# Electrical Spin Injection and Detection in Ferromagnet-Semiconductor Heterostructures

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# Outline

✧ Generic model of spin transport in diffusive regime (metals)

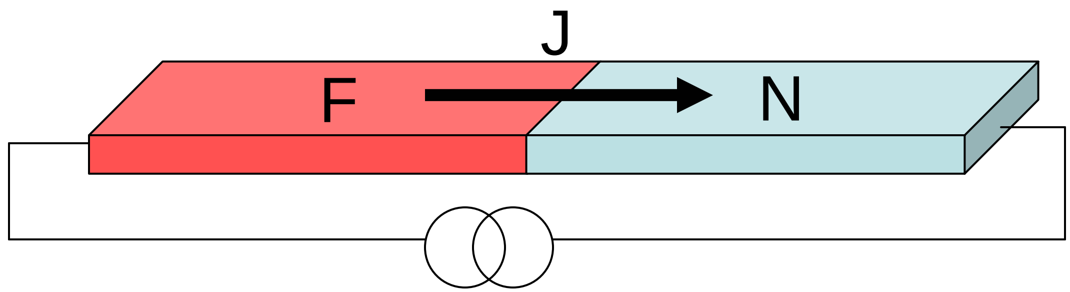
✧ Non-local electrical spin detection + precession

✧ Ferromagnet-semiconductor-ferromagnet spin valves and agreement with the generic model

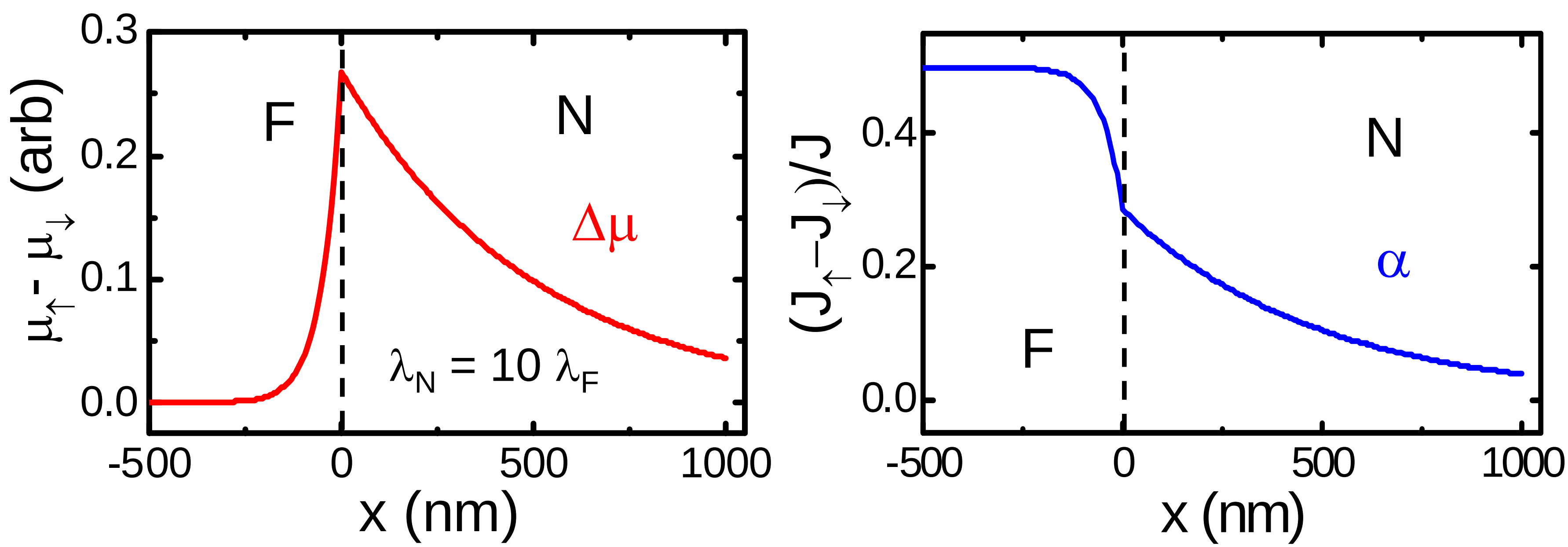
✧ What are the outstanding questions?

- What determines the sign and magnitude of the injected spin polarization?
- How can the results of an electrical detection measurement be interpreted?
- Dynamics and transport of non-equilibrium spin polarization: hyperfine and spin-orbit effects

## Spin Injection from a Ferromagnet (e.g. Fe) into a Normal Metal (e.g. Cu)

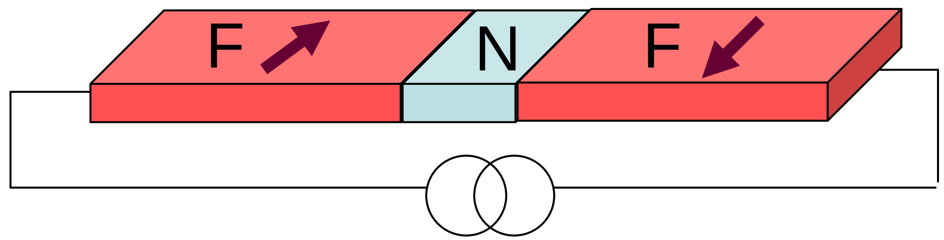



Given $J$, solve the diffusion equation in both materials, subject to continuity of $\mu_\uparrow$, $\mu_\downarrow$, $J_\uparrow$, and $J_\downarrow$ at the F/N interface.




M. Johnson and R. Silsbee, Phys. Rev. Lett. **55**, 1790 (1985)

# Detection of the spin polarization




- In the context of the above model,* it is possible to calculate the magnetoresistance

$$\frac{\Delta R}{R} = \frac{R_{\uparrow\downarrow} - R_{\uparrow\uparrow}}{R_{\uparrow\uparrow}}.$$

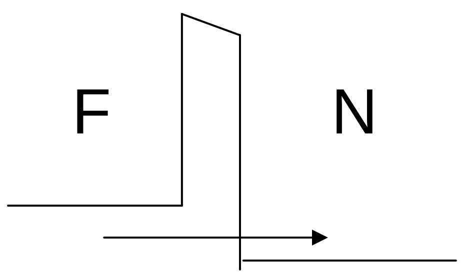
- The "conductivity mismatch" problem makes this signal small, particularly in the case where the normal metal is highly resistive (an *ersatz* semiconductor). Reality, however, will be more complicated.

*T. Valet and A. Fert, Phys. Rev. B **48**, 7099 (1993)

# Tunnel Barriers

- It is possible to re-formulate the model with an "interfacial resistance" $R_I$.*
- In the tunneling limit, how do we think about spin injection and detection? If we ignore dispersion, the tunneling current in each band should be proportional to the DOS $\times$ a transmission coefficient:

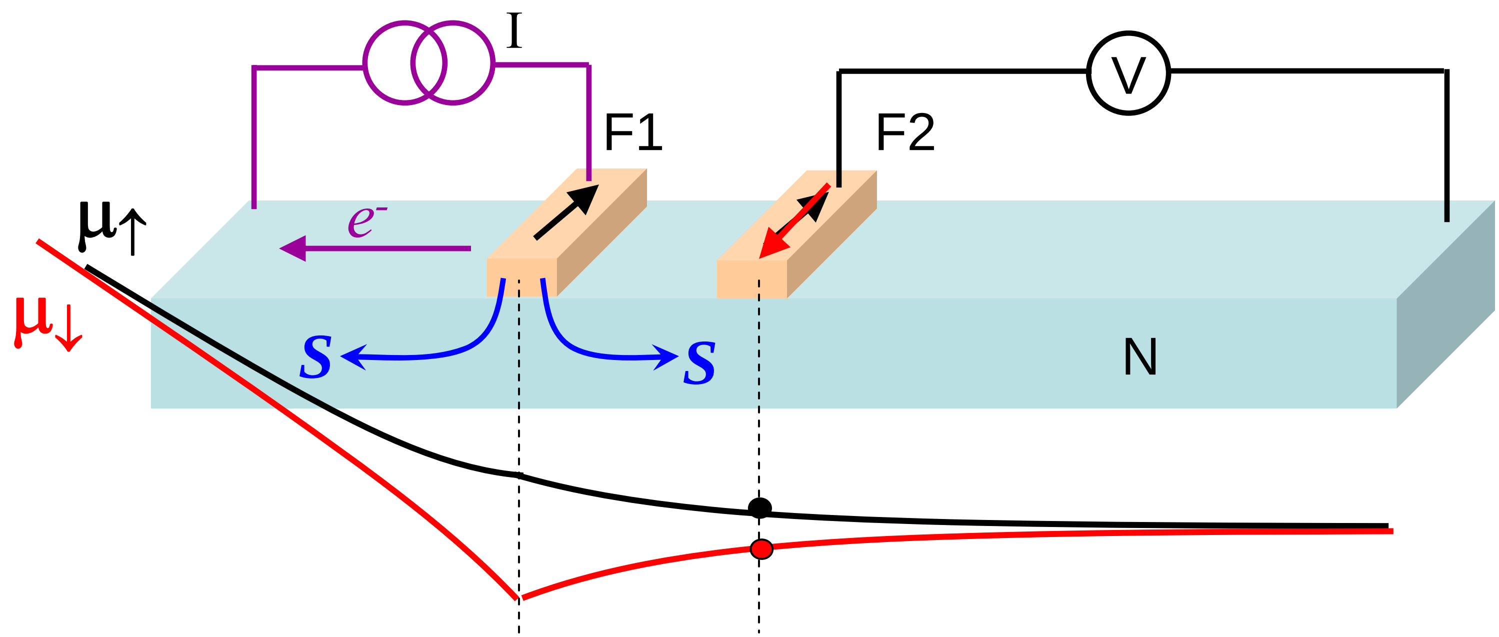
$$\alpha_{\text{int}} = \frac{T_\uparrow N_\uparrow - T_\downarrow N_\downarrow}{T_\uparrow N_\uparrow + T_\downarrow N_\downarrow}$$



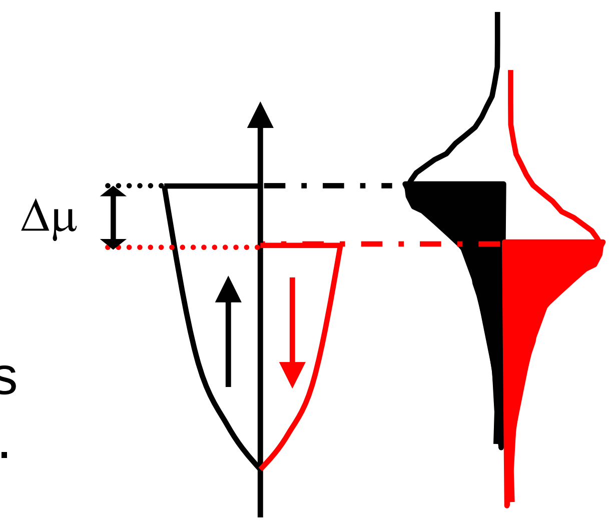

- In practice, we should account for dispersion ($k_{F\uparrow} \neq k_{F\downarrow}$). Furthermore, matrix elements for $\uparrow$ and $\downarrow$ will not be the same. For crystalline barriers, these considerations will be particularly important.

* A. Fert and H. Jaffres, Phys. Rev. B **64**, 184420 (2001)

# A slightly different approach: the non-local measurement



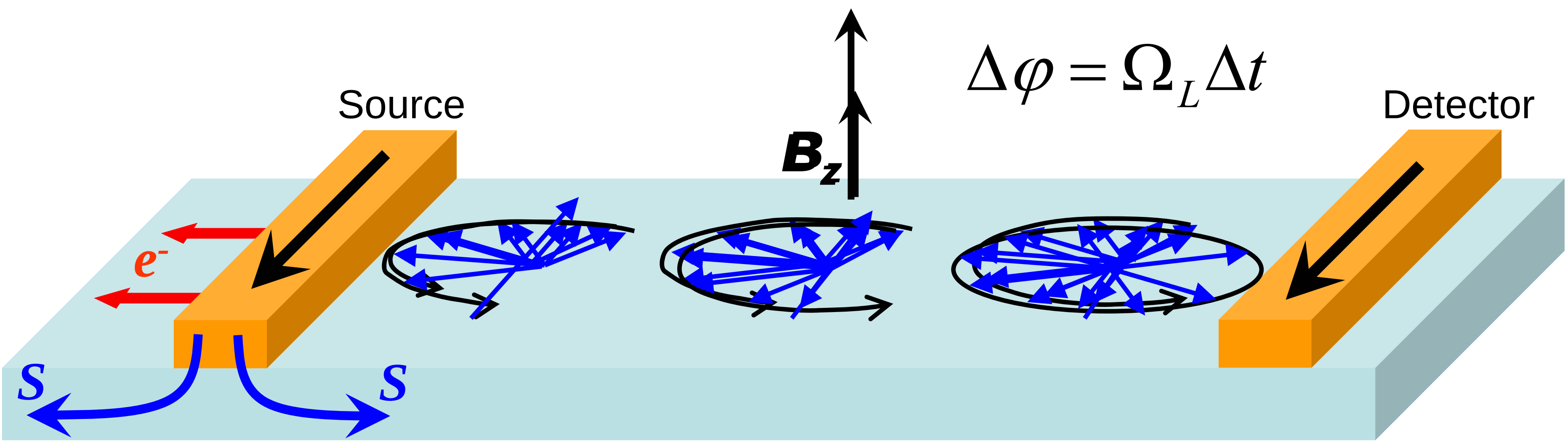

- Pure potentiometric measurement: no *charge* current flows in F2.
- The electrochemical potential is measured for each state of F2 (seemingly straight-forward).
- The (less than 100%) polarization of F2 reduces the signal from the ideal value (discussed later).
- F2 draws a spin current. This can perturb N.




