Giant Magnetoresistance (T7)

1 Introduction

The discovery of giant magnetoresistance effect (GMR) in 1988 led to miniaturizatin of magnetic field sensors and significant enhancement of density of data storage on hard disc drives in a short time. This was one of the reasons behind the Noble Prize winning by Peter Grünberg (Jülich) and Albert Fert (Orsay) who led two research teams. GMR effect is a change in resistivity of magnetic multilayer stack as a result of magnetisation vectors mutual reorientation (see Fig. 1 and 2). The project is a study of the resistance dependence on external magnetic field - which influence the magnetisation behaviour and hence lead to GMR effect. The studied sample is the heterostructure of NiFe/Au/Co/Au. The obtained result should allow to trace the magnetisation evolution in the external magnetic field.

The aim of the experiment is to observe Giant Magnetoresistance effect in metallic multilayers and to study its dependence on the magnitude of the external magnetic field and its direction with respect to magnetisation. The obtained results should allow for tracing the magnetisation evolution in the external magnetic field.

1.1 Magnetism

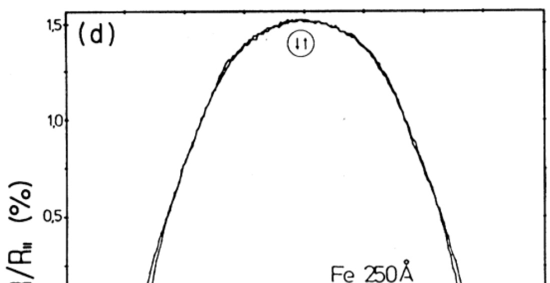


Figure 1: Relative resistance change for the two layers of iron coupled antiferromagnetically (in zero magnetic field) as a function of the external magnetic field. Arrows in circles indicate magnetization vector orientations. In the bottom part of the picture anisotropic magnetoresistance for iron [1].

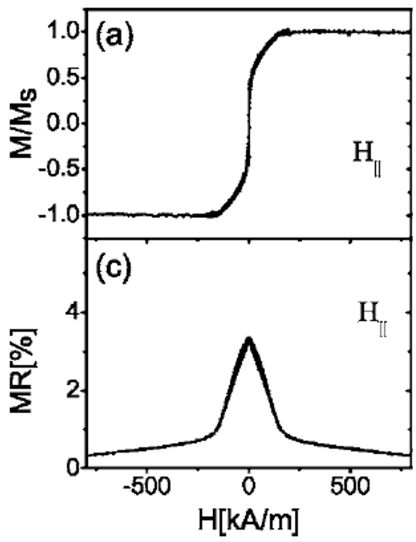


Figure 2: Magnetisation evolution and relative resistance change as a function of magnetic field for NiFe/Au/Co/Au multilayers [2].

Matter can exhibit different behavior in response to an external magnetic field. The most universal behavior, because related just to the wavefunctions of electrons, is (i) diamagnetism

that manifests itself by the emergence of a small magnetic moment with the orientation opposite to that of the magnetic field. Without magnetic field a pure diamagnet has no magnetic moment. On top of diamagnetism, some materials, especially these with unpaired electrons, exhibit (ii) paramagnetism. It means that upon application of the external magnetic field the magnetic moments (present in a material even without the external magnetic field but in a disordered manner) orient towards the magnetic field direction producing significant net magnetic moment. Finally, (iii) ferromagnetism occurs when magnetic moments remain oriented in a specific direction even without the external magnetic field. The exchange interaction (Coulomb repulsion coinciding with Pauli exclusion principle) is responsible for that. Magnetization for a ferromagnet is not zero $M \neq 0$ in zero magnetic field at least locally within a magnetic domain.
It is useful to consider magnetic susceptibility χ when referring to the magnetic properties. It is defined as:

$$\chi = \frac{dM}{dH}, \tag{1}$$

where M is magnetisation (magnetic moment μ per unit volume) and H is the magnetic field. In general, magnetic B-field depends both on H and magnetization M: $\vec{B} = \mu_0(\vec{H} + \vec{M})$. When $M(H)$ is linear, then we obtain: $B = \mu_0(1+\chi)H = \mu_0\mu_r H$.
For diamagnets χ is small and temperature independent. For a paramagnet χ is positive and inversely proportional to temperature $\chi \propto 1/T$. Ferromagnets are ordered below a certain temperature called Curie temperature T_C. They exhibit anisotropy and it can be shown that $\chi \propto 1/(T - T_C)$.

