

# Towards nanospintronics [DOI: 10.1051/EPN:2007008]

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“WHEN we get to the very, very small world - say circuits of seven atoms - we have a lot of new things that would happen that represent completely new opportunities for design. We can use, not just circuits, but some system involving the quantized energy levels, or the interactions of quantized spins...” suggested R.P. Feynman in a famous visionary talk in 1959. This statement forecasts the present development of two very active trends in solid state physics: molecular electronics and spin electronics (or spintronics). Molecular electronics involve charge transport through the quantized energy levels of a molecule, whose spectrum is possibly controlled by an external voltage. Spintronics involve the control of electronic transport through the spin degree of freedom [see *e.g.* the article by A. Fert et al. in the special issue on Magnetism, *EPN* 34, N°6 (2003)]. Although these fields had developed independently so far, some researchers have started to combine them. Nano-spintronics investigates the interplay between quantum transport through molecules or nanoparticles and spin-dependent phenomena induced, for example, by magnetic electrodes. Beyond the fundamental purpose of investigating the physics of low-dimensional electronic systems, this topic of research could have many potential applications in the future. For instance, it could lead to the implementation of the counterpart of the field-effect transistor (FET), namely the spin-FET, in which spin transport would be controlled through an electrostatic gate. Nanospintronics could also be useful for building spin-based quantum bits, *i.e.* devices in which single spins would be used to encode quantum information. In this context, one can imagine to manipulate quantum information by using gate-controlled effective magnetic fields.

## Electrical polarizer/analyzer experiments

Electronic spin has emerged as a primary tool to control current transport in electronic devices. One basic building block of spintronics is the spin-valve. This element consists of two ferromagnetic electrodes contacted through a “spacer” such as a thin insulating barrier or a non-magnetic metal (Fig.1, left). Electrons can pass through the insulating barrier by quantum mechanical tunneling or can freely propagate through the non-magnetic metal. The spin-valve effect is based on the existence of spin-dependent densities of states in the two ferromagnetic electrodes. In a simplified description, the state of a ferromagnetic metal can be described with a polarization vector  $\vec{P}$ . The metal contains electrons with two opposite spin directions, one majority direction parallel to  $\vec{P}$ , with a density of states  $N_M$ , and one minority direction parallel to  $-\vec{P}$ , with a density of states  $N_m$ , such that  $|\vec{P}| = (N_M - N_m) / (N_M + N_m) \neq 0$ . A spin polarization  $|\vec{P}| = 100\%$  means that only one spin species can propagate through the metal. Let us assume that the spin valve can be either in a parallel or in an antiparallel configuration, *i.e.* the polarization of the two ferromagnetic electrodes can be either parallel or antiparallel. If the transmission probability of the

electrons through the spacer is energy and spin independent, the resistance of the spin-valve is simply determined by this configuration. In the extreme case of fully polarized ferromagnets ( $|\vec{P}| = 100\%$ ), the situation is analogous to a polarizer/analyzer experiment in optics (Fig.1, right). The majority and minority spin directions correspond to the two polarizations of light. In the parallel configuration, the “polarizer” and the “analyzer” are matched, thus spins incident from one electrode are allowed to propagate to the other. In the antiparallel configuration, the “polarizer” and the “analyzer” are crossed. Therefore, a spin from one electrode cannot propagate to the other electrode, and no current can flow through the device. The spin valve thus acts as a switch (or a valve) which can be turned on or off simply by changing the configuration of the ferromagnets. In practical devices, the spin polarization is not 100% and minority carriers can conduct, but the spin valve resistance is larger in the antiparallel configuration. Since the configuration of the ferromagnets can be controlled by applying an external magnetic field, spin valves can be operated as particularly sensitive local magnetic sensors. This phenomenon, discovered about 20 years ago [1,2], is the basic principle nowadays of hard-disk read-out in computers.

