Spin Transport in Epitaxial Heusler Alloy/ III-V Semiconductor Heterostructures

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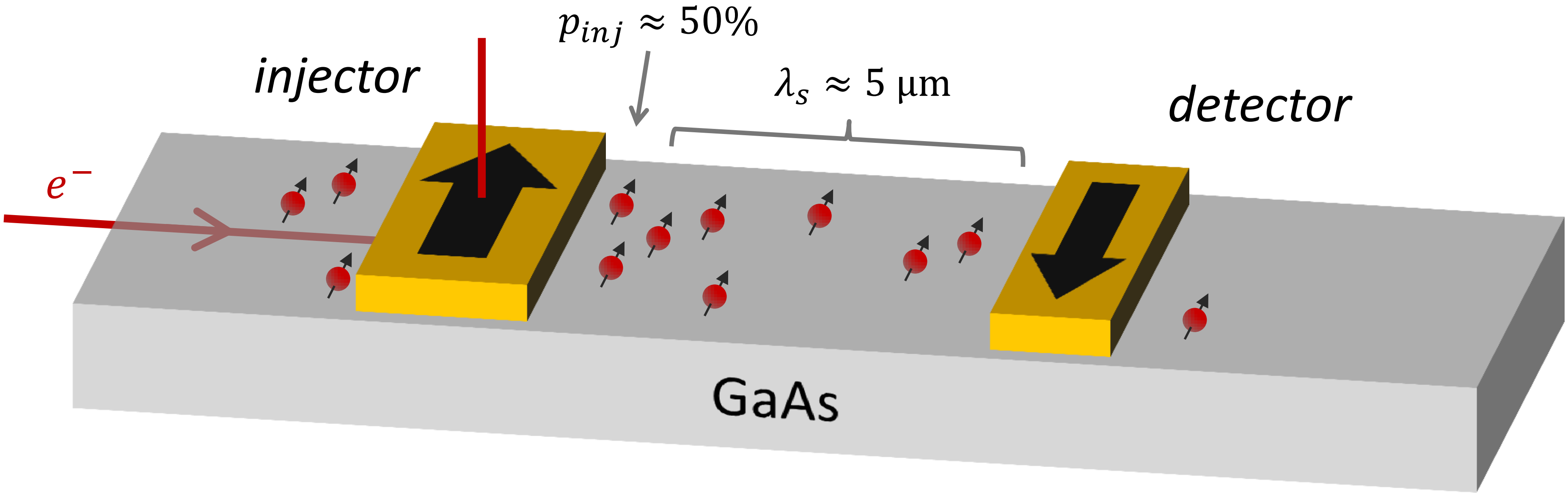
Outline

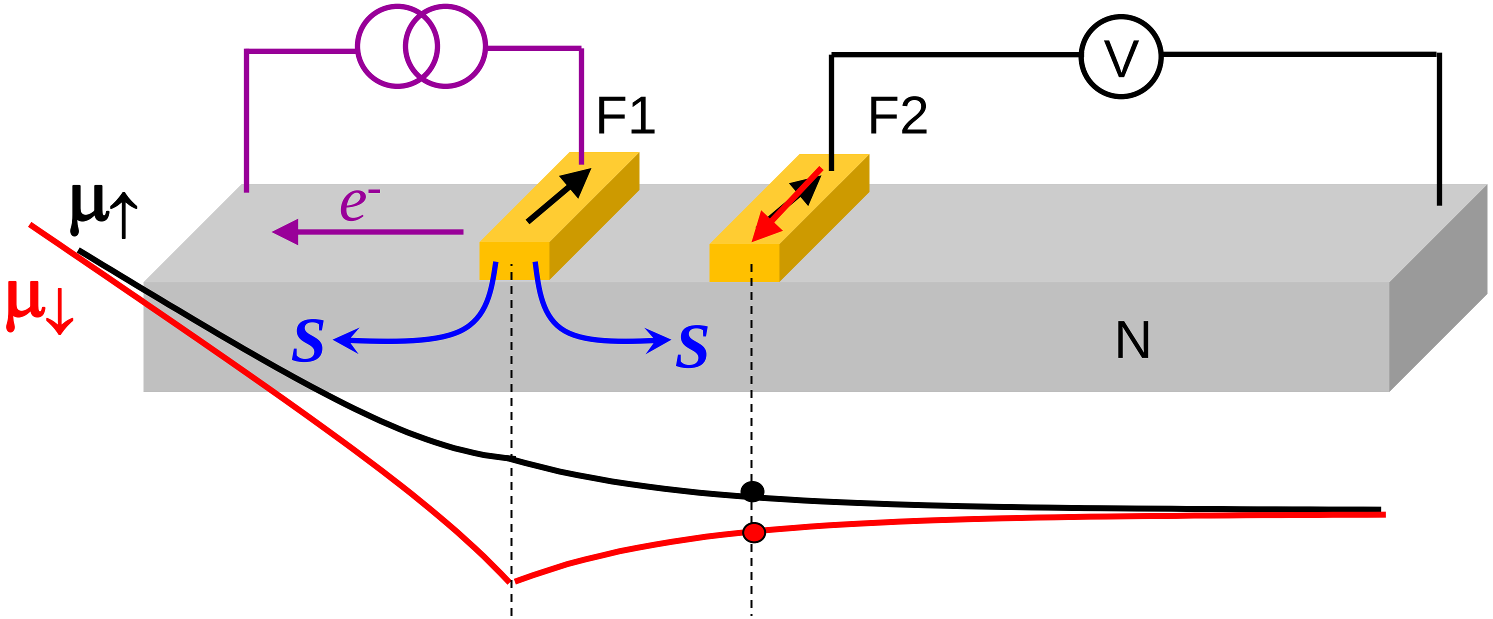
- **Why lateral spin valves**
- Why Heuslers: the $Co_2Fe_xMn_{1-x}Si$ family
- Progress in semiconductor lateral spin valves
- Improvements in high temperature performance
- Microwave detection of spin accumulation

Lateral spin valve

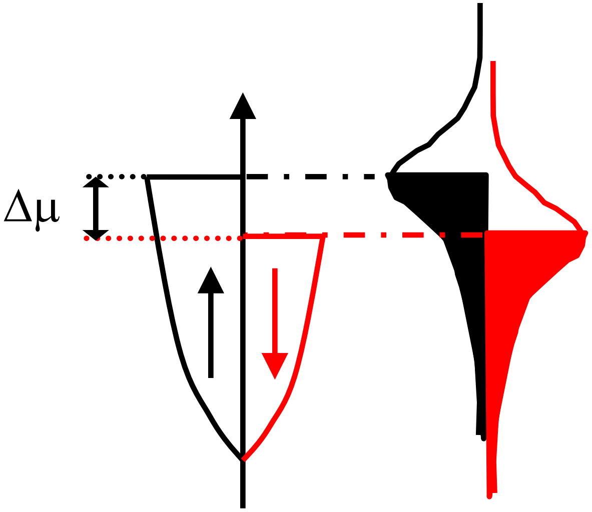
- Allows the study of spin-physics in wide array of materials systems
  - ferromagnetic contacts (Fe, Co, Py, Co_2MnSi, etc.)
  - metallic channels (Al, Cu, Ag, etc.); $p \ll 1\%$
  - semiconducting channels (GaAs, Si, Ge, graphene, etc.)
- Can quantify injection rates, detection efficiencies, spin-lifetimes, etc.



The non-local 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.
- F2 draws a spin current. This can perturb N (irrelevant in this system)



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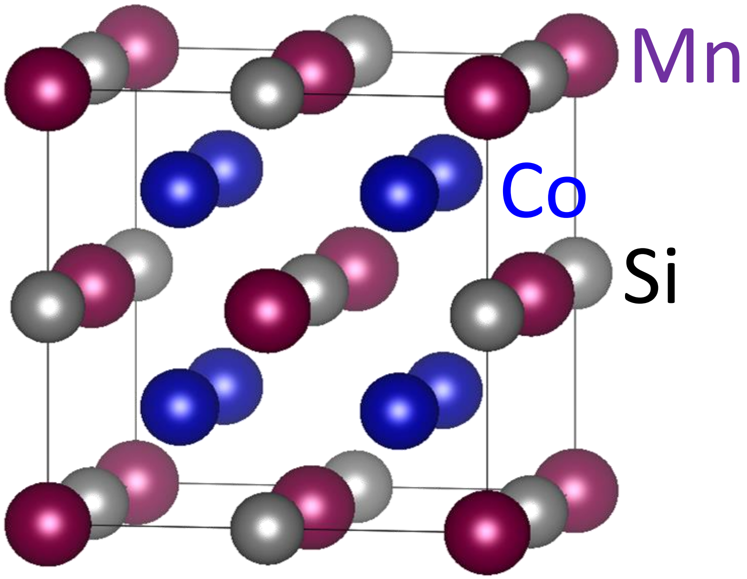
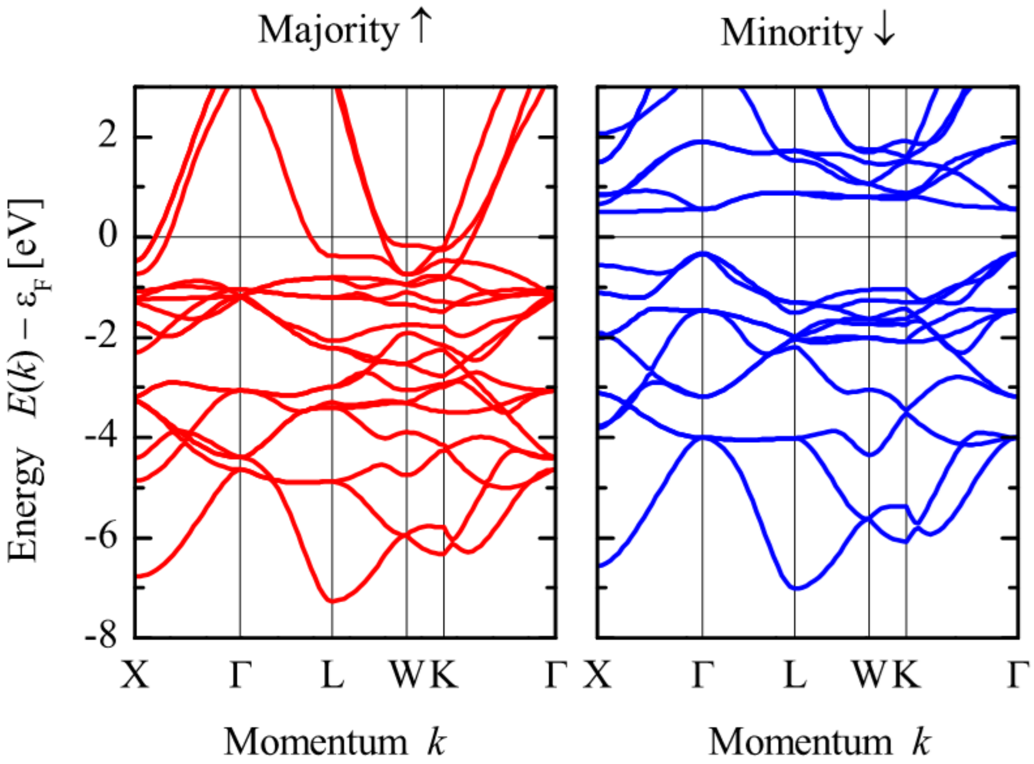
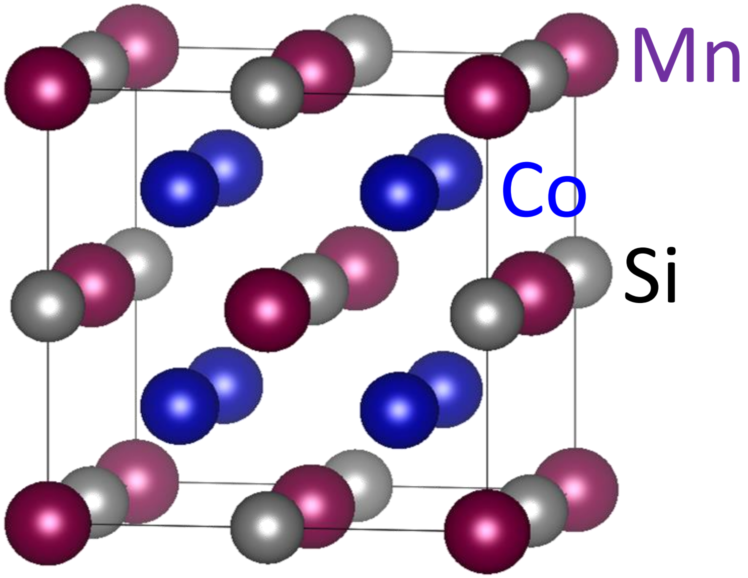
Co_2MnSi – a potential half-metal

