Reliability of spin-to-charge conversion measurements in graphene-based lateral spin valves

C K Safeer, Franz Herling, Won Young Choi, Nerea Ontoso, Josep Inglà-Aynés, Luis E Hueso, and Felix Casanova

1 CIC nanoGUNE BRTA, 20018 Donostia-San Sebastian, Basque Country, Spain
2 Department of Physics, Clarendon Laboratory, University of Oxford, Oxford, United Kingdom
3 IKERBASQUE, Basque Foundation for Science, Bilbao, Basque Country, 48009, Spain
* Author to whom any correspondence should be addressed.
E-mail: f.casanova@nanogune.eu

Abstract

Understanding spin physics in graphene is crucial for developing future two-dimensional spintronic devices. Recent studies show that efficient spin-to-charge conversions (SCCs) via either the inverse spin Hall effect or the inverse Rashba–Edelstein effect (IREE) can be achieved in graphene by proximity with an adjacent spin–orbit coupling (SOC) material. Lateral spin valve devices, made up of a graphene Hall bar and ferromagnets, are best suited for such studies. Here, we report that signals mimicking the IREE can be measured in pristine graphene possessing negligible SOC, confirming that these signals are unrelated to SCC. We identify either the anomalous Hall effect in the ferromagnet or the ordinary Hall effect in graphene induced by stray fields as the possible sources of this artefact. By quantitatively comparing these options with finite-element-method simulations, we conclude the latter better explains our results. Our study deepens the understanding of SCC measurement schemes in graphene, which should be taken into account when designing future experiments.

1. Introduction

Graphene is an outstanding material for long-distance coherent spin transport [1-4] due to its weak intrinsic spin–orbit coupling (SOC) and negligible hyperfine interaction. For the same reason, it is not the preferred material for active spintronics device applications which require strong SOC. However, theoretical studies suggested that SOC can be induced in graphene via either proximity by combining it with materials possessing large SOC [5-12] or adatom decoration [13-16]. As a consequence, spin–orbit effects such as the direct or inverse spin Hall effect (SHE and ISHE) [17] and the Rashba–Edelstein effect (REE and IREE) [18] have been predicted theoretically [6, 7, 11, 13-16]. Experimentally, an efficient spin-to-charge conversion (SCC) due to ISHE was first unequivocally observed in graphene/MoS$_2$ van der Waals heterostructures [19]. Later, SCC was reported in different systems of graphene combined with other transition metal dichalcogenides [21-25], layered topological insulators [26] or insulating bismuth oxide (Bi$_2$O$_3$) [27].

In all the SCC studies in graphene published so far [19-27], a graphene-based lateral spin valve (LSV) device has been used for the measurements. Graphene-based LSVs have also been used to measure SCC in other SOC materials [20, 27-30, 35, 36]. The basic measurement layout is shown in figures 1(c)-(h): an electrical current injected across a ferromagnet/graphene interface creates a spin accumulation which then diffuses as a spin current towards the proximitized graphene region. There, SCC leads to the creation of a transverse charge current, thus a corresponding non-local output voltage ($V_{NL}$) is measured across the graphene/SOC material Hall bar. The two SCC mechanisms in proximitized graphene [19], ISHE and IREE result in the conversion of out-of-plane (figure 1(a)) and in-plane spins (figure 1(b)), respectively. They can be differentiated by performing

