The story so far:

- Devices based on ferromagnetism have found tremendous utility in technology.
- Ferromagnetism at the nm scale is increasingly important, and physical effects (e.g. superparamagnetism) not usually seen in large devices will become relevant imminently.
- Physics of carriers in ferromagnets is an active area of research - the interplay between magnetization and current is still being explored.

Today:

- Extraordinary magnetoresistance
  Learning a lesson from a nanostructured material, and applying it to an engineered device.
- Magnetic Random Access Memory (MRAM)
  Using GMR and TMR in a 21st century form of core memory.
- Other applications of nanoscale magnetic particles
  Magnetorheological fluids
  Chemical or immunoassay
  Medical applications
Extraordinary Magnetoresistance

In 1998, Thio and Solin at NEC were studying an extremely narrow band gap semiconductor, Hg$_{x}$Cd$_{1-x}$Te.

They discovered, much to their surprise, that this material exhibited an extremely large magnetoresistance at room temperature:

EMR

What is going on in this material?

Electrons dominate transport in this material because $\mu_e \sim 10^5$ cm$^2$/Vs even at room temperature (!) (very small electron effective mass), and $\mu_e/\mu_h \sim 200$.

Compositional fluctuations on length scales < 1 micron can result in small inclusions of metallic material with much higher conductivity than the nominal semiconductor:
EMR - mechanism

What do these high conductivity inclusions do?

- In substantial magnetic fields, $B$ is perpendicular to $E$ because the Hall field is very large.
- For very metallic inclusions, $E$ is perpendicular to the surface of the inclusion.

Result:

- In low magnetic fields, current flows mostly through inclusions - conductance is high.
- In high enough fields, current flows mostly around inclusions - conductance much lower.

Image from Thio, NEC

EMR - application

Once the mechanism was understood, Solin et al. started engineering structures to magnify this effect.

Now use $n$-type InSb film (again, high mobilities, largely because $m_e \sim 0.014 m_0$).

Instead of accidental inhomogeneous pockets, deliberately introduce Au regions (Ohmic contact to $n$-InSb).
EMR - application

Nonmagnetic read head (!) with very narrow active region and large MR effects.
Should be immune to magnetization noise, since contains no FM material.

Magnetic Random Access Memory

The same spin-dependent scattering that has been used to produce GMR and TMR materials for HDD read heads can be used for nonvolatile computer memory.
Remember ferrite cores?

MagRAM Architecture

Image from IBM website
MRAM

Two possible architectures:
- GMR-based
- TMR-based

IBM betting on TMR design.
Refining tunnel junctions - 1 nm Al₂O₃ tunnel barriers, FeCo alloy for ferromagnet layers.

Imagine:
- As fast as DRAM.
- As nonvolatile as flashRAM.
- Instant-boot computers.

Motorola, IBM trying to move this technology into production by 2004.
Motorola has already demonstrated 1Mb MRAM chip (June ‘02).
Other applications of nanoscale magnetism

- Magnetoassay
- Magnetorheological fluids
- Medical applications

Magnetoassay

There is a big market for biocompatible FM nanoparticles.

The basic idea:
- Functionalize outside of biocompatible FM particle with particular compound that binds to some analyte.
- Expose to bio system and see whether things bind to the magnetic particle.
Magnetoassay

Problems:

• Most magnetic materials aren’t very biocompatible.

• Often researchers try to win by mixing materials with high $M$ values into relatively inert polymer beads.

• Downside: beads end up being large.

• Tricky to handle FM particles without them sticking together.

Magnetoassay

Advantages:

Cheap, fast, reliable, easy to detect w/o fancy optics.

Image from Naval Industrial Partners website
Magnetorheological fluids

Ferrofluids are colloidal suspensions of sub-micron FM particles (often Fe₃O₄).

Without an applied magnetic field, just act like a viscous fluid.

With an applied magnetic field, effective viscosity can change by several orders of magnitude (!):

Magnetorheological fluids

Highly useful in things like magnetic clutches.
Suggested for applications like body armor.
Suggested for magnetic actuation in medical applications

Image from Technorama.ch website
Medical applications

Similar to magnetoassay, only this time for treatment.

Coat nanoscale FM particles with compound that binds to desired analyte (e.g. prostate specific antigen).

Allow biocompatible FM particles into body.

• Locate analyte by FM resonance.
• Cook tumors by FM resonance heating.
• MRI contrast agents
Spintronics

Basic idea: use spin as well as charge of electron for information processing / useful devices.

Problems:

• Need to get spin-polarized electrons - would like to do so without enormous magnetic fields.

• Would like to manipulate spin degree of freedom, again without big magnets if possible.

  Upside: can drag spin along with charge.

  Downside: spin is not conserved, per se.

• Want to read out spin information somehow.

Sources of spin polarized carriers

Two main ways of getting carriers with net spin polarization:

• Ferromagnetic contacts

  Recall our numbers for polarization in some common ferromagnets: (from Meservey et al., Phys. Rep. 238, 173 (1994))

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

• Optical pumping with circularly polarized light

![Image from Awschalom group, UCSB]
Definitions

Much of the language used to discuss dynamics of electron spins in solids is taken from NMR community.

$T_1$: the time for a nonthermal net spin polarization to relax back to its equilibrium value.

$T_1$ times are set by relaxation mechanisms that can exchange angular momentum with carriers: “spin-lattice relaxation time”.

Can vary quite a bit because of different relaxation mechanisms. Ex: thin gold films: ~ 45 ps.

Definitions

$T_2$: the time for a population of coherently prepared spins to “dephase”.

Due to local inhomogeneities plus spin-spin interactions, the precessing spins gradually get further and further out of step.

