Spintronics in Non-magnetic Semiconductors

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Publicity

- “Giving it a whirl” Dallas Morning News, Sep. 6 (1999)
- “‘Spin’ could be quantum boost for computers” New York Times, Aug. 21, 2001
- “Here’s a switch, for quantum computing” USA Today, Jan. 28 (2003)

“Spintronics” appeared in APS News Jun. 1998; in scientific journals from 1999
Introduction

- **Spintronics**
  - The study and use of devices that operate by controlling electrons or electrically charged particles

- **Spin-based Electronics**
  - Fabrication of devices using
    - Creation of a non-equilibrium spin density
    - Manipulation of spins by external fields
    - Detection of resulting spin state
Some Interesting Old Stuffs

- Hanle Effect
  - Wood and Ellett (1923/1924)
  - Hanle (1924)
    - Depolarization of luminescence by transverse magnetic field

- Optical Pumping
  - Brossel and Kastler (50’s-60’s)
  - Non-equilibrium distribution of atomic angular moments
    - Creation, manipulation, and detection
History - continue

- Lampel (1968)
  - Application of optical pumping in atomic physics to semiconductor (Si)
  - Conduction-band electrons, rather than the bound electrons in atom
- Ecole Polytechnique (Paris) and at Ioffe Institute (St. Petersburg) (70’s – 80’s)
- Tunneling Magnetoresistance (TMR, 1975)
- Spin Valve Effect
  - Giant Magnetoresistance (GMR, 1988)
  - Room-temp. GMR (1991)
Spin Interactions in Semiconductors

- **Magnetic Interaction**: Direct dipole-dipole interaction between magnetic moment of paired electrons.

- **Hyperfine Interaction**: Magnetic interaction between electron $e^-$ and nuclear spins, especially the non-zero-spin lattice nuclei.

- **Spin-orbit Interaction**: "Relativity": effective $B = (v/c) \times E$ for spin orientation, detection, and relaxation.

Optical Spin Orientation and Detection

- Ideally polarization ~ 100%

- Detection
  Using the coupling of orbital selection rule to spin selection rule
Optical Spin Orientation and Detection

- Ideally polarization ~ 100%
- or 50 % for bulks

Detection

Using the coupling of orbital selection rule to spin selection rule
Figure 2. (a) Set-up for the time-resolved photoluminescence spectroscopy. (b) One circularly polarized component of the time-resolved PL of a 25 nm GaAs/(Al,Ga)As QW after excitation with a 2 ps, circularly polarized laser pulse. A magnetic field $B$ perpendicular to the excitation direction leads to a Larmor precession of the optically excited electron spins around the axis of the magnetic field with a Larmor frequency $\omega_L = g^*\mu_B B/\hbar$, where $g^*$ is the electron Landé $g$-factor and $\mu_B$ is the Bohr magneton (see [4] for further details).
Spin Relaxation

- Dissipation of initial spin state
  - “Spin decoherence”
- The result of fluctuating action in time magnetic fields
  - Effective (not “real”) fields
    - Amplitude, or the precession frequency $\omega$
    - Correlation time, $\tau_c$
Spin Relaxation Time $\tau_s$

- For a time interval $t$, the total squared angle is

\[
\frac{t}{\tau_c} \times (\omega \tau_c)^2 = \omega^2 \tau_c t
\]

squared angle

- $\omega \tau_c << 1$
  - $\tau_s >> \tau_c$
  - Spin vector experiences a slow angular diffusion

- $\omega \tau_c >> 1$
  - At a time $\sim 1/\omega$, spin projection random field is transverse to destroyed
  - After time $\tau_c$, spin polarization disappears. preserved

$\tau_s \sim \tau_c$
Spin Relaxation Mechanisms

- **Elliott-Yafet**
  - Relax via ordinary momentum scattering if the lattice ions induce spin-orbit coupling in e\(^{-}\) wave function
  - System possesses a center of symmetry (e.g. elemental metals)

- **D’yakonov-Perel’**
  - System lacks inversion asymmetry
  - Spin precession with Larmor freq. \(\Omega(k) = (e/m)B_e(k)\), along with momentum scattering, leads to spin dephasing.

- **Bir-Aronov-Pikus**
  - Involving a simultaneous flip of spins due to electron-hole exchange coupling

- **Hyperfine interaction**
Spin Relaxation Mechanisms

**Elliot-Yafet**: metal, small-gap semiconductor (InSb)

**D’yakonov-Perel’**: n type III-V (GaAs) or II-VI (ZnSe)

**Bir-Aronov-Pikus**: p type semiconductors
D’yakonov-Perel’ Mechanism in Semiconductors

- Bulk III-V
  - Larmor freq.
  - Spin splitting $\sim k^3$ (Dresselhaus, 1955)

- Two-dimensional III-V systems
  - Two distinct Hamiltonians that contribute
    - Bulk inversion asymmetry (BIA)
    - Structural inversion asymmetry (SIA)
  - Both give spin splitting $\sim k$, but predict a different dependence of $\tau_s$ on the QW orientation relative to the principal axes

\[
\Omega = \alpha h^2 (2m_e^3 E_g)^{-1/2} \mathbf{k}
\]
\[
\mathbf{k} = \left[ k_x (k_y^2 - k_z^2), k_y (k_z^2 - k_x^2), k_z (k_x^2 - k_y^2) \right]
\]
Origins of Inversion Asymmetry

- Bulk inversion asymmetry
  - Zincblende structures

- Interface asymmetry
  - Non-common atom

- Structural inversion asymmetry
  - External field or composition
Rashba Spin-Orbit Interaction

2D Electron Gas

Conduction band edge

Electric field

Dispersion relation

\[ \varepsilon = \frac{\hbar^2 k_{\parallel}^2}{2m^*} \pm \alpha |\vec{k}_{\parallel}| \]

\( \vec{k}_{\parallel} \): wavevector in 2D plane
How To Determine Spin-orbit Coupling constant

FIG. 2. The resistive field at $T=0.5$ marked by arrows shown by the dotted line.

$|\delta| = \left\{ \sqrt{(1-\nu_0)\hbar \omega_c} + (2\Delta_R)^2 \right\}^{1/2} - \hbar \omega_c \approx$

$$
\begin{cases}
2|\Delta_R| - \hbar \omega_c & \text{if } \hbar \omega_c \ll \frac{2|\Delta_R|}{1-\nu_0} \\
|\nu_0|\hbar \omega_c & \text{if } \hbar \omega_c \gg \frac{2|\Delta_R|}{1-\nu_0}
\end{cases}
$$
To Be Concluded ..