Ferromagnetism and Electronic Transport

There are a number of effects that couple magnetization to electrical resistance. These include:

• Ordinary magnetoresistance (OMR)
• Anisotropic magnetoresistance (AMR)
• Giant magnetoresistance (GMR)
• Tunneling magnetoresistance (TMR)
• Ballistic magnetoresistance (BMR)
• Colossal magnetoresistance (CMR)

We’ll look briefly at the physics taking place in each of these.

Ordinary magnetoresistance (OMR)

This is the same magnetoresistance that comes about in normal metals.

• (Total internal) magnetic induction affects orbits of electrons at Fermi surface.
• Result of tightening orbits at higher fields is a positive magnetoresistance.
• \( H \parallel J \) has a weaker effect than \( H \) perp. to \( J \).
• In polycrystalline materials and those where boundary scattering is important, again can have interplay between magnetic induction and disorder.
• In clean metals, OMR typically ~ \( B^2 \), and can be ~ 10% at 10 Tesla
Anisotropic magnetoresistance (AMR)

Pointed out experimentally as early as 1930s (though really solidly confirmed in 1960s) that FM material measured resistance depends on relative directions of $M$ and $J$.

Data from bulk permalloy (80% Ni, 20% Fe).
- Resistance lower if $M$ perpendicular to $J$.
- Resistance higher if $M$ parallel to $J$.

Anisotropic magnetoresistance

Physical origin: spin-orbit coupling leads to spin-dependent scattering of conduction electrons.

Conduction in (for ex.) Ni due to 4s and 3d electrons.

Crudely, the 3d orbitals are affected by $M$, and are mixed (slightly reoriented) so that they present a larger scattering cross-section to electrons moving parallel to $M$.

More scattering = higher resistance.
Anisotropic magnetoresistance

Typical size of effect: ~ 1%.

Typical field scale: determined by physics of reorienting $M$.

- In bulk permalloy, 5 - 10 Oe.
- In permalloy wires with large aspect ratios, ~ 1 T.

Weak temperature dependence (competition between this scattering and other scattering mechanisms) - effect gets slightly larger at lower $T$.

Giant Magnetoresistance

- Discovered in laboratory c. 1988.
- Not a trait of pure FM materials! Requires nanostructured composites of FM and nonmagnetic metals.
- Superlattice of very thin alternating layers of FM and N metals.
- Original configuration = current in plane
Giant Magnetoresistance

Physical origin: spin-dependent transmission of carriers at interfaces between N and FM metals.

- There is some net spin polarization of the carriers.
- Density of states as a function of spin orientation is affected by $M$.
- Spins that are the majority species in one orientation of $M$ are the minority species (lower DOS at Fermi level) in regions when $M$ is oppositely directed.

![Diagram showing aligned and antialigned states](image)

aligned = low resistance  antialigned = high resistance

Giant Magnetoresistance

- Typical size of effect: ~ 100%. Depends on percentage of spin polarized carriers at Fermi level, and zero-field coupling between neighboring FM layers.
- Note that relative directions of $M$ and $J$ not directly relevant.
- Typical field scale: determined by physics of reorienting relative directions of adjacent FM layer magnetizations. Usually arranged to be low.
- Interface quality is crucial.
- Coupling between adjacent FM layers oscillates with thickness of N layers: layer thicknesses and roughness must also be controlled.
- Effect gets larger at lower $T$ and for cleaner metal layers as other scattering contributions are reduced.
Device geometries

- Original device was current-in-plane (CIP).
- If interfaces really dominate, GMR effects should be substantial in current-perpendicular-to-plane (CPP) devices, and they are.

How are these systems actually used? *Spin-valve* geometry.

Use antiferromagnetic “pinning layer” to lock magnetization of one FM layer.

Other FM is made to be magnetically soft - $M$ easily realigns in small fields.

Tunneling magnetoresistance

Spin-dependent density of states should have other consequences.

Is possible to make FM-I-FM tunnel junctions.

Tunneling conductance depends strongly on relative densities of states of spin species.

In fact, tunneling magnetoresistance (TMR) is used to determine spin polarization at Fermi level.
Tunneling magnetoresistance

Define spin polarization $P$ as

$$P = \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow}$$

Here the $N$s are proportional to the relevant densities of states at the Fermi level.

Model of Julliere (1975):

Tunneling conductance will be proportional to tunneling rates, and tunneling rates will be proportional to number of carriers trying to tunnel (DOS of one FM) and number of available states (DOS of other FM).

