Quick Review over the Last Lecture

Family of Hall effects:

(a) ( )
(b) ( )
(c) ( )

(d) ( ) high H
(e) ( )
(f) ( )

18 Other Spintronic Devices

- Spin caloritronics
- Berry’s phase
- Spin mechatronics
- Zeeman splitting
- Spin optics

Spin injection from a ferromagnet

Magnetic field application

Electric field application

Thermal gradient introduction

Electromagnetic wave introduction
Spin Seebeck Effect

**K. Uchida et al., Nature 455, 778 (2008);**

**K Uchida et al., J. Phys.: Condens. Matter 26, 343202 (2014).**

Spin Seebeck and Nernst Effects

Figure of merit $ZT$:

where $T$: temperature, $\sigma$: electrical conductivity and $\kappa$: thermal conductivity.


Spin Nernst Effect

Persistent current:

- induced by a magnetic flux threading a mesoscopic ring
  \(\rightarrow\) **Aharonov-Bohm effect**
  - The persistent current oscillates with the flux.

- induced by a magnetic field rotating slowly in time
  \(\rightarrow\) **Berry (geometrical) phase**
  - Non-uniform external magnetic fields are required.
  - Spin-polarised persistent current can be generated.

The Einstein de Haas effect describes the rotation of a magnetised body due to the conservation of angular momentum, by the application of a magnetic field.*

The Barnett effect describes the inverse effect, where a body exhibits an increased magnetisation due to mechanical rotation.**

The coupling between rotation and magnetisation and magnetisation and spin currents is well established.

In 2011 Matsuo et al. proposed a new method for the direct generation of a spin current via mechanical rotation.***

\[ J_S = 2enR\eta_{SO} \frac{\hbar 2\pi f}{2\varepsilon_F} \omega_C \]

- \( J_S \) = spin current density
- \( e \) = electron charge
- \( n \) = electron density
- \( R \) = radius of rotation
- \( \eta_{SO} \) = spin orbit coupling strength, 0.59
- \( f \) = frequency
- \( \varepsilon_F \) = Fermi energy
- \( \omega_C = qB/m \) for electron wave packet

* A. Einstein and W. J. de Haas, KNAAW Proc. 18, 696 (1915);
** S. J. Barnett, Phys. Rev. 6, 239 (1915);
• In a similar vein, one can observe the Barnett field in a rotating body observing a shift in the NMR.

• The nuclear $g$ factor dependence of the NMR shift is observed to measure the Barnett field.*

• The presence of a spin current may be detected by the magneto-optical Kerr effect (MOKE).

• This allows for direct probing of the conduction electrons.

**Spin LED structures:**

<table>
<thead>
<tr>
<th>Structures</th>
<th>Spin polarisation</th>
<th>Refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Spin-polarised electron injection:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>300 nm BeMgZnSe + BeMnZnSe / 100 nm n-AlGaAs / 15 nm i-GaAs QW / ... / p-GaAs</td>
<td>~ 42% @ &lt;5 K</td>
<td>R. Fiederling et al., Nature 402, 787 (1999).</td>
</tr>
<tr>
<td>360 nm CdMnTe / 1400 nm CdTe</td>
<td>~ 30% @ 5 K</td>
<td>M. Oestreich et al., Appl. Phys. Lett. 74, 1251 (1999).</td>
</tr>
<tr>
<td>12.5 nm Fe / AlGaAs / GaAs QW / GaAs</td>
<td>~ 13% @ 4.5 K</td>
<td>A. T. Hanbicki et al., Appl. Phys. Lett. 80, 1240 (2002).</td>
</tr>
<tr>
<td>8 nm NiFe + 2 nm CoFe / 1.4 nm AlOx / 15 nm AlGaAs / 100 nm GaAs QW / GaAs</td>
<td>&gt;9.2% @ 80 K</td>
<td>V. F. Motsnyi et al., Appl. Phys. Lett. 81, 265 (2002).</td>
</tr>
<tr>
<td>20 nm (Co, Fe &amp; NiFe) / 2 nm Al2O3 / 50 nm n-AlGaAs / 50 nm si-AlGaAs / 20 nm si-GaAs QW / ... / GaAs</td>
<td>0.8%, 0.5% &amp; 0.2% @ RT</td>
<td>T. Manago et al., Appl. Phys. Lett. 81, 694 (2002).</td>
</tr>
<tr>
<td><strong>Spin-polarised hole injection:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>300 nm p-GaMnAs / 20-220 nm GaAs / 10 nm InGaAs QW</td>
<td>~ 1% @ &lt;31 K</td>
<td>Y. Ohno et al., Nature 402, 790 (1999).</td>
</tr>
</tbody>
</table>

