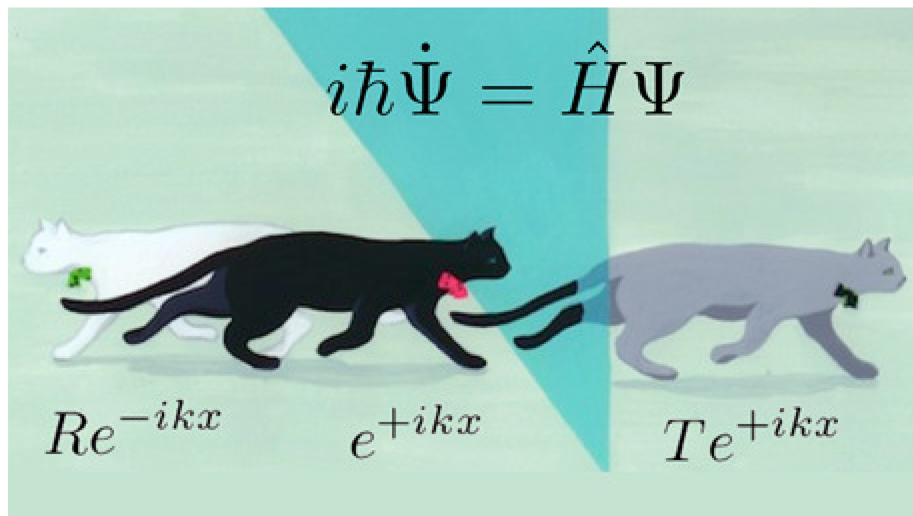
Exploring Quantum Physics

Coursera, Spring 2013   Instructors: Charles W. Clark and Victor Galitski

Guest Lecture: Electron Spin

Part V: Nonequilibrium Spin Injection

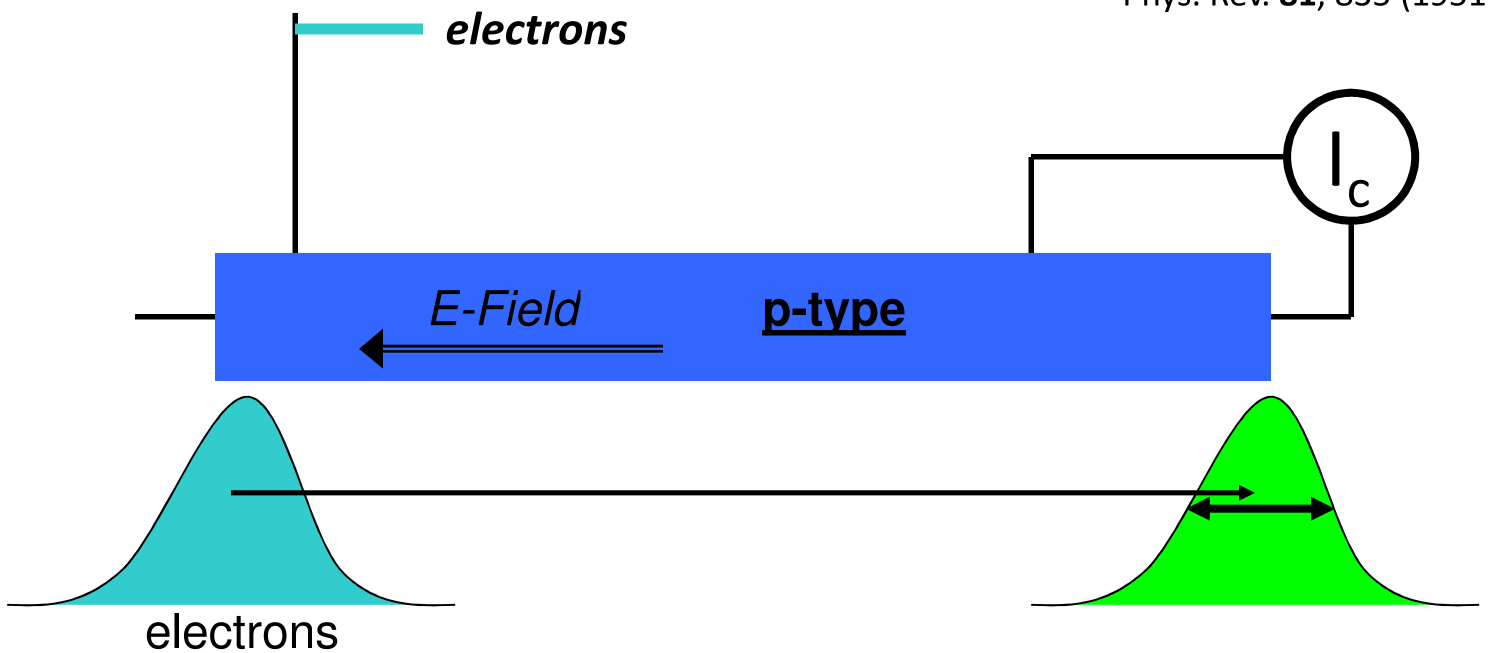


Guest lecturer:
Prof. Ian Appelbaum, U. Maryland Physics Dept.
http://appelbaum.physics.umd.edu

