Quick Review over the Last Lecture

Magnetic skyrmions: *

<table>
<thead>
<tr>
<th></th>
<th>Skyrmions</th>
<th>Domain walls</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size [nm]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Velocity [m/s]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Critical current density [A/cm²]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Voltage-controlled memory: *

* A. Fert et al., Nature Nanotechnol. 8, 152 (2013);
16 Three-Terminal Devices

- Spin-polarised transistors
- Lateral spin-valves
- Spin injection
- Spin accumulation
- Johnson transistors

Spin-Polarised Field Effect Transistor

- Spin transistor was originally proposed by Datta and Das.

- Fe/GaAs is one of the leading systems for obtaining efficient spin-polarised injection into a semiconductor (SC). **

- GaAs has long carrier spin lifetimes and large spin diffusion lengths.

- Fe is an ideal injector as it has:
  - high Curie temperature
  - low coercivity
  - good lattice matching with GaAs

- The intrinsic Schottky barrier that forms at the Fe/SC interface overcomes the limitations due to the conductivity mismatch.

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Spin Transport - Spin-poled electrons → SC → Spin-poled electrons

Spin FET structures:

<table>
<thead>
<tr>
<th>Structures</th>
<th>Spin polarization</th>
<th>Refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>FM / 2DEG Hall-bar-type structures:</td>
<td></td>
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</tbody>
</table>

| FM / 2DEG asymmetric structures:       |                   |                                            |
| 60 nm NiFe / InAs 2DEG / GaAs          | ~ 0.2% @ < 10 K   | C.-M. Hu et al., Phys. Rev. B 63, 125333 (2001). |

| Schottky (tunnel) diodes (FM / SC):    |                   |                                            |
| 3.5 nm Fe / 2 nm Oxide / n-GaAs        | ~ 5% @ <RT        | A. Filipe et al., Phys. Rev. Lett. 80, 2425 (1998). |

Spin-Polarised Electrons in GaAs

> 100 µm spin diffusion length: *

Experimental studies have shown that spin injection can be achieved leading to a majority spin accumulation.

Spin injection / extraction has been observed using both optical * and electrical ** techniques.

A bias dependant polarisation inversion has been observed, the origin of which remains unknown.

Knowledge of the mechanism(s) responsible for the polarisation inversion required for the development of future devices.

Possible Origins of Spin Polarisation Reversal

- There are two promising candidates to explain the polarisation inversion:
  - Tunnelling through interface resonance states (IRS). *
  - Tunnelling from bound states in the semiconductor. **

- It has been shown that the contribution arising from bound states can be varied through control of the doping profile.

- The strength and position of IRS is sensitive to the atomic interface structure. *

* S.A. Crooker et al., Science 309, 2191 (2005);

* S Honda et al., J. Phys. D: Appl. Phys. 43, 135002 (2010);
There are several proposals for the interface structure of Fe / GaAs (001) films.

Calculations suggest that the abrupt interface is energetically favourable for As-terminated surfaces (often used to limit diffusion).

Previous calculations predict that minority carrier interface states lie 0.3 eV below the top of the Schottky barrier.
- These are yet to be observed experimentally.

Calculations are yet to be performed for inter-atomic spacings measured experimentally.

<table>
<thead>
<tr>
<th>Abrupt</th>
<th>Partially intermixed</th>
<th>Fully intermixed</th>
<th>Fe&lt;sub&gt;3&lt;/sub&gt;Ga</th>
</tr>
</thead>
<tbody>
<tr>
<td>As-rich</td>
<td>Ga-rich*.,**</td>
<td>Least favourable</td>
<td>After over-annealing</td>
</tr>
</tbody>
</table>

* T. J. Zega et al., Phys. Rev. Lett. 96, 196101 (2006);

Previous Experimental Observations

There have been two previous reports on experimental observations of the Fe/GaAs interface. *,**,

The two studies reported different interfacial structures.

Both reports did not observed the abrupt interface.

Experimental values for the Schottky barrier height range from 0.2 to 0.8 eV. ***, ****

* T. J. Zega et al., Phys. Rev. Lett. 96, 196101 (2006);
** J. M. LeBau et al., Appl. Phys. Lett. 93, 121909 (2008);
*** H. Kurebayashi et al., Appl. Phys. Lett. 91, 102114 (2007);
The figure shows an unfiltered HAADF-STEM image the Fe / GaAs interface.

Two different interfacial structures are observed.
- Abrupt (first report)**
- Partially mixed (as reported previously)*

Analysis of the intensity profiles (z-contrast) taken across the interfaces suggest that Fe is responsible for the partially mixing.

From the areas observed the film is ~ 95% abrupt.

Peak Positions of IRSs

* L. R. Fleet et al., IEEE Trans. Magn., 47, 2756 (2011);
- No spin polarisation reversal induced by a bias voltage.
  → Agrees with calculations.