M. Johnson and R. H. Silsbee, Phys. Rev. Lett. **55**, 1790 (1985)

# Precession

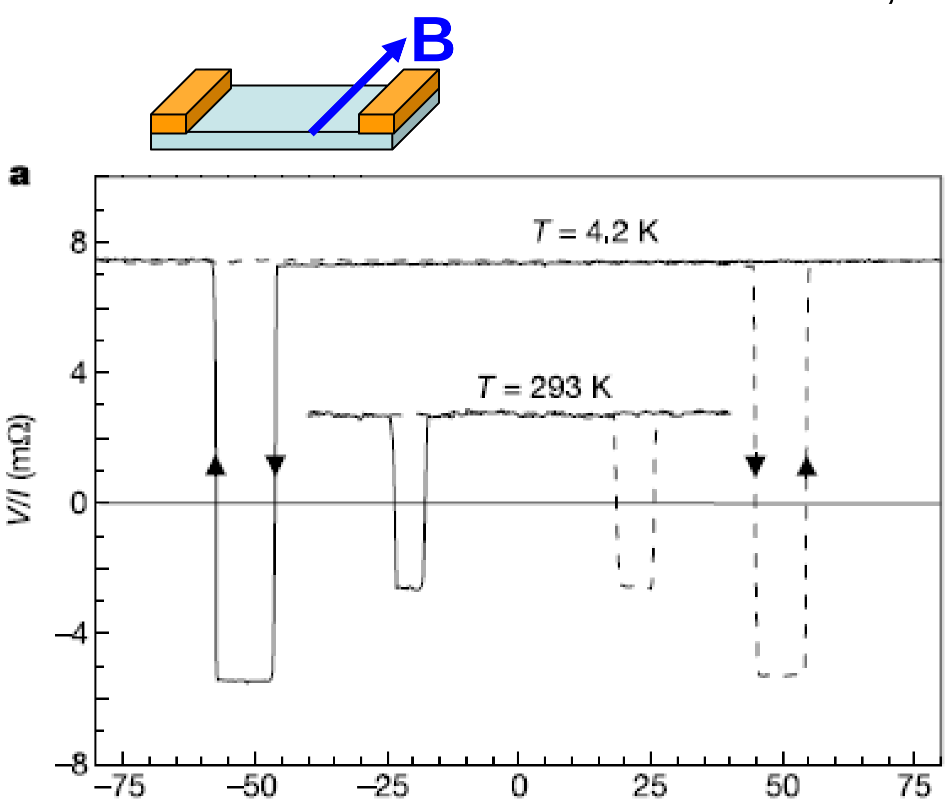
Besides the spin-polarized currents themselves, *magnetic fields* provide the only other "handle" by which we can manipulate the spin in the N region of a *metallic* F/N/F device.



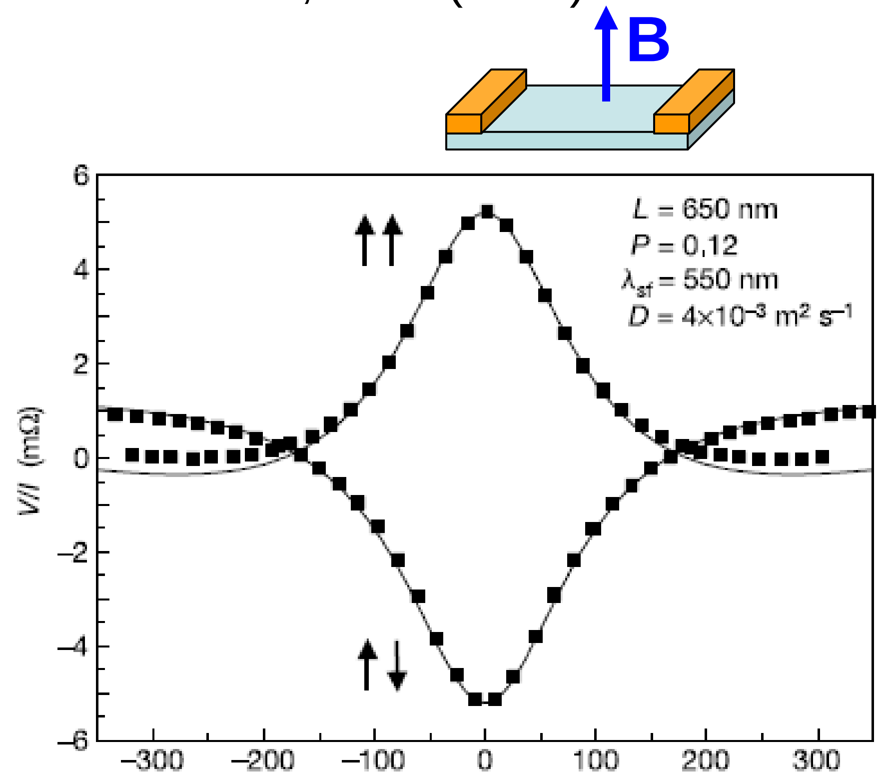

A transverse magnetic field suppresses spin accumulation in the case of diffusive spin transport.  This is known as the *Hanle effect*.

# Johnson-Silsbee experiment for metals

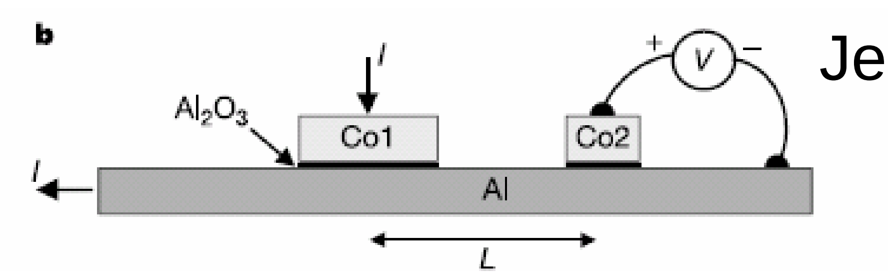
M. Johnson and R. H. Silsbee, Phys. Rev. Lett. **55**, 1790 (1985)




B (mT)




B (mT)




Jedema *et al.*, Nature **416**, 713 (2002)

## What makes semiconductors “different”?

1) Spin polarizations are large (~ 10 % in the devices I will discuss)

2) Electric fields are large (drift effects)

3) Spin-orbit effects (well-defined symmetries)

4) Hyperfine effects [related to (1), much bigger than (3) in GaAs]

5) Role of metal-insulator transition (dirty secret?)

# Spin-orbit coupling

Do perturbation theory in $(\nabla V \times \mathbf{p}) \cdot \boldsymbol{\sigma}$

$$E = \frac{\hbar^2 k^2}{2m^*} - g\mu_B \frac{\hbar}{2} \vec{\sigma} \cdot \vec{B} + \frac{\hbar}{2} \vec{\sigma} \cdot \vec{\Omega}(k) + \frac{\hbar}{2} \vec{\sigma} \cdot \vec{\Omega}_{BR}(k) + \frac{\hbar}{2} \tilde{C} \vec{\sigma} \cdot \vec{\varphi}(k)$$

In increasing order of obscurity:

$\Omega_x = C k_x (k_y^2 - k_z^2)$ - bulk inversion asymmetry (Dresselhaus)[1]

$\vec{\Omega}_{BR} = \vec{k} \times \nabla V$ - structural inversion asymmetry (Rashba)[2]

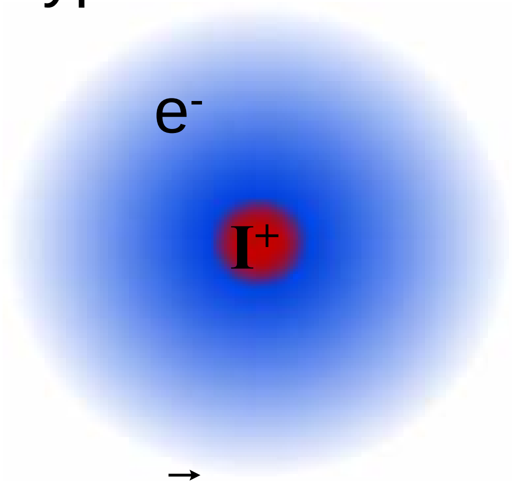
$\varphi_x = \varepsilon_{xy} k_y - \varepsilon_{xz} k_z$ - uniaxial strain[3]

Note that $\Omega_x$, $\Omega_{BR}$, and $\varphi$ "look like" *k*-dependent magnetic fields.

- I do not want to overdo this point, however. There are some aspects, such as spin dephasing, in which the spin-orbit fields are rather different (due to the dependence on *k*).

# Hyperfine interaction and dynamic nuclear polarization

Hyperfine contact interaction (enhanced by localization):




$$\vec{B} = B\hat{z}$$

$$H = -\frac{16\pi}{3I}\mu_B \mu_n \left|\Psi(R)\right|^2 \hat{\mathrm{I}} \cdot \hat{\mathrm{S}}$$

Rate equation for nuclear polarization:

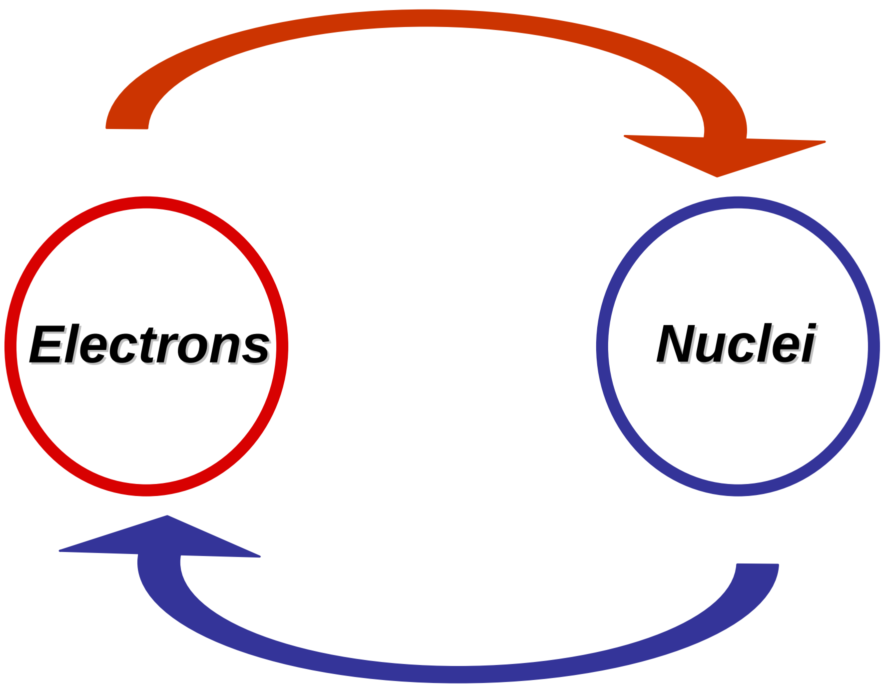
$$\frac{d\langle I_Z \rangle}{dt} = \frac{1}{T_{pol}}\left(\langle S_Z \rangle k - \langle I_Z \rangle\right) - \frac{1}{T_1}\langle I_Z \rangle$$

Ansatz:

$$\frac{T_{pol}}{T_1} = \xi \left(\frac{B_L}{B_{app}}\right)^2 \quad \Rightarrow \quad \langle I_Z \rangle = k \langle S_Z \rangle \frac{B_{app}^2}{B_{app}^2 + \xi B_L^2}$$

