Strong interfacial exchange field in a heavy metal/ferromagnetic insulator system determined by spin Hall magnetoresistance

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Abstract: Spin-dependent transport at heavy metal/magnetic insulator interfaces is at the origin of many phenomena at the forefront of spintronics research. A proper quantification of the different spin-dependent interface conductances is crucial for many applications. Here, we report the first measurement of the spin Hall magnetoresistance (SMR) of Pt on a purely ferromagnetic insulator (EuS). We perform SMR measurements in a wide range of temperatures and fit the results by using a microscopic model. From this fitting procedure we obtain the temperature dependence of the spin conductances ($G_s$, $G_i$ and $G_r$), disentangling the contribution of field-like torque ($G_i$), anti-damping-like torque ($G_r$), and spin-flip scattering ($G_s$). An interfacial exchange field of the order of 1 meV acting upon the conduction electrons of Pt can be estimated from $G_r$, which is at least three times larger than $G_i$ below the Curie temperature. Our work provides an easy method to quantify this interfacial spin-splitting field, which play a key role in emerging fields such as superconducting spintronics and caloritronics, and topological quantum computation.

Keywords: spin Hall magnetoresistance, spin-mixing conductance, europium sulfide, interfacial exchange field

Spin transport in systems consisting of magnetic insulators (MIs) and non-magnetic metals is of extreme importance in the field of spintronics. The spin currents through the interface of such heterostructure are at the origin of many phenomena, from spin pumping\(^1\) to spin Seebeck effect\(^2\), or spin Hall magnetoresistance\(^3,4,13-21,5-12\). The spin transport at the interface can be described in terms of three parameters: the spin-sink conductance $G_s$, which originates when the electron spins of the non-magnetic metal are collinear with the MI magnetization\(^22-24\), and the real and imaginary part of the spin-mixing conductance, $G_{1 \pm}= G_r + i G_i$ (refs 25,26), which originate from torques that the electron spins of the non-magnetic metal exert to the magnetization of the MI when they are noncollinear. $G_i$ is determined by the Slonczewski (or anti-damping-like) torque, an important quantity in spin-transfer torque magnetic random-access memory (STT-MRAM) devices, currently ready for mass production\(^27\). On the other hand, $G_i$ quantifies the exchange field between the electron spins of the non-magnetic metal and the magnetic moments of the MI, which induces a field-like torque. This interfacial exchange field is very relevant in different areas. For instance, when the non-magnetic metal is a superconductor, it leads to a spin-splitting field, even in the absence of an external magnetic field\(^28-31\). Such spin-splitting in superconductors are subjected to intense research\(^32,33\) because of their possible applications in cryogenic memories\(^34\), thermoelectric...
Spin Hall magnetoresistance (SMR) is a simple, yet powerful technique that can be used to quantify the spin-dependent interface conductances. When a heavy metal (HM), with a sizable spin Hall effect, is placed in contact with a MI, the SMR appears as a modulation of the HM resistivity, governed by $G_r - G_s$ (ref 42), which follows the relative orientation between the magnetization ($\mathbf{M}$) in the MI and the spin-Hall induced spin accumulation ($\mathbf{\mu}_s$) in the HM. SMR has been extensively studied in different MIs, for instance, ferrimagnetic insulators such as Y$_3$Fe$_5$O$_{12}$ (refs 3,4,6,7,9,10,13,16,43), Tm$_3$Fe$_5$O$_{12}$ (refs 44,45), Gd$_3$Fe$_5$O$_{12}$ (compensated ferrimagnet)$^8$ or CuOSeO$_2$ (spiral ferrimagnet)$^{46}$, antiferromagnetic insulators such as NiO$_2$, Cr$_2$O$_3$ and CoO (refs 11,15,20,21,47,48), low dimensional ferromagnets$^{49}$ or even paramagnetic insulators$^{18,50-52}$. SMR also shows up as an anomalous Hall-like contribution in the HM, in this case governed by $G_i$ (ref 42). In the studied cases with ferrimagnetic garnets, $G_r$ is at least one order of magnitude larger than $G_i$ (refs 7,9,10,26,44,45). In 2006, A. Brataas et al. $^{25}$ suggested that, at the interface with a ferromagnetic insulator (FMI), such as an europium chalcogenide, $G_i$ might dominate over $G_r$, a prediction also pointed out more recently by some of the authors from a microscopic model of SMR$^{32}$. However, up to date, there are no reports characterizing SMR in a purely FMI, mainly because of the small number of FMIs with large enough Curie temperature ($T_c$) available.