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Figure 1. (a) Schematic diagram of the REE in proximitized graphene. The green region represents graphene proximitized with an adjacent SOC material (not shown). An electrical current applied along $y$ creates a spin accumulation with polarization along $x$ at the proximitized region which then diffuses in the graphene channel. (b) Schematic diagram of the SHE in proximitized graphene. An electrical current applied along $y$ creates a spin current diffusing along $x$ with spin polarization along $z$. (c) SCC measurement scheme. The spins are injected by applying a current between the ferromagnet and graphene and SCC is measured by probing $V_{\text{NL}}$ across the graphene Hall bar. $V_{\text{NL}}$ is due to spin precession in the $y-z$ plane if the magnetic field is applied along the $x$-axis ($B_x$) and (d) in the $x-y$ plane if the magnetic field is applied along the $z$-axis ($B_z$). (e) The expected antisymmetric Hanle spin precession curves for the cases explained in panels (c) and (d). The red and blue curve corresponds to the initial magnetization of the ferromagnetic electrode set along $+y$ axis and $-y$ axis, respectively. (f) SCC due to the variation of the spin polarization via pulling the magnetization of the ferromagnetic electrodes with the magnetic field applied along $x$-axis ($B_x$) and (g) $z$-axis ($B_z$). (h) The expected $V_{\text{NL}}$ vs $B$ curve for the cases explained in panels (e) and (f). The red and blue curve corresponds to the initial magnetization of the ferromagnetic electrode set along $+y$ axis and $-y$ axis, respectively.

The SCC measurements in the presence of an in-plane ($B_x$) or out-of-plane ($B_z$) magnetic field as shown in figures 1(c)–(h). Initially, the magnetization of the ferromagnet and therefore the polarization of the injected spins are aligned along its easy axis ($y$). Then, a magnetic field $B_x$ ($B_z$) is applied along the hard axis and causes a change in the polarization of the spins arriving at the Hall bar region in two ways. Firstly, at low magnetic fields, the spins precess in the $y-z$ ($y-x$) plane during their diffusion [31, 32] in the graphene channel as shown in figures 1(c) and (d). Hence, the polarization of the spins arriving at the Hall bar region rotates, giving rise to oscillations in $V_{\text{NL}}$. Because the converted spins are perpendicular to the injected ones, $V_{\text{NL}}$ becomes an asymmetric Hanle spin precession curve vs $B_x$ ($B_z$) as shown in figure 1(e). This Hanle precession curve reverses its sign if the initial easy axis magnetization of the ferromagnet is reversed. Secondly, as the magnetic field gets stronger, the magnetization of the ferromagnetic electrode gets pulled and subsequently saturated towards the hard axis, correspondingly changing the polarization of the injected spins. $B_x$ and $B_z$ tilt the injected spins along the $x$ (figure 1(f)) and $z$ axis (figure 1(g)), respectively, resulting in an S-shaped $V_{\text{NL}}$ vs $B$ curve as schematically shown in figure 1(h). This curve is independent of the initial orientation of the ferromagnet along the easy axis (as seen for the superposed red and blue curves). In summary, if an in-plane SCC is observed obtaining an S-shaped $V_{\text{NL}}$ vs $B_x$ curve due to contact pulling (figure 1(f)) or/and an antisymmetric Hanle spin precession (figure 1(d)) $V_{\text{NL}}$ vs $B_z$ curve, the SCC mechanism is considered to be IREE in proximitized graphene [21–23]. It is also worth noting that SCC can also occur via ISHE in the SOC material on top of graphene, which also results in in-plane SCC [19, 20, 28, 29, 33–36], making it hard to distinguish from IREE in graphene. However, if an out-of-plane SCC is measured by obtaining an antisymmetric Hanle
V_{NL} \text{ vs } B_x \text{ curve (figure 1(c))} \text{ or/and an S-shaped } 
V_{NL} \text{ vs } B_y \text{ curve (figure 1(g))}, the SCC is reported to be 
due to ISHE in proximitized graphene \cite{[19, 21, 22, 24, 27]}.

In this article, we report that an S-shaped \( V_{NL} \text{ vs } B \) 
curve can be obtained both in pristine graphene as well as
in graphene combined with a high-SOC material (Bi\(_2\)O\(_3\)). Therefore, this observation is unrelat-
ed to SCC in graphene arising from any SOC phe-
nomenon, and, most likely, due to measurement arte-
facts related to the variation of the magnetization of
the ferromagnet. We conclude that the only unam-
biguous method to measure SCC using graphene-
based LSVs is the spin precession measurement.