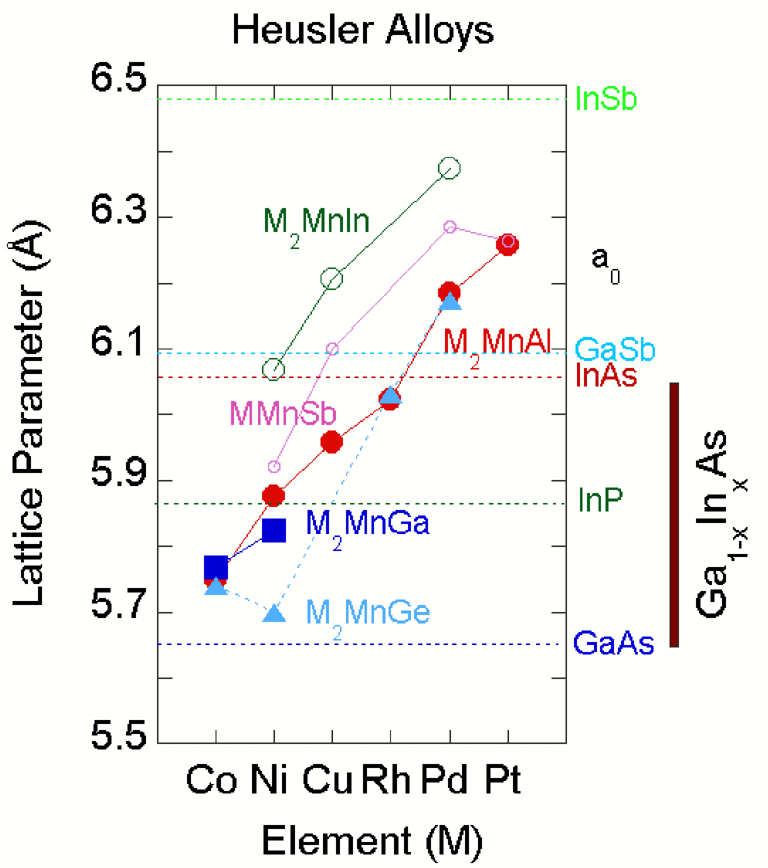




- Predicted to be a half-metal with a relatively large minority gap
- Lattice-matched to GaAs

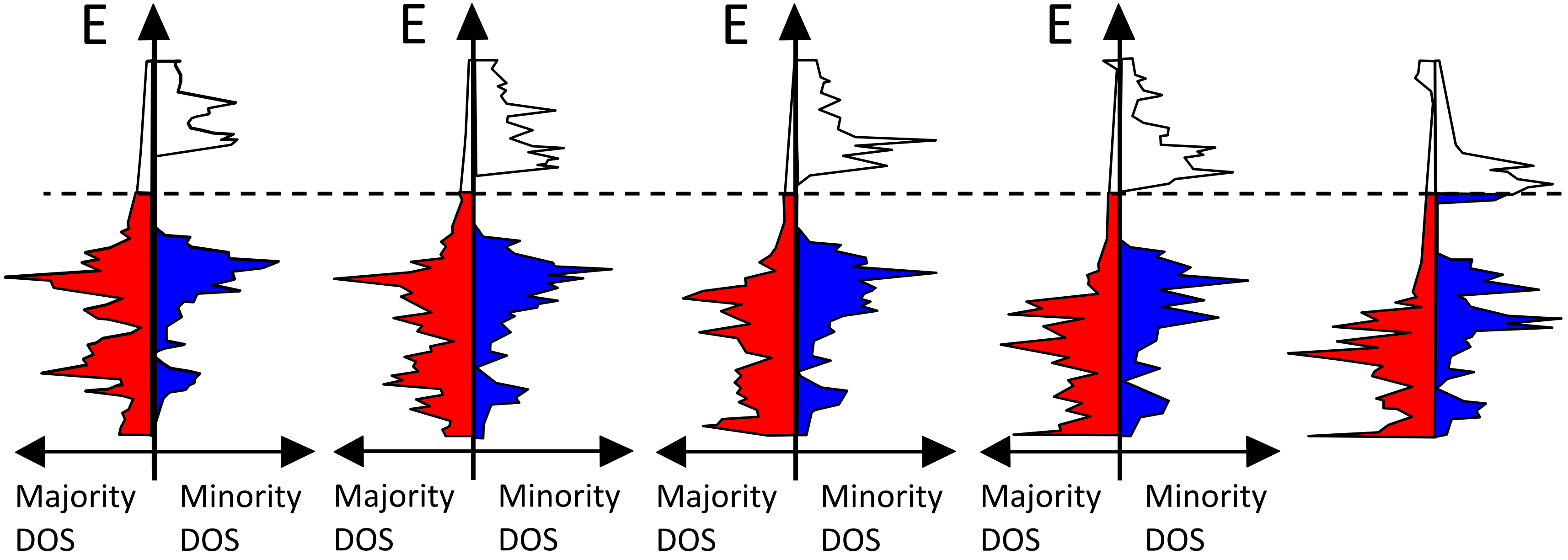
Co_2MnSi – a potential half-metal





- Predicted to be a half-metal with a relatively large minority gap
- Lattice-matched to GaAs
- Spin injection will work [see Dong *et al.*, Appl. Phys. Lett. **86**, 102107 (2006) for Co_2MnGe/GaAs]

General idea: Fermi level in a rigid band model



Co_2MnSi $Co_2Mn_{0.5}Fe_{0.5}Si$ Co_2FeSi

- Can we tune the Fermi level through the minority spin gap?

B. Balke *et al.*, Solid State Communications **150**, 529–532 (2010).

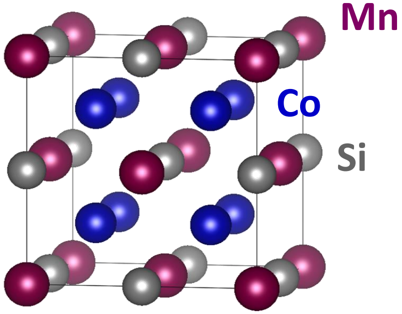
Heusler alloy: Co_2MnSi

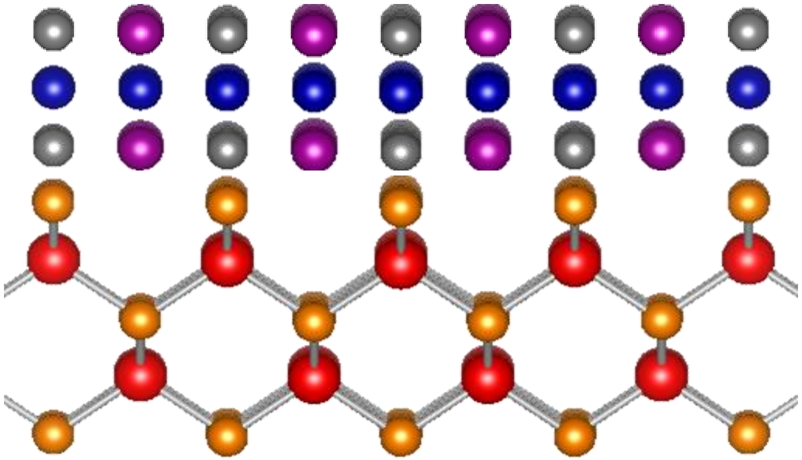
Co_2MnSi

$L2_1$ ordered

$T_c = 985\ \mathrm{K}$

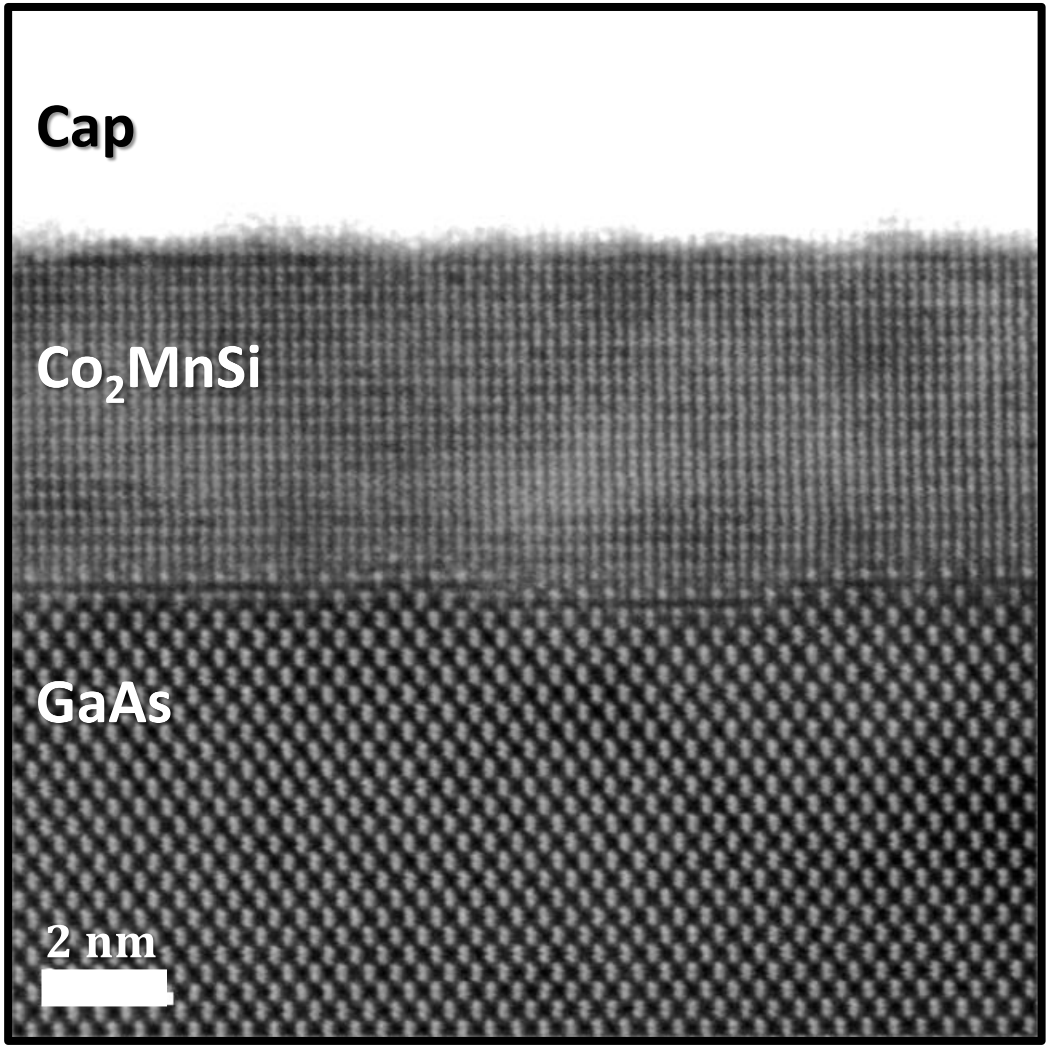
$M_{sat} = 4.97\mu_B$





Near perfect lattice match to GaAs

$a = 5.65\ \text{Å}$



(STEM courtesy of Paul Voyles, UW Madison)

Useful features of these alloys

- As indicated by work on MTJ’s, the tunneling polarization is high; Co_2MnSi is half-metallic or nearly so.

