PYL 102

Monday, Nov. 3, 2024

Magnetoresistance

Resistivity in metals

Conductivity is given by: $$\sigma = \frac{ne^2\lambda}{\hbar k_F}$$

The finite mean free path arises from the presence of defects, phonons, e-e scattering etc.

We know that Fermi electrons are responsible for conductivity: free electrons.

How does e transport depends on orbital s, d etc?

s electron behaves as almost free e's, any scattering from impurities is very weak. d orbitals are much narrower than s e's, so m* will be higher.

$$m^* = \frac{1}{d^2E/dk^2}$$

If band is narrower e's will interact much more strongly with lattice than for a wide free electron band. This means that they are much more affected by the imperfections so τ is much shorter for d e's than for e's.

This means that d e's contribute less than s e's to the conductivity.

Spin dependent transport properties

Under the presence of a magnetic field an electron can spin in one of two directions, its own field, aligns with the external field, “up” or aligns opposite to the external field, “down”. In a magnetic material most electrons are aligned in the direction of the net magnetic field—that is, there are more up electrons than down electrons. This distinction between up and down electrons is carried over to nonmagnetic materials.

There must be difference in conductivities for e’s in majority (spin-up) and minority (spin-down) spin bands and little spin mixing so that two channels act independently.

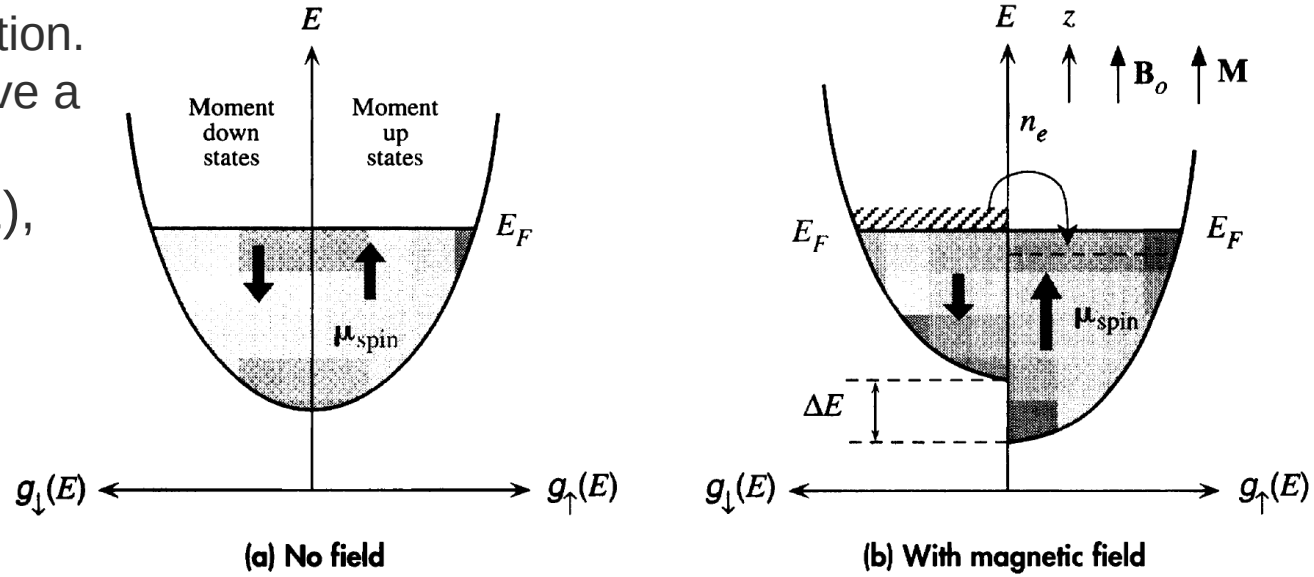
Giant magnetoresistance is a term for a significant >5% change in electrical resistivity as the sample magnetization is changed.

For spin dependent scattering, the lateral dimension must be small compared with the e mean free path.

Pauli spin paramagnetism in metals due to conduction electrons

The paramagnetism arises from the alignment of the spins of conduction electrons with the applied magnetic field. A conduction electron in a metal has an extended wave function and does not orbit any particular metal ion. The conduction electron's magnetic moment arises from the electron spin alone (1/2 and -1/2). In the absence of a magnetic field, the energies of magnetic moment up and down states (or wavefunctions) are the same. Both states have the same energy, and both are equally occupied.

