ConceptGraphene

New Electronics Concept: Wafer-Scale Epitaxial Graphene

Small or medium-scale focused research project

WP4 Spin transport devices

Deliverable 4.1 “Report on spin transport in graphene on SiC”

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Nature of deliverable: R = Report

Dissemination level: PU = Public

Due date of deliverable: M18

Actual submission date: M18

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Deliverable Summary

Deliverable 4.1 “Report on spin transport in graphene on SiC”

In this deliverable we report successful spin injection and transport through epitaxial graphene on silicon carbide. We performed spin valve and spin Hanle precession measurements to extract spin transport properties. We report a high spin relaxation time of 1.3 ns at room temperature up to 2.3 ns at 4 Kelvin. From our Hanle precession measurements we obtained a low spin diffusion coefficient when compared to the diffusion coefficient obtained from electronic (Hall) measurements.

The measured difference can be explained with the use of a model, introducing localized states in the vicinity of the graphene transport channel. The details of the model will be presented in D4.3 about spin transport.

The experimental research on spin transport in epitaxial graphene described in this report has been performed by the Groningen node of the consortium. The epitaxial graphene samples have been provided by the Linköping and Erlangen nodes.

1. **Introduction**

Since 2007 the Groningen group has successfully pioneered experimental work on spin transport in exfoliated graphene. Graphene is a promising material for spintronic devices, such as spin transistors or spin qubits, due to its high spin relaxation lengths of ~2 μm at room temperature [1]. We are interested in spin transport properties such as the spin relaxation length, the spin relaxation time and the spin diffusion coefficient. Also we study the fundamental nature of spin relaxation mechanisms. So far, the commonly used SiO_2 substrate for exfoliated graphene flakes seems to limit charge carrier mobility and thereby presumably spin lifetimes. Changing to epitaxial graphene gives us the opportunity to study the effect of the SiC substrate and the buffer layer on spin transport, and compare these results with previous results obtained on exfoliated graphene. Furthermore it clears the way for graphene based spintronic devices and applications in the future where the large area of epitaxial graphene can be taken advantage of.

2. Investigation of spin transport mechanisms in epitaxial graphene

We developed a method to fabricate non-local lateral spin valve devices of epitaxial graphene on SiC. These devices are used to investigate spin transport properties of the material. Using the non-local spin valve we can experimentally determine the spin relaxation time τ_S, spin diffusion coefficient D_S and spin relaxation length λ_S [1].

2.1 Sample fabrication

In figure 1a and 1b we show a non-local spin valve device, which separates current path and voltage measurements to exclude any charge related signals [2],[3]. The spin valve consists of a narrow graphene strip, in this case with a width of 1 μm. Initially the whole chip is covered with graphene. To define a strip we use standard electron beam lithography (EBL) techniques and a negative tone resist (Ma-N), after which the rest of the graphene is etched away using O_2 reactive ion etching. The graphene strip is then cleaned in argon/hydrogen atmosphere to remove any polymer remains. After this a 0.8 nm layer of aluminum (Al) is evaporated on the sample and then oxidized in air. This creates an aluminum oxide (AlOx) tunnel barrier, which is essential to avoid the impedance mismatch between graphene and ferromagnetic contacts. In the final step, the 45 nm thick Cobalt (Co) contacts are defined using EBL techniques and a positive resist.

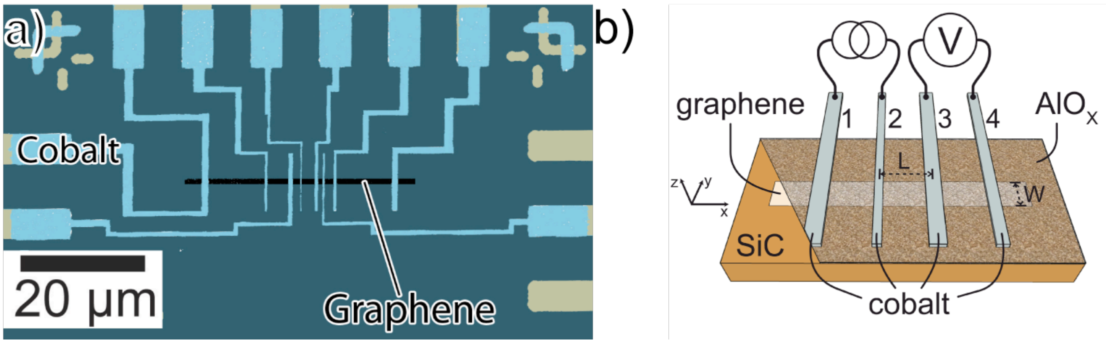

figure 1: a) Colored SEM image of an epitaxial graphene on SiC spin valve device. b) Non-local spin valve schematics. Contact 2 is called the injector and contact 3 the detector.