- As suggested by the cartoons on the previous viewgraphs, the density of states at the Fermi level is relatively small. This is a corollary to the fact that E_F changes so rapidly with composition.

- Grown on (100) GaAs, they have a very large in-plane uniaxial anisotropy. This turns out to be of practical utility.

- The LLG damping is particularly small for Co_2MnSi (~ 0.003 at high temperatures)

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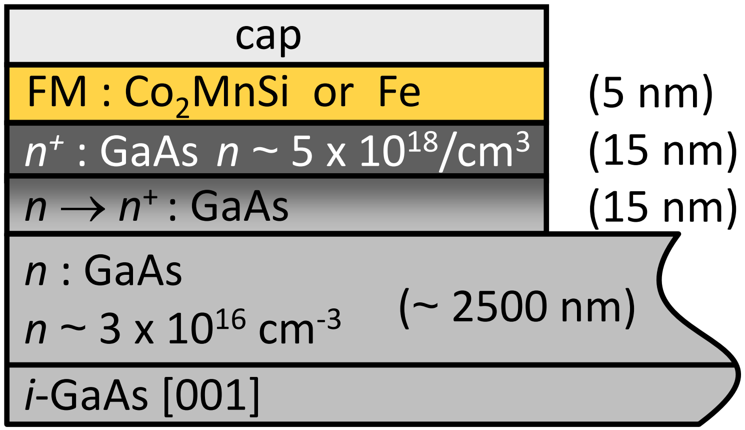
FM/*n*-GaAs Heterostructures



cap

FM : Co_2MnSi or Fe (5 nm)

n^+ : GaAs $n \sim 5 \times 10^{18}/cm^3$ (15 nm)

$n \rightarrow n^+$: GaAs (15 nm)

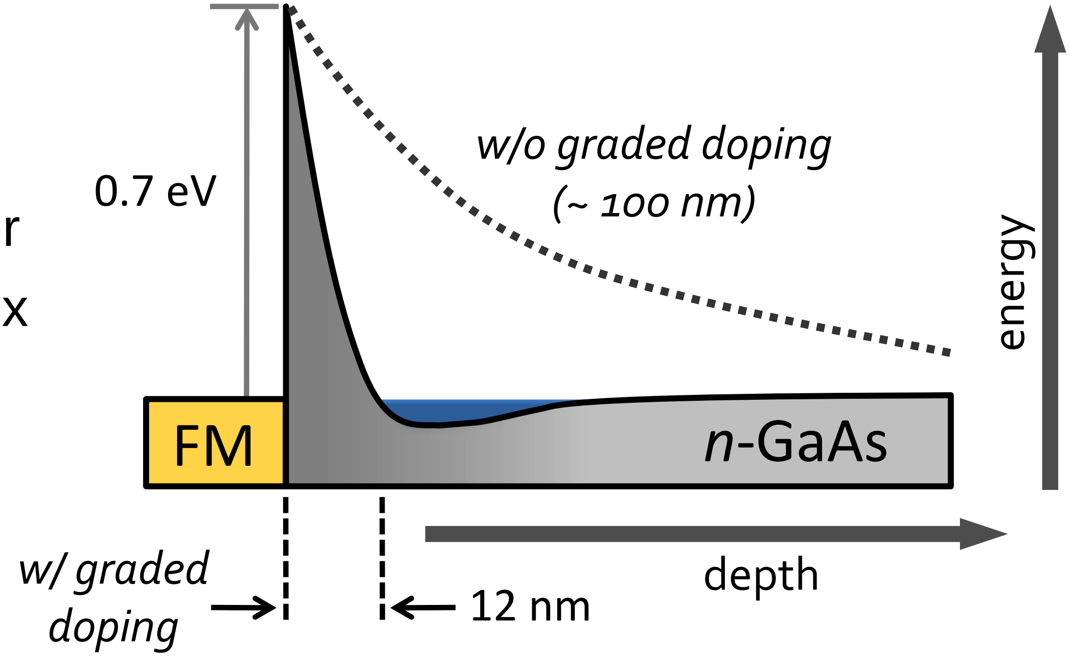
n : GaAs

$n \sim 3 \times 10^{16}$ cm^{-3} (~ 2500 nm)

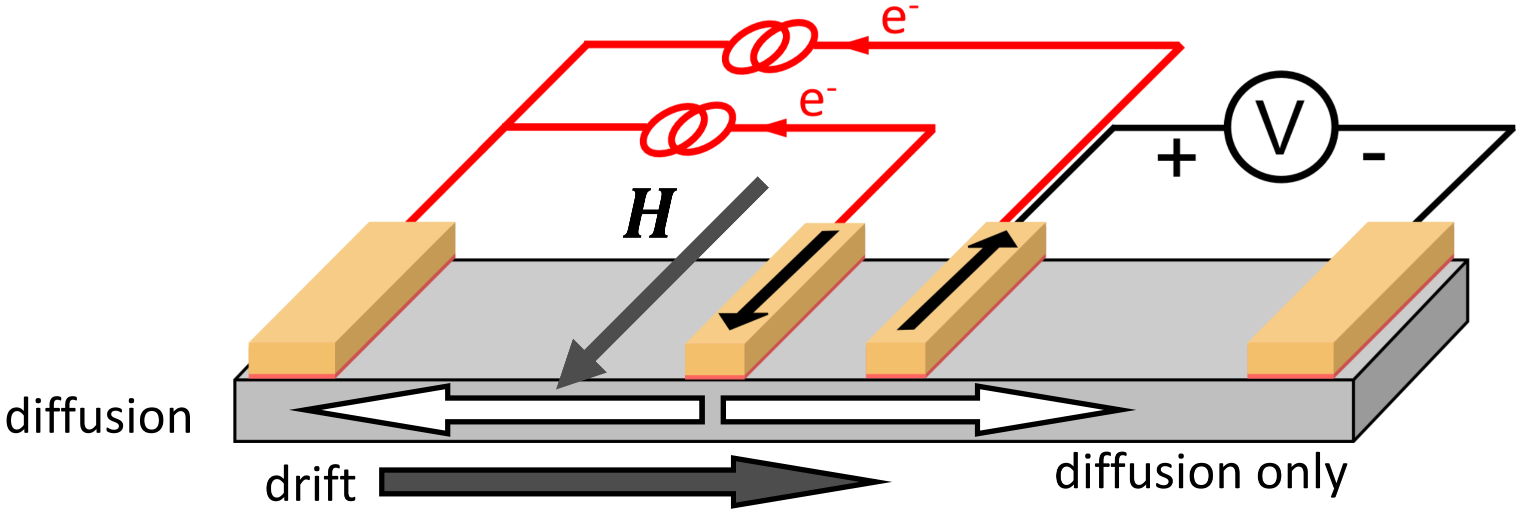
i-GaAs [001]

- Epitaxially grown along [001]
- Fe polarization at Fermi level ≈ 40%
- Co_2MnSi proposed to be half-metallic
- Surface-induced FM anisotropy

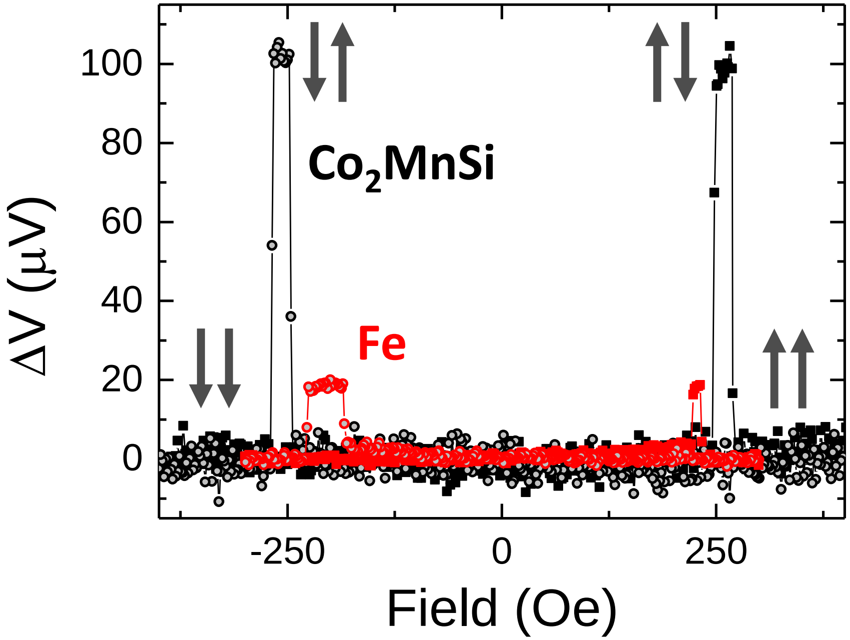
- Graded doping used to 'thin' natural forming Schottky barrier
- Interface states lead to complex bias dependence



Lateral spin valve



unbiased (non-local)



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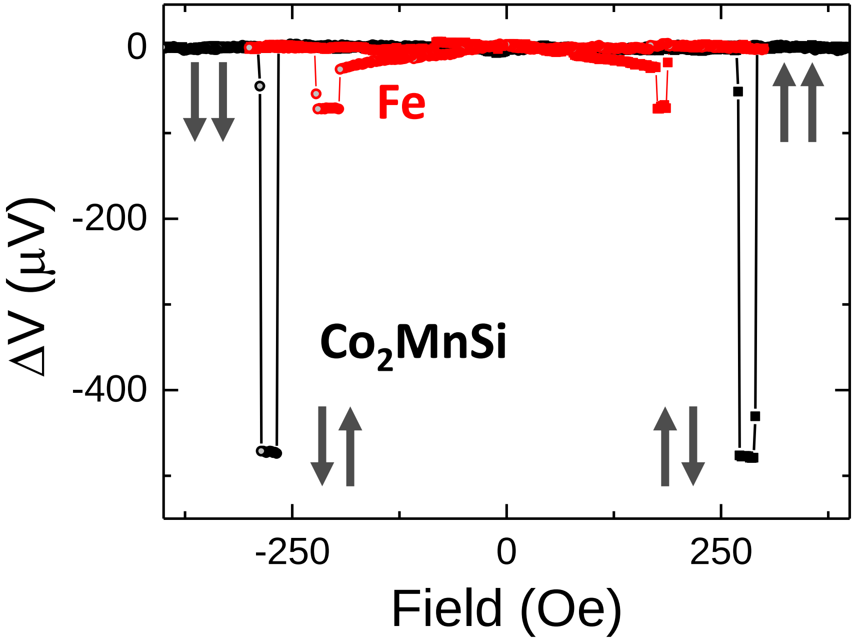