Non-equilibrium transport in semiconductors

Minority charge-carriers: Haynes-Shockley Experiment

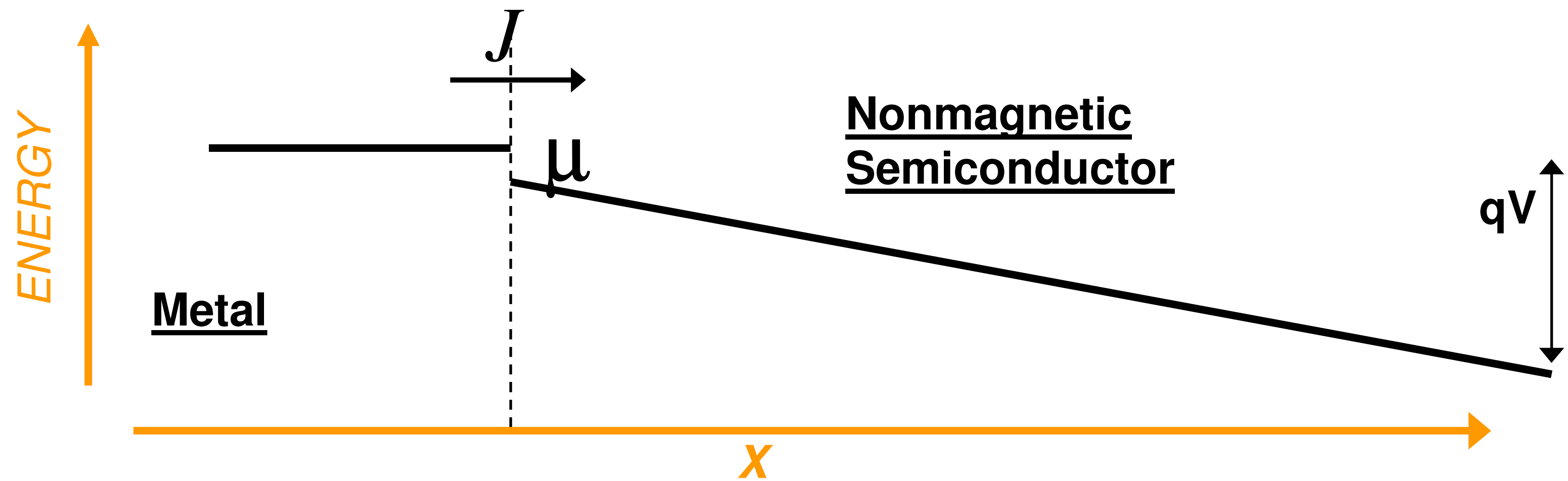
Phys. Rev. **75**, 691 (1949)
Phys. Rev. **81**, 835 (1951)



…led to development of bipolar devices:
junction transistors, thyristors, etc…
The solid-state revolution!

- Minority Carrier Mobility
- Minority Carrier Diffusion Coefficient
- Minority Carrier Lifetime