2. Device fabrication

Figure 2(a) shows the scanning electron microscope
image of the used device. At first, a bilayer graphene
(BLG) flake was exfoliated onto a highly doped Si sub-
strate covered with SiO\(_2\). The number of layers was
identified according to the optical contrast and the
Raman spectrum \cite{[37]} (see supplementary informa-
tion S1 (available online at stacks.iop.org/2DM/9/
015024/media)). Then, using electron-beam litho-
graphy and reactive ion etching, the graphene flake
was shaped into a Hall bar with three crosses.
Subsequently, using electron-beam lithography fol-
lowed by thermal and electron-beam evaporation, Cr
(5 nm)/Au (40 nm) contacts were connected to the
graphene Hall bar. Using similar steps, Bi\(_2\)O\(_3\) (5 nm)
was deposited in the middle of two Hall bars and sev-
eral TiO\(_2)/Co (35 nm) ferromagnetic electrodes were
placed on top of the graphene channel to create LSVs.
TiO\(_2\) (w0.3 nm) barriers were used to ensure efficient
spin injection into graphene \cite{[38]}. The widths of
the ferromagnetic electrodes are alternating (\~{}450
and \~{}300 nm) so that they have different coercive fields
due to different shape anisotropy, enabling parallel
and antiparallel configurations by applying a mag-
netic field along their easy axis.

In the manuscript, we focus on the measurements
performed at \( T = 50 \text{ K} \). Room temperature meas-
urements are shown in supplementary information
S4. To verify the reproducibility of our results, sim-
ilar measurements were performed in the left side
(figure 2(a)) of the same device (Device 1, supple-
mentary information S5) and on additional devices
(Device 2 and 3, supplementary information S6 and
S7 respectively).

3. Results

3.1. Spin transport measurements

In the first step, the spin transport parameters of
the pristine graphene were extracted. For this, the
typical Hanle spin precession measurement using a
conventional four-terminal non-local geometry \cite{[1]}
was performed. An electrical current (\( I_c \)) of 10 \( \mu \text{A} \)
was applied between the Co electrode 4 and Au elec-
trode E and the non-local voltage (\( V_{NL} \)) was mea-
sured between Co electrode 3 and Au electrode A,
from which the corresponding non-local resistance
(\( R_{NL} = \frac{V_{NL}}{I_c} \)) was calculated. Initially, the magnetiz-
ations of the ferromagnets were set to the paral-
lel and antiparallel configurations by applying \( B_y \).
Then, for each initial state, \( B_y \) was swept from 0
to 0.6 T and 0 to \~{}0.6 T and the corresponding
variations in \( R_{NL} \) (\( R_{NL}^0 \) and \( R_{NL}^P \)) were obtained as
shown in figure 2(b). Subsequently, the contribu-
tions to \( R_{NL} \) due to pure spin precession (supple-
mentary information S10, figure S10(a)) and the rotation
angle of the Co magnetization (figure 2(c)) were dis-
entangled as explained in \cite{[19]}. The pure spin preces-
sion curve was then fitted using the solutions of the
Bloch equation \cite{[19, 39]}, obtaining the spin lifetime of
graphene (\( \tau_E \)) \~{}92 \pm 10 \text{ ps}, the spin diffusion con-
stant of graphene (\( D_E \)) \~{}(10.1 \pm 1) \times 10^{-2} \text{ m}^2\text{ s}^{-1},
and the spin polarization at the Co/graphene inter-
face (\( P \)) \~{}4.4 \pm 0.1\%. The details of the fitting are
explained in supplementary information S10. A simi-
lar measurement and analysis were performed using the
LSV made up of Co electrodes 2 and 3 (figure 2(a))
where the graphene channel consists of the Hall bar
region with Bi\(_2\)O\(_3\) deposited in the middle, which is
also explained in supplementary information S10.