Spin drift-diffusion model

DIFFUSION CONSTANT – ***Same for spin and charge?***

$$eD = \nu\, n \frac{\partial \mu}{\partial n}$$

(Einstein relation)

ν	drift mobility
n	carrier concentration
$\partial\mu/\partial n$	bulk modulus

steady state

$$0 = \frac{\partial \vec{p}}{\partial t} = \nu E \frac{\partial \vec{p}}{\partial x} + D \frac{\partial^2 \vec{p}}{\partial x^2} - \gamma \vec{B} \times \vec{p} - \frac{\vec{p}}{\tau_s} + \dot{\vec{p}}_0$$

drift & diffusion ***Larmor precession*** ***relaxation*** ***injection rate***

SPIN LIFETIME – ***Reasonable values for* n-GaAs?**

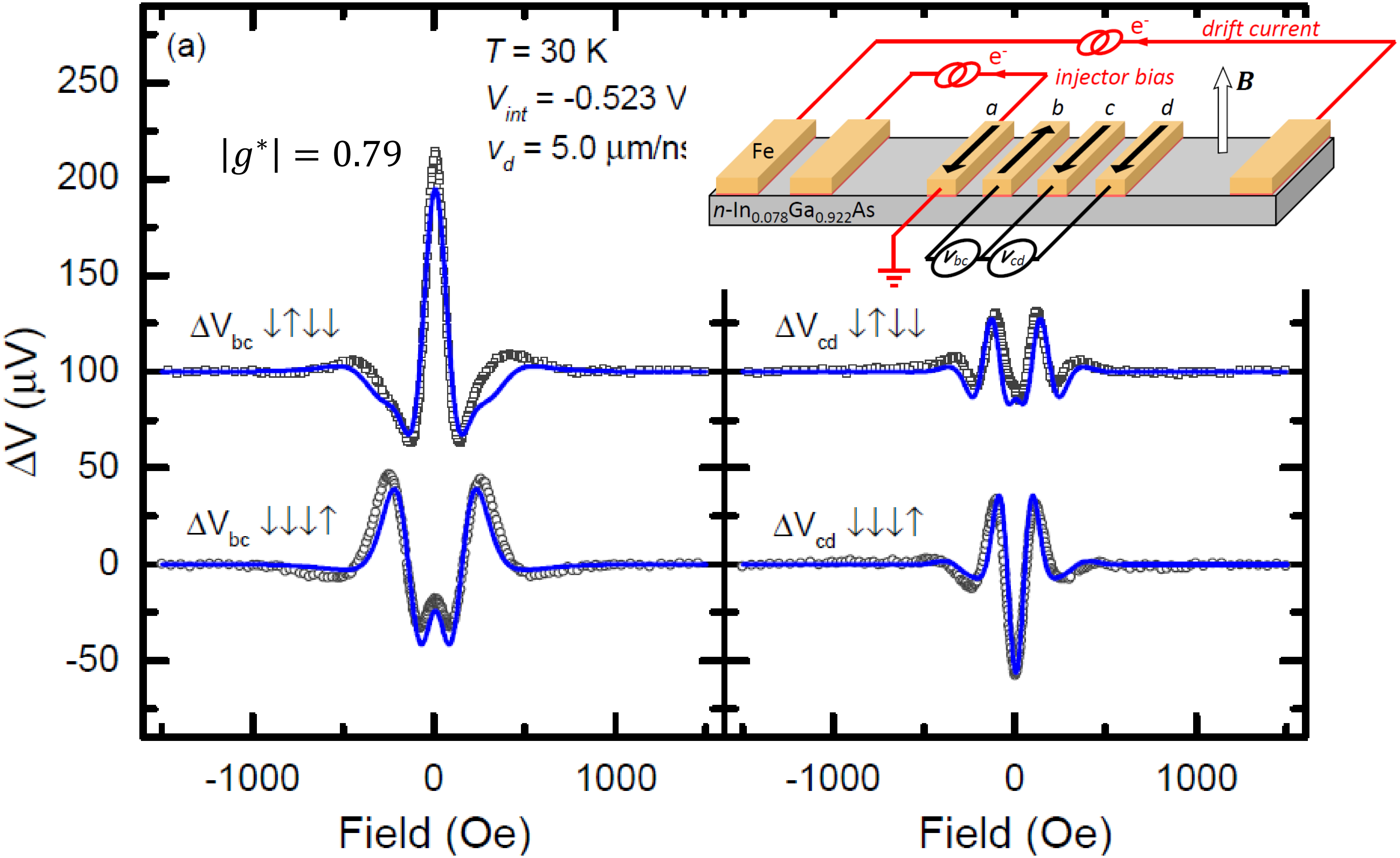
$$\tau_s^{-1} \propto \alpha^2 \varepsilon^3 \tau_p$$

(Dyakonov-Perel)

ε	electron energy
α	spin-orbit prefactor (Dresselhaus)
τ_p	momentum relaxation time

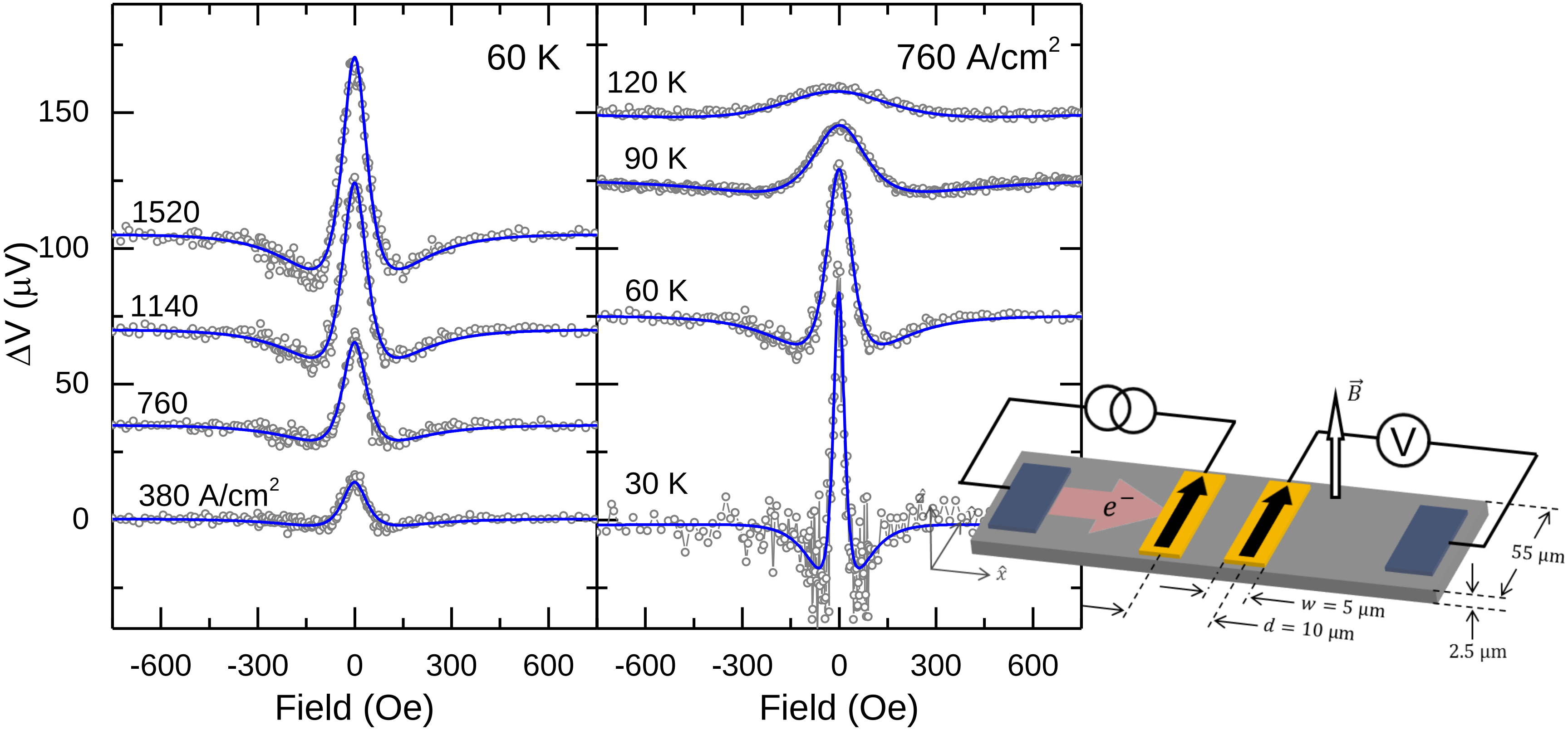
D	d
τ_s	s
$\vec{p}$	fr
E	e
ν	m
γ	gyromagnetic ratio
$\vec{B}$	magnetic field

The full time of flight experiment: add drift



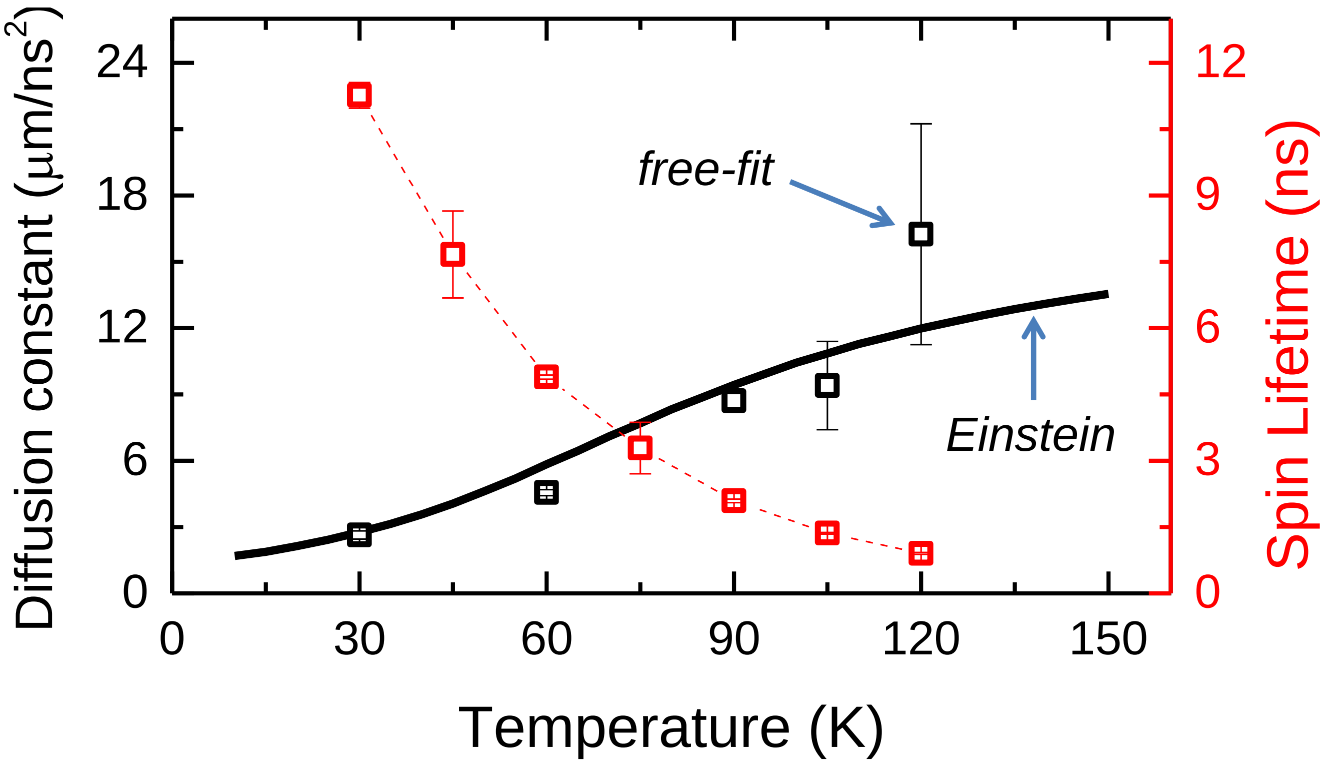
- Solid curves are the analytic solution

