Symposium Spin-Orbit Coupling and Spin Relaxation in Graphene and Carbon Nanotubes (SYGN)

jointly organized by
the Low Temperature Physics Division (TT),
the Magnetism Division (MA),
the Semiconductor Physics Division (HL),
the Thin Films Division (DS), and
the Metal and Material Physics Division (MM)

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Overview of Invited Talks and Sessions

(Lecture room H1)

Invited Talks

SYGN 1.1	Mon	14:00–14:35	H1	**Models for spin-orbit coupling in graphene** — •Francisco Guinea
SYGN 1.2	Mon	14:35–15:10	H1	**Spin-orbit coupling and spin relaxation in carbon nanotube quantum dots** — •Ferdinand Kuemmeth
SYGN 1.3	Mon	15:10–15:45	H1	**Spin-orbit interaction in carbon nanotubes probed in pulsed magnetic fields** — •Sungho Jhang
SYGN 1.4	Mon	16:00–16:35	H1	**Wigner molecules and spin-orbit coupling in carbon-nanotube quantum dots** — •Massimo Rontani
SYGN 1.5	Mon	16:35–17:10	H1	**Spin relaxation and decoherence in graphene quantum dots** — •Guido Burkard
SYGN 1.6	Mon	17:10–17:45	H1	**Spin transport in graphene field effect transistors** — •Bart van Wees

Sessions

SYGN 1.1–1.6	Mon	14:00–17:45	H1	**Spin-Orbit Coupling and Spin Relaxation in Graphene and Carbon Nanotubes**

SYGN 1: Spin-Orbit Coupling and Spin Relaxation in Graphene and Carbon Nanotubes

Time: Monday 14:00–17:45 Location: H1

Invited Talk SYGN 1.1 Mon 14:00 H1

Models for spin-orbit coupling in graphene — •Francisco Guinea — Instituto de Ciencia de Materiales de Madrid. CSIC. Cantoblanco. 28049 Madrid. Spain

The spin-orbit coupling in the carbon atom is relatively weak, due to its low nuclear charge. This makes graphene an interesting material for spintronics applications. Nevertheless, the intrinsic spin-orbit coupling can lead, at least at low temperatures, to the spin Hall effect, with topologically protected edge currents. Extrinsic effects, like electric fields, corrugations, and impurities, can modify significantly the spin-orbit coupling. Similar effects take place in carbon nanotubes. Models for the effect of impurities and corrugations are reviewed[1-3], and compared to available experimental data.

Work done in collaboration with D. Huertas-Herrero, A. Brataas, and A. H. Castro-Neto.

[1] Spin-orbit coupling in curved graphene, fullerenes, nanotubes, and nanotube caps, D. Huertas-Hernando, F. Guinea, A. Brataas, Phys. Rev. B. vol. 74, 155426 (2006). [2] Impurity-Induced Spin-Orbit Coupling in Graphene, A. H. Castro Neto and F. Guinea, Phys. Rev. Lett., vol. 103, 026804 (2009). [3] Spin-Orbit-Mediated Spin Relaxation in Graphene, D. Huertas-Herrero, F. Guinea, A. Brataas, Phys. Rev. Lett. vol. 103, 146801 (2009).

Invited Talk SYGN 1.2 Mon 14:35 H1

Spin-orbit coupling and spin relaxation in carbon nanotube quantum dots — •Ferdinand Kuemmeth — Harvard University, Cambridge, MA, USA

This talk presents transport measurements through single and double quantum dots that elucidate the role of spin-orbit coupling on the energy spectrum and spin-relaxation in carbon nanotubes.

In a one-electron quantum dot the lowest shell consists of four quantum states associated with spin up/down and clockwise/counterclockwise orbital motion around the circumference of the nanotube. These states are resolved by application of a magnetic field parallel to the nanotube. Sub-Kelvin tunneling spectroscopy reveals that spin-orbit coupling breaks the four-fold degeneracy expected at zero magnetic field, by favoring parallel alignment of the electron's orbital and spin magnetic moment. For the one-hole quantum dot antiparallel alignment is observed, demonstrating that spin-orbit coupling also breaks electron-hole symmetry [Nature 452, 449 (2008)].

In double quantum dots Pauli blockade is observed and utilized to study spin-relaxation. In 12C nanotubes the leakage current displays a minimum at B=0 whereas a maximum is observed in 13C devices. We attribute the first effect to spin-relaxation via spin-orbit coupling - a phenomenon which is suppressed near B=0 due to time reversal symmetry. We explain the second effect by hyperfine coupling to the nuclear spins, resulting in fast electron-nuclear flip-flop processes at B=0 [Nature Phys. 5, 321 (2009)].

Invited Talk SYGN 1.3 Mon 15:10 H1

Spin-orbit interaction in carbon nanotubes probed in pulsed magnetic fields — •Sungho Jhang[1], Magdalena Marganska[2], Yurii Skourski[3], Dominik Preusche[1], Benoit Witkamp[4], Milena Grifoni[2], Herre van der Zant[4], Joachim Wosnitza[3], and Christoph Strunk[1] — [1]Institute of Experimental and Applied Physics, University of Regensburg, Germany — [2]Institute for Theoretical Physics, University of Regensburg, Germany — [3]Dresden High Magnetic Field Laboratory, Forschungszentrum Dresden-Rossendorf, Germany — [4]Kavli Institute of Nanoscience, Delft University of Technology, The Netherlands

A source of spin-polarized electrons is one of the important building blocks of a future spin-based electronics. Very high degrees of polarization can potentially be achieved by exploiting spin-orbit interaction (SOI). Based on the low atomic number Z = 6 of carbon the spin-orbit interaction in carbon nanotubes (CNTs) was mostly believed to be very weak, until a recent experiment [1] has demonstrated the effect of spin-orbit interaction in clean CNT quantum dots. Here we present magneto-conductance (MC) data for an open CNT-quantum wire obtained in pulsed magnetic fields, which exhibit a peculiar split MC peak close to the charge neutrality point. Our analysis of the MC data suggests that this splitting is intimately connected to the SOI and the tube chirality and that the current in the peak regions can be up to 100% spin-polarized, which calls for application in future CNT-based spintronic devices.