Metal-Semiconductor Ohmic Contacts

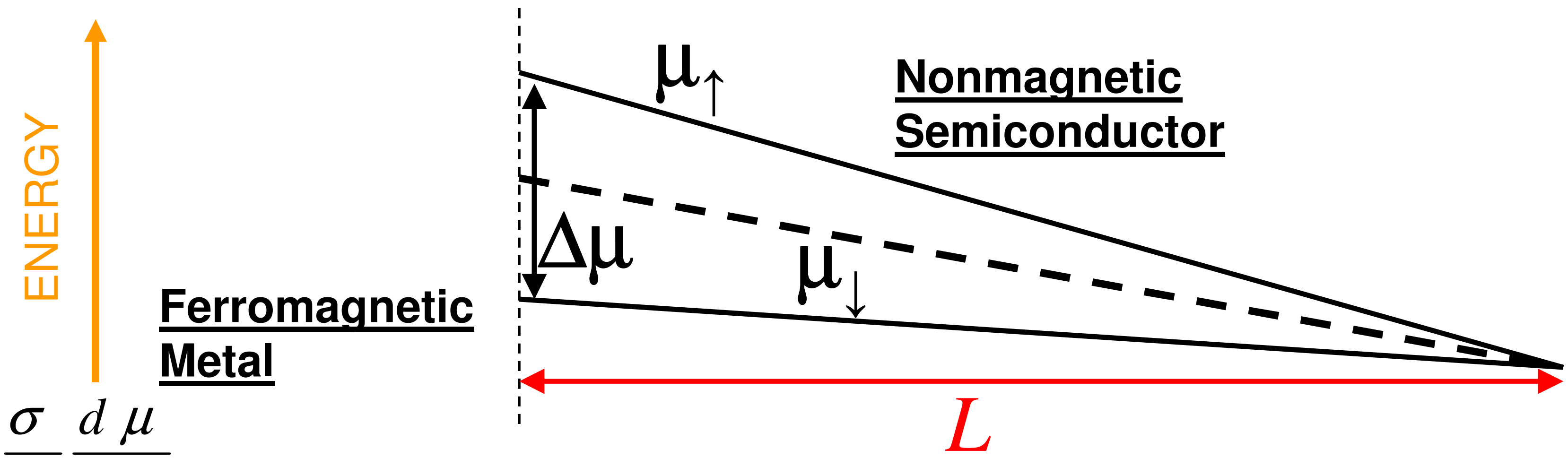


Current density — conductivity — Electrochemical potential — Electron charge

$$J = \frac{\sigma}{q} \frac{d\mu}{dx}$$

- Current density: J
- conductivity: σ
- Electrochemical potential: μ
- Electron charge: q

Ferromagnet-Semiconductor Ohmic Contact



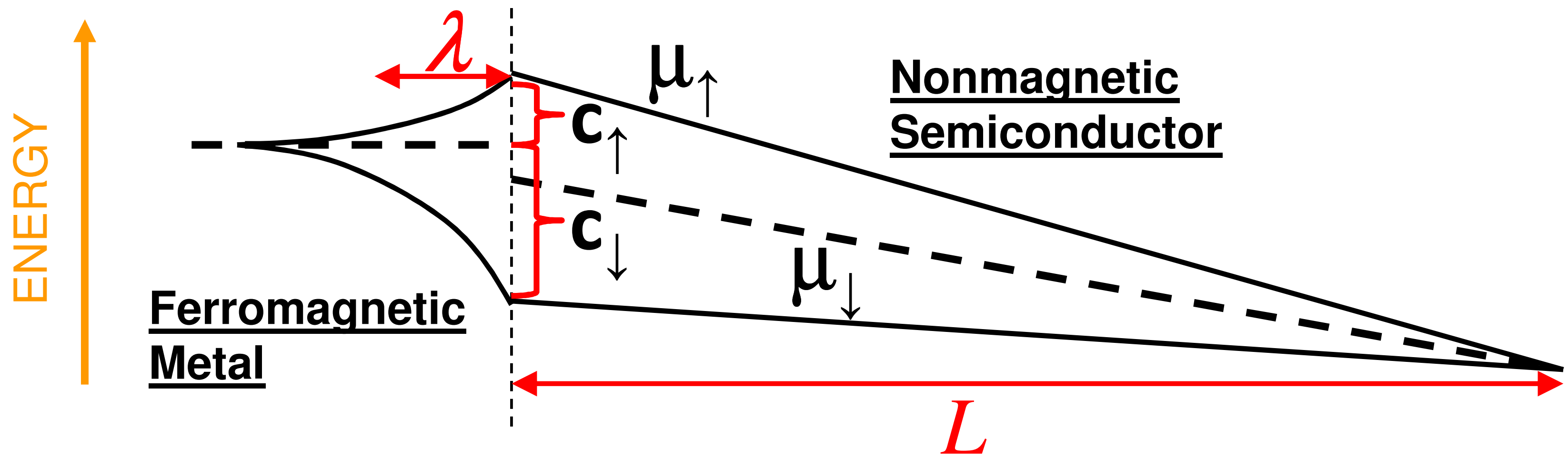
$$J = \frac{\sigma}{q}\frac{d\mu}{dx}$$

$$J_{\uparrow} = \frac{\sigma_s}{2Lq}\left(\frac{qJL}{\sigma_s} + \frac{\Delta\mu}{2}\right) = \frac{J}{2} + \frac{\sigma_s \Delta\mu}{4Lq}$$

$$J_{\downarrow} = \frac{\sigma_s}{2Lq}\left(\frac{qJL}{\sigma_s} - \frac{\Delta\mu}{2}\right) = \frac{J}{2} - \frac{\sigma_s \Delta\mu}{4Lq}$$

$$P = \frac{J_{\uparrow} - J_{\downarrow}}{J} = \frac{\sigma_s \Delta\mu}{2LJq}$$

