Spintronics in Non-magnetic Semiconductors

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Publicity

- “Giving it a whirl” Dallas Morning News, Sep. 6 (1999)
- “Spintastic!” NewScientists, Jun. 16 (2001), p.13
- “'Spin' could be quantum boost for computers” New York Times, Aug. 21, 2001
- “A new spin on computing ..” San Francisco Chronicle, Dec. 10 (2001)
- “Here’s a switch, for quantum computing” USA Today, Jan. 28 (2003)
- “New spin for electronics” Computerworld, Aug. 21 (2003)
- Also in Photonics Spectra (2003) & Chemistry World (2004)

“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

    Spins of

- 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 elections in atom
- Ecole Polytechnique (Paris) and at Ioffe Institute (St. Petersburg) (70's – 80's)
- Tunnelin Magnetoresistance (TMR, 1975)
- Spin Valve Effect
  - Giant Magnetoresistance (GMR, 1988)
  - Room-temp. GMR (1991)

Magnetoelectronics

Spin Interactions in Semiconductors

Magnetic Interaction

Direct dipole-dipole int. between magnetic moment of paired electrons

Hyperfine Interaction

Magnetic int. between e^- and nuclear spins
Especially the non-zero-spin lattice nuclei

Spin-orbit Interaction

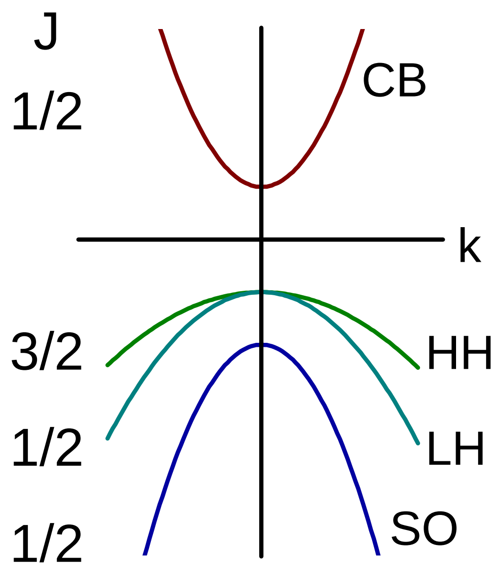
"Relativity": effective $\boldsymbol{B}=(\boldsymbol{v}/c)\times\boldsymbol{E}$
Spin orientation, detection, relaxation