Assume that tunneling preserves spin (clean interfaces, etc.).

$$G_{\uparrow\uparrow} \sim (N^\uparrow)^2 + (N^\downarrow)^2 \quad G_{\uparrow\downarrow} \sim 2N^\uparrow N^\downarrow$$

Combining with definition of $P$,

$$G_{\uparrow\uparrow} \sim \frac{1}{2}(1 + P^2)(N^\uparrow + N^\downarrow)^2$$

$$G_{\uparrow\downarrow} \sim \frac{1}{2}(1 - P^2)(N^\uparrow + N^\downarrow)^2$$

Compute ratios, and unknown factors drop out:

$$\frac{G_{\uparrow\uparrow} - G_{\uparrow\downarrow}}{G_{\uparrow\downarrow}} = \frac{(1/R_{\uparrow\uparrow}) - (1/R_{\uparrow\downarrow})}{(1/R_{\uparrow\downarrow})} = \frac{\Delta R}{R_{\uparrow\downarrow}} = \frac{2P^2}{1-P^2}$$

$$\frac{\Delta R}{R_{\uparrow\downarrow}} = \frac{2P^2}{1+P^2}$$


Ni: 23%  Fe: 40%  Co: 35%  NiFe: 32%
Tunneling magnetoresistance

- Typical size of effect: ~ 100%. As in GMR, depends on percentage of spin polarized carriers at Fermi level.
- Note that relative directions of \( M \) and \( J \) not directly relevant.
- Typical field scale: determined by physics of reorienting relative directions of adjacent FM layer magnetizations. Usually arranged to be low.
- Interface quality is again crucial - growing good tunnel barriers is very tough without doing odd things to the magnetic properties at the interface.
- Should be ~ temperature independent.

Ballistic magnetoresistance

GMR (1988)

BMR (1988)

- Nano- or atomic-scale point contacts between FM electrodes
- Magnetization apparently changes direction on length scale shorter than (elastic?) scattering length.

Result: very large magnetoresistive effects, postulated to be for similar physics reasons as TMR.
Ballistic magnetoresistance

- First measured using mechanical break junction technique.
- Effect can be large – factor of 3 change in conductance!

Unanswered questions:
- Truly ballistic?
- Magnetic “dead layer”?
- Magnetostriction?
- How large can effect be?

Colossal magnetoresistance

- (Re)discovered in 1993.
- Takes place in specific family of compounds, perovskites of the form $A_1^x B_x MnO_3$, where $A = \{La, Pr, Nd, Sm\}$, $B = \{Ca, Sr, Ba\}$.
- Physical mechanism is completely different than any described so far.
Colossal magnetoresistance

• Size of effect: ~ 100000% (!)

• Extremely temperature and doping dependent - challenging to get useful, reproducible behavior at room temperature.

• Mechanism: phase transition between conductive FM ordering of Mn ions and insulating AFM ordering of Mn ions.

Replacing rare earths with light metals changes some of the Mn from Mn$^{3+}$ to Mn$^{4+}$. Charge can hop from Mn to Mn via the oxygen anions. Strong FM exchange favors hopping of aligned spins (high conductance).

• Still not well understood!

• Of much interest because of large effects and very high spin polarization of carriers.

Spin currents and magnetization

We’ve been talking about how $M$ affects $J$, ability to transport charge, as manifested through magnetoresistive effects.

One can also consider the converse: can a current $J$ of carriers with a net spin polarization affect $M$?

Yes!

• A current with a net spin polarization means a flow of angular momentum from one region to another.

• This results in a net torque on the spins in those regions, and for high enough torques, it can be energetically favorable for domains to rearrange themselves.
Spin currents and magnetization

Here’s an example, involving current flow into a GMR multilayer.

Change in magnetization direction of one of the layers is detectable by GMR effect - change in electrical resistance.

Note, should be *asymmetric* in current direction!

Spin currents and magnetization

Myers et al., Science 285, 867 (1999)

Katine et al., PRL 84, 3149 (2000)

Clear demonstration of current-induced magnetization reversal.

Ability to manipulate $M$ without applying external fields is potentially very attractive technologically.

One example of spintronics that we’ll cover soon.
Spin currents and magnetization

Can do more - time-domain studies!
Direct measurements of current-induced torques.
Summary

• Magnetization can affect electronic conduction through several mechanisms:
  • Local $B$ field (OMR)
  • Band structure and scattering (AMR)
  • Spin-dependent transmission and scattering (GMR, TMR)
  • Coupling between charge and magnetic order (CMR)
• Current can also affect magnetization, as shown in current-induced magnetization reversal experiments.

Next time

Demands of data storage industry, particularly magnetic.