# Hyperfine interaction:  the effective field $B_N$

***Hyperfine interaction: angular momentum transfer***




***Effective magnetic field***

Effective nuclear magnetic field:

$$\vec{B}_N = f_l b_N \frac{I(I+1)}{S(S+1)} \frac{(\vec{S}\cdot\vec{B}_{app})\vec{B}_{app}}{B_{app}^2 + \xi B_L^2}$$

$$f_l \equiv leakage\ factor$$

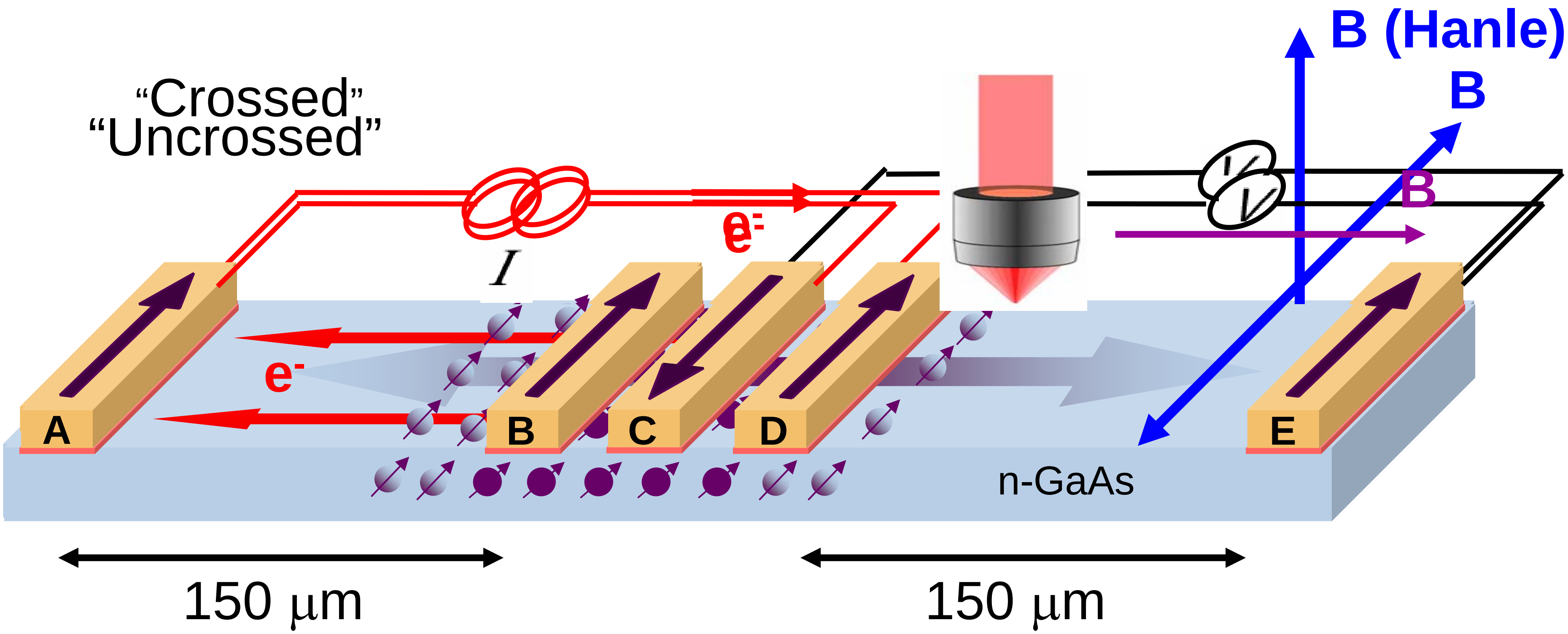
in GaAs:

$$b_N \approx 5\ \mathrm{T}$$

Electrons feel:

$$\vec{B}_{Total} = \vec{B}_{app} + \vec{B}_N$$

# Non-local electrical spin detection in Fe/GaAs

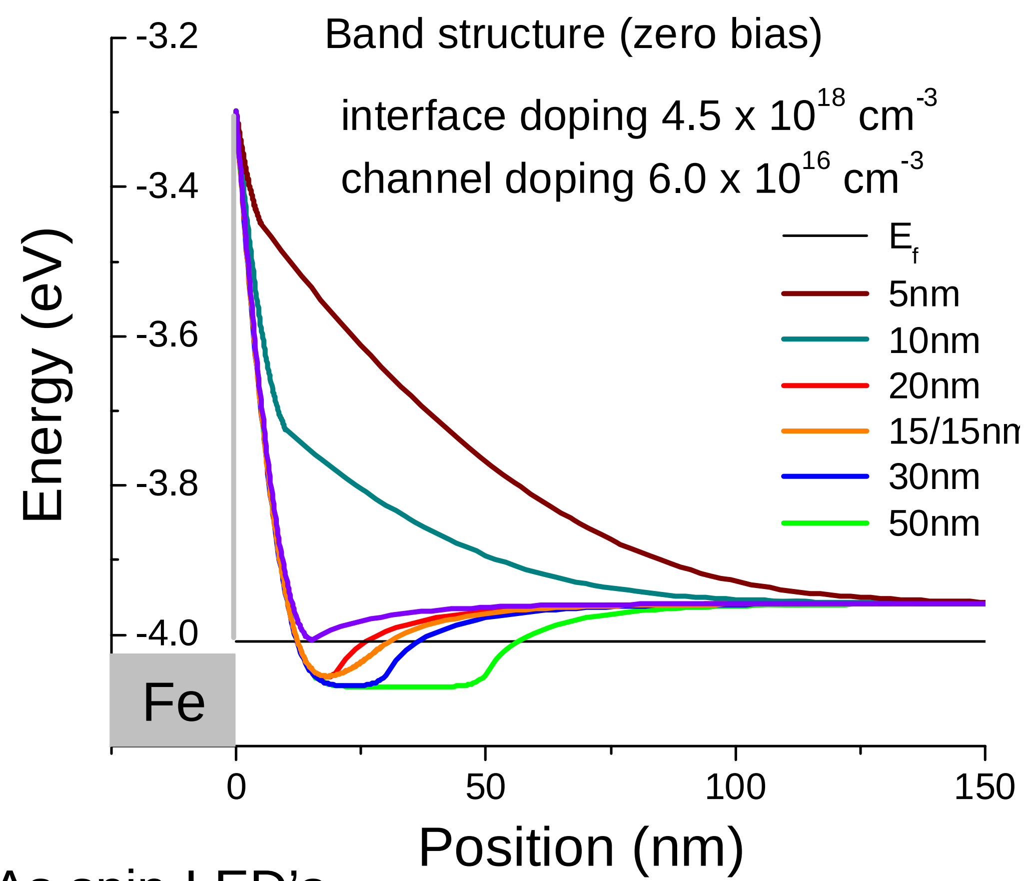



Central contacts: 10 x 50 microns; 12 micron center to center spacing

MOKE can be used to measure the spin polarization in the channel: J. Stephens *et al.*, Phys. Rev. Lett. **93**, 097602 (2004); S.A. Crooker *et al.*, Science **309**, 2191 (2005).

# Epitaxial Fe/GaAs (100) Schottky tunnel barriers

| |
|---|
| **Al cap** |
| **5 nm Fe film deposited in-situ on As-rich c(4×4) surface** |
| ***n*$^+$ GaAs:Si ~5 x $10^{18}$/cm$^3$** |
| **2500 nm *n* GaAs:Si channel ~5 x $10^{16}$/cm$^3$** |
| **i GaAs buffer** |
| **SI GaAs substrate (001)** |




- Design based on Fe/GaAs spin-LED's
- GaAs epilayer doping: n = 2 x $10^{16}$ - 1 x $10^{17}$ cm$^{-3}$
- Interfacial doping: n$^+$ ~ 5 x $10^{18}$ cm$^{-3}$

Graded interfacial doping profile:
A. T. Hanbicki *et al.,* Appl. Phys. Lett. **82**, 4092 (2003).

# Estimation of size of signal

For the case of an Fe spin detector:

$$\Delta V = \eta \cdot P_{Fe} \frac{\Delta \mu'}{e}$$

Spin detection efficiency: $\eta$ ~ 0.5

Fe spin polarization: $P_{Fe}$ = 42%

Assuming GaAs is a Pauli-like metal ($n$ = 5 × $10^{16}$ $cm^{-3}$):

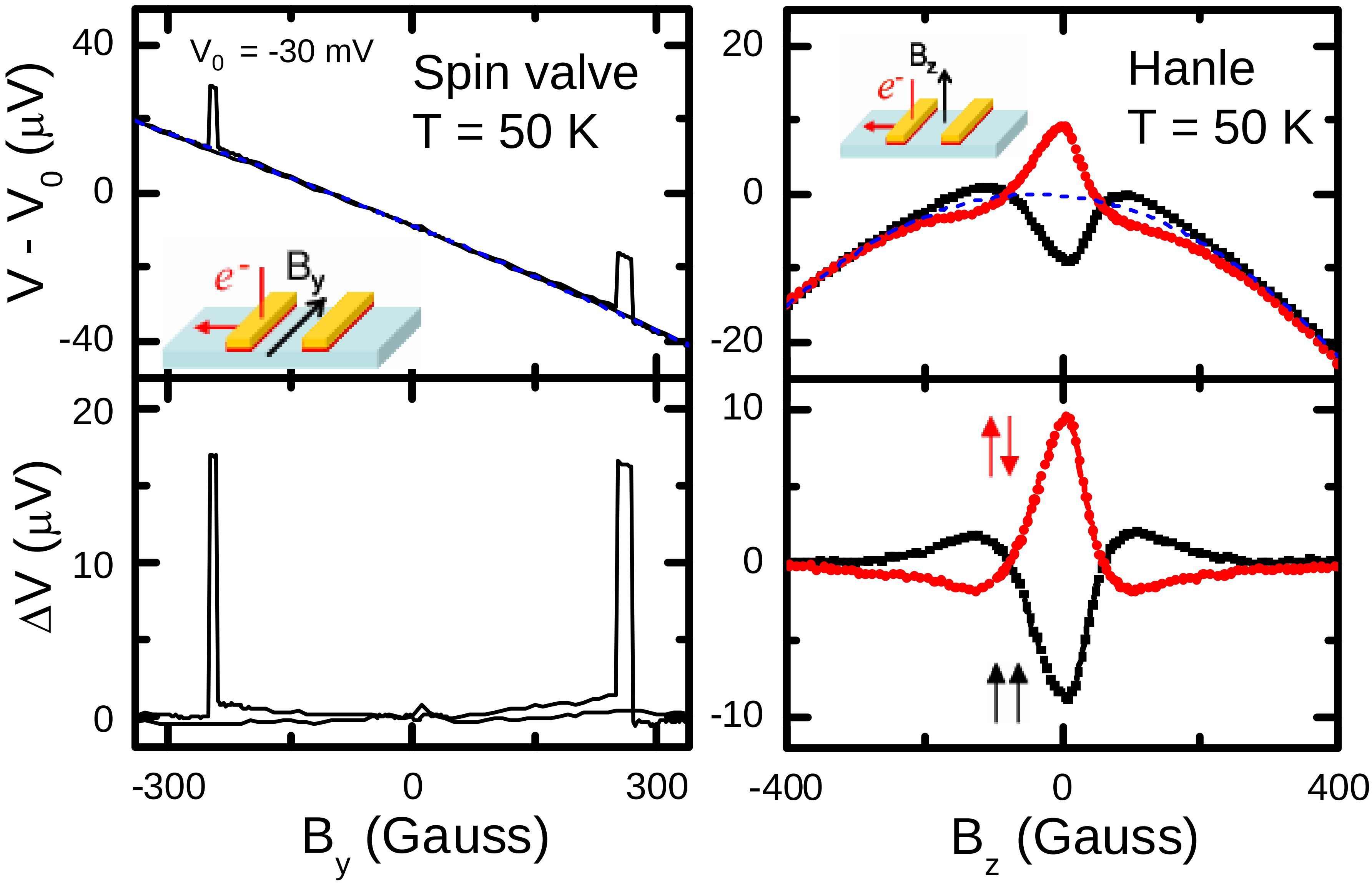
$$\Delta \mu' = \frac{n_{\uparrow} - n_{\downarrow}}{\frac{\partial n}{\partial E}} = \frac{2}{3} \frac{\hbar^2}{2m^*} (3\pi^2 n)^{2/3} P'_{GaAs}$$

$$\Downarrow$$

$$\Delta V = \frac{\eta \cdot P_{Fe}}{e} \frac{\hbar^2 (3\pi^2 n)^{2/3}}{3m^*} P'_{GaAs}$$