In the presence of an applied field B_0 along the z direction. For electron's magnetic moment along the field will have a lower potential energy. In the presence of a field B_0, all states with magnetic moment up, and hence g (E), are lowered in energy by βB_0, where β is the Bohr magneton. All states with magnetic moment down are raised by βB_0.

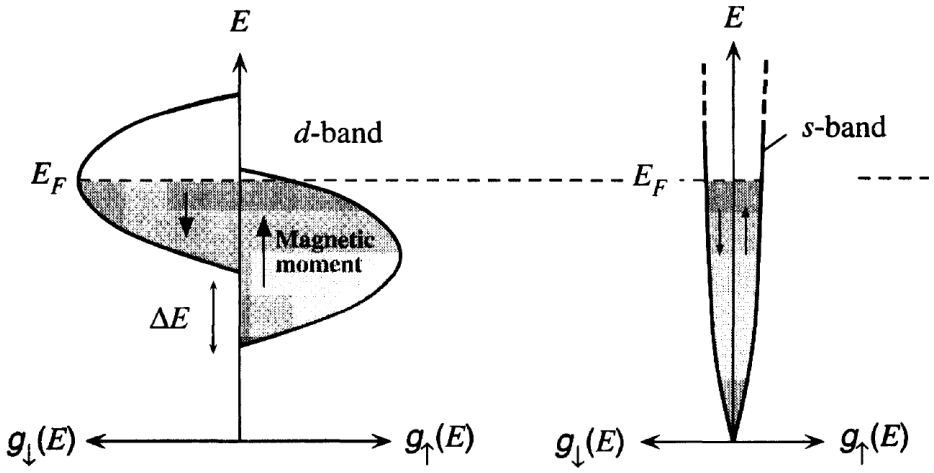


The electrons with magnetic moment down near E_F can now find lower energy states in the $g_\downarrow(E)$ band and hence flip their spins and transfer to the $g_\uparrow(E)$ band. So, there are now more electrons in states with spin up. When averaged over all conduction electrons there is now a net magnetic moment per conduction electron along the z direction or the applied field.

$$X\_para = (u\_o)B^2\, g(E\_F)$$

Energy band model of ferromagnetism

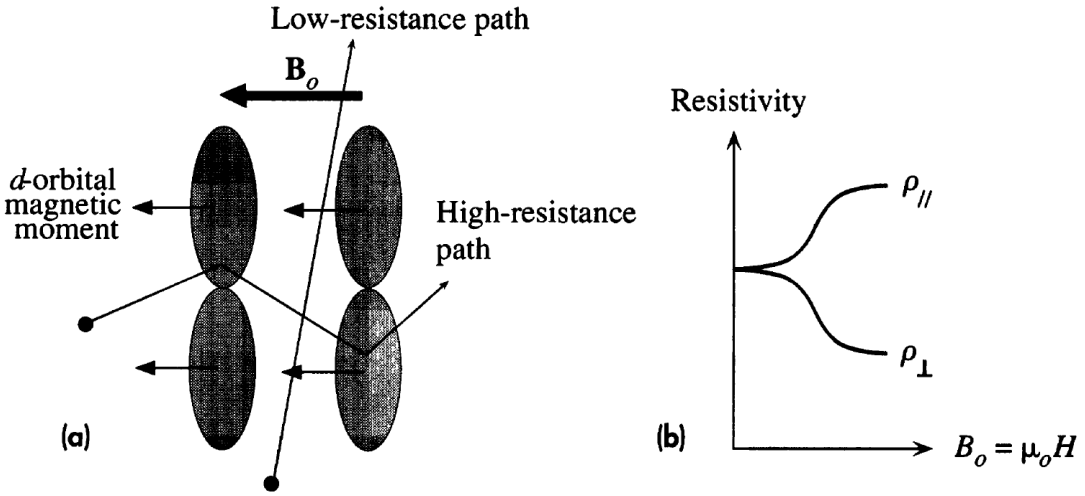
The valence electrons belong to the whole crystal. The exchange energy causes the spin magnetic moments of two electrons to line up parallel to each other so that their energy is lowered. In magnetic metals such as Fe, Ni, and Co s -band and the d-band are important. The two bands overlap but the s -band is much wider. We can represent the density of states for magnetic moment up and magnetic moment down states separately.



In d-band, the density of states g (E) for up states is lowered by ΔE with respect to the density of states for down states due to the exchange energy. The energy lowering Δ E for the s-band can be neglected. All the states up to the Fermi energy are occupied. For Fe, the d-band up states are filled almost to the top of the band (96% full), and magnetic moment down states are filled roughly halfway. Thus, there are many more electrons with moments up than moments down.

