One analytical approach of Rashba–Edelstein magnetoresistance in 2D materials

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Abstract. We study analytically the Rashba–Edelstein magnetoresistance in a structure made from an insulator ferromagnet, such as yttrium iron garnet, and a 2D material with direct and inverse Rashba–Edelstein effects, such as SLG and MoS$_2$. Our results represent an efficient way of analyzing the Rashba–Edelstein effects. In addition, it also presents a concrete analysis of the exchange field acting on the accumulation of spins.

1 Introduction

2D spintronics has gained an important meaning in data storage technologies, in many those cases, the 2D materials are non-magnetic, however, magnetism can be induced at the interface of those materials. Among some methods, two of them are broadly applied to induce magnetism on 2D material. The first method is to introduce vacancies or adding atoms producing spin polarization [1–3]. The other one is to induce magnetism of the adjacent magnetic materials via the magnetic proximity effect [4–7]. Recently was discovered that 2D magnetic van der Waals crystals have intrinsic magnetic ground states at the atomic scale, providing new opportunities in the field of 2D spintronics [8,9]. Furthermore, it was discovered that several materials as single-layer graphene (SLG) and molybdenum disulfide (MoS$_2$) [10–12] can also be used for spin-charge current conversion [13–18]. Due to their layered structures, MoS$_2$ and SLG can be easily prepared with one or several atomic layers to explore the transport properties. SLG and semiconducting MoS$_2$ have 2D electronic states that are expected to exhibit remarkable pseudospin and spin-momentum locking, respectively [10,19–22]. These are essential ingredients for the charge-to-spin current conversion by the direct Rashba–Edelstein effect (REE) or for spin-to-charge current conversion by the inverse Rashba Edelstein effect (IREE). Another fundamental ingredient is the broken inversion symmetry at material surfaces and interfaces [1–3,23–27].

Although the change of electrical resistance of ferromagnets has been studied for a long time, providing a fundamental understanding of spin-dependent transport in different structures [24–26], the transport properties of 2D materials still present themselves as a challenge. One of the most important effects in spin-dependent transport is the spin Hall magnetoresistance (SMR) [27–29]. In 3D materials, the SMR is explained by the spin-current reflection and reciprocal spin-charge conversion caused by the simultaneous action of the spin Hall effect (SHE) [30–32] and inverse spin Hall effect (ISHE) [33]. The challenge is to explore the magnetoresistance induced in 2D materials [34,35]. In this paper, we present a study based on direct and inverse Rashba–Edelstein effects that describes the magnetoresistance in 2D materials, which is called of Rashba–Edelstein magnetoresistance (REMR).

2 2D materials in contact with a magnetic insulator

The REMR is induced by the simultaneous action of direct and inverse Rashba–Edelstein effects and therefore a nonequilibrium proximity phenomenon. The magnetoresistance study was carried out with arrangement as illustrated in Fig. 1 below.

The effects of the spin current in 2D materials are very important for phenomena of transport. Considering the Ohm’s law for 2D materials with direct and inverse Rashba–Edelstein effects and therefore a nonequilibrium proximity phenomenon can be understood by the relation between thermodynamic driving...
force and currents that reflects Onsager’s reciprocity by the symmetry of the response matrix:

\[
\begin{pmatrix}
\tilde{J}_C \\
\tilde{J}_{Sz} \\
\tilde{J}_{Sy}
\end{pmatrix} = \frac{1}{R_{2D}} \begin{pmatrix}
\frac{1}{\lambda_{REE}} \hat{x} \times & \frac{1}{\lambda_{REE}} \hat{y} \times & \frac{1}{\lambda_{REE}} \hat{z} \\
\frac{1}{\lambda_{REE}} \hat{y} \times & 1 & 0 \\
\frac{1}{\lambda_{REE}} \hat{z} \times & 0 & 1
\end{pmatrix}
\begin{pmatrix}
-\nabla\mu_C/e \\
-\nabla\mu_{Sz}/2e \\
-\nabla\mu_{Sy}/2e
\end{pmatrix},
\]