2.2 Spin transport measurements

The measurement scheme for the nonlocal geometry is presented in figure 1a. A spin polarized current *I* is sent from contact 2 (the injector) to contact 1, generating a spin accumulation at contact 2 that diffuses in positive and negative *x*-direction. The AlO_x barrier separates the MLEG from the Co contacts and avoids reabsorption of the injected spins in the higher conducting cobalt. The exponential decaying spin accumulation generates a nonlocal voltage V_{nl} between the spin sensitive contact 3 (the detector) and contact 4, which can be measured as a function of the magnetic field. In a spin valve measurement, the magnetic field B_y, aligned with the contacts, is first used to bring the magnetization of the electrodes into a parallel configuration and is then ramped in the opposite direction. When the magnetization of one of the electrodes is switched, the measured voltage shows an abrupt change. The magnetic switching fields of the contacts are different due to different coercive fields that are achieved by different width of the contacts [3].

In figure 2a we show a spin valve measurement at room temperature and at 4K. We measure V_{nl} and then normalize with the injected current to get the non-local resistance R_{nl}. As we sweep the magnetic field one of the Co electrodes switches its magnetization direction, resulting in an anti-parallel configuration of the detector and injector. At this particular B-field we see an abrupt change in R_{nl}. As we further sweep the magnetic field, also the other contact switches and the configuration of injector and detector is again parallel, resulting in the original value for R_{nl}. This measurement is a direct proof that we are able to inject, transport and detect spins in the epitaxial graphene device.

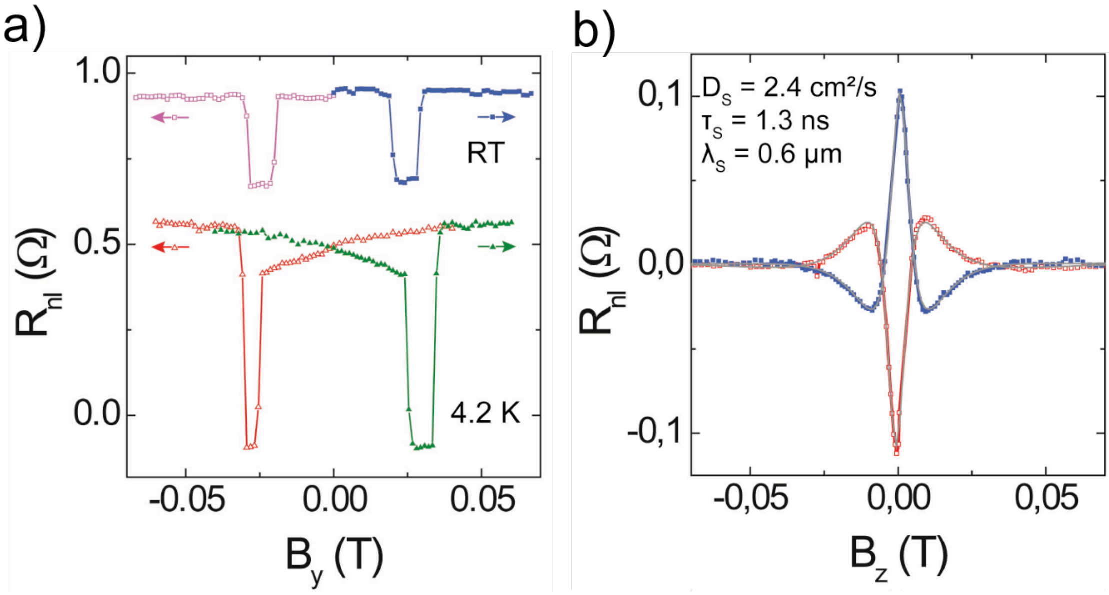

figure 2: a) Spin valve measurement at RT and 4K. At 4K we see that the spin valve effect is more pronounced. b) Hanle precession measurement (points) and fit (line) for parallel (blue) and anti-parallel (red) configuration.