Non-local Hanle fitting



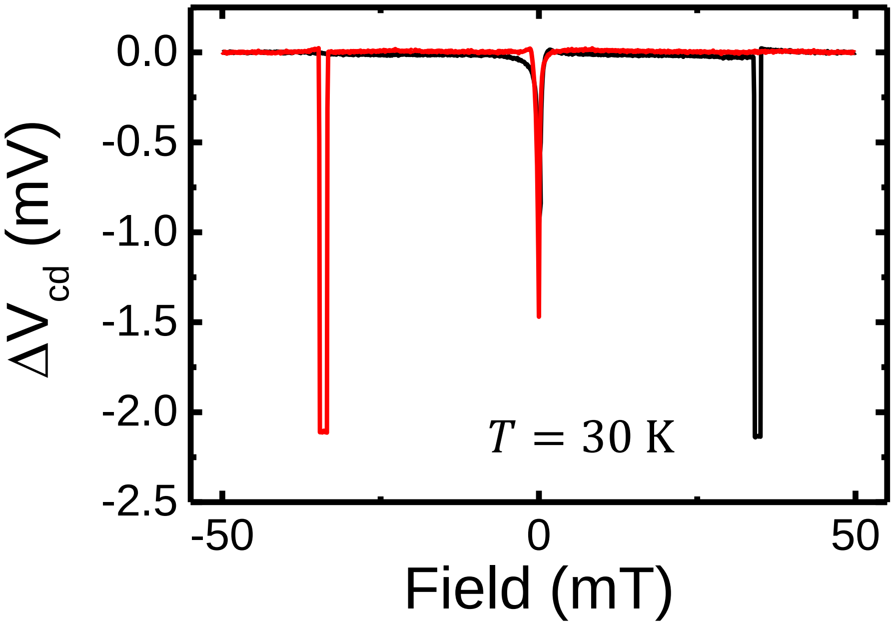
- Multiple biases at each temperature fit with a single set of parameters
- Hanle curves with ‘lobes’ allow extraction of diffusion constant

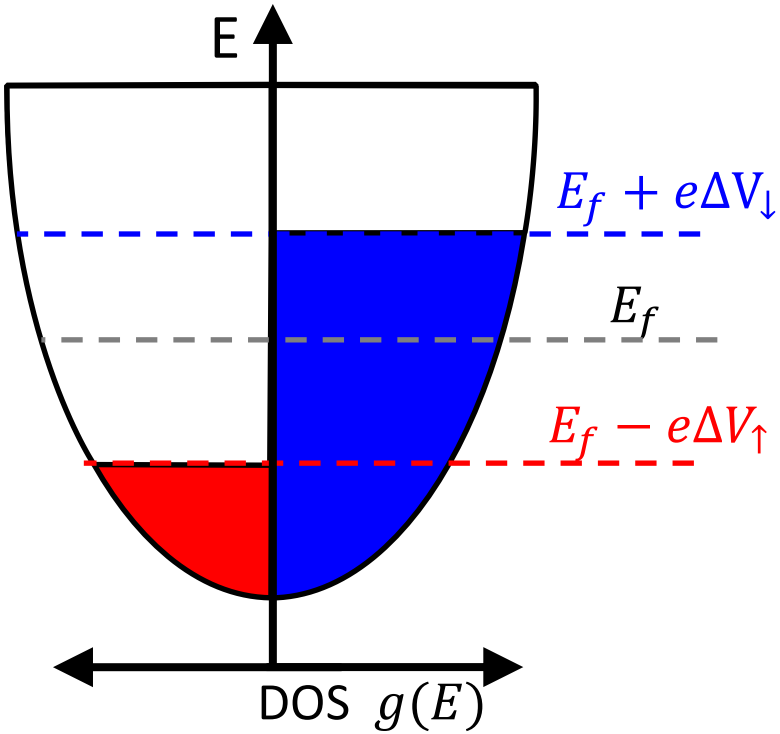
Spin lifetime and diffusion constant



- Allowing D to be a fitting parameter yields values in agreement with the Einstein relation: spin and charge diffusion constants are the same.
- Larger uncertainty at higher temperatures due to disappearance of ‘lobes’

Estimates of the spin polarization





- We can set a lower bound for the spin-polarization if we assume a perfect detection efficiency ($\eta = 1$)

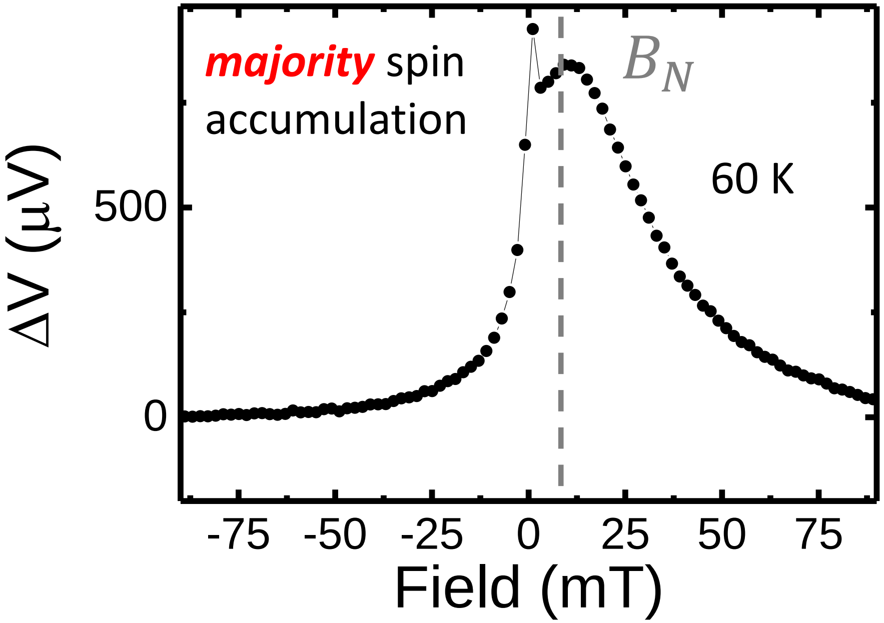
$$n_{\uparrow(\downarrow)} = \int_0^{E_f \pm \frac{e}{\eta} V_{\uparrow(\downarrow)}} g(E)dE \qquad p = \frac{n_\uparrow - n_\downarrow}{n_\uparrow + n_\downarrow} = 60\%$$

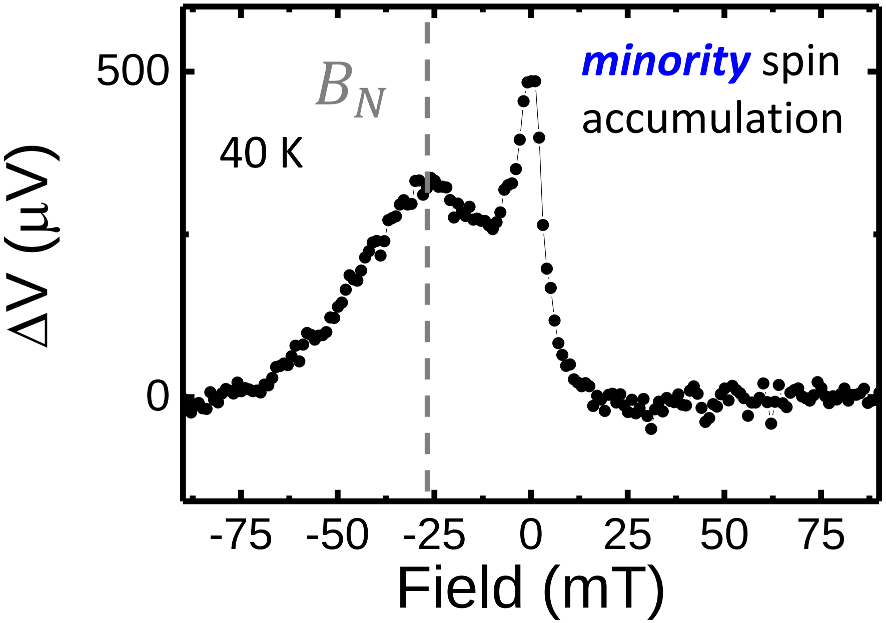
$$\eta = 1$$

- The measured spin splitting ΔV is half of the Fermi energy $E_f = 5$ meV

Sign of the spin accumulation by Hanle measurements

Exploit hyperfine coupling:

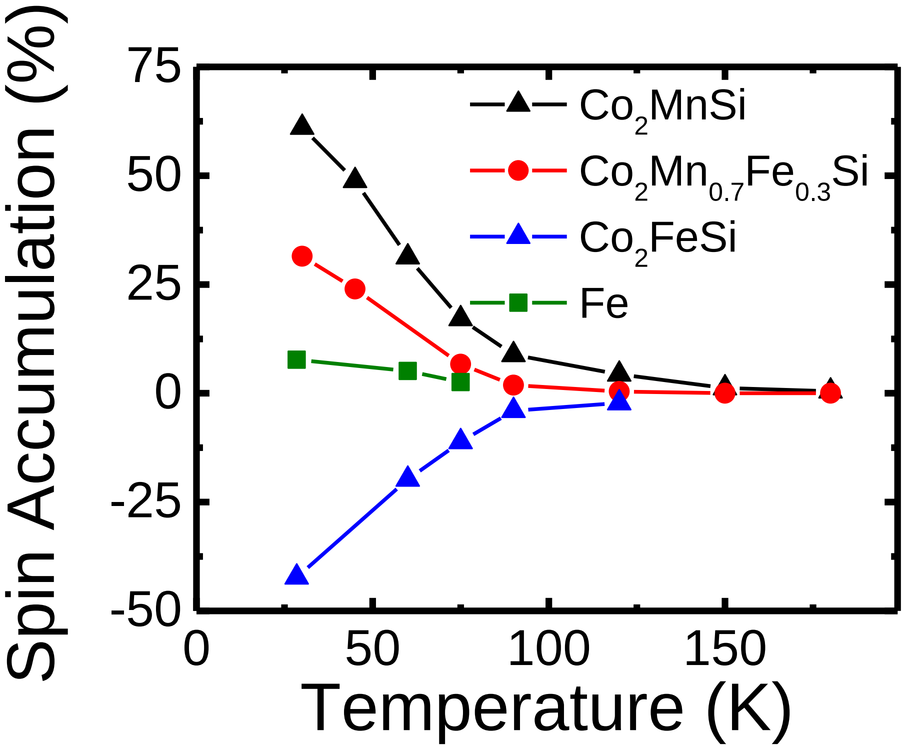

$Co_2MnSi/GaAs$


$Co_2FeSi/GaAs$

Sign of the spin polarization in the bulk GaAs can be determined in the presence of a hyperfine field