Ferromagnet-Semiconductor Ohmic Contact



$$J_\uparrow = \frac{\sigma_\uparrow}{\lambda q}\left(\frac{qJ\lambda}{\sigma_{FM}} - c_\uparrow\right)$$

$$J_\downarrow = \frac{\sigma_\downarrow}{\lambda q}\left(\frac{qJ\lambda}{\sigma_{FM}} + c_\downarrow\right)$$

$$\Delta\mu = c_\uparrow + c_\downarrow$$

$$\Delta\mu = \left(\frac{qJ\lambda}{\sigma_{FM}} - \frac{qJ_\uparrow\lambda}{\sigma_\uparrow}\right) + \left(\frac{qJ_\downarrow\lambda}{\sigma_\downarrow} - \frac{qJ\lambda}{\sigma_{FM}}\right)$$

"Fundamental Obstacle to Spin Injection"

Using definitions:

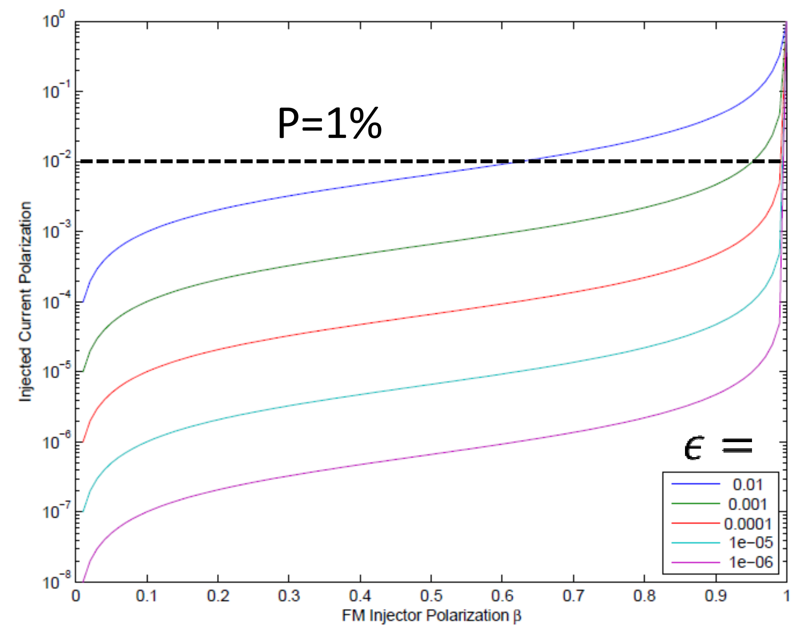
$$P = \frac{J_\uparrow - J_\downarrow}{J} \qquad \beta = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}$$

$$J_\uparrow = J\frac{1+P}{2},\ J_\downarrow = J\frac{1-P}{2},\ \sigma_\uparrow = \sigma_{FM}\frac{1+\beta}{2} \text{ and } \sigma_\downarrow = \sigma_{FM}\frac{1-\beta}{2}$$

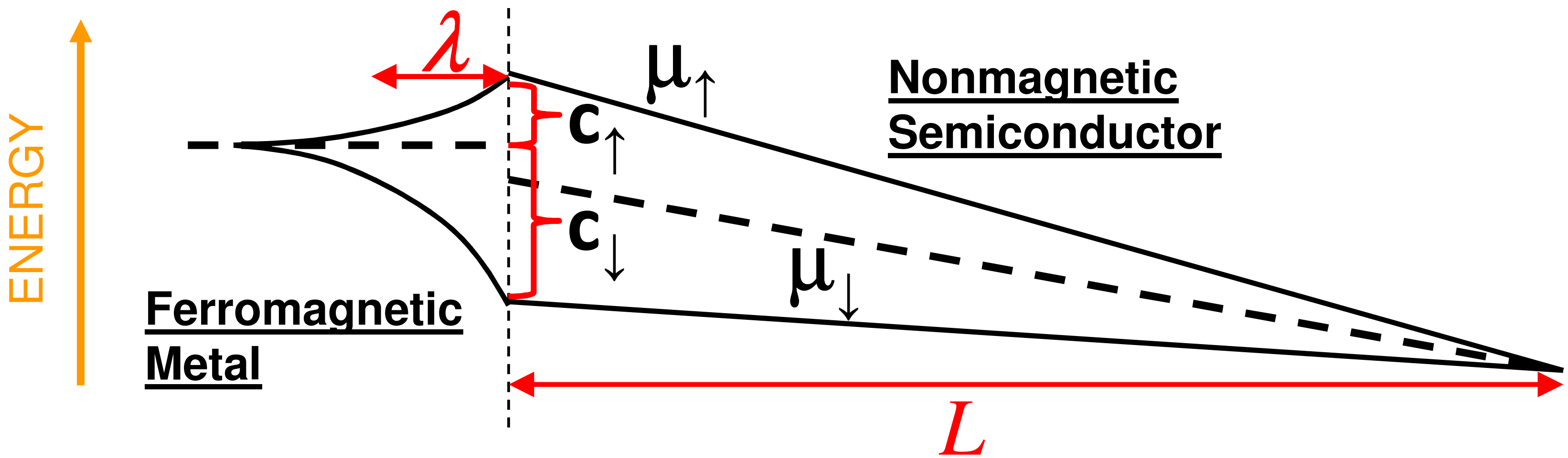
We obtain on the FM side $\Delta\mu = \frac{2\lambda Jq}{\sigma_{FM}}\left(\frac{\beta - P}{1-\beta^2}\right)$

