Interfacing ferromagnets with semiconductors

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Spin injection and detection

Injection → / Detection ↓	electrical	optical
electrical	GMR E-Hanle	Photogalvanic effect
optical	Spin-LED, SHE Electric FPE	Photo FPE

FPE Ferromagnetic proximity effect

Content

- Ferromagnetic proximity effect
  - Spin-polarization by reflection
  - Interface spin-transfer torque dephasing
  - Hanle effect electrical spin detection
- Electrical detection of current-induced spins
  - Spin current generation by spin-orbit interaction
  - Onsager relations for SO|F interfaces
  - Point contacts
- Detection of current-induced spins by ferromagnets

Collaborators


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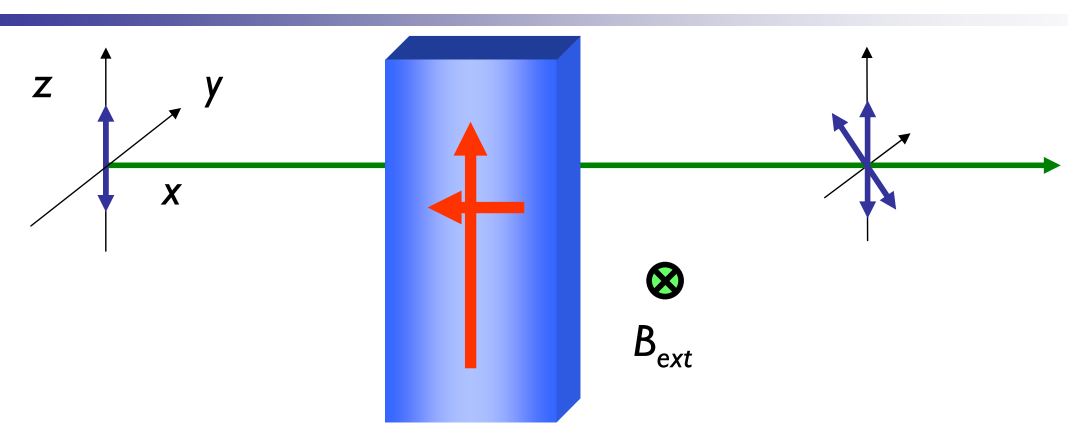
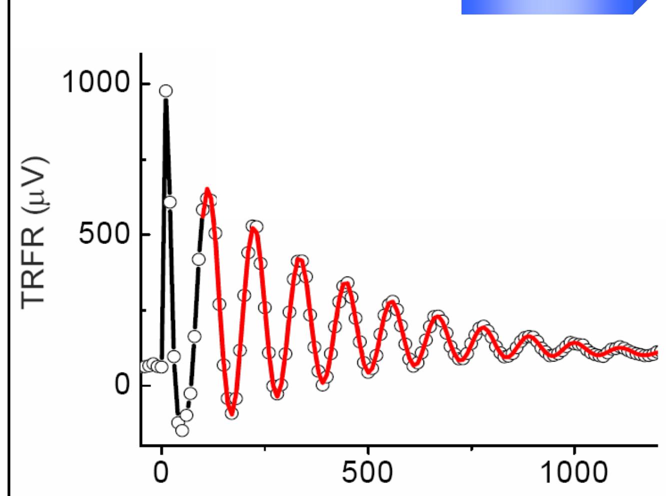
Thanks to:
Jason Stephens
David Awschalom
Georg Schmidt

Time-dependent Faraday/Kerr spectroscopy

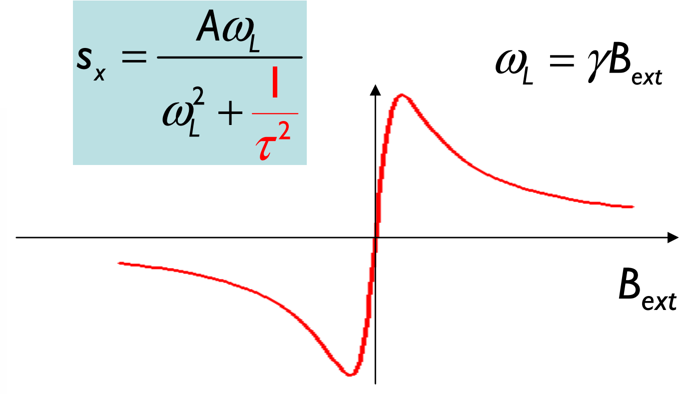




Time integrated signal:

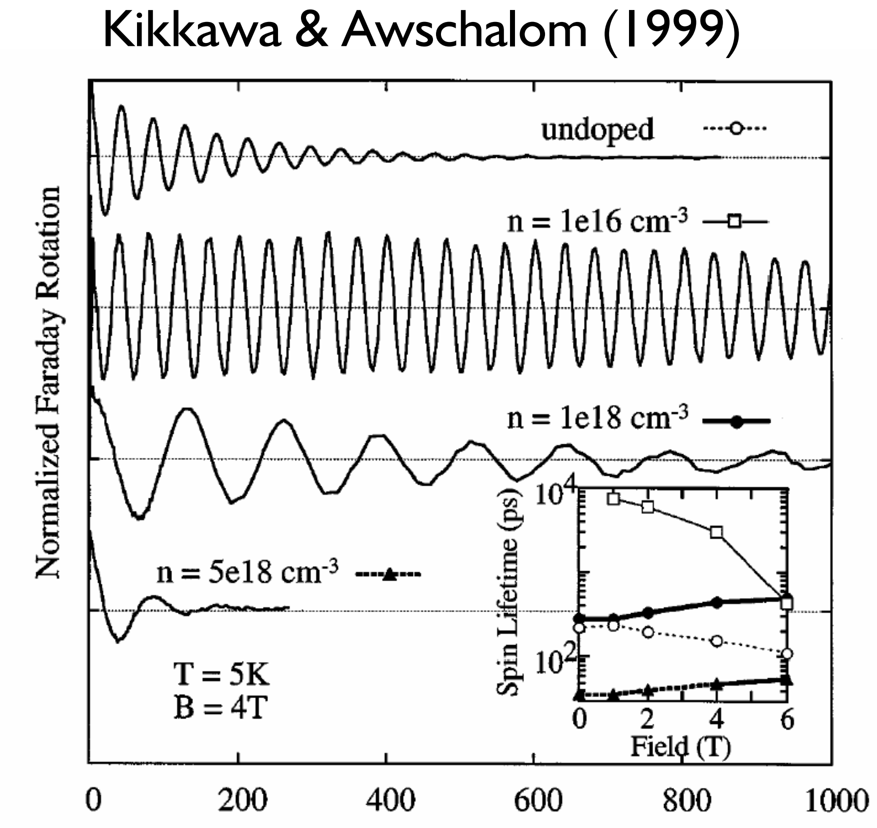
$$s_x = \frac{A\omega_L}{\omega_L^2 + \frac{1}{\tau^2}}$$