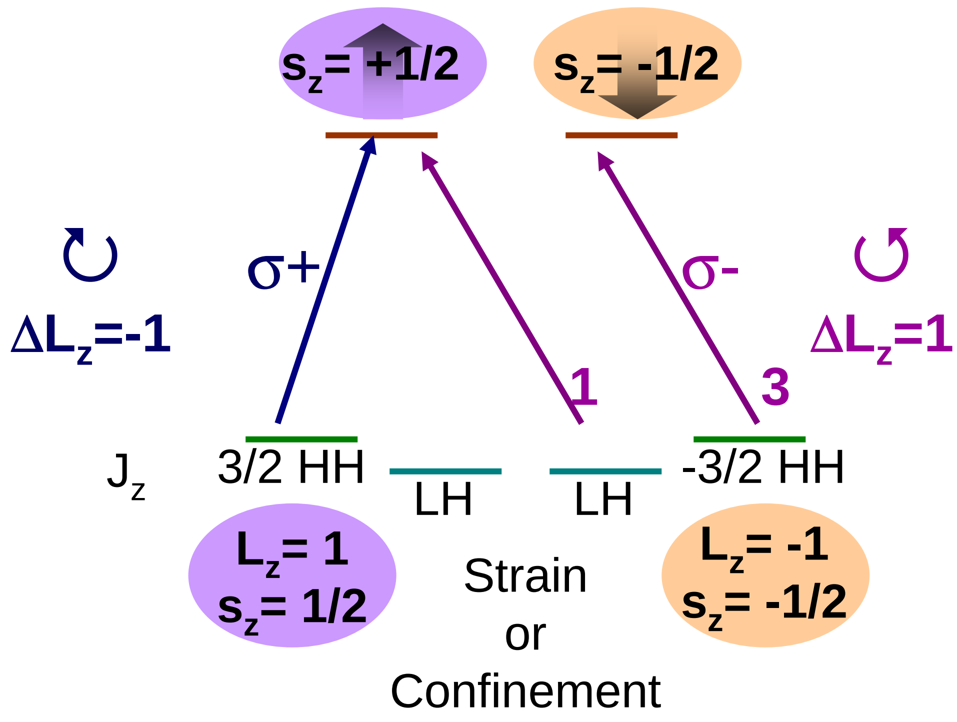
Exchange Interaction

Result of Coulomb int.
Spin-dep. Due to Pauli exclusion princile
Spin injection

Optical Spin Orientation and Detection

- Ideally polarization ~ 100%



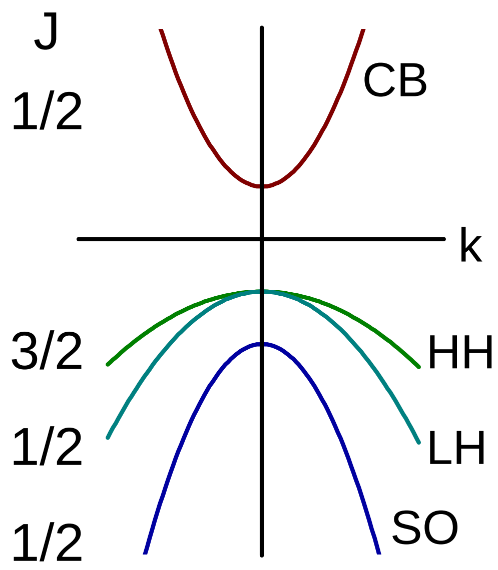


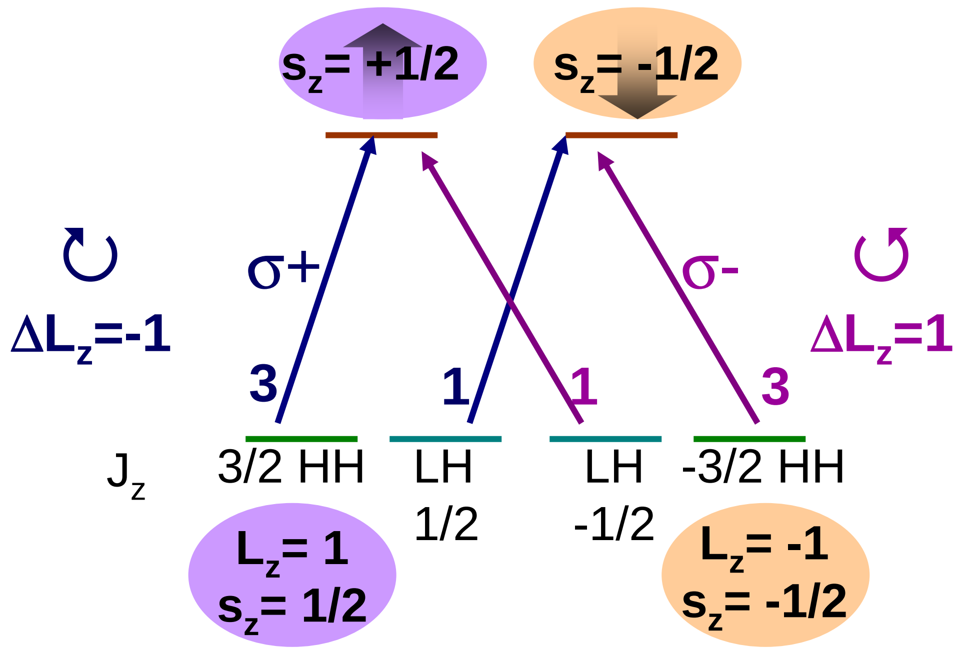
- Detection

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

Time-Resolve Pholomuniescence

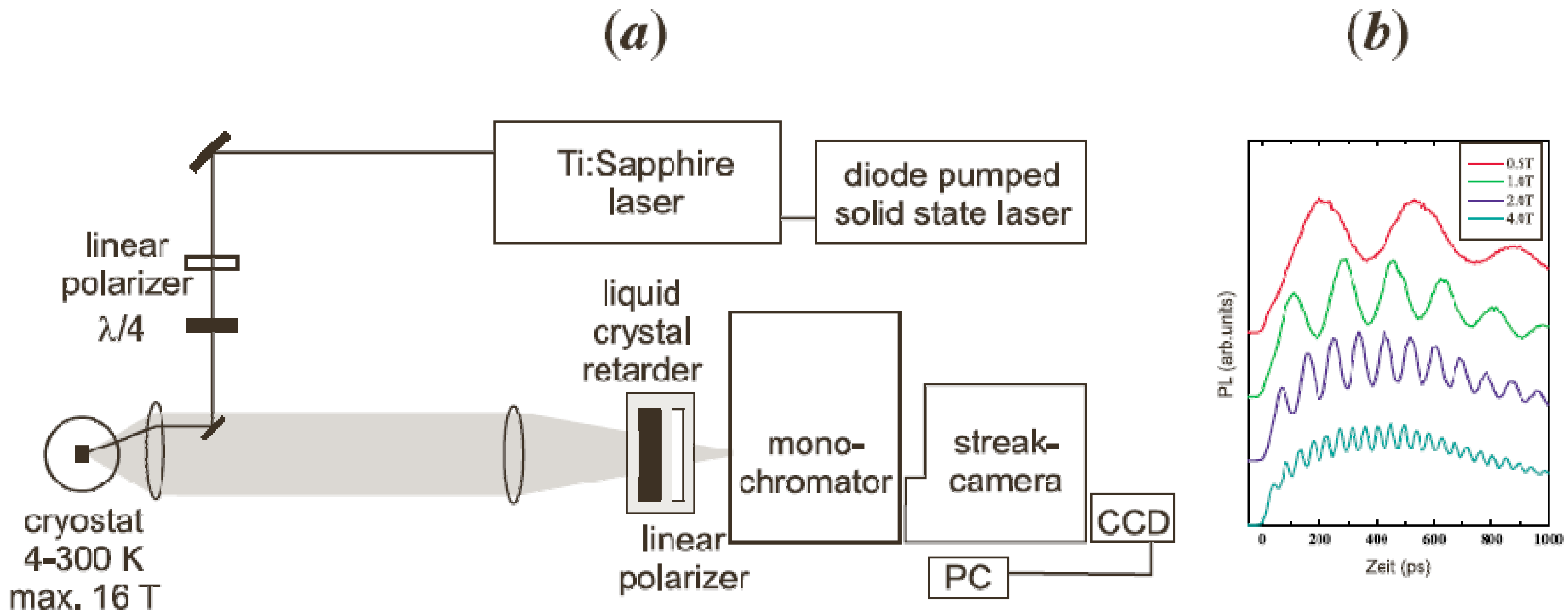
