

Chapter 29

Nano-Devices Based on Spin-Transfer Torque Effects

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Abstract The discoveries of giant magneto-resistance and spin-transfer torque effects are milestones in the history of magnetism. During the last two decades, they have fueled a conspicuous research activity in the field of nanotechnology, giving rise even to a new scientific branch, the spintronics, a neologism for spin-based electronics. From the very beginning, in fact, experimental results pointed out several potential applications of spintronic devices, such as magnetic random-access-memories, sensors, nano-oscillators, modulators and receivers working at microwave frequency. An overview of these devices will be here provided, emphasizing their behavior and the applications.

29.1 Introduction

The two scientists Fert and Gruenberg received the 2007 Nobel prize in physics for the discovery of the Giant Magneto-Resistance (GMR) effect in 1988 [1, 2]. Such phenomenon is observed in thin film structures composed of alternating ferromagnetic and non magnetic layers, and it manifests itself as a significant change in the electrical resistance of the structure depending on whether the magnetizations of adjacent ferromagnetic layers are in a parallel or an antiparallel alignment. The overall resistance turns out to be relatively low in the former case and relatively high in the latter one. Eight years after the discovery of GMR effect, in 1996, Slonczewski and Berger predicted that a direct electric current passing through a magnetic material, opportunely thick, becomes spin-polarized along the direction

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of its local magnetization vector. If such a spin-polarized current presents a sufficiently large amplitude and now traverses a second magnetic layer, it can transfer its spin-angular momentum and destabilize the static equilibrium orientation of the magnetization of this latter layer [3, 4]. This phenomenon is known as Spin-Transfer Torque (STT) effect and it can be accounted as the dual of the GMR one, as the GMR effect describes how the electrical configuration is affected by changes of the magnetic state, whereas the STT one describes how the magnetic state is affected by changes of electrical quantities. The discovery that spin-polarized currents can modify a magnetic state opened several perspectives for a new class of nano-scale magnetic devices that specifically take advantage of spin properties instead of, or in addition to, the degree of freedom given by the charge. The corresponding new research area was consequently called spintronics, a short notation for “spin-based electronics”.

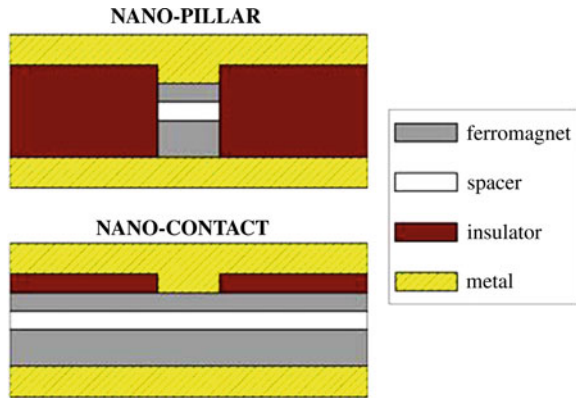
29.2 Spintronic Devices

From the beginning, GMR and STT effects have been studied in multilayer systems called “spin-valve”. A classical spin-valve consists of: a thicker magnetic layer, called fixed or pinned layer (PL), which acts as the spin-polarizer; a thinner magnetic layer, called free layer (FL), which is the one generally subjected to the action of the spin-transfer torque; and a non magnetic spacer, used to avoid exchange coupling between PL and FL. Depending on the electrical conductivity of the intermediate layer, it is possible to build up either “classical” spin-valve (CSV) devices, if the spacer is a metal, or non-classical magnetic tunnel junctions (MTJ), if the spacer is an insulator. Within the class of nano-scale devices, the two most common experimental geometries are the so-called: nano-pillar and nano-contact (or point-contact). The main differences existing between them involve both the lateral sizes and the current density distribution. In fact, nano-contact devices generally present larger lateral dimensions (in the order of tens of microns) with respect to those of nano-pillar (hundreds of nanometers). In addition, the perpendicular-to-plane applied current involves the whole physical (cross-section) area of pillar devices, whereas only a reduced region (the contact area, typically of the radius of 10–80 nm) in nano-contact devices (see Fig. 29.1). The structural differences between these geometries imply not only different technological applications, but also require different approaches in the corresponding numerical investigations [5, 6].