$$\omega_L = \gamma B_{ext}$$

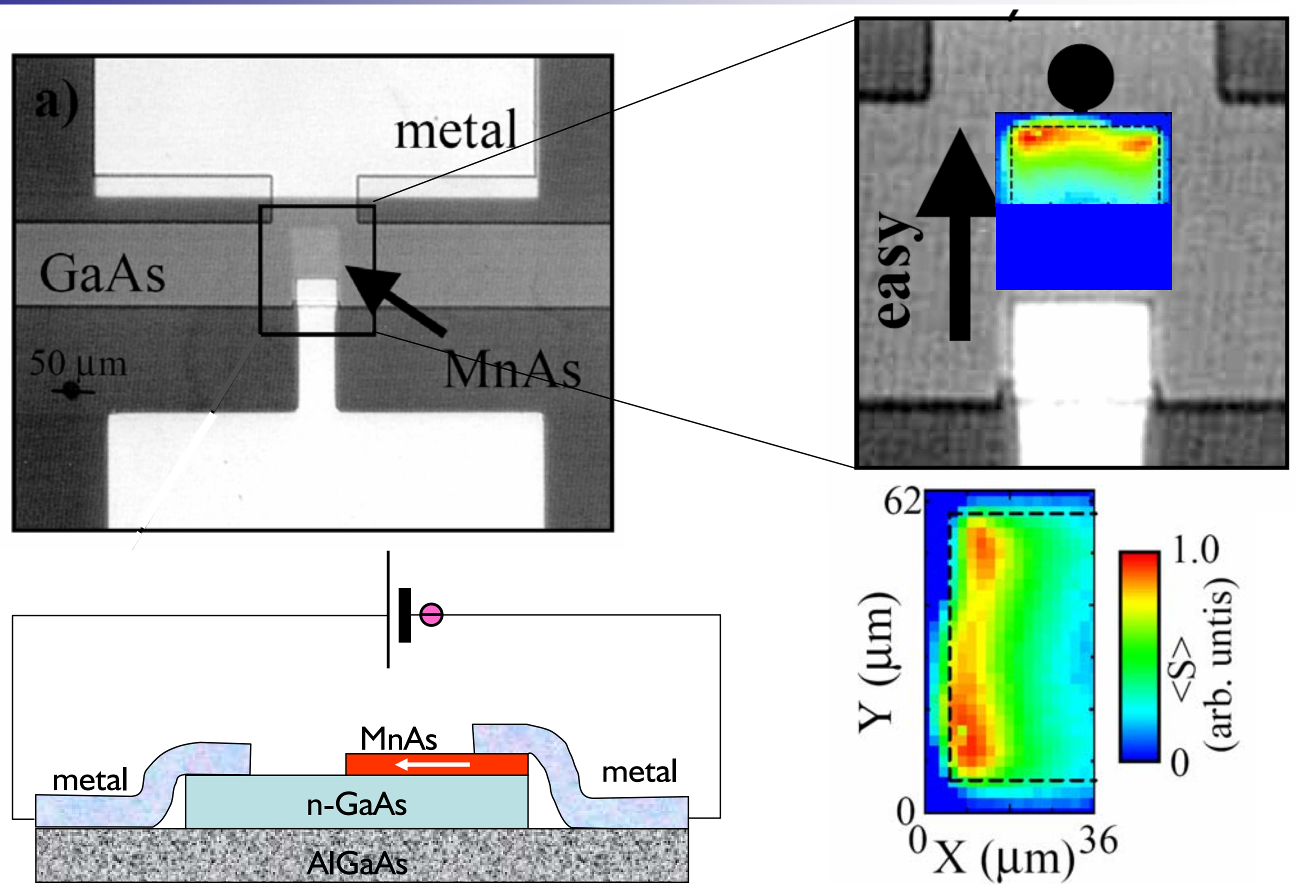


Spin coherence life time in n-type GaAs

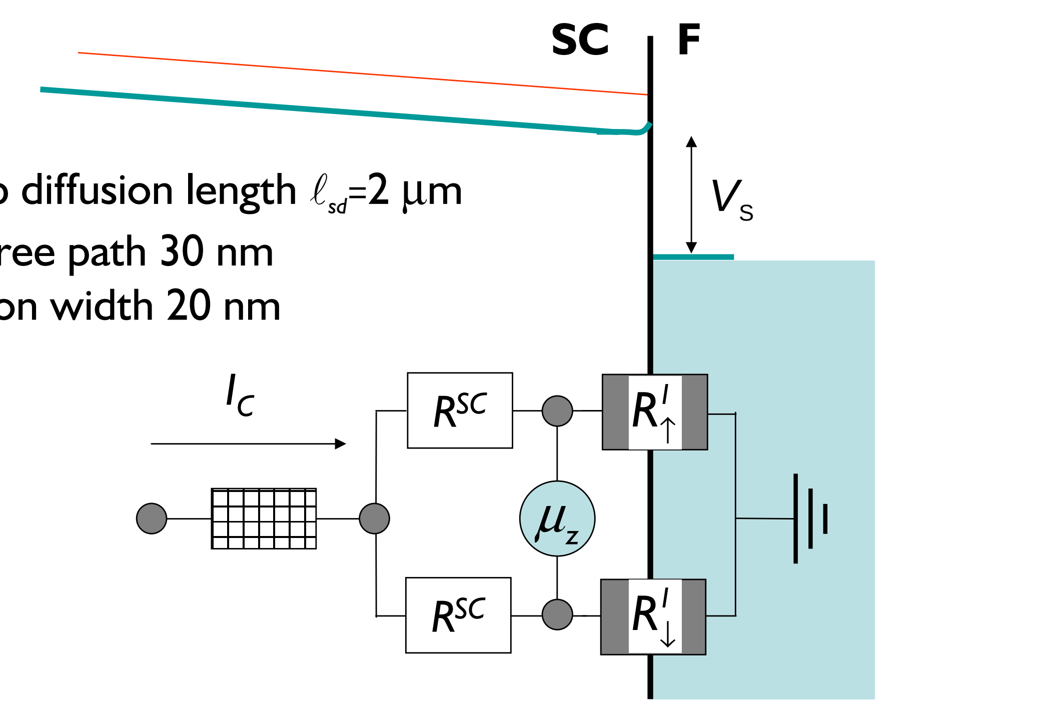
Kikkawa & Awschalom (1999)



J. Stephens *et al.* (2004)



Zero magnetic field resistor model



- spin-flip diffusion length ℓ_{sd}=2 µm
- mean-free path 30 nm
- depletion width 20 nm

R^{SC} single-spin resistance of spin-coherent part of semiconductor

$R_\downarrow(I_C)$ spin ↓ interface resistance including depletion region

μ_z interface spin accumulation

Conductance mismatch and Schottky barriers

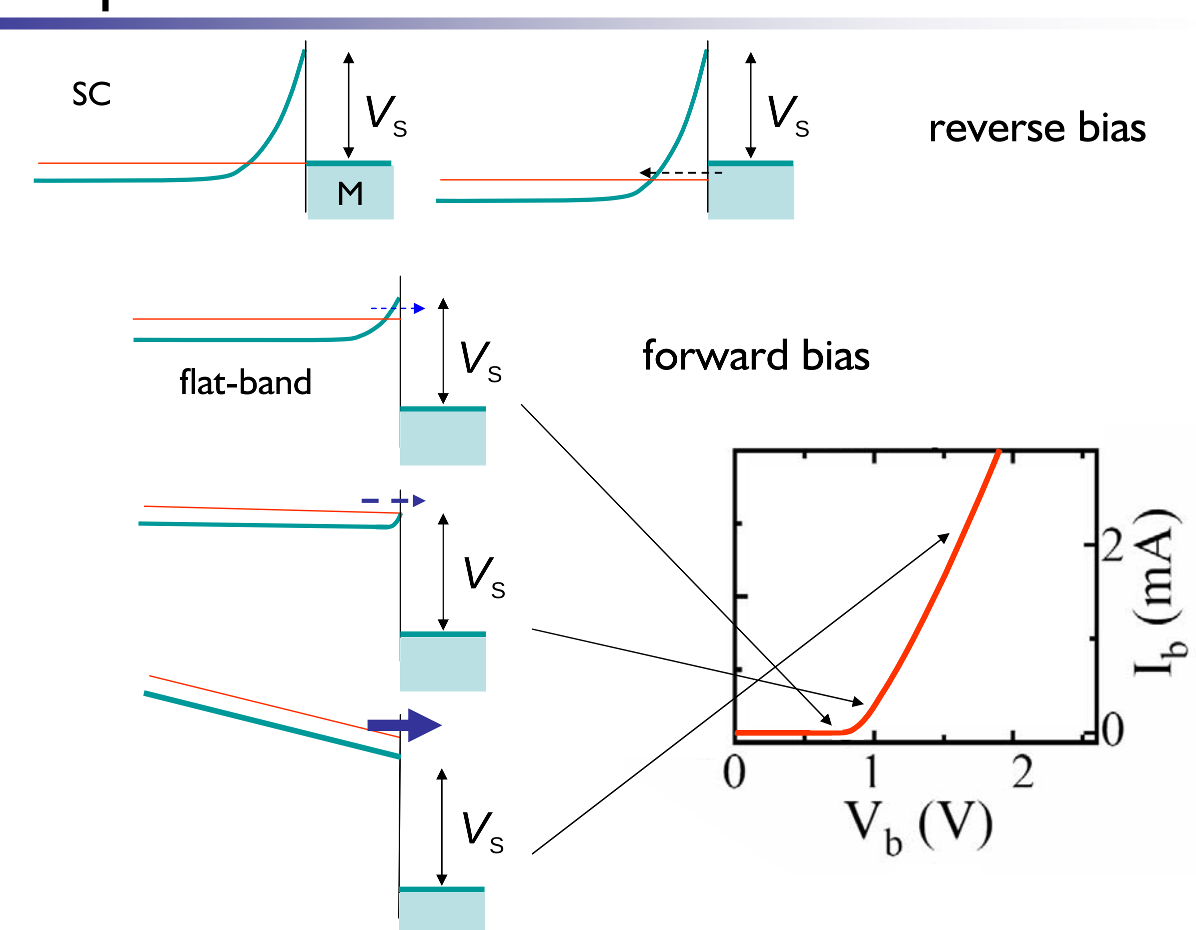
Spin current: $$I_\uparrow - I_\downarrow = \frac{I_z^{(0)}}{1+\dfrac{G^I(\varepsilon_F)}{2G^{SC}(\varepsilon_F)}}$$

$$eI_z^{(0)} = \int_0^{\varepsilon_F} \left(G_\uparrow^I(\varepsilon) - G_\downarrow^I(\varepsilon)\right) d\varepsilon$$