## Spin Field Effect transistors using molecules ?

An increase of resistance upon switching from the parallel to the antiparallel configurations is expected for conventional spin-valves. Nevertheless, when the transmission probability through the spin valve spacer is either energy or spin dependent, the resistance change upon switching between the parallel to the antiparallel orientation is not necessarily positive. The possibility of controlling the magnitude and the sign of this quantity, called the *magnetoresistance*, would allow new spintronics devices to be built. This task requires that appropriate spacers be found which can allow such a control. Molecules are ideal candidates to implement this new functionality because they can be coupled to ferromagnetic electrodes and they allow a good coupling between electronic transport and local electric fields.

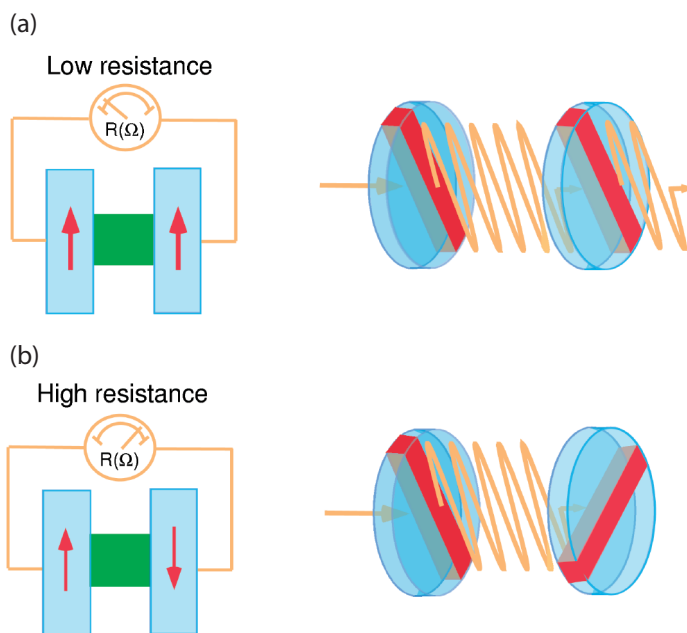
The analogy with polarizer/analyzer experiments turns out to be illuminating in this situation also. Indeed, it has been used to describe the basic principle of one of the most famous proposals of a spintronic device suggested in 1990 by S. Datta and B. Das [3]. The electro-optic modulator is a widely used analogue in which an incoming linearly polarized beam propagates through a birefringent medium. The rotation of the beam polarization is controlled by applying to the medium an electric field which changes the refractive index of the medium in a specific direction. The polarization of the beam is subsequently analyzed. For electrons, an analogue of the birefringent medium is a ballistic single mode conductor with an electrically tunable spin-orbit coupling (Rashba effect). The spin-orbit coupling induces a magnetic field in the

moving frame of the electrons, which causes spin precession. If the Rashba field is low, little spin precession occurs between the two ferromagnetic electrodes. The device thus acts as a regular spin-valve with a positive magnetoresistance. If the field is such that each spin precesses by  $\pi$  upon travelling through the ballistic region, the magnetoresistance of the device becomes negative. Two dimensional electron gases (2DEGs), which can be realized in semiconductor heterostructures, have been primarily envisioned for the implementation of the Datta-Das transistor. However, the electrical injection of spins in 2DEGs has turned out to be very difficult to achieve. To date, such a device has not been realized experimentally.