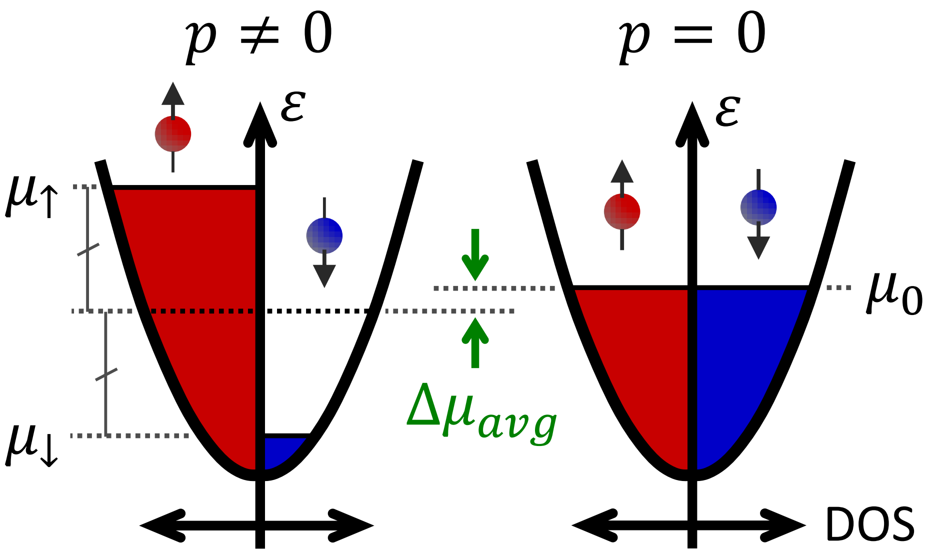
$$\vec{B}_{tot} = \vec{B} - b_H \frac{\vec{S} \cdot \vec{B}}{B^2} \vec{B}$$

$Co_2Mn_{1-x}Fe_xSi$: comparison with Fe



- Polarizations determined by “biased detector technique”
- Sign determined by hyperfine field
- Sign change in going from Co_2MnSi to Co_2FeSi is expected, but overall sign is *backwards*

Interlude: (Scalar) Spin EMF



- Current in each spin-channel:

carrier densities

electrostatic potential

$$\vec{j}_{\uparrow(\downarrow)} = n_{\uparrow(\downarrow)}\nu\vec{\nabla}\left[\mu_{\uparrow(\downarrow)} - e\Phi\right]$$

spin-indep. mobility

chemical potentials

- Expand chemical potentials w.r.t. p:

$$\mu_{\uparrow(\downarrow)} \approx \mu_0 + (-)\frac{\partial\mu}{\partial n}np + \underbrace{\frac{\partial^2\mu}{\partial n^2}n^2p^2}$$

asymmetric shift: $\Delta\mu_{avg}$

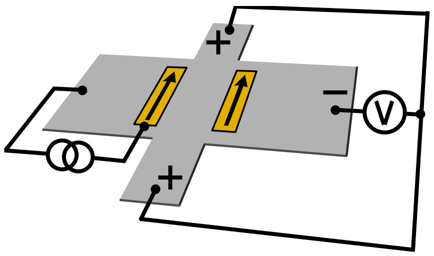
- Result:

spin-generated EMF

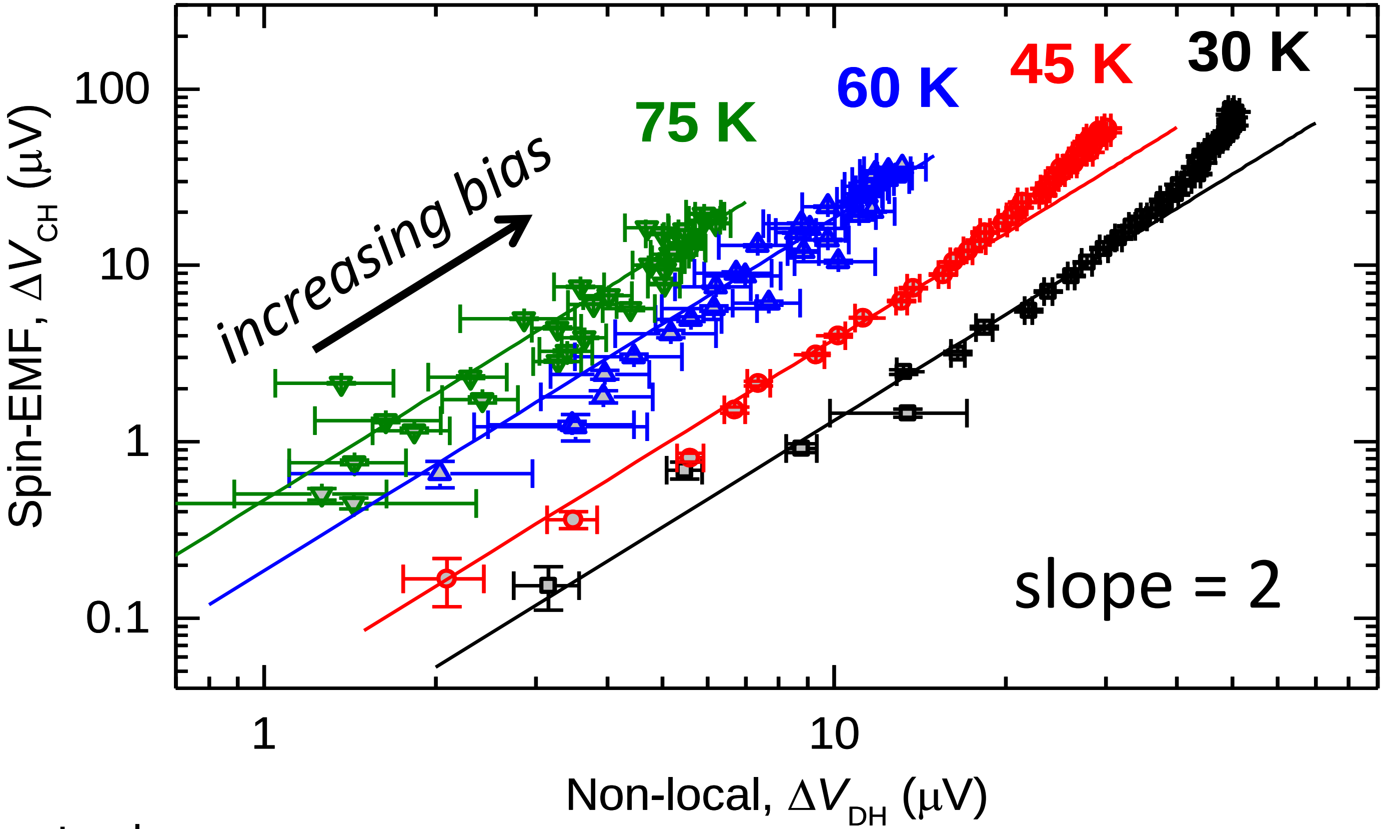
$$\vec{j} = \sigma\vec{\nabla}\left(kp^2 - \Phi\right)$$

$$k = \frac{1}{2e}\left(\frac{\partial\mu}{\partial n}n + \frac{\partial^2\mu}{\partial n^2}n^2\right) = \frac{2}{9}\frac{E_f}{e}$$

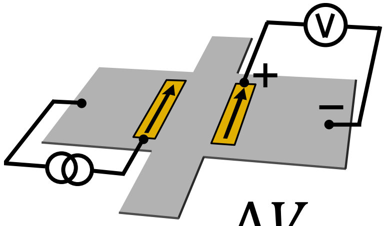
Quadratic dependence



$\Delta V_{CH} \propto p^2$

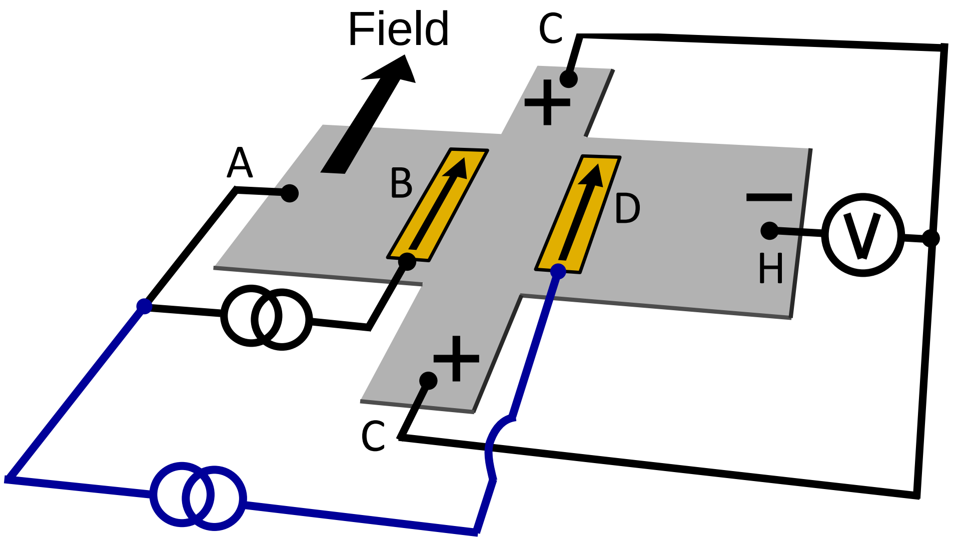


- Log-log plot of magnitudes demonstrates quadratic dependence
- Deviation at large bias due to large E-field at injector (drift effects)