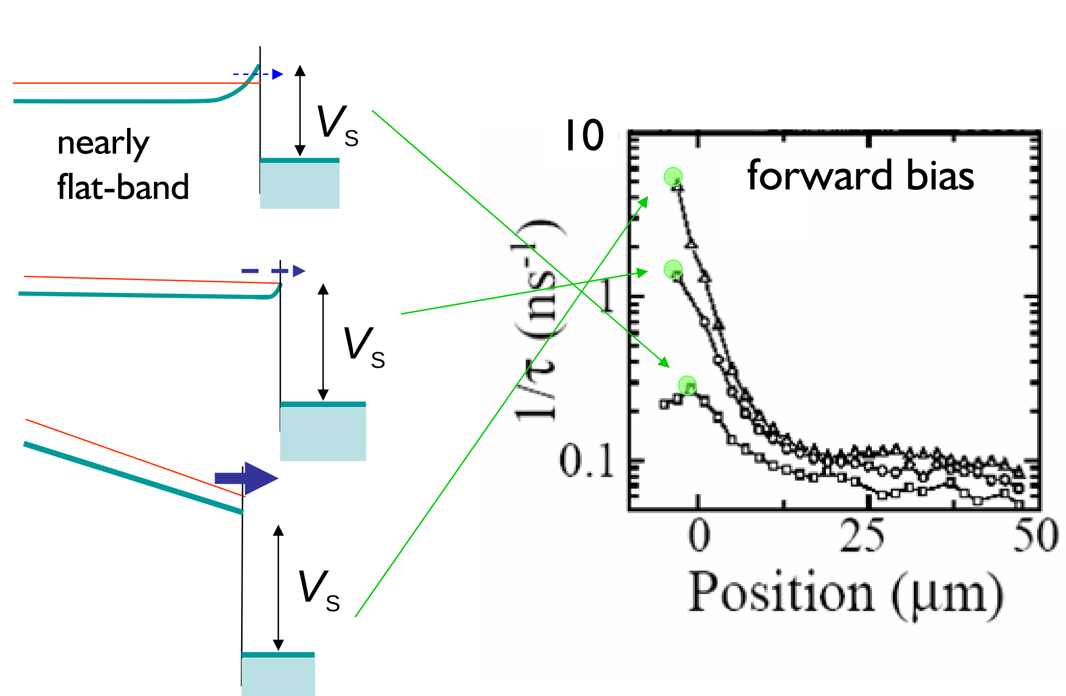
Spin accumulation: $$\mu_\uparrow - \mu_\downarrow = -\frac{I_\uparrow - I_\downarrow}{G^{SC}(\varepsilon_F)}$$

A small semiconductor conductance G^{SC} suppresses the spin current (Schmidt *et al.*, 2000) but enhances the spin accumulation

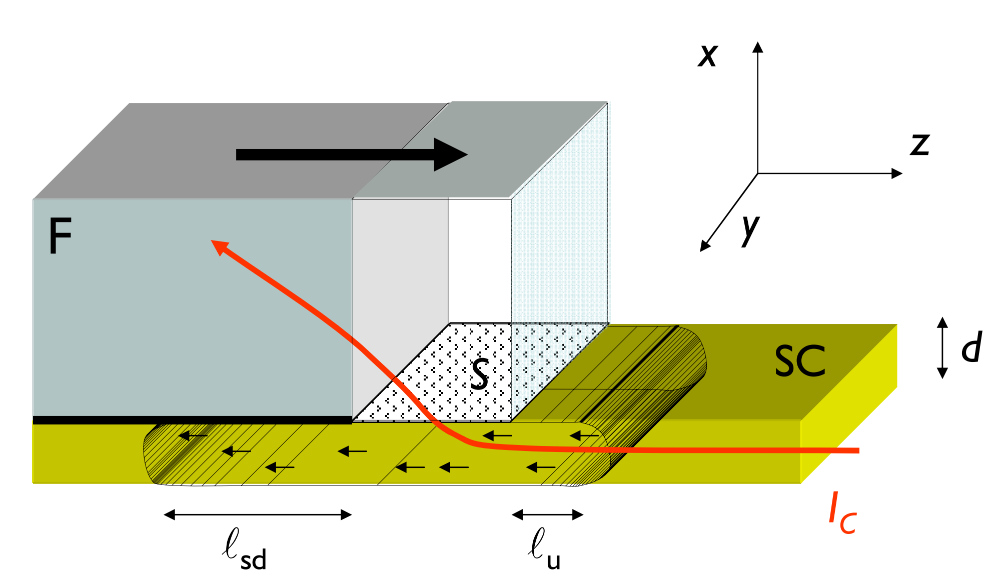
Band profiles



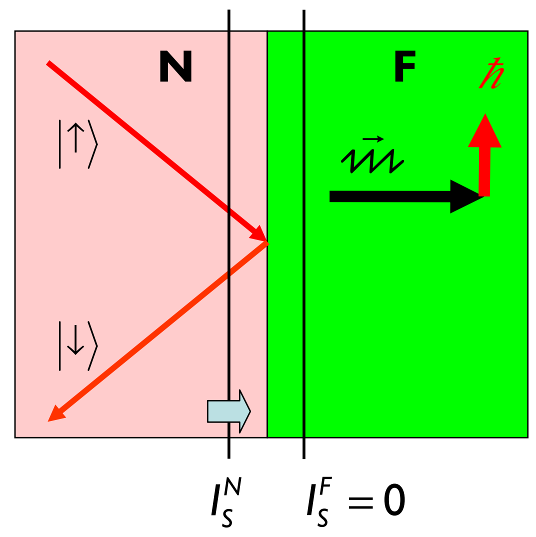
What F giveth F taketh away



Spin accumulation distribution



Slonczewski's spin-transfer torque



Absorbed spin current = magnetization torque

$$L_z = \left(I_s^N\right)_z = \frac{\hbar}{2}\frac{G^{\uparrow\downarrow}}{e^2}\left(\mu_N^{\uparrow} - \mu_N^{\downarrow}\right) = -\frac{ds_z}{dt}$$

$G^{\uparrow\downarrow}$ spin-mixing conductance

With magnetic field

Solve steady state charge and spin rate equations: $\frac{d\vec{s}\left(I_c,\vec{B}\right)}{dt} \sim \vec{I}_s^{\,In} - \vec{I}_s^{\,Out} = 0$

$$\frac{s_x/e}{I_0} = \frac{A\omega_L}{\omega_L^2 + \frac{1}{T^2}}$$

T spin-life time

$$\frac{1}{T} \overset{R^{SC}\gg R^I}{=} \frac{|\eta|}{T^I}\sqrt{\frac{1}{\mathrm{Re}\,\eta}} \overset{\eta\to 1}{=} \frac{1}{T^I}$$

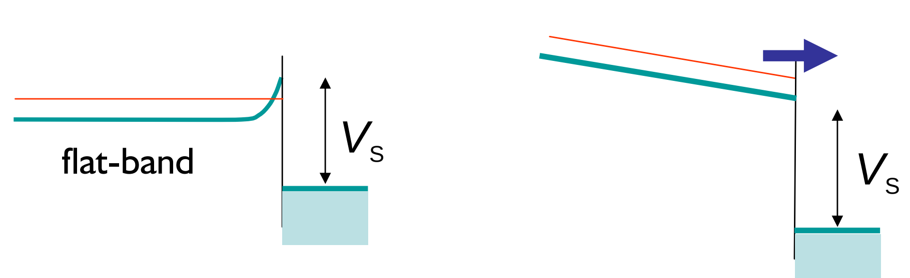
$\eta = \frac{2G^I_{\uparrow\downarrow}}{G^I}$ relative mixing conductance

$T^I = e^2 \vartheta^{SC} R^I$ interface spin-relaxation time (ϑ^{SC} SC-DOS)