In this letter, we report the SMR in a HM such as Pt on top of EuS, a FMI with a $T_c$ around 19 K. The temperature dependence of the SMR amplitudes can be fit using either random phase approximation (RPA) or Weiss field theory (WFT) model with the microscopic theory for SMR$^{42}$. From the fittings, we can quantify the exchange interaction between the conduction electrons of Pt and the localized moments of Eu (~18 meV), as well as the values of $G_r$, $G_i$, and $G_s$ as a function of temperature. We demonstrate that, in a FMI where there is no compensation of magnetic moments at the interface, $G_i$ is larger than $G_r$. The precise quantification of the interfacial exchange field from $G_i$ is relevant in many fields where this quantity plays a crucial role.

A detailed description of the fabrication process and characterization of the EuS/Pt samples is given in methods. Figure 1a shows the temperature dependence of the EuS magnetization measured by SQUID at constant magnetic field ($\mu_0 H = 0.01$ T). EuS exhibits a ferromagnetic behavior with a broad transition at $T_c \sim 19$ K, in agreement with previous reports$^{53,54}$, but the magnetization does not saturate down to 4 K, a trend observed in similarly evaporated EuS films$^{55}$. Importantly for the SMR measurements, the TEM analysis (Figure 1b) shows the good quality of the interface between the Pt and EuS, where EuS has the right composition and crystalline structure.
Figure 1. (a) Temperature dependence of the EuS magnetization measured at $\mu_0 H = 0.01$ T. (b) TEM image of the SiO₂/Pt/EuS heterostructure. The solid lines on the right side represent the composition profile along the sample thickness. The colors correspond to Si (blue), O (green), Pt (purple), Eu (red), and S (yellow). (c-d) Normalized longitudinal ($\Delta \rho_L / \rho$) and transverse ($\rho_T / \rho$) ADMR measurements at 2.5 K along the three relevant $H$-rotation planes ($\alpha$, $\beta$, $\gamma$) (see sketches on the right side) for different applied magnetic fields: (c) $\mu_0 H = 0.1$ T and (d) $\mu_0 H = 2$ T, respectively.

According to the original SMR theory\(^\text{12}\), the longitudinal and transverse resistivity in a HM layer in contact with a MI depends on the direction of the MI magnetization as follows:

$$
\rho_L = \rho + \Delta \rho_0 + \Delta \rho_1 \left( 1 - m_z^2 \right), \\
\rho_T = \Delta \rho_1 m_x m_y + \Delta \rho_2 m_z,
$$

where $m = (m_x, m_y, m_z)$ is a unit vector along $M$, $\rho$ is the Pt resistivity, $\Delta \rho_0$ accounts for a resistivity correction due to the spin Hall effect, and $\Delta \rho_1$ and $\Delta \rho_2$ are the SMR amplitudes.

