Introduction to Spin Electronics

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Any sufficiently advanced technology is indistinguishable from magic
Arthur C. Clarke

I. The field of spin electronics

Spin Electronics, Magnetoelectronics and Spintronics are different names for the same thing : the use of electron's spins in information circuits. Its roots can be traced back into the early works of spin transport phenomena, among which processes like scattering, tunneling, or injection would sit in the front row. Conventional electronic devices use only the charge of the electron as the carrier of the information. In classical conductors as copper or in semiconductor as silicon the spin direction of the electrons is random, and so the spin polarisation is zero. This spin polarisation is defined as the difference of the spin–up(majority) and spin-down(minority) electrons that contribute to the electrical transport with respect to the total amount of conducting electrons : $P = (n\uparrow - n\downarrow)/(n\uparrow + n\downarrow)$ [1]. With such a material even a simple spin electronic device as for example a spin valve, that let only pass through electrons with one specific spin direction, would not work. For every spin orientation there would be always the same amount of electrons which would pass through the filter (Fig.1a). For spin electronics are needed special new materials, which have asymmetry in the spin direction of the conducting electrons. As higher this spin polarisation is, as better are the signal to noise ratio and efficiency of the spin electronic devices. Spin-polarised transport occurs naturally in any material for which there is an imbalance of the spin population at the Fermi level (Fig. 1b). The spin-split band structure of ferromagnetic metals produces a net spin polarisation in a transport measurement, but the sign and magnitude of that polarisation depend on the specific measurement being made. A ferromagnetic metal may be used as a source of spin-polarised carriers injected into a semiconductor, a superconductor, or a normal metal or can be used to tunnel through an

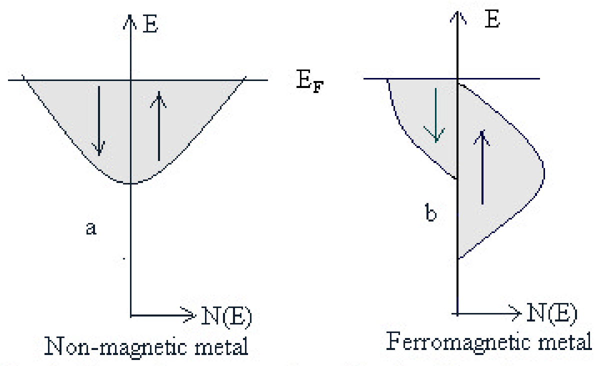
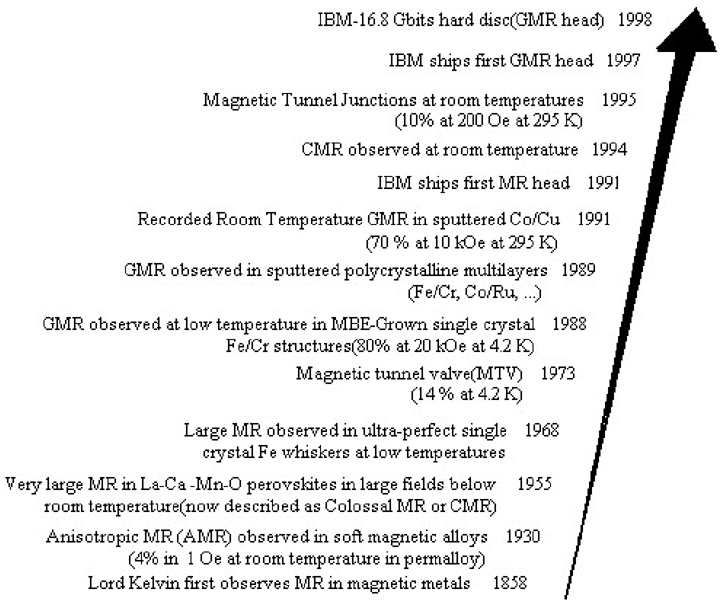


Fig. 1. Schematic representation of the densities of states

insulating barrier. Materials that are only partially polarised (such as Fe, Co, Ni and their alloys, which have a polarisation P of 40 to 50%) are, however adequate for technological applications [1]. In these materials there are also s and p electrons at the Fermi level.

II. History of magnetoresistance(MR)

In the technical sense the spin electronics refers to a new electronics which uses *magnetoresistance effects* in device applications [2]. Magnetoresistance (MR) is the change in electrical resistance of a conductor by a magnetic field. In non-magnetic conductors, it is relatively small. In magnetic materials and magnetic multilayers, the spin polarisation of the electrons leads to large MR effects in small magnetic fields. Historically, the origin of spin electronics can be found in the discovery of interlayer exchange coupling and giant magnetoresistance (GMR) in magnetic multilayers. Since the discovery of GMR in 1988 [3,4] the new field of magnetoelectronics has expanded rapidly and the large number of developments and patents indicate a huge potential for innovation and new technology. A fascinating example is a new high-density mini-disc-drive of 16.8 Gbits with the read head based on GMR-effect brought into the market by IBM in 1998 [2].