Comparisonn with experiments

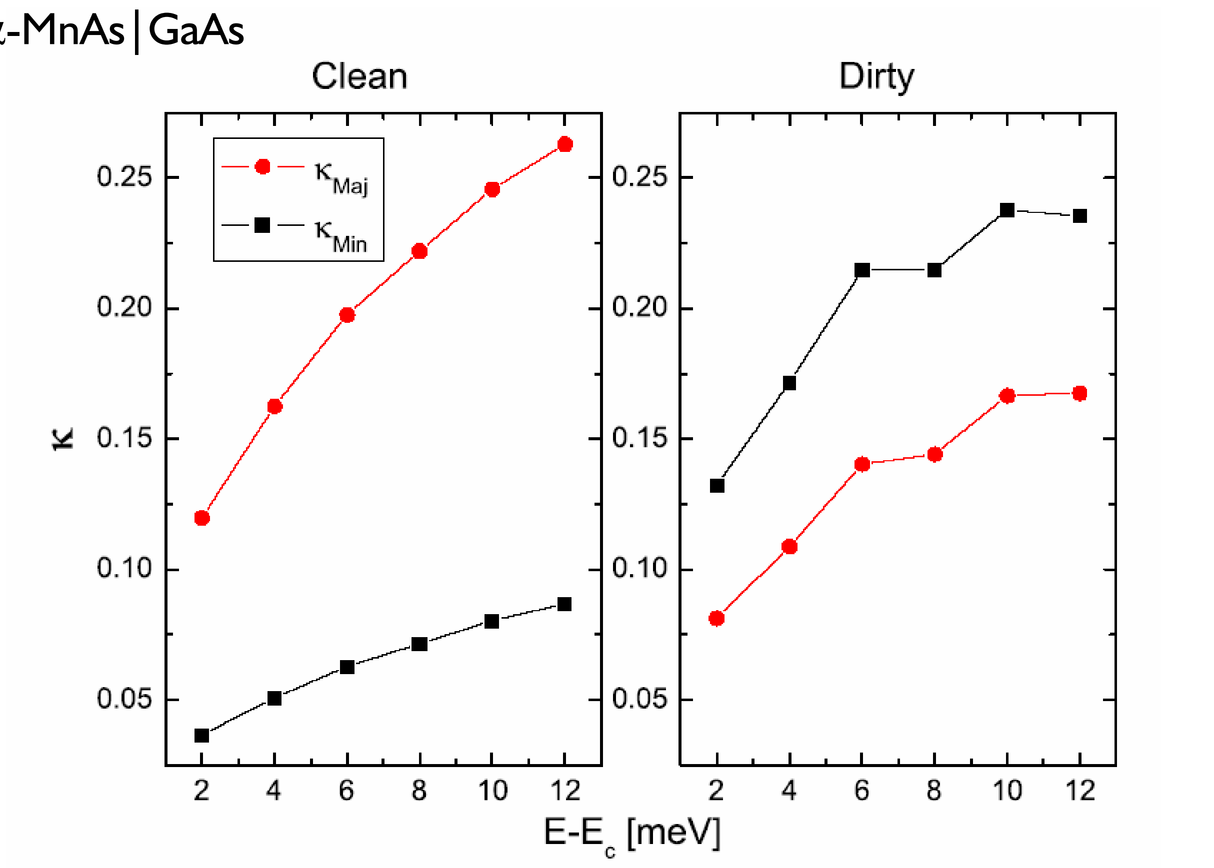
I_C (mA)	$\frac{1}{T}$ (ns^{-1})	R^{SC} (Ω)	SR^I $\left(\frac{f\Omega\, m^2}{10^{-5}}\right)$	κ
0.3	0.25	43	25	0.004
1.1	1.2	63	5.2	0.014
2.7	6	111	1.1	0.074

