Spin Transport in Epitaxial Heusler Alloy/III-V Semiconductor Heterostructures

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Outline

• Why lateral spin valves
• Why Heuslers: the Co$_2$Fe$_x$Mn$_{1-x}$Si family
• Progress in semiconductor lateral spin valves
• Improvements in high temperature performance
• Microwave detection of spin accumulation
Lateral spin valve

- Allows the study of spin-physics in wide array of materials systems
  - ferromagnetic contacts (Fe, Co, Py, Co$_2$MnSi, etc.)
  - metallic channels (Al, Cu, Ag, etc.); $p \ll 1\%$
  - semiconducting channels (GaAs, Si, Ge, graphene, etc.)
- Can quantify injection rates, detection efficiencies, spin-lifetimes, etc.

\[ p_{inj} \approx 50\% \]
\[ \lambda_s \approx 5 \mu m \]
The non-local 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.
- F2 draws a spin current. This can perturb N (irrelevant in this system)
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Co$_2$MnSi – a potential half-metal

- Predicted to be a half-metal with a relatively large minority gap
- Lattice-matched to GaAs
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- Predicted to be a half-metal with a relatively large minority gap
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- Spin injection will work [see Dong et al., Appl. Phys. Lett. 86, 102107 (2006) for Co$_2$MnGe/GaAs]
General idea: Fermi level in a rigid band model

Can we tune the Fermi level through the minority spin gap?

Heusler alloy: $\text{Co}_2\text{MnSi}$

$\text{Co}_2\text{MnSi}$

- L2$_1$ ordered
- $T_c = 985 \text{ K}$
- $M_{\text{sat}} = 4.97 \mu_B$

Near perfect lattice match to GaAs

$a = 5.65 \text{ Å}$

(STEM courtesy of Paul Voyles, UW Madison)
Useful features of these alloys

- As indicated by work on MTJ’s, the tunneling polarization is high; $\text{Co}_2\text{MnSi}$ is half-metallic or nearly so.

- As suggested by the cartoons on the previous viewgraphs, the density of states at the Fermi level is relatively small. This is a corollary to the fact that $E_F$ changes so rapidly with composition.

- Grown on (100) GaAs, they have a very large in-plane uniaxial anisotropy. This turns out to be of practical utility.

- The LLG damping is particularly small for $\text{Co}_2\text{MnSi}$ ($\sim 0.003$ at high temperatures)
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**FM/n-GaAs Heterostructures**

- Epitaxially grown along [001]
- Fe polarization at Fermi level $\approx 40\%$
- $\text{Co}_2\text{MnSi}$ proposed to be half-metallic
- Surface-induced FM anisotropy

- Graded doping used to ‘thin’ natural forming Schottky barrier
- Interface states lead to complex bias dependence
Lateral spin valve

\( \Delta V (\mu V) \) vs. Field (Oe) for different conditions:

- **unbiased (non-local)**
  - \( \Delta V \) shows a response to the field for \( Co_2MnSi \) and appears to be independent of the presence of Fe.

- **biased (non-local)**
  - \( \Delta V \) shows a pronounced response to the field and is sensitive to the presence of Fe.

The diagram illustrates the effect of a magnetic field \( H \) on the voltage \( \Delta V \) for different materials and conditions.
Spin drift-diffusion model

**DIFFUSION CONSTANT – Same for spin and charge?**

\[ eD = \nu n \frac{\partial \mu}{\partial n} \]

(Einstein relation)

\[ \frac{\partial \mathbf{p}}{\partial t} = \nu E \frac{\partial \mathbf{p}}{\partial x} + D \frac{\partial^2 \mathbf{p}}{\partial x^2} - \frac{\gamma \mathbf{B} \times \mathbf{p}}{\tau_s} + \frac{\mathbf{p}}{\tau_s} + \mathbf{p}_0 \]

**SPIN LIFETIME – Reasonable values for n-GaAs?**

\[ \tau_s^{-1} \propto \alpha^2 \varepsilon^3 \tau_p \]

(Dyakonov-Perel)

- \( D \): diffusion constant
- \( \tau_s \): spin lifetime
- \( \mathbf{p} \): fractional number polarization
- \( E \): electric field
- \( \nu \): drift mobility
- \( \gamma \): gyromagnetic ratio
- \( \mathbf{B} \): magnetic field
- \( \varepsilon \): electron energy
- \( \alpha \): spin-orbit prefactor (Dresselhaus)
- \( \tau_p \): momentum relaxation time

steady state

relaxation

injection rate

Larmor precession

drift & diffusion
The full time of flight experiment: add drift

\[ g^* = 0 \]

- Solid curves are the analytic solution
Non-local Hanle fitting

- Multiple biases at each temperature fit with a single set of parameters
- Hanle curves with ‘lobes’ allow extraction of diffusion constant
Spin lifetime and diffusion constant