3.2. Non-local measurements using SCC geometry

After confirming an efficient spin transport in our
device, we performed SCC measurements in the
graphene/Bi\(_2\)O\(_3\) region. For this, \( I_c \) was applied
between Co electrode 2 and Au electrode A and
\( V_{NL} \) was measured using Au electrodes C and D across
the graphene/Bi\(_2\)O\(_3\) Hall bar (figure 2(a)). As plot-
ted in figure 3(a), an S-shaped \( R_{NL} \text{ vs } B_x \) curve was
obtained. This measurement may indicate SCC of in-
plane spins (see figures 1(f) and (h)), hence the pos-
sibility of IREE in graphene/Bi\(_2\)O\(_3\). Since our previous
study shows that ISHE can occur in graphene/Bi\(_2\)O\(_3\)
due to proximity-induced SOC \cite{[27]}, obtaining IREE
in the same system is a plausible scenario. To further
investigate this option, we performed a control exper-
iment across the pristine graphene region by apply-
ing \( I_c \) between Co electrode 2 and Au electrode E
while \( V_{NL} \) was measured using Au electrodes A and
B. Interestingly, as shown in figure 3(b), we again
observe the S-shaped \( R_{NL} \text{ vs } B_x \) curve, saturating at
the same field values, but with an amplitude even
larger than that of the graphene/Bi\(_2\)O\(_3\) region. Since
pristine graphene possesses negligible SOC, we con-
clude that the measured signal must have a different
origin, unrelated to SCC.

Even though we can conclude that the signal
observed across pristine graphene is not related
to SCC, the \( R_{NL} \text{ vs } B_x \) curve obtained across the
graphene/Bi\(_2\)O\(_3\) region can still be due to either arte-
facts alone or a mixture including SCC by IREE. An
easy way to test the possibility of in-plane SCC by
Figure 2. (a) False coloured scanning electron microscope image of the graphene LSV device measured. The Cr/Au electrodes, TiO$_x$/Co electrodes, and Bi$_2$O$_3$ regions are highlighted in yellow, purple, and green, respectively. The measurements were performed in the device region highlighted by the dashed box. (b) Symmetric Hanle curves measured at 50 K and $V_g = 10$ V for initial parallel (blue curve) and antiparallel (red curve) states of the two ferromagnets across the pristine graphene region, using electrical configuration $V_{3A}I_{4E}$. (c) $\beta$, the angle between the magnetization and its easy axis ($y$), as a function of $B_x$ extracted from the measurement in panel b. The details of the analysis are explained in the supplementary information S10.

IREE is to induce spin precession by applying $B_z$ (figure 1(d)) in which an antisymmetric Hanle curve (figure 1(e)) is expected. Since the spin precession occurs in the graphene channel and is separated from the variation of the Co magnetization, any artefact arising from the ferromagnet can be avoided and only pure spin-related phenomena will be detected. The amplitudes of the signals in figures 3(a) and (b) are in the order of mT and, if they arise from SCC, a similar or smaller amplitude is expected for the spin precession signal. However, as shown in figures 3(c) and (d), a large and linear $R_{NL}$ vs $B_z$ signal (in the order of $\Omega$s) was observed, which most likely hinders detection of any spin precession signal. It is well known that, even in non-local geometries, a small spurious current can diffuse from the injector acquiring a $y$-component in the graphene channel [40]. The linear signal observed here is most likely the spurious current-induced ordinary Hall effect (OHE) in graphene in the presence of $B_z$. Due to the large OHE in graphene [41], a small spurious current can create a local voltage large enough to dominate over the non-local SCC voltage. Since such small charge current spreading is unavoidable, we conclude that it is not possible to detect spin precession using $B_z$ in our samples. However, the spin precession using $B_z$ would be measurable [20, 22, 35, 36] by minimizing the spurious current effects in different ways: Firstly, optimizing the graphene/oxide/ferromagnet tunnel barrier to increase spin injection while lowering the spurious current injection by improving homogeneity, which is generally achieved at larger interface resistance ($\sim k\Omega$s) [4, 42]. Secondly, fabricating a LSV device with a narrower graphene channel width and longer distance between the Co electrode and the Hall bar. Since this also reduces the spin current reaching the detector, a compromise for the device dimensions has to be found to obtain a detectable output signal. Using graphene with better spin transport properties for example through encapsulation will make this easier. Thirdly, the design can also incorporate the recently proposed [26] LSV with an orthogonal graphene channel. Here, the in-plane spin precession can be measured by applying $B_x$ instead of $B_z$ so that the $B_z$-induced spurious effects can be minimized.