The s-band is filled up to E_F and there are almost equal numbers of spin up and down electrons. The ferromagnetic effect arises from the behavior of electrons mainly in the d-band. Electrical conduction, on the other hand, is determined by electrons in the s-band. The spin of the electron cannot be flipped easily in a scattering process. An s-electron with its moment down can be easily scattered into the empty states in the corresponding moment-down d-band, but the moment-up electron has no states in the moment-up d-band into which it can be scattered. Conduction occurs by moment-up electrons, these are the favoured electrons for conduction.

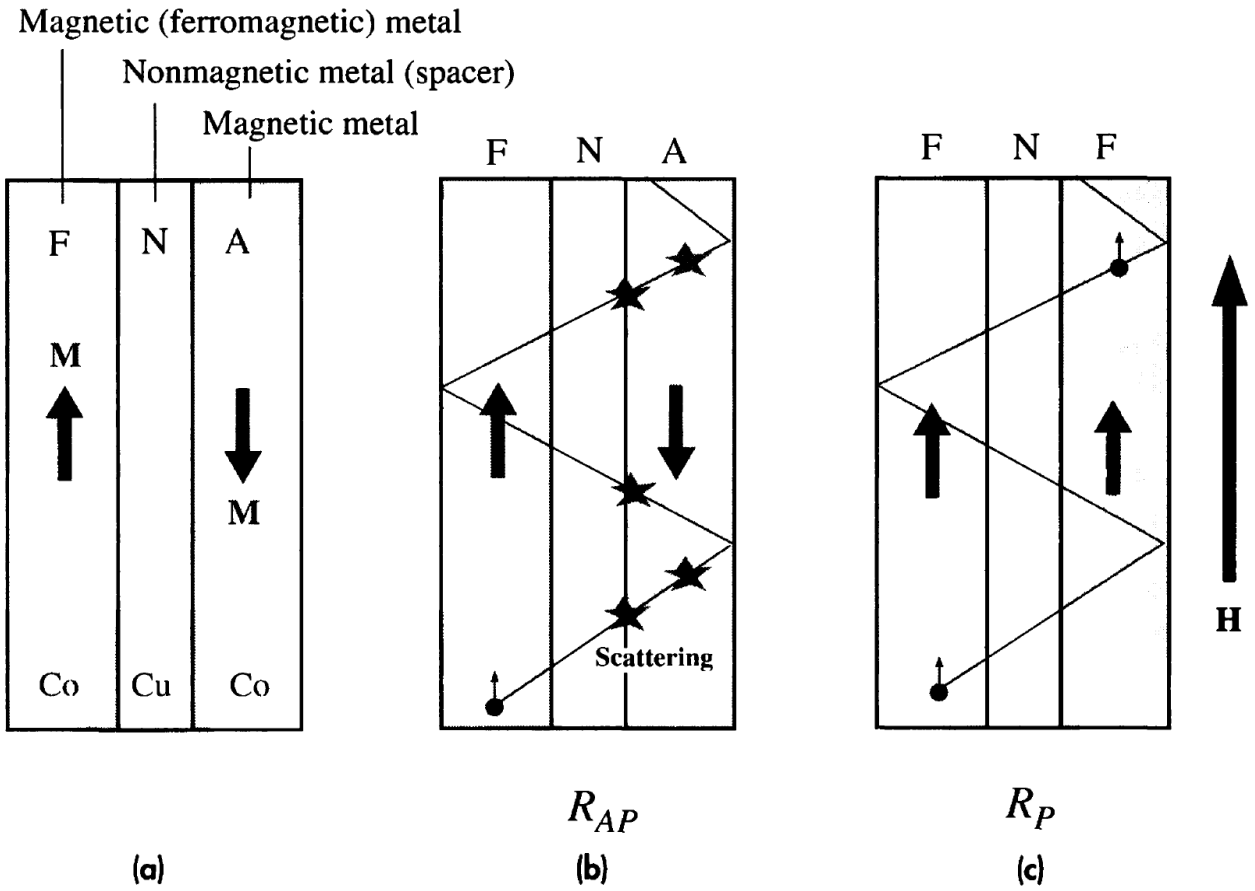
Magnetoresistance



Magnetoresistance refers to the change in the resistance of a material when it is placed in a magnetic field. When a nonmagnetic metal such as copper is placed in a magnetic field, the change in its resistivity is very small and has no real practical use. When a magnetic metal, such as iron, is placed in a magnetic field, the change in the resistivity depends on the direction of the current flow with respect to the magnetic field. The change in the resistivity due to the applied magnetic field is anisotropic.