$P'_{GaAs}$ = 1% at the detector $\Rightarrow$ $\Delta V$ ~ 10 μV

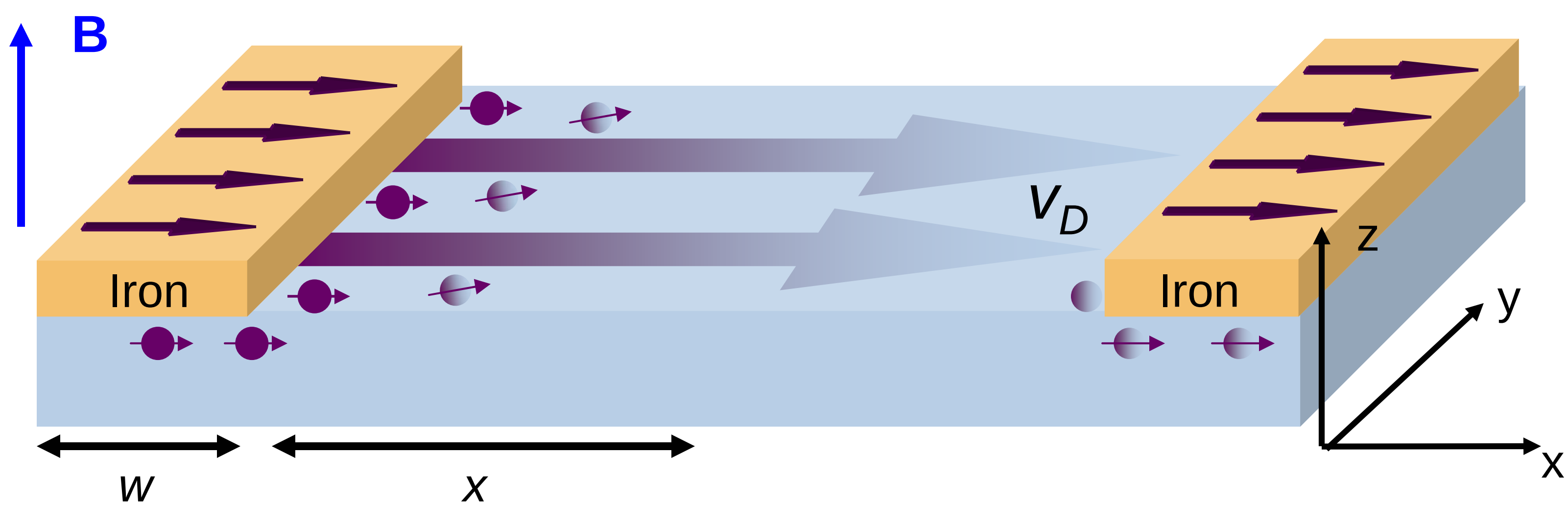
# Spin valve and Hanle effects



# Modeling the Hanle Curves: Drift-Diffusion Model

- Account for diffusion, drift, and relaxation:

$$\frac{\partial \vec{S}(x,t)}{\partial t} = -v_d \frac{\partial \vec{S}(x,t)}{\partial x} + D\frac{\partial^2 \vec{S}(x,t)}{\partial x^2} - \frac{\vec{S}(x,t)}{\tau_s} - \vec{\Omega}\times\vec{S}$$



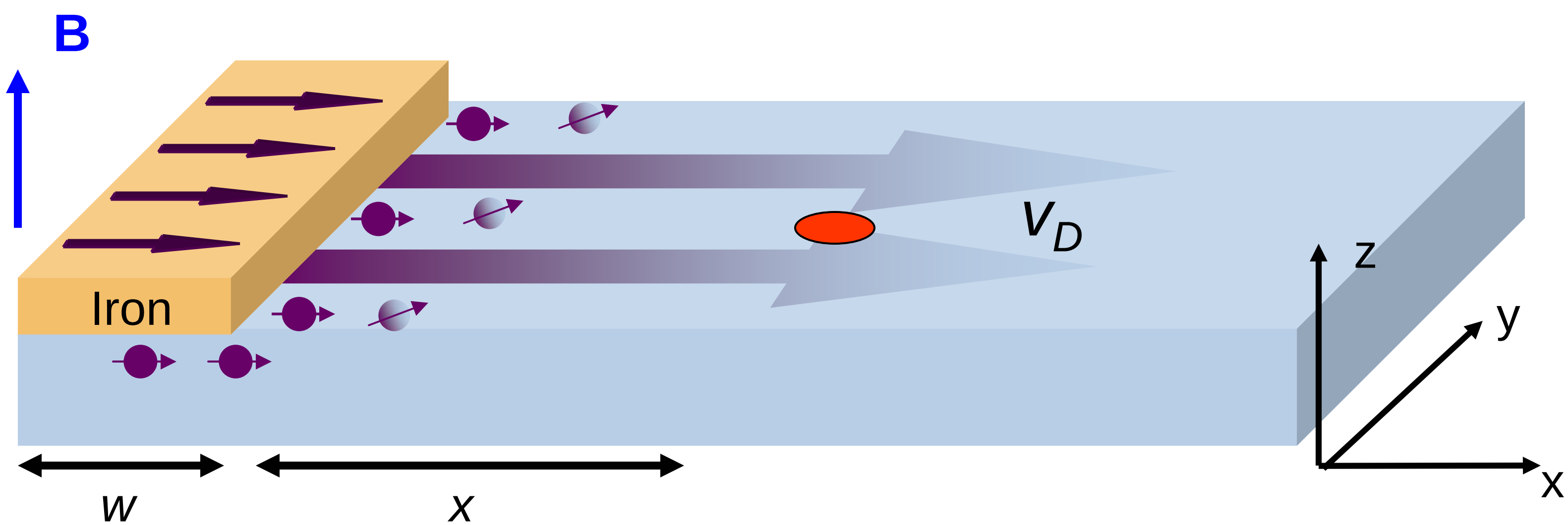

$D$ = diffusion constant
$v_d = \mu E$ = drift velocity
$\tau_s$ = spin lifetime

$\Omega$ = Larmor frequency
$w$ = width of contact
$x$ = distance from edge of contact

# Drift-Diffusion Model

- Integrate over time (steady-state solution) and spatial extent of source

$$S_z(x) = \int_x^{x+w} \int_0^{\infty} \frac{S_{x0}}{\sqrt{4\pi Dt}} e^{-\frac{(x'-v_d t)^2}{4Dt} - \frac{t}{\tau_s}} \cos(\Omega t)\, dt\, dx'$$




$D$ = diffusion constant
$v_d = \mu E$ = drift velocity
$\tau_s$ = spin lifetime

$\Omega$ = Larmor frequency
$w$ = width of contact
$x$ = distance from edge of contact

# Modeling of Hanle curves

Now integrate over detector coordinates:

$$S(B) = \int\int\int_0^\infty \frac{S_0}{\sqrt{4\pi Dt}} e^{-\frac{(x'-x-v_d t)^2}{4Dt} - \frac{t}{\tau_s}} \cos(\Omega t) dt dx dx'$$

$D$ = diffusion constant (determined from transport)

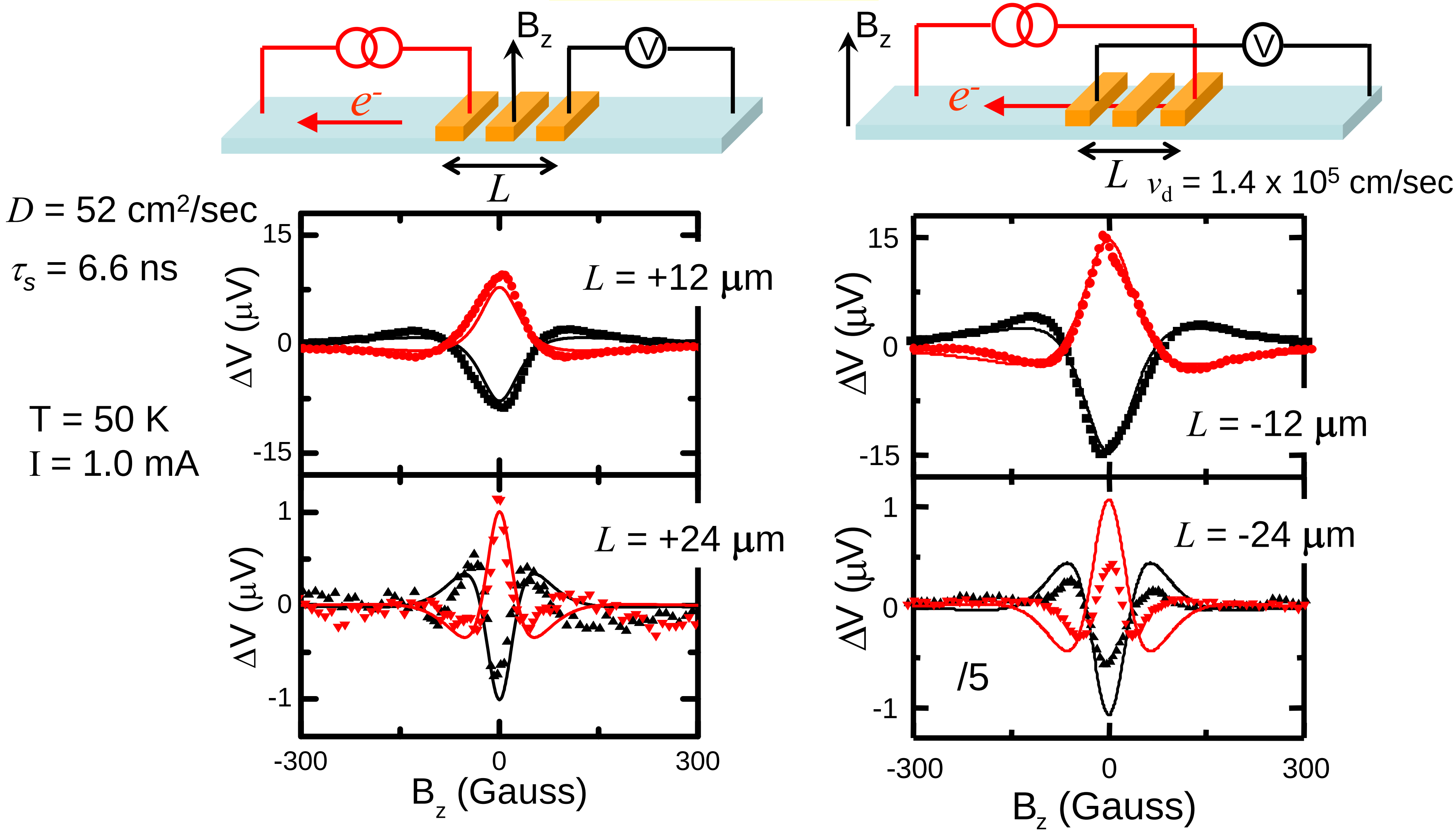
$\tau_s$ = spin lifetime (determined from optical measurements)

$v_d$ = drift velocity

$\Omega = g\mu_B B/\hbar =$ Larmor frequency ($g$ = -0.44)

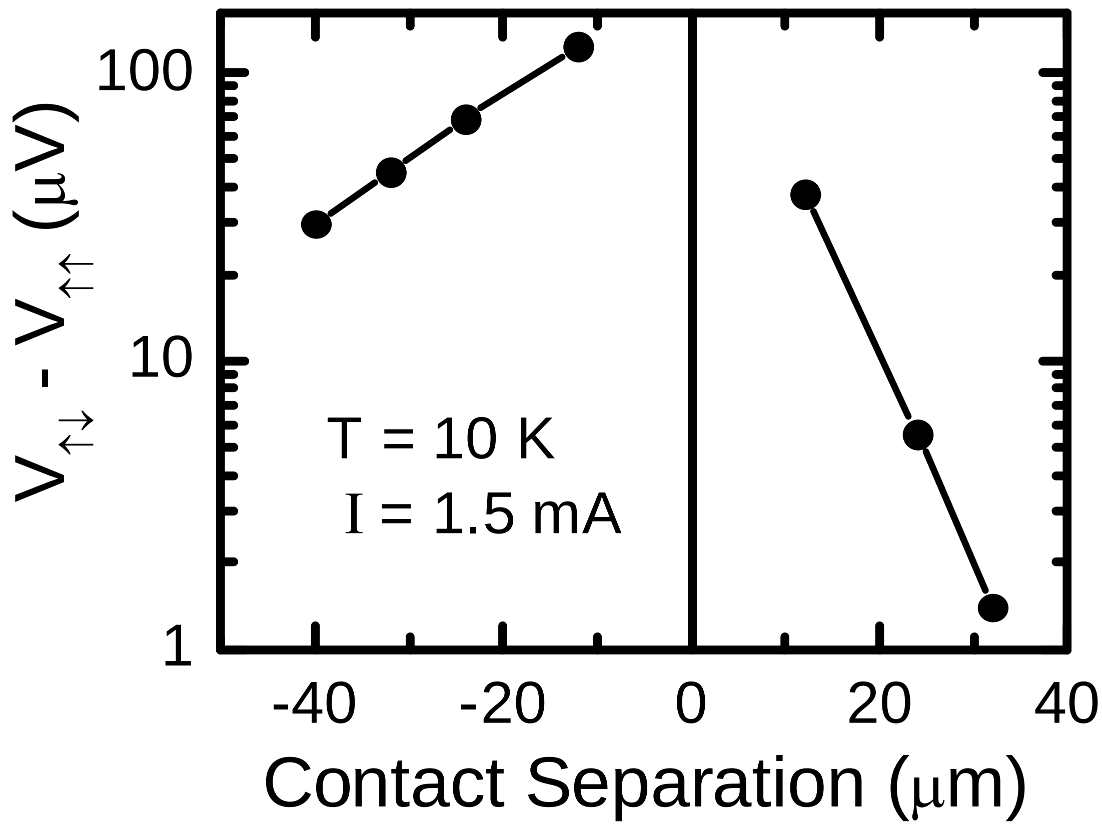
$S_0$ = spin injection rate (the only free parameter)

