} e^{-t_{s}/\lambda_{N}}}{R_{NL}^{\Delta N} e^{-t_{s}/\lambda_{N}}} \right)^{2},$$

where $\lambda_{N} = \frac{\lambda_{f}}{\sqrt{1 + \tan \tau_{f}}}$ and $R_{NL} = R_{N} e^{\Delta N}/t_{N} w_{N}$ are an effective spin-diffusion length and an effective spin-resistance of the NM, respectively, and $R_{F} = \lambda_{f}^{\Delta N} w_{N}^{\Delta N} e^{-t_{s}/\lambda_{f}}$ is the spin resistance of the NM, $\tau_{f}$ is the spin-relaxation time of the NM, and $\lambda_{f} = 2 \mu_{B} B_{f}/h$ is the Larmor frequency, with $\mu_{B}$ being the Bohr magneton and $h$ being the reduced Planck constant. $\rho_{Cd} (=1.2 \ \mu \Omega \ cm)$ is obtained by measuring the resistance of Cu for every $L$, and performing a linear fit for each sample, whereas $\rho_{P} (=22.4 \ \mu \Omega \ cm)$ and $\rho_{P} (=11.5 \ \mu \Omega \ cm)$ are obtained in two different devices, where Py and Co were deposited under the same nominal conditions as for the LSVs. We use $\lambda_{P} = 5 \ \text{nm}$ (Ref. 21) and $\lambda_{Co} = 36 \ \text{nm}$.\textsuperscript{21} The dimensions $w_{N}$, $w_{P}$, and $L$ are measured by Scanning Electron Microscopy (SEM) for each device. Therefore, $P_{I}$, $P_{F}$, and $\lambda_{P}$, $\lambda_{Co}$ are the parameters to be fitted from Hanle measurements, assuming that $P_{I} = P_{N}$ and $P_{F} = P_{I} \times $B in our device. To be more precise, one needs to take into account that the magnetization of the FM electrodes can be tilted out-of-plane due to $B_{Z}$. The following equation is used to correct for such tilting:\textsuperscript{3,4,6}

$$R_{NL}^{P(AP)}(B_{Z}, \theta) = \pm R_{NL}^{P(AP)}(B_{Z}) \cos^{2} \theta + |R_{NL}(B_{Z} = 0)| \sin^{2} \theta,$$
where “+” and “−” signs correspond to the P and AP magnetizations of the FM electrodes, \( R_{NL}(B_Z) \) is the one from Eq. (1), and \( \theta \equiv \theta(B_Z) \) is the angle between the magnetization of the FM electrodes and \( B_Z \); its dependence with \( B_Z \) can be extracted from the anisotropic magnetoresistance (AMR) measurements of the FM electrodes as a function of \( B_Z \). Hence, in order to obtain the spin polarizations and spin-diffusion length from the Hanle measurements, the data were fitted to Eq. (2) (see upper inset of Fig. 1(b)).

In the case of NLSV measurements, we have an in-plane magnetic field \( B_f \), and Eq. (1) reduces to the following:

\[
R_{NL} = \frac{2R_N}{\left( 1 + 2 R_{RI} + 2 R_{RF} \right)} \left( 1 + \frac{1}{P_{RF}} \frac{R_{RF1}}{R_N} + \frac{1}{P_{RF}} \frac{R_{RF2}}{R_N} \right) \left( \frac{P_{F1} R_{I1}}{1 - P_{F1}^2 R_N} + \frac{P_{F} R_{I1}}{1 - P_{F}^2 R_N} \right) \left( \frac{P_{F1} R_{I2}}{1 - P_{F1}^2 R_N} + \frac{P_{F} R_{I2}}{1 - P_{F}^2 R_N} \right) e^{-L_{k} / \gamma_{NL}},
\]

III. RESULTS AND DISCUSSION

For sample #1, with a non-zero interface resistance, \( p_{NL}^{NLSV} = 0.043 \pm 0.003, \quad p_{NL}^{NLSV} = 0.038 \pm 0.004, \quad \lambda_{Cu}^{NLSV} = 1159 \pm 100 \text{ nm} \) were obtained from the fitting of the NLSV measurements to Eq. (3). The measured data and the fitting are shown in Fig. 1(b). The value of \( \lambda_{Cu}^{NLSV} \) is in good agreement with our previous results, whereas the low value of \( p_{NL}^{NLSV} \) has also been reported and discussed before. Note that \( P_{I1} \) and \( P_{F} \) are coupled, as seen from Eqs. (1)–(3), since sample #1 is not fully in the tunnelling regime. Only when \( \frac{P_{RF1}}{1 - P_{RF1}^2} > \frac{P_{RF2}}{1 - P_{RF2}^2} \) (i.e., for the tunnelling or transparent regimes), \( \lambda_{Cu}^{NLSV} \) is not deviated from the NLSV values for any of the distances \( L \) (see Fig. 2(a)).