The change in resistivity is limited to a few percent. The origin of anisotropic magnetoresistance (AMR) is that the electrons traveling along the field experience more scattering than those traveling perpendicular to the field. Resistivity depends on the current flow direction with respect to the applied magnetic field.

A very large magnetoresistance, called giant magnetoresistance (GMR), has been observed in certain special multilayer structures, which exhibit substantial changes in the resistance (> 10%) when a magnetic field is applied. The special multilayer structure in its simplest form has two ferromagnetic layers (such as Fe or Co) separated by a nonmagnetic transition metal layer (such as Cu), called the spacer.



The magnetic layers are thin (<10 nm), and the nonmagnetic layer is even thinner. The magnetizations of the two ferromagnetic layers are not random, they depend on the thickness of the spacer because the two layers are coupled indirectly through this thin spacer. In the absence of an external field, two magnetic layers are coupled in such a way that their magnetizations are antiparallel. This arrangement is also called an antiferromagnetically coupled configuration. We can apply an external magnetic field to one of the layers and rotate its magnetization so that the two magnetizations are now in parallel. This parallel configuration is frequently called ferromagnetically coupled layers. The two structures have a giant difference in their resistances, hence the term giant magnetoresistance.

The difference in the resistances Rp and Rap in this simple trilayer is roughly 10% or less. But, in multilayered structures, which have a series of alternating magnetic and nonmagnetic layers, the change in the resistance can be large, exceeding 100% at low temperature and 60-80% at room temperature.

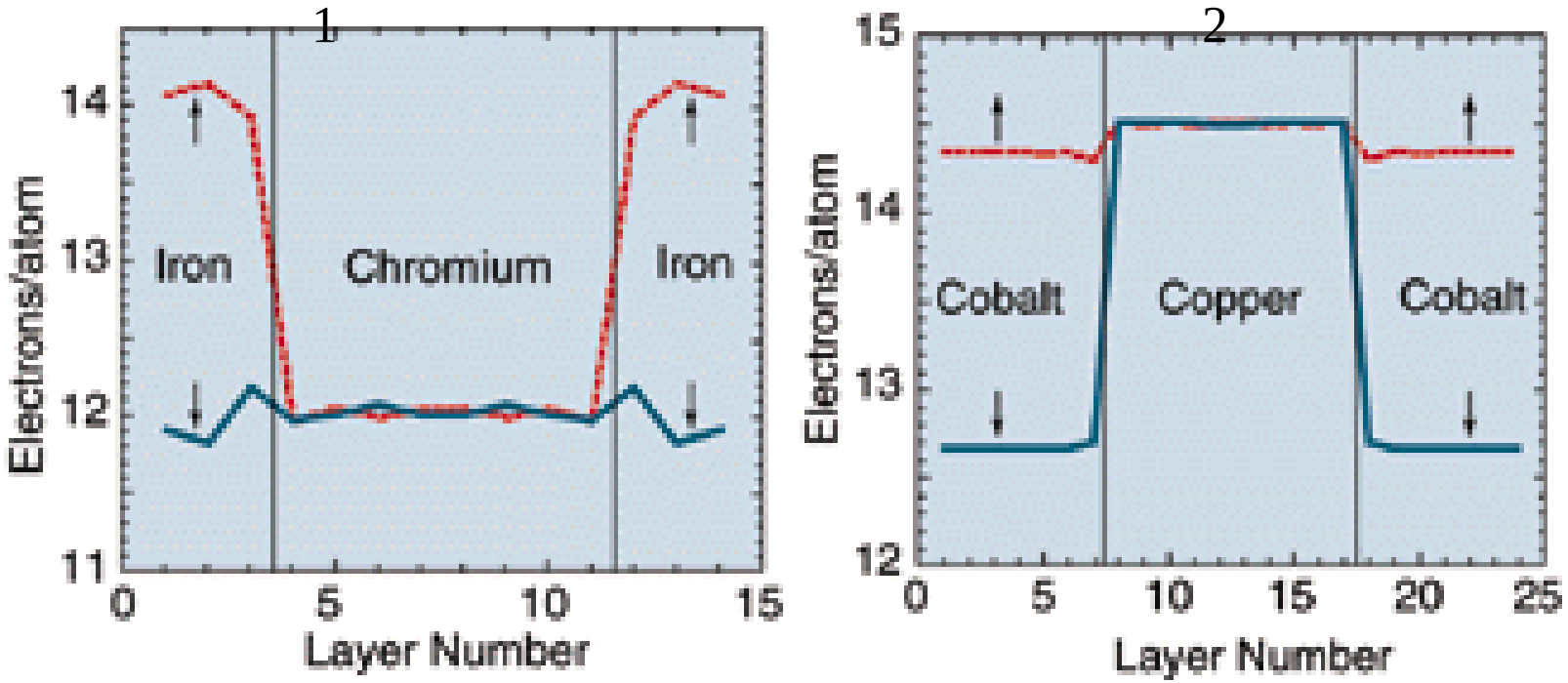
Sample	Structure and layer thicknesses	$\Delta R/R_P$ (%)	Temperature (K)
CoFe/CAgCu/CoFe	Trilayer	4–7	300
NiFe/Cu/Co	Trilayer, 10/2.5/2.2 nm (spin valve)	4.6	300
$Co_{90}Fe_{10}/Cu/Co_{90}Fe_{10}$	Trilayer, 4/2.5/0.8 nm (spin valve)	7	300
$[Co/Cu\ ]_{100}$	100 layers of Co/Cu, 1 nm / 1 nm	80	300
$[Co/Co]_{60}$	60 layers Co/Cu, 0.8 nm / 0.83 nm	115	4.2