The longitudinal ($R_L = V_L / I$) and transverse ($R_T = V_T / I$) resistance are measured using the standard configurations shown in the sketches on the right side of Figure 1. Figures 1c and 1d show the longitudinal ($\Delta \rho_L / \rho$) and transverse ($\rho_T / \rho$) angular dependent magnetoresistance (ADMR) measurements at 2.5 K with the magnetic field ($\mu_0 H = 0.1$ T and 2 T, respectively) rotating along three main planes ($\alpha$, $\beta$, and $\gamma$) defined in the sketches on the right side of the panels. $\Delta \rho_L / \rho$ and $\rho_T / \rho$ are obtained as $\Delta \rho_L / \rho = [R_L(\alpha, \beta) - R_L(90^\circ)] / R_L(90^\circ)$, where $R_L(90^\circ) = 170 \Omega$, and $\rho_T / \rho = (L/w)[R_T(\alpha) - R_T(90^\circ)] / \rho$, where $\rho$ is $\sim 47 \mu\Omega \cdot \text{cm}$. At $\mu_0 H = 0.1$ T (Figure 1c), only the longitudinal (transverse) ADMR in $\alpha$–plane follows the $\cos^2(\cos \cdot \sin)$ dependence predicted by eqs 1 (refs 3,5,7,9,16,49), because only the in-plane magnetization follows the external field, as expected from the shape anisotropy of a soft ferromagnet such as EuS. In order to saturate the EuS film out-of-plane, we applied $\mu_0 H = 2$ T (Figure 1d). In this case, a clear $\cos^2$ dependence of the longitudinal ADMR in $\alpha$– and $\beta$–plane and a $\cos \cdot \sin$ dependence of the transverse ADMR in $\alpha$–plane is observed, all with a similar amplitude, which corresponds
This symmetry follows well eqs 1, and is linked to the interaction between $\mathbf{\mu}_s$ induced by the spin Hall effect$^{56,57}$ in the Pt when a charge current is applied and the magnetic moments of the EuS at the interface. When $\mathbf{\mu}_s$ and the magnetic moments are parallel, the spins are reflected at the interface and converted back into a charge current by the inverse spin Hall effect, decreasing the overall Pt resistance. However, when $\mathbf{\mu}_s$ and the magnetic moments are perpendicular, $\mathbf{\mu}_s$ exerts a torque to $\mathbf{M}$ and part of the spin angular momentum is absorbed by the MI, resulting in an increase of the Pt resistance. In the case of $\gamma$-plane, no modulation is expected from eqs 1. Nonetheless, there is a small modulation not related to SMR, which has been previously identified as weak antilocalization (WAL) that appears in Pt at low temperatures and large out-of-plane field$^{58,59}$.

Figure 2. (a) Longitudinal FDMR measurements performed along the three main axes at 2.5 K in a range of magnetic fields between 4 T and –4 T (see sketch for the definition of the axes, color code of the magnetic field direction, and measurement configuration). (b) Zoom of panel a at low magnetic fields between 0.1 and -0.1 T, where the magnetization reversal occurs. (c) Transverse FDMR measurements performed with the applied magnetic field in plane at $\alpha = 45^\circ$ and $\alpha = 135^\circ$. The red arrow shows the amplitude corresponding to $\Delta \rho_1 / \rho$. (d) Transverse resistivity measurement in Hall configuration (see sketch for the measurement configuration). Dash purple lines correspond to the linear fit performed at large magnetic fields and extrapolated to zero. The red arrow shows the amplitude corresponding to $\Delta \rho_2 / \rho$.

The observation of SMR in our system is confirmed by the longitudinal field dependent magnetoresistance (FDMR) measurements shown in Figure 2a in the three main axes (see sketch in the figure). The curve with applied $H_z$ should be the same as the one with $H_x$ due to the spin symmetry by SMR: in both cases, $\mathbf{\mu}_s$ is perpendicular to the EuS magnetization, leading to a high resistance state. The fact that, at large magnetic fields, the FDMR with $H_z$ is larger than with $H_x$ is
a clear feature of the WAL in Pt. The curve with $H_y$ applied shows lower resistance than that the ones with $H_x$ and $H_z$ as expected from SMR. The slight increase of the FDMR with $H_y$ is also related to WAL\textsuperscript{59}. At low magnetic fields, a clear gap corresponding to the $\Delta \rho_1/\rho$ amplitude appears between the curve with $H_x$ (and with $H_z$) and the curve with $H_y$, with peaks around zero field corresponding to the reversal magnetization of EuS (~5 mT in plane) (see Figure 2b). The same information can be obtained, with larger signal to noise ratio, from the transverse resistivity. Figure 2c plots the transverse FDMR, with the magnetic field applied in plane, at angles $\alpha = 45^\circ$ and $\alpha = 135^\circ$ (corresponding to the maximum and minimum resistance values), confirming both the $\Delta \rho_1/\rho$ amplitude and the magnetization reversal around ~5 mT. In the case of $H_z$, the magnetization reversal occurs at larger values (~1.5 T) because the magnetic hard axis of the EuS film lies out of plane.