To further verify our results, the same measurements as those in figures 2 and 3 were performed in a different part of Device 1, in Device 2 and in Device 3 (see supplementary information S5–S7). We obtained similar $R_{NL}$ vs $B_x$ and $R_{NL}$ vs $B_z$ curves, confirming the reproducibility of our results. Since Device 3 was made of monolayer graphene Hall bar,
we also conclude that the spurious effect is qualitatively independent of the number of graphene layers.

4. Discussion

The $R_{NL}$ vs $B_z$ curve in figure 3(d) does not show any saturation behaviour, while $R_{NL}$ vs $B_x$ in figure 3(b) saturates at $\pm 1500$ Oe, the same value at which the magnetization of the Co electrode saturates (figure 2(c)). This indicates that the shape of the $R_{NL}$ vs $B_x$ curve is directly related to the variation of the Co magnetization. To further confirm this, we fabricated another device (supplementary information S8) with Co and Au electrodes placed at the right and left side of the graphene Hall bar, respectively. As shown in figure 4(a), the S-shaped $R_{NL}$ vs $B_x$ curve was only obtained when the Co electrode was used as the injector, but not for the Au electrode, further confirming the dependency on the Co magnetization variation.

As reported previously [21–23, 25, 26, 43], a possible mechanism explaining our results is the stray field-induced OHE in graphene. An out-of-plane magnetic field applied to graphene can cause OHE. As the Co magnetization tilts and saturates towards the $x$ direction, an out-of-plane stray field generated at the edges of the Co electrode through the graphene channel linearly increases and saturates. In combination with a small spurious current from the ferromagnetic injector this could lead to OHE in graphene resulting in a linearly varying and saturating $R_{NL}$ vs $B_x$ curve as we observed in figures 3(a) and (b).

A control experiment to check the above-mentioned possibility is to perform gate voltage ($V_g$)-dependent measurements. For the hole and electron-doped regimes in graphene, which can be obtained by applying $V_g$, opposite signs for the OHE are expected and a corresponding sign change is also expected for the $R_{NL}$ vs $B_x$ curve. To verify this possibility, we performed different measurements as a function of $V_g$ as shown in figures 4(b)–(d). At first, using a four-probe configuration ($V_{34}/I_{AE}$), the sheet resistance of graphene was measured as a function of $V_g$ (figure 4(b)). The charge neutrality point was observed at $V_g \sim +5$ V, confirming hole and electron carriers dominate transport in the channel for $V_g < +5$ V and $V_g > +5$ V, respectively. Then, the Hall resistance ($R_{HALL}$) as a function of $B_x$ was obtained at different $V_g$ (figure 4(c)) by applying the current along the graphene channel (contacts 1 and E) and measuring the voltage across the Hall bar (contacts A and B). A linearly varying $R_{HALL}$ vs $B_x$ was observed with opposite slopes for electron and hole-doped regimes. The OHE here should be caused by a $B_z$ field.
component originated from a small out-of-plane tilt between the sample and \( B_x \). After confirming the sign reversal of the OHE, we then performed \( R_{\text{NL}} \) vs \( B_x \) measurements at different \( V_g \) (figure 4(d)). Interestingly, unlike the previous reports, we did not observe any sign reversal. A similar \( V_g \)-dependent measurement was also obtained across the graphene/Bi\(_2\)O\(_3\) Hall bar region as shown in supplementary information S3. It is important to note that these measurements further confirm the absence of IREE, as such a SCC signal is also expected to change sign for the two regimes [21–23, 25, 26].

