Spin injection

For devices, *all-electrical* spin injection is desirable.

Three materials combinations:

- FM Metal - N metal
- FM Metal - semiconductor
- FM semiconductor - semiconductor

Will look at these, and explain the difficulties associated with each.

At same time, will get a sense of proposed spintronic devices.

Spin injection from metals into metals

Charge current drags excess spin population into N metal.

Electrostatic potential adjusts itself for appropriate equilibrium.
Spin injection from metals into metals

Here’s a more recent demonstration of this idea.

Now use nanofabricated permalloy (F1, F2) and copper (N).

Many possible measurement configurations.

Py pieces small enough to be single domain.

Py pieces have differing geometric anisotropies: magnetization can be controllably flipped one at a time!

Conventional spin-valve geometry:

$I$ in 1 and out 7; $V$ btw. 4 and 9.

Analogous to CPP GMR device.

Does not work well here - AMR and Hall effects in the Py strips are too big.

Instead, Jedema et al. use nonlocal geometry as described above.

$I$ in 1 and out 5; $V$ between 6 and 9.

Antiparallel $M$: should see higher voltage (effective 4-terminal resistance) because of nonequilibrium spin buildup in Cu cross region.
Nonlocal spin valve effect

When sweeping in-plane field, shorter Py piece flips first.

As predicted, higher voltages measured when Py magnetizations are antialigned.

Note that this works even at room temperature!

Can do quantitative analysis by modeling spin diffusion process in device.

Quantitative analysis (signs and portents)

Jedema et al. do simple 1d diffusion analysis, where they allow the electrons to freely pass back and forth across the F-N interfaces (can get spin flip scattering w/in the Py, for example).

Results work fairly well; get sensible results for $P$ and $L_s$.

Note long values of $L_s$ even at room temperature!

\[
\Delta R = \frac{p^2 L_s}{\sigma_{NWT}} \exp(-L/2L_s) \frac{M}{(M+1)\sinh(L/2L_s) + \cosh(L/2L_s)}
\]

\[M = \frac{L_s \sigma_F}{L_s \sigma_n (1 - p^2)}\]
Quantitative analysis (signs and portents)

Johnson points out that interpreting data in this system is actually quite subtle.

- Need to worry about where spin injection really happens.
- Need to worry about 2d diffusion of spin in lateral arms all the time.
- Disagreement over treatment of interface scattering.

**Sign of things to come:** even in an all-metal system (high carrier densities, generally negligible Hall effects), it’s hard to get agreement on what constitutes unambiguous spintronic action.

Spin injection from metals into semiconductors

Things get even uglier when worrying about spin injection from FM metals into semiconductors.

Why do people care about this?

- Potential integration with existing semiconductor technology.
- Low carrier densities permit gating for further device possibilities.
- Clean materials mean much longer spin lifetimes and distances.
- Very clever device designs exist that take advantage of physics present in semiconductors.
A spin transistor

One example: the Datta-Das spin transistor

Working principle: because of relativistic effects (!), electric fields look, to the moving electrons, like they have a small magnetic field component.

This is enhanced in materials with strong spin-orbit scattering (no inversion symmetry = III-V) - the Rashba Effect.

Datta-Das transistor

Applied gate voltage changes local electric field in channel.

That is seen by the moving carriers as a slight magnetic field causing precession of the spins.

Depending on amount of precession, should get improved conduction or not.
Spin injection from metals into semiconductors

Why hasn't anyone gotten this to work yet?

1) It's very hard to inject net spin polarization directly from a metal into a semiconductor!

Two spin channels add in parallel, assuming negligible spin flip scattering in semiconductor.

Can solve this problem and compute the spin polarization of the current in the semiconductor, \( P_{sc} \), and compare it with \( P \), the polarization in the FM.

\[
P_{sc} = P \cdot \left( \frac{R_{FM}}{R_{SC}} \right) \left( \frac{2}{2(R_{FM}/R_{SC}) + (1 - P^2)} \right)
\]

- So, while spin polarization of current in semiconductor is proportional to that in FM, it’s reduced by a factor of 
  \( R_{FM}/R_{SC} \), which can be \( \sim 10^{-4} \)!
- Conductance mismatch between materials will cause big suppressions of spintronic effects.

Spin injection from metals into semiconductors

\[ \frac{\Delta R}{R_H} = \frac{P^2}{1 - P^2} \frac{R_{FM}^2}{R_{SC}^2} \left[ 4\left( \frac{R_{FM}}{R_{SC}} \right) + 2\left( \frac{R_{FM}}{R_{SC}} \right)^2 + 1 \right] \]

Spin valve type effects are reduced quadratically in the mismatch!

Spin injection from metals into semiconductors

Why hasn’t anyone gotten this to work yet?

2) It’s very hard to eliminate local Hall effects in systems with very low carrier densities!

For example, Monzon et al. at Cal Tech spent several years trying to do these experiments, only to eventually decide that they could not see anything that couldn’t be explained by Hall effects from stray fields.
Possible solution to FM-SC interface problem

How do you avoid the conductance mismatch problem?
Make *tunnel junctions* rather than direct Ohmic contacts!

In last 1-2 years, people have made much more progress in all-electrical spin injection into semiconductors.

Hall problems and interpretation of results continue to be problematic.

Spin Hall effect

- Because of spin-orbit coupling, it’s possible for a pure spin current to be produced in response to an *electric* field.
- Can be *intrinsic* due to strain + band structure.
- Can be *extrinsic* due to impurity scattering.

New MOKE measurements in GaAs and InGaAs

Kato *et al.*, Science (on-line, 11/11/04)
Spin Hall effect

- Definite accumulation of spin species at opposite edges of sample!
- Apparently independent of crystalline axes – suggests that this is the *extrinsic* spin Hall effect.
- 30 years of hunting pay off.
- Possible source of spins for manipulation without external fields, magnetic dopants, etc.

Next time

Magnetic semiconductors
Spins for quantum computation
Wrap-up