- Allowing $D$ to be a fitting parameter yields values in agreement with the Einstein relation: spin and charge diffusion constants are the same.
- Larger uncertainty at higher temperatures due to disappearance of ‘lobes’
Estimates of the spin polarization

We can set a lower bound for the spin-polarization if we assume a perfect detection efficiency ($\eta = 1$)

$$ n_{\uparrow(\downarrow)} = \int_{E_f \pm e\Delta V_{\uparrow(\downarrow)}} g(E) dE $$

$$ p = \frac{n_{\uparrow} - n_{\downarrow}}{n_{\uparrow} + n_{\downarrow}} = 60\% $$

The measured spin splitting $\Delta V$ is half of the Fermi energy $E_f = 5$ meV

$T = 30$ K
Sign of the spin accumulation by Hanle measurements

Exploit hyperfine coupling:

\[ \Delta V (\mu V) \]

\[ \text{Field (mT)} \]

\[ \text{Co}_2 \text{MnSi/GaAs} \]

\[ \text{majority spin accumulation} \]

\[ B_N \]

\[ 60 \text{ K} \]

\[ \text{Co}_2 \text{FeSi/GaAs} \]

\[ B_N \]

\[ 40 \text{ K} \]

\[ \text{minority spin accumulation} \]

Sign of the spin polarization in the bulk GaAs can be determined in the presence of a hyperfine field

\[ \vec{B}_{tot} = \vec{B} - b_H \frac{\vec{S} \cdot \vec{B}}{B^2} \vec{B} \]
Co$_2$Mn$_{1-x}$Fe$_x$Si: comparison with Fe

- Polarizations determined by “biased detector technique”
- Sign determined by hyperfine field
- Sign change in going from Co$_2$MnSi to Co$_2$FeSi is expected, but overall sign is \textit{backwards}
Interlude: (Scalar) Spin EMF

- Expand chemical potentials w.r.t. $p$:

$$\mu_{\uparrow(\downarrow)} \approx \mu_0 + (-) \frac{\partial \mu}{\partial n} np + \frac{\partial^2 \mu}{\partial n^2} n^2 p^2$$

asymmetric shift: $\Delta \mu_{avg}$

- Current in each spin-channel:

$$\vec{j}_{\uparrow(\downarrow)} = n_{\uparrow(\downarrow)} \nu \nabla \left[ \mu_{\uparrow(\downarrow)} - e\Phi \right]$$

- Result:

$$\vec{j} = \sigma \nabla \left( kp^2 - \Phi \right)$$

$$k = \frac{1}{2e} \left( \frac{\partial \mu}{\partial n} n + \frac{\partial^2 \mu}{\partial n^2} n^2 \right) = \frac{2 E_f}{9 e}$$
Quadratic dependence

\[ \Delta V_{CH} \propto p^2 \]

Log-log plot of magnitudes demonstrates quadratic dependence

Deviation at large bias due to large E-field at injector (drift effects)
Dual-injector experiment

- Spins injected simultaneously at FM contacts B and D
- Clear spin valve signals observed at contact C
- Low-field features due to hyperfine interactions

Polarization vs. Temperature

\[ p_{\text{inj}} = \frac{n_{\uparrow} - n_{\downarrow}}{n_{\uparrow} + n_{\downarrow}} \]

- For \( p > 0.3 \), need to account for ‘Thompson’ effect: \( k = k(p) \)
- Results are independent of any assumptions about interfacial spin injection/detection efficiencies
- This resolved the “three-terminal” discrepancy
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What about room temperature?

- **Biased detector**

  \[ \Delta V_{NL} = \eta(I_{det}) \frac{P(I_{inj})n}{e} \frac{\partial \mu}{\partial n} \]

- \( \Delta V_{NL} \) is linear in spin injection rate, \( I_{inj} \), with fixed non-zero detector bias \( I_{det} \).

- \( \Delta V_{NL} \) becomes larger with detector bias \( I_{det} \), which we interpret as a detector bias dependence of \( \eta \rightarrow \eta(I_{det}) \).

- We also see saturation of \( \Delta V_{NL} \) at large \( I_{det} \).
Complication: Tunneling AMR (TAMR)

\[\frac{e}{(2\pi)^3 \hbar} \sum_{\sigma} \int dE d^2k_T(E,k) [f_F(E_\sigma) - f_N(E)] \]

\[T_{\text{aniso}} \propto \sin^2(\theta) [f(\alpha, \gamma) + g(\alpha, \gamma) \cos(2\phi)] \]

\[\alpha: \text{Rashba spin-orbit coupling constant} \]
\[\gamma: \text{Dresselhaus spin-orbit coupling constant} \]

\[R = R_0 + \Delta R_{\text{in}} \sin^2(\theta) \cos^2(\phi) + \Delta R_{\text{out}} \sin^2(\theta) \]

A. Matos-Abiague et al., PRB, 80, 045312 (2009)
K. Wang et al., PRB, 88, 054407 (2013)
Ramifications for a biased detector

- *Any* contact rotation leads to a TAMR contribution to the “three-terminal” signal; i.e. an additional field-dependent voltage at the detector. This is large and only weakly temperature-dependent.

