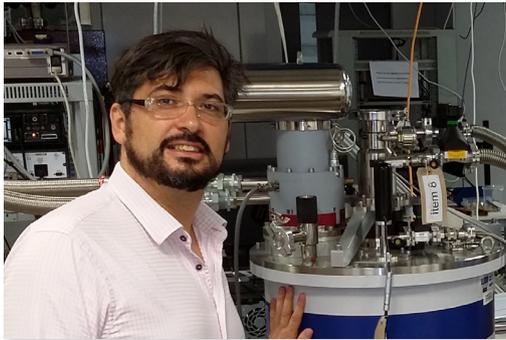


On the way to a graphene spin field effect transistor

How Prof. Barbaros Özyilmaz is using a **Teslatron™PT** from **Oxford Instruments** at the Department of Physics, NanoCore and Graphene Research Centre, National University of Singapore (NUS)



Prof. Barbaros Özyilmaz



Figure 1a. **Teslatron™PT Cryofree®** system at Barbaros Özyilmaz lab

Introduction

This application note describes some experiments at low temperature in a magnetic environment, used for the development of a graphene-based spin field effect transistor. The measurements have been carried out using Oxford Instruments' **TeslatronPT Cryofree®** superconducting magnet system, with two specially designed measurement probes. The main experimental work has been published in Reference [1].

Background

Graphene, being only one atom thick, is sensitive to the properties of the substrate on which it is placed. For example, graphene is not itself a superconductor, but inherits such properties when deposited on top of a superconducting material, due to the proximity effect. When graphene is deposited on hexagonal boron nitride, the energy spectrum of graphene is modified and additional Dirac points are formed. Therefore, new phenomena could emerge when graphene interacts with a substrate. Such flexibility in material and thus device design is central to new applications which can be enabled by two-dimensional (2D) materials.

Intrinsic spin-orbit coupling (SOC) in graphene is weak, making graphene a promising material for spintronics, where the long spin mean-free-path of charge carriers is essential for practical purposes. However, weak SOC also means poor control of the spin. This limitation has been overcome by using the proximity effect when graphene is deposited on a tungsten disulphide substrate, which has strong SOC (reference [1]). By means of graphene with strong and weak SOC, one would expect that room temperature operation of graphene-based spin field effect transistor is getting closer.

In the study of non-local magneto-resistance in graphene deposited on top of tungsten disulphide (WS_2), high magnetic field with two orientations with respect to the graphene's plane is used. These measurements are essentially to distinguish between orbital and spin effects. A rotational probe (Figure 1b) is used because it is desirable to perform all experiments without exposing the sample to ambient conditions.



Figure 1b. Rotating probe with chip holder



Figure 1c. Hall bars (Graphene is not visible)

Methods

The heterostructure is fabricated by sequential transfer of WS_2 and graphene on top of an oxidised silicon substrate. Graphene is patterned into a Hall bar by electron beam lithography. Then, Cr/Au Ohmic contacts to graphene are formed as shown in Figure 1c.

Standard four-terminal measurements of the resistance are performed using a lock-in amplifier (Stanford Research Systems SR830). The low-frequency oscillator output is connected to the current contact number 1 in series with a large resistance (10 MOhm), as shown in the circuit diagram in the inset of Fig. 2a on the next page. The current contact number 6 is grounded. The voltage drop across the sample is measured (numbers 3 and 5 on the diagram) by two probes connected to the differential input of the lock-in amplifier. The gate voltage is applied using a DC source (Keithley 6430). For non-local measurements a constant current flows from contact 2 to contact 3 and the voltage is measured by the pair of contacts 5 and 4. The current contacts used for measurements are indicated by black colour and the potential probes are shown by red numbers in the insets of Figure 2a.

Special measurement probes and cryomagnetic system

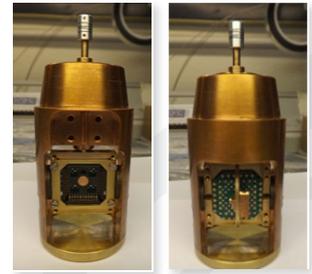
Oxford Instruments' 12 T, 50 mm bore VTI **Teslatron**PT system is used for this experiment to control temperature and to sweep magnetic field. Two measurement probes were specially designed for the graphene experiments at NUS.

The first probe is a two position rod (0 and 90 degrees) fixed at room temperature. The second is a manual 180 degree rotator. One of the probes may be rotated parallel to the field, via a rotator provided at the NW50 flange at the top of the VTI, which enables all experiments to be performed without exposing the sample to ambient conditions.

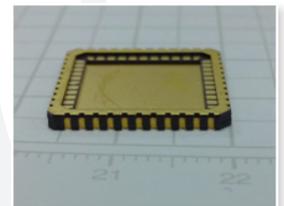
The key advantages of using two these special measurement probes are:

- The sample is in a vacuum can that is pumped to 1×10^{-5} Torr and heated to 420 K outside the VTI. This enables the sample to be outgassed, or annealed, and protects it from coming into contact with air or helium gas
- The sample is on a chip carrier with multiple electrical connections
- When loaded into the VTI, the sample will achieve a base temperature of less than 1.6 K, even with the sample in vacuum, and a maximum temperature of 300 K
- The sample can be at different angles to the field

Both probes are fitted with 48 wires for use, 44 connected to the chip and four left free. 42 SWG PTFE coated constantan wire is used. In addition, four 42 SWG constantan wires and two 36 SWG copper wires are fitted for the Cernox™ sensor and the Watlow Firerod heater fitted to the rotator body.



