Physics and measurements of common magnetoresistance phenomena: AMR, AHE, GMR, TMR

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Since the discovery of the giant magnetoresistance effect (GMR) by Albert Fert and Peter Grünberg in 1988 the Spin Electronics represents an excellence research field, rewarded by the Nobel Prize for Physics in 2007. This is related to the potential applications of the spin dependent conduction in the field of sensors and data transfer, processing and storage. More recently, in 2014, the prestigious Millennium Technology Prize was awarded to S.S.P. Parkin for breakthrough in magnetic disk drive storage capacity, heralding era of cloud computing.

Even the most complex spintronics devices embedded in the last generation technologies have at origin some basic spin and charge dependent transport phenomena. The aim of this lesson is to illustrate some major phenomena such as*: Anisotropic Magnetoresistance (AMR)*, the *Anomalous Hall Effect (AHE)*, the *Giant Magnetoresistance (GMR)* and the *Tunneling Magnetoresistance (TMR)*. When appropriate, we are distinguishing on different transport geometries: current-in-plane (CIP) and current-perpendicular-to-plane (CPP). After a brief explanation of the physical basis for each of these phenomena, we are going to illustrate it with major historical examples from the literature up to the state-of-the art in the field, followed by common and next generation device applications.

Anisotropic magnetoresistance

The resistivity of a ferromagnetic film submitted to an in-plane magnetic field varies with the angle ? between the flowing current *I* and the film magnetization *M* [Tsy] as: $\rho(\theta) = \rho_\perp + (\rho_\parallel - \rho_\perp)\cos^2\theta$. The $\rho_\parallel$ and $\rho_\perp$ define the extreme resistivities when the current is either parallel or perpendicular to the magnetization. Phenomenologically, the AMR arises from the scattering asymmetry of electrons induced by the spin-orbit interaction, typically stronger when they flow along a direction parallel to the magnetization [RefAMR]. Historically, the AMR in $Ni_{80}Fe_{20}$ has been used as main magnetoresistance (MR) effect in early generations of read heads, before using the GMR. In practice, as we will illustrate, in magnetic multilayered systems where the CIP-GMR signal is small, the measured magnetoresistance effect has to be always corrected with respect to AMR, using specific compensated transport geometries.

Anomalous Hall effect

When a conductor is placed in a magnetic field, the Lorenz force pushes the electrons against one side of a conductor, defining the so-called Hall Effect. However, in ferromagnetic metals, this effect can be order of magnitude higher than in non-magnetic systems. This defines the anomalous Hall Effect (AHE). The origin of AHE is complex, often controversial, and involves intrinsic and extrinsic mechanisms [NagRMP2010]. The intrinsic mechanisms are mainly correlated to the material band structure. Within external electric field, electrons acquire an anomalous velocity perpendicular to the electric field, related to their Berry's phase curvature. The extrinsic mechanisms, *side-jump* and *skew-scattering*, implicate scattering. As a result, electrons with opposite spin are deflected along opposite directions. In *side-jump*, the electron velocity is deflected in opposite directions by opposite electric fields experienced when approaching and leaving an impurity. The *skew-scattering* represents a symmetric scattering due to the effective spin-orbit coupling of the electron or the impurity. Each mechanism has a specific scaling low. In this lesson we will illustrate how AHE analysis, within proper scaling law framework [TiaPRL2009], can be used to extract mechanisms responsible for AHE. Furthermore, we will illustrate the use of AHE measurements as a versatile magnetic analysis tool. From anomalous Hall effect measurements in variable temperature on lithographically patterned stripe lines with transverse Hall contacts, we can extract the variation of the anisotropy.

Giant Magnetoresistance

The GMR effect represents the variation of the resistance of a magnetic multilayer system, constituted by alternating ferromagnetic and nonmagnetic metallic layers, with respect to the relative orientation of the magnetization directions in the ferromagnetic films. Historically, the GMR was discovered in multilayers coupled antiferromagnetically [BaiPRL1988, BinPRB1989]. There, at remanence, an antiferromagnetic antiparallel (AP) configuration has been naturally stabilized, in contrast to the parallel (P) configuration attained at saturation for large in plane applied magnetic fields. For applications, the GMR effect has been successfully implemented developing the *hard-soft architecture* of *spin valves*. In this architecture two magnetic layers with different magnetic rigidity are involved, one magnetically soft, called free layer, and the other magnetically hard, which is the reference fixed layer. Within a field window where the hard layer is magnetically locked, the free layer can be manipulated, providing a magnetorezistive signal defined as: $GMR = (R_{AP} - R_P) / R_P$ and a dependence of the multilayer resistance in $\cos(\theta)$ with respect to the relative angle between the magnetizations of the soft and the hard magnetic layers, respectively. Several solutions for achieving the hard magnetic subsystem are briefly illustrated, from Synthetic Antiferromagnets to Exchange Bias. We will explicitly discuss GMR measuring and applications for both CIP and CPP geometries.

Tunnel magnetoresistance

When two ferromagnetic films are separated by an extremely thin insulating barrier, the electron could flow across by quantum tunneling. The system is called Magnetic Tunnel junction (MTJ). The tunneling current is spin-dependent and, likewise a spin valve, the tunnel resistance depends on the relative configuration of the MTJ's magnetic electrode's magnetizations. The *TMR* effect is defined as $TMR = (R_{AP} - R_P) / R_P$ with respect to the MTJ resistances in AP and P configurations. A special attention will be devoted to the TMR effects in MTJ, as elementary bricks of read-head sensors in high density hard disks and magnetic random access memories. After the historical analysis of TMR in polycrystalline MTJs, where the electronic transport is well described within the free-electron models, we will underline the correlation between the electronic structure and the magneto-transport properties in single crystalline MTJs [YuaJPD2007,TiuJPCM2007]. In these systems, the TMR effects are triggered by band structure features and symmetry dependent transport effects. The conduction channels are determined by electrons with given symmetry of their Bloch functions, as selected within the ferromagnetic electrodes. They will be selectively attenuated within the single crystal tunnel barrier, as a function of corresponding symmetry. Furthermore, we will illustrate by original experimental results how innovative magneto-transport characteristics and spin-torque properties can be tailored by either interfacial engineering or by involving magnetic electrodes constituted from complex alloys, from simple transition metal to full Heusler systems. Beyond standard TMR phenomena, we will briefly discuss the effect of the spin-orbit coupling in magnetic tunnel junctions by distinguishing Anisotropic Tunneling Magnetorezistance (ATMR) and Tunneling Anisotropic Magnetoresistance (TAMR) effects [MatPRB2008].

Beyond the specific analysis of the each magnetorezistive phenomena, this lesson will indirectly sequentially illustrate the complexity of the experimental techniques involved in the elaboration of the experimental systems where they are measured: from single magnetic films, to complex magnetic multilayers (GMR, MTJ) lithographically patterned for current-in-plane or current-perpendicular-to-plane transport geometries. Therefore, we will rapidly shot on aspects related to ultra-high vacuum deposition techniques (sputtering, molecular beam epitaxy), in-situ characterization tools (RHEED), lithography techniques for patterning of CPP devices (optical, e-beam), tunneling spectroscopy experiments, atomic/magnetic force microscopy, XRD, TEM and HR-TEM, surface analysis techniques (AES, XPS, XMCD, spin polarized photoemission), different other static and dynamic (HF) magnetic and magneto-transport characterization tools.

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