History of magnetoresistance

III. Overview on the different magnetoresistance effects

a) *Anisotropic magnetoresistance* (AMR)

The AMR measures the change in the resistance seen when the current flowing through a ferromagnetic sample changes from being parallel to the internal magnetisation to being perpendicular to it. The difference ranges between 2 and 3% ($Ni_{81}Fe_{19}$ alloys-Permalloy) [2].

b) *Giant magnetoresistance* (GMR)

Metallic multilayers (superlattices) composed of alternating ferromagnetic and non-magnetic spacer layers, each a few atomic layers thick, display fascinating properties. An important observation is that layers of 3d transition metals ferromagnets are indirectly magnetically exchange coupled via spacer layer comprised of almost any of the non-ferromagnetic 3d, 4d and 5d transition metal. The magnetic coupling oscillates between ferromagnetic and antiferromagnetic coupling with thickness of the spacer layer and its strength varies systematically with the spacer d-band filling [5]. It is found that the resistance is high when the neighbouring magnetic layers have antiparallel magnetic moments and it is low when the moments are aligned in a saturating magnetic field (Fig.2). The relative reduction of the

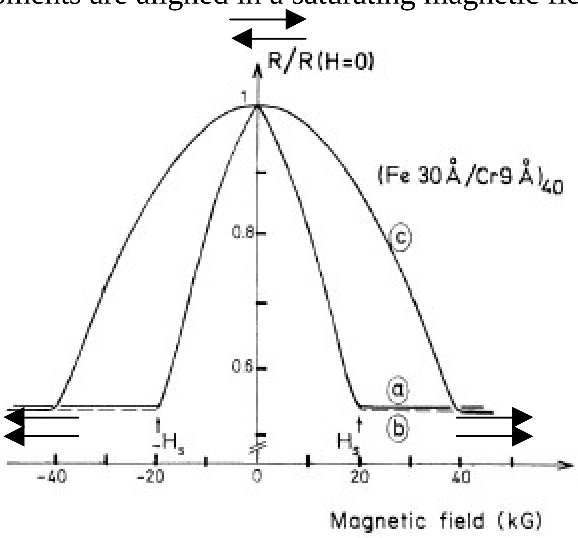


Fig. 2. Magnetoresistance of a (Fe30 Å / Cr 9 Å)$_{40}$ superlattice at 4.2 K. The current is along (110) and the field is in the layer plane along the current direction(a), in the layer plane perpendicular to the current(b), or perpendicular to the layer plane(c) [3].

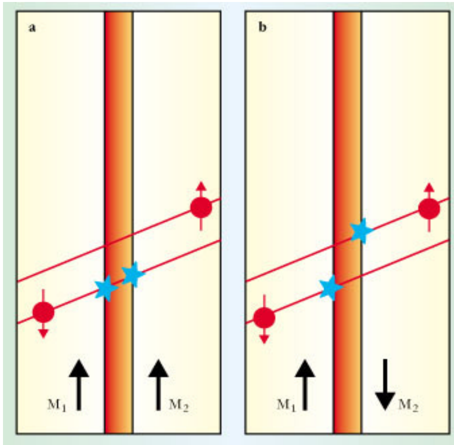


Fig.3. Schematic picture of the GMR mechanism

resistance can be as large as 100 % [6]. This effect is called "giant magnetoresistance". The saturation field H_s is required to overcome the antiferromagnetic interlayer coupling between the Fe layers and align the magnetizations of consecutive layers. It was suggested that spin – dependent scattering at the interfaces and in the bulk is responsible for the magnetoresistance. Experiments showed the predominance of spin-dependent scattering at the ferromagnet/spacer layer interfaces (Fig. 3) [7]. The spin diffusion length L_s of carriers injected into a paramagnetic metal from a ferromagnetic contact is much longer than a superlattice unit cell [8]. This means that the current is carried separately by up- and down-spin conduction electrons (two channels in parallel). The electron mean-free path l_σ in a ferromagnetic metal is spin dependent ($l_\uparrow \neq l_\downarrow$). This arises because $N(E_F)$ available for scattering are different for up- and -down spins (Fig.1). It follows from these two considerations that an electron of a given spin travelling in a superlattice sees regions of different local resistivities ($\rho_\sigma \sim N_\sigma(E_F)$; $\sigma = \uparrow, \downarrow$) [9]. Figure 3 shows the electron trajectories in the two channels for parallel(a) and antiparallel(b) configurations. The current in the parallel configuration is shorted by the spin-up channel, so that the resistance is much smaller with respect to the antiparallel configuration, where the electrons of both channels are alternatively majority and minority spin electrons and the shorting by one of the channels disappears.