- The ratio of the uniaxial to fourfold anisotropies is larger in Co$_2$Mn$_{1-x}$Fe$_x$Si than in Fe. This makes the Heuslers very forgiving.

La Bella *et al.*, PRL 83, 2989 (1999).
Devices operating at room temperature

- Use of Co$_2$FeSi as injector/detector
- Electron beam lithography
- Performance today comparable to low-T performance as of a few years ago (particularly size of non-local voltage)
- Spin diffusion length at 300 K is ~ 800 nm
Temperature dependence

We fit to the steady state solution of the drift-diffusion equation to extract the spin relaxation time constant $\tau_s$.

\[
\frac{dP}{dt} = 0 = -\frac{P}{\tau_s} + \nabla^2 P - v \nabla P + F
\]

This allows us to determine the spin diffusion length $\lambda$.

By measuring the separation dependence, we extract the spin diffusion length $\lambda$.

Temperature dependence, separation dependence, fitted $\tau_s$ (ns), temperature (K), separation (μm), fitted $\tau_s$ (ns), temperature (K), separation (μm).
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What about Hanle measurements?

- Conventional wisdom: these become difficult or impossible at high temperatures because the lifetime is “too short”

- This is reinforced by the fact that the g-factor in GaAs is so small (i.e. -0.44 instead of 2)

- Ordinary magnetoresistance is very large
Hanle measurement at room temperature fails

- Signal/Background $\sim 10^{-4}$
- Impossible to extract spin signal at room temperature in n-GaAs system
What about Hanle measurements?

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- Solution: use the Hanle concept (sensitivity to precession), but exploit the fact that spins can precess in the FM as well as the semiconductor.
Solution: modulate the injector with FMR

- This is a three-terminal measurement with microwave excitation
- Signal is the difference of the 3T signal with and without microwave field

**Cap**
- FM

<table>
<thead>
<tr>
<th>Layer</th>
<th>Description</th>
<th>Thickness</th>
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<tbody>
<tr>
<td>$n^+$: GaAs</td>
<td>$n \sim 5 \times 10^{18}/\text{cm}^3$</td>
<td>(18 nm)</td>
</tr>
<tr>
<td>$n \rightarrow n^+$: GaAs</td>
<td></td>
<td>(15 nm)</td>
</tr>
<tr>
<td>$n$: GaAs</td>
<td>$n \sim 3 \times 10^{16} \text{ cm}^{-3}$</td>
<td>(5 nm)</td>
</tr>
<tr>
<td>$i$-GaAs [001]</td>
<td></td>
<td>(~ 2500 nm)</td>
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FM: Co$_2$MnSi, Co$_2$FeSi, Fe

Skipping details...

FM is denoted by a shielded circle, and $H_0$ is the magnetic field.
Spin accumulation leads to an FMR peak in $\Delta V$

- A strong resonance peak is observed (note the sign is negative)
- The peak position is well described by the Kittel's formula

At forward bias, the FMR signal is dominated by spin accumulation

Linewidth determined by $\alpha \sim 0.003$ for Co$_2$MnSi at room temperature
Modeling FMR spin detection

\[ V = \eta I_s \int_{-\infty}^{t} \hat{m}(t) \cdot \hat{s}(t') \frac{1}{\sqrt{2\pi D(t - t')}} e^{-\frac{t-t'}{\tau_s}} dt' \]

\[ V_{FMR} = \eta I_s \frac{1}{2} (\varphi_{in}^2 + \varphi_{out}^2) \sqrt{\frac{\tau_s}{2D}} \left( \sqrt{\frac{1}{2\sqrt{1 + \omega^2 \tau_s^2}}} + \frac{1}{2(1 + \omega^2 \tau_s^2)} - 1 \right) \]

- \( I_s \): Spin injection current
- \( \eta \): Detection efficiency
- \( D \): Spin diffusion constant
- \( \tau_s \): Spin lifetime
- \( \varphi_{in} \varphi_{out} \): Precession cone angles
Temperature dependence (comparison with NLSV)

- Agreement with spin-valve data for both Co$_2$FeSi and Co$_2$MnSi
Frequency dependence

- Spin lifetime extracted agrees with those obtained from spin-valve measurements.
- At high temperatures, this technique is much more sensitive than the conventional spin valve approach.
Summary

- $\text{Co}_2\text{Mn}_{1-x}\text{Fe}_x\text{Si}$ is a very effective spin injector/detector for GaAs

- The high polarization helps, although in our case the highest polarizations measured are about 70%.

- There are other features of these materials that are as “useful” as the high polarization.

- Lateral spin valves useful as quantitative tools up to room temperature.

- Microwave detection of spin accumulation is a complementary technique, particularly when $\tau_s$ is short.