Next, we performed measurements with a Hall configuration (i.e., transverse resistivity with $H_z$, see sketch in Figure 2d). At large $H_z$, we observe a linear dependence of $\rho_T$ with $H_z$ that corresponds to the ordinary Hall effect in the Pt. At low $H_z$, $\rho_T$ shows an anomalous Hall-like feature which follows the out-of-plane magnetization reversal of EuS. This observed feature corresponds to the $\Delta \rho_2$ term of the SMR theory (eqs 1). $\Delta \rho_2$ appears when the magnetization is out-of-plane since $\mathbf{\mu}_s$ precesses around $m_z$, an effect quantified by $G_i$. Since the spin polarization rotates from the $y$– to the $x$–direction, the inverse spin Hall effect acting in the Pt converts the spins back to charge current along the $y$–direction, leading to the measured transverse voltage\textsuperscript{12}. An anomalous Hall effect origin caused by magnetic proximity effect in Pt has been ruled out recently by using Au instead of Pt\textsuperscript{7}. $\Delta \rho_2/\rho$ can be extracted from Figure 2d with the intercept of the linear fittings at large (positive and negative) magnetic fields. According to the original SMR theory\textsuperscript{12}, $\Delta \rho_1/\rho$ essentially depends on the real part of the spin-mixing conductance, whereas $\Delta \rho_2/\rho$ mostly depends on the imaginary part. The anomalous Hall-like amplitude, which has only been reported few times in ferrimagnetic garnets\textsuperscript{7,9,10,26,44,45}, is small because $G_i$ is at least one order of magnitude smaller than $G_r$ in these ferrimagnetic insulators due to the partial compensation of the magnetic moments at the surface. Nonetheless, in our EuS/Pt system, we can see a clear $\Delta \rho_2/\rho$ amplitude. Figure 3b plots the temperature dependence of both $\Delta \rho_1/\rho$ and $\Delta \rho_2/\rho$, showing that $\Delta \rho_2/\rho$ is larger, in absolute value, than $\Delta \rho_1/\rho$. Both amplitudes disappear close to the $T_c$ of the EuS film.
Figure 3. (a) Temperature dependence of the experimental EuS magnetization (blue open squares) and of the spin-operator $S_{||}$ (dark yellow line) extracted from the fitting of the experimental curve to the RPA model for ferromagnetism. (b) Temperature dependence of the normalized SMR amplitudes $\Delta \rho_1/\rho$ (extracted from the transverse FDMR at $\mu_0 H = 0.1$ T as the example shown in Figure 2c) and $\Delta \rho_2/\rho$ (extracted from the Hall configuration measurement as the example shown in Figure 2d). The open dots represent the experimental data and the solid (dashed) lines are the amplitudes obtained with RPA (WMF) model and the microscopic theory$^{42}$. (c) Temperature dependence of the real part ($G_\rho$), imaginary part ($G_\iota$) of the spin-mixing conductance and the spin-sink conductance ($G_s$). The solid (dashed) lines are calculated values from the best fits obtained with the RPA (WMF) model.
In the original SMR theory\textsuperscript{12}, the spin-mixing conductance terms are assumed to be temperature and field independent. The spin current at the HM/MI interface is given by\textsuperscript{60,61}

\[-e J_{s,z} = G_s \mu_s + G_r \mathbf{n} \times [\mathbf{n} \times \mu_s] + G_i \mathbf{n} \times \mu_s,
\]

where \( e \) is the elementary charge, \( J_{s,z} \) is the spin current flowing in \( z \) direction, \( \mu_s \) the vector of the spin accumulation and \( \mathbf{n} \) is the unit vector in the direction of the applied magnetic field \( H \). \( G_i \) and \( G_r \) are the spin-mixing conductance terms. The spin-sink conductance \( G_s \) is related to the spin-flip scattering at the interface and plays an important role for the excitation of magnons in MIs\textsuperscript{62–65}. Since we are interested in the temperature dependence of the spin-mixing conductances, it is necessary to use a microscopic derivation of these parameters. As shown in ref 42, the different spin conductances can be defined in terms of the spin-spin correlation functions of the local magnetic moments at the surface of the MI. This allows to study their temperature and magnetic field dependencies\textsuperscript{62}. Hence, \( G_r, G_i \) and \( G_s \) are defined as\textsuperscript{1}

\[
G_r = e^2 v_F \left( \frac{1}{\tau_l} - \frac{1}{\tau_i} \right),
\]

\[
G_i = -\frac{e^2}{\hbar} n^{2D}_{\text{imp}} v_F J_{\text{int}} \langle \hat{S}_\parallel \rangle,
\]

\[
G_s = -e^2 v_F \frac{1}{\tau_i},
\]