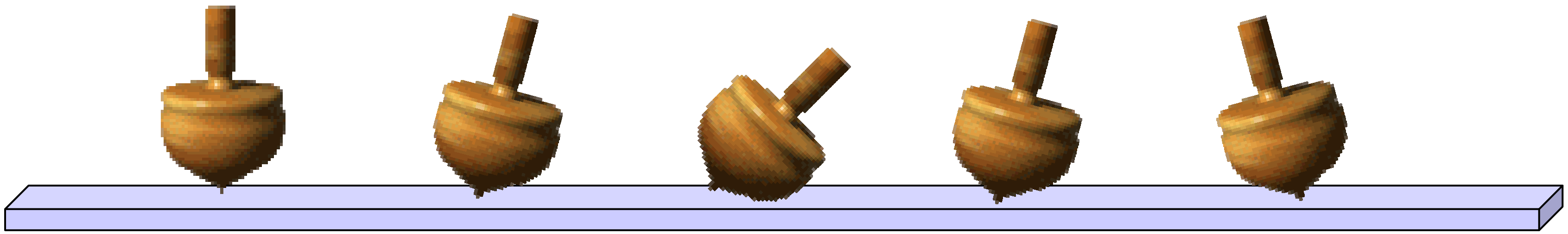


Figure 2. (*a*) Set-up for the time-resolved photoluminescence spectroscopy. (*b*) One circularly polarized component of the time-resolved PL of a 25 nm GaAs/(Al,Ga)As QW after excitation with a 2 ps, circularly polarized laser pulse. A magnetic field B perpendicular to the excitation direction leads 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 μ_B is the Bohr magneton (see [4] for further details).

