Spin-dependent tunnel transport and spin polarisation

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The field of spin electronics keeps expanding and spin-dependent transport phenomena can be found in many different conduction mechanisms. In his lecture, Henri Jaffres will present mechanisms based on diffusive conduction. The key parameters for diffusion are scattering centers, mean free path, spin flip scattering ... In this lecture the case of transport through an insulating barrier will be introduced. When the electrodes on both sides of the barrier are ferromagnetic, one can also observe spin-dependent resistance i.e. tunnel magnetoresistance (TMR). However the study of TMR, requires theoretical tools which are different from the ones used to describe Giant Magnetoresistance for example. Surface properties are much more relevant than the properties of the electrodes far from the barrier.

In the first part of the lecture, the tunnel effect and its magnetic upgrade will be presented. Even if the tunnel effect dates from the beginning of the quantum era, spin-dependent tunnelling is a very recent field. The historical experiments are 30-year-old and the real development of the subject started in the 1990s. In the second part, emphasis will be put upon spin polarisation in two ways. At first I will show how spin-dependent transport through interfaces is one of the main source of information about the spin polarisation of metals and finally a quite recent class of materials will be introduced : the 100% spin polarised half metallic ferromagnets (HMF). Their existence above 0 K and their properties will be discussed.

1 Spin-dependent tunnel effect

1.1 Tunnel effect

Conduction through an insulating barrier is a purely quantum effect. This gives rise to a non ohmic behaviour of the transport properties. A simple analysis of experimental I-V curves [1] allows the determination of the key parameters (barrier height, barrier thickness). The next problem is how to introduce the spin dependence.

1.2 Magnetic tunnel effect

In 1972, tunnel magnetoresistance was observed on a cermet sample (magnetic particles embedded in an insulating matrix [2] [3]. In 1975 this system was simplified to a trilayer (ferromagnet(cobalt)/ insulator(germanium)/ ferromagnet(iron)) and a first theoretical model was proposed [4] introducing the effect of the spin polarisation P of the conduction band of the magnetic electrodes.

$$P = \frac{D\uparrow(E_F) - D\downarrow(E_F)}{D\uparrow(E_F) + D\downarrow(E_F)}$$

Since then, the technology has progressed, the samples have improved and large room temperature tunnel magnetoresistances has been achieved in 1995 [5] [6]. On the theoretical side, more complete models have been proposed (the barrier nature and parameters do not appear in Jullière's model) [7][8] but the situation is not yet completely clear.

1.3 Modelling

We will evolve from Jullière's model to recent models which includes the ferromagnetism of the electrodes in a clearer way. The tunnelling process should be treated using polarised electrons as an hypothesis, however, in a first stage, the comparison model-experiment was not very convincing. More realistic (and more complicated) treatments of both interfaces had to be used. Not only the sign and order of magnitude of the TMR effect must be predicted but second order dependences such as the temperature and bias dependence of TMR have also to be understood. These dependences can help choosing between models and give a deeper understanding of the tunnelling process and moreover since applications require 300-450 K working temperatures and a few hundred millivolt bias, zero K-zero bias properties are not sufficient.

1.4 Experimental

Tunnel magnetoresistance went from being an exotic type of low temperature magnetoresistance to a status where its magnitude at room temperature (40%) is similar or larger to that of giant magnetoresistance. It is being considered for industrial applications. The main steps to make a tunnel junction will be presented and examples of real junctions will be shown.

2 Spin polarisation

At the beginning, the interpretation of TMR values was such that not only the size of the effect was not correct but even the sign of the effect was different in the model and the experiment [9]. Taking into account not the spin polarisation from the band structure calculations but the one of the tunneling electrons, which have more of an "s" character and recalculating the band structure for interfaces brings a better understanding of the experimental facts [10] [11].

2.1 What is spin polarisation ?

Several definitions of the spin polarisation exist. The spin polarisation of the density of states at the Fermi level is the usual one but often renormalisation using the Fermi velocity is needed [13]. Different experiments do not always measure the same polarisation and great care has to be taken before comparing spin resolved photoemission[14] , TMR, Andreev reflexion [15] or metal/ insulator/ superconductor junctions [17] experiments.

2.2 Half metallic ferromagnets

In 1983, DeGroot et al. showed that a ferromagnetic material with complete spin polarisation at the Fermi level, i.e. no minority carrier at E_F, may exist : the first one was NiMnSb [12]. From the *ab initio* calculations point of view several other materials have been claimed to be half metallic ferromagnets (CrO_2, Fe_3O_4, $La_{0.7}Sr_{0.3}MnO_3$ ...) From the experimental point of view the situation is not that clear. No reproducible experimental 100% polarisation at 300 K has ever been showed [15] and even the existence of such materials is still controversial. Polarisations higher than the ones of the usual Ni,Co,Fe based alloys have been experimentally found but their temperature dependence and stability versus disorder or surface state is an open question [16].

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