$G^I \equiv \kappa G^{Sharvin}$

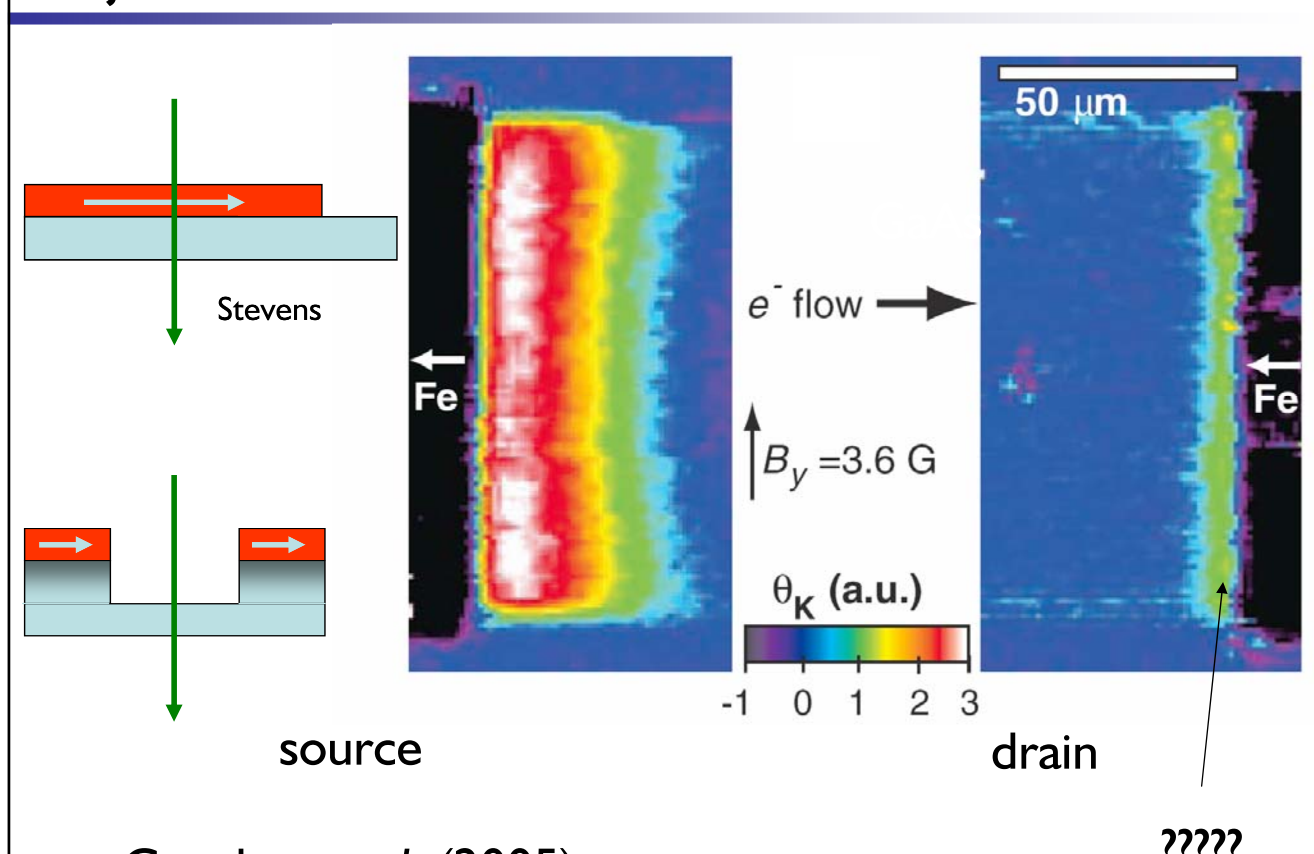


Intrinsic interface transparency $G^I \equiv \kappa G^{Sharvin}_{SC}$

α-MnAs|GaAs

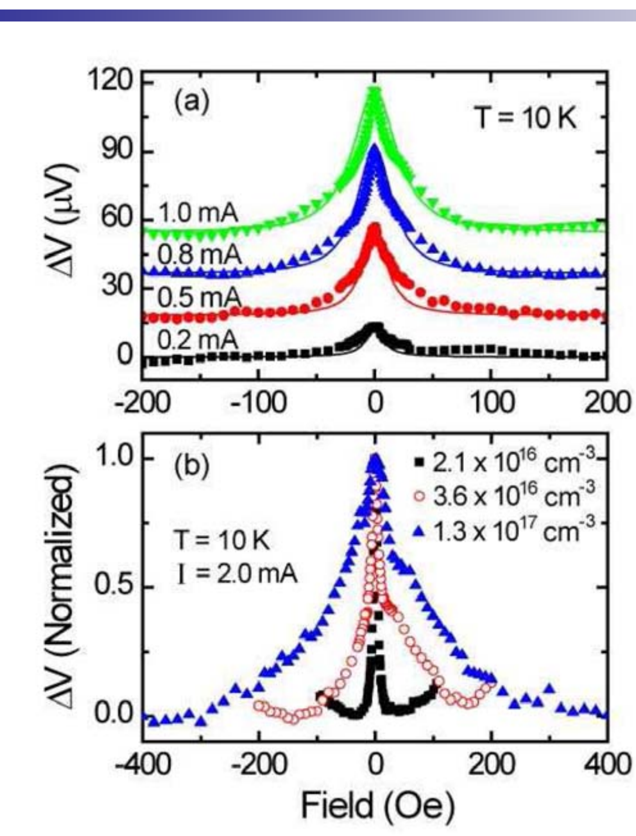


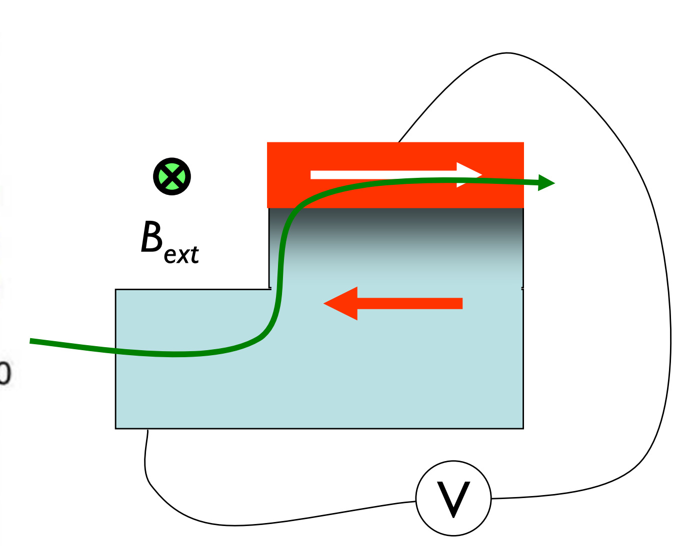
Injection and detection



Crooker *et al*. (2005)

Electrical Hanle effect

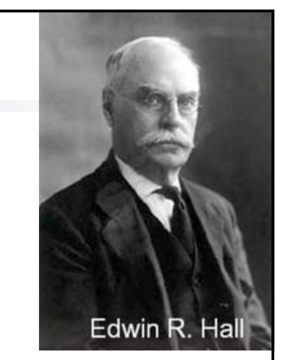




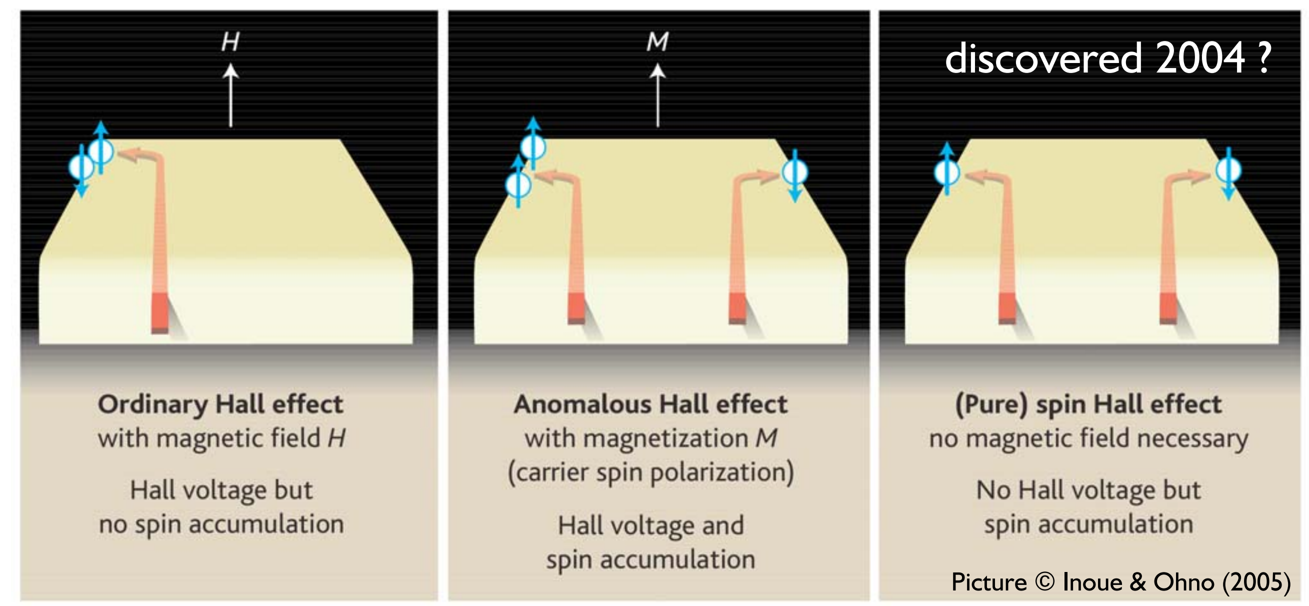
All electrical detection of spin-accumulation in a semiconductor.

Lou *et al*. (2006)

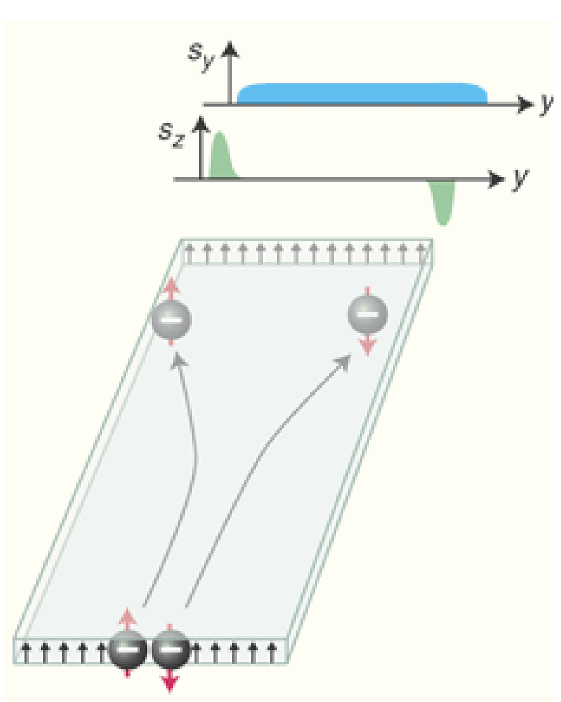
Hall effects



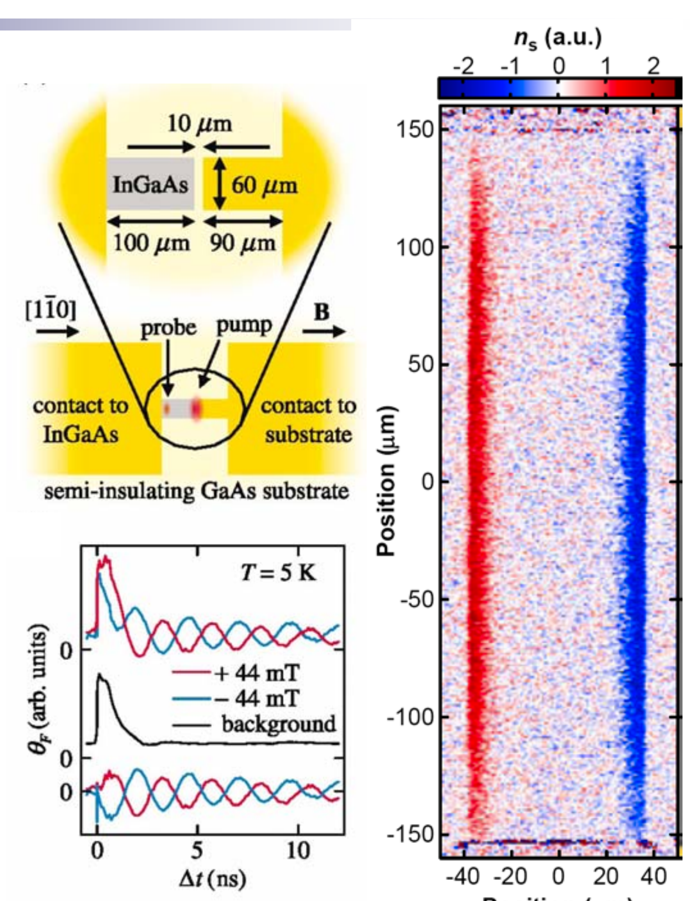
Discovered 1880 | Discovered 1881 | Predicted 1971/2003



Current-induced spin accumulation

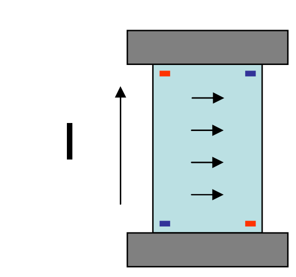


Kato *et al.* (2004a,b)
Wunderlich *et al.* (2005)