The front and back view of the chip holder attached to the rotating probes



Chip holder



Specially designed measurement probes



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Experimental results

Figure 2a shows the conductivity of graphene as a function of gate voltage measured at 1.5 K. Hole mobility is estimated to be $18,000 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$ whereas for the electrons it is $\sim 25,000 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$. Saturation of conductivity is observed above the threshold voltage of 15 V. This is caused by the saturation of the electron concentration, as can be seen in Figure 2b, where the quantum Hall effect in graphene is modified by the presence of underlying WS_2 .

The most remarkable result is measured by non-local spin transport at room temperature as shown in Figure 2c. This is a common feature for the non-local resistance near zero gate voltage, which is due to an Ohmic leakage contribution. However, the largest value of the non-local resistance is observed in the saturated regime above 15 V. To clarify the origin of this unusual signal, non-local resistance was measured in parallel to the graphene plane magnetic field. An apparent signal, which depends on the in-plane magnetic field, is measured at 30 V (Figure 2d). This indicates a strong SOC in graphene induced by the substrate. *Ab initio* fully relativistic density functional theory calculations show that this effect is caused by the sulphuric vacancies in WS_2 .

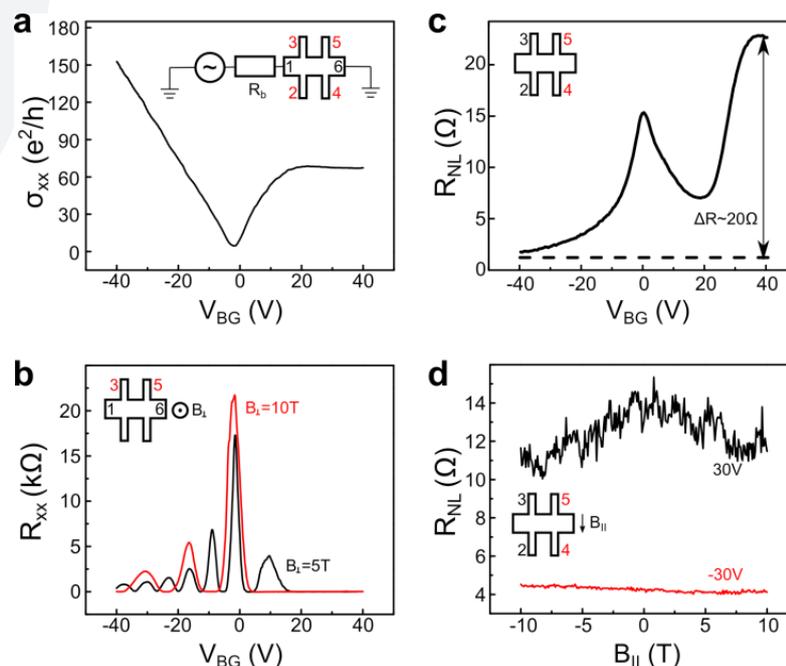


Figure 2a. Conductivity of graphene.

Figure 2b. Resistance of graphene in high magnetic field.

Figure 2c. Non-local resistance measured at room temperature.

Figure 2d. Non-local resistance as a function of in-plane magnetic field for two gate voltages.

Conclusion and outlook

In summary, The Barbaros Özyilmaz lab has demonstrated substrate-induced enhancement of SOC in graphene. At the same time the mobility of charge carriers in graphene has not been decreased, which paves the way to creation of a graphene spin field effect transistor that operates at room temperature.

Reference:

[1] A. Avsar, J. Y. Tan, T. Taychatanapat, J. Balakrishnan, G. K. W. Koon, Y. Yeo, J. Lahiri, A. Carvalho, A. S. Rodin, E. C. T. O'Farrell, G. Eda, A. H. Castro Neto & B. Özyilmaz Nature Commun. 5, 4875 (2014).

About the **TeslatronPT** and special probes

The **TeslatronPT** is a **Cryofree** superconducting magnet system, providing top loading access to a sample in a variable magnetic field / low temperature environment. These systems provide magnetic fields up to 18 T, with their integrated variable temperature inserts providing sample temperatures from 1.5 K to 300 K. These capabilities enable measurements to be carried out for innovative experiments in the field of nanotechnology and nano-structures, such as the one explained in this application note. The two special probes described here, including one with automated perpendicular rotation, have been developed by Oxford Instruments in consultation with the Barbaros Özyilmaz group specifically for graphene and 2D materials research, and are generally available.

About the Barbaros Özyilmaz lab at NUS

The main lab is a Cryogen free low temperature high magnetic field measurement facility consisting of six individual set ups. These range from VTI systems with magnetic fields up to 16 T, to top-loading dilution refrigerators with vector fields and base temperatures down to 20 mK. The Graphene Research Centre is dedicated to device physics, based on 2D crystals and their heterostructures. This lab works in diverse research areas ranging from fundamental research including spintronics and chemical reactivity studies to applied research, such as in the fields of flexible electronics, nanoengines, transparent conducting electrodes and energy storage and conversion.



TeslatronPT
Cryofree system

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