where \( e = \mid e \mid \) is the electron charge, \( R_{2D} \) is the resistance of 2D material, \( \mu_C \) is the charge chemical potential, \( \tilde{\mu}_S \) is the spin accumulation, \( \tilde{J}_C \) is the charge current density and \( \tilde{J}_S \) is the spin current density. The direct Rashba–Edelstein is represented by the lower diagonal elements that generate the spin currents in the presence of an applied current density, which generates an electric field, in the following chosen to be in the \( \hat{x} \) direction \( \vec{E} = E_x \hat{x} = -\hat{x}(\partial_x \mu_C/e) \). On the other hand, the inverse Rashba–Edelstein effect is governed by element above the diagonal that connect the gradients of the spin accumulations to the charge current density. The spin accumulation \( \tilde{\mu}_S \) is obtained from the spin-diffusion equation in the 2D materials

\[
\nabla^2 \tilde{\mu}_S = \frac{\tilde{\mu}_S}{\lambda_{SD}},
\]

where \( \lambda_{SD} \) is the spin-diffusion length. Spin accumulation is always due to spin diffusion, which even for a 2D material such as graphene has spin diffusion in the \( z \)-direction. For 2D materials with thickness \( l_{2D} \) in the \( \hat{x} \) direction the solution of equation (2) is

\[
\tilde{\mu}_S(z) = \tilde{\mu}_0 e^{-z/\lambda_{2D}} + \tilde{\mu}_1 e^{z/\lambda_{2D}},
\]

where the constant column vectors \( \tilde{\mu}_0 \) and \( \tilde{\mu}_1 \) are determined by the boundary conditions at the interfaces. According to Eq. (2), the spin current in 2D materials consists of spin diffusion process. For a system homogeneous in the \( x-y \) plane, the spin current density flowing in the \( \hat{z} \) direction is

\[
\tilde{J}_S^z(z) = -\left( \frac{1}{2eR_{2D}\lambda_{REE}} \right) \partial_z \tilde{\mu}_S = J_{SO}^{REE} \hat{y},
\]

where \( J_{SO}^{REE} = E_x/R_{2D}\lambda_{REE} \) is the bare Rashba–Edelstein current, i.e., the spin current generated directly by the REE and \( \lambda_{REE} \) is the REE length. At the interfaces \( z = l_{2D} \) and \( z = 0 \) the boundary conditions demand that \( \tilde{J}_S^z(z) \) is continuous. The spin current at \( z = l_{2D} \) interface vanishes, \( \tilde{J}_S^z(z = l_{2D}) = \tilde{J}_S^z = 0 \). On the other hand, in general at the magnetic interface the spin current density \( \tilde{J}_S^{FM} \) is governed by the spin accumulation and spin-mixing conductance \([36]\), such that:

\[
\tilde{J}_S^{FM}(\tilde{m}) = g_r \tilde{m} \times \left( \tilde{m} \times \tilde{\mu}_S \right) + g_i \left( \tilde{m} \times \frac{\tilde{\mu}_S}{e} \right),
\]

where \( \tilde{m} = (m_x, m_y, m_z)^T \) represents a unit vector along the magnetization and \( g_{r1} = g_r + ig_i \) the complex spin-mixing interface conductance per unit length and resistance. It is agreed that \( g_r \) characterizes the efficiency of the interfacial spin transport and the imaginary part \( g_i \) can be interpreted as an effective exchange field acting on the spin accumulation. According with Eq. (5) a positive current corresponds to up spins moving from FM towards 2D. In particular for FM insulator, this spin current density is proportional to the spin transfer torque acting on the ferromagnet

\[
\vec{\tau}_{STT} = -\frac{\hbar}{2e} \tilde{m} \times \left( \tilde{m} \times \tilde{J}_S^{FM}(\tilde{m}) \right) = \frac{\hbar}{2e} \tilde{J}_S^{FM}(\tilde{m}).
\]