with

\[
\frac{1}{\tau_i} = \frac{2\pi}{T} n^{2D}_{\text{imp}} v_F J_{\text{int}} \omega_L^m n_B (\omega_L^m) [1 + n_B (\omega_L^m)] \langle \hat{S}_\parallel \rangle, \quad \frac{1}{\tau_L} = \frac{1}{2\tau_i} + \frac{\pi}{\hbar} n^{2D}_{\text{imp}} v_F J_{\text{int}} \langle \hat{S}_\parallel^2 \rangle,
\]

where \( T \) is the temperature, \( n_B = 1/(e^{\hbar \omega_B/T} - 1) \) is the Bose-Einstein distribution function, \( \omega_L^{m} = \omega_B - \langle \hat{S}_\parallel \rangle \sum_J J_{ij}/\hbar \) with \( J_{ij} \) being the coupling constant of the Heisenberg ferromagnet, \( \omega_B = g\mu_B B/\hbar \) with \( g \) the gyromagnetic factor and \( \mu_B \) the Bohr magneton, \( v_F \) is the density of the electronic states per spin species in the HM at the Fermi level, \( J_{\text{int}} \) is the exchange interaction between the electron spins in the Pt and the magnetic moments of the FMI, \( n^{2D}_{\text{imp}} \) is the surface density of localized magnetic moments at the interface, and \( \hbar \) the reduced Planck constant. \( \hat{S}_\parallel \) is the longitudinal spin operator of a representative local moment, with \( \langle \hat{S}_\parallel \rangle \) being the spin expectation value, which is the projection of the localized moment parallel to \( H \). In addition, \( \langle \hat{S}_\parallel^2 \rangle \) is the spin-spin correlation function obtained from \( \hat{S}_\parallel \). Due to the spontaneous magnetization in a FMI, the spin relaxation times become anisotropic (\( \tau_\parallel \neq \tau_\perp \)) leading to the appearance of SMR. In this scenario, the SMR amplitudes \( \Delta \rho_1/\rho \) and \( \Delta \rho_2/\rho \) are given by

\[
\Delta \rho_1/\rho = \theta_{2\text{SH}}^2 \left[ F(G_s, \lambda) - \Re [F(G_s - G_{11}, \Lambda)] \right],
\]

\[
\Delta \rho_2/\rho = \theta_{2\text{SH}}^2 \Im [F(G_s - G_{11}, \Lambda)],
\]

\textsuperscript{1} It is important to emphasize that in order to write eq 2 in this customary form \( G_i \) is a negative quantity. See ref 42 for more details.
where \( \frac{1}{\Lambda} = \sqrt{\frac{1}{\Lambda^2} + \frac{1}{\Lambda^m}} \) with \( \lambda_m = \sqrt{\frac{\partial h}{\partial \rho |_{B=0}}} \). \( D \) the diffusion coefficient of the HM, \( \lambda \) the spin diffusion length of the HM, and \( \theta_{SH} \) the spin Hall angle of the HM. The auxiliary function \( \mathcal{F}(G, \lambda) \) is defined as

\[
\mathcal{F}(G, \lambda) = \frac{2\lambda}{d_N} \tanh \left( \frac{d_N}{2\lambda} \right) \frac{1-\rho \frac{G \lambda}{\coth \left( \frac{d_N}{\lambda} \right)}}{1-2\rho \frac{G \lambda}{\coth \left( \frac{d_N}{\lambda} \right)}}.
\]