Two different hypotheses can explain the gate dependent studies mentioned above. Firstly, the origin of the artefact cannot be OHE at the graphene Hall bar. However, if the OHE is from the graphene region near the Co electrode where the stray field is maximum and has a different doping compared to the Hall bar region, the carrier type will be unchanged with the applied gate voltages. To experimentally check whether this is the case, we fabricated a graphene Hall bar device with Co deposited on the Hall cross as explained in supplementary information S8. The transfer curve of the pristine graphene region showed the charge neutrality point at \( V_g \sim +4 \) V (figure S9(b)). However, the Hall measurement in the graphene/Co region did not change sign for \(-10 \text{ V} \leq V_g \leq +10 \text{ V}\) (figure S9(c)) confirming the carrier type is unchanged. Secondly, due to the anomalous Hall effect (AHE) in the ferromagnetic Co electrode, a voltage along the in-plane \( y \) direction can build up in Co with magnetization along \( x \) [44], when a current is applied along \( z \). If the adjacent graphene Hall bar probes this voltage, an S-shaped \( R_{\text{NL}} \) vs \( B_x \) curve could be obtained. Importantly, the sign of AHE is expected to be independent of \( V_g \), explaining our gate measurements shown in figure 4(d).

To quantitatively understand the contributions to the output signal from those two effects, we performed 3D finite element method simulation using COMSOL Multiphysics (the details of the simulation are explained in supplementary information S11) as shown in figure 5. For both calculations, the experimentally measured Co (50 \( \mu \Omega \text{ cm} \)) and graphene (162 \( \mu \Omega \text{ cm} \)) resistivities have been used. Considering the saturation magnetization of the Co electrode (\(1.4 \times 10^6 \text{ A m}^{-1}\)) [45], the \( z \)-component of its stray field is obtained. The stray field is maximum near the ferromagnetic edge and negligible at the Hall bar region. Then, the OHE for an electron concentration in graphene of 3.6 \( \times \) 10\(^{11}\) cm\(^{-2}\) was calculated. This OHE affects the electric potential profile of the Hall bar (detector) causing a voltage difference measured across the Hall bar (figure 5(a)). Due to the complexity in the calculations, the minimum thickness of graphene that can be used here is limited to 8 nm. By plotting the nonlocal signal as a function of graphene thickness at a detector distance of 600 nm (the same detector distance used for the experiment with the device shown in figure 2(a)) and extrapolating the linear plot to the thickness of BLG (0.8 nm), a nonlocal signal of \(\sim 65 \text{ m} \Omega\) was obtained (figure 5(c)).

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**Figure 4.** (a) \( R_{\text{NL}} \) vs \( B_x \) measurements using Co and Au injectors obtained using the device explained in supplementary information figure S8(a). The S-shaped behaviour was obtained only when the ferromagnetic injector was used. (b) Sheet resistance of graphene (\( R_{\text{Gr}}^{\text{sheet}} \)) as a function of \( V_g \) measured using four-probe electrical configuration \( V_{\text{d}1}V_{\text{d}2} \). (c) The \( R_{\text{NL}} \) vs \( B_x \) measurements using electrical configuration \( V_{\text{d}1}V_{\text{d}2} \) for different \( V_g \). The \( R_{\text{NL}} \) vs \( B_x \) measurements across the pristine graphene region, (d) for different \( V_g \) from \(-20 \) to \(20 \text{ V} \) at \( I_c = 10 \mu \text{A} \), (e) for \( I_c = 1, 2, 5, 10, 20 \mu \text{A} \) at \( V_g = -10 \text{ V} \), (f) in the SCC and charge-to-spin conversion geometries using electrical configuration \( V_{\text{d}1}V_{\text{d}2} \) and \( V_{\text{d}1}V_{\text{d}2} \), respectively. All measurements are taken at 50 K.
Figure 5. The electric potential profiles obtained from 3D finite element method simulations due to (a) stray-field-induced OHE for 8 nm thick graphene, where a transparent ferromagnet/graphene interface has been considered, and (b) AHE in the ferromagnetic electrode where pinholes indicated by red arrows and an insulating TiO$_x$ barrier are considered. The current of 10 µA is applied to the lower end of the Co electrode and flows to the right end of the graphene channel (green arrow) while the voltage is measured across the Hall probes. The voltage drop following the current line is set out of range to highlight the electric potential profile at the non-local region. Further details of the simulations are explained in supplementary information S11. (c) Amplitude of the OHE, measured at 600 nm from the ferromagnet edge, as a function of the graphene thickness. Since the simulation is limited to 8 nm of graphene, the linear plot is extrapolated to 0.8 nm, which is assumed to be the thickness of BLG. (d) Amplitude of the AHE- (blue) and OHE-induced (red) non-local resistances as a function of distance between the detector (centre of the Hall bar) and the edge of the ferromagnet.