$$P = \frac{\sigma_s \Delta\mu}{2LJq} = \frac{\beta\epsilon}{1+\epsilon-\beta^2}$$

$$\epsilon = \frac{\sigma_s \lambda}{\sigma_{FM} L}$$



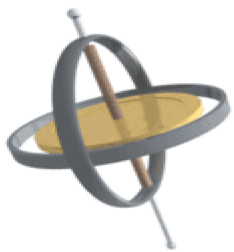
- Ohmic transport from a ferromagnetic metal will not result in appreciable spin injection… unless it's a nearly "perfect" half-metallic ferromagnet w/ ~100% spin polarization!

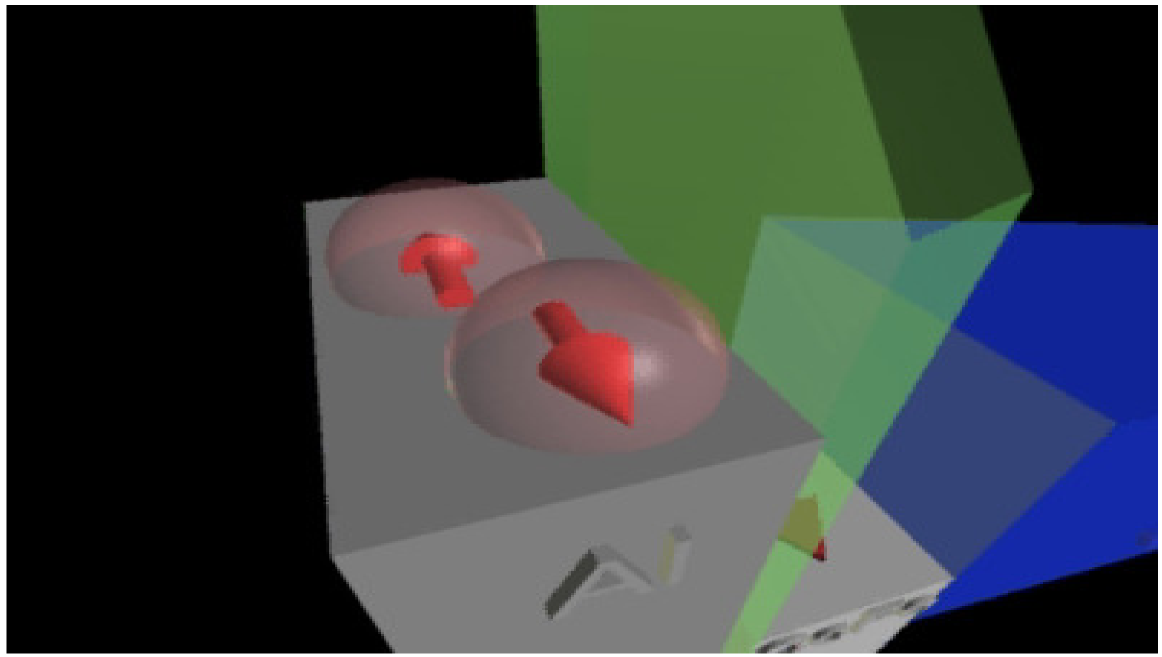


ENERGY
λ
μ↑
Nonmagnetic
Semiconductor
c↑
c↓
μ↓
Ferromagnetic
Metal
L

Spin Precession

precession angle → $\theta = \omega t$ (ω: precession frequency; t: Transit time)