The GMR effect was also observed in granular magnetic systems (heterogeneous alloys such as Co-Cu, Co-Ag, Fe-Au, Fe-Cu etc) [10]. The Co and Fe clusters are single domain particles. Each particle has a magnetic moment, whose direction in the matrix is random oriented. It follows that the total magnetisation of the system is zero. This state corresponds to the antiferromagnetic coupled multilayers. High resistance occurs when the magnetic axes of the particles are not aligned (H = 0). Low resistance is obtained when the magnetic axes are aligned by the applied magnetic field.

c) *Tunnel magnetoresistance* (TMR)

TMR is obtained with tunnel junctions in which two ferromagnetic layers (electrodes F_1 and F_2) are separated by a thin insulating layer (barrier). Electrons can tunnel between the electrodes and the spin is conserved in the tunneling process. In the parallel configuration, the tunneling is from majority to majority spin states and from minority to minority spin states. In the antiparallel configuration, the tunneling is from majority to minority spin states and vice-versa (Fig.4). This leads to different values of the tunnel resistance in the parallel and antiparallel configurations. The TMR ratio can reach 65% at 4.2 K and 40% at room temperature (with transition metal electrodes) [11].

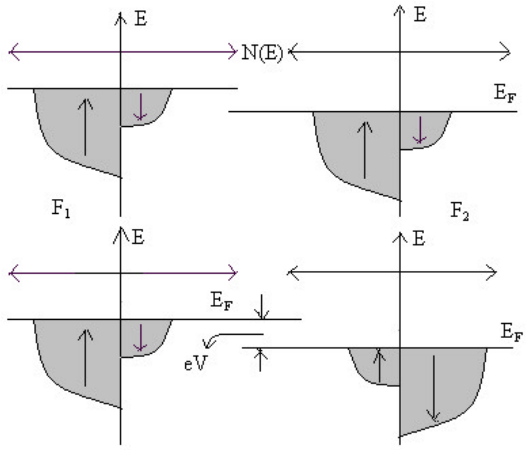


Fig. 4. Density of states of the two electrodes in the parallel and antiparallel configurations

d) *Colossal magnetoresistance* (CMR)

CMR is a colossal MR effect found in mixed valence manganese oxides ($La_{1-x}A_xMnO_3$, A = Sr, Ca and Ba) [12]. These materials exhibit charge, orbital and magnetic ordering. They undergo a simultaneous metal to insulator transition and ferromagnetic to paramagnetic transition. The transition from paramagnetism to ferromagnetism is accompanied by a sudden reduction in the resistivity. CMR is observed close to Curie temperature T_c in this regime. The same loss of resistivity should be observed in an applied magnetic field, since this aligns the electrons spins and also prevents the scattering caused by spin disorder. CMR ratio can reach as much as 100% in magnetic fields of a few teslas.

e) *Giant magnetoimpedance* (GMI).

GMI can be defined as the change of the impedance response of a conducting soft ferromagnet, subjected to an AC current of small amplitude, when a DC magnetic field is applied [13]. GMI is observed at higher frequencies when the magnetic penetration depth, or skin depth δ, is smaller than the sample thickness. The applied current flows effectively just in a shell of thickness δ, near the surface, giving rise to increased values of both the real and imaginary parts of the impedance. Application of the axial magnetic field leads to a considerable decrease of the transverse permeability, increase of the penetration depth, and hence to a decrease of both the resistance and reactance ($\Delta Z/Z \approx 80\%$). GMI has been studied in amorphous and nanocrystalline wires, ribbons and films with high magnetic permeability.

IV. Outlook. Applications

There are continuing efforts to find 100% spin-polarised conducting materials. These are materials that have only one occupied spin band at the Fermi level (half ferromagnetic and half antiferromagnetic metals). There is still much to learn about the spin injection and spin transport in semiconductor, about the nature of the coupling across semimetal, semiconductor and even insulators interlayers. The study of layered magnetic structures is one of the hottest topics in magnetism today, due to growing applications in magnetic sensors and in magnetic storage media. The GMR effect has turned out to be very useful for sensors, particularly those for read heads in computer hard-disk drives. Other potential applications for GMR lie in robotics and sensors to control mechanical movements by using the so called exchange-biased spin-valve layered structures. Even more exciting inventions are the prototypes of novel non-volatile magnetic random access memory devices (MRAM), which are based on tunneling magnetoresistance (TMR) in magnetic tunneling junctions, and of spin-field effect and –valve transistors, hybrid devices in which ferromagnetic and semiconducting materials have been functionally integrated [14].

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