Electrical Spin Injection and Detection in Ferromagnet-Semiconductor Heterostructures

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Outline

✧ Generic model of spin transport in diffusive regime (metals)
✧ Non-local electrical spin detection + precession
✧ Ferromagnet-semiconductor-ferromagnet spin valves and agreement with the generic model
✧ What are the outstanding questions?

- What determines the sign and magnitude of the injected spin polarization?
- How can the results of an electrical detection measurement be interpreted?
- Dynamics and transport of non-equilibrium spin polarization: hyperfine and spin-orbit effects
Given $J$, solve the diffusion equation in both materials, subject to continuity of $\mu^\uparrow$, $\mu^\downarrow$, $J^\uparrow$, and $J^\downarrow$ at the F/N interface.

Detection of the spin polarization

\[ \Delta R = \frac{R_{\uparrow \downarrow} - R_{\uparrow \uparrow}}{R_{\uparrow \uparrow}}. \]

• In the context of the above model,* it is possible to calculate the magnetoresistance

• The “conductivity mismatch” problem makes this signal small, particularly in the case where the normal metal is highly resistive (an ersatz semiconductor). Reality, however, will be more complicated.

Tunnel Barriers

• It is possible to re-formulate the model with an “interfacial resistance” $R_i$. *

• In the tunneling limit, how do we think about spin injection and detection? If we ignore dispersion, the tunneling current in each band should be proportional to the DOS $\times$ a transmission coefficient:

$$\alpha_{\text{int}} = \frac{T_{\uparrow}N_{\uparrow} - T_{\downarrow}N_{\downarrow}}{T_{\uparrow}N_{\uparrow} + T_{\downarrow}N_{\downarrow}}$$

• In practice, we should account for dispersion ($k_{F\uparrow} \neq k_{F\downarrow}$). Furthermore, matrix elements for $\uparrow$ and $\downarrow$ will not be the same. For crystalline barriers, these considerations will be particularly important.

A slightly different approach: the non-local measurement

- Pure potentiometric measurement: no *charge* current flows in F2.
- The electrochemical potential is measured for each state of F2 (seemingly straight-forward).
- The (less than 100%) polarization of F2 reduces the signal from the ideal value (discussed later).
- F2 draws a spin current. This can perturb N.

Besides the spin-polarized currents themselves, *magnetic fields* provide the only other “handle” by which we can manipulate the spin in the N region of a *metallic* F/N/F device.

A transverse magnetic field suppresses spin accumulation in the case of diffusive spin transport. This is known as the *Hanle effect*. 

$$\Delta \varphi = \Omega_L \Delta t$$
Johnson-Silsbee experiment for metals


What makes semiconductors “different”?

1) Spin polarizations are large (~ 10 % in the devices I will discuss)

2) Electric fields are large (drift effects)

3) Spin-orbit effects (well-defined symmetries)

4) Hyperfine effects [related to (1), much bigger than (3) in GaAs]

5) Role of metal-insulator transition (dirty secret?)
Spin-orbit coupling

Do perturbation theory in \((\nabla V \times \mathbf{p}) \cdot \sigma\)

\[
E = \frac{\hbar^2 k^2}{2m^*} - g\mu_B \frac{\hbar}{2} \vec{\sigma} \cdot \vec{B} + \frac{\hbar}{2} \vec{\sigma} \cdot \vec{\Omega}(k) + \frac{\hbar}{2} \vec{\sigma} \cdot \vec{\Omega}_{BR}(k) + \frac{\hbar}{2} \vec{C} \vec{\sigma} \cdot \vec{\phi}(k)
\]

In increasing order of obscurity:

\[
\Omega_x = Ck_x (k_y^2 - k_z^2) \quad \text{- bulk inversion asymmetry (Dresselhaus)}^1
\]

\[
\vec{\Omega}_{BR} = \vec{k} \times \nabla V \quad \text{- structural inversion asymmetry (Rashba)}^2
\]

\[
\varphi_x = \varepsilon_{xy} k_y - \varepsilon_{xz} k_z \quad \text{- uniaxial strain}^3
\]

Note that \(\Omega_x,\ \Omega_{BR},\ \text{and}\ \varphi\) “look like” \(k\)-dependent magnetic fields.