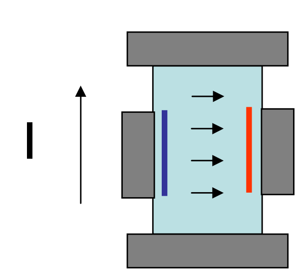


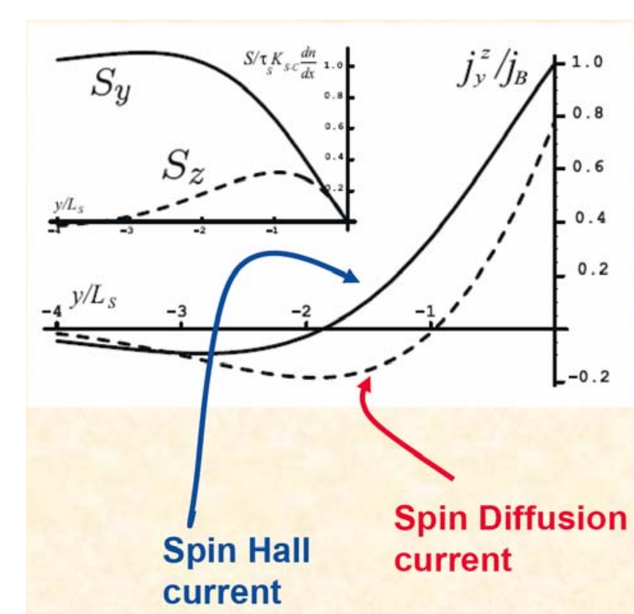
Disordered Rashba 2DEG

The spin Hall current vanishes in the bulk 2DEG (Inoue *et al.*, 2004)



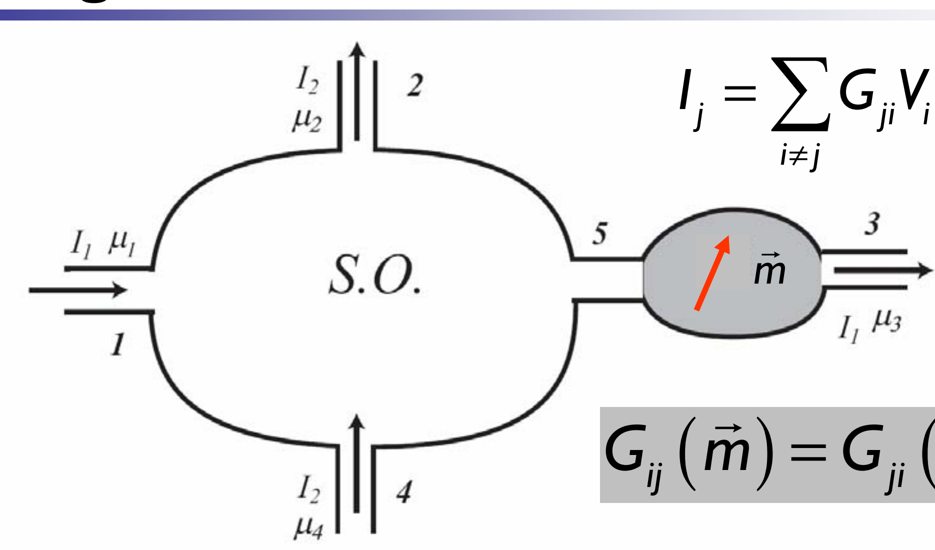
Mishchenko et *al.* (2004)





Adagideli *et al.* (2005)
Rashba (2005)

Onsager-Büttiker relations



$$I_j = \sum_{i \neq j} G_{ji} V_i$$

$$G_{ij}\left(\vec{m}\right) = G_{ji}\left(-\vec{m}\right)$$

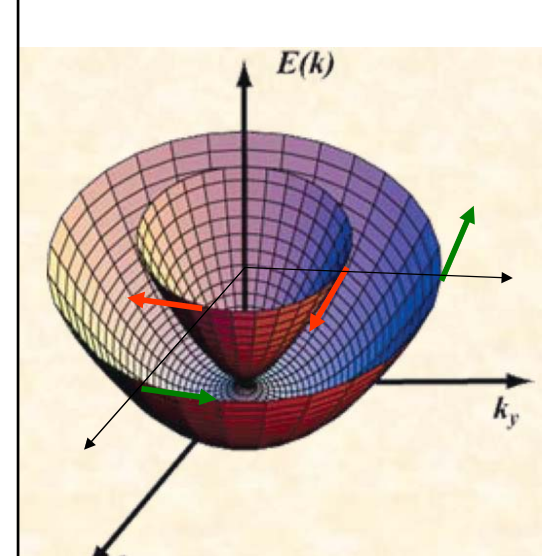
Two-terminal: $G\left(\vec{m}\right) = G\left(-\vec{m}\right)$

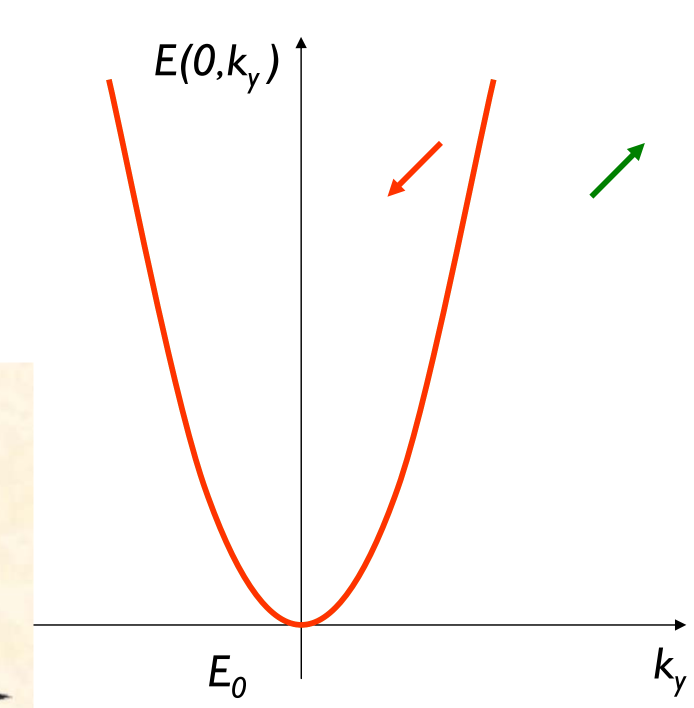
SO-generated spin accumulations cannot be measured by flipping a contact magnetization.

Energy bands of Rashba 2DEG

2D free electrons:

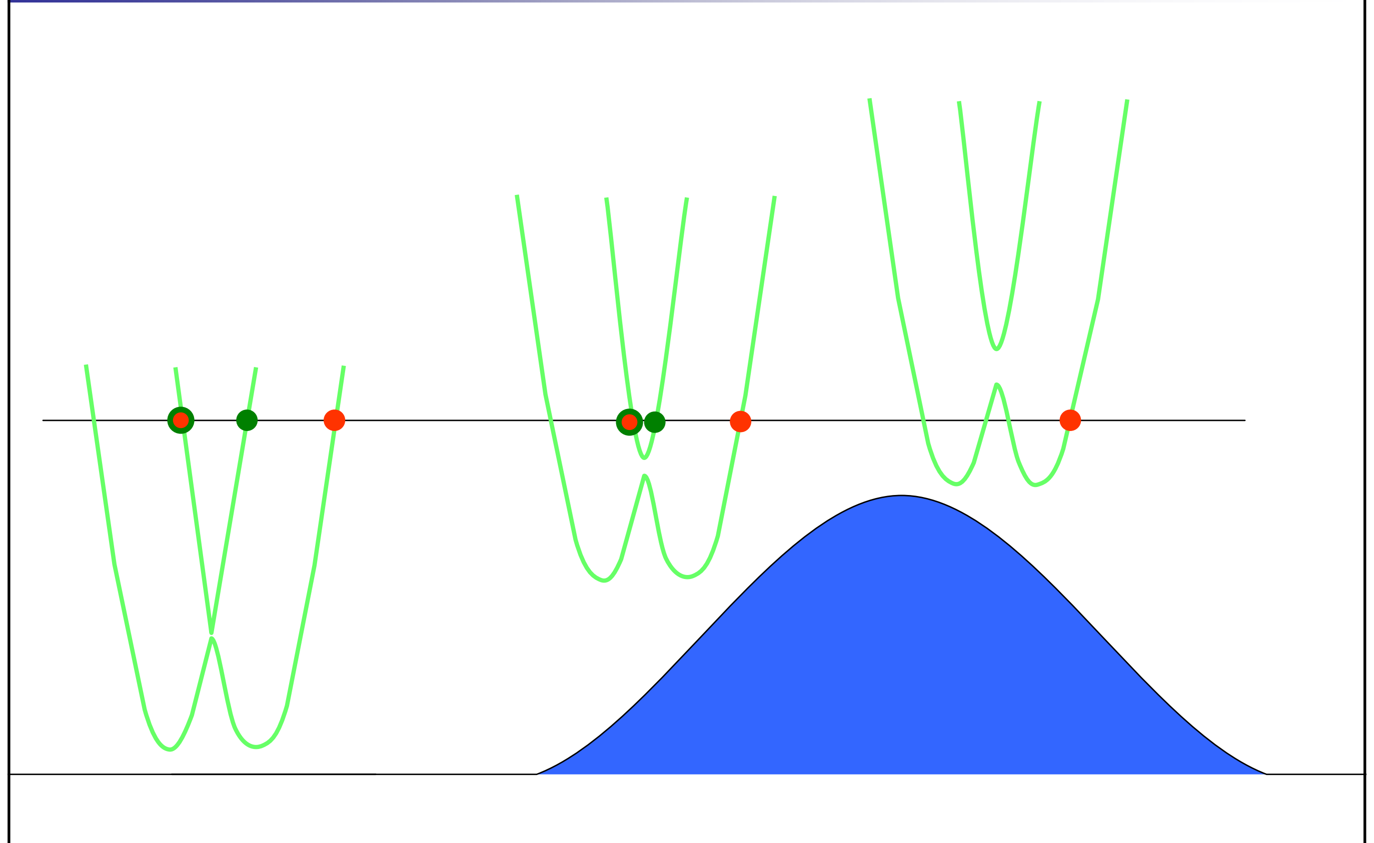
$\mathbf{H}_{SO} \sim \lambda\left(\sigma_y k_x - \sigma_x k_y\right)$