Using the boundary conditions discussed before, it is possible to determine the coefficients \( \tilde{p} \) and \( \tilde{q} \), which leads to the spin accumulation for structures 2DM/FM

\[
\tilde{\mu}_S(z) = -\mu_{SO} \left[ \frac{\sinh \left( \frac{2z-l_{2D}^D}{2\lambda_{SD}} \right)}{\sinh \left( \frac{l_{2D}^D}{2\lambda_{SD}} \right)} \right] \hat{y}
\]

\[
+2e\lambda_{2D}\lambda_{REE}R_{2D} \left[ \frac{\cosh \left( \frac{2z-l_{2D}^D}{2\lambda_{SD}} \right)}{\sinh \left( \frac{l_{2D}^D}{2\lambda_{SD}} \right)} \right] \tilde{J}_S^{FM}(\tilde{m}),
\]

where \( \mu_{SO} \equiv |\tilde{\mu}_S(0)| = 2e\lambda_{2D}\lambda_{REE}R_{2D}\mu_{SO}^{REE} \tanh \left( l_{2D}^D/2\lambda_{2D} \right) \) is the spin accumulation at the interface in the absence of spin transfer, i.e., when \( g_{r1} = 0 \). Furthermore, according with Eq. (5), the spin accumulation at \( z = 0 \) becomes

\[
\tilde{\mu}_S(0) = \mu_{SO} \tilde{\mu} + 2\lambda_{2D}\lambda_{REE}R_{2D} \mu_{SO}^{REE} \tanh \left( \frac{l_{2D}^D}{2\lambda_{SD}} \right)
\times [g_r \{ \tilde{m} \cdot (\tilde{m} \cdot \tilde{\mu}_S(0)) - \tilde{\mu}_S(0) \} + g_i \tilde{m} \times \tilde{\mu}_S(0)]
\]
The spin current through the FM/2DM interfaces reads

\[
\hat{m} \cdot \hat{\mu}_S(0) = m_y \mu_{SO},
\]

\[
\hat{m} \times \hat{\mu}_S(0) = \mu_{SO} \left[ \frac{\hat{m} \times \hat{y}}{\mathcal{R}_{2D} \lambda_{REE}} + \frac{2m_y \lambda_{2D} g_{11} \coth \left( \frac{\lambda_{2D}}{\lambda_{2D}} \right)}{\mathcal{R}_{2D} \lambda_{REE}} + 2\lambda_{2D} g_{11} \coth \left( \frac{\lambda_{2D}}{\lambda_{2D}} \right) \right] \hat{m},
\]

\[
\hat{m} \times \hat{\mu}_S(0) = \mu_{SO} \left[ - \frac{2\lambda_{2D} g_{11} \coth \left( \frac{\lambda_{2D}}{\lambda_{2D}} \right)}{\mathcal{R}_{2D} \lambda_{REE}} + 2\lambda_{2D} g_{11} \coth \left( \frac{\lambda_{2D}}{\lambda_{2D}} \right) \right] \hat{\mu}_S(0),
\]

where \( \hat{m} \cdot \hat{\mu}_S(0) \) and \( \hat{m} \times \hat{\mu}_S(0) \) are

\[
\begin{align*}
\hat{m} \cdot \hat{\mu}_S(0) & = m_y \mu_{SO}, \\
\hat{m} \times \hat{\mu}_S(0) & = \mu_{SO} \\
& \left[ \frac{\hat{m} \times \hat{y}}{\mathcal{R}_{2D} \lambda_{REE}} + \frac{2m_y \lambda_{2D} g_{11} \coth \left( \frac{\lambda_{2D}}{\lambda_{2D}} \right)}{\mathcal{R}_{2D} \lambda_{REE}} + 2\lambda_{2D} g_{11} \coth \left( \frac{\lambda_{2D}}{\lambda_{2D}} \right) \right] \hat{m} \\
& - \left[ \frac{2\lambda_{2D} g_{11} \coth \left( \frac{\lambda_{2D}}{\lambda_{2D}} \right)}{\mathcal{R}_{2D} \lambda_{REE}} + 2\lambda_{2D} g_{11} \coth \left( \frac{\lambda_{2D}}{\lambda_{2D}} \right) \right] \hat{\mu}_S(0),
\end{align*}
\]

and

\[
\hat{\mu}_S(0) = \mu_{SO} \left[ \frac{A(1 + A) \hat{m} + B(\hat{m} \times \hat{y}) + (1 + A) \hat{y}}{A^2 + B^2} \right],
\]

where

\[
A = 2\lambda_{2D} \lambda_{REE} R_{2D} g_{11} \coth \left( \frac{\lambda_{2D}}{\lambda_{2D}} \right)
\]

\[
B = 2\lambda_{2D} \lambda_{REE} R_{2D} g_{11} \coth \left( \frac{\lambda_{2D}}{\lambda_{2D}} \right).
\]