In order to fit simultaneously the temperature dependence of the two SMR amplitudes, we need to model the magnetic ordering in EuS. For this, we used two possible approaches: the random phase approximation (RPA) and the Weiss mean field theory (WMF). First of all, by using the RPA model, we fit the experimental magnetization (Figure 3a) to extract the exchange integral for first neighbors, \( J_1 \) (12 first neighbors), and the second neighbors, \( J_2 \) (6 second neighbors) for 4f electrons in EuS. The values extracted from the model fit are 0.27kB for \( J_1 \) and -0.12kB for \( J_2 \), which match well the experimental ones obtained by neutron scattering, \( J_1 = 0.221kB \) and \( J_2 = -0.100kB \) (refs 66,67). In the RPA model, we calculate \( \langle S_\parallel \rangle \) and \( \langle S_\perp^2 \rangle \) from the obtained \( J_1 \) and \( J_2 \) values, whereas in the WMF model, we use the experimental magnetization as \( \langle S_\parallel \rangle \) and from \( \langle S_\parallel \rangle \), we calculate \( \langle S_\perp^2 \rangle \) (ref 42). As for the Pt parameters, we take the values of \( \lambda \) (~1.3 nm) and \( \theta_{SH} \) (~0.19) corresponding to the Pt resistivity at each temperature\(^{68}\). Figure 3b shows the fits of the SMR amplitudes \( \Delta \rho_1/\rho \) (purple lines) and \( \Delta \rho_2/\rho \) (blue lines) to the RPA (solid lines) and WMF (dashed lines) models, with \( J_{int} \) and \( n_{imp}^{2D} \) being the only free parameters. The fits reproduce reasonably well the two experimental curves for both the RPA and WMF models. The parameter values obtained in the fittings are: i) \( J_{int} = 21.3 \text{ meV} \) (RPA) and 14.8 meV (WMF), which is the exchange interaction between the conduction electrons in Pt and the localized magnetic moments in EuS and is ferromagnetic \( J_{int} > 0 \); (ii) \( n_{imp}^{2D} = 0.10/\alpha^2 \) (RPA) and 0.14/\( \alpha^2 \) (WMF), with \( \alpha = 5.94 \) Å being the EuS lattice parameter. The best fitting parameters are similar for both methods, which strengthen the reliability of the obtained values. The obtained \( J_{int} \) here is much smaller than other experimental accessible values, for instance \( J_{int} = 350 \text{ meV} \) for Co/Cu (ref 69). \( n_{imp}^{2D} \) values are 10–14\% of the ideal value, but they depend on the slicing of the lattice surface and the quality of the HM/FMI surface. The difference between the RPA model and the experimental data arises from the fact that EuS does not behave as an ideal ferromagnet and the \( M(T) \) curve cannot be fully captured by a simple model (see Figure 3a). In this regard, the WMF model gives a better fit because it uses the experimental \( M(T) \) curve to extract one of the required parameters (\( \langle S_\parallel \rangle \)).

From the same fitting parameters obtained from the fits in Figure 3b, we use eqs 4 to calculate \( G_r, G_i \), and \( G_s \) as a function of temperature, which are plotted in Figure 3c. At low temperatures, when the EuS magnetization saturates, \( G_r \) and \( G_i \) are largest since \( \langle S_\parallel \rangle \), and thus the torque, is maximum. However, because the magnetization is frozen, the conservation of the angular momentum leads to a reduction of the spin-flip scattering and hence to a suppression of \( G_s \). In contrast, at higher temperatures and close to \( T_c \), with the absence of net magnetization due to the randomized spins (\( \langle S_\parallel \rangle \rightarrow 0 \)), \( G_r \) and \( G_i \) vanish to zero because of the isotropic relaxation time (see eqs 5), whereas |\( G_s \)| becomes maximum. A key point of the obtained results is that we experimentally demonstrate for the first time that in a FMI such as EuS, \( G_i \) is larger than \( G_r \), at least 3 times larger at the lowest measured temperature (2.5 K), as predicted in ref 25 for europium.
chalcogenides. According to our results, we can confirm that the field-like torque plays an important role in Pt/EuS because all magnetic moments of the interface contribute to the interfacial exchange field, as opposed to the ferrimagnetic case\textsuperscript{7,9,10,26,44,45}, where there is a compensation of the magnetic moments.

A recent work based on spin sinking in lateral spin valves estimates $|G_i| \approx 3 \times 10^{12} \, \Omega^{-1} \text{m}^{-2}$ in EuS/Cu at 10 K\textsuperscript{25}, with EuS being also evaporated on top, in good agreement with our value of $|G_i| \approx 1.1 \times 10^{12} \, \Omega^{-1} \text{m}^{-2}$ at the same temperature. Another work on EuS evaporated on graphene estimates an interfacial exchange field $>14 \, \text{T}$ based on measurements of the Zeeman spin Hall effect at 4.2 K (ref 40). We can calculate the interfacial exchange field $h_{ex}$ that is related to $G_i$ obtained from our SMR measurements by using the following expression\textsuperscript{12}: $h_{ex} = G_f/\pi G_0 v_F b$, where $G_0$ is the conductance quantum, and $b$ is a length of the order of the mean free path ($l$). From the value $G_i \approx 7.0 \times 10^{12} \, \Omega^{-1} \text{m}^{-2}$ observed at the lowest temperature, and taking typical values $v_F \approx 3-4 \times 10^8 \, \text{m} \text{s}^{-1}$ (ref 70) for a metal and $l \approx 10^{-9} \, \text{m}$ for highly resistive Pt, we obtain $h_{ex} = 0.72-0.96 \, \text{meV}$ (equivalent to $12.4-16.6 \, \text{T}$), in good agreement with ref 40.