[1] F. Kuemmeth et al., Nature (London) 452, 448 (2008).

15 min. break

Invited Talk SYGN 1.4 Mon 16:00 H1

Wigner molecules and spin-orbit coupling in carbon-nanotube quantum dots — •Massimo Rontani — CNR-INFM Research Center S3, Modena, Italy

The paradigm of few-electron complexes in quantum dots (QDs) relies on the 'particle-in-a-box' idea that lowest-energy orbitals are filled according to Pauli's exclusion principle. If Coulomb repulsion is sufficiently strong to overcome the kinetic energy cost of localization, a different scenario is predicted: a 'Wigner' molecule (WM) forms, made of electrons frozen in space according to a geometrical pattern. Despite considerable experimental effort, evidence of the WM in semiconductor QDs has been elusive so far. Here we demonstrate theoretically that WMs occur in gate-defined QDs embedded in typical semiconducting carbon nanotubes (CNTs), even in the presence of strong spin-orbit coupling. The signatures of the WM state must be searched -and indeed have already been observed - in tunneling spectra. Through exact diagonalisation (ED) calculations, we unveil the inherent features of the electron molecular states. We show that, like nuclei in a usual molecule, electrons have localized wave functions and hence negligible exchange interactions. The molecular excitations are vibrations around the equilibrium positions of electrons. ED results are well reproduced by an ansatz vibrational wave function, which provides a simple theoretical model for transport experiments in ultraclean CNTs.

Invited Talk SYGN 1.5 Mon 16:35 H1

Spin relaxation and decoherence in graphene quantum dots — •Guido Burkard — Dept. of Physics, Univ. of Konstanz, Germany

Graphene is a promising material for electron spin qubits due to its low concentration of nuclear spins and relatively weak spin-orbit coupling [1]. Despite the expected weakness of spin relaxation and decoherence effects, the time scales for these processes are relevant for coherent spin manipulations in graphene. We have calculated the spin relaxation time T_1 of a single spin in graphene quantum dots [1,2] as a function of the magnetic field B. In quantum dots without coupling between the valleys K and K' in the graphene band structure, there is an effective time-reversal symmetry breaking which prevents the Van Fleck cancellation at $B = 0$ known from semiconductor quantum dots. This leads to a distinct value of the exponent α in the power law $T_1 \propto B^\alpha$ which can be different from the value for semiconductor quantum dots. In the context of spin decoherence, we have also studied the form of the hyperfine interaction with ^{13}C atoms in graphene and find that it leads to a spin-valley coupling [3]. In the transport current through a double quantum dot, we find that the valley degeneracy and hyperfine-induced spin-valley coupling in graphene lead to features in the Pauli blockade that are qualitatively different from the known effect for semiconductor quantum dots.

[1] B. Trauzettel, D.V. Bulaev, D. Loss, and G. Burkard, Nature Phys. **3**, 192 (2007). [2] P. Recher, J. Nilsson, G. Burkard, and B. Trauzettel, Phys. Rev. B **79**, 085407 (2009). [3] A. Palyi and G. Burkard, Phys. Rev. B **80**, 201404(R) (2009).

Invited Talk SYGN 1.6 Mon 17:10 H1

Spin transport in graphene field effect transistors — •Bart van Wees — Zernike Institute of Advanced Materials, University of Groningen, Groningen, The Netherlands

I will give an overview of electron spin injection, spin transport, spin precession and manipulation in graphene. The use of the so-called non-local geometry using graphene FET devices with ferromagnetic contacts allows a detailed experimental investigation. After a basic introduction I will discuss that: a) Spins can be transported through a graphene layer with a spin relaxation length of about 1.5 micrometer. By applying a perpendicular magnetic field Hanle spin precession can be studied and information about spin relaxation and the carrier diffusion can be obtained [1,3]. b) By applying a large DC electric field the transport of spins between injector and detector can be manipulated (sped up or slowed down) using carrier drift [2]. c) Spins can be

injected with an injection efficiency up to 20 percent. This injection efficiency can be enhanced by a current bias which takes the carriers away from the injecting contacts [4]. d) We have observed a scaling between the spin relaxation times and lengths and the carrier mobility in graphene [5,6]. I will discuss the possibility that in clean intrinsic graphene spin relaxation lenghts of 100 micrometer in graphene at room temperature might be possible. [1] N. Tombros et al., Nature 448, 571 (2007)[2] N. Tombros et al., Phys. Rev. Lett. 101, 046601 (2008) [3] C. Jozsa et al., Phys. Rev. Lett. 100, 236603 (2008) [4] C. Jozsa et al., Phys. Rev. B 79, 081402 R (2009) [5] M. Popinciuc et al.,accepted for Phys. Rev. B. [6] C. Jozsa et al, Phys. Rev. B 80, 241403 (2009)