The spin current through the FM/2DM interfaces reads

\[
\hat{J}_S^{FM} = \left( \frac{\mu_{SO}}{e \mathcal{R}_{2D} \lambda_{REE}} \right) \times
\]

\[
\begin{align*}
& \left[ 1 \right] \im \left\{ \frac{g_{11}}{\mathcal{R}_{2D} \lambda_{REE}} + \frac{2\lambda_{2D} g_{11} \coth \left( \frac{\lambda_{2D}}{\lambda_{2D}} \right)}{\mathcal{R}_{2D} \lambda_{REE}} \right\} \left[ \hat{m} \times \hat{y} \right]
\end{align*}
\]

\[
+ \left( \frac{\mu_{SO}}{e \mathcal{R}_{2D} \lambda_{REE}} \right) \times
\]

\[
\begin{align*}
& \left[ \im \right] \left\{ \frac{g_{11}}{\mathcal{R}_{2D} \lambda_{REE}} + \frac{2\lambda_{2D} g_{11} \coth \left( \frac{\lambda_{2D}}{\lambda_{2D}} \right)}{\mathcal{R}_{2D} \lambda_{REE}} \right\} \hat{m} \times (\hat{m} \times \hat{y}).
\end{align*}
\]

In this way, the spin accumulation is,

\[
\hat{\mu}_S(0) = \im \left\{ \frac{2\lambda_{2D} g_{11}}{\mathcal{R}_{2D} \lambda_{REE}} + \frac{2\lambda_{2D} g_{11} \coth \left( \frac{\lambda_{2D}}{\lambda_{2D}} \right)}{\mathcal{R}_{2D} \lambda_{REE}} \right\}
\]

\[
\times \left\{ \frac{\cosh \left[ \frac{-z \lambda_{2D}}{\lambda_{2D}} \right]}{\sinh \left[ \frac{z \lambda_{2D}}{\lambda_{2D}} \right]} \right\} \left( \hat{m} \times \hat{y} \right)
\]

\[
+ \re \left\{ \frac{2\lambda_{2D} g_{11}}{\mathcal{R}_{2D} \lambda_{REE}} + \frac{2\lambda_{2D} g_{11} \coth \left( \frac{\lambda_{2D}}{\lambda_{2D}} \right)}{\mathcal{R}_{2D} \lambda_{REE}} \right\}
\]

\[
\times \left\{ \frac{\sinh \left[ \frac{-z \lambda_{2D}}{\lambda_{2D}} \right]}{\sinh \left[ \frac{z \lambda_{2D}}{\lambda_{2D}} \right]} \right\} \left( \hat{m} \times \hat{y} \right).
\]

The inverse Rashba–Edelstein effect drives a charge current in the \( xy \) plane by the diffusion spin current component flowing along the \( z \) direction. The total longitudinal (along \( \hat{z} \)) component is

\[
\frac{J_{C,long}(z)}{J_{CO}} = 1 + 4 \left( \frac{\lambda_{REE}}{l_{2D}} \right)^2 \left[ \frac{\cosh \left( \frac{-z \lambda_{2D}}{\lambda_{2D}} \right)}{\cosh \left( \frac{z \lambda_{2D}}{\lambda_{2D}} \right)} \right] \left( 1 - m_y^2 \right)
\]

\[
\times \left\{ \frac{2\lambda_{2D} g_{11} \tanh \left( \frac{z \lambda_{2D}}{2\lambda_{2D}} \right)}{\mathcal{R}_{2D} \lambda_{REE}} + \frac{2\lambda_{2D} g_{11} \coth \left( \frac{z \lambda_{2D}}{2\lambda_{2D}} \right)}{\mathcal{R}_{2D} \lambda_{REE}} \right\} \left( \hat{m} \times \hat{y} \right) \]

\[
+ \left\{ \frac{\sinh \left[ \frac{-z \lambda_{2D}}{2\lambda_{2D}} \right]}{\sinh \left[ \frac{z \lambda_{2D}}{2\lambda_{2D}} \right]} \right\} \left( \hat{m} \times \hat{y} \right).
\]

and transverse or Rashba–Edelstein component is

\[
\frac{J_{C,trans}(z)}{J_{CO}} = 4 \left( \frac{\lambda_{REE}}{l_{2D}} \right)^2 \left[ m_x m_y Re - m_y Im \right]
\]