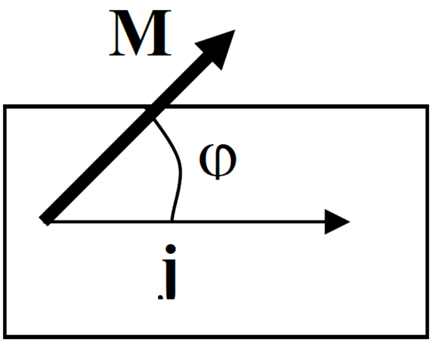
1.2 Magnetoresistance

Magnetoresistance (MR) is the relative change of resistance caused by the external magnetic field.

$$MR = \Delta R/R_0 = \frac{R(H) - R(H=0)}{R(H=0)} \tag{2}$$

This effect is commonly used for data encoding, because high/low resistance states (induced by the magnetic filed) can be interpreted as zeros/ones in binary data storage. In solid state physics there are multiple effects leading to the resistance change. In particular, a dependence of a carrier lifetime on energy, presence of multiple carrier types in a material, quantum interference, coupling between the orbital and spin magnetic moments, carrier localization or change of dimensionality due to the strong magnetic field - all these phenomena lead to a certain type of magnetoresistance. We will not describe them here in detail, but there is one effect - anisotropic magnetoresistance (AMR) - that we explain before ultimately focusing on GMR.

Resistance can depend on a direction along which it is measured. It happens in crystals having a distinguished axis due to a strain, internal electric field or magnetization direction. The last case is particulatly interesting and it is called anisotropic magnetoresistance (AMR) and it has been known since XIX century. Here, the change of the resistance that depends on the direction of the current flow with respect to magnetization (hence, the magnetic field may even not be necessary in the experiment). It is illustrated in Fig. The magnitude of AMR is small, usually a fraction of single $\%$ at room temperature. Neverthe less, it was used as a read-out operation in first magnetic memories, before GMR was introduced. The research on AMR in ultrathin metallic layers led to the discovery of GMR.



$\rho = \rho_\perp + \Delta\rho \cdot \cos^2(\varphi)$, where:
$\Delta\rho = \rho_\| - \rho_\perp$
$\rho_\|$ - resistivity for a current along the magnetization direction ($\varphi = 0°$),
$\rho_\perp$ - resistivity for a current perpendicular to the magnetization direction ($\varphi = 90°$),

Figure 3: Orientation of the $\vec{M}$ and $\vec{j}$ vectors for the illustration of AMR effect. See also bottom curve in Fig. 1.

The GMR effect is a dependence of resistance on the mutual orientation of magnetic metallic multilayers in a heterostructure as indicated in Fig. 1 and Fig. 2. The external magnetic field is responsible for reorientation of magnetization vectors of the layers. They reorient in different field magnitudes due to different coercivities. The simplest way of understanding the effect is taking into account the spin degree of freedom and scattering that depends on spin. In a ferromagnetic metal density of state at the Fermi level is different for up and down spins (Fig. 4a), which leads to different scattering for these two spin directions and different resistivity values. Fig 4b shows ratio between $\rho_\uparrow$ and $\rho_\downarrow$ for different ferromagnetic metals. It can be seen that disproportion can be large. To describe conductivity, two-current model can be introduced. It can be understood in terms of two resistors connected in parallel, where any processes related to spin flip (change from up to down or reverse) are neglected.
Two current model is always considered for a single ferromagnetic layer of metal with magnetization M. Some carriers for instance with up spin are scattered strongly. If we reverse the magnetization direction the other type of the carries is scattered strongly. An interesting case occurs for a set of two adjacent layers (usually separated by a non-magnetic spacer to allow independent manipulation of layers' magnetizations). If their $\vec{M}$ vectors have opposite orientation, spin-up carriers will be scattered strongly in one layer and spin-down electrons will be scattered strongly, too, in another layer. However, if the magnetization vectors have the same orientation, one carrier type will not be scattered strongly, which will result in small resistance state. If we have an ability to control the orientation of $\vec{M}$ we can switch between high and low resistance states. Relative change or resistivity is much larger than for AMR and reaches several tens of percents. Therefore, the effect has been named giant magnetoresistance. The magnitude of GMR effect depends on $\propto \cos(\gamma)$, where γ is the angle between the magnetization vectors. Hence, from $R(B)$ dependence, the evolution of magnetization vectors in the external magnetic field can be determined indirectly.

