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Graphene, an Ideal Material for Spintronics?

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1. Introduction

Present day electronics is based on the charge degree of freedom, whereby the flow and storage of charge carriers is used for information processing. The emergence of spintronics offers a step forward with the usage of the spin degree of freedom. The introduction of new materials into electronic devices with enhanced spin functionality opens the door for faster, energy-efficient and reconfigurable electronics. Graphene, a one-atom-thick layer of carbon, has risen as an attractive material system for the transport of both charge and spin currents with the potential to realize this vision of future spintronic technology. Therefore it is paramount to understand the mechanisms currently limiting spin transport in graphene-based devices and to develop new spintronic architectures that take advantage of its excellent transport properties, such as high electronic mobility or ambipolar electric field effect. Here we present recent results addressing the fundamental questions mentioned above regarding the suitability of graphene as an ideal material to realize spintronic devices.

2. General objectives

Our main goal is to understand spin transport in graphene-based mesoscopic devices, specifically field-effect transistors where both electron and hole regimes are attainable. In our devices spin transport occurs mainly via diffusion, where the fundamental parameters to be studied are the spin relaxation time τ_S (which describes the rate at which spin information is lost within graphene) and the spin relaxation length λ_S (which describes how long does the spin information travels before it is lost). These two parameters determine the time and length scales available for the development of future spintronic devices and therefore need to be quantified. Furthermore, we explore how the semimetallic nature of graphene, with properties intermediate to those of metals and semiconductors, can lead to new spintronic architectures.

3. Method of approach

We study pure spin currents in graphene by separating charge transport from spin transport. To achieve this we use a nonlocal measurement technique, where the spin detection takes place in a part of the circuit different from that where the charge current is present. Magnetic electrodes with thin oxide tunnel barriers are used for electrical spin injection into graphene or for detection of nonlocal spin accumulation. By applying an in-plane magnetic field the magnetizations of the injector and detector electrodes are aligned parallel or antiparallel, resulting in distinct nonlocal signals or the so called spin-valve effect. This technique allows to unambiguously identify spin transport [1].

To quantify the spin transport parameters we apply an out-of-plane magnetic field, which causes the injected spins to rotate leading to the appearance of Hanle precession curves. The resulting nonlocal spin accumulation in graphene μ_S can then be described with the Bloch eq. (1),

$$D_S \nabla^2 \mu_S - \frac{\mu_S}{\tau_S} + \gamma(B \times \mu_S) = 0 \qquad (1)$$

where D_S is the spin diffusion coefficient, τ_S the spin relaxation time mentioned before, B the applied magnetic field and γ the gyromagnetic ratio. Finally, the spin relaxation length can be obtained as $\lambda_S = \sqrt{(D_S \tau_S)}$.

4. Significant results

Since the first demonstration of spin transport in graphene [1] it was realized that the spin parameters, although already showing remarkable values at room temperature, where much lower than expected by theory and where limited by extrinsic factors. Given the two-dimensional nature of graphene, these extrinsic factors can be traced back to the strong effect of interactions with the supporting substrate, usually SiO_2, or with impurities at the graphene surface. Therefore, we have taken steps towards exploring the intrinsic properties by fabricating spintronic devices featuring suspended graphene bridges, as shown in Fig. 1.

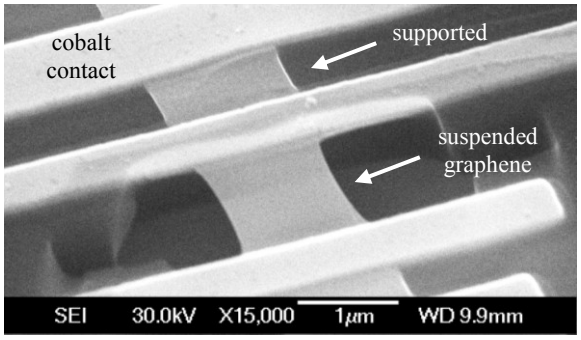

Fig. 1 Scanning electron micrograph of a spintronic device featuring both high-quality suspended graphene and supported graphene regions contacted by ferromagnetic cobalt electrodes [2].