\[
\times \left\{ \frac{2\lambda_{2D} g_{11} \tanh \left( \frac{z \lambda_{2D}}{2\lambda_{2D}} \right)}{\mathcal{R}_{2D} \lambda_{REE}} + \frac{2\lambda_{2D} g_{11} \coth \left( \frac{z \lambda_{2D}}{2\lambda_{2D}} \right)}{\mathcal{R}_{2D} \lambda_{REE}} \right\} \left( \hat{m} \times \hat{y} \right) \]

\[
+ \left\{ \frac{\sinh \left[ \frac{-z \lambda_{2D}}{2\lambda_{2D}} \right]}{\sinh \left[ \frac{z \lambda_{2D}}{2\lambda_{2D}} \right]} \right\} \left( \hat{m} \times \hat{y} \right).
\]
where \( J_{CO} = E_x/(R_{2D} \lambda_{REE}) \) it is the charge current driven by the external electric current. Expanding the longitudinal resistance governed by the current in the \( x \)-direction of the applied field to leading order in \( \lambda_{REE}^2 \) and averaging the electric currents over the 2DM thickness, it is found

\[
\langle R_{2D} \rangle_{\text{long}} = \left( \frac{\lambda_{REE} E_x}{J_{C,\text{long}}} \right) R_{2D} + \Delta R_{2D}^{(0)} + (1 - m_y^2) \Delta R_{2D}^{(1)},
\]

(19)

and

\[
\langle R_{2D} \rangle_{\text{trans}} \approx -\left( \frac{J_{C,\text{trans}}}{E_x} \right) \left( \frac{1}{R_{2D} \lambda_{REE}} \right)^2 = m_x m_y \Delta R_{2D}^{(1)} + m_y \Delta R_{2D}^{(2)},
\]

(20)

where

\[
\Delta R_{2D}^{(0)} = -\left( \frac{2 \lambda_{REE}}{l_{2D}} \right)^2 \left( \frac{2 \lambda_{2D}}{l_{2D}} \right) \tanh \left( \frac{l_{2D}}{2 \lambda_{2D}} \right),
\]

(21)

\[
\Delta R_{2D}^{(1)} = \left( \frac{2 \lambda_{REE}}{l_{2D}} \right)^2 \left( \frac{2 \lambda_{2D}}{l_{2D}} \right) \times \text{Re} \left[ \frac{2 \lambda_{2D} g_{i1} \tanh^2 \left( \frac{l_{2D}}{\lambda_{2D}} \right)}{R_{2D} \lambda_{REE} + 2 \lambda_{2D} g_{i1} \coth \left( \frac{l_{2D}}{\lambda_{2D}} \right)} \right],
\]

(22)

\[
\Delta R_{2D}^{(2)} = \left( \frac{2 \lambda_{REE}}{l_{2D}} \right)^2 \left( \frac{2 \lambda_{2D}}{l_{2D}} \right) \times \text{Im} \left[ \frac{2 \lambda_{2D} g_{i1} \tanh^2 \left( \frac{l_{2D}}{\lambda_{2D}} \right)}{R_{2D} \lambda_{REE} + 2 \lambda_{2D} g_{i1} \coth \left( \frac{l_{2D}}{\lambda_{2D}} \right)} \right],
\]

(23)

and \( \Delta R_{2D}^{(0)} < 0 \), this suggests that the resistance is reduced by the Rashba interaction.

### 3 Discussion and applications

#### 3.1 Different 2D magnetoresistances

For small thickness (2D surface) \( l_{2D} \ll \lambda_{2D} \) the Eqs. (21), (22) and (23) are written as

\[
\frac{\Delta R_{2D}^{(0)}}{R_{2D}} = -\left( \frac{2 \lambda_{REE}}{l_{2D}} \right)^2,
\]

(24)

\[
\frac{\Delta R_{2D}^{(1)}}{R_{2D}} = 2 \left( \frac{\lambda_{REE}}{l_{2D}} \right)^2 \left[ \frac{g_i R_{2D} \lambda_{REE} l_{2D}}{l_{2D} + 2 g_i R_{2D} \lambda_{REE} \lambda_{2D}} \right],
\]