# Hanle Curves




- Spin drift in the “crossed” geometry enhances the spin signal
- $S_0$ is the the same for all fits

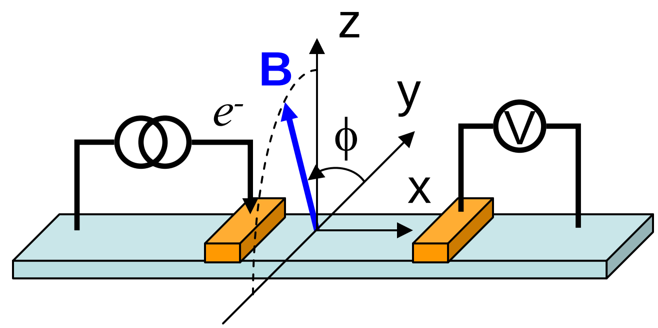
# Dependence on injector/detector separation



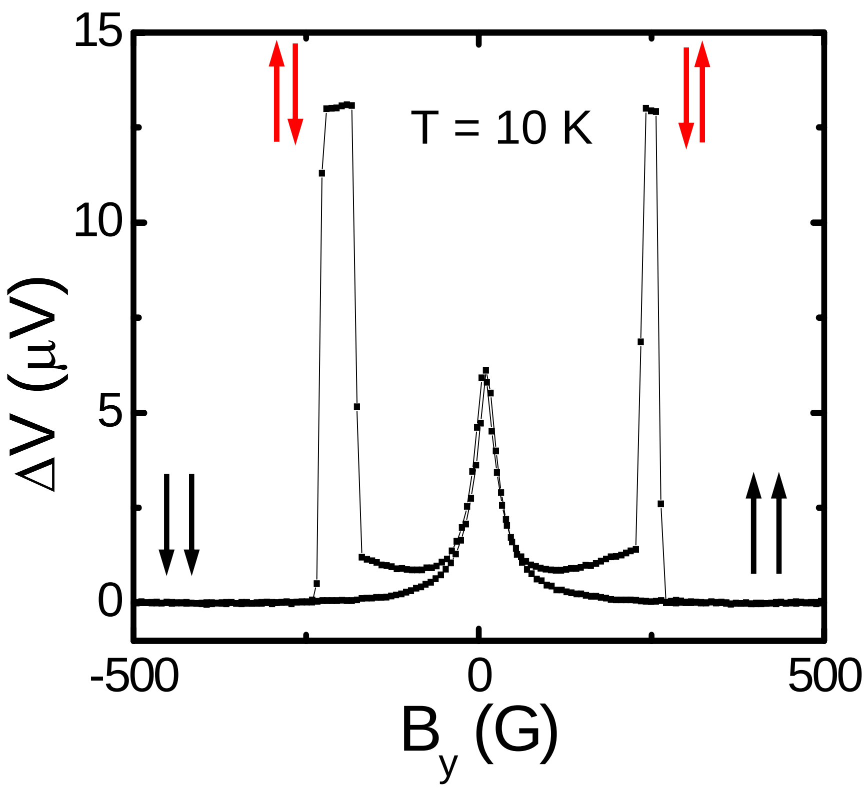

- Note "upstream" and "downstream" drift/diffusion lengths*
- Consistent with Hanle measurements

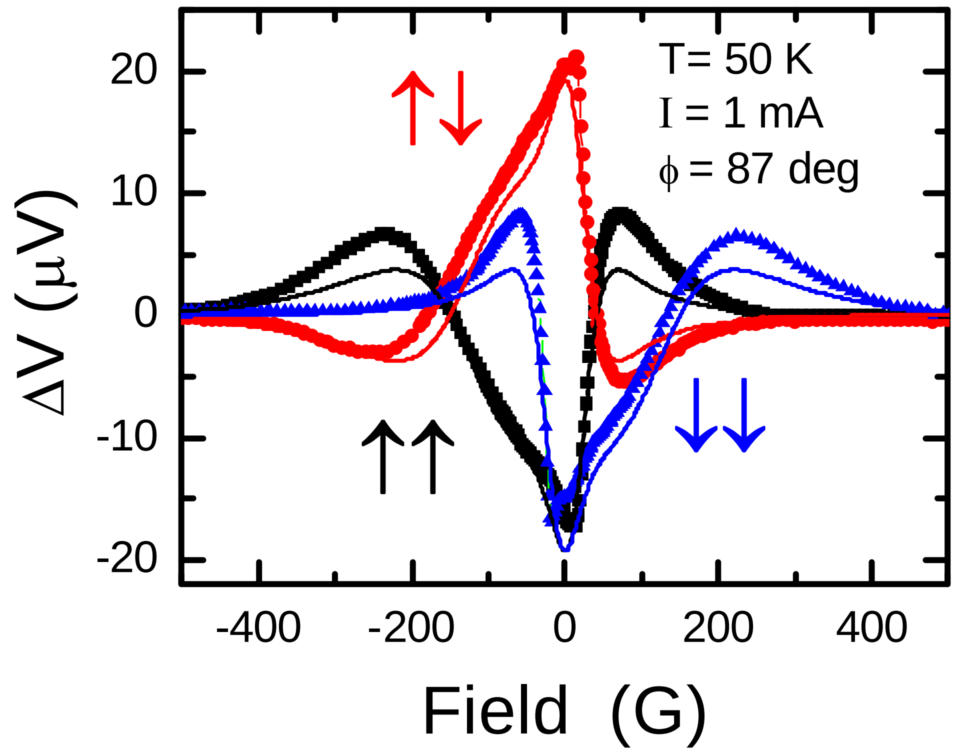
*Yu and Flatté, Phys. Rev. B **66**, 235202 (2002)

# Sensitivity to Hyperfine Effects



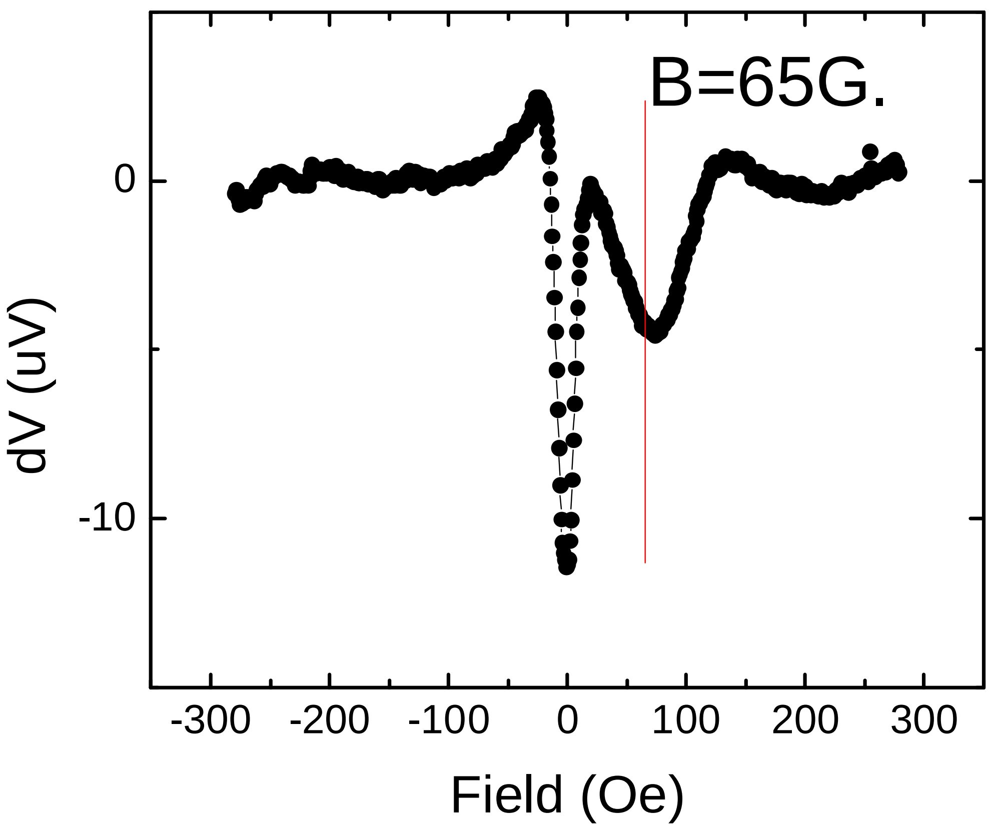

Zero-field Anomaly

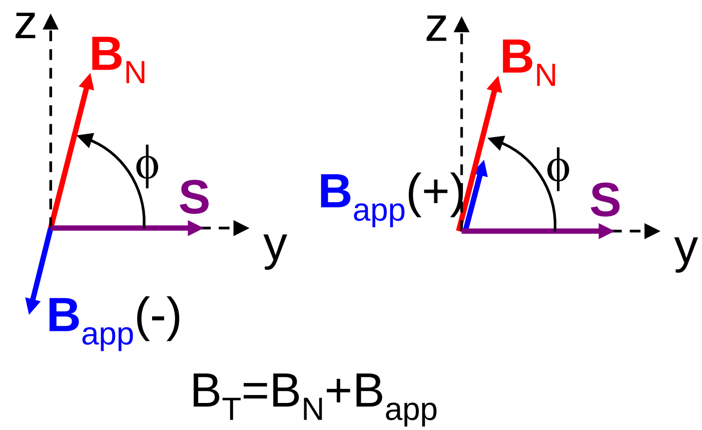


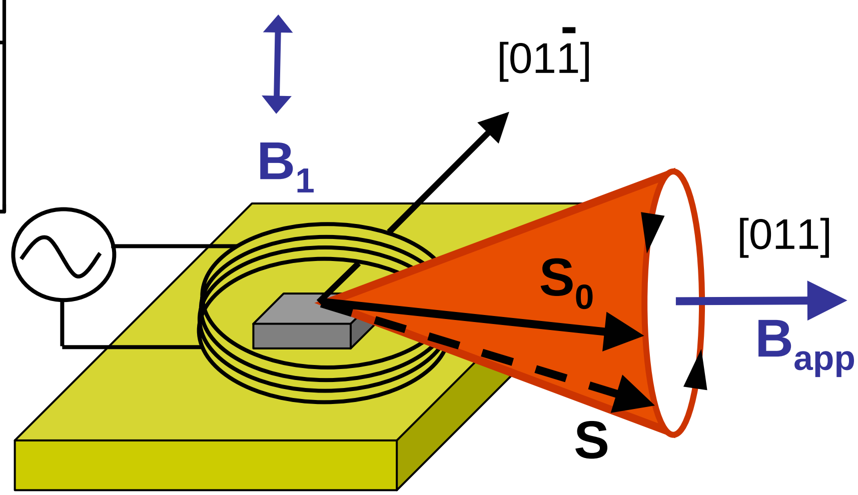



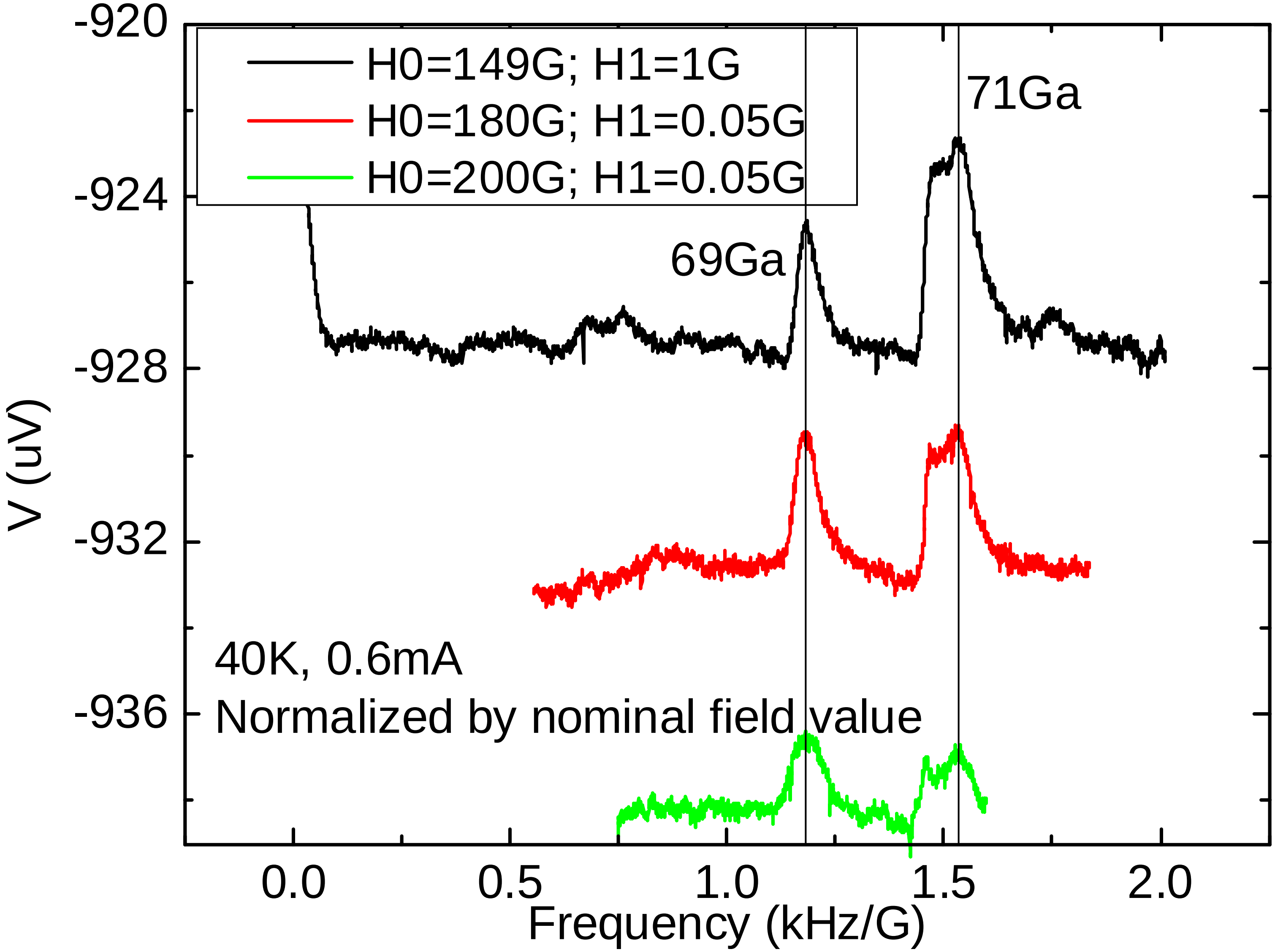

- Zero-field anomaly (dependent on sweep rate) appears below 50 K
- Hanle curves can be fitted by accounting for hyperfine field