2 What should you know before undertaking the project?

General facts related to the solid-state physics and metals:

a. Band structures of solids, Bloch function, k-vector, band structure $E(k)$, electron in solid state, density of states and its dependence on energy

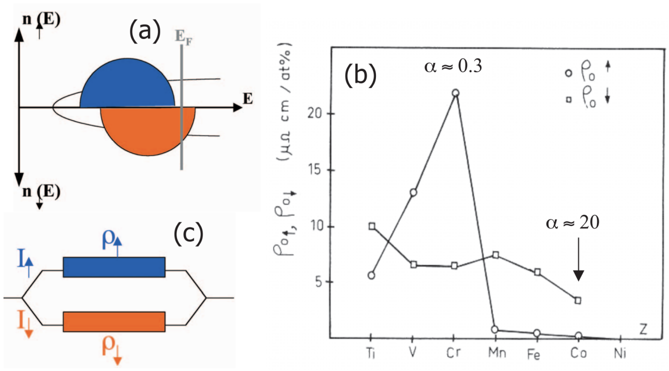


Figure 4: (a) Density of states in the conduction band for the ↑↓. Square root dependence shows the density of states originating from s orbitals, colorful semicircles represent d orbitals split due to the exchange interaction, (b) resistivities $\rho_\uparrow$ and $\rho_\downarrow$ for different metals, (c) schematic illustration of the two-current model [3].

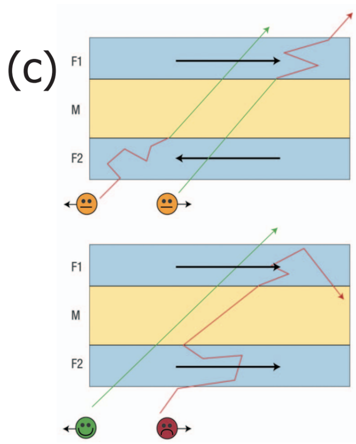


Figure 5: The scheme of GMR occurrence for the out-of-plane configuration (the effect can be also present for the in-plane configuration, i.e. curent along the layers [3].

b. Drude model of conductivity, mobility, scattering of carriers, mean free path and carrier lifetime, ordinary Hall effect.

Specific details related to magnetism and experimental technique:

c. Magnetic moment, magnetization, interaction of matter with magnetic field: diamagnetism and paramagnetism.
d. Exchange interaction and long range orders: ferromagnetism, antiferromagnetism.
e. Magnetic anisotropies, hard and easy magnetic axes, magnetization dependence on magnetic field for easy and hard axes. Hysteresis loop and coercivity.
f. Ferromagnetic metals and its band structures.
e. Methodology - four point voltage measurement, Hall effect for a single carrier type, determination of Hall coefficient with elimination of parasitic effects such as asymmetry or thermoelectric forces.

You are expected to refer not only to this instruction but also to the literature (you will find suggested literature at the end with the first three positions as strongly recommended [?, ?, ?]).

3 Sample investigated

The studies samples are metallic multilayers $(\text{NiFe/Au/Co/Au})_N$, where N is the repetition number. The layers were deposited on the non-conductive Si substrate. They were produced in the Institute of Molecular Physics PAS (IFM PAN) in Poznan, Poland. In the neighbourhood of Au, cobalt has magnetization perpendicular to the layer, permalloy (NiFe) - in-plane of the layer.