For sample #2, with transparent interfaces, we can approximate \( R_f = 0 \) in Eqs. (1)–(3) in order to obtain \( p_{NL}^{NLSV} \) and \( \lambda_{Cu}^{NLSV} \). From NLSV measurements as a function of \( L \), we obtained \( p_{NL}^{NLSV} = 0.36 \pm 0.01 \) and \( \lambda_{Cu}^{NLSV} = 1125 \pm 62 \text{ nm} \). However, for Hanle measurements, spin-diffusion lengths ranging between \( \lambda_{Hanle}^{Cu} = 557 \pm 26 \text{ nm} \) and \( 1245 \pm 58 \text{ nm} \) were obtained. The spin polarization of Py also changed between \( \lambda_{Hanle}^{Py} = 0.34 \pm 0.01 \) and \( 0.63 \pm 0.02 \). Note that in this case, \( R_{NL} \) as a function of \( B_Z \) was only measured for the PFM magnetization of the FM electrodes. As shown in Fig. 2(a), the obtained \( \lambda_{Hanle}^{Cu} \) values present a clear deviation from the NLSV values with a strong dependence on \( L \); for low values of \( L \) (\( \lambda_{Hanle}^{Cu} \)), the agreement between both methods is excellent but, as \( L \) increases, \( \lambda_{Hanle}^{Cu} \) starts to deviate from \( \lambda_{Hanle}^{Cu} \). The highest discrepancy occurs for \( L \sim \lambda_{Hanle}^{Cu} \) and, for longer \( L \) (\( \lambda_{Hanle}^{Cu} \)), the deviation of \( \lambda_{Hanle}^{Cu} \) tends to reduce. \( \lambda_{Hanle}^{Py} \) changes with the opposite tendency to that of \( \lambda_{Hanle}^{Cu} \), showing a coupling between both fitting parameters (Fig. 2(b)). The observed deviation for \( L \sim \lambda_{Hanle}^{Cu} \) is clearly originated from a bad fitting of the data. However, this deviation is very reproducible for all measured samples and, thus, intrinsic to LSVs with transparent contacts. Figure 3 shows the measured \( R_{NL} \) as a function of \( B_Z \) in sample #2 for the three mentioned regimes, together with the simulated curves of \( L \) (\( \lambda_{Hanle}^{Cu} \), the agreement between both methods is excellent but, as \( L \) increases, \( \lambda_{Hanle}^{Cu} \) starts to deviate from \( \lambda_{Hanle}^{Cu} \). The highest discrepancy occurs for \( L \sim \lambda_{Hanle}^{Cu} \) and, for longer \( L \) (\( \lambda_{Hanle}^{Cu} \)), the deviation of \( \lambda_{Hanle}^{Cu} \) tends to reduce. \( \lambda_{Hanle}^{Py} \) changes with the opposite tendency to that of \( \lambda_{Hanle}^{Cu} \), showing a coupling between both fitting parameters (Fig. 2(b)). The observed deviation for \( L \sim \lambda_{Hanle}^{Cu} \) is clearly originated from a bad fitting of the data. However, this deviation is very reproducible for all measured samples and, thus, intrinsic to LSVs with transparent contacts. Figure 3 shows the measured \( R_{NL} \) as a function of \( B_Z \) in sample #2 for the three mentioned regimes, together with the simulated curves of