As mentioned in the introduction, the interfacial exchange field plays a crucial role in several applications. Therefore, an accurate control of it is very important. For example, for bolometers and cryogenic memories\textsuperscript{34,35} based on the spin-splitting induced in EuS/Al bilayers, the effective spin-splitting field induced in Al is given by $h_{eff} = h_{ex} b/d_{Al}$, where $d_{Al}$ is the thickness of the Al layer. If we assume the same order of magnitude of the interfacial $h_{ex}$ that we obtain for Pt, for $d_{Al} \approx 3-10 \, \text{nm}$ (refs 30,39) we obtain $h_{eff} \approx 0.07-0.3 \, \text{meV}$, whereas the superconducting gap for Al at low temperatures is approximately $\Delta \approx 0.2 \, \text{meV}$ (ref 30). In order to observe coexistence between superconductivity and the spin-splitting field, the effective exchange field may not exceed the paramagnetic limit, which at low temperatures is $h_{eff} < 0.7 \Delta \approx 0.14 \, \text{meV}$ (ref 71). Hence, for the observation of a clear spin-split Bardeen–Cooper–Schrieffer (BCS) density of states, special care should be taken in the fabrication of EuS/Al bilayers.

In summary, we characterize the spin transport in a Pt/EuS interface, where EuS is a pure ferromagnetic insulator below $\sim 19 \, \text{K}$, by using spin Hall magnetoresistance. We observe a substantial AHE-like contribution of the SMR, driven by a large imaginary part of the spin-mixing conductance. We apply a microscopic theory of SMR to extract relevant parameters such as the exchange interaction between the conduction electrons in Pt and the localized magnetic moments in EuS ($j_{int} \sim 15-21 \, \text{meV}$). We also obtain the temperature dependence of the interfacial spin conductances, experimentally demonstrating a larger field-like torque ($G_i$) than anti-damping-like torque ($G_f$) in a heavy metal/magnetic insulator interface. The strong interfacial exchange field associated to $G_i$ is estimated as $0.72-0.96 \, \text{meV}$ ($12.4-16.6 \, \text{T}$). Therefore, SMR measurements offer a simple way to quantify effective exchange fields which are of interest in different areas of Condensed Matter Physics, such as proximity effects in superconducting hybrid systems.

**Methods. Device fabrication.** EuS/Pt samples were prepared by patterning a Pt Hall bar (width $w=500 \, \mu\text{m}$, length $L=900 \, \mu\text{m}$, and thickness $d_{Pt}=5 \, \text{nm}$) on top of a SiO$_2$ (150 nm)/Si substrate by photolithography process and magnetron-sputtering deposition (80 W; 3 mTorr). A EuS layer was ex-situ evaporated on top of the Pt film. For growing the EuS, the patterned sample was inserted in a UHV preparation chamber (base pressure $5 \times 10^{-9} \, \text{mbar}$) and left for twelve hours.
at room temperature to remove the water absorbed at the Pt surface. EuS was grown by means of sublimation of a stoichiometric EuS powder (99.9% purity) in a commercial e-beam evaporator. During preparation the substrate was kept at room temperature and the growth rate was calibrated with a quartz microbalance (0.5 nm/min). The total thickness of the EuS layer is 14 nm.

**Materials Characterization.** The magnetic properties of the EuS film were studied by superconducting quantum interference device (SQUID). The quality of the Pt/EuS interface by (scanning) transmission electron microscopy (S)TEM, performed on a TitanG2 60–300 electron microscope (FEI Co., The Netherlands). The composition profiles were acquired in STEM mode utilizing energy dispersive X-ray spectroscopy (EDX) signal.

**Electrical measurements.** Magnetotransport measurements were carried out in a liquid-He cryostat at temperatures $T$ between 2.5 K and 40 K, externally applied magnetic fields $\mu_0 H$ up to 9 T, and a 360º sample rotation.

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**Notes**
The authors declare no competing financial interest.

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