- I do not want to overdo this point, however. There are some aspects, such as spin dephasing, in which the spin-orbit fields are rather different (due to the dependence on \(k\)).
Hyperfine interaction and dynamic nuclear polarization

Hyperfine contact interaction (enhanced by localization):

\[ H = -\frac{16\pi}{3I} \mu_B \mu_n |\Psi(R)|^2 \hat{I} \cdot \hat{S} \]

Rate equation for nuclear polarization:

\[ \frac{d\langle I_Z \rangle}{dt} = \frac{1}{T_{pol}} \left( \langle S_Z \rangle k - \langle I_Z \rangle \right) - \frac{1}{T_1} \langle I_Z \rangle \]

Ansatz:

\[ \frac{T_{pol}}{T_1} = \xi \left( \frac{B_L}{B_{app}} \right)^2 \Rightarrow \langle I_Z \rangle = k \langle S_Z \rangle \frac{B_{app}^2}{B_{app}^2 + \xi B_L^2} \]
Hyperfine interaction: the effective field $B_N$

**Effective nuclear magnetic field:**

$$\vec{B}_N = f_l b_N \frac{I(I+1)}{S(S+1)} \frac{(\vec{S} \cdot \vec{B}_{app}) \vec{B}_{app}}{B_{app}^2 + \xi B_L^2}$$

$f_l \equiv$ leakage factor

in GaAs:

$$b_N \approx 5 \text{ T}$$

Electrons feel:

$$\vec{B}_{Total} = \vec{B}_{app} + \vec{B}_N$$
Non-local electrical spin detection in Fe/GaAs

“Crossed”
“Uncrossed”

MOKE can be used to measure the spin polarization in the channel: J. Stephens et al., Phys. Rev. Lett. 93, 097602 (2004); S.A. Crooker et al., Science 309, 2191 (2005).
- Design based on Fe/GaAs spin-LED’s
- GaAs epilayer doping: \( n = 2 \times 10^{16} - 1 \times 10^{17} \text{ cm}^{-3} \)
- Interfacial doping: \( n^+ \sim 5 \times 10^{18} \text{ cm}^{-3} \)

Graded interfacial doping profile:
Estimation of size of signal

For the case of an Fe spin detector:

\[ \Delta V = \eta \cdot P_{Fe} \frac{\Delta \mu'}{e} \]

Spin detection efficiency: \( \eta \sim 0.5 \)

Fe spin polarization: \( P_{Fe} = 42\% \)

Assuming GaAs is a Pauli-like metal \((n = 5 \times 10^{16} \text{ cm}^{-3})\):

\[ \Delta \mu' = \frac{n_\uparrow - n_\downarrow}{\frac{\partial n}{\partial E}} = \frac{2}{3} \frac{\hbar^2}{2m^*} (3\pi^2 n)^{2/3} P'_{GaAs} \]

\[ \Delta V = \eta \cdot P_{Fe} \frac{\hbar^2 (3\pi^2 n)^{2/3}}{3m^*} P'_{GaAs} \]

\( P'_{GaAs} = 1\% \) at the detector \( \Rightarrow \) \( \Delta V \sim 10 \mu V \)
Spin valve and Hanle effects

Spin valve

$V_0 = -30 \text{ mV}$

$T = 50 \text{ K}$

$V - V_0 \text{ (μV)}$

$B_y \text{ (Gauss)}$

Hanle

$T = 50 \text{ K}$

$\Delta V \text{ (μV)}$

$B_z \text{ (Gauss)}$
Modeling the Hanle Curves: Drift-Diffusion Model

- Account for diffusion, drift, and relaxation:

\[
\frac{\partial \tilde{S}(x, t)}{\partial t} = -v_d \frac{\partial \tilde{S}(x, t)}{\partial x} + D \frac{\partial^2 \tilde{S}(x, t)}{\partial x^2} - \frac{\tilde{S}(x, t)}{\tau_s} - \Omega \times \tilde{S}
\]

\(D = \text{diffusion constant}\)

\(v_d = \mu E = \text{drift velocity}\)

\(\tau_s = \text{spin lifetime}\)

\(\Omega = \text{Larmor frequency}\)

\(w = \text{width of contact}\)

\(x = \text{distance from edge of contact}\)
Drift-Diffusion Model

- Integrate over time (steady-state solution) and spatial extent of source

\[ S_z(x) = \int_{x}^{x+w} \int_{0}^{\infty} \frac{S_{x0}}{\sqrt{4\pi Dt}} e^{-\frac{(x'-v_d t)^2}{4Dt}} \frac{t}{\tau_s} \cos(\Omega t) dt dx' \]

- \( D = \) diffusion constant
- \( v_d = \mu E = \) drift velocity
- \( \tau_s = \) spin lifetime
- \( \Omega = \) Larmor frequency
- \( w = \) width of contact
- \( x = \) distance from edge of contact
Modeling of Hanle curves