# Resonant Depolarization of Nuclei





H0=149G; H1=1G
H0=180G; H1=0.05G
H0=200G; H1=0.05G
71Ga
69Ga
40K, 0.6mA
Normalized by nominal field value
-920
-924
-928
-932
-936
V (uV)
0.0
0.5
1.0
1.5
2.0
Frequency (kHz/G)

# Brief Synopsis

- Fe/GaAs Schottky tunnel barriers function as both electrical spin injectors and detectors
- Observation of Hanle effect (up to 120 K); widths consistent with spin lifetime and transport measurements
- Outstanding agreement with drift-diffusion model for spin transport in semiconductor
- Order of magnitude of non-local signal in agreement with expectations based on spin-LED measurements

Other recent reports on electrical spin detection in ferro-semi:

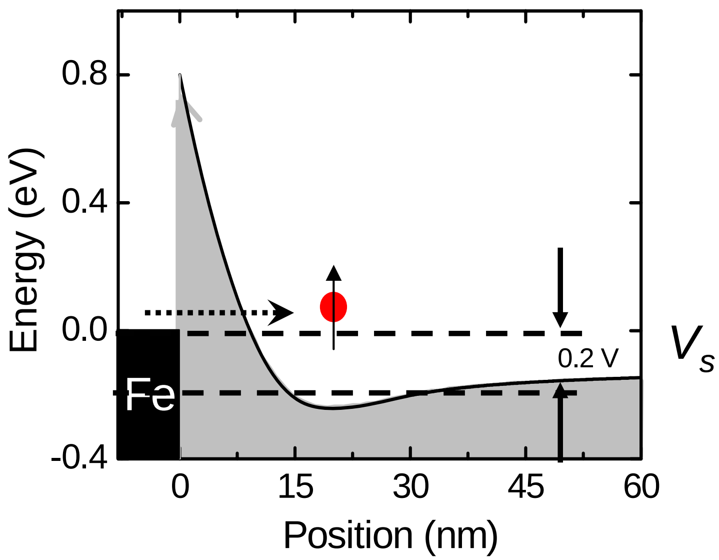
FeCo/Si (Delaware), Co/graphene (Groningen)

MnAs/GaAs (Michigan), Fe/Si (NRL)

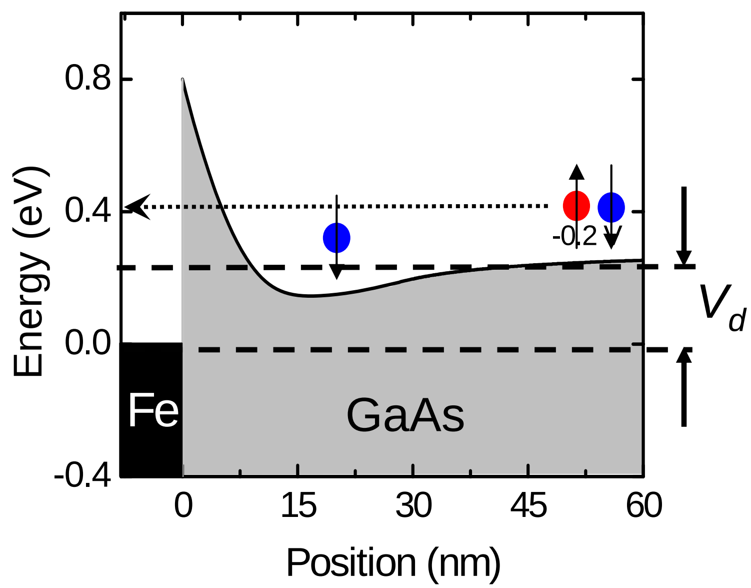
What is not understood?

# Spin accumulation under forward bias

Spin injection (reverse bias)




Spin accumulation (forward bias)

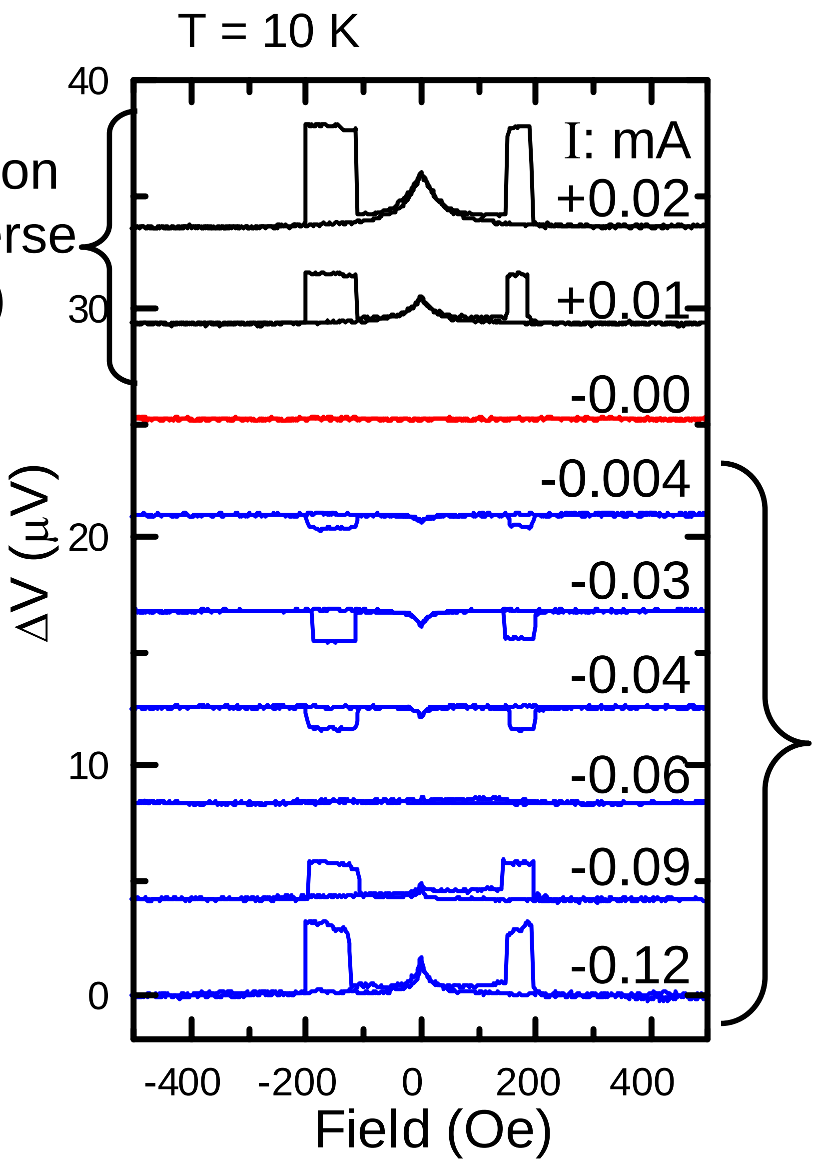



- Spin accumulation at forward-biased MnAs/GaAs barriers:
  Stephens *et al.,* PRL **93**, 097602 (2004)
- Spin-dependent reflection
- In the linear response regime, we expect the sign of the polarization under forward bias to be opposite that injected under reverse bias

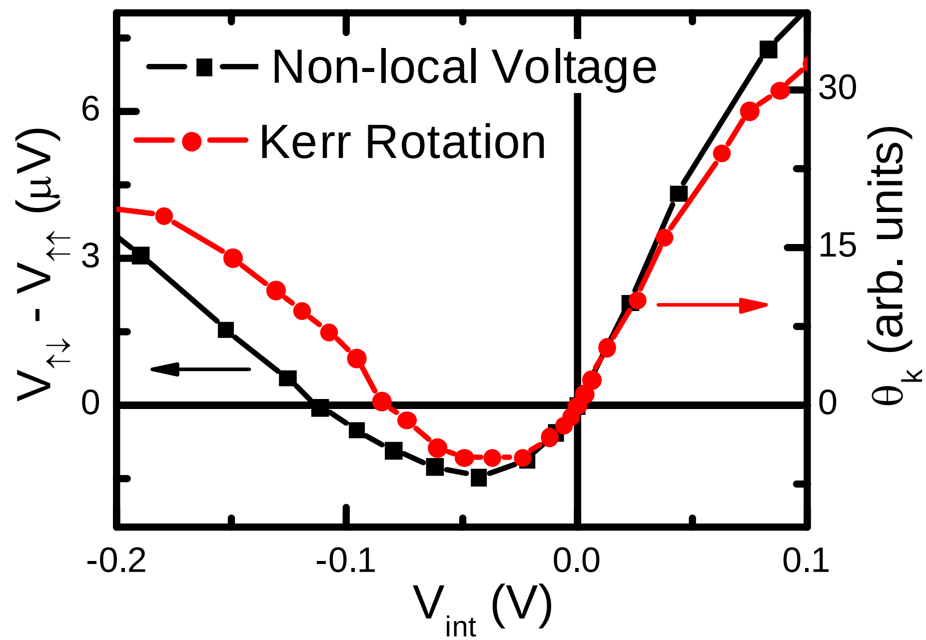
See Ciuti *et al.*, Phys. Rev. Lett. **89**, 156601 (2002); also Bauer and co-workers

# Bias dependence and sign of the non-local signal

Injection (Reverse bias)

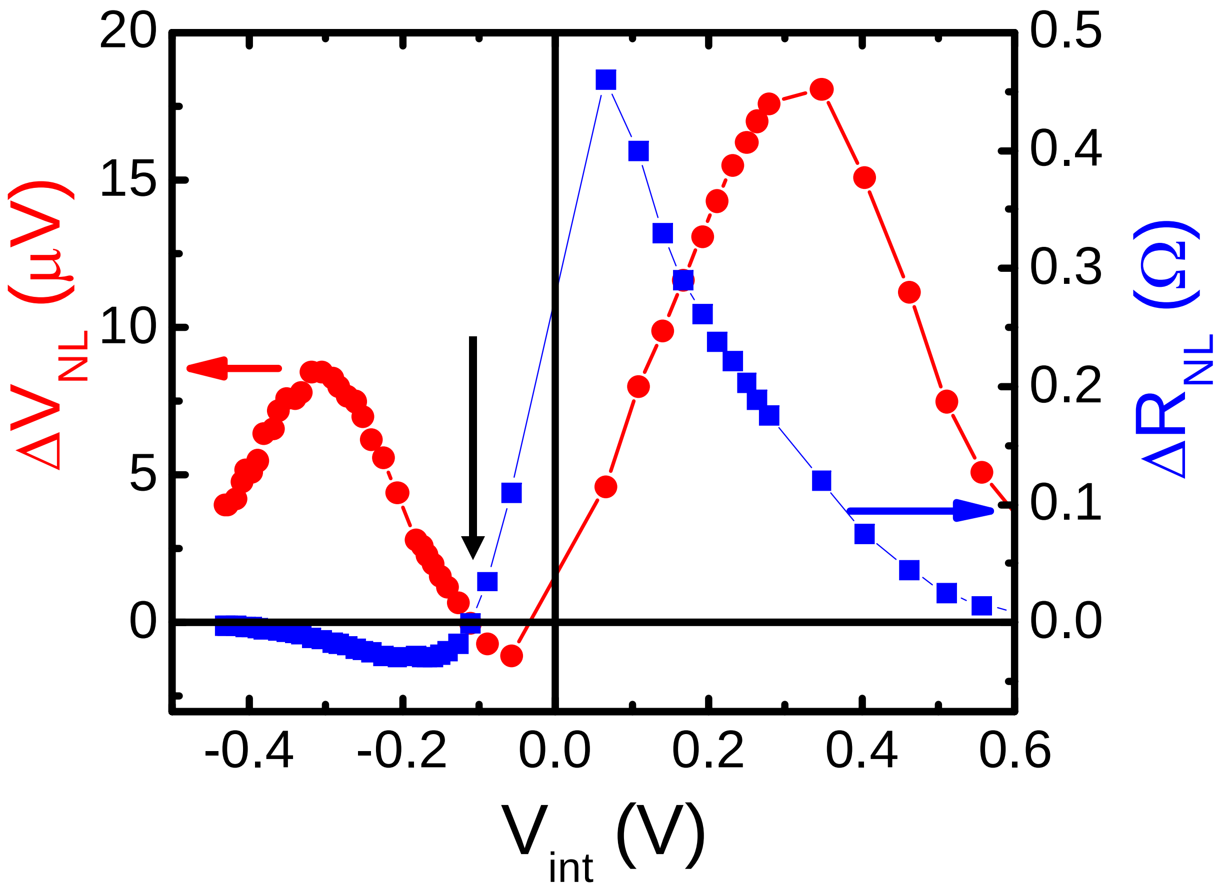



(Forward bias)