The GMR effect is often measured by quoting the change in the resistance with respect to Rp,

$$\left(\frac{\Delta R}{R_p}\right)_{\text{GMR}} = \frac{R_{\text{AP}} - R_P}{R_p}$$

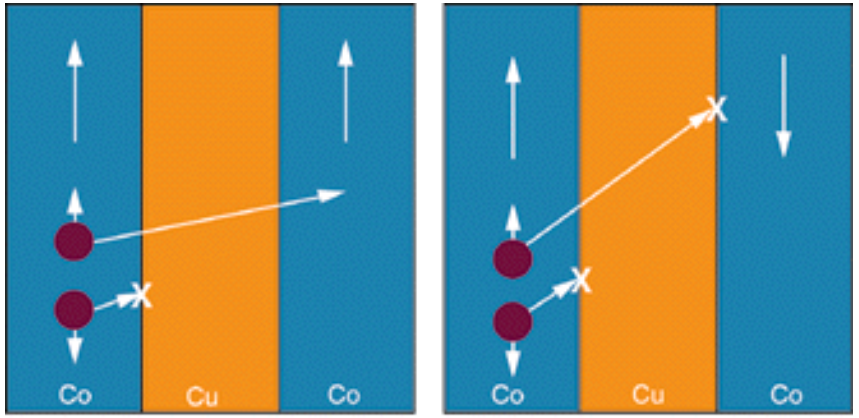
If the angle between the magnetization vectors M1 and M2 of the two magnetic layers is θ

$$\frac{\Delta R}{R_P} = \left(\frac{\Delta R}{R_P}\right)_{\text{max}} \frac{1 - \cos\theta}{2}$$



Figs show the number of up and down spin e's calculated for each atomic layer of a system consisting of eight chromium layers embedded in iron and for a system consisting of ten copper layers embedded in cobalt. Both of these systems show a large GMR. For the iron-chromium layers, note that the number of down-spin electrons is about the same in the iron and chromium, but the number of up-spin electrons is very different. Conversely, the number of up-spin electrons is very similar on each layer of the copper-cobalt system, but the number of down-spin electrons changes abruptly at the interfaces.

Source: www.ornl.gov Prof. Butler, Zhang and Nicholson



Magnetic field

Low resistivity

No magnetic field

High resistivity

Let us consider the case in which the ferromagnetic layers are cobalt and the nonmagnetic layer is copper.

• The up-spin electrons hardly notice any difference in the number of electrons per atom as they travel from the ferromagnetic layer to the nonmagnetic layer. To them the lattice potential is smooth and almost defect free.

• On the other hand, the down-spin electrons see a large difference in electron numbers between atoms of copper and cobalt. They see many bumps at the interface.

• When excess spins in the two ferromagnetic layers have the same direction up-spin electrons travel freely from one ferromagnetic layer across the interface to the other ferromagnetic layer snd down-spin electrons will scatter strongly at both interfaces.

• When the excess spins in the two ferromagnetic layers have opposite directions both the up- and down-spin electrons will scatter at one of the interfaces.

• The electrical resistivity for the aligned case should be lower because up-spin electrons in this case experience very little resistance and act like a short circuit.