![Graph](image-url)
in order to clarify this issue, Fig. 3 also shows the simulated curves of Eq. (2), using now the $R_{NL}$ expression from Eq. (S13) in Ref. 8 (red dashed lines). For the simulations, in addition to the $P_{Py}^{NLSV}$ and $\lambda_{Cu}^{NLSV}$ values obtained from the fittings of the NLSV measurements, a value of $G_r = 3.9 \times 10^{14} \Omega^{-1} m^{-2}$ was used as the real part of the spin-mixing conductance of the Py/Cu interface.\textsuperscript{8,23,24} For the $L \gg \lambda_{Cu}^{NLSV}$ regime, Eq. (S13) from Ref. 8 follows quite accurately the measured data. However, in the $L \ll \lambda_{Cu}^{NLSV}$ regime, the simulated curves start to deviate from the experimental results. The discrepancy is highest for the $L \ll \lambda_{Cu}^{NLSV}$ regime, where the measured data are more affected by the precession, suggesting that the diffusion time is longer, an effect already reported to alter the fitted $P_L$ in LSVs using Eq. (3).\textsuperscript{11}

In order to obtain the value of $\lambda_{Cu}^{Hanle}$ by fitting Eq. (2) with $R_{NL}$ from Ref. 8, we fixed all the parameters except for $\lambda_{Cu}^{Hanle}$, which was left as the fitting parameter. This was done for the sake of simplicity, given the complexity of Eq. (S13) from Ref. 8. Figure 4 shows the obtained values of $\lambda_{Cu}^{Hanle}$ as a function of $L$ using that equation. For comparison, the $\lambda_{Cu}^{Hanle}$ values obtained by using Eq. (1), already shown in Fig. 2(a), are also plotted. The tendency is the same observed in the simulations, where $\lambda_{Cu}^{Hanle}$ and $\lambda_{Cu}^{NLSV}$ are in good agreement in the $L \gg \lambda_{Cu}^{NLSV}$ regime, but $\lambda_{Cu}^{Hanle}$ decreases when $L \ll \lambda_{Cu}^{NLSV}$. Therefore, Eq. (S13) from Ref. 8, which considers both the spin backflow and the anisotropic spin absorption at the FM/NM interfaces, does not work at the $L \ll \lambda_{Cu}^{NLSV}$ regime, showing that both mentioned effects are not enough to account for the disagreement between the current Hanle models and the measured curves.

A possible source of interference is the effect of nearby FM electrodes in the LSVs, but it is discarded by performing control experiments.\textsuperscript{16,25} Taking into account that the discrepancy occurs at short channel distances (see green triangles in Fig. 4), the origin could be attributed to the use of a one-dimensional spin-diffusion model to derive the used equations,\textsuperscript{5,8} which could no longer be a good approximation. Indeed, the region of the NM channel under the FM injector, where the spin-polarized electrons spend time diffusing, has been shown to influence the effective spin polarization of the FM in LSVs\textsuperscript{11} and would also affect the non-local Hanle curves.\textsuperscript{26}
IV. CONCLUSIONS

To summarize, we performed non-local Hanle measurements in LSVs with transparent and finite interface resistances, and we compared the spin-diffusion length of Cu, $\lambda_{Cu}$, obtained from such measurements to the one obtained from NLSV measurements as a function of $L$. Whereas, in the case where we have a finite FM/NM interface resistance, both methods are in excellent agreement, in the case of transparent interfaces an anomalous behaviour is observed, which depends on the distance $L$ between both FM electrodes. Although taking into account the spin backflow and the anisotropic spin absorption at the FM/NM interfaces can explain some of the observed disagreements, an additional interference that influences the non-local Hanle measurements is detected when $L \ll \lambda_{Cu}$. Such effect is beyond the understanding of the current one-dimensional spin diffusion models, evidencing the need for a more complete model that takes into account three dimensional effects. Hence, care should be taken when obtaining spin-transport information from such type of measurements in LSVs with transparent interfaces.

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16See supplementary material at http://dx.doi.org/10.1063/1.4922247 for details on the fitting of the Hanle data and on experimental results in additional samples.
22Py is a soft magnetic material; therefore, when starting from an initial AP state, the magnetization of one of the electrodes was always swiped back into the P state in the presence of a high enough BZ, preventing us from measuring RNL at the AP state for the whole range of BZ.
25The effect of the nearby electrodes is considered due to the design of our devices, which consist of several LSVs on a row. However, by systematically varying the distance of the nearby Py/Cu LSVs with transparent interfaces, the same behaviour as in Fig. 2(a) is observed,16 ruling out any effect coming from the adjacent electrodes.