Spin torques in spin valves and domain walls

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Spintronics traditionally relies on a basic device called a 'spin valve' composed of two ferromagnetic layers separated by a nonferromagnetic one. Depending on the relative magnetic orientation of the ferromagnetic layers, the resistance of the stack switches between low and high values, thus demonstrating the influence of charge carriers' spins (controlled via the magnetization) on the electrical properties of the device. The non magnetic spacer layer can also be a tunneling barrier which leads to very large magnetoresistance (over 500% effects are obtained in Fe/MgO/Fe). These have been commercialized as magnetic fields sensors and memory elements where the information is stored in the magnetization. This has triggered an impressive increase in the density of data storage which largely contributed to the revolution of information technologies.

A more recent advance relies on the effect of a spin polarized current on ferromagnetic layers[1]. It has indeed been demonstrated that the angular momentum lost by spin carriers as their polarization changes direction passing through differently magnetized layers is given to the local magnetization and is able to switch it. This is an important new addition to spintronics as it opens the way to a pure electrical control of magnetization in spin valves. Furthermore, spin currents can also affect the magnetization dynamics and even induce ferromagnetic resonance. Specially designed spin valves can therefore be used as integrable and agile and nano radio-frequency sources (a clear dependence of the emitted frequency with the input current intensity) much in demand for applications. The early prediction[2] and subsequent confirmation that domain walls, the regions separating different magnetic domains, can also be moved by (spin-polarized) electrical currents offers an attractive alternative in designing novel devices such as sensors and magnetic random-access memories. Indeed, domain walls are now considered as possible objects for high-speed logic, where each wall represents a single bit. In IBM's racetrack memory[3] project, the walls can be moved with a current and the information read, either with optical techniques or electrically. Driven by these enormous prospects for technological applications, active studies of domain walls are underway worldwide.

In this lecture, the different spin-transfer torques, often studied independently will be addressed. I will cover theory and experiments on magnetization reversal, domain-wall displacement and nano-oscillators. Indeed, since the first theoretical proposal on spin-transfer torque—reported by Berger and Slonczewski independently—spin-transfer torque has been experimentally demonstrated in vertical magnetoresistive nano-pillars and lateral ferromagnetic nano-wires. In the former structures, an electrical current flowing vertically in the nano-pillar exerts spin torque onto the thinner ferromagnetic layer, which can be used to either reverse magnetization or generate radio-frequency. In the latter structures, an electrical current flowing laterally in the nano-wire exerts torque onto a domain wall and moves its position by rotating local magnetic moments within the wall, i.e., domain wall displacement.

The theoretical understanding of magnetization dynamics during reversal as well as domain wall displacement can be understood using the conventional Landau--Lifshitz–Gilbert (LLG) equation, adding a spin-torque term. Basic analytical models will be introduced which can explain the details of the spin current induced magnetization dynamics and domain wall motion mechanisms. A short overview on materials and potential applications will conclude the lecture.

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[1] L. Berger, Phys. Rev. B 54, 9353 (1996); J. Slonczewki, J. Magn. Magn. Mater. 159, L1 (1996).
[2] L. Berger, J. Appl. Phys. 49, 2156 (1978) and J. Appl. Phys. 55, 1954 (1984).
[3] S.S.P. Parkin, "Shiftable magnetic shift register and method of using the same," U.S. Patent 6,834,005 (2004).