- Sign change at zero bias (expected)
- Very small region of linear response
- Direct correspondence between non-local signal and polarization measured with Kerr rotation

# Bias dependence and non-local resistance



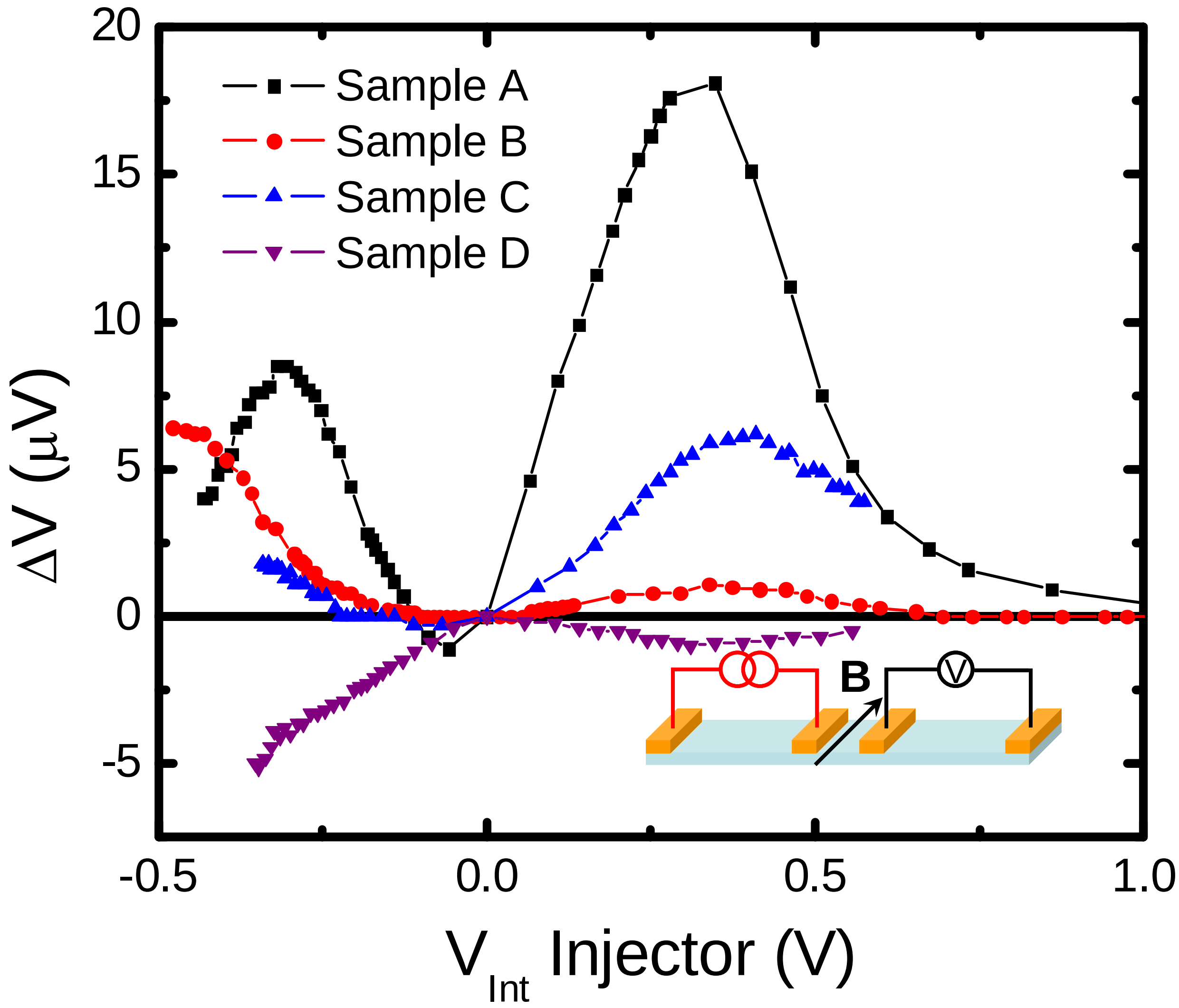

- Sign reversal at forward bias
- Sign of $\Delta V$ for majority polarization is determined by the *slope* at zero bias
- The observed polarization is (almost) always *majority* as determined by MOKE

See also, J. Moser *et al,* Appl. Phys. Lett. **89**, 162106 (2006)

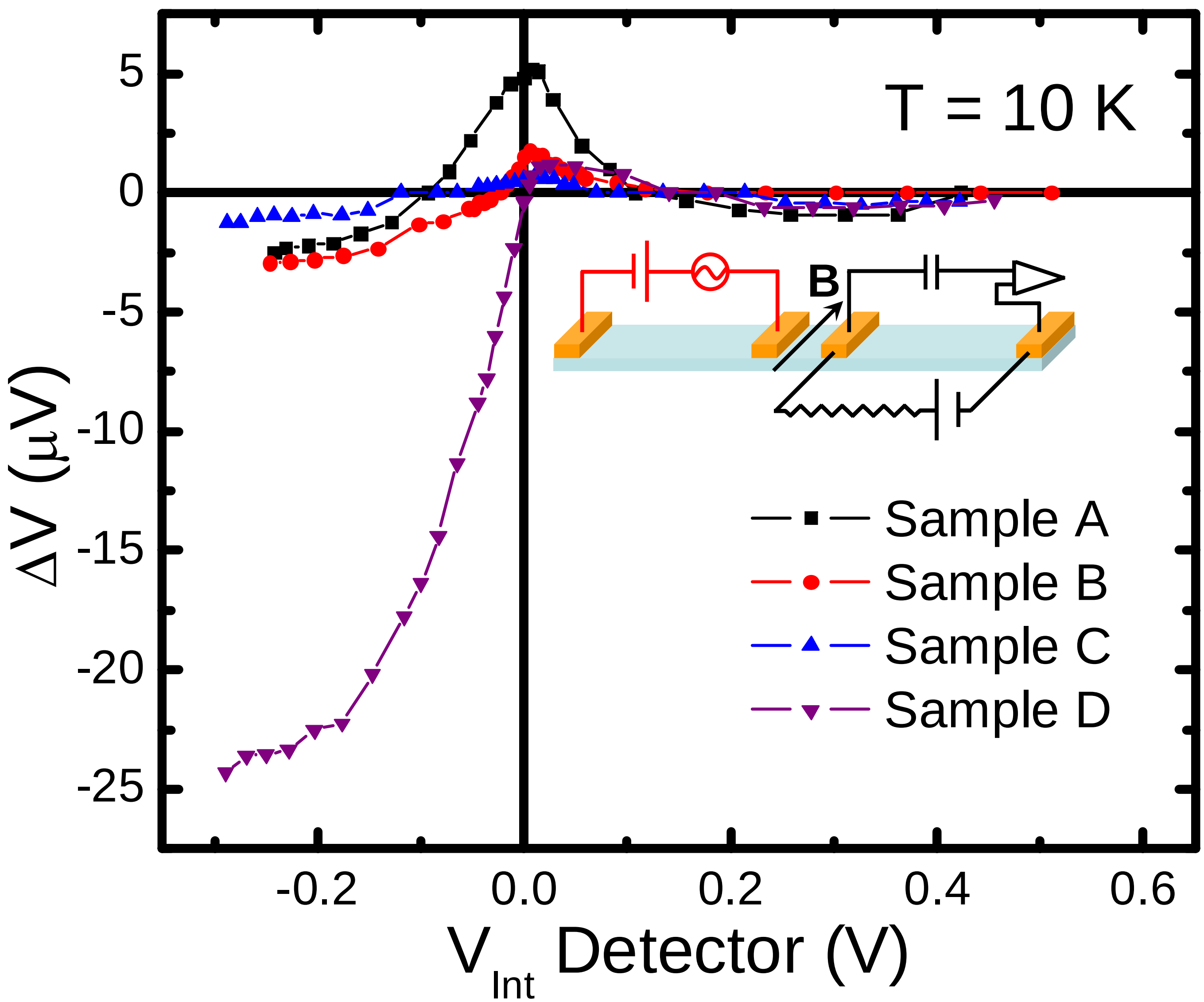
# Dispersion in bias dependence

| Sample | Schottky Thickness (nm) | Channel Doping ($cm^{-3}$) |
|---|---|---|
| A | 15/15 | $3.5 \times 10^{16}$ |
| B | 20 | $3.5 \times 10^{16}$ |
| C | 25 | $3.5 \times 10^{16}$ |
| D | 15/15 | $5.0 \times 10^{16}$ |

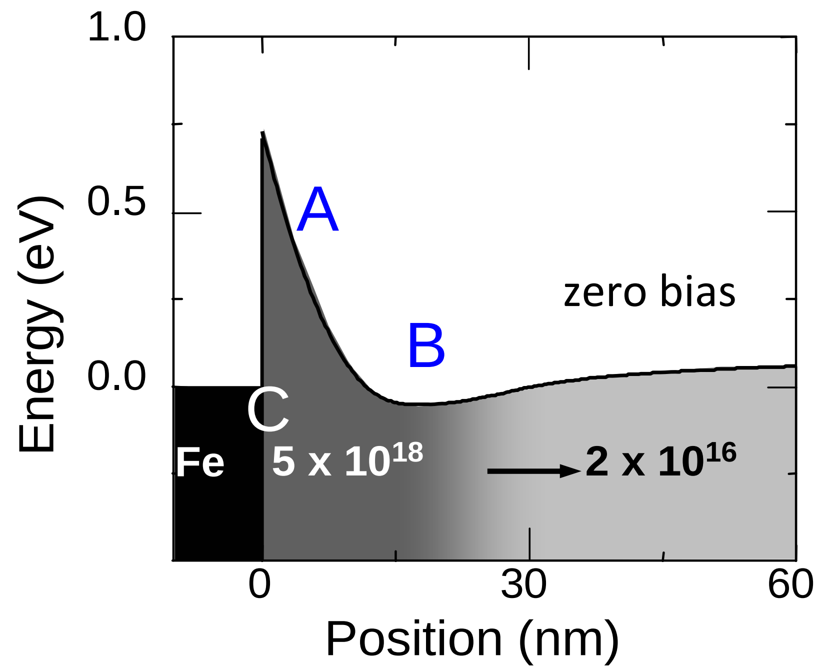
- The *sign of ΔV* depends on exactly where the Fermi level lines up at the Fe/GaAs interface. It can change upon annealing.