Oestreich et al. 1996

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 ω
    - Correlation time, τ_c



Spin Relaxation Time τ_s

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

# of random step

$$\underbrace{t/\tau_c}_{\text{\# of random step}} \times \underbrace{(\omega\tau_c)^2}_{\text{squared angle}} = \omega^2\tau_c t \xrightarrow[\text{to define } \tau_s]{\sim 1} \boxed{1/\tau_s \sim \omega^2\tau_c}$$

squared angle

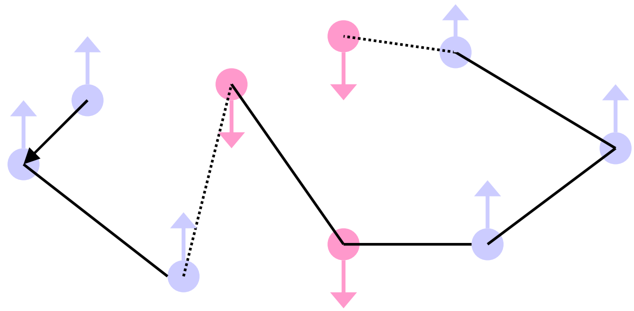
- $\omega\tau_c << 1$ $\boxed{\tau_s >> \tau_c}$
  - Spin vector experiences a slow angular diffusion
- $\omega\tau_c >> 1$
  - At a time ~ $1/\omega$, spin projection transverse to / along random field is destroyed / preserved
  - After time τ_c, spin polarization disappears.

$\boxed{\tau_s \sim \tau_c}$

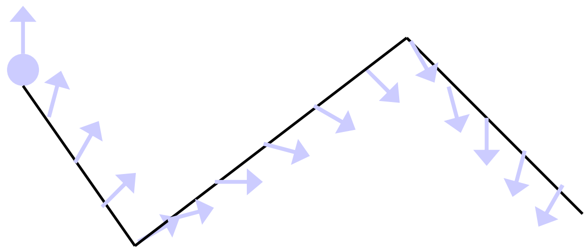
Spin Relaxation Mechanisms

- Elliott-Yafet
  - Relax via ordinary momentum scattering if the lattice ions indeuce spin-orbit coupling in e^- wave function
  - System posses a center of symmetry (e.g. elemental metals)
- D'yakonov-Perel'
  - System lacks inversion asymmetry
  - Spin precesseion with Larmor feq. $\Omega(\mathbf{k})=(e/m)\mathbf{B}_e(\mathbf{k})$, 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

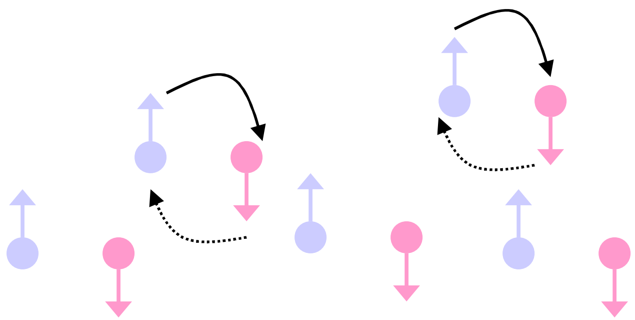
Spin Relaxation Mechanisms



Elliot-Yafet: metal, small-gap semicoductor (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.

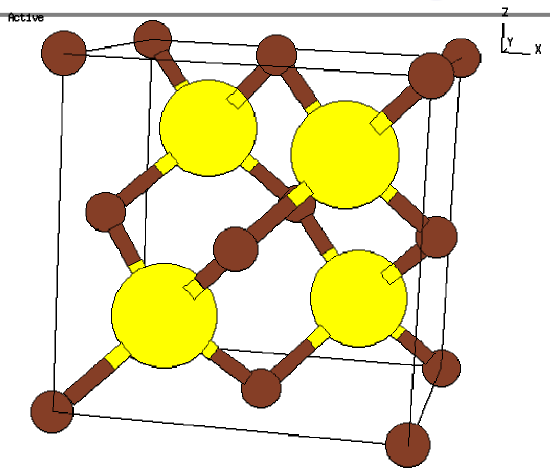
$$\mathbf{\Omega} = \alpha\hbar^2 (2m_c{}^3 E_g)^{-1/2} \boldsymbol{\kappa}$$