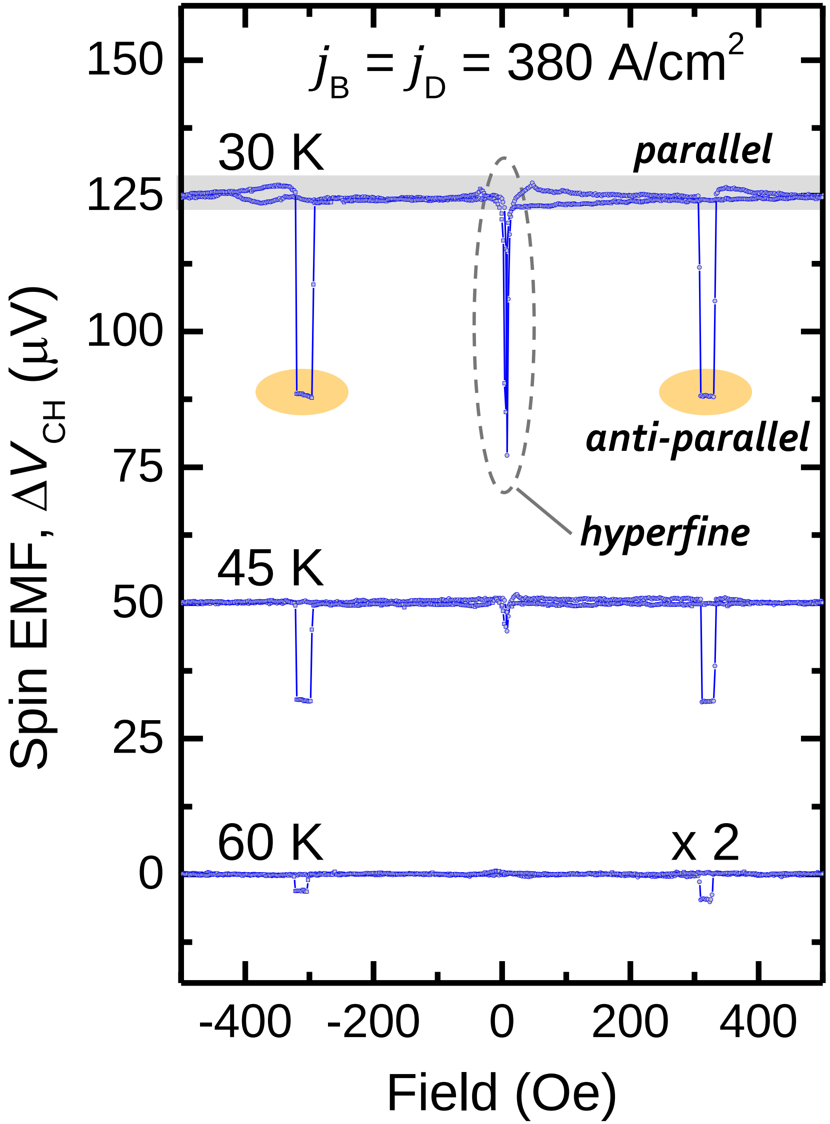


$\Delta V_{DH} \propto p$

Dual-injector experiment

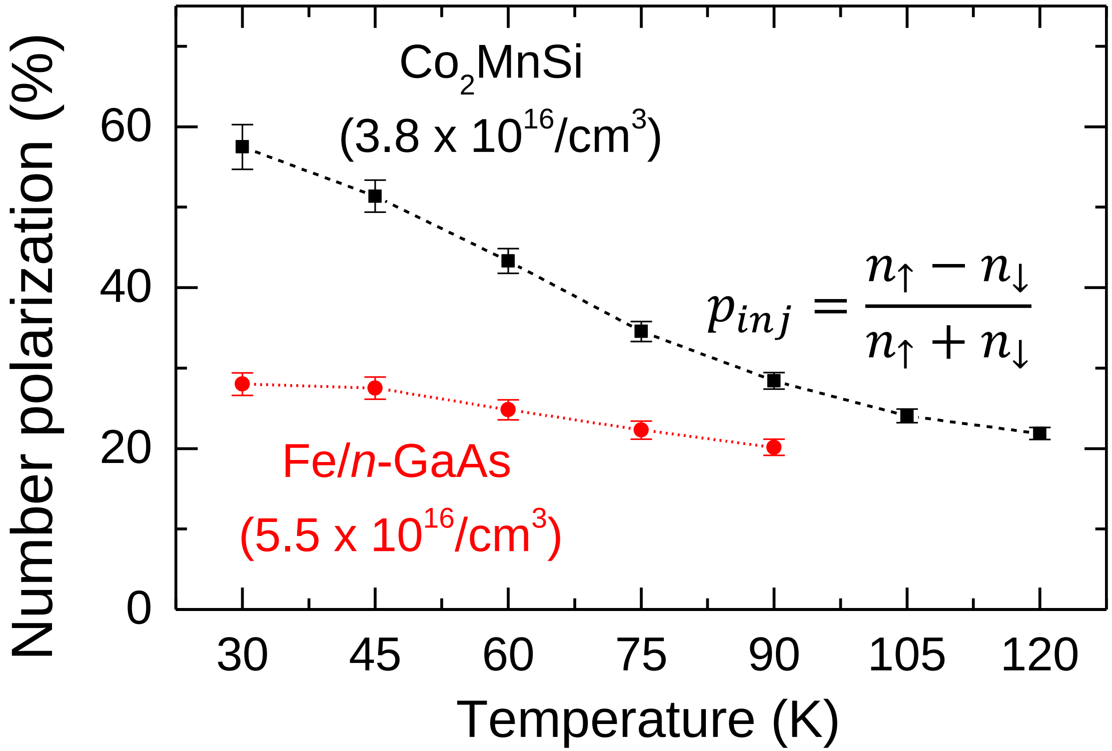


- Spins injected simultaneously at FM contacts B and D
- Clear spin valve signals observed at contact C
- Low-field features due to hyperfine interactions



I. J. Vera-Marun *et al.*, Nature Phys. **8**, 313 (2012).

Polarization vs. Temperature



- For $p > 0.3$, need to account for ‘Thompson’ effect: $k = k(p)$
- Results are independent of any assumptions about interfacial spin injection/detection efficiencies
- This resolved the “three-terminal” discrepancy

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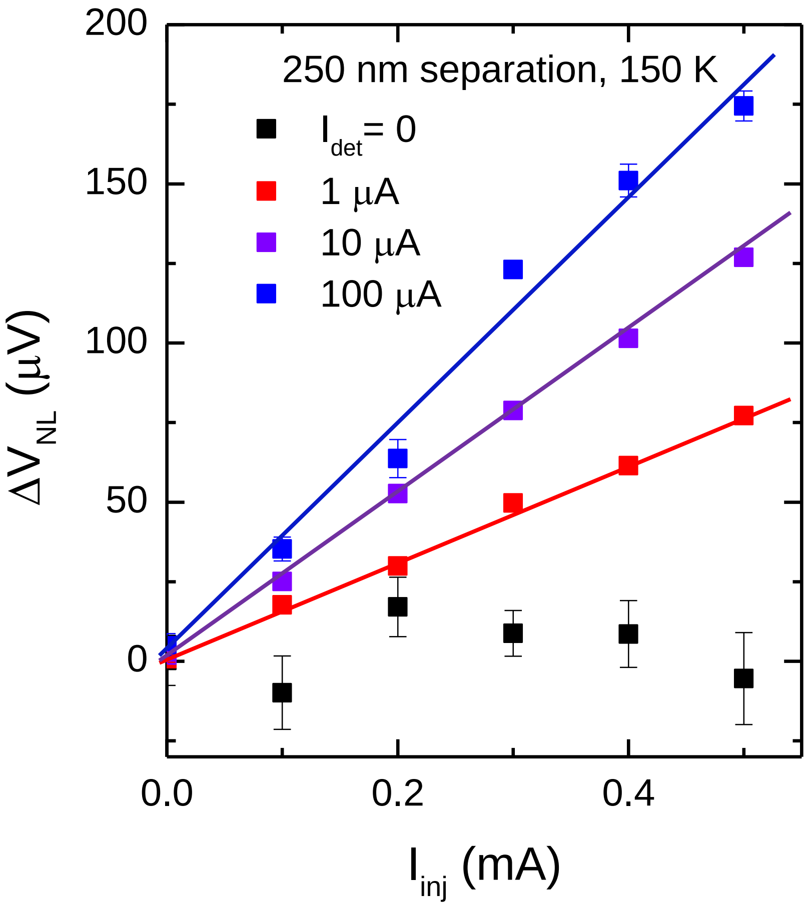
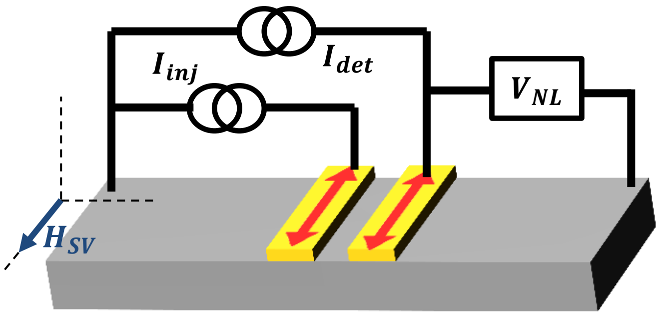
What about room temperature?

- Biased detector





- ΔV_{NL} is linear in spin injection rate, I_{inj}, with fixed non-zero detector bias I_{det}

- ΔV_{NL} becomes larger with detector bias I_{det}, which we interpret as a detector bias dependence of $\eta \rightarrow \eta(I_{det})$

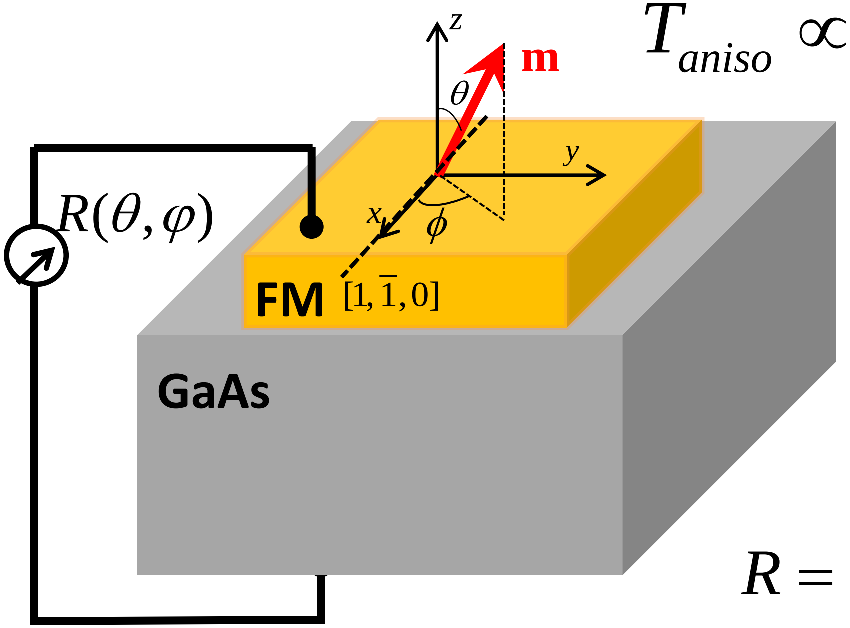
$$\Delta V_{NL} = \eta(I_{det}) \frac{P(I_{inj})n}{e} \frac{\partial \mu}{\partial n}$$

- We also see saturation of ΔV_{NL} at large I_{det}.

Complication: Tunneling AMR (TAMR)

$$\frac{e}{(2\pi)^3\hbar}\sum_{\sigma}\int dE d^2k_{\parallel}T_{\sigma}(E,k_{\parallel})[f_F(E_{\sigma})-f_N(E)]$$

$$T_{aniso}\propto\sin^2(\theta)[f(\alpha,\gamma)+g(\alpha,\gamma)\cos(2\phi)]$$



α : Rashba spin-orbit coupling constant

γ : Dresselhaus spin-orbit coupling constant

$$R=R_0+\Delta R_{in}\sin^2(\theta)\cos^2(\phi)+\Delta R_{out}\sin^2(\theta)$$

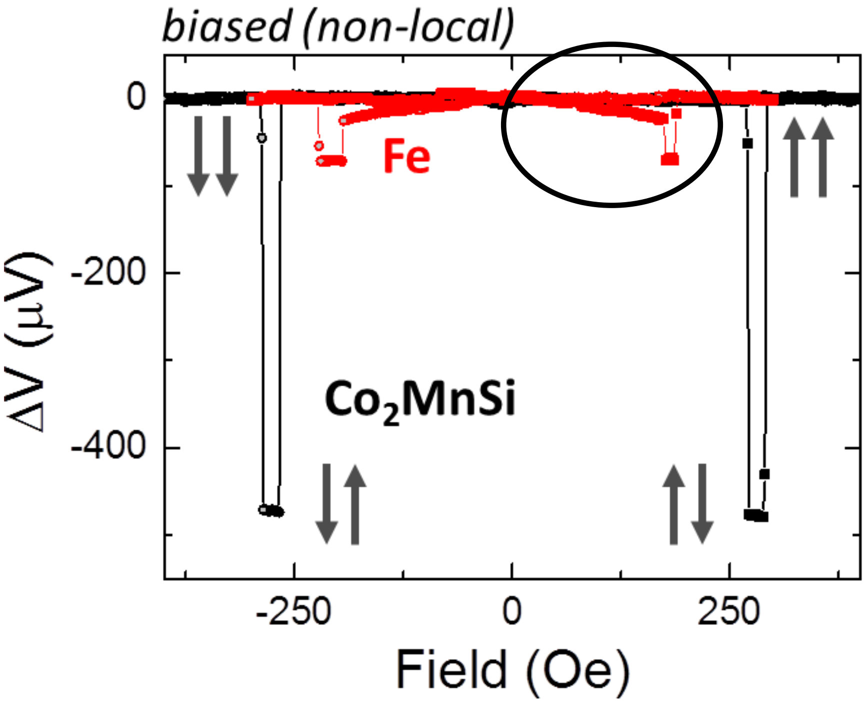
J. Moser et al., *PRL,* **99,** 056601 (2007)

A. Matos-Abiague et al., *PRB*, **80,** 045312 (2009)

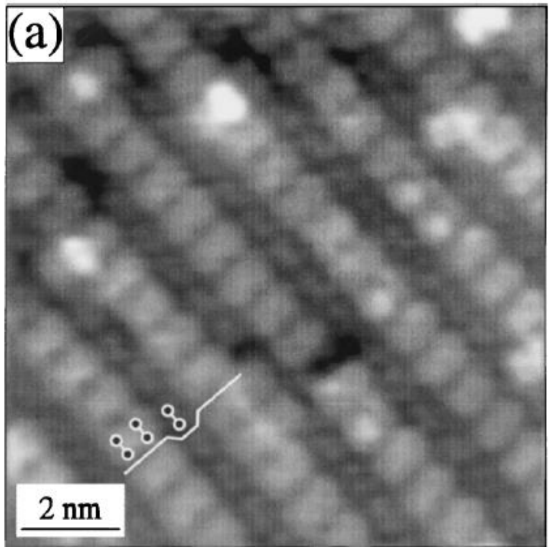
K. Wang et al., *PRB*, **88,** 054407 (2013)

Ramifications for a biased detector

- *Any* contact rotation leads to a TAMR contribution to the“three-terminal” signal; i.e. an additional field-dependent voltage at the detector. This is large and only weakly temperature-dependent.



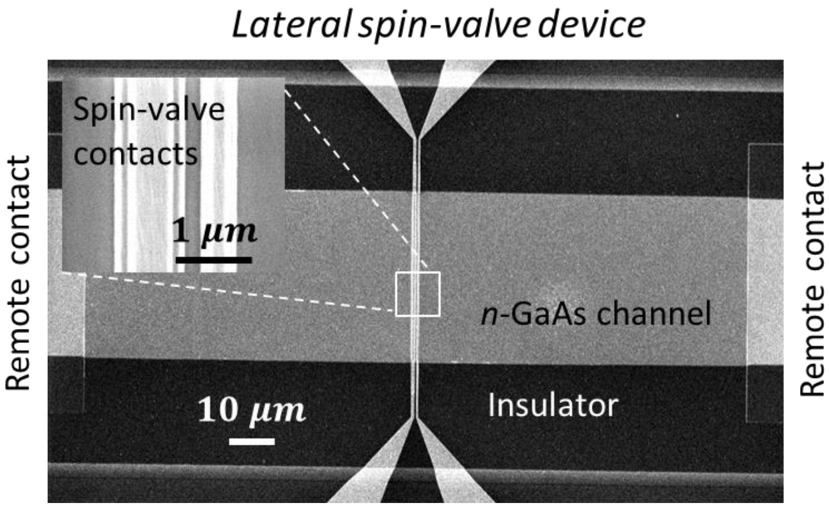
2-fold surface symmetry

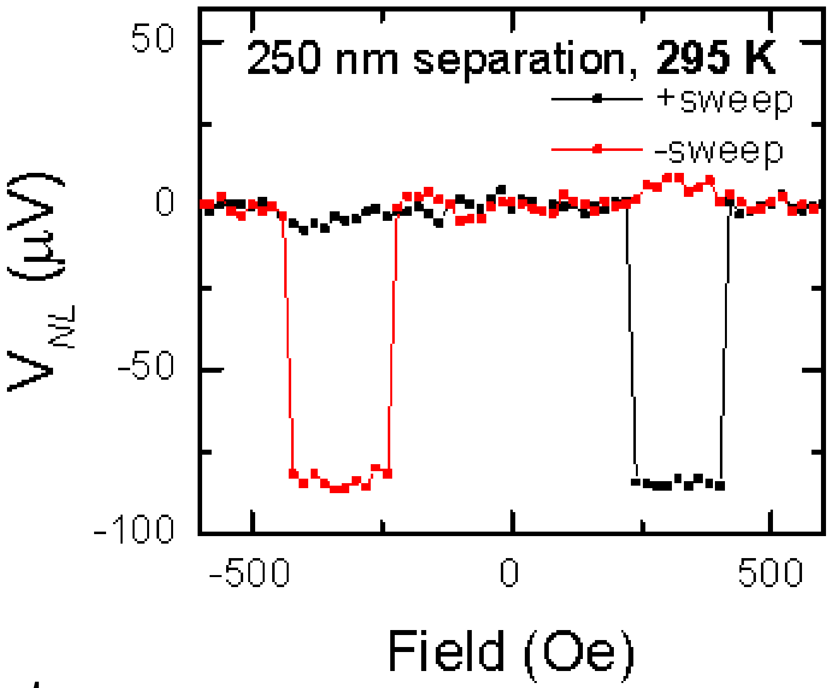


La Bella *et al.*, PRL **83**, 2989 (1999).

- The ratio of the uniaxial to fourfold anisotropies is larger in $Co_2Mn_{1-x}Fe_xSi$ than in Fe. This makes the Heuslers very forgiving.

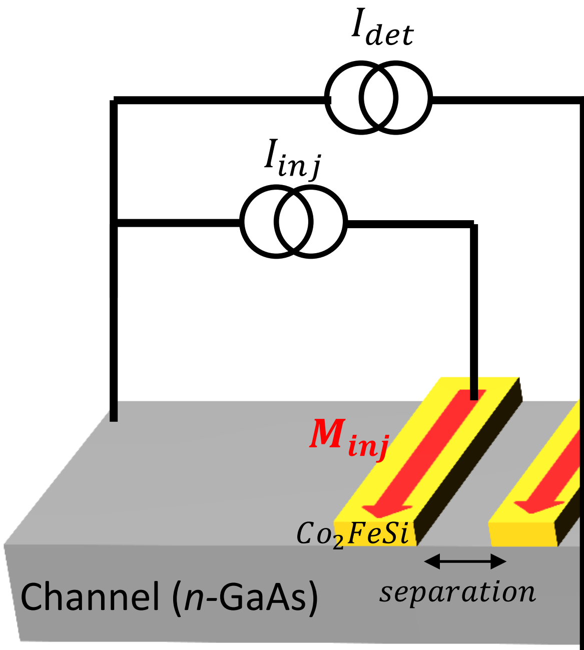
Devices operating at room temperature



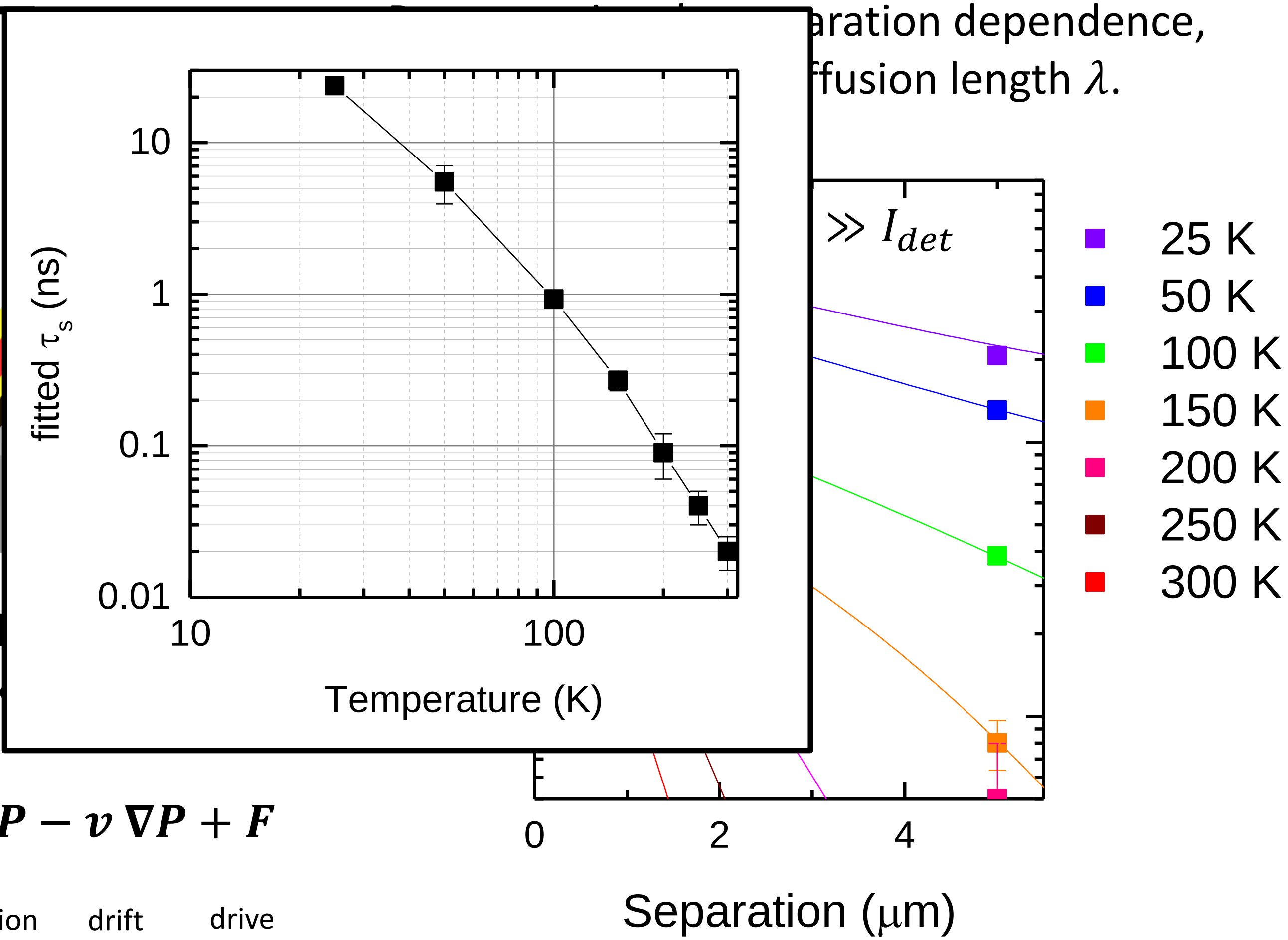


- Use of Co_2FeSi as injector/detector
- Electron beam lithography
- Performance today comparable to low-T performance as of a few years ago (particularly size of non-local voltage)
- Spin diffusion length at 300 K is ~ 800 nm

Temperature dependence



aration dependence,
ffusion length λ.



We fit to the steady state sol
drift-diffusion equation to ex

$$\frac{d\boldsymbol{P}}{dt} = 0 = -\frac{\boldsymbol{P}}{\tau_s} + D\nabla^2\boldsymbol{P} - \boldsymbol{v}\,\nabla\boldsymbol{P} + \boldsymbol{F}$$

relaxation diffusion drift drive

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