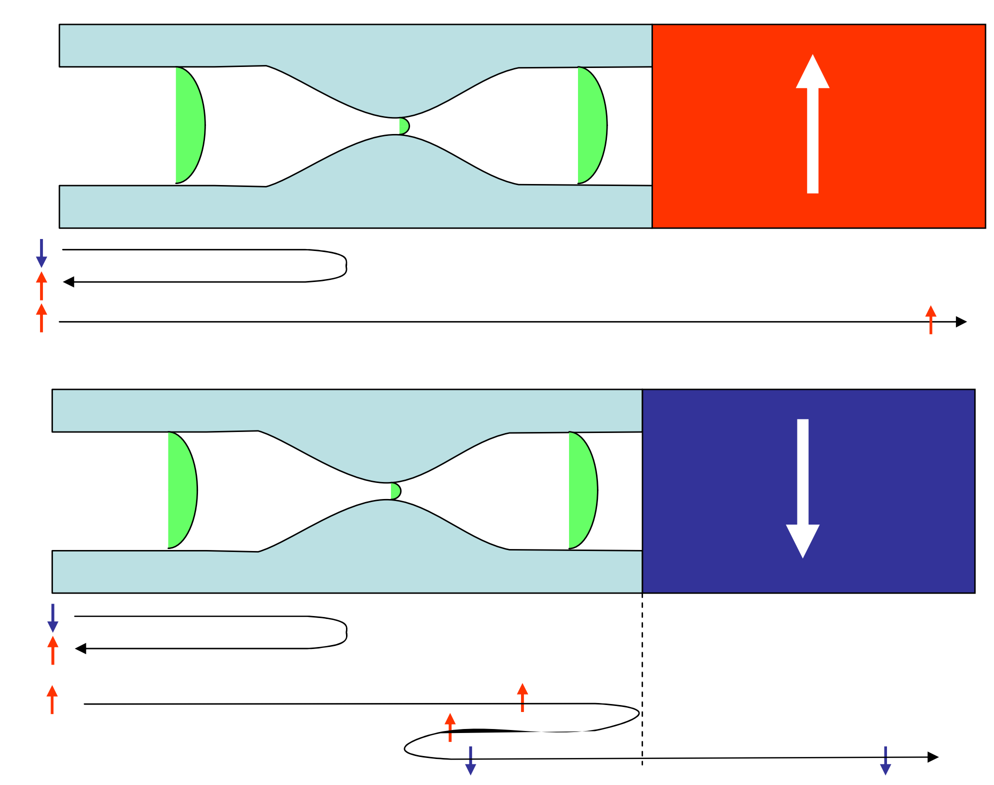
Quantum point contacts

Mishchenko & Silvestrov, 2005.



Fully spin-polarized current!