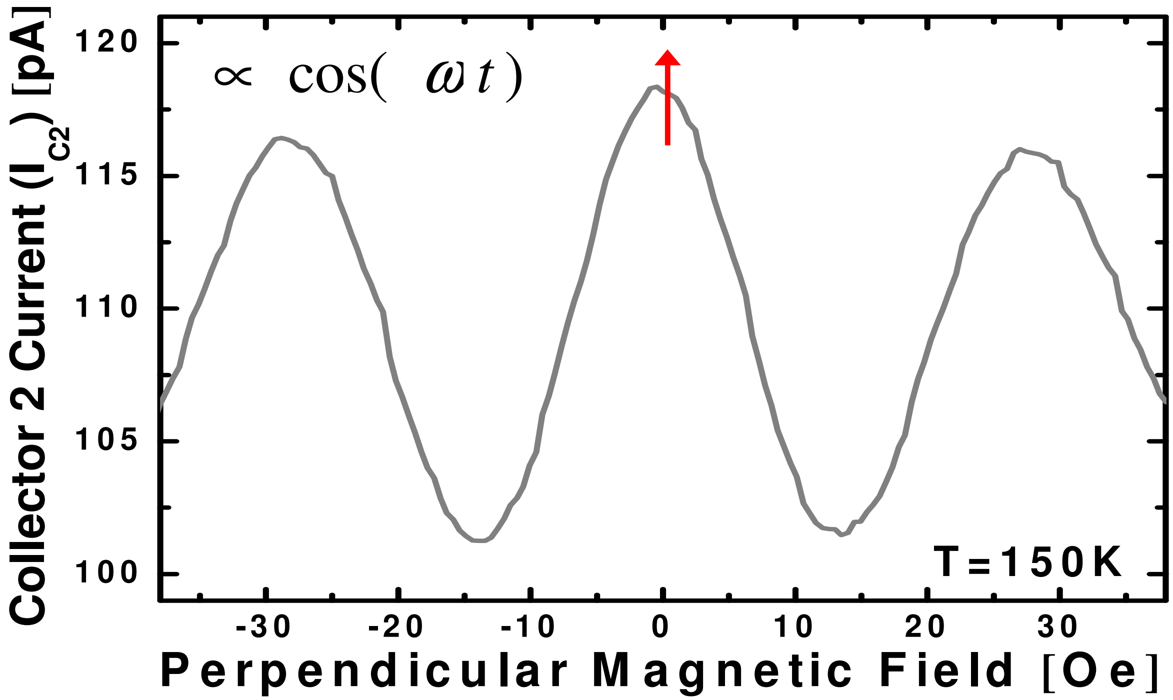


Spin Precession: example measurment

precession frequency

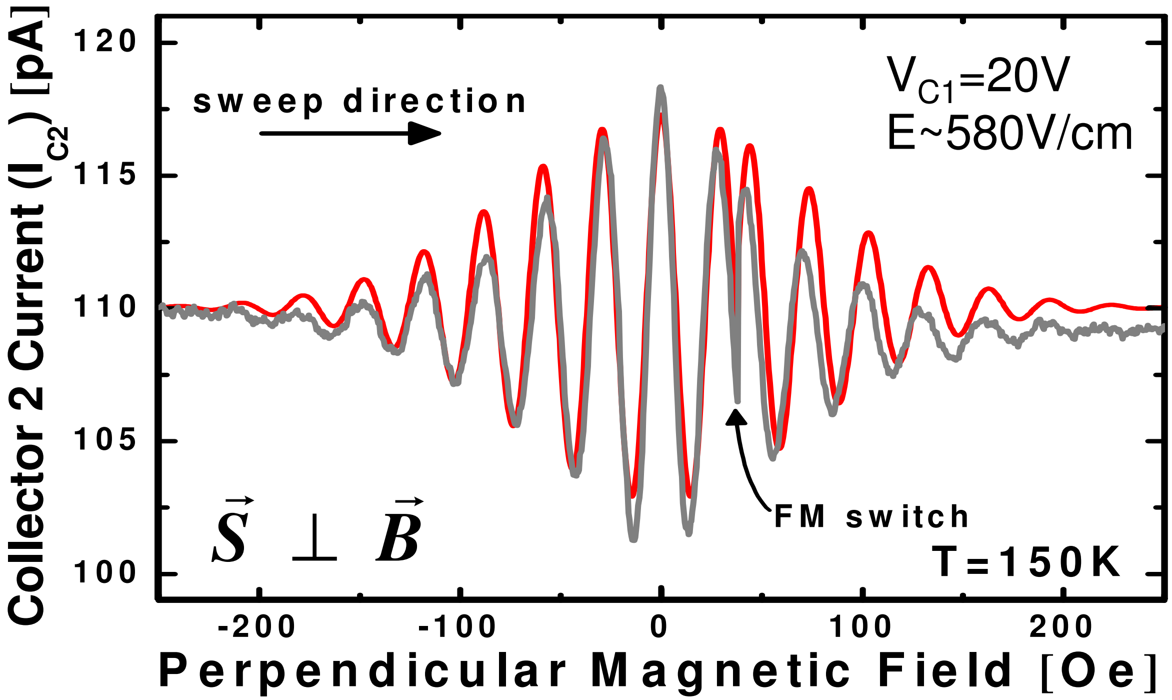
Transit time

precession angle → $\theta = \omega t$



$$\omega = \frac{g \mu_B B}{\hbar}$$

Spin precession (Hanle): transport through 350 μm Si



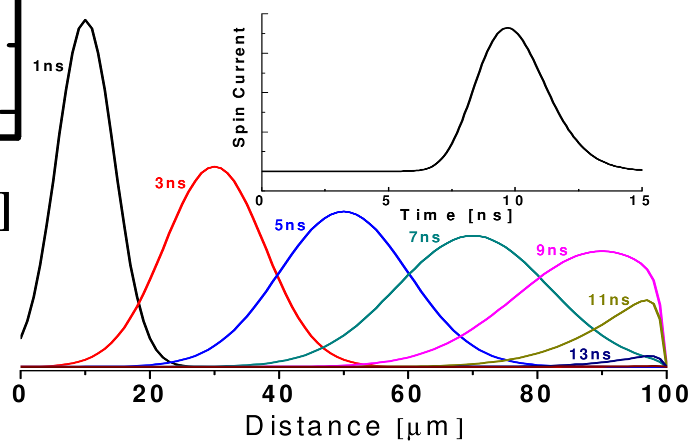
$$\theta = \omega t$$

$$\omega = \frac{g \mu_B B}{\hbar}$$

$$\Delta\theta = \omega\Delta t$$

"dephasing"