Rashba Effect for Gating

Gate operation in a spin FET:

For the modulation of spin-polarised electrons in a semiconductor, the spin-orbit interaction Hamiltonian can be derived from the Dirac equations:

\[ H_{SO} = \frac{q\hbar^2}{4m^2c^2}(\sigma \cdot [\vec{E} \times \vec{p}]) \]

where \( q, h, m, c, \sigma, \vec{E} \) and \( \vec{p} \) are the electron charge, Planck constant, electron mass, speed of light, Pauli matrices, electric field and electron momentum, respectively. By comparison with the Rashba Hamiltonian \( H_R = \eta_{SO}(\sigma \times \vec{k}) \cdot \vec{v} \) (\( \vec{k} \) : wave vector and \( \vec{v} \) : unit vector perpendicular to plane),

\[ H_R = \frac{q\hbar^2}{4m^2c^2}(\sigma \cdot [\vec{E} \times \vec{p}]) = \frac{q\hbar^2}{4m^2c^2} \frac{V_G}{d} (\sigma \times \vec{k}) \cdot \vec{v} \]

The spin-orbit interaction constant \( \eta_{SO} \) can be obtained by using a gate voltage \( V_G \) and distance between an electron path and a gate length \( d \):

\[ \eta_{SO} = \frac{q\hbar^2}{4m^2c^2} \]

Gate operation in a spin FET: *

For commonly-used InGaAs 2DEG, a 180° phase shift can be achieved for a separation between an injector and a detector:

\[ l = \frac{\Delta \theta \hbar^2}{2m^* \eta_{SO}} \approx \mu m, \]

and gate length:

\[ w = \frac{\hbar^2}{2m^* \eta_{SO}} \approx \mu m. \]

The corresponding electric field required is estimated to be

\[ \frac{V_G}{d} = \frac{4m^*c^2\eta_{SO}}{q\hbar^2} \approx 4.3 \times 10^{10} \text{ V/m} \] (\( m^* \) is the electron effective mass).

This provides \( d \sim 1 \text{ nm} \) and \( V_G \sim 43 \text{ V} \).

These values are very difficult to realise with present nano-fabrication techniques and requires a further improvement of the spin-orbit interaction constant \( \eta_{SO} \).


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Recent Demonstration of Spin FET Operation

Gate operation in a NiFe / InGaAs / NiFe spin FET: *

Theoretical Studies - \textit{FM} $\rightarrow$ \textit{SC}

**FM / SC Interfaces:**

**Ohmic contacts:**
- Diffusive process: 100\% spin polarisation in FM is crucial.
  - DMS, Heusler compounds and half-metallic FM as FM
  
  \cite{Schmidt2000}

**Schottky / tunnel barrier contacts:**
- Ballistic process:

**Spin coherence length:**
- Spin life time:

**Spin modulation:**
- Spin orientation $\propto$ gate voltage

Spin Injection into Si

**Ballistic spin injection into Si:**

\cite{Jonker2007}
Johnson Transistors

All-metallic transistors:

$\begin{align*}
\text{injector} & \quad 100 \, \mu m \\
\text{detector} & \quad 50 \, \mu m \\
1.5 \, \text{cm}
\end{align*}$

Recent Improvement

Lateral spin-valve structures with Co / Al / Co nano-wires:

$\begin{align*}
e^- & \quad \text{Ferromagnet 1} \\
& \quad \text{Non-magnet} \\
& \quad \text{Ferromagnet 2}
\end{align*}$
A pure spin current can be generated in a lateral spin-valve structure:

\[ \mathbf{j}_s = -\frac{\hbar}{2e} (\mathbf{j}_\uparrow - \mathbf{j}_\downarrow), \]
\[ \mathbf{j}_c = \mathbf{j}_\uparrow + \mathbf{j}_\downarrow. \]

These currents follow the diffusion equation. For the spin current, the spin diffusion equation is written as

\[ \nabla^2 (\mu_\uparrow - \mu_\downarrow) = \frac{1}{D\tau_{sf}} (\mu_\uparrow - \mu_\downarrow) \equiv \frac{1}{\lambda^2} (\mu_\uparrow - \mu_\downarrow), \]

where \( \lambda \) is the spin diffusion length and \( \tau_{sf} \) is the spin flip time.

### Spin Diffusion Length

Spin diffusion length determines the distance without spin flip:

<table>
<thead>
<tr>
<th>Materials</th>
<th>Spin diffusion length [nm] (300 K)</th>
<th>Resistivity [( \mu \Omega \cdot cm )] (300 K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>350 ~ 600 (293 K)</td>
<td>3.2 ~ 9.1</td>
</tr>
<tr>
<td>Cu</td>
<td>350 ± 50 (293 K)</td>
<td>2.9</td>
</tr>
<tr>
<td>Ag</td>
<td>132 ~ 152 (298 K)</td>
<td>4.9 ~ 5.5</td>
</tr>
<tr>
<td>Au</td>
<td>60 (293 K)</td>
<td>5.2</td>
</tr>
<tr>
<td>Pt</td>
<td>3.8 +0.7/-0.3</td>
<td>18 ± 0.7</td>
</tr>
<tr>
<td>Ta</td>
<td>1.9 +0.3/-0.5</td>
<td>200±15</td>
</tr>
<tr>
<td>CoFe</td>
<td>6.2 +0.3/-0.7</td>
<td>20 ± 1.3</td>
</tr>
<tr>
<td>NiFe</td>
<td>5.2 +1.8/-0.9</td>
<td>30 ± 3</td>
</tr>
<tr>
<td>Co</td>
<td>7.7 +1.8/-2.2</td>
<td>25 ± 2.4</td>
</tr>
</tbody>
</table>

\[ \Lambda_{R_{NL}} = 4 \frac{p^2 R_{FM}^2}{(1 - P^2)^2 R_{NM}} \exp \left( -\frac{d}{\lambda_{NM}} \right) \]

where \( P = I_\uparrow - I_\downarrow / I_\uparrow + I_\downarrow \) : current polarisation of FM, \( \lambda_{NM} \) : spin diffusion length in NM and \( R_{NM} = \rho_N \lambda_{NM} / w_N t_N \) and \( R_{FM} = \rho_{FM} \lambda_{FM} / w_{FM} w_N \) : NM and FM spin resistances.

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