Spin transport and spintronics with graphene

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Spintronics is a paradigm focusing on spin as the information vector in fast and ultra-low-power non volatile devices such as the new STT-MRAM. In particular spintronics is expected to provide beyond CMOS solutions for the realization of spin logic circuits in which logic gates acting on the spin process an information coded and propagated by spin currents. The recent discovery of graphene has opened novel exciting opportunities for such devices as long spin diffusion lengths can be expected from the small spin-orbit coupling of carbon and its large Fermi velocities. Multiple possibilities of spin manipulation inside graphene by proximity effects with other materials can also be anticipated. We will successively discuss these two issues, propagation of spin currents to long distance (spin relaxation time) and spin manipulation.

The published experimental spin relaxation times, in most cases derived from the analysis of Hanle effects in lateral spin valves, are scattered in a relatively broad range and generally smaller than was intitially expected for graphene. We will show that some uniformisation of the data can be obtained by taking into account the spin absorption by the contact between graphene and magnetic electrodes in the interpretation of Hanle experiments. In transport measurments on lateral spin valves the spin diffusion length can be derived from the dependence of the MR signal on the contact resistances. We will show that highly efficient spin transport can occur in epitaxial graphene grown on the C-face of SiC leading to large spin signals and macroscopic spin diffusion lengths (~100 microns), a key enabler for the advent of envisioned beyond-CMOS spin-based logic architectures [1]. On the technical side of the preparation of lateral spin valves, we will also show that a thin graphene passivation layer can prevent the oxidation of a ferromagnet, enabling its use in novel humide/ambient low-cost processes for spintronics devices, while keeping its highly surface sensitive spin current polarizer/analyzer behavior and adding new enhanced spin filtering property[2].

The experimental studies on mechanisms of spin manipulation in graphene circuits are still in their initial stage. However some very interesting results have already been obtained, as, for example, those of Balakrishnan et al who have demonstrated the introduction of Spin-Orbit Coupling (SOC) in hydrogenated graphene and the resulting generation of spin current by SHE [3]. Local introduction of SOC could also be used manipulate the polarization of spin currents. The road is open to the exploration of various similar effects induced by impurities, defects, edges, adatoms, absorbed molecules or interfaces with other materials, and we will discuss the resulting perspective for technology.

We will be able to conclude that many different experiments begin to unveil promising uses of graphene for spintronic devices.

[1] B. Dlubak et al., *Nature Physics* **8**, 557 (2012); P. Seneor, et al., *MRS Bulletin* **37**, 1245 (2012)
[2] B. Dlubak et al., *ACS Nano* **6**, 10930 (2012); R. Weatherup, et al., *ACS Nano* **6**, 9996 (2012)
[3] Balakrishnan et al, Nature Physics **9,** 284 (2013)