By applying a perpendicular magnetic field B_Z while measuring the non-local voltage, we obtain the spin Hanle precession curve. The spin dynamics in the device are described by to Bloch equation:

$$0 = D\nabla^2\vec{s} - \frac{\vec{s}}{\tau_S} + \vec{\omega_L} \times \vec{s}$$

We determine τ_S, D_S and $\lambda_S = \sqrt{(\tau_S D_S)}$ by fitting these measurements with the Bloch equation, which describes diffusion, relaxation and precession in the material. In figure 2b we show such a Hanle measurement and its fit.

2.3 Results

We fabricated Hall-bars and top gated electronic devices with an AlOx dielectric, to measure electronic properties of epitaxial graphene. We estimated graphene charge carrier mobility μ and charge diffusion coefficient D_C and found comparable results to measurements performed in the Linköping and Erlangen groups, with μ of~1,900 cm^2/Vs and D_C of ~190 cm^2/s. In different devices we also measured spin transport properties of epitaxial graphene, with room temperature values of τ_S = 1.3 ns, D_S = 2.4 cm^2/s and λ_S = 0.6 μm. We measured the highest reported τ_S (up to 2.3 ns at 4 Kelvin) in single layer graphene so far, though we measure a very low D_S of 4 cm^2/s .

In the above results it is striking that the diffusion coefficient obtained by Hall measurements is a factor of 50-80 higher than the diffusion coefficient obtained by spin transport measurements. We will address this issue further on.

We published our results on spin transport in epitaxial graphene on SiC in Nanoletters in February 2012 [4]. The publication was the first report on spin transport in epitaxial graphene on SiC and also the first publication on spin transport in graphene on another substrate than silicon dioxide.

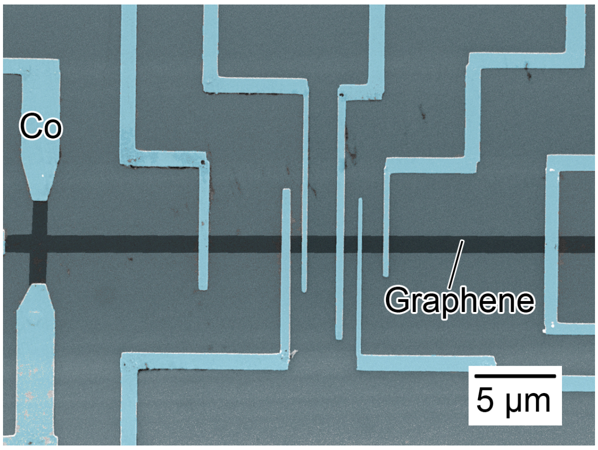

figure 3 : Combined electronic and spintronic devices, with a cross to measure Hall voltage (left side of the device) and ferromagnetic contacts to perform spin valve and Hanle precession measurements (right side of the device).

To further investigate the difference between the diffusion coefficient that we obtained from electronic transport measurements (D_C) and the diffusion coefficient obtained from spin transport measurements (D_S), we combined electronic and spintronic devices (figure 3). Using these combined devices we confirm earlier results of an apparent inconstancy between D_C and D_S. We found values of ~180 for D_C and ~6 cm^2/s for D_S.

2.4 Possible explanation for the measured difference between spin and charge diffusion coefficients

Comparing the diffusion coefficient D obtained by Hanle and Hall-measurement leads us to believe that measured spin relaxation time and D_S could be greatly influenced by localized states present in the vicinity of the conducting graphene channel. The nature of these states is currently unknown, they are possibly present either in the substrate as defects or dangling bonds, in the buffer layer, in aluminum islands within the tunnel barrier or they might be some interface states between graphene and substrate. The described states are non-conducting, meaning electrons cannot hop between the states. Electrons that hop into these states could have a different relaxation time τ_S^* and Larmor frequency ω_L^*. Due to extra relaxation and precession in these states, the spin transport in the graphene channel is described by an effective Bloch equation.

The model described above could provide us with an explanation for the measured difference in diffusion coefficients D_C and D_S, because we currently fit our Hanle precession data using the original Bloch equation. This would result in a measured diffusion coefficient attributed to just transport through the channel, while it is in fact also influenced by the localized states in the direct vicinity of the channel. We are currently working on the details of this model, [5] and the results will be presented in more detail in *D4.3 Theory on spin transport and spin injection in epitaxial graphene* due in month 30 of the project.

3 References

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