This signal value is in the same order of magnitude as the experimental one. AHE also affects the electric potential as shown in figure 5(b). Here, an anomalous Hall angle of 1% \[46\] has been used for the calculation. As shown in figure 5(d), the signals for both cases decrease as the distances between the detector and the edge of the ferromagnet increase. Also, the contribution from the AHE is very small (~1 mΩ) compared to that from the OHE. Therefore, we conclude the source artefact contributing to the non-local measurement should be OHE, while a small contribution from the AHE may still exist.

Finally, we performed two experiments usually taken as evidence for SCC in these systems. Firstly, to check the dependence on the strength of the electrical current, $R_{\text{NL}}$ vs $B_z$ was measured for $I_C = 1, 2, 5, 10, 20$ µA (figure 4(e)). It shows a linear response, i.e. the amplitude of $R_{\text{NL}}$ is independent of the applied current. The linear response also leads to Onsager reciprocity as shown in figure 4(f), which was measured by exchanging the current and voltage terminals. These two features were also reported to appear for SCC due to IREE \[20–23, 25, 26, 28, 29, 35, 36\]. Since the artefacts caused by the spurious current, originating from OHE or AHE, have a linear response and therefore fulfill Onsager reciprocity, such measurements should not be used as confirmation of SCC in graphene LSV devices.

In summary, we performed SCC-like measurements in graphene and in graphene proximitized with a SOC material. An S-shaped $R_{\text{NL}}$ vs $B_z$ signal mimicking the previously reported SCC signal due to IREE was observed in pristine graphene where, due to the low SOC, any SCC mechanism should be negligible. Therefore, we conclude our signal is due to non-SCC-related artefacts. By performing gate-dependent measurements, we conclude that two scenarios can explain our observation: the OHE in the graphene region near the ferromagnetic electrode or the AHE in the ferromagnet itself. The quantification of these scenarios with 3D simulations indicates that our result can be explained by considering only OHE. Finally, we would like to point out that extreme care should be taken while using the S-shaped $R_{\text{NL}}$ vs $B_z$ measurements for the quantitative and qualitative interpretation of SCC using graphene-based LSVs. Only spin precession measurement should be used for unambiguous SCC claims. As in our $R_{\text{NL}}$ vs $B_z$ measurements, it might be impossible to perform spin precession if the signal due to spin-unrelated effects dominates over the SCC signal. In this case, additional efforts to minimize artefacts by carefully designing
the dimensions of the graphene channel and electrodes [20, 22, 35, 36], the ferromagnet/graphene interface to reduce the spurious current, or adapting the recently reported new geometrical design for the graphene-based LSVs [26] will be required.

Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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ORCID iDs

C K Safeer https://orcid.org/0000-0003-2396-9730
Franz Herling https://orcid.org/0000-0002-4304-8173
Josep Inglá-Aynés https://orcid.org/0000-0001-9179-1570
Luis E Hueso https://orcid.org/0000-0002-7918-8047
Félix Casanova https://orcid.org/0000-0003-0316-2163

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