due to diffusion

$$\int_0^\infty P(t)\cos(\omega t)dt$$

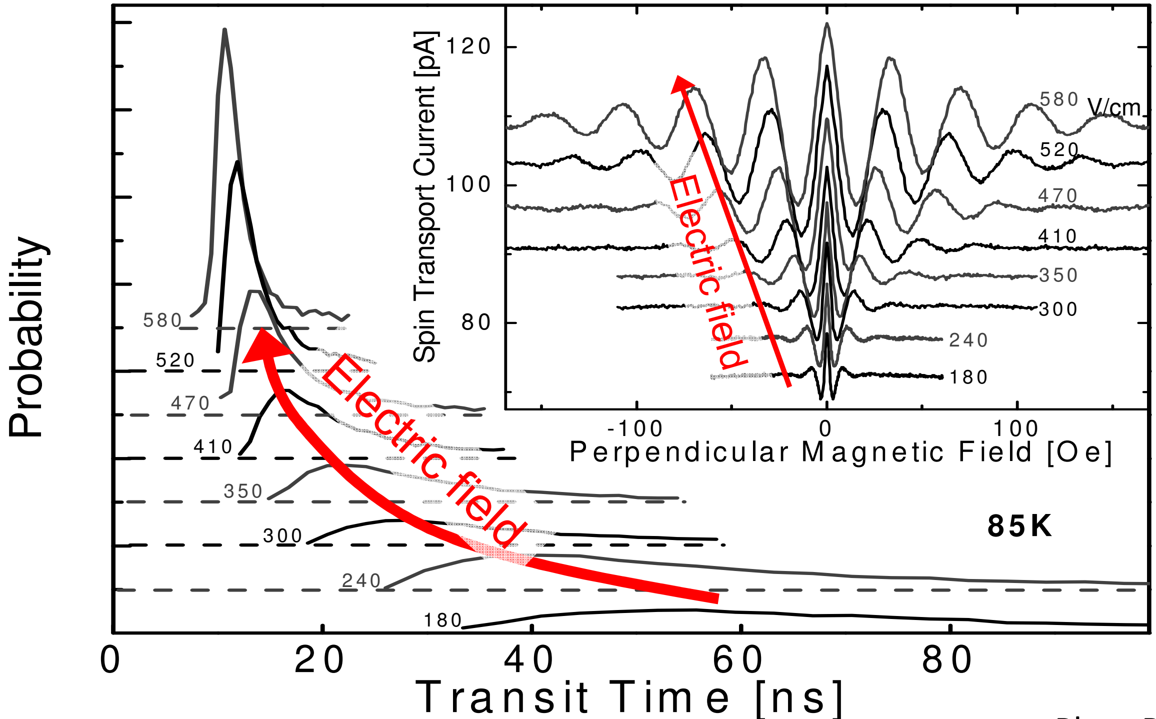


PRL **99**, 177209 (2007); PRB **77**, 165331 (2008); and APL **95**, 152501 (2009)

Spin-Current Transport-Time Distribution

$$\int_0^{\infty} P(t)\cos(\omega t)dt = \mathrm{Re}\left\{\int_{-\infty}^{\infty} P(t)e^{-i\omega t}dt\right\}$$

"Time-of-flight" from a DC measurement via the Fourier transform: the "Larmor clock"!:

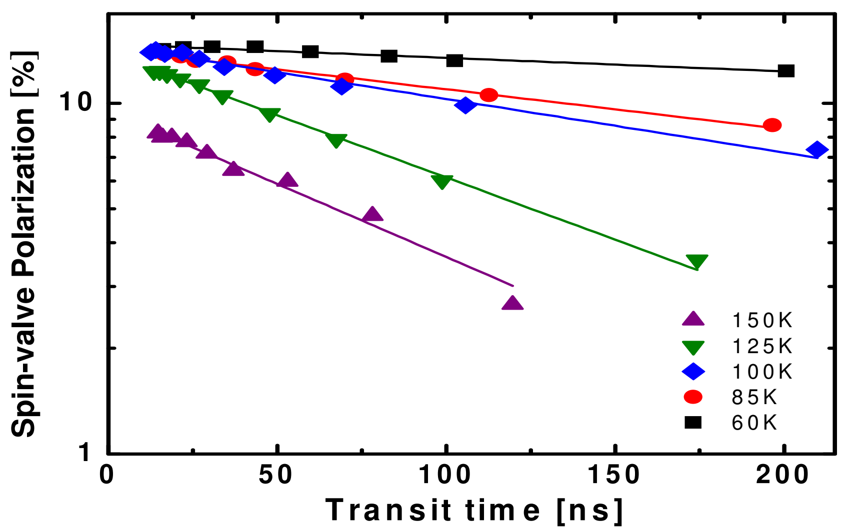


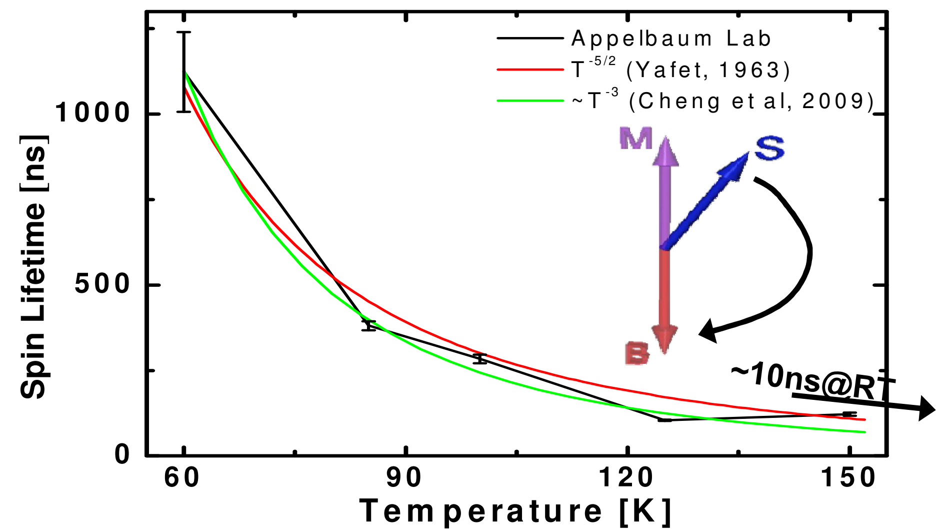
Spin **mobility** and **diffusion coefficient** from mean and standard deviation

PRL **103**, 117202 (2009)

Phys. Rev. B Rapid Comm. **82**, 241202(R) (2010)

Spin Lifetime Extraction





PRL 99, 177209 (2007)
And in "Spin Transport and Magnetism in Electronic Systems" Zutic and Tsymbal, eds.

Spin-Relaxation: Elliot scattering

- Dominant spin-relaxation process in inversion-symmetric materials like silicon
- Spin-orbit interaction: wavefunction not pure spin eigenstates:

$$|k,\Uparrow\rangle = a|k,\uparrow\rangle + b|k,\downarrow\rangle$$
$$|k,\Downarrow\rangle = a^*|k,\downarrow\rangle - b^*|k,\uparrow\rangle$$

$|a|^2 + |b|^2 = 1$

Transition rate via Fermi's golden rule: $T_{i\to f} = \frac{2\pi}{\hbar}\left|\langle f|H'|i\rangle\right|^2 \rho,$

$$T_{k\uparrow\to k'\downarrow} = |\langle k',\Downarrow|H'|k,\Uparrow\rangle|^2 = |\,(a\langle k',\downarrow| - b\langle k',\uparrow|)H'(a|k,\uparrow\rangle + b|k,\downarrow\rangle)\,|^2$$

$$= |a^2\langle k',\downarrow \cancel{|H'|} k,\uparrow\rangle - b^2\langle k',\uparrow \cancel{|H'|} k,\downarrow\rangle$$
$$+ab(\langle k',\downarrow|H'|k,\downarrow\rangle - \langle k',\uparrow|H'|k,\uparrow\rangle)|^2$$

$$\approx b^2|\langle k'|H'|k\rangle|^2 \qquad (\text{for } a\sim 1)$$

$$= b^2 T_{k\to k'}$$

Brought to you by….

"CAREER: Silicon Spintronics" ECCS-0901941

"Scalable Digital Spin Logic Devices" ECCS-1231855

http://appelbaum.physics.umd.edu/