The exact sample structure with corresponding thickness expressed in nm is: $[\text{NiFe (2) / Au(2) / Co (0.8) / Au (2)}]_N$ with N up to 15. Electrical contacts are made from indium (9N) baked for 2 hours at $T = 190\,^\circ\text{C}$, which allows for In interdiffusion to the layers.

4 Experimental procedures

1. Familiarizing with the experimental setup.

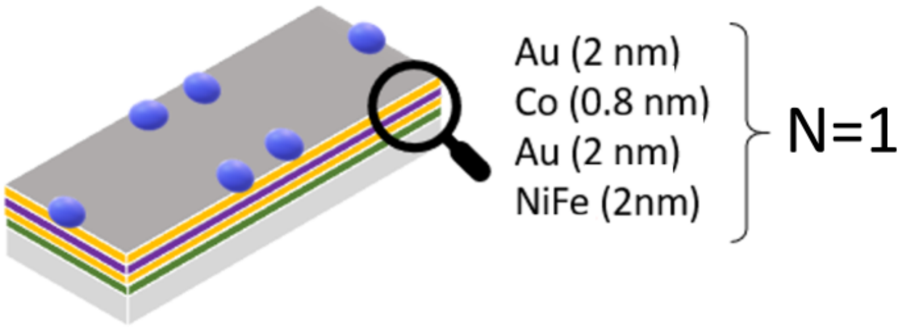


Figure 6: Sample scheme with blue spheres indicating electrical contacts.

   (a) Multichannel voltmeter Keithley 2000 is equipped with so-called scanner card, which allows for a measurement of 10 distinct voltages. A proper input should be chosen (FRONT/REAR) and then the voltage can be read by pressing OPEN/CLOSE.
   (b) Power supplies for the sample and the magnet. Both of them can either stabilize voltage or current.
2. Calibration of the electromagnet $\rightarrow$ determination of the magnetic field ($\mathbf{B}$, measured by a teslameter) on the current magnitude ($\mathbf{I_B}$) flowing through the coil. The $\mathbf{H}$ field is proportional to the current. The current is measured by the voltage drop accross the standarized resistor in series with the coil. Since $\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M})$, where μ_0 is free space permeability equal to $\mu_0 = 4\pi \cdot 10^{-7}\,\mathrm{N/A^2}$, the contribution to $\mathbf{B}$-field may also come from electromagnetic pole pieces (remanence). You should determine how strong is the effect. The maximum current for electromagnet is $I_{\mathrm{Bmax}} = 10\,\mathrm{A}$.
3. Measurements of GMR samples.
   (a) Two-point resistance check of the sample (between contacts 7-8, 1-2, 4-5, 1-4).
   (b) A cable resistance determination in a 4 point measurement as a training.
   (c) Measurement of I-V (current-voltage) curves at room temperature $\rightarrow$ for the samples A and B and determination of the samples resistance. The maximum sample current $I_{\mathrm{max}} = 10\,\mathrm{mA}$.
   (d) Measurement of the resistance as a function of magnetic field at room temperature for sample A $\rightarrow$ magnetoresistance and evolution of magnetization determination.
   (e) Measurement of the resistance as a function of magnetic field at room temperature for sample B $\rightarrow$ magnetoresistance and evolution of magnetization determination (+for IND students: Hall voltage analysis.)
   (f) Measurement of the resistance as a function of magnetic field at liquid nitrogen temperature for sample A or B $\rightarrow$ magnetoresistance and evolution of magnetization determination (+for IND students: Hall voltage analysis in B sample.)

5 What should you include in the report?

The report must include the following parts:
1. Abstract - here you summarize what has been done in a concise manner.
2. Theoretical introduction - where you briefly recall fundamentals relevant to the achieved results, studied effects and the material.
3. Description of the methodology - it answers the question how the experiment was done, what was the setup and the sample as if someone else wanted to reproduce the result.

4. Results and analysis - where you present obtained data in a clear way, describe the observations (do not treat anything as obvious), determined parameters and comment on them and interpret it.
5. Summary and conclusions - where you recap the most important results and draw conclusions.

The report should have a form of a scientific publication. During report writing remember about enumerating all the equations and figures. When using external resources or citing, please provide references in the bibliography at the end. Refer to the supervisor of the project in case of doubts.

References

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