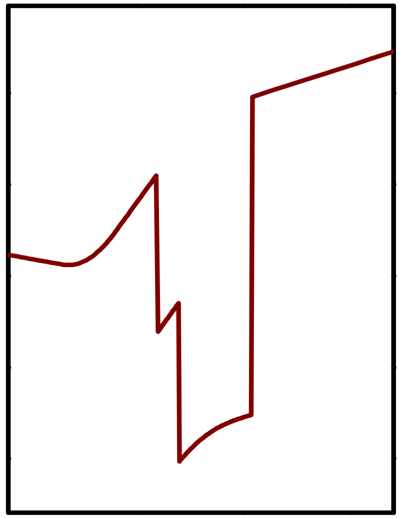
$$\boldsymbol{\kappa} = [k_x(k_y{}^2 - k_z{}^2), k_y(k_z{}^2 - k_x{}^2), k_z(k_x{}^2 - k_y{}^2)]$$

  - Spin splitting ~ 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 ~ k, but predict a different dependence of τ_s on the QW orientation relative to the principal axes

Origins of Inversion Asymmetry

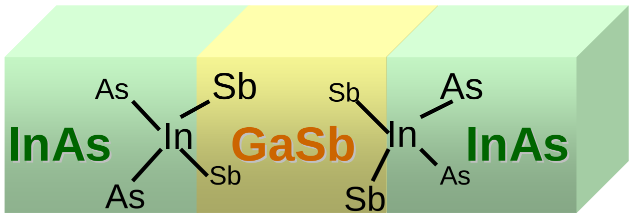
- Structural inversion asymmetry
  - External field or composition





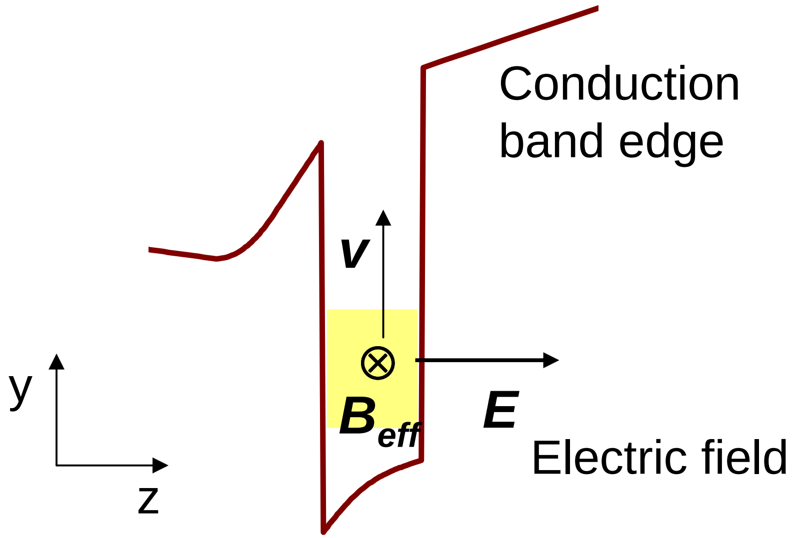
- Bulk inversion asymmetry
  - Zincblende structures

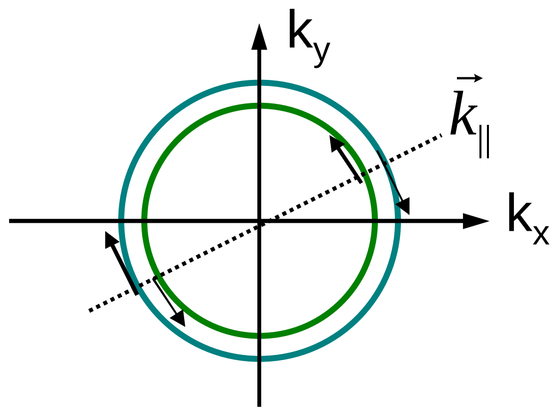
- Interface asymmetry
  - Non-common atom