Now integrate over detector coordinates:

\[ S(B) = \int \int \int_{0}^{\infty} \frac{S_0}{\sqrt{4\pi Dt}} e^{\frac{(x'-x-v_d t)^2}{4Dt}} \frac{t}{\tau_s} \cos(\Omega t) dt dx dx' \]

\( D = \) diffusion constant (determined from transport)
\( \tau_s = \) spin lifetime (determined from optical measurements)
\( v_d = \) drift velocity
\( \Omega = g \mu_B B / \hbar = \) Larmor frequency \((g = -0.44)\)
\( S_0 = \) spin injection rate (the only free parameter)
Spin drift in the “crossed” geometry enhances the spin signal

- $S_0$ is the same for all fits
Dependence on injector/detector separation

- Note “upstream” and “downstream” drift/diffusion lengths*
- Consistent with Hanle measurements

Zero-field Anomaly

- Zero-field anomaly (dependent on sweep rate) appears below 50 K
- Hanle curves can be fitted by accounting for hyperfine field
Resonant Depolarization of Nuclei

$B = 65 \text{G}$. 

$B_T = B_N + B_{\text{app}}$ 

$[01\bar{1}]$ 

$B_1$
40K, 0.6mA
Normalized by nominal field value

- $\text{H}_0 = 149\, \text{G}; \text{H}_1 = 1\, \text{G}$
- $\text{H}_0 = 180\, \text{G}; \text{H}_1 = 0.05\, \text{G}$
- $\text{H}_0 = 200\, \text{G}; \text{H}_1 = 0.05\, \text{G}$
Brief Synopsis

- Fe/GaAs Schottky tunnel barriers function as both electrical spin injectors and detectors
- Observation of Hanle effect (up to 120 K); widths consistent with spin lifetime and transport measurements
- Outstanding agreement with drift-diffusion model for spin transport in semiconductor
- Order of magnitude of non-local signal in agreement with expectations based on spin-LED measurements

Other recent reports on electrical spin detection in ferro-semi:
  FeCo/Si (Delaware), Co/graphene (Groningen)
  MnAs/GaAs (Michigan), Fe/Si (NRL)

What is not understood?
Spin accumulation under forward bias

- Spin accumulation at forward-biased MnAs/GaAs barriers: Stephens et al., PRL 93, 097602 (2004)
- Spin-dependent reflection
- In the linear response regime, we expect the sign of the polarization under forward bias to be opposite that injected under reverse bias

See Ciuti et al., Phys. Rev. Lett. 89, 156601 (2002); also Bauer and co-workers
Bias dependence and sign of the non-local signal

- Sign change at zero bias (expected)
- Very small region of linear response
- Direct correspondence between non-local signal and polarization measured with Kerr rotation
Bias dependence and non-local resistance

- Sign reversal at forward bias
- Sign of $\Delta V$ for majority polarization is determined by the slope at zero bias
- The observed polarization is (almost) always majority as determined by MOKE

• The sign of $\Delta V$ depends on exactly where the Fermi level lines up at the Fe/GaAs interface. It can change upon annealing.
Sensitivity to detector bias

$T = 10 \text{ K}$

$\Delta V ($ $\mu$V$)$

$V_{\text{Int}}$ Detector (V)

- Sample A
- Sample B
- Sample C
- Sample D
Beyond Julliere

A. Effects of dispersion

B. Bound states in the semiconductor

C. Interfacial Band Structure
What about a two terminal measurement?

- There are pronounced *bias-dependent* effects in a two-terminal measurement that do not depend on the relative magnetizations of source and detector.
- These are not due to the usual suspects (conventional AMR or local Hall).
Tunneling anisotropic magnetoresistance


Due to rotation of \( \mathbf{M} \) with respect to crystal axes (not current)

Spin-orbit coupling + tunneling

Dominant component from surface states with uniaxial symmetry

Summary

• Several important aspects of spin transport in Ferro-Semi-Ferro structures are in agreement with the “generic model” for diffusive spin transport.
• The dependence on bias, however, is markedly non-linear
• There is a correspondence between the doping profile (band structure in the semiconductor), the associated $JV$ curves, and the non-local spin signal [not discussed today]
• It is possible to measure separately the dependence on the injector and detector bias voltages
• A two-terminal measurement is strongly dependent on spin-orbit effects at the Fe/GaAs interface (at least for epitaxial samples)