The suspended graphene regions do not interact with the substrate and exhibit high quality transport, with electronic mobilities above 100 000 $cm^2/(V\ s)$. From Hanle precession experiments we extracted large spin diffusion coefficients D_S which lead to large spin relaxation lengths of 5 µm. By comparison of the extracted spin transport parameters to those from standard suspended samples, we conclude that current experiments are limited by extrinsic effects from the substrate and we were able to give a higher bound for the intrinsic spin-orbit coupling in graphene [2].

An alternative approach is to modify the graphene surface by placing adatoms which introduce localized electronic states and increase the spin-orbit coupling in graphene. We have realized this by including hydrogen adsorbates in graphene via plasma hydrogenation. After this modification we observe strong changes in the Hanle precession experiments which indicate an enhancement of the spin relaxation time τ_S [3]. This observation yields experimental input to current theories addressing the nature of spin relaxation in graphene.

For graphene to serve as an ideal material for spintronics we must go beyond standard devices and develop novel architectures that exploit its unique electronic properties. One example is its linear electronic dispersion, with a conductivity strongly dependent on energy, and a Fermi energy which is fully tunable from hole to electron regimes via the electric-field effect.

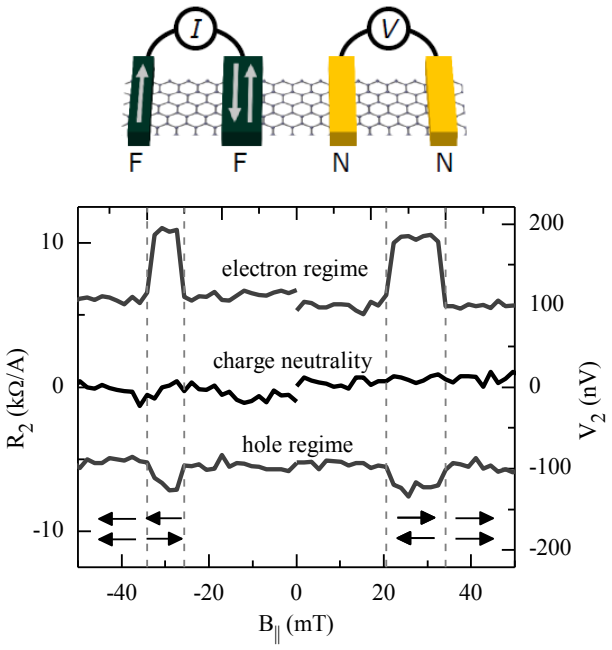

Fig. 2 Detection of pure spin currents in graphene by using nonmagnetic (N) contacts, made possible by a nonlinear interaction between spin and charge currents in graphene. We observe a nonlinear spin-valve effect, when aligning parallel (↑↑) or antiparallel (↑↓) the ferromagnetic (F) injectors. The effect shows a sign reversal when going from the electron to the hole regime [4].

This tunability is ideal for exploring novel energy-dependent spintronic effects, such as the nonlinear conversion of spin currents to charge signals depicted in Fig. 2. The ability to create large spin accumulations in graphene, together with the energy-dependent transport, leads to nonlinear spintronic phenomena in graphene. These nonlinear effects can be used for detecting spin currents even with nonmagnetic detectors, or for manipulating spin accumulations with charge currents [4]. Such mechanisms allow new device architectures which are generally applicable to the field of semiconductor spintronics.

3. Conclusions

We have presented fundamental studies on spin transport in graphene. We make use of its two-dimensional nature, where its interaction with the substrate or surface impurities determine its transport properties, by either removing the substrate altogether achieving high-quality graphene or by modifying its surface with adatoms. The resulting changes in spin transport parameters allow us to better understand the mechanisms controlling the flow of spin information in graphene. This understanding, together with novel device architectures made possible due to nonlinear spintronic effects, offer bright prospects for using graphene as an ideal platform for developing spintronic technologies.

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