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**Optically-Induced Spin-Polarised Electrons**

**Photoexcitation:**

Electrons spin-polarised by introducing circularly polarised light

Circularly polarised electroluminescence (EL):

Circularly polarised light generated by spin-polarised electrons at a quantum well (QW)
Photon Energy Dependence

Spin polarisation \( \propto \) asymmetry in spin transport effect:

\[
A = \frac{(I^n - I^o)}{(I^n + I^o)}
\]

A decreases with increasing photon energy.

\( \propto \) spin polarisation in GaAs


Spin Electronics with Optical Methods

Spin-polarised inverse photoemission

Spin-polarised STM

Photoexcitation

Spin-polarised LED

Quick Review over this Module

<table>
<thead>
<tr>
<th>Category</th>
<th>Year</th>
<th>Event/Discovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical spin generation</td>
<td>1980</td>
<td>DWI theory</td>
</tr>
<tr>
<td>Spin-orbit effects</td>
<td>1999</td>
<td>Large spin-orbit effect</td>
</tr>
<tr>
<td>Electric field application</td>
<td>1999</td>
<td>Spin Hall theory</td>
</tr>
<tr>
<td>Electromagnetic wave application</td>
<td>1993</td>
<td>Spin injection</td>
</tr>
<tr>
<td>Spin-band splitting</td>
<td>2003</td>
<td>Spin injection</td>
</tr>
<tr>
<td>Influence of thermal gradient</td>
<td>2009</td>
<td>Spin injection</td>
</tr>
<tr>
<td>Geometrical phase</td>
<td>2009</td>
<td>Persistent current theory</td>
</tr>
<tr>
<td>Mechanical rotation</td>
<td>2010</td>
<td>Spin Hall effect</td>
</tr>
<tr>
<td>Materials</td>
<td>1980</td>
<td>Half-metallic Heusler alloy</td>
</tr>
<tr>
<td>Products</td>
<td>1993</td>
<td>High-density storage systems</td>
</tr>
</tbody>
</table>

Summary of Spintronic Devices

- 3rd Generation "3D / quantum"
- 2nd Generation "Spin dynamics"
- 1st Generation "Spin transport"

Spin Memories
- Mott type
- Dirac type

Spin Transistors
- Spin sources
- Quantum spintronics
- Spin interference
- 3D structures

Spin Operation
- Spin resonance
- Spin transfer
- Spin accumulation
- Spin injection / detection

Spin Sources
- Spin injection / detection
- Spin transport
- Spin resonance

Spin Transistor
- MRT
- GMR

Spin Memories
- MRAM
- Spin Seebeck
- Spin Hall

Spin Transistor
- Spin transistor
- Lateral spin-valve
- Spin-torque oscillator

1D
- Spin-torque oscillator
- Spin Hall

2D
- Spin Seebeck
- HDD read head

3D
- MRAM
- HDD write head

Spin interference
- Electromagnetic shield
- Electro-magnetic generator
- Electro-magnetic motor

Spin moment
- Permanent magnet
- Electromagnetic generator
- Electromagnetic motor

Stray field
- Recording media
- Magnetic hyperthermia
- Magnetic tagging

Spin interference
- HDD write head
- HDD read head

Spin interference
- HDD write head
- HDD read head

Electro-magnetic generator
- Electro-magnetic motor
- Recording media
Spintronics is one of the most exciting subject in nano-electronics: