# Electrical Spin Injection and Detection in Ferromagnet/Semiconductor Devices

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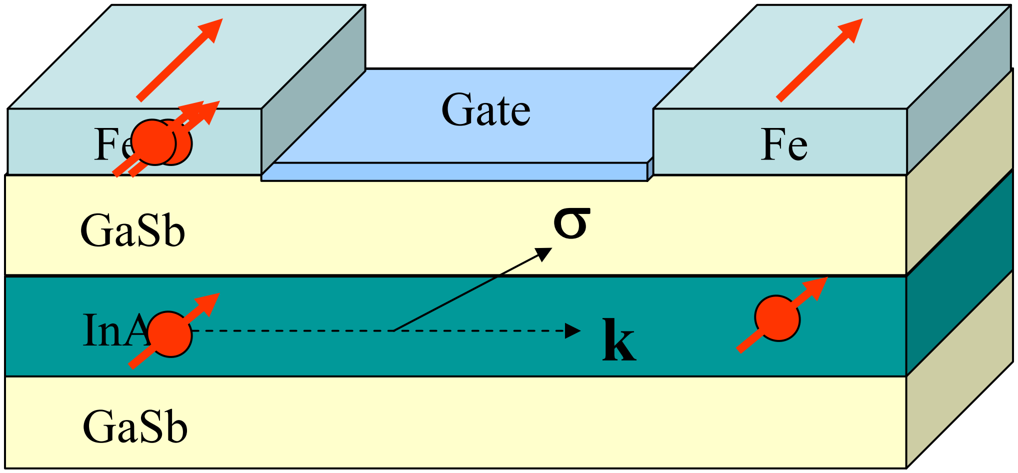
- ✧ Spin transport in ferromagnet/semiconductor devices
- ✧ Injection → Transport → Detection* in one device
- ✧ Electrical detection of spin accumulation

Supported by DARPA SPINS, ONR, NSF MRSEC 02-12032, and the LANL LDRD Program

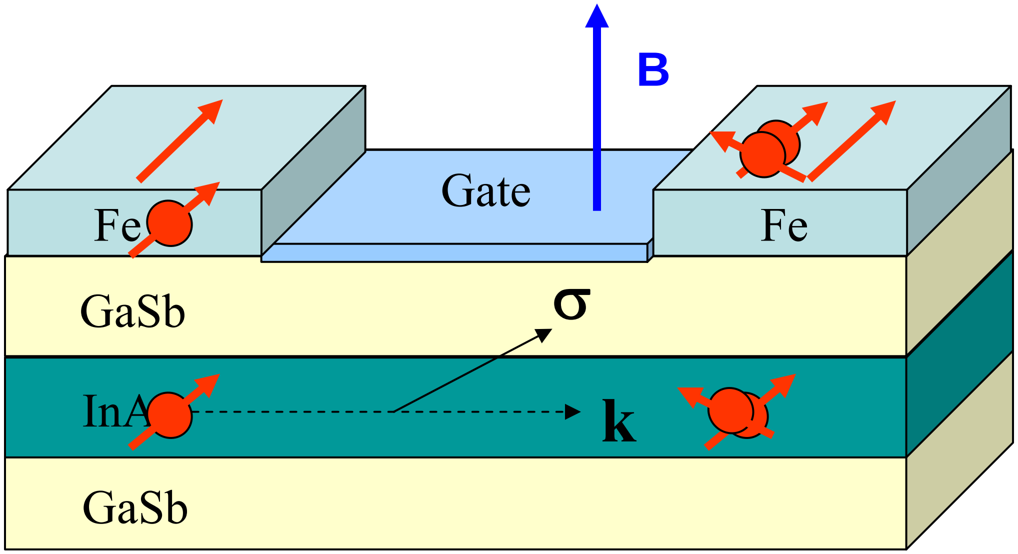
# “Ritual viewgraph” showing a spin-FET



Datta and Das, Appl. Phys. Lett. **56**, 665 (1990)

- Inject spins from a ferromagnetic source
- Transport in the channel (minimize relaxation)
- Detection at drain contact
- Transimpedance depends on relative magnetizations of source and drain

# “Ritual viewgraph” showing a spin-FET



Spin-orbit interaction:

$$H_{so} = \alpha(\boldsymbol{\sigma}\times\mathbf{k})\bullet\mathbf{z}$$

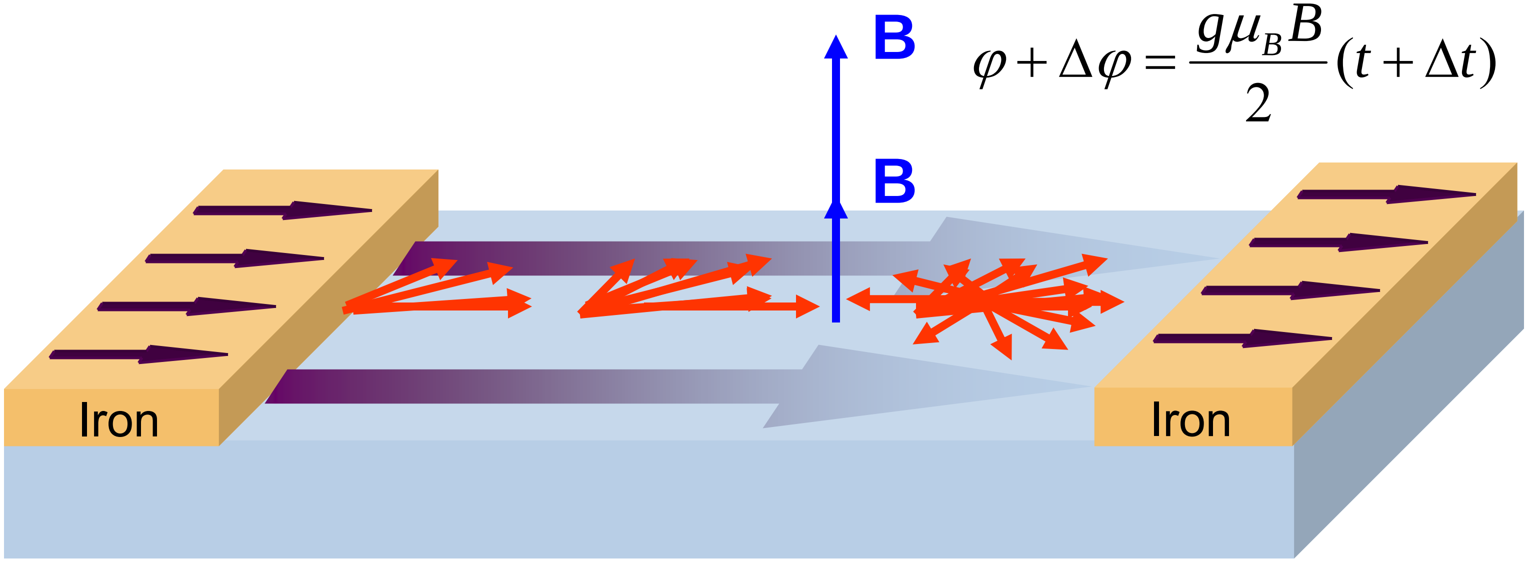
or $$H_{so} = -\boldsymbol{\mu}\cdot\mathbf{B}_{eff}(\mathbf{k})$$

Datta and Das, Appl. Phys. Lett. **56**, 665 (1990)

- Inject spins from a ferromagnetic source
- Control the orientation of the spins arriving at the drain (relative to the magnetization of the drain contact)
- Transport in the channel (minimize relaxation)
- Detection at drain contact
- Transimpedance should depend on precession angle
- Transimpedance depends on relative magnetizations of source and drain

This has not yet been successfully implemented (no Hanle effect)

# Hanle Effect for diffusive spin transport

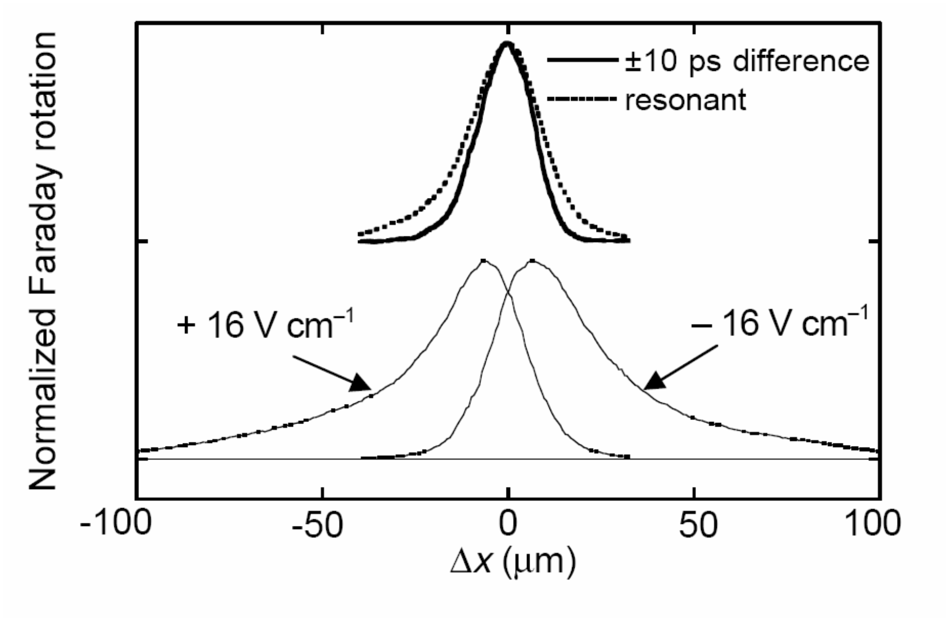


$$\varphi + \Delta\varphi = \frac{g\mu_B B}{2}(t + \Delta t)$$

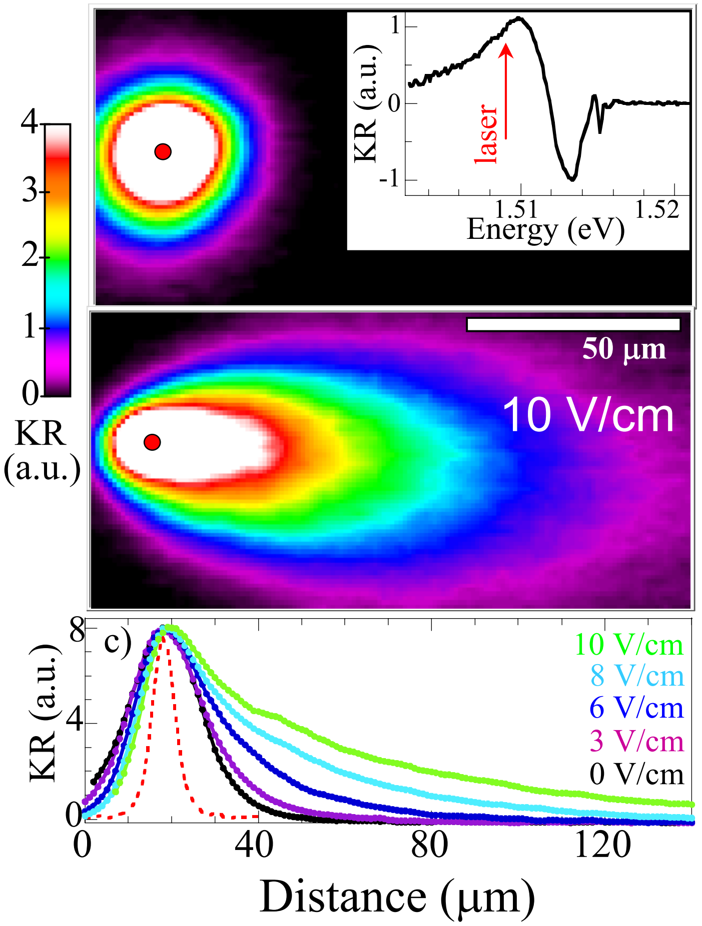
- Application of a transverse field induces precession but also dephasing due to a distribution of transport times (diffusion)
- Spin-dependent signal should be suppressed in large fields
- This can usually be done in a geometry that leaves the magnetizations of the electrodes fixed
- Metallic F-N-F systems have passed this test:
  Johnson and Silsbee: Phys. Rev. Lett. **55**, 1790 (1985)
  Jedema *et al.*, Nature **416**, 713 (2002)

# Things that work Part I:  Spin transport in GaAs

J. M. Kikkawa and D. D. Awschalom
Nature **397**, 6715 (1999)



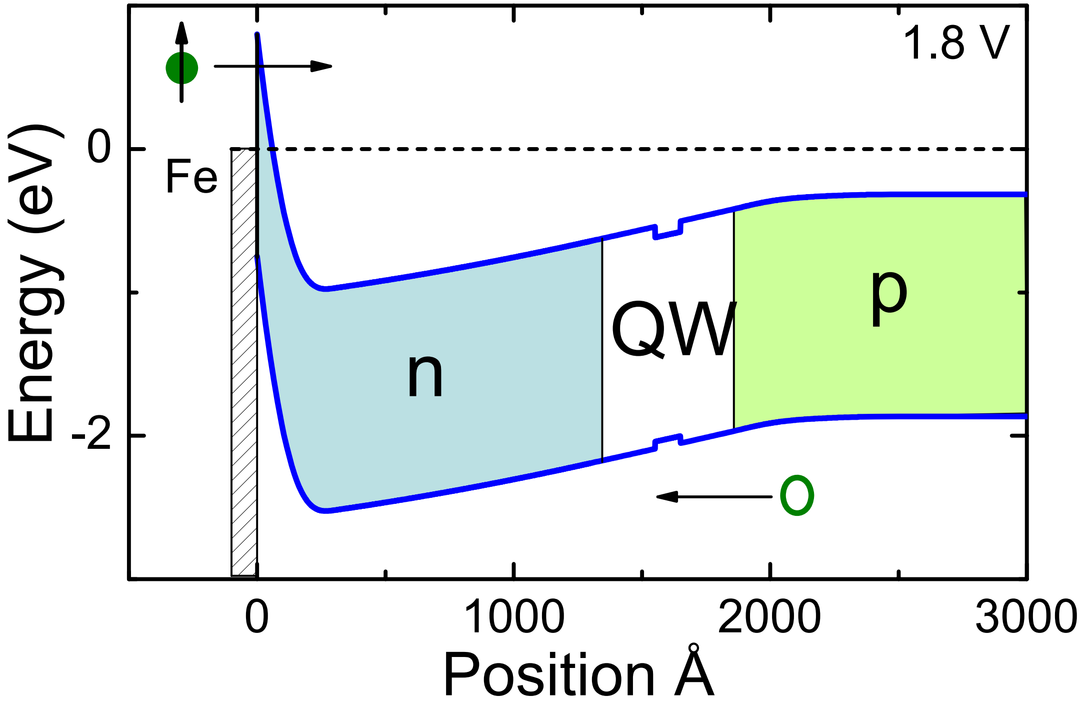
Doping: 1- 3 x $10^{16}$ cm$^{-3}$
Spin drift lengths > 100 microns
Diffusion constant ~ 10 cm$^2$/s
Spin lifetime:  100 nsec

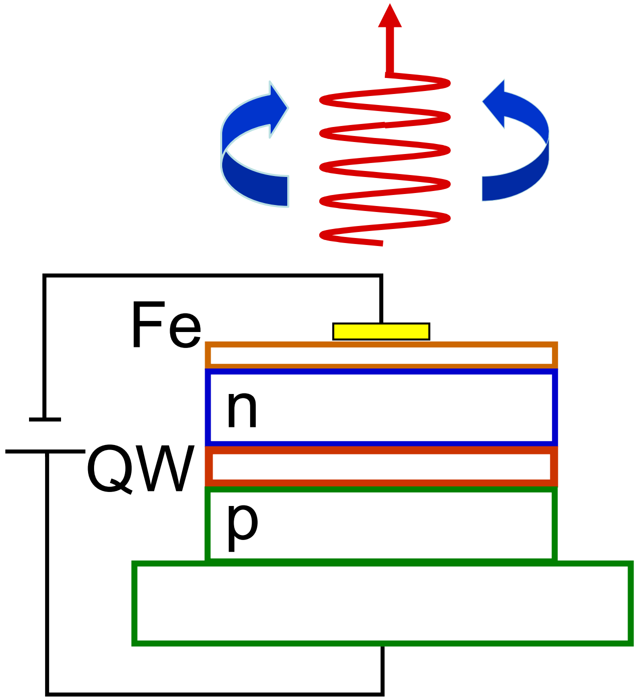


S. A. Crooker and D. L. Smith
Phys. Rev. Lett. **94**, 236601 (2005)

This imposes no practical limitations.  2D systems are more difficult…..

# Things that work Part II:  Electrical spin injection

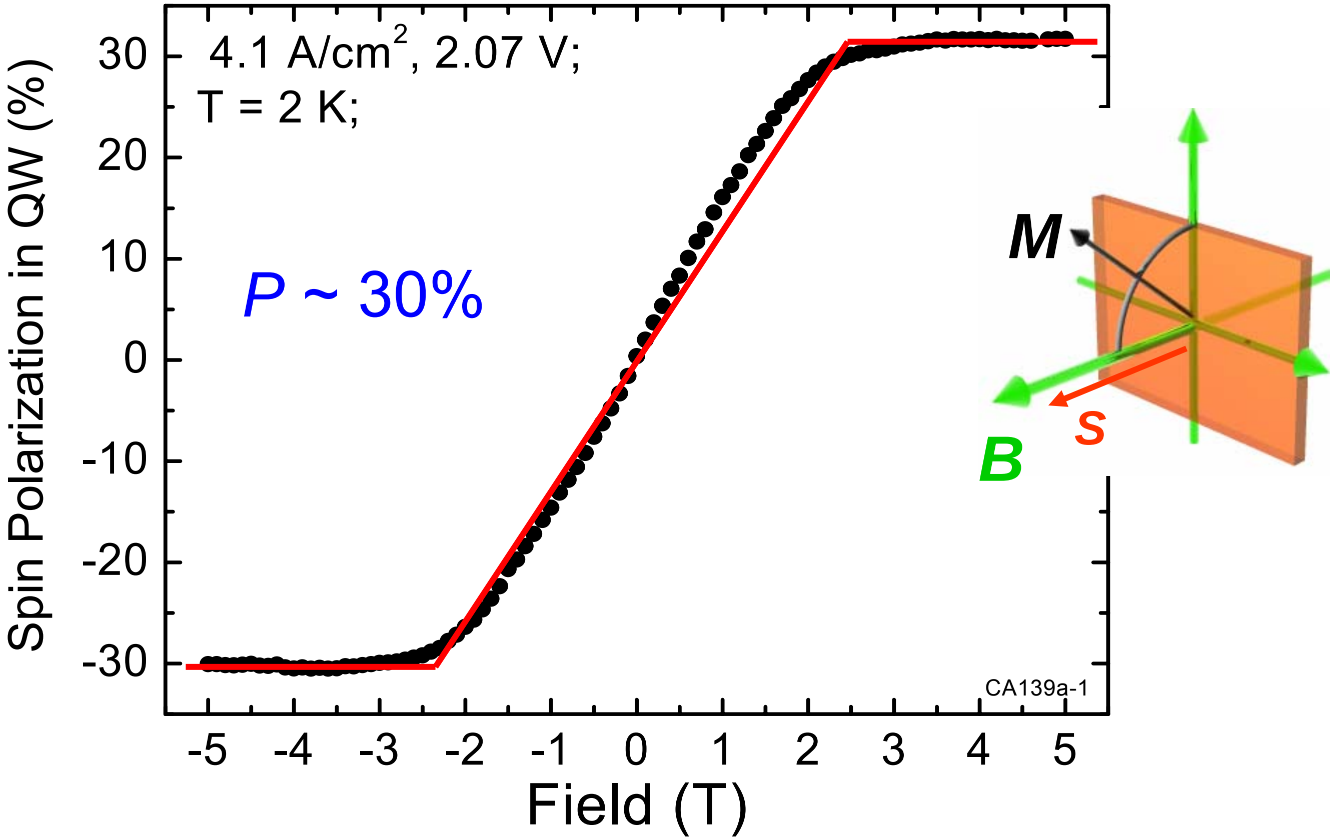




Schottky diode + p-i-n diode

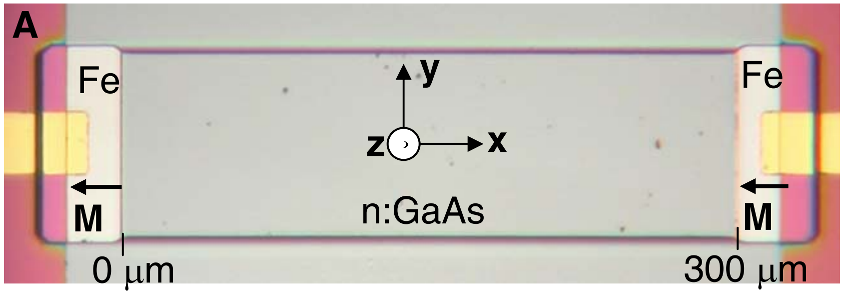
Graded doping profile:  A. T. Hanbicki *et al.*, Appl. Phys. Lett. **82**, 4092 (2003)

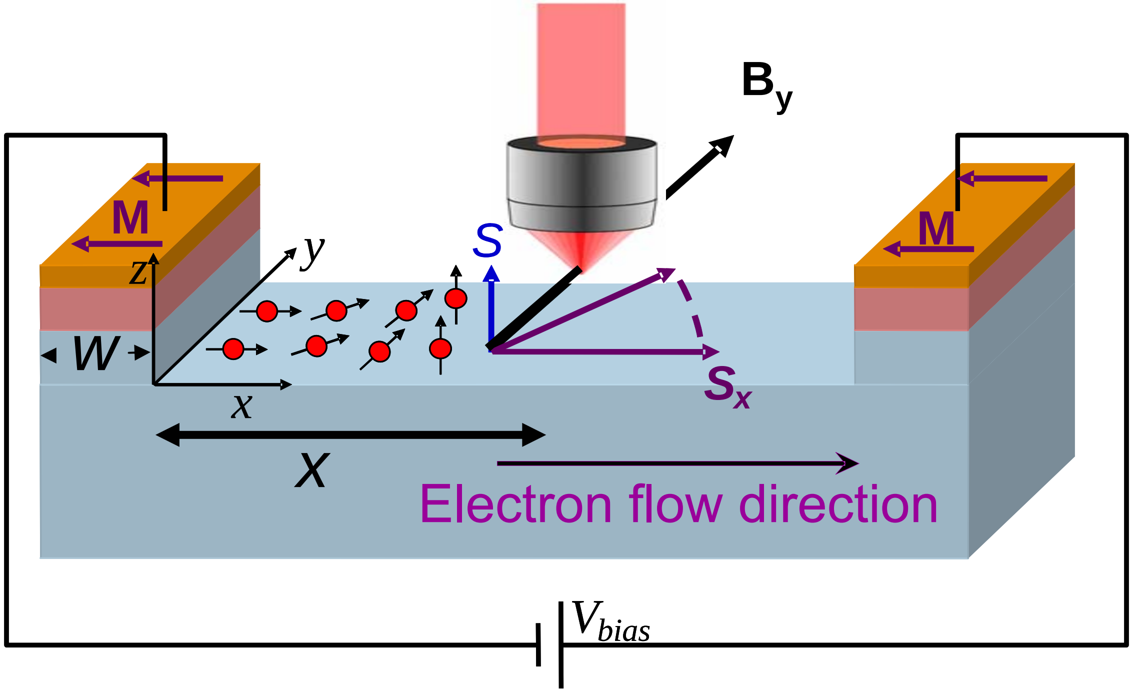
# Electrical spin injection: PDI,NRL, IMEC, IBM, Minnesota

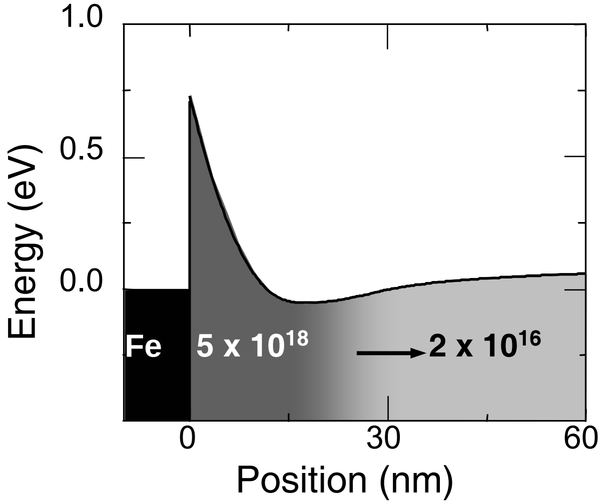


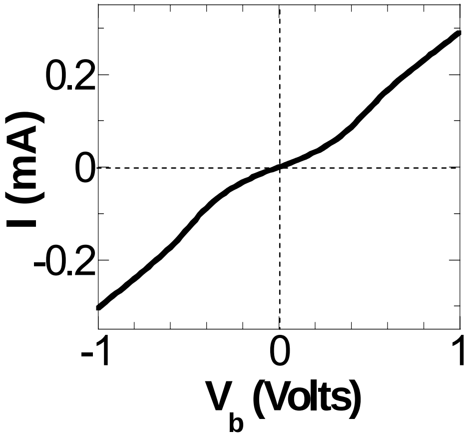
- But: EL polarization is used to detect the injected spins “at the source”
- This has limited the amount of physics done with these devices

# Simple channel device + Kerr microscopy + Precession





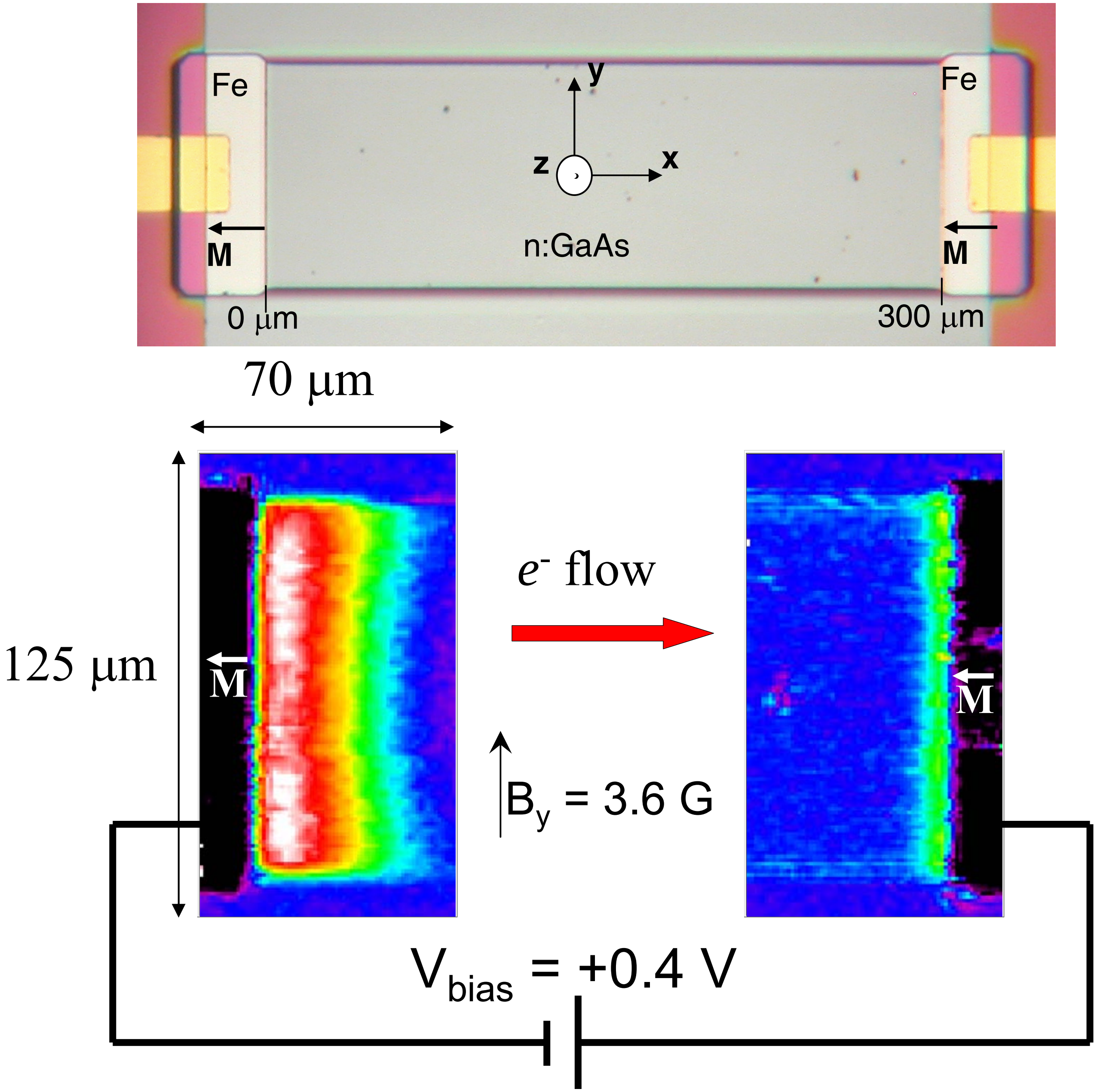




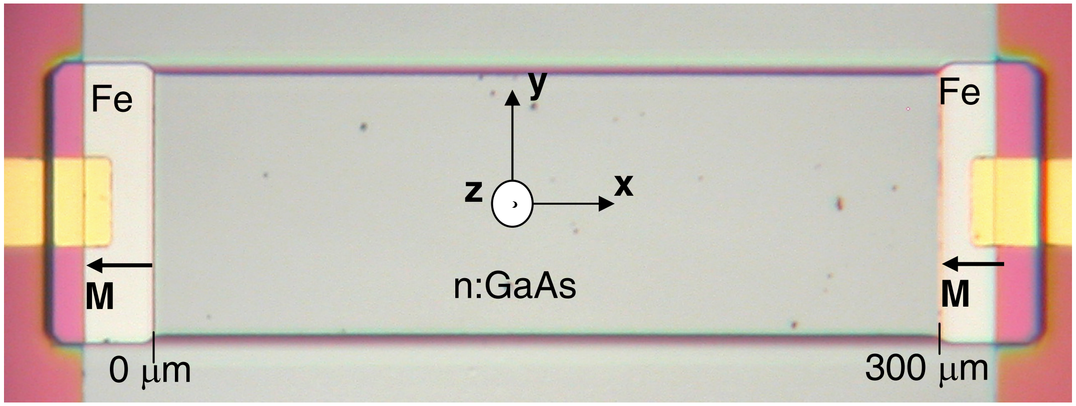
Hanle MOKE:  J. Stephens *et al.*, Phys. Rev. Lett. **93**, 097602 (2004).

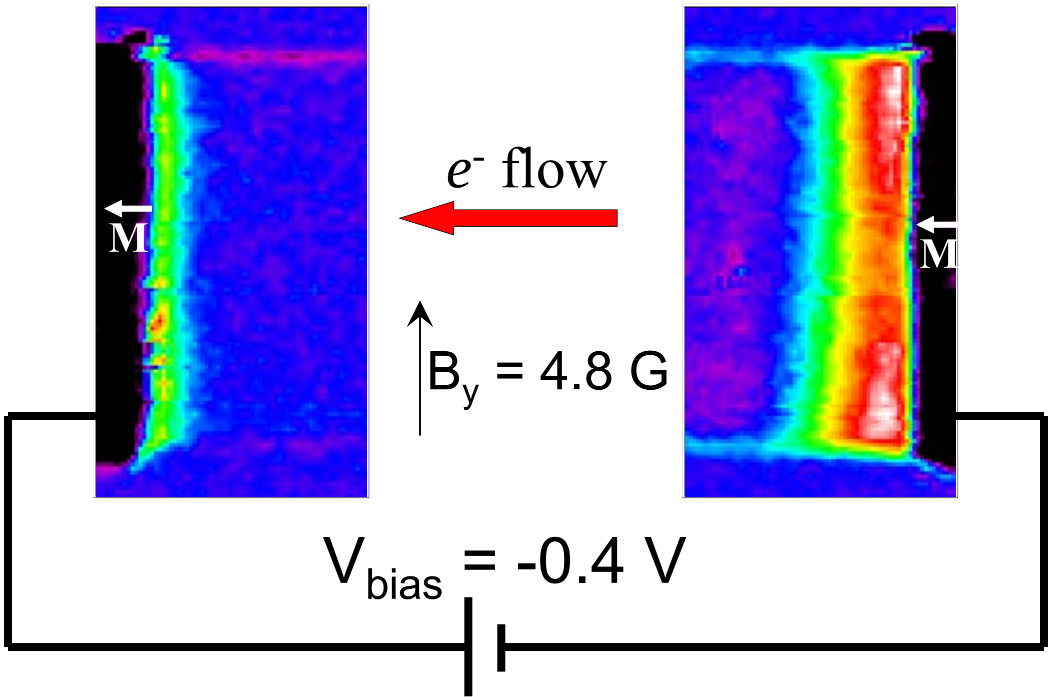
- Contact magnetization is unchanged by the applied field.
- Polar Kerr microscopy detects the *z*-component of the spin.

# Kerr image under bias and in a small transverse field



# Reverse the bias current.....



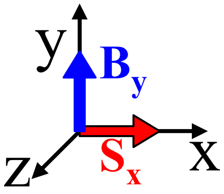


$e^{-}$ flow

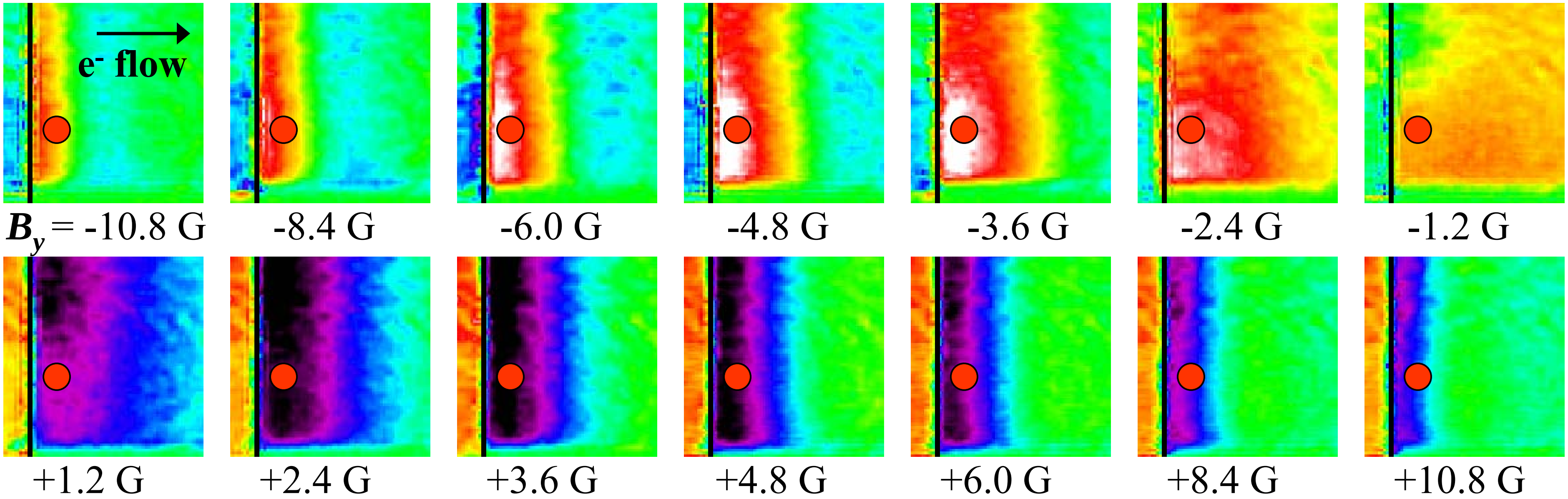
$B_y$ = 4.8 G

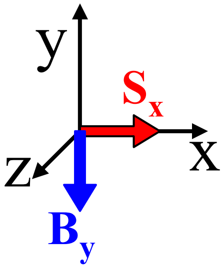
$V_{bias}$ = -0.4 V

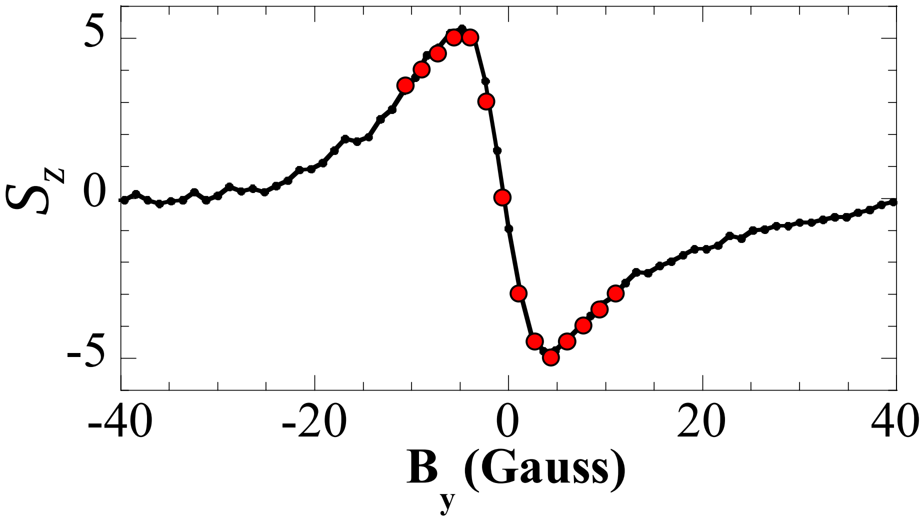
# Measure $S_z$ versus $B_y$ : “Hanle curve”

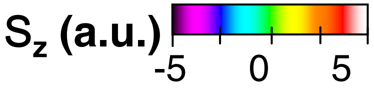


$B_y$ tips $S_x$ into or out-of-plane: $\frac{d\vec{S}}{dt} = \gamma \vec{S} \times \vec{B}$



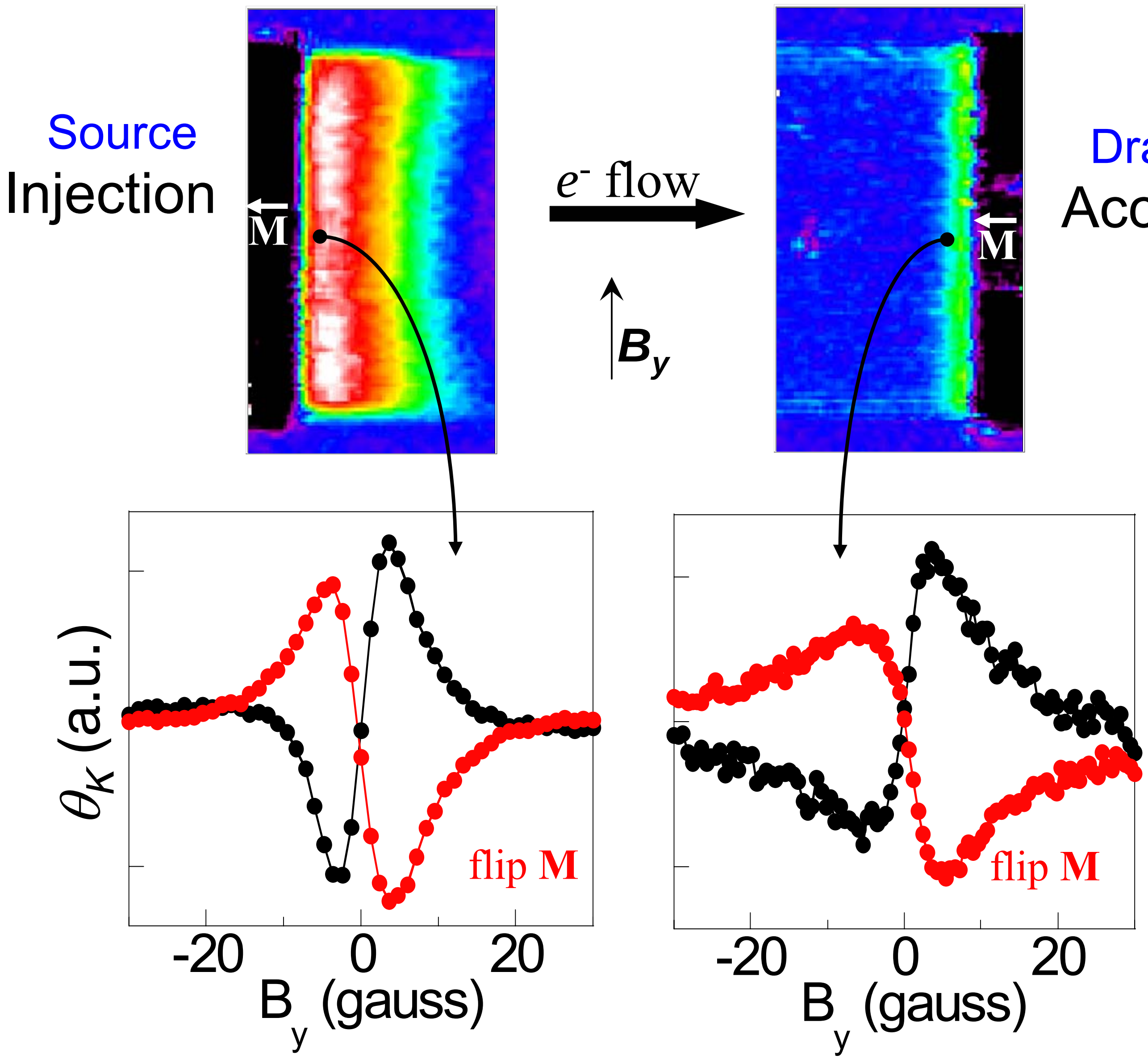






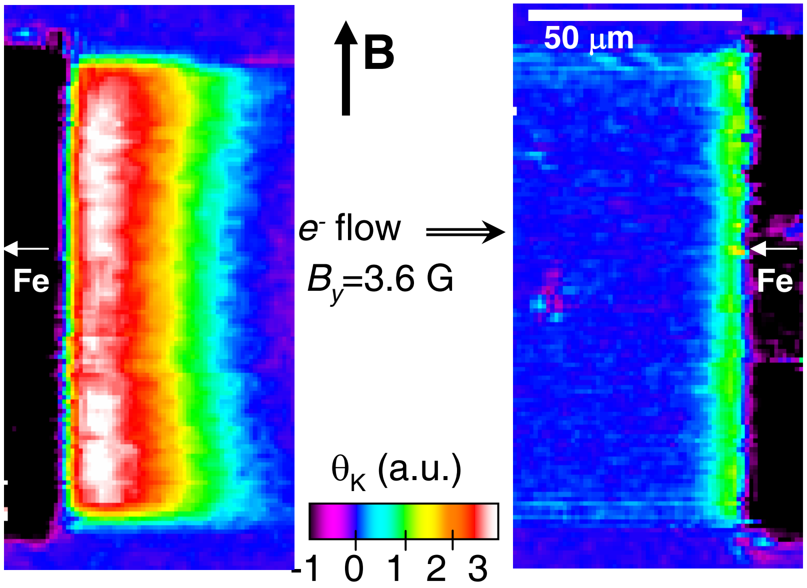
- These “Hanle curves” contain all the physics
- *Explicitly* due to spin precession

# Dependence of Hanle signal on the magnetization



In both cases:
*majority* spin
polarization is observed
in the semiconductor

# Summary of Principal Observations

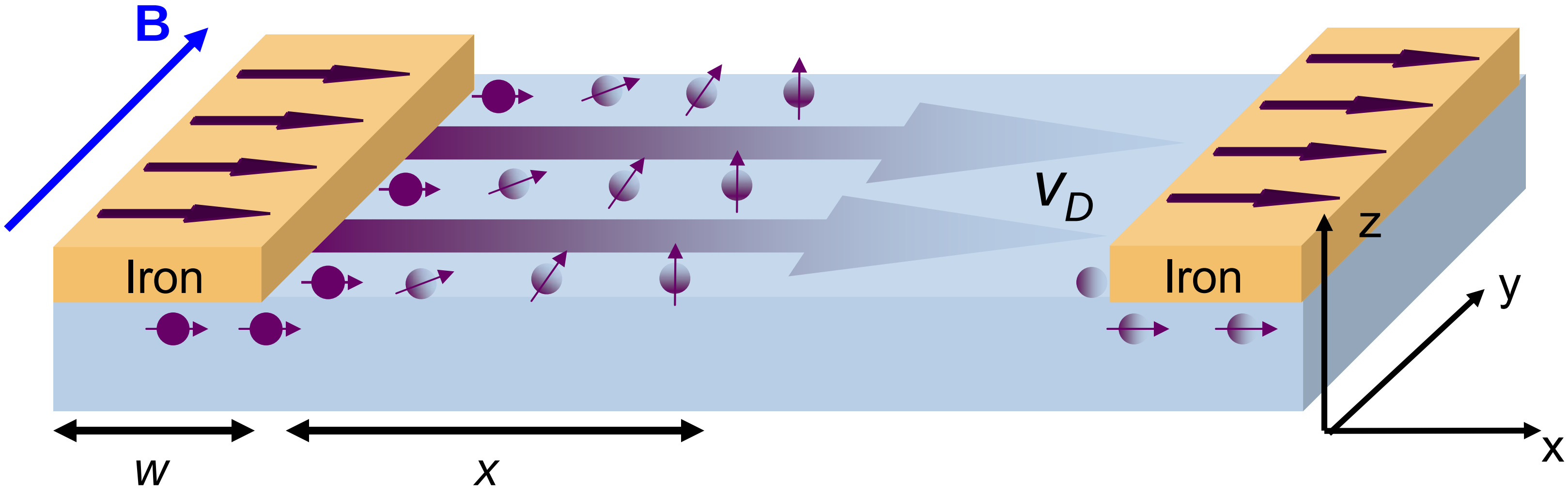


- Cloud of spins emitted from the source ($l_D$ ~ 30 microns)
- Polarization ~5% near the injection contact (not well-calibrated)
- Sign corresponds to injection of majority spins
- Sign reverses when the magnetization is reversed
- Spin accumulation is observed near the forward-biased drain contact; as observed under MnAs/GaAs barriers: Stephens *et al.*, PRL **93**, 097602 (2004)
- The sign of the accumulated polarization is the same as the injected polarization

# 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

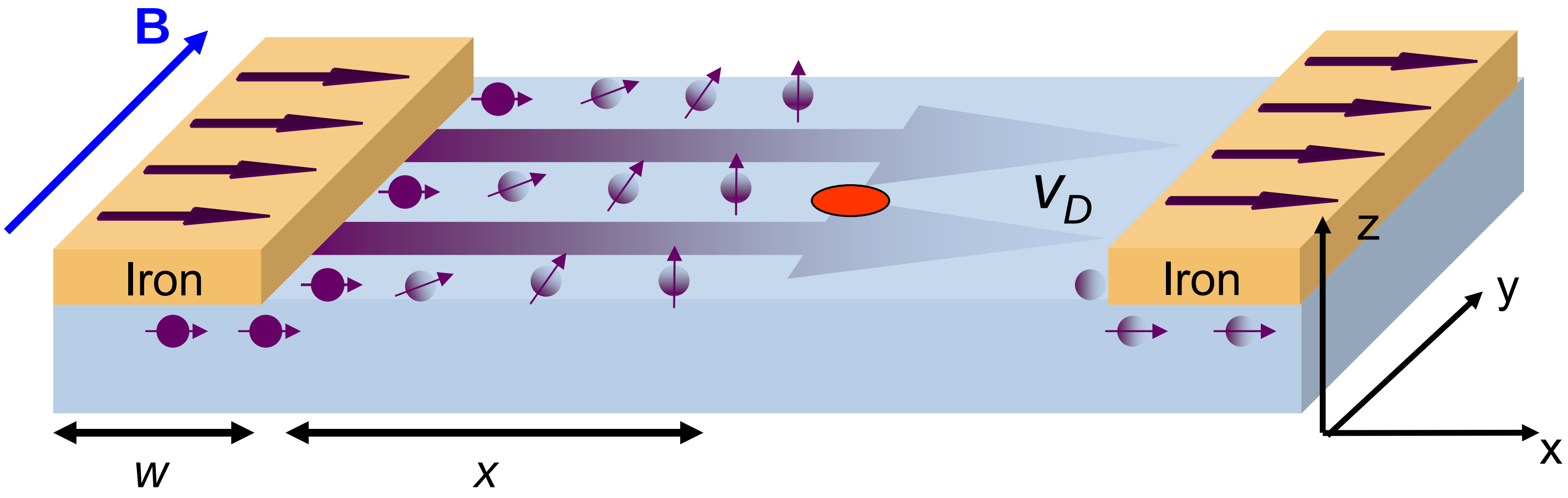
$w$ = width of contact

$x$ = distance from edge of contact

# Drift-Diffusion Model

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

$$S_z(x) = k \int_{x}^{x+w} \int_{0}^{\infty} \frac{S_{x0}}{\sqrt{4\pi D t}} e^{-\frac{(x'-v_d t)^2}{4Dt} - \frac{t}{\tau_s}} \sin(\Omega t)\, dt\, dx'$$



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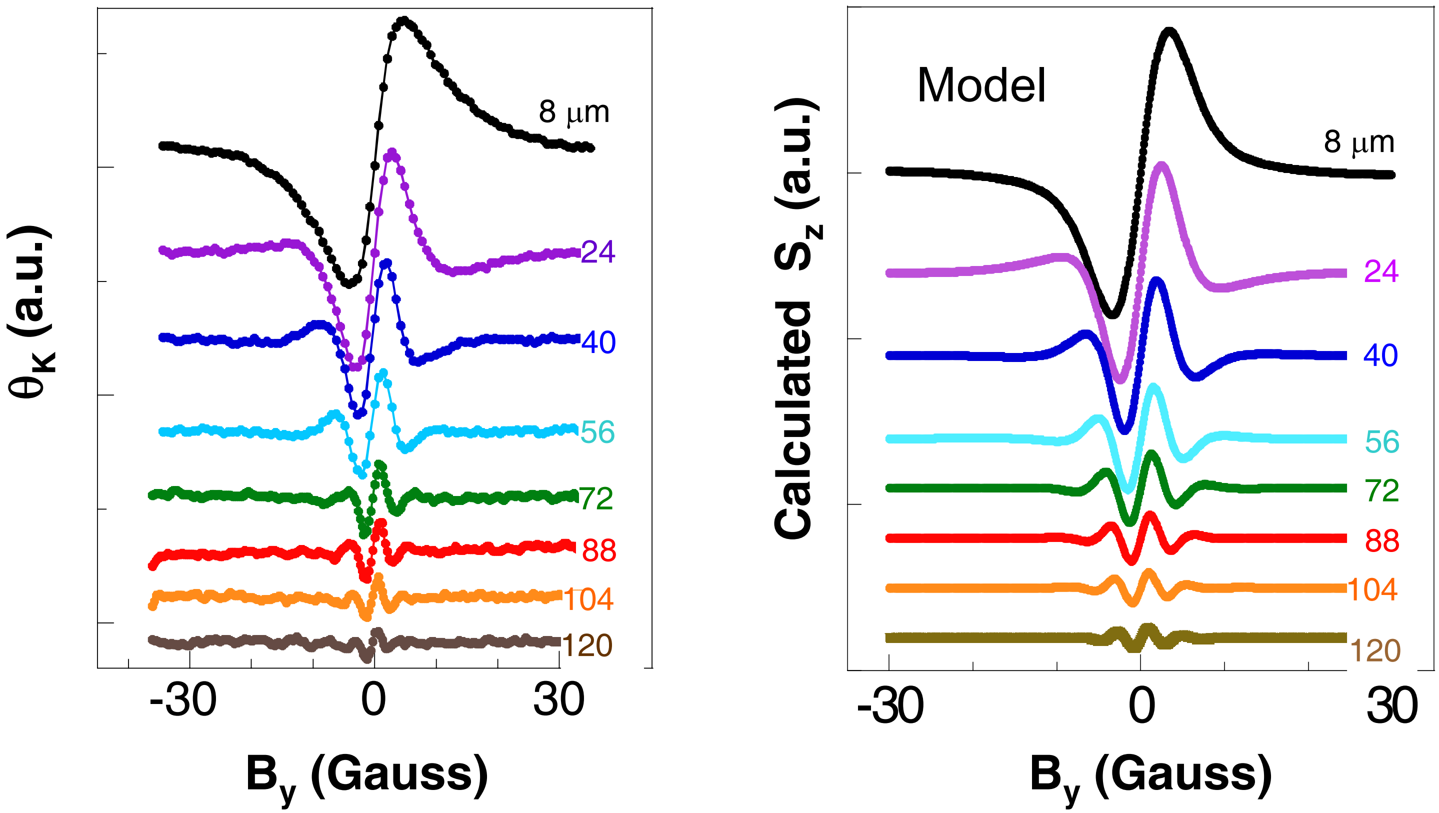
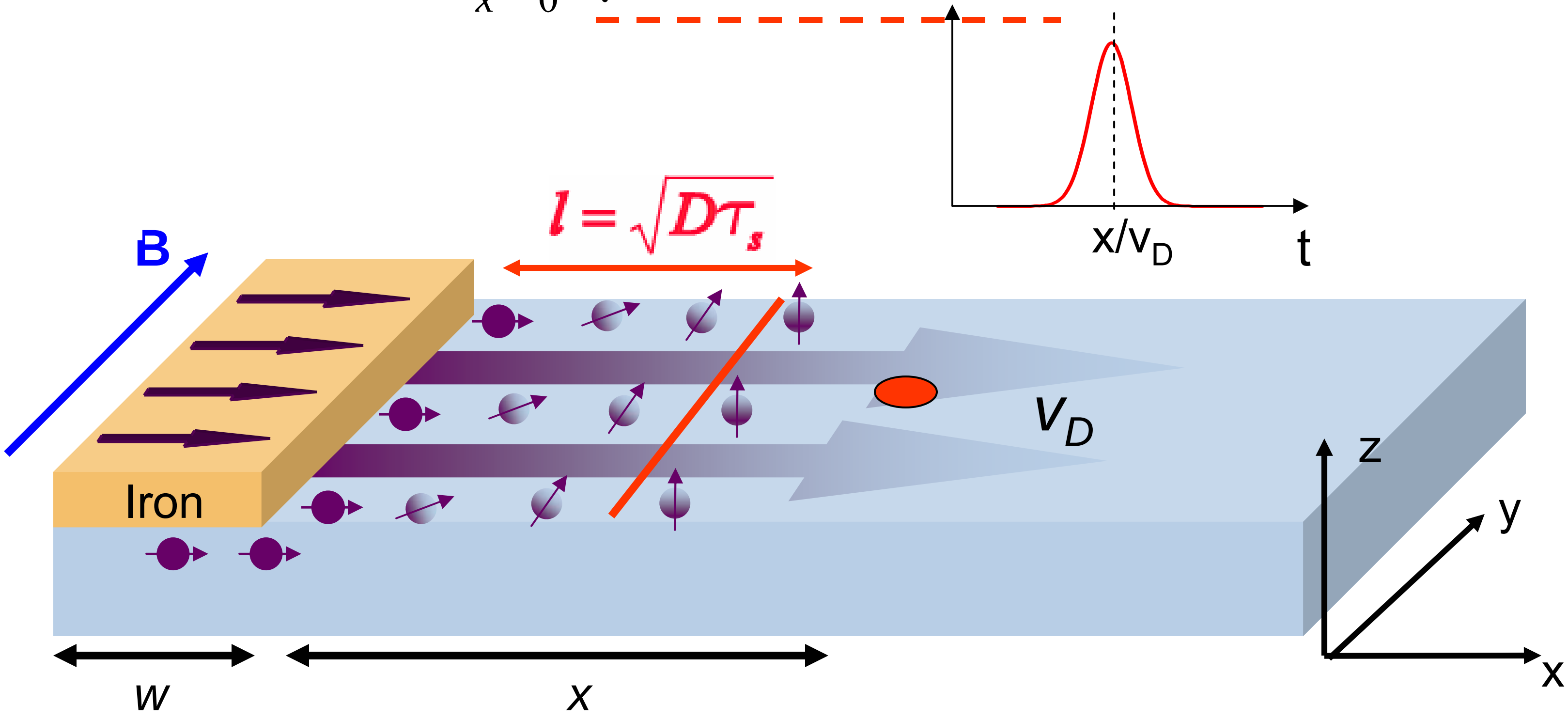
# Vary distance of probe beam from the source contact



- There are four parameters ($\tau_s$ = 125 ns, $D$ = 10 cm$^2$/s, $v_D$ = 2.8 × 10$^4$ cm/s, and an amplitude $S_0$), which are the same for all curves.
- Near-field regime (dominated by diffusion, which sets width of Hanle "envelope")
- Drift regime: $l > \sqrt{D\tau_s}$ ; precession during time-of-flight (oscillations)

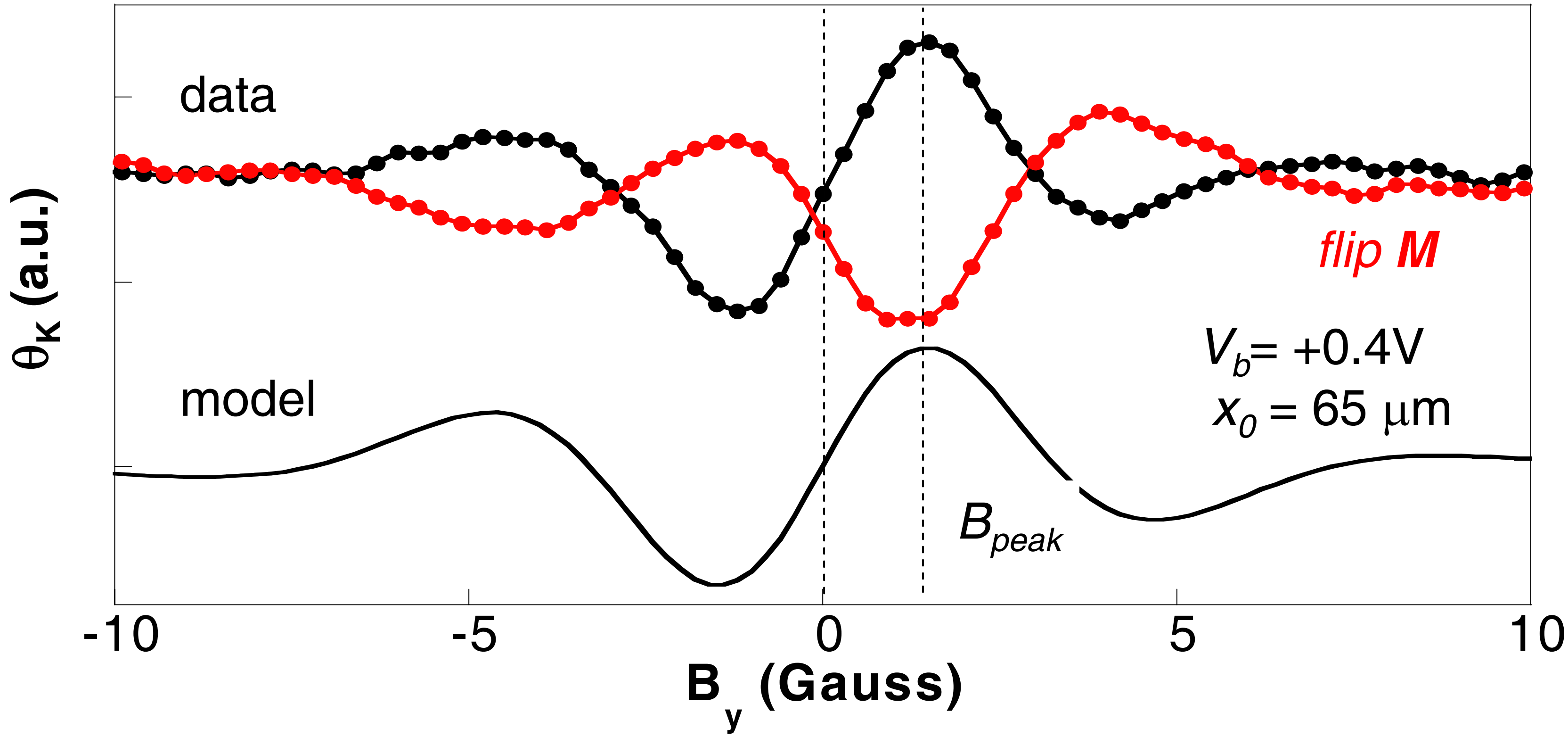
# Far field: precession during time-of-flight

$$S_z(x) = k \int_{x}^{x+w} \int_{0}^{\infty} \frac{S_{x0}}{\sqrt{4\pi D t}} e^{-\frac{(x'-v_d t)^2}{4Dt}-\frac{t}{\tau_s}} \sin(\Omega t)\,dt\,dx'$$



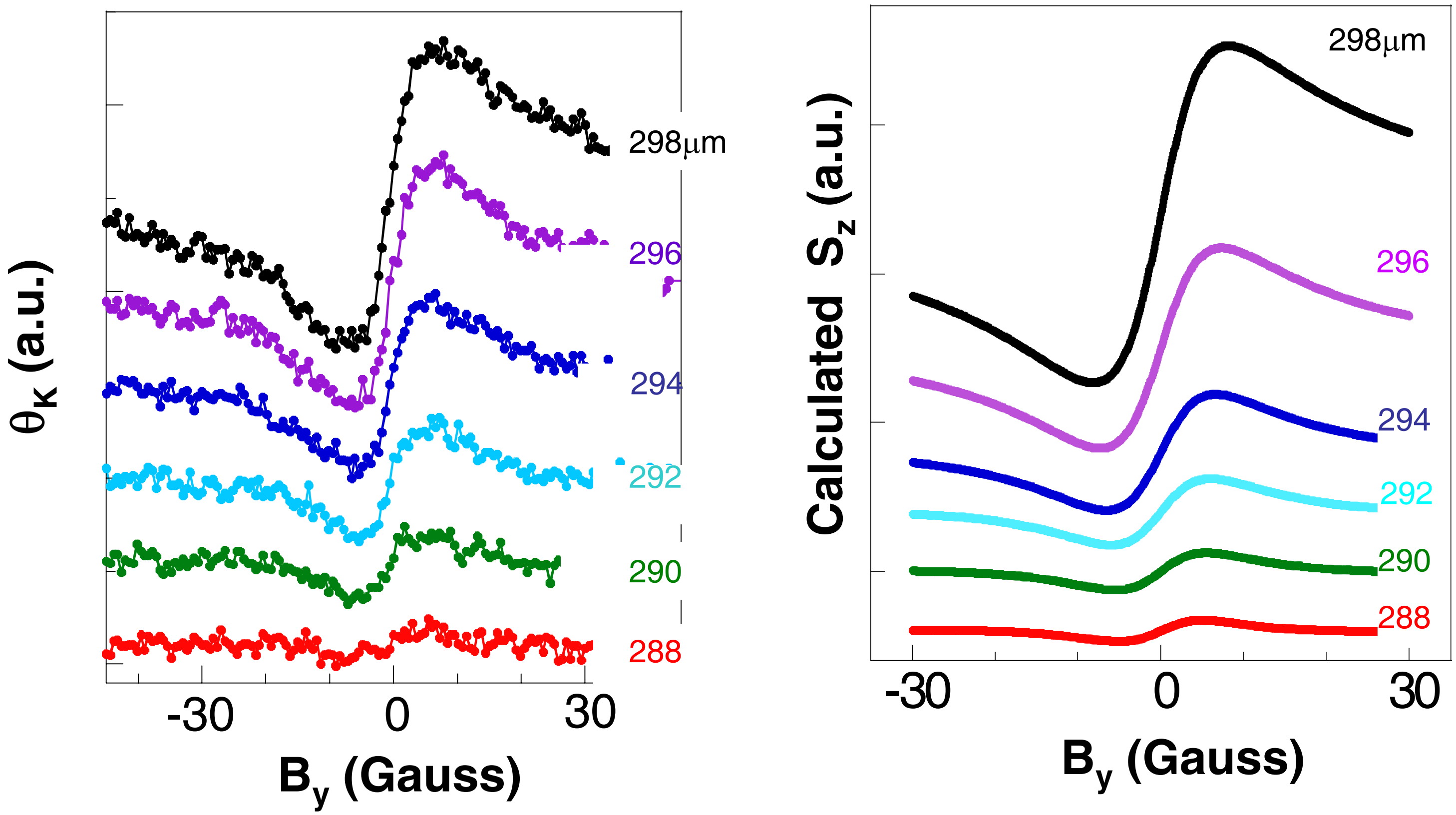
# Far field:  precession during time-of-flight

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



At $x_0$ = 65 μm, $B_{peak}$ = 1.35 Gauss, T = $\pi/2\Omega_L$ ~ 300 ns, or $v_d$ ~ $2.8\times10^4$ cm/s

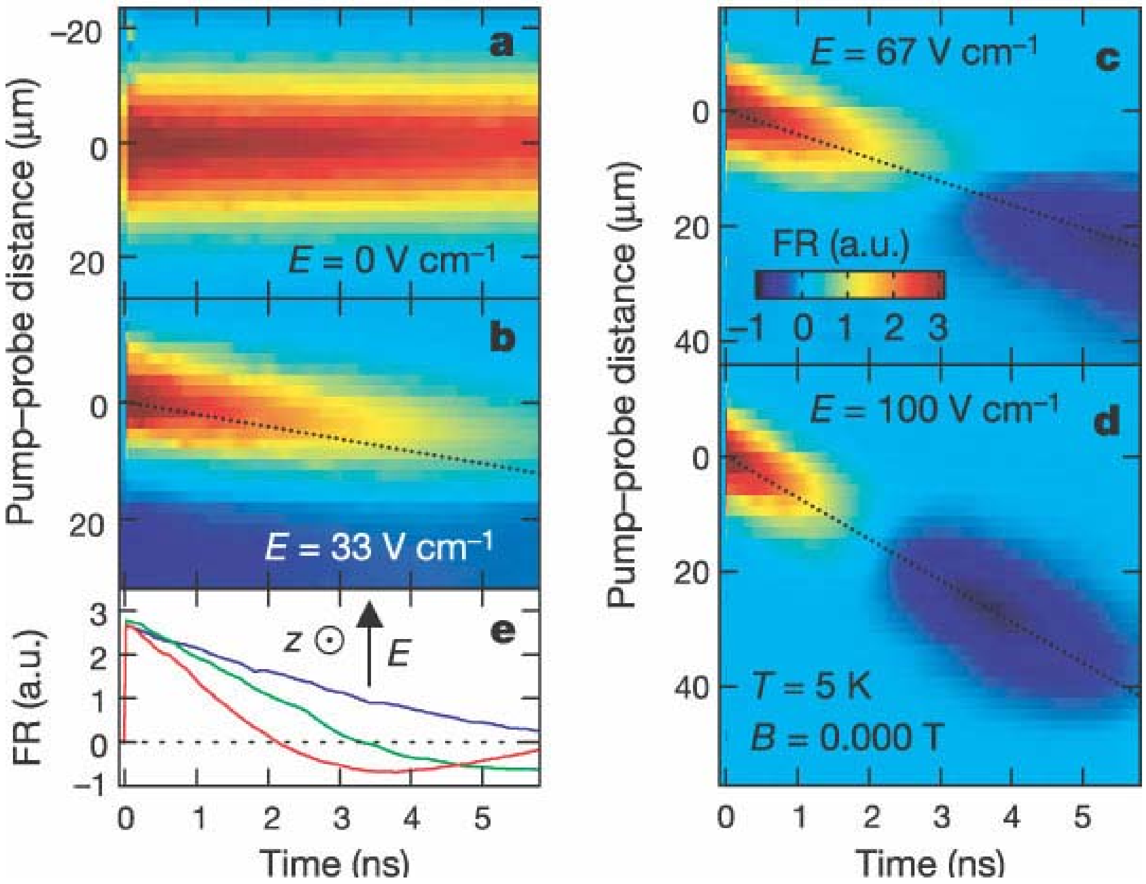
# Vary distance of probe beam from the *drain* contact

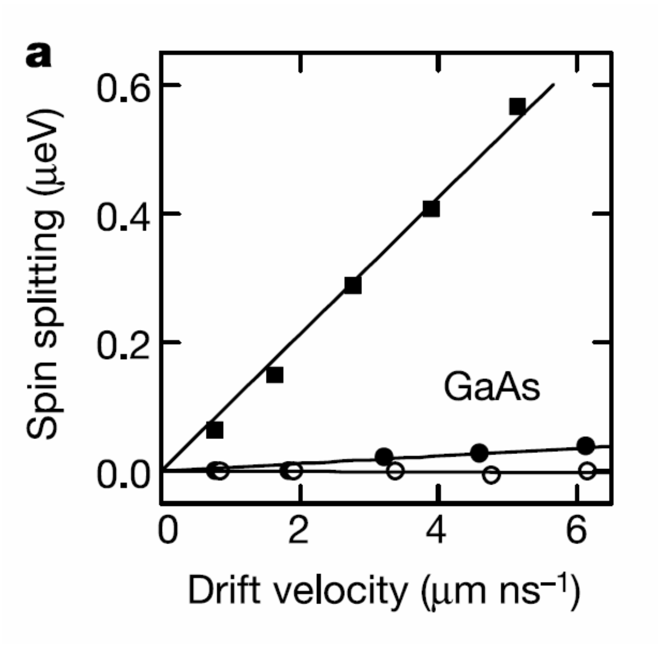


- Near the drain: diffusion is “fighting” drift → rapid attenuation with distance
- One needs a relatively transmissive barrier (so that electric fields are small) in order to see the spin accumulation in the channel region
- Can we say any more about this?

# Observation of precession due to strain:

Y. Kato *et al.*, Nature **47**, 50 (2004)



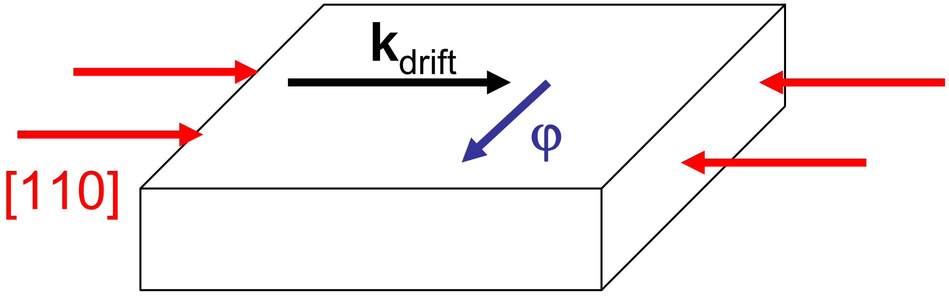


$$E = -g\mu_B \frac{\hbar}{2}\vec{\sigma}\cdot\vec{B} + \frac{\hbar}{2}\widetilde{C}\vec{\sigma}\cdot\vec{\varphi}(k)$$

- Effective magnetic field depends on magnitude and *direction* of **k.**

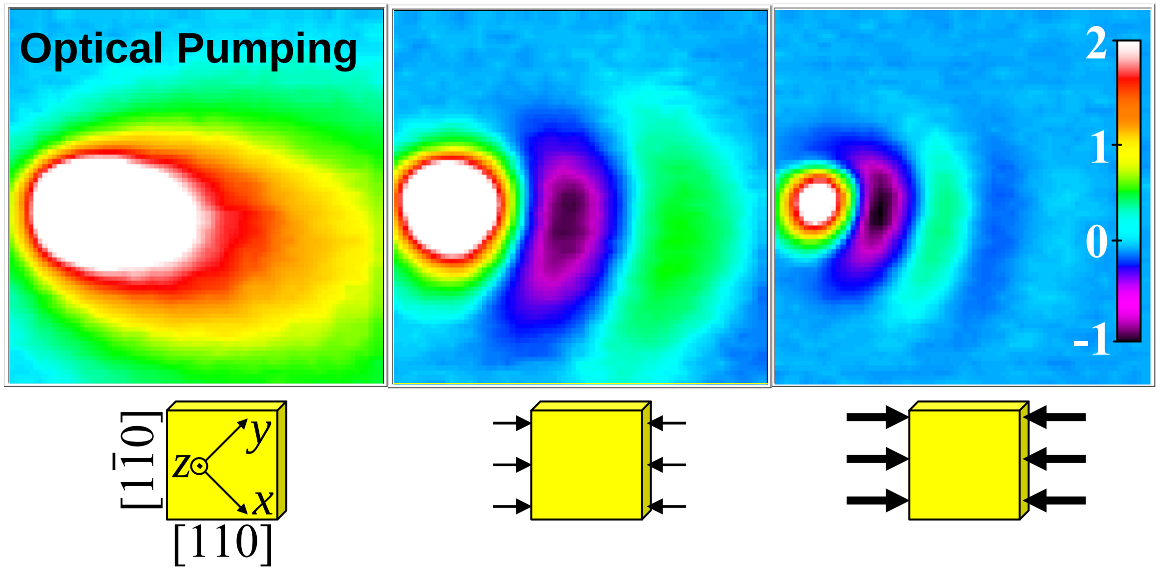
# Put the sample in a vise....

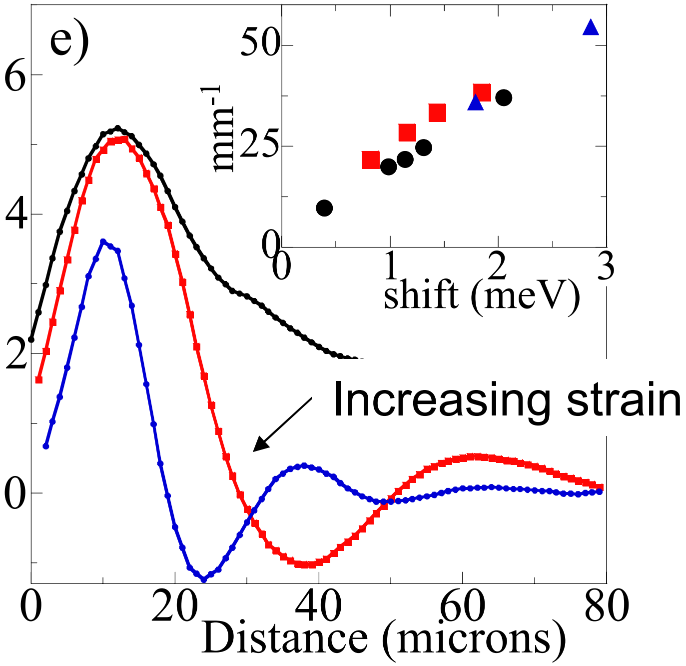
S. A. Crooker and D. L. Smith
Phys. Rev. Lett. **94**, 236601 (2005)



Stress along <110> directions: Strain tensor has only two (identical) off-diagonal elements. Effective field φ is always *orthogonal* to **k.**

$$\vec{\varphi} = \varepsilon_{\alpha\beta}(k_y, -k_x)$$

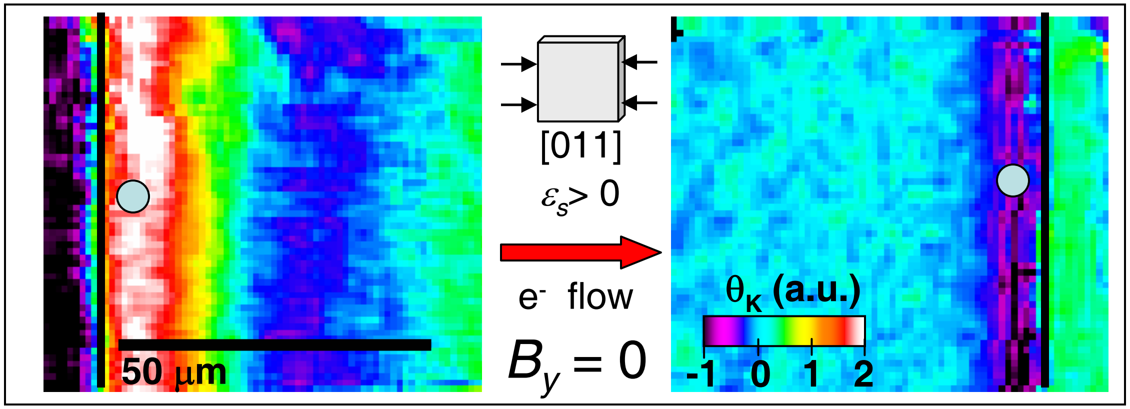




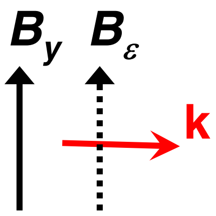
$B_{applied} = 0$; $v_d \sim 3 \times 10^4$ cm/sec

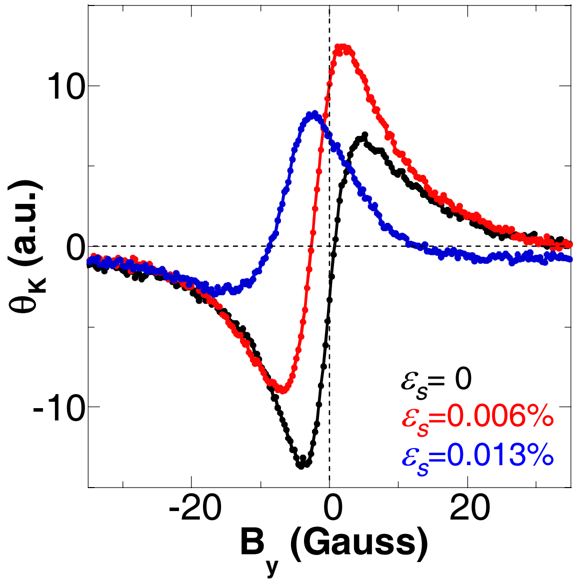
# A means to measure momentum of the spin-polarized electrons:

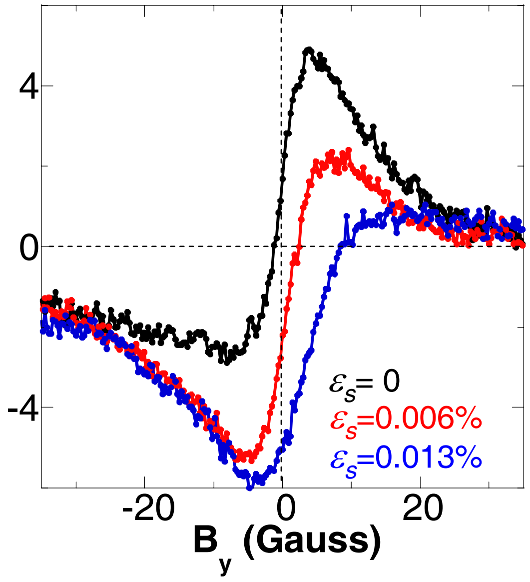
Source

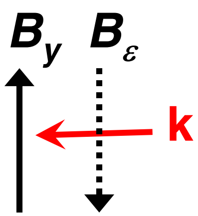


Drain





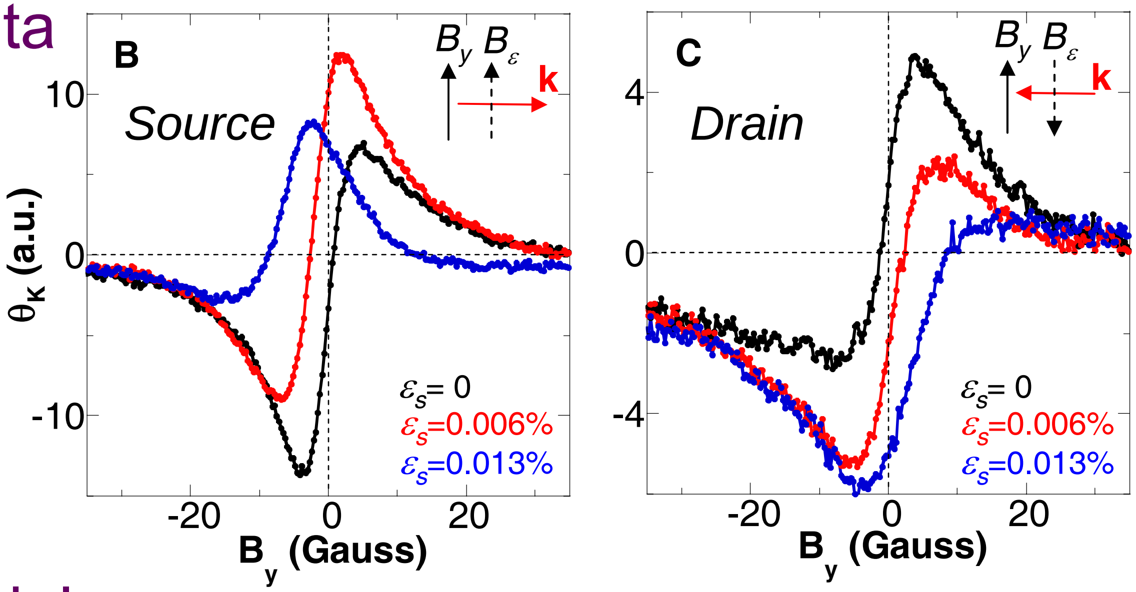




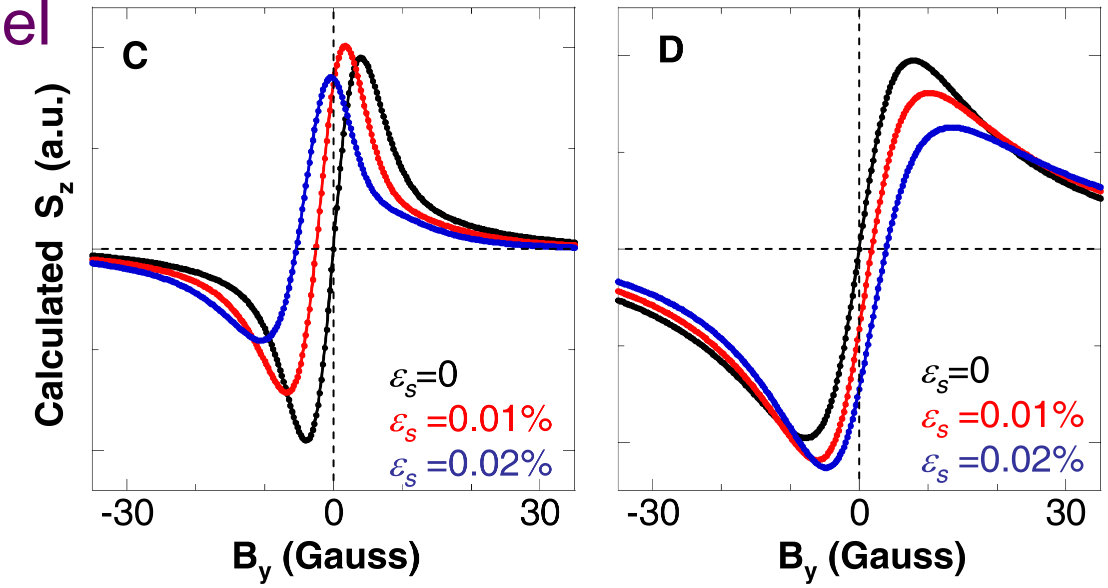
- At opposite ends of the channel, the Hanle curves shift in ***opposite*** directions with increasing strain. *The (diffusive) spin current at the drain is flowing against the charge current*. See also M. Hruska *et al.*, Phys. Rev. B **73,** 075306 (2006).

# Strain effects in the drift-diffusion model

Data



Model



Why the bizarre shape?

Diffusion in 1D leads to inhomogeneous broadening for “real fields,” but not for the k-dependent “effective fields.”

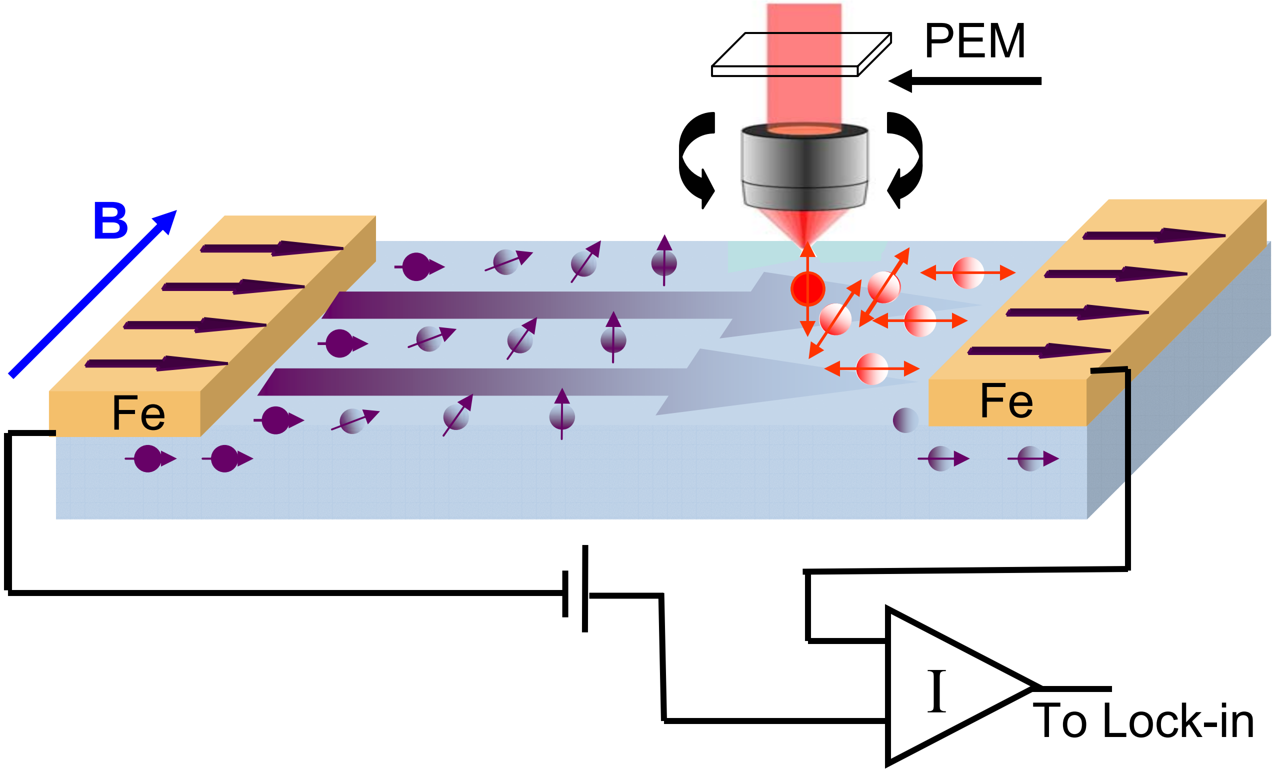
# What is going on at the drain?

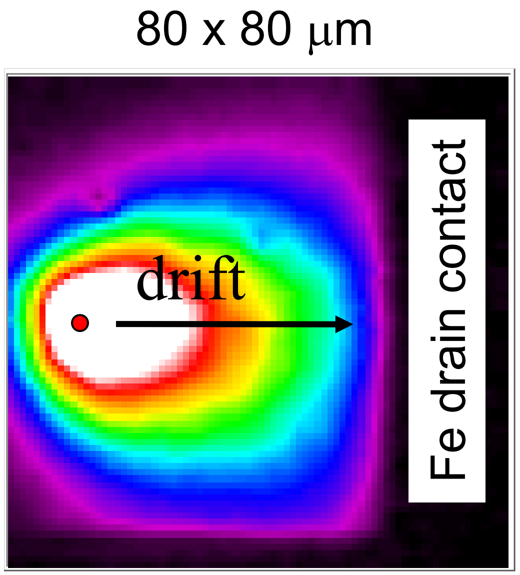
1. The spin accumulation is due to reflection from the ferromagnetic drain contact, as observed in MnAs/GaAs by Stephens *et al.*
2. The devices under study here have more transparent tunnel barriers. It is much easier for electrons to diffuse “backwards” against the drift current, which is why spin polarization can be observed in the channel.
3. This is (apparently) not filtering by the tunnel barrier, at least in the sense predicted by the *average* density of states, which gives the wrong sign. Energy-selective or *k*-selective spin filtering may be a possibility. See arguments of Ciuti, McGuire, and Sham.
4. The mechanism is relatively efficient. The spin polarization at the drain is of the same order of magnitude as at the source.

# Electrical spin detection[*]

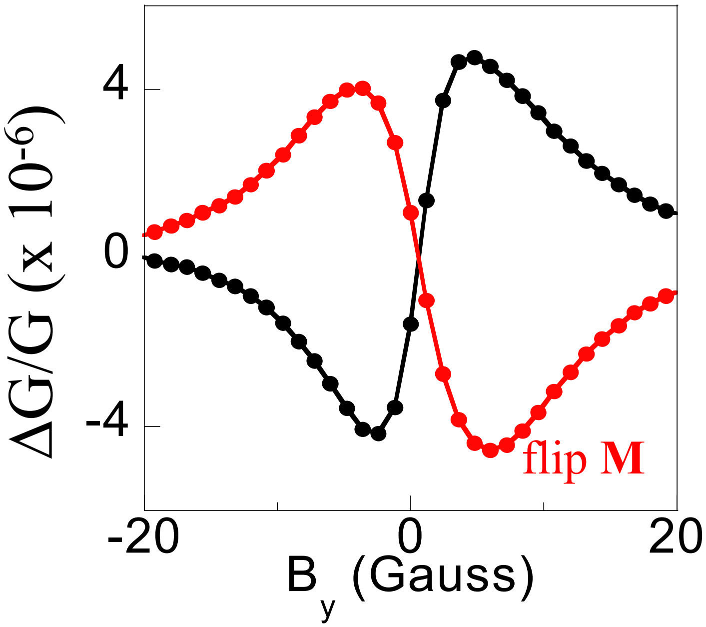
- The above data imply that the conductance of the minority spin channel at the drain should be *higher* than the conductance of the majority channel.
- Can we verify this explicitly?

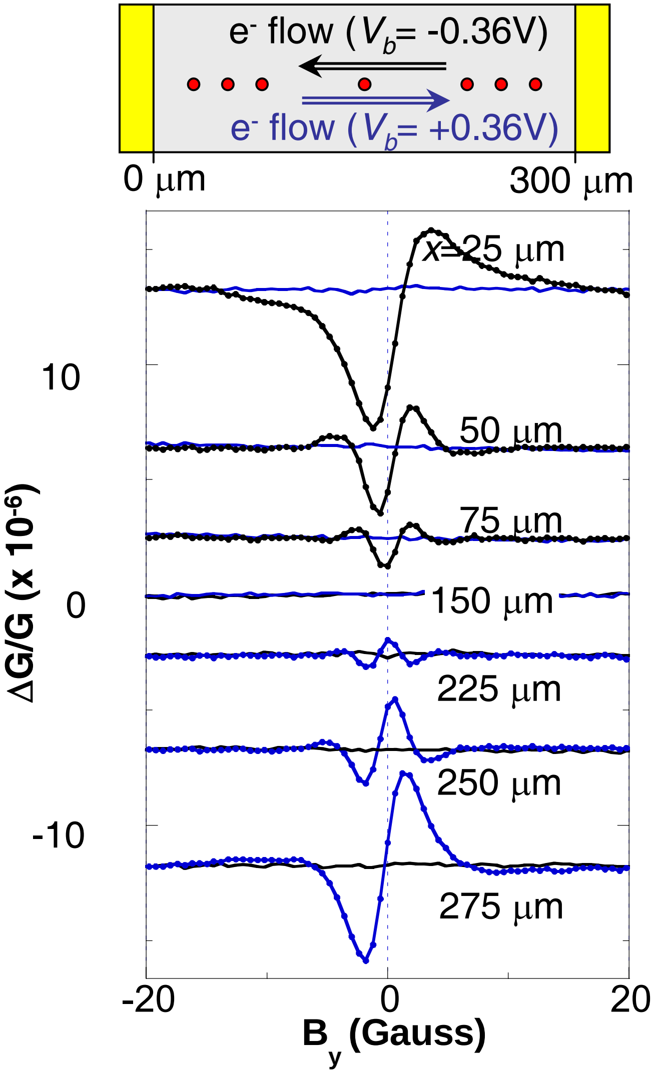
Inject spins of a known sign *optically* and measure the conductance:





# Schottky tunnel barriers can serve as electrical spin detectors:





- Hanle effect observed; inverts when magnetization is reversed
- Signal only for flow into drain contact

- Conductance is higher for the minority channel, consistent with the sign of the spin accumulation.

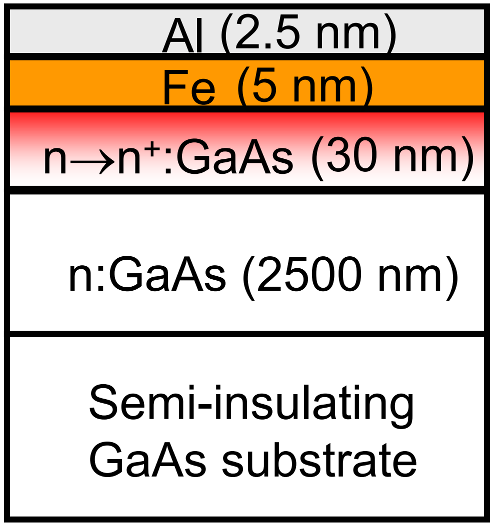
# Summary

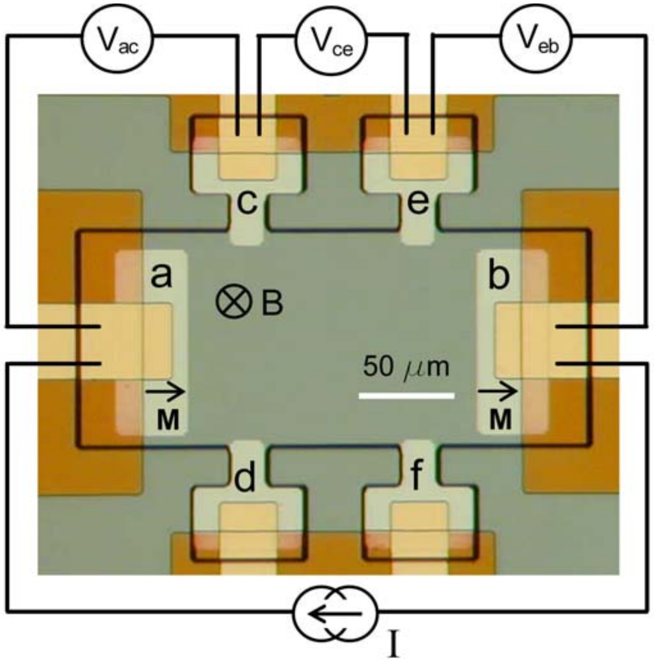
1. It is possible to study separately each "element" of a spin transport device: source, channel, and drain.
2. A definitive demonstration of a ferromagnetic-semiconductor device that functions as both a source and detector of spin-polarized electrons (passes the "Hanle test").
3. This has given us a very good idea of what to look for in a "real" transport experiment, without the assistance of photons. We know that there is spin accumulation at the drain, even in the absence of a spin-polarized source.
4. We know what to look for in the magnetic field dependence (also temperature dependence and doping dependence, which I have not discussed here).

S. A. Crooker *et al.*, Science **309**, 2191 (2005).

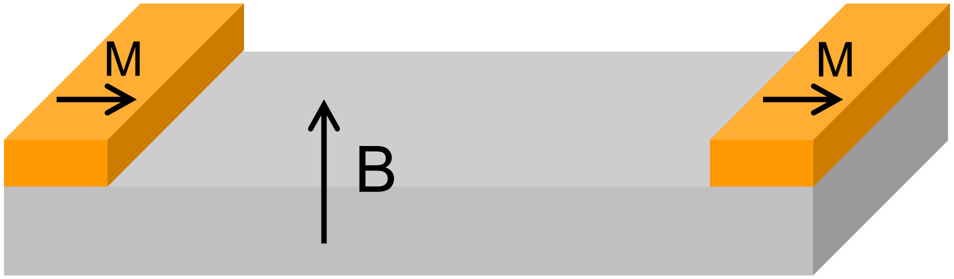
# Transport

Sample grown using MBE





- GaAs channel: 150x100 μm
- Fe contact: 40x100 μm



- Samples studied: $2 \times 10^{16}/\text{cm}^3 \leqslant n \leqslant 3 \times 10^{17}/\text{cm}^3$
- Al control sample: replace Fe with Al

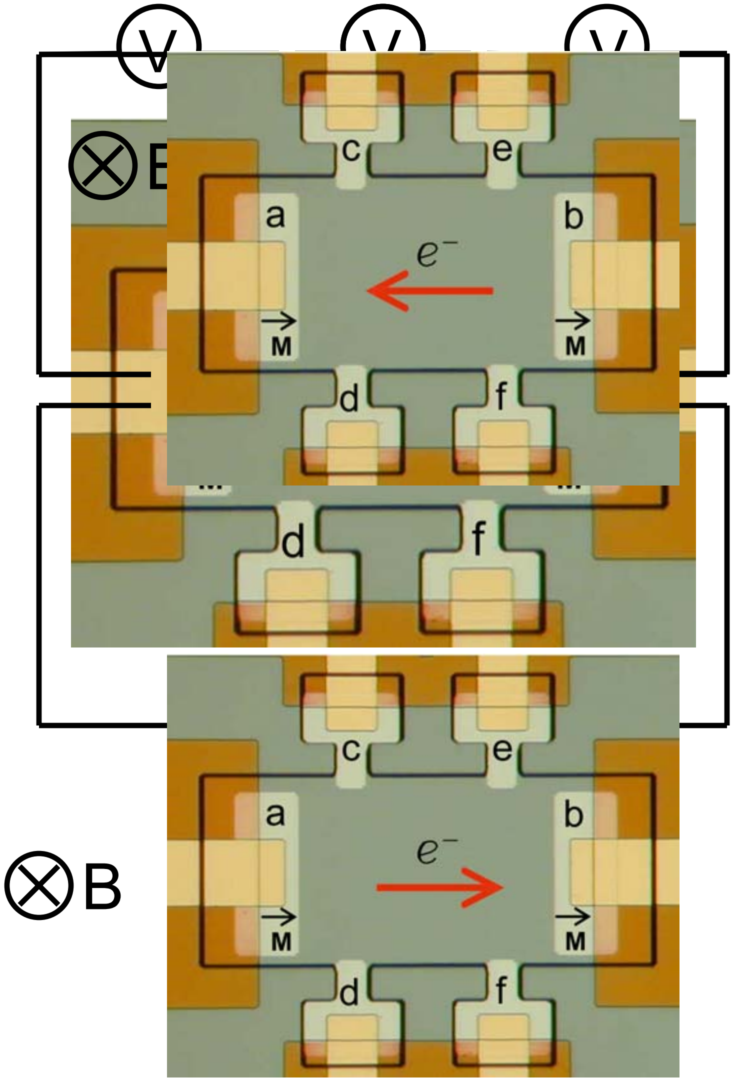
- Applied magnetic field is small, ~100 Oe
  - ➢ Fe magnetization is fixed.
- Channel length >> spin drift and diffusion length

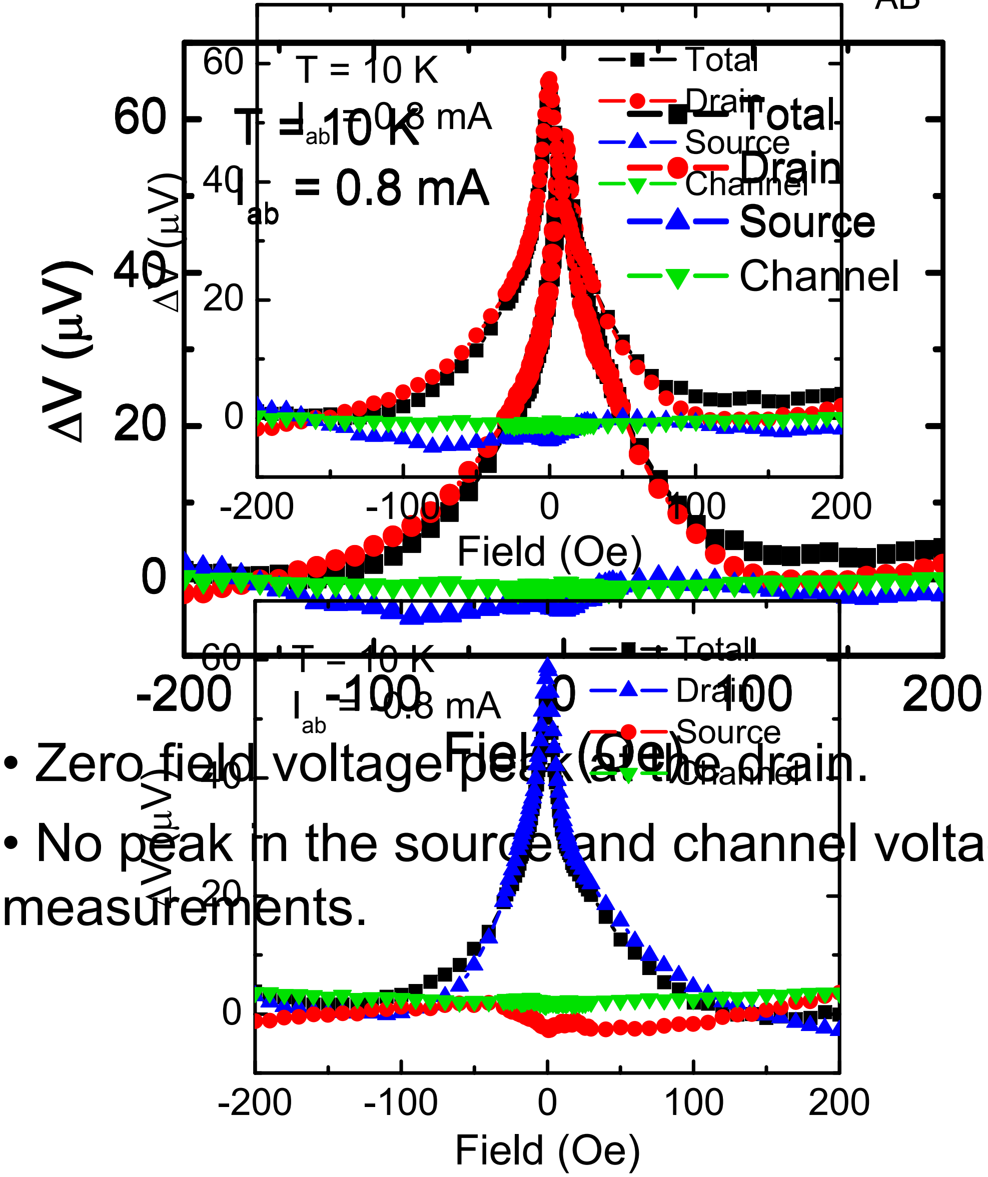
**Graded doping structure:**
A. T. Hanbicki *et al*., Appl. Phys. Lett. **82**, 4092 (2003).

n = $3.6 \times 10^{16}/cm^3$

# Source/Drain Asymmetry

$V_{AB} \approx 0.5$ V

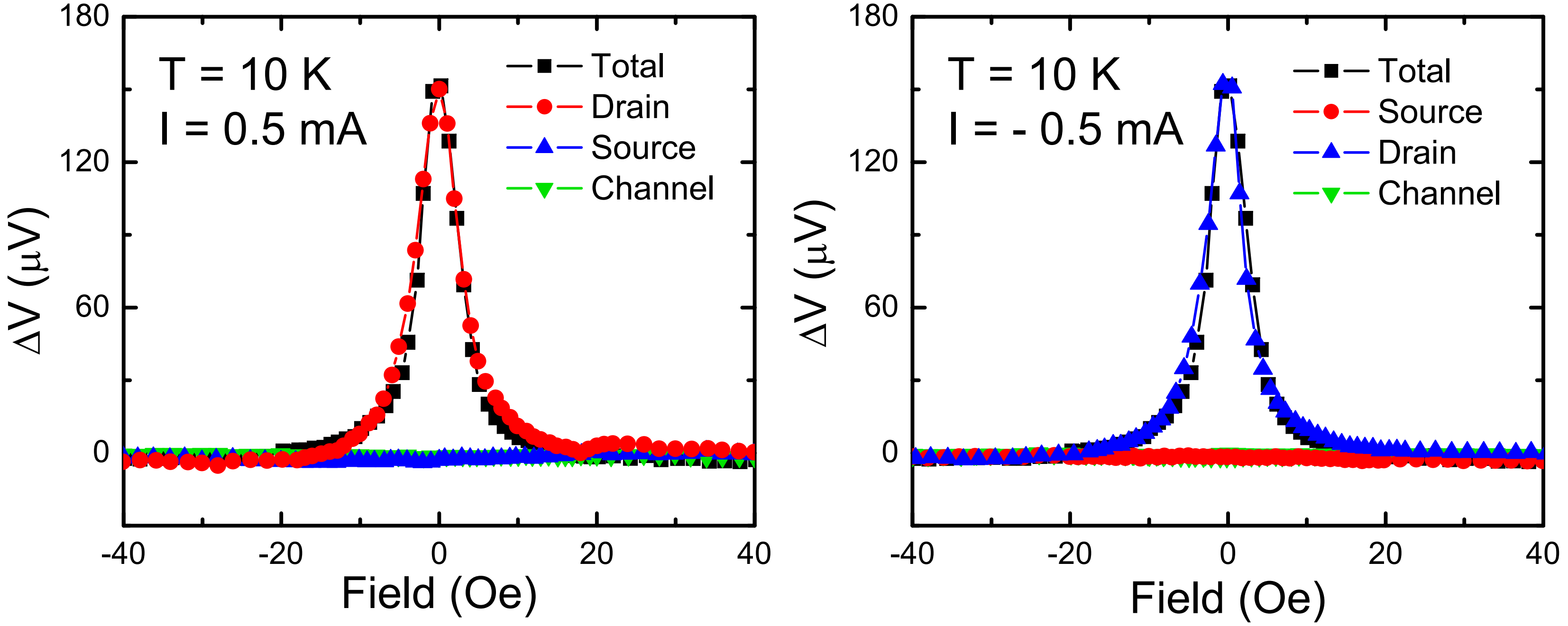




- Zero field voltage peak at the drain.
- No peak in the source and channel voltage measurements.

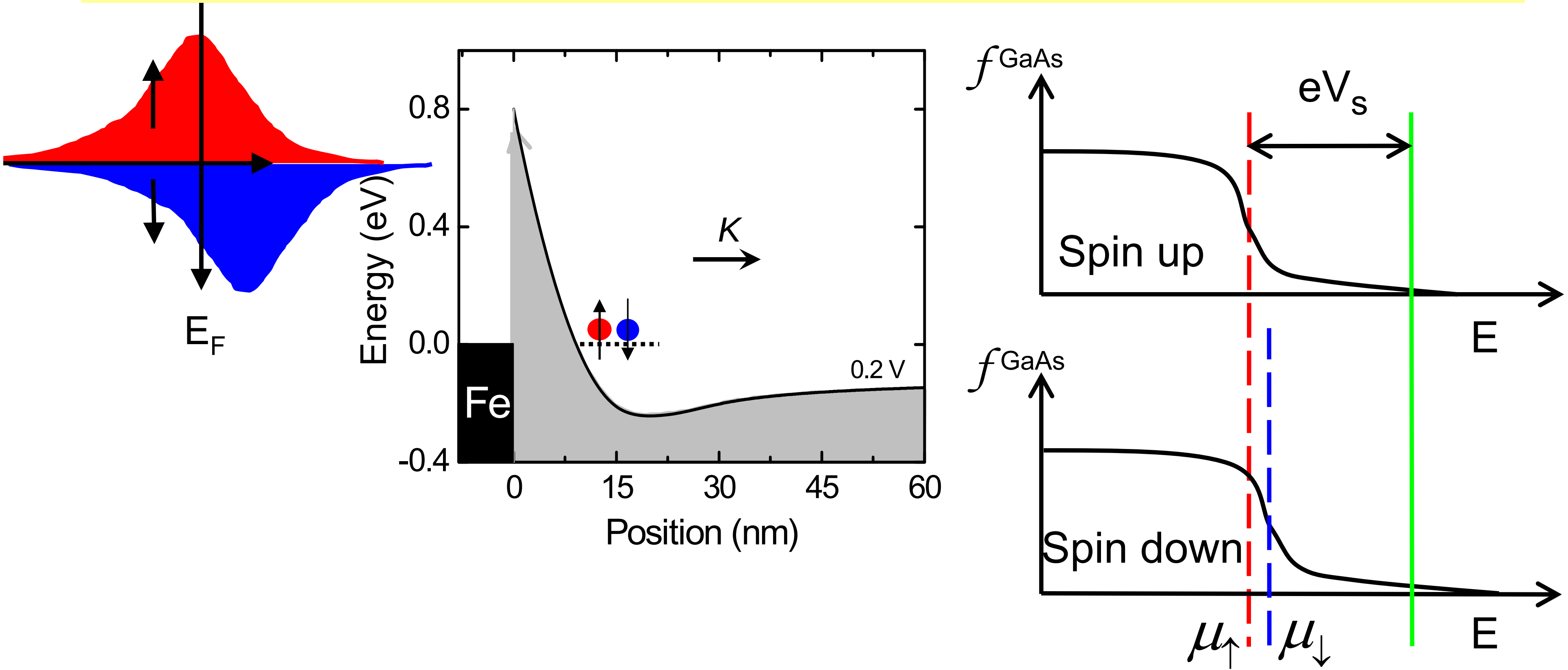
# Source/Drain Asymmetry

n = 2 **x** $10^{16}/cm^3$



- Voltage peak and source/drain asymmetry observed on samples: $2 \times 10^{16}/cm^3 \leqslant n \leqslant 1.5 \times 10^{17}/cm^3$
- This appears to be a generic feature of this barrier profile
- No peak observed on the Al control sample
- Contact magnetization has remained fixed

# Source voltage: insensitive to polarization in GaAs



Tunnelling at the source:

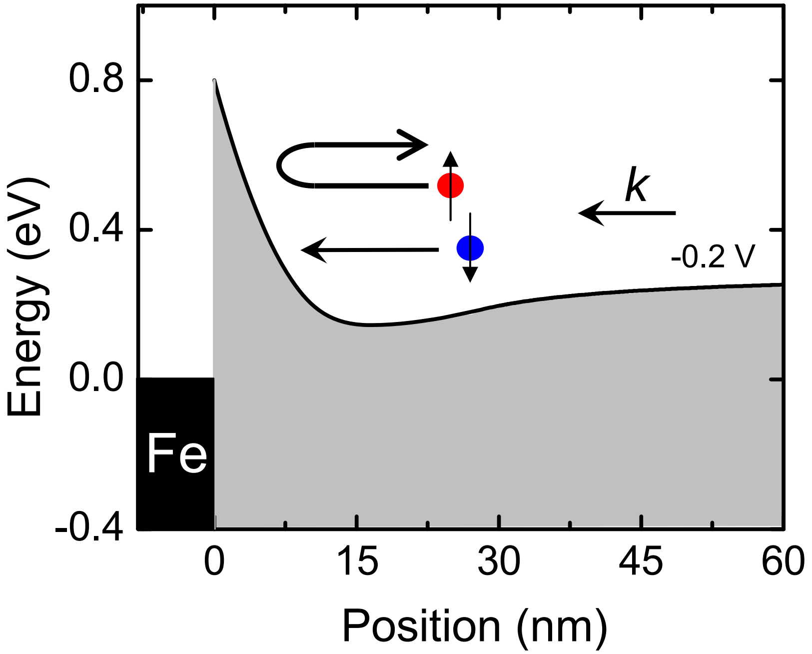
$$j_{\uparrow,\downarrow} \propto \underline{f(E)\, g^{\mathrm{Fe}}_{\uparrow,\downarrow}(E)}\, T_{\uparrow,\downarrow}(E, eV_s)\, \underline{[1 - f(E + eV_s, \mu_{\uparrow,\downarrow})]}$$

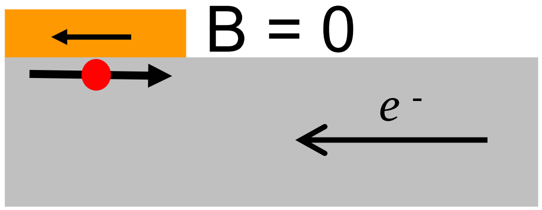
occupied states in Fe

Tunnelling matrix element

unoccupied states in GaAs

# Drain voltage is polarization-dependent





Tunneling at the drain:

$$j_{\uparrow,\downarrow} \propto \underbrace{f(E - eV_d - \mu_{\uparrow,\downarrow})\, g^{\mathrm{GaAs}}(E - eV_d)}_{\text{occupied states in GaAs}}\, \underset{\downarrow \atop \text{Matrix element}}{T_{\uparrow,\downarrow}(E,V_d)}\, \underbrace{[1 - f(E)]}_{\text{unoccupied states}}$$

**Spin accumulation: experiment and theory**

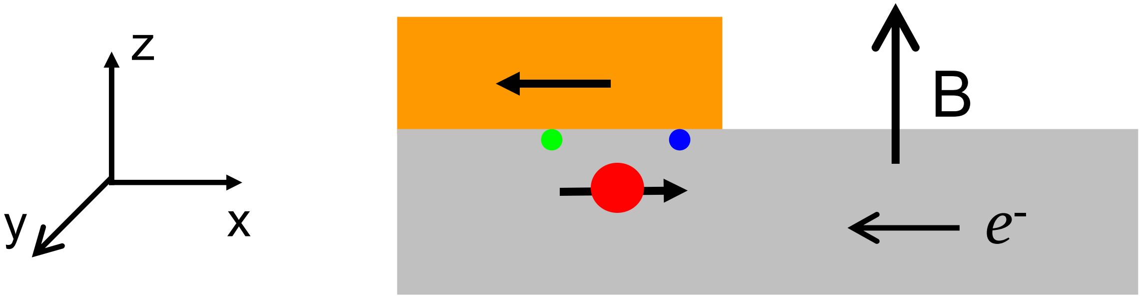
[1] R. K. Kawakami, *et al*., Science **294**, 131 (2001)

[2] C. Ciuti, *et al*., Phys. Rev. Lett. **89**, 156601 (2002).

[3] J. Stephens *et al*., Phys. Rev. Lett. **93**, 097602 (2004).

[4] S. Crooker *et al*., Science **309**, 2191 (2005)

# Modeling: spin drift-diffusion model



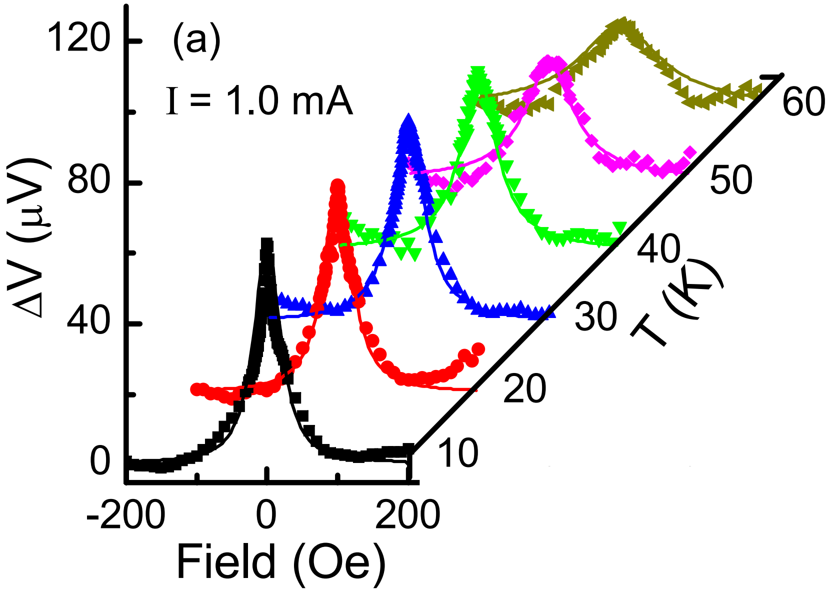
$$S_x(B) = \int_0^{L_{eff}} dx_1 \int_0^{L_{eff}} dx_2 \int_0^{\infty} dt \frac{S_0}{\sqrt{4\pi Dt}} e^{-\frac{(x_2 - x_1 + \upsilon_d t)^2}{4Dt} - \frac{t}{\tau_s}} \cos(\frac{g\mu_B B}{\hbar} t)$$

- Time scales that play a role: $\tau_s$, $L_{eff}/v_d$, $L_{eff}^2/D$ , $4D/v_d^2$

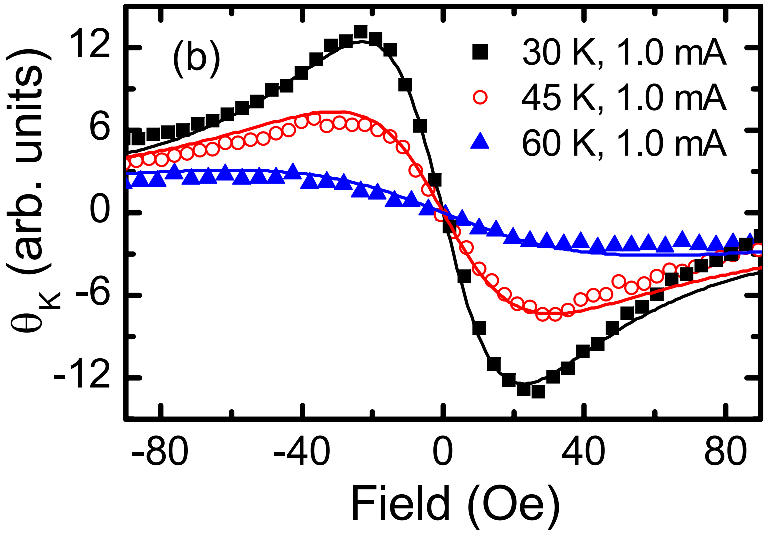
Modeling parameters:

| | |
|---|---|
| $D$ = spin diffusion constant: | determined from transport |
| $v_d$ = spin drift velocity: | determined from transport |
| $\tau_s$ = spin relaxation time: | determined from optical Hanle effect |
| $L_{eff} = 15$ μm < $L_{Fe} = 40$ μm: | fixed parameter |
| $S_0$ = spin generation rate: | unknown, free parameter |

# Detection of Spin Accumulation at the Drain

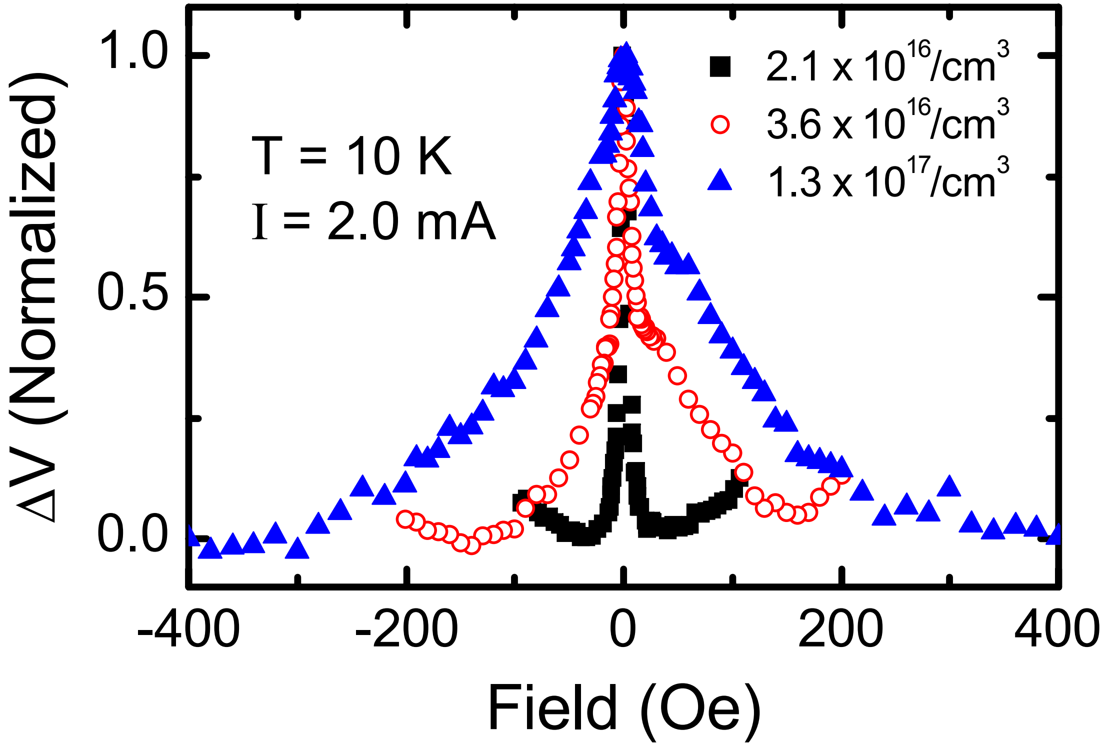


Electrical detection; curves are fits with the drift-diffusion model



Optical detection of spin injection from the source, modeled with the same parameters (except for the amplitude)

# Doping Dependence



- Increase of half-width with doping is expected (decrease of spin lifetime)
- Sharp peak at zero field due to hyperfine effects
  - Observed at high bias at intermediate dopings
  - All biases at low (~ 2 x $10^{16}$ $cm^{-3}$) dopings (?)

# Summary (Part II)

- The spin accumulation at the drain can be detected in a Hanle-style experiment.
- Consistency with optical measurements strongly supports the interpretation of the transport measurements.
- The signal is not sensitive to the sign of the polarization.
- The obvious next step is a non-local measurement (in progress – with some success)
- The source-drain measurement is more problematic. In this respect, the effect demonstrated here is a nuisance, and a non-local measurement appears to be essential.

X. Lou *et al.*, Phys. Rev. Lett. **96** 176603 (2006)