Very recently, carbon nanotubes have emerged as an alternative to semiconductor heterostructures for the implementation of spin logic devices [4,5]. Two different types of carbon nanotubes can be fabricated: single-wall nanotubes (SWNTs) and multi-wall nanotubes (MWNTs). A SWNT consists of a single graphene sheet that is rolled up into a cylinder. A MWNT consists of a set of coaxially stacked graphene cylinders. A spin-valve can be formed by evaporating two separate ferromagnetic contacts on a nanotube lying on an highly doped silicon substrate. The silicon substrate can be used as a capacitive gate for the nanotube because its surface is oxidized. At low temperatures, quantum interferences occurring in the nanotube (just as for particles in a box) select the energy of electrons crossing the spin-valve. In situations where electronic interactions effects can be neglected inside the nanotube, one can push further the analogy with optics since the carbon nanotube then behaves like a Fabry-Perot electronic interferometer [6]. Due to multiple coherent reflections in the “Fabry-Perot cavity”, the magnetoresistance of the spin-valve does not depend only on the configuration of the ferromagnets, but also on whether constructive interferences take place in the interferometer (Fig.2). Provided that the transmission from the nanotube to the two ferromagnets is very asymmetric, the magnetoresistance of the spin valve is negative if the nanotube is on resonance. If it is off resonance, the picture of the conventional spin valve is recovered, and the magnetoresistance is positive. The on/off resonance regimes can be tuned by varying the gate voltage of the nanotube since this modifies the wavelength, hence the “optical path” of the electronic waves. This allows the magnetoresistance of the device to be changed in a controlled way, as found experimentally for SWNTs connected to ferromagnetic contacts [4,5].

The Spin-FET principle described above is very general. In principle, any kind of molecule can be used to implement such a device. In cases where electronic interactions are significant, in the molecule, the description of electronic transport becomes more complicated. The molecule can, for instance, behave as a quantum dot which is characterized by at least two energy scales. The first one is the intrinsic level spacing arising from size quantization of the electronic orbitals, already

present in the Fabry-Perot case. The second one is the charging energy characterizing the Coulomb blockade effect caused by the very small capacitance (a few aF) of the tunnel junctions used to contact the molecule. Nevertheless, the features recently observed [4] in such a case can be qualitatively understood in terms of polarizer/analyzer experiments with a Fabry-Perot interferometer. One practical difference between optics and spin electronics is that it is difficult to find ferromagnetic materials with a spin polarization close to 100%. This is *a priori* even more difficult for materials which can be coupled to molecules. However, this is essential to obtain efficient Spin FETs, that is devices transforming spin information into sizable electric signals. This important step towards spin logic devices has been made very recently by using the highly spin-polarized manganite  $\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}_3$  (LSMO) to contact carbon nanotubes [7].



▲ **Fig. 1:** a) Schematic diagram of a spin valve in the parallel configuration (left) and its optical analogue (right). The spin-valve consists of two ferromagnetic electrodes (blue blocks) electrically connected through a “spacer” such as a tunnel barrier or a non-magnetic metal (green block). The magnetic polarization  $\vec{P}$  of each ferromagnetic electrode is represented as a red arrow which indicates the direction of majority spins. It is the analogue of the polarization axis (red line) of each optical polarizer (blue disk) in the right scheme. In the parallel configuration, the resistance of a conventional spin valve is low. This corresponds to having aligned polarizers and a maximal transmission of photons in the optical scheme. b) Schematic diagram of a spin valve in the antiparallel configuration (left) and its optical analogue (right). The resistance in this configuration is high for conventional spin valves.

## Towards the manipulation of a single electronic spin

The spin-FET described above allows a gate control of spin-transport in the statistical sense, that is for an average current corresponding to a large number of electrons. In the context of quantum information processing, it would be very interesting to achieve a further control of the spin degree of freedom, *i.e.* to find ways to control directly a *single* electronic spin using a gate electrode. Electron-electron interactions are recognized as a very important ingredient to manipulate the spin in confined conductors. The Coulomb blockade effect already evoked above tends to force the occupation of the conductor by a single spin. This is the basic principle of spin-based quantum bits [8]. In multiple quantum-bit devices, the selective control of the spin-precession of a single spin would require one to apply a tunable local magnetic field to each spin. The presence of ferromagnetic contacts can induce various types of local effective magnetic fields in molecules, which could be very useful in this context.