This process goes on simultaneously with $T_1$ processes.

In dirty (lots of scattering) systems, can have $\tau << T_1, T_2$, so not much difference between the two.

In clean systems (semiconductors), however, the distinction can be important!

$\frac{1}{T_2^*} = \frac{1}{T_1} + \frac{1}{T_2}$. 
Spin relaxation mechanisms

Things get more complicated in metals because the electrons move.

- Because of spin-orbit coupling, $z$-component of spin is no longer a good quantum number.
- Correct single-particle Bloch eigenstates are lin. comb. of spin-up and spin-down.
- Result: changes of wavevector $k$ have some chance to “flip” particular carrier from a mostly spin-up state to a mostly spin-down state, and vice-versa.

Mathiesson’s rule

Since any momentum relaxation scattering process can cause spin flips with some likelihood, expect $T_1 \sim \tau$ with some coefficient, expected to depend only on material.

Note that impurities of different $Z$ and phonons (which locally modulate lattice structure) also cause changes in spin-orbit coupling, and can scatter carriers from one spin state into another.
Spin relaxation mechanisms

• Materials with no inversion symmetry complicate matters.
• With SO scattering, carriers act like there is an effective internal magnetic field that depends on momentum, $B(k)$.
• Result: spins precess in that internal field.
• Relaxation results because of momentum scattering: $T_1 \sim \tau$ again, though this effect is washed out at large applied magnetic fields.

Spin relaxation mechanisms

• This mechanism is exchange between electrons and holes.
• Recall, holes have considerably different spin-orbit interactions than electrons; coupling them together via exchange effectively shortens lifetime of spin states of electrons.
• Only relevant in semiconductors, where electron and hole wavefunctions are comparatively larger (lower carrier density) and have more overlap.
Spin lifetime and diffusion

In disordered materials, it’s often more useful to talk about a spin diffusion length, $L_s$, rather than a lifetime.

Typical distance diffused by a carrier before a spin-flip event.

Spin injection in an all-metal system

Ohmic injection of spin-polarized carriers seems intuitively like it should be readily achievable:

Expect to find an excess spin polarization in the normal metal that decays ~ exponentially moving away from the FM-N interface.

Typical decay length: $L_s$, spin-flip scattering length. In Au, $D \sim 0.01 \text{ m}^2/\text{s}$, giving $L_s \sim (D T_f)^{1/2} = 0.6$ microns.
Direct detection of magnetization?

How much excess magnetization are we talking about? Could we measure it directly, by something like MFM?

Number of excess spins pumped in per second: \( P (I/e) \).

Lifetime of spins \( \sim T_1 \) for the normal metal.

Suppose FM = iron (\( P = 0.4 \)) and N = Au (\( T_1 = 40 \text{ ps} \)).

For 1 microamp current, \( N = P (I/e) T_1 = 100 \).

Very hard to find 100 excess spins spread out over \( \sim w \times 0.6 \text{ microns} \)….

Other ways of detecting magnetization

The numbers don’t work out well for the direct detection (via magnetic fields) of the injected magnetization.

Have to use other properties of that magnetization to infer its presence and magnitude.

- Signatures in conductance = Hanle effect, spin accumulation
- Signatures in optical response = Faraday rotation
- Signatures in optical emission = circularly polarized light
Spin injection in an all-metal structure


Use one FM contact as an injector of electrons, and a closely spaced second FM contact as a detector (“analyzer”) (permalloy).

Normal paramagnetic underlayer (aluminum).

Idea is that nonequilibrium magnetization in paramagnet produces a voltage difference between detector and ground.

\[ V = \frac{P\eta \mu_B M}{2e} \]

Here \( \eta \) is an efficiency of injection at interface.

Hanle effect

Idea is to use applied transverse field to cause injected spins to precess.

Projection of injected \( M \) along direction of detector \( M \) is what goes into determining the voltage detected.

Since distance \( L \) is fixed, expect voltage to oscillate with orientation of \( B \).

Note: this experiment actually measures \( T_2^* \) rather than \( T_1 \).
Hanle effect

Johnson and Silsbee, *PRL* 55, 1790 (1985)

Actually works. Johnson and Silsbee arrive at $T_2$ numbers that agree well with those obtained in ESR experiments.

First solid demonstration of spin injection.

Found that $\eta$ defined above typically $<< 1$: interfaces matter critically in spin injection experiments.

Faraday rotation


- Optical pump to produce lots of spin-polarized e-h pairs.
- Kerr angle oscillates as polarized carriers precess in applied magnetic field.
- ZnCdSe quantum well material used in this experiment.
Faraday rotation

Much longer lifetimes ($T_2^*$) seen in doped quantum wells when compared with undoped ones.

Why?

Holes (rapid spin relaxing anyway due to SO) recombine with spin-unpolarized electrons already present due to doping!

Result is that remaining (spin-polarized) electrons are not severely hurt by recombination with holes.

Long lifetimes and long coherence are potentially very useful for quantum computation….  

Faraday rotation

More advanced experiment does same thing but spatially resolved, in doped GaAs.

This time, can watch cloud of spin-polarized electrons as it spreads (diffusion), drifts in an applied electric field, and shrinks (spin relaxation).
Optical emission

Spin injection from *magnetic semiconductor* into nonmagnetic semiconductor.

Built-in LED structure.

Annihilation of spin-polarized electron with (unpolarized) hole can only happen in optical emission case if the resulting light is circularly polarized.

Optical signature shows FM hysteresis, and coincides precisely with FM signature of GaMnAs as seen in SQUID measurements.
Next time:

The ugliness of electrical spin injection.
Spin valves and spin transistors.