(25)

\[
\frac{\Delta R_{2D}^{(2)}}{R_{2D}} = -\left( \frac{\lambda_{REE}}{l_{2D}} \right)^2 \left( \frac{2 g_i R_{2D} \lambda_{REE} l_{2D} \lambda_{2D}^2}{l_{2D} + 2 g_i R_{2D} \lambda_{REE} \lambda_{2D}^2} \right).
\]

(26)

In Fig. 2, it is shown the different 2D magnetoresistances \( \Delta R_{2D}^{i}/R_{2D} \) as a function of thickness \( l_{2D} \) with \( i = 0, 1, 2, g_i = 2.4 \times 10^7 \text{ m}^{-1} \text{Ω}^{-1} \), \( g_r = 2.4 \times 10^7 \text{ m}^{-1} \text{Ω}^{-1} \), \( R_{2D} = 0.2 \times 10^6 \text{ Ω} \), and \( \lambda_{REE} = 0.13 \times 10^{-9} \text{ m} \) for MoS\(_2\) [17,37]. The real \((g_r)\) and imaginary \((g_i)\) parts of the spin-mixing interface conductance were obtained considering the complex spin-mixing interface conductance module equal to the effective spin-mixing interface conductance obtained by spin pumping measurements [17]. After we consider the dimensions of the structure, we get that the real \((g_r)\) and imaginary \((g_i)\) parts of the spin-mixing interface conductance are the same for the YIG/MoS\(_2\) structure, which is an result extremely reasonable, considering the YIG/MoS\(_2\) interface has both intrinsic spin-orbit coupling and proximity effect. The different behaviors described by 2D magnetoresistances in Fig. 2 reveal that are effects that can be measured differently and separately.

#### 3.2 REE length

In accords with Fig. 2 the REE is an effect of the order of \( \lambda_{REE}^2 \) that becomes relevant only when \( l_{2D} \) is sufficiently small. Now is important discuss the limit in which the spin current transverse due the spin accumulation to \( \vec{m} \) is completely absorbed as an spin transfer torque without reflection \( \Gamma = g_r \gg 1/(\lambda_{REE} R_{2D}) \), which occurs in 2D interface. The spin current at the interface is then

\[
\frac{J_S^{(FM)}}{J_{SD}} = \frac{\Gamma}{m \times (\vec{m} \times \hat{y})},
\]

(27)
and the maximum magnetoresistance for the FM/2DM structure is

$$\frac{\Delta R^{(1)}_{2D}}{R_{2D}} = \left( \frac{2\lambda_{REE}}{l_{2D}} \right)^2 \left( \frac{\lambda_{2D}}{l_{2D}} \right) \times \tanh \left( \frac{l_{2D}}{\lambda_{2D}} \right) \tan h^2 \left( \frac{l_{2D}}{2\lambda_{2D}} \right),$$

(28)

but for small thickness (2D interface) \( l_{2D} \ll \lambda_{2D} \), we have

$$\lambda_{REE} = \lambda_{2D} \eta,$$

(29)

where \( \eta = (\Delta R^{(1)}_{2D}/R_{2D})^{1/2} \). In Fig. 3, it is shown RRE length \( \lambda_{REE} \) in nm as a function of the REMR \( \eta \) for SLG and MoS\(_2\), with spin diffusion length of \( \lambda_{SLG} = 1.0 \times 10^{-6} \) m [25, 34] and \( \lambda_{MoS_2} = 2.35 \times 10^{-9} \) m [16, 34, 35], respectively.

### 3.3 Experimental applications

#### 3.3.1 YIG/SLG

The SLG has been considered to be very promising materials for spintronic applications [6, 7, 21, 22, 26]. However, due to the low atomic number of carbon, intrinsic graphene has a weak SOC and thus very small spin Hall effect [26]. SLG have 2D electronic states that are expected to exhibit remarkable pseudospin. This gives rise to a proximity effect that results in long-range ferromagnetic ordering in graphene, as observed in YIG/SLG [5, 26, 38]. In fact, the SLG on the YIG film represent one excellent example for application of the study proposal here. For SLG, it was possible to consider the effective thickness \( l_{SLG} = 2 \times 10^{-10} \) m, \( \Delta R^{(1)}_{2D}/R_{2D} = 0.5 \times 10^{-8} \) and the spin diffusion length \( \lambda_{SLG} = 1.0 \times 10^{-6} \) m as in Refs. [26, 38]. Then, using the Eq. (29) is obtain for graphene RRE length \( \lambda_{REE} = 0.7 \times 10^{-10} \) m, which is in accord with the value measured with electric spin pumping experiments [26].