Polarization-dependent phase shifts are well known in optical fibre physics. They arise for example from the induced birefringence of an optical fibre under stress. These effects usually lead to inaccuracies in interferometric measurements because they change the optical path for two different polarizations [9]. The spintronics counterpart of this effect is the so-called Spin Dependence of Interfacial Phase Shifts (SDIPS), which affects, via the spin, the phase of the electronic wave functions. In a cavity, the SDIPS generates an effective field which depends of the “optical path” [10]. The latter is controlled, in the case of molecular spin-valves, by the gate electrode. The presence of electronic interactions in the molecule can lead to additional gate-tunable effects other than that arising from the SDIPS. An effective field of 70T

measured in  $C_{60}$  molecules coupled to ferromagnetic electrodes has been attributed to Coulomb interaction effects [11]. One could imagine using these effective fields to perform single spin operations in the context of quantum information applications. ■

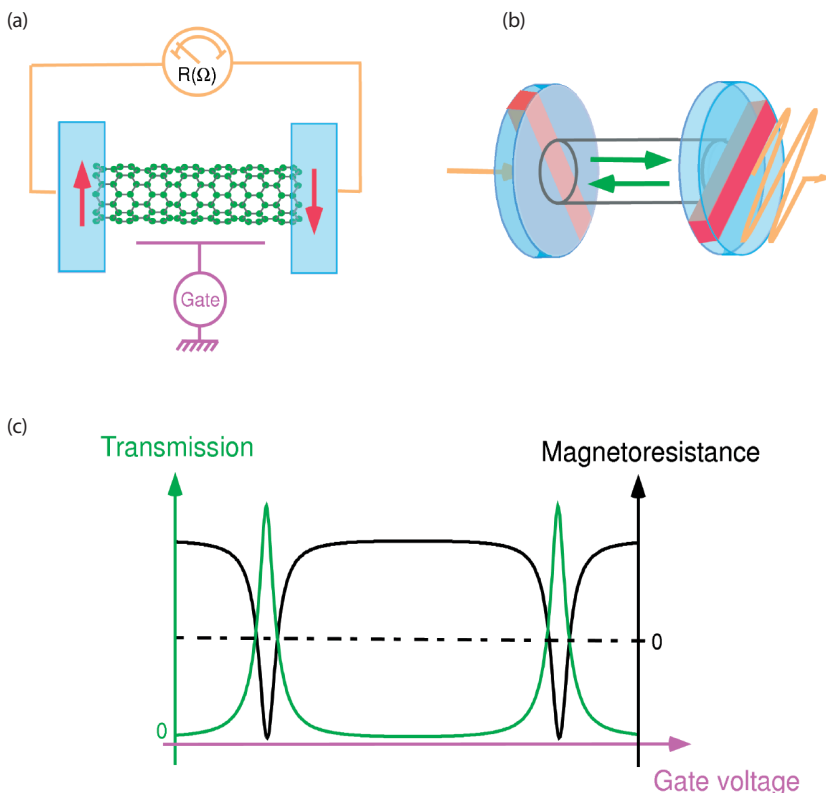
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◀ **Fig. 2:** a) Schematic diagram of a Spin Field Effect Transistor made out of a Single Wall Carbon Nanotube contacted to two ferromagnetic electrodes and capacitively connected to a gate voltage source. We assume that the couplings between the nanotube and the two ferromagnets are very asymmetric. We present here the case of an antiparallel configuration for the ferromagnetic contacts. Assuming that the gate voltage is such that the interferences occurring inside the nanotube are constructive, the resistance of the transistor is lower in this configuration than in the parallel configuration. This leads to a negative magnetoresistance. b) Fabry-Perot interferometer inserted between a polarizer and an analyzer. This device would be the optical counterpart of the circuit of panel a). c) Typical transmission and magnetoresistance as a function of the gate voltage, for the spin-transistor of panel a). The magnetoresistance becomes negative when the transmission of the transistor is resonant.