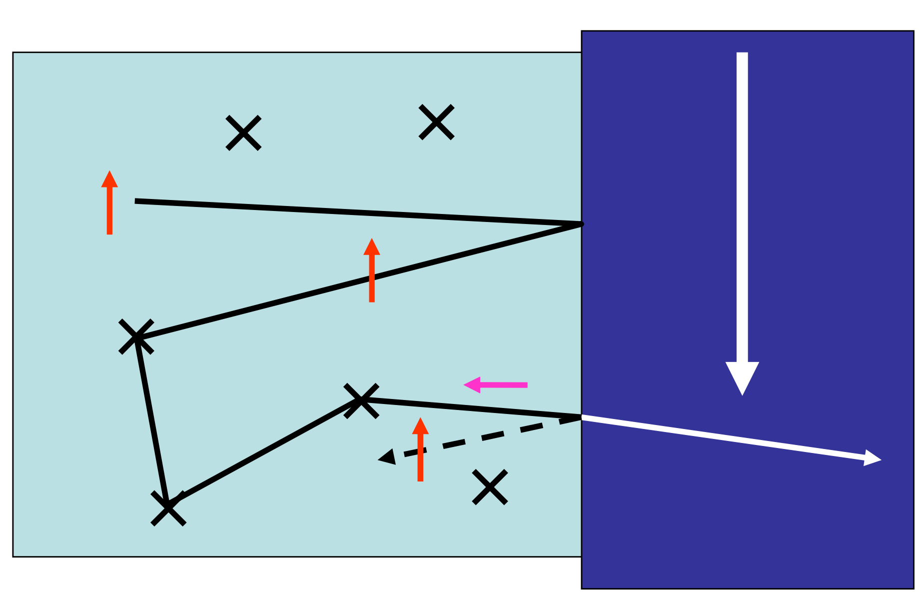
Multiple scattering



$G(\vec{m}) = G(-\vec{m})$

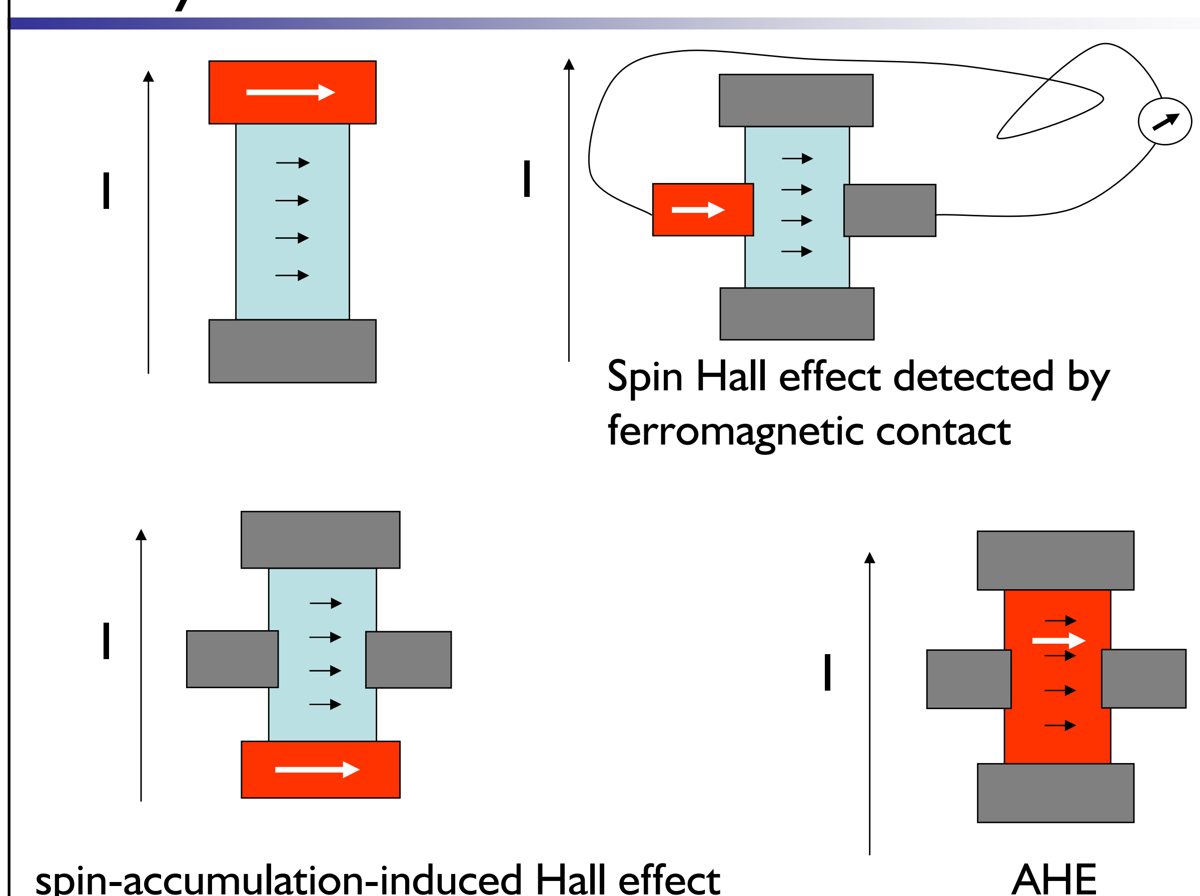
Diffuse Rashba sytems

Spin diffusion equation: $G(\vec{m}) = G(-\vec{m})$

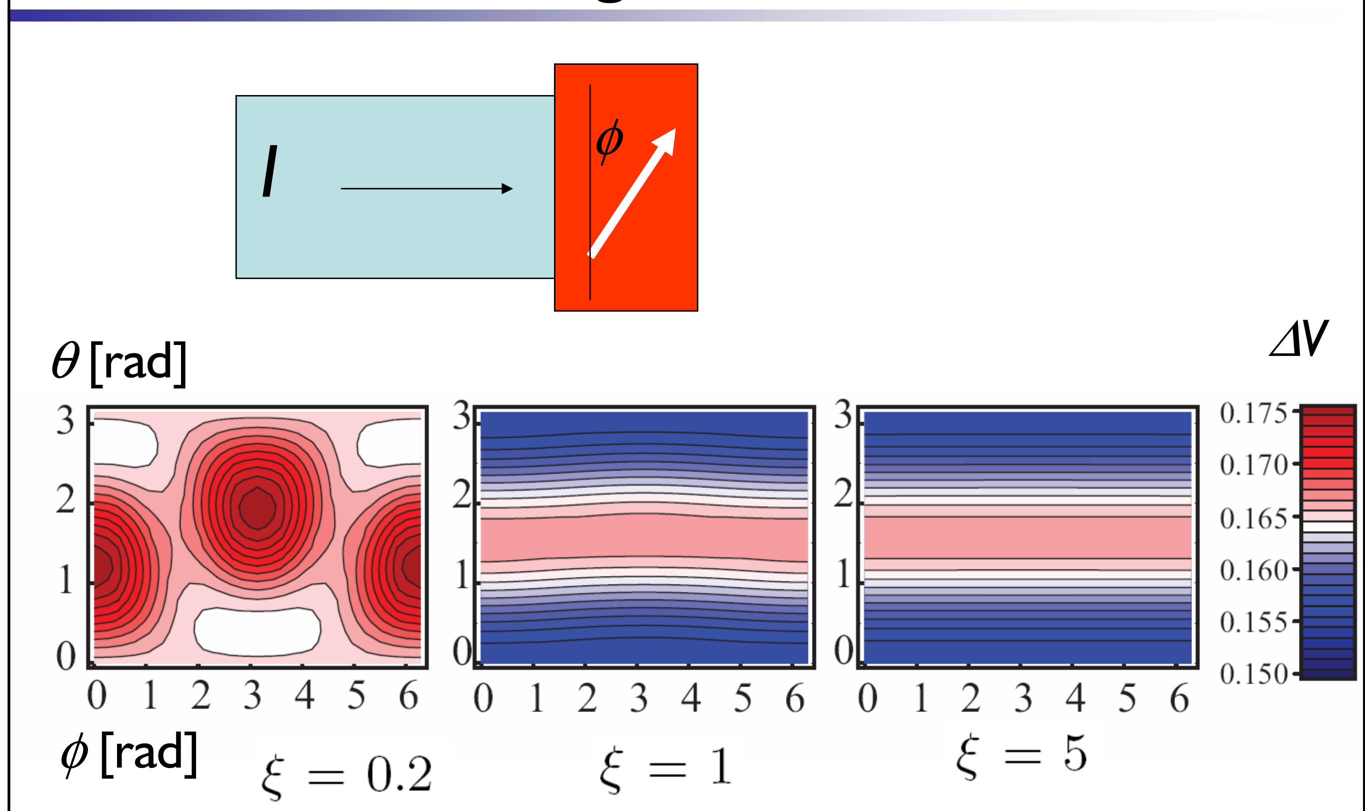


Analogy: reflectionless tunneling

Many-terminal detection

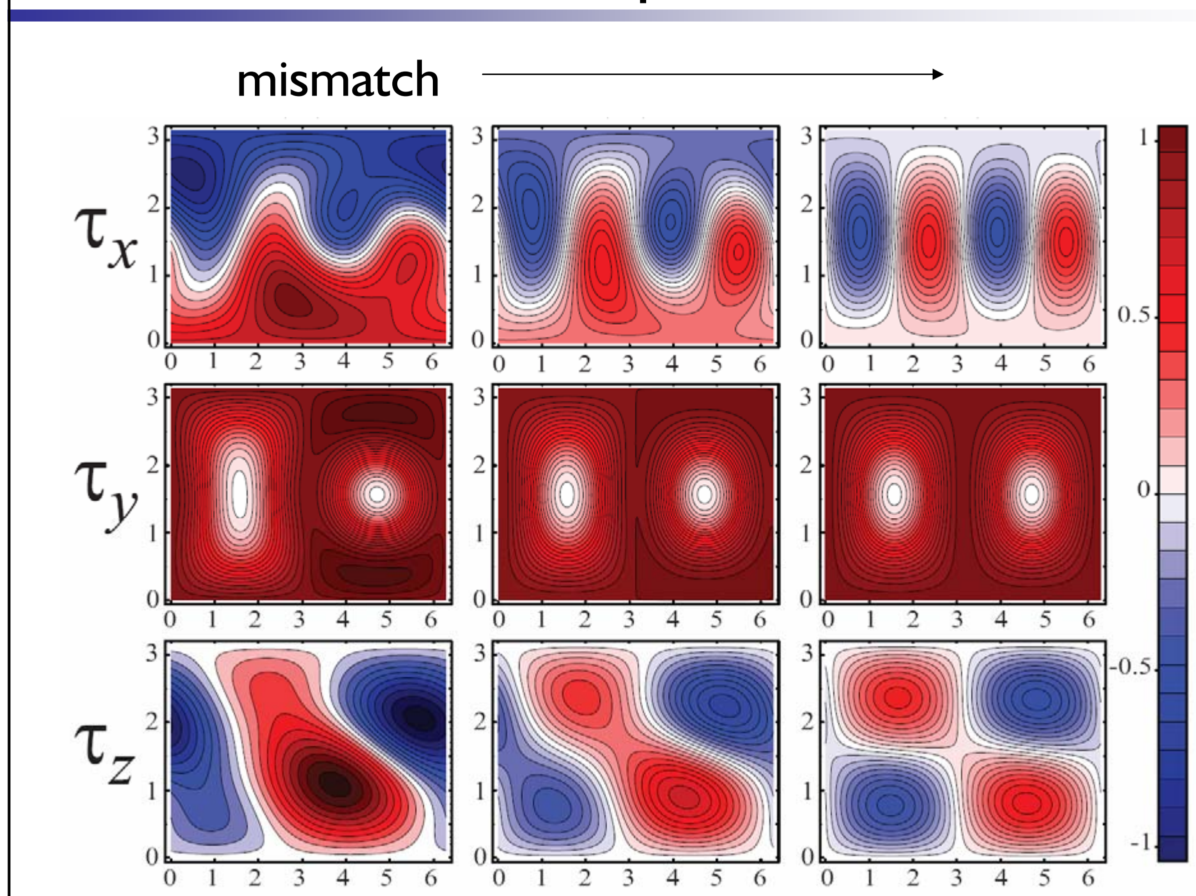


Current-induced angular MR



$$\xi = \alpha k_F \tau / \hbar$$

Current-induced torque



Conclusions

- The conductance mismatch increases spin-accumulation and decreases the spin-current.
- The optical Hanle effect can measure the interface conductance.
- The electrical Hanle effect can detect spin accumulation.
- Current-induced spin accumulations can be measured by ferromagnetic contacts.
- Current-induced spin accumulations can switch magnetizations.