### 3.3.2 YIG/MoS\(_2\)

Several materials in the family of transition metal dichalcogenides (TMDs) [12–20] can also be used for spin–charge conversion [17, 37]. Due to their layered structure, the TMD can be easily prepared with one or several atomic layers as to tailor the transport properties. One important TMD material, molybdenum disulfide (MoS\(_2\)), has attracted widespread attention for a variety of next-generation electrical and optoelectronic device applications because of its unique properties [12–20]. For MoS\(_2\) it, was used the thickness \( t_{MoS_2} = 2.4 \times 10^{-9} \) m, the spin diffusion length \( \lambda_{MoS_2} = 2.35 \times 10^{-9} \) m [17, 37, 38] and the REMR, \( \Delta R^{(1)}_{2D}/R_{2D} = 3 \times 10^{-6} \). Hence, for YIG/MoS\(_2\) we obtain with Eq. (29) one RRE length of \( \lambda_{REE} = 0.13 \times 10^{-9} \) m, which is also in good agreement with value measured with electric spin pumping experiments [17]. In Fig. 4, it is shown the REMR \( \Delta R^{(1)}_{2D}/R_{2D} \) as a function of MoS\(_2\) RRE length \( \lambda_{REE} \) (nm). The point in red was measured in Ref. [38].

#### 3.3.3 Exchange field acting on the spin accumulation

One ferromagnetic material in atomic contact with 2D material generates a exchange field. The exchange-coupling is characterized here by \( H_{J}^{ex} = E_{J}^{ex} g_i/2e \), which was obtained using the Eqs. (5) and (6). The term \( E_{J}^{ex} \) is the exchange energy, which for the YIG/2DM interface is \( E_{J}^{ex} = 1.92 \pm 0.96 \times 10^{-20} \) J (or \( E_{J}^{ex} = 0.12 \pm 0.06 \) eV) [17, 37, 40–43]. For the YIG/SLG structure [22, 26, 37] with resistance of \( R_{2D} = 9 \times 10^3 \) \( \Omega \), the imaginary part of the spin-mixing interface conductance is of the order of \( g_i = 4.4 \times 10^8 \) m\(^{-1}\)T\(^{-1}\), thus the exchange field found was of \( H_{J}^{ex} = 2.64 \pm 1.32 \times 10^7 \) A/m (or \( \mu_0H_{J}^{ex} = 33.2 \pm 16.6 \) T). Already for the YIG/MoS\(_2\) structure [17, 37], the imaginary part of the spin-mixing interface conductance is of the order of


$g_i = 2.4 \times 10^7 \text{ m}^{-1}\Omega^{-1}$. In this case, the exchange field obtained was of $H_{2D}^{\text{Exc}} = 1.44 \pm 0.72 \times 10^6 \text{ A/m}$ (or $\mu_0H_{2D}^{\text{Exc}} = 1.8 \pm 0.9 \text{ T}$). The intensity of exchange field acting on the spin accumulation is of the order of exchange field due to the proximity effect obtained by others methods [41, 42].

4 Conclusion

In summary, we present a study that describes the Rashba–Edelstein magnetoresistance in 2D materials. The study was applied the measures of REMR makes at room temperature in single layer graphene and in the 2D semiconductor MoS$_2$ in contact with the ferromagnetic insulator yttrium iron garnet (YIG) measured by the modulated magnetoresistance technique. In the presented discussion, the change in the electrical resistance is reminiscent of the magnetoresistance despite the fact that 3D SOC is not responsible for the magnetoresistance in 2DM. Furthermore, the measured REE lengths for these two materials are in good agreement with the study, this is, which represents a good validation for the present analytical proposal, opening one new method to study the REMR. As far as we know, there is no theory in the literature that makes a comprehensive analysis of REMR in 2D Materials allowing obtaining experimental parameters. Thus, our work, in addition to allowing this, presents a concrete analysis of the exchange field acting on the spin accumulation.

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Author contributions

All authors contributed to the study conception and design.

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Conflict of interest All the authors declare that there is no conflict of interest.

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