29.3 Applications

Depending on the geometry, on the properties of the layered magnetic structure, on the magnitude and orientation of the external bias field, the STT effect can lead either to the switching of the magnetization direction or to a stable precession of

Fig. 29.1 Nano-pillar and nano-contact spin valve geometries



the magnetization of the thinner FL. These particular physical phenomena offer the possibility to design and build up a new class of devices and applications that includes, for example, magnetoresistive random access memory, logic gates, diodes and transistors, nano-oscillators, modulators and receivers.

29.3.1 GMR and TMR Sensors

A classical spin-valve structure can be used as a magnetic field sensitive device, exploiting GMR effect. The presence of an external magnetic field, in fact, can adjust the direction of the magnetization vector in the FL respect to the PL magnetization, increasing or decreasing the output resistance of the device. In the two opposite cases (aligned and not aligned layers), the change in resistance is typically 10–20%, compared with a maximum sensitivity of a few percent for other types of magnetic sensors. This explains the reason of the term “giant”, although it seems incongruous for a nanotechnology device. Tunnel Magneto-Resistance (TMR) is an extension of GMR effect. It takes place when spin-polarized electrons travel perpendicularly to the layers across a thin insulating tunnel barrier (replacing the non ferromagnetic spacer, as in MTJ structures). Since this process is forbidden in classical physics, TMR is a strictly quantum mechanical phenomenon. TMR sensors, for the above-described reasons, get larger magnetoresistance values and a larger sensitivity [7]. The main advantages of GMR and TMR sensors are the sensitivity and the reducing size and power requirement. On the other hand, random high-value fields may represent a problem for the devices.

29.3.2 Magnetic RAM

GMR and TMR devices are used commercially by hard disk drive manufacturers. The read-heads of the modern hard disk drives work, in fact, on the basis of spin-valves and magnetic tunnel junctions. Such structures, besides, can be used as

memory cells, since it is possible to associate two different logic states to the different electric configurations (e.g. bit 0 = low-resistance state, bit 1 = high-resistance state). This is also the basic working principle of magnetic random-access memories, MRAM, one of the most common systems of non-volatile memory. The increasing interest in nano-scale memories, of course, has given rise to plentiful studies on this application of spin-valve structures [8]. In particular, nano-pillar geometries have been analyzed to get the magnetization switching driven by spin-polarized currents, even in the absence of an external magnetic field.

29.3.3 Nano-Oscillators

If the magnetization of the FL undergoes a persistent precession, rather than switching phenomena, the output signal might manifest itself as a periodic variation of the resistance of the device which could be used to build up nano-scale oscillators. Nano-contact geometry becomes particularly suitable to design microwave spin-transfer oscillators with very narrow linewidths because it combines the advantages of having a larger effective volume and a negligible influence of edge roughness and defects. Numerous experimental [9] and numerical [10, 11] analyses have described the nature of such spin-wave modes, showing, for instance, how the output frequency depends on the applied current.

29.3.4 Radio-Frequency Modulators

When a point-contact structure is subjected to the simultaneous action of a direct current and an alternative current, it works as a non linear amplitude and frequency modulator. The direct current fixes the carrier frequency, while the alternative term acts as modulating signal. The output spectra obtained by means of numerical simulations and experiments, in fact, agree with the predictions of the analytical model of analog modulation, in which variations of amplitude and frequency with the modulating input signal are taken into account [12].

29.4 Conclusions

We have described some physical properties of magnetic multilayer structures, GMR, TMR and STT. These structures, in their different and possible geometries, turn out to be very useful in the field of nanotechnology.

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