Sensitivity to detector bias



# Beyond Julliere

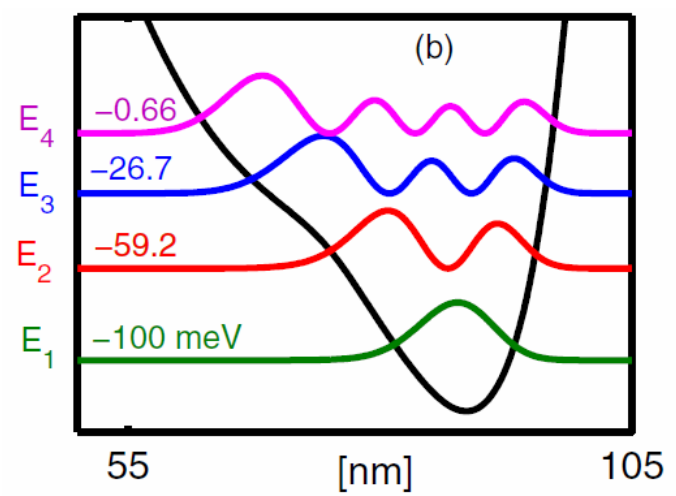



### A. Effects of dispersion

*S.O. Valenzuela et al., Phys. Rev. Lett.* ***94****, 196601 (2005)*

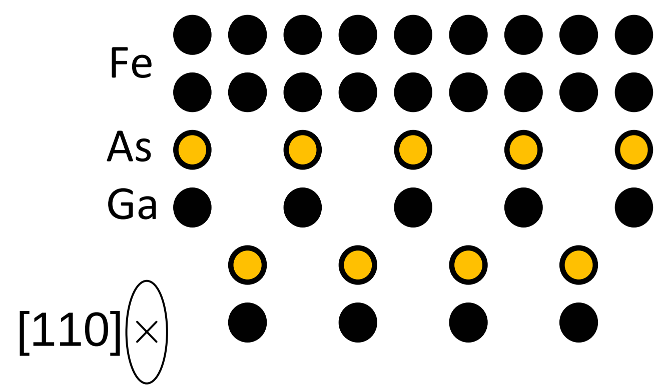
### B. Bound states in the semiconductor

*H. Dery and L.J. Sham, Phys. Rev. Lett.* ***98****, 046602 (2007)*

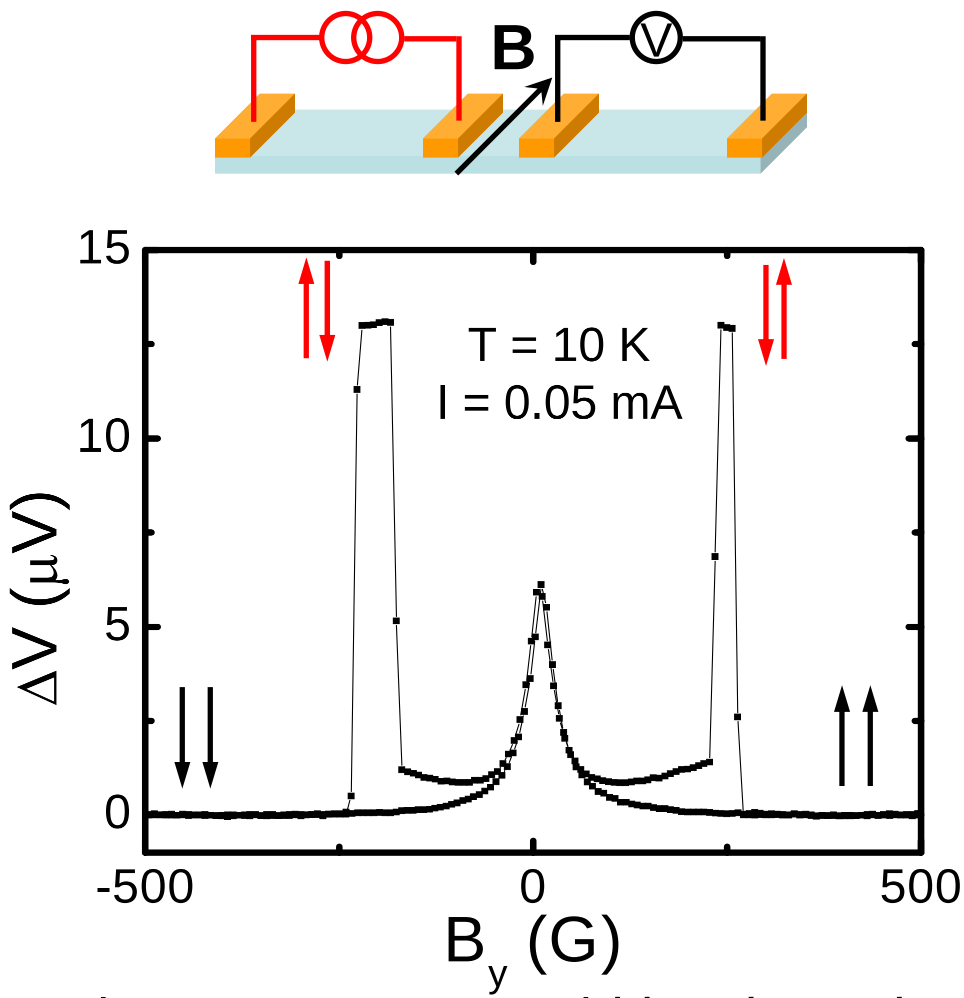


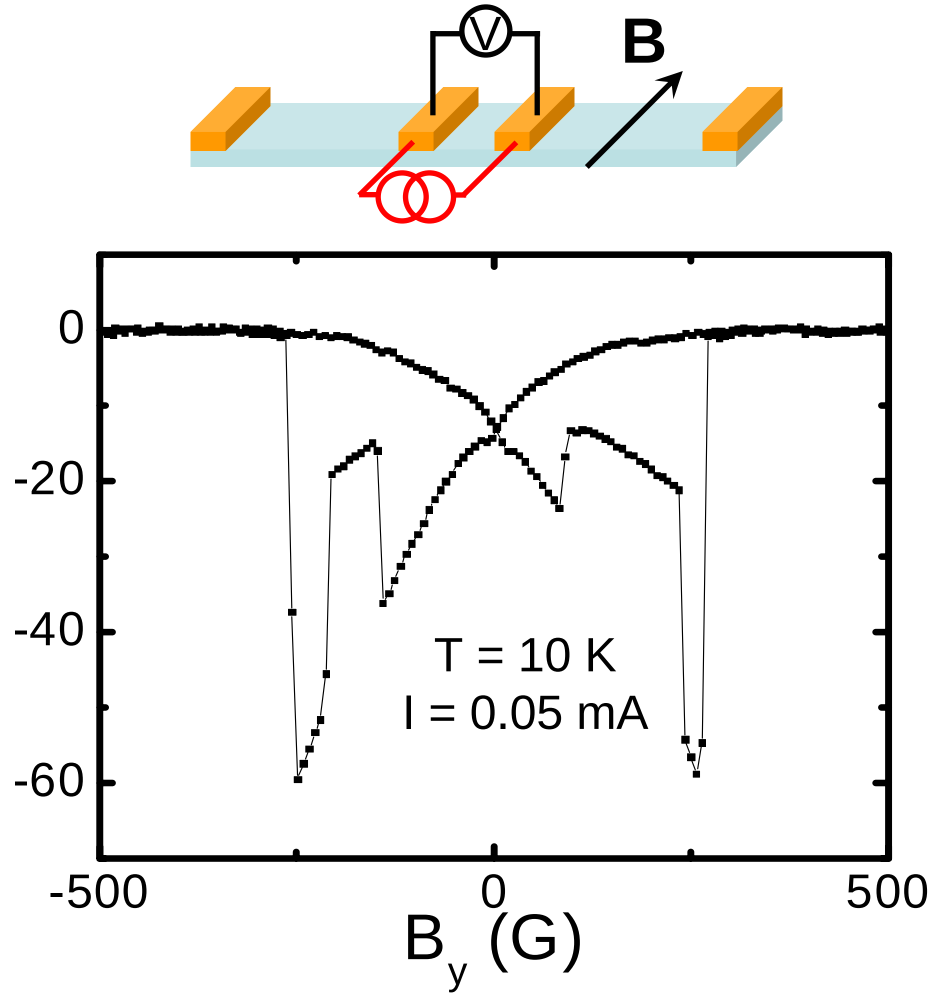

### C. Interfacial Band Structure

*A.N. Chantis et al., Phys. Rev. Lett.* ***99****, 196603 (2007)*



# What about a two terminal measurement?

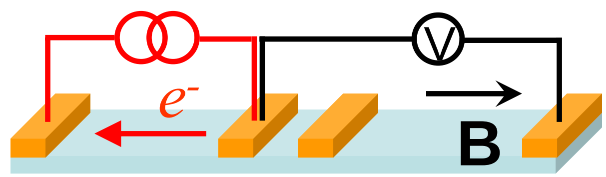


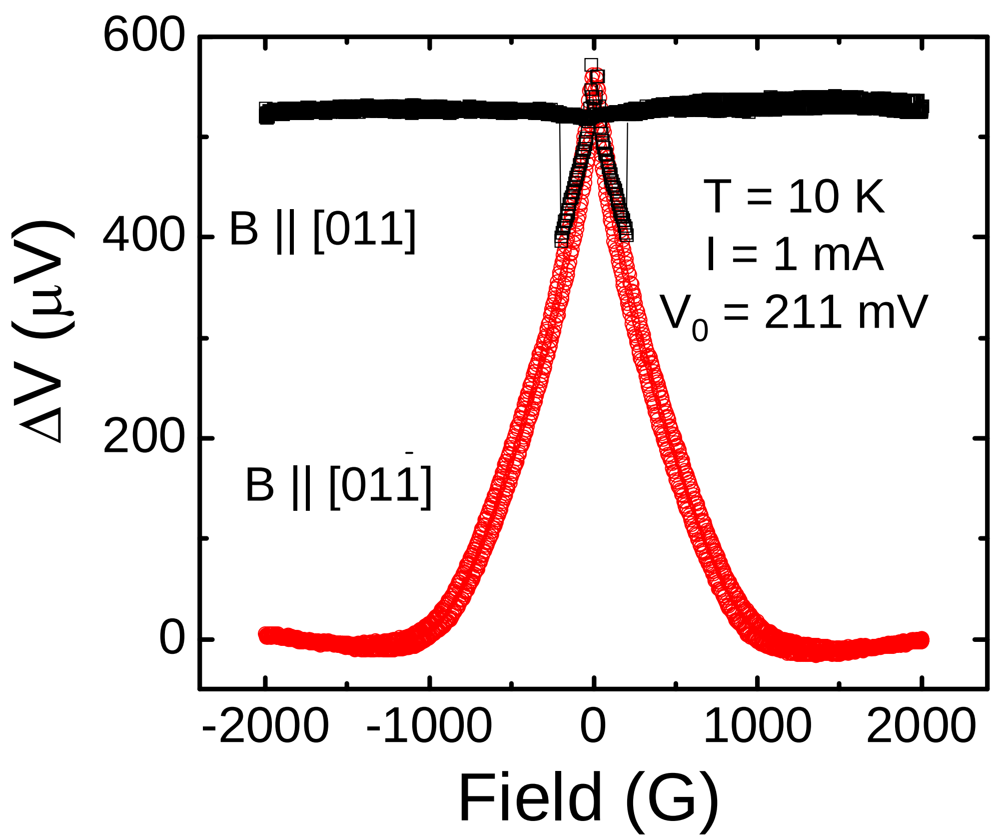



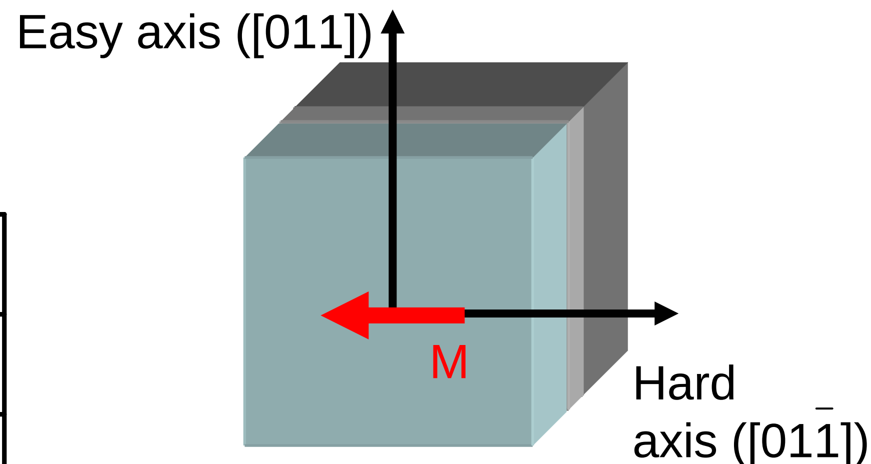

- There are pronounced *bias-dependent* effects in a two-terminal measurement that do not depend on the relative magnetizations of source and detector
- These are not due to the usual suspects (conventional AMR or local Hall)

# Tunneling anisotropic magnetoresistance

C. Gould *et al.*, Phys. Rev. Lett. **93**, 117203 (2004)




- Due to rotation of **M** with respect to crystal axes (not current)
- Spin-orbit coupling + tunneling
- Dominant component from surface states with uniaxial symmetry

J. Moser *et al.*, Phys. Rev. Lett. **99**, 056601 (2007)

## Summary

- Several important aspects of spin transport in Ferro-Semi-Ferro structures are in agreement with the “generic model” for diffusive spin transport.
- The dependence on bias, however, is markedly non-linear
- There is a correspondence between the doping profile (band structure in the semiconductor), the associated *JV* curves, and the non-local spin signal [not discussed today]
- It is possible to measure separately the dependence on the injector and detector bias voltages
- A two-terminal measurement is strongly dependent on spin-orbit effects at the Fe/GaAs interface (at least for epitaxial samples)