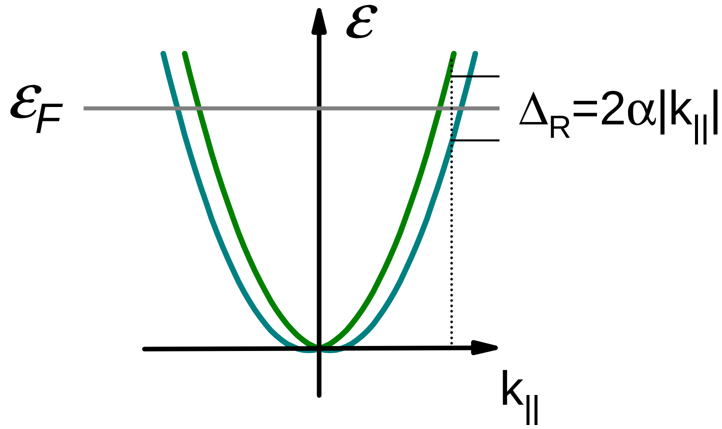


Rashba Spin-Orbit Interaction

- 2D Electron Gas





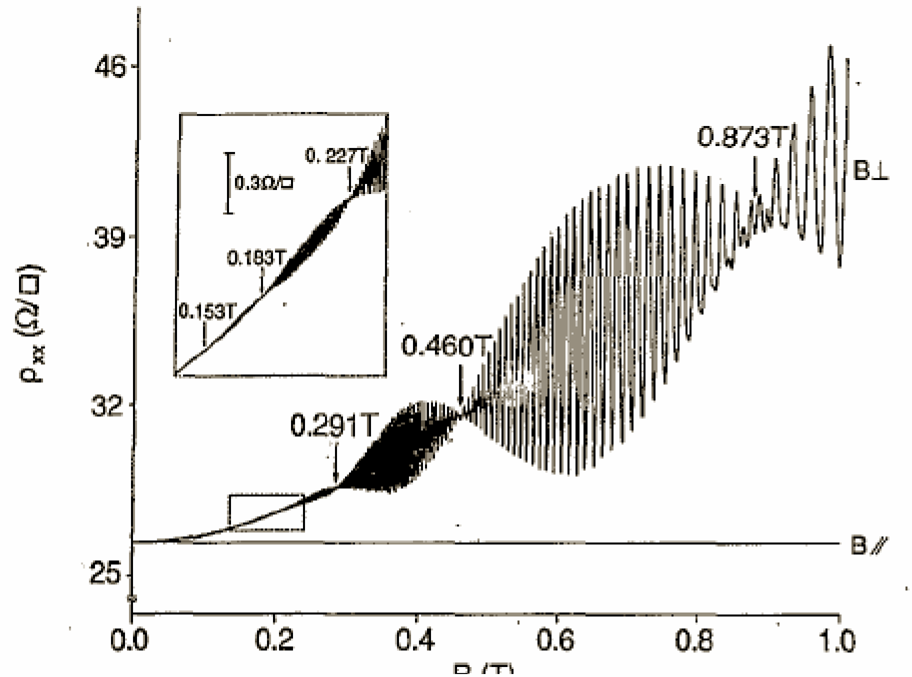


Dispersion relation

$$\varepsilon = \frac{\hbar^2 k_{||}^{\,2}}{2m^*} \pm \alpha \left| \vec{k}_{||} \right|$$

$\vec{k}_{||}$: wavevector in 2D plane

How To Determine Spin-orbit Coupling constant



Das and Datta, PRB(1989)

FIG. 2. The resi
ic field at T=0.5 K
marked by arrows.
shown by the dotted

$$|\delta| = \{[(1-\nu_0)\hbar\omega_c]^2 + (2\Delta_R)^2\}^{1/2} - \hbar\omega_c \simeq \begin{cases} 2|\Delta_R| - \hbar\omega_c & \text{if } \hbar\omega_c \ll \dfrac{2|\Delta_R|}{1-\nu_0} \\ |\nu_0|\hbar\omega_c & \text{if } \hbar\omega_c \gg \dfrac{2|\Delta_R|}{1-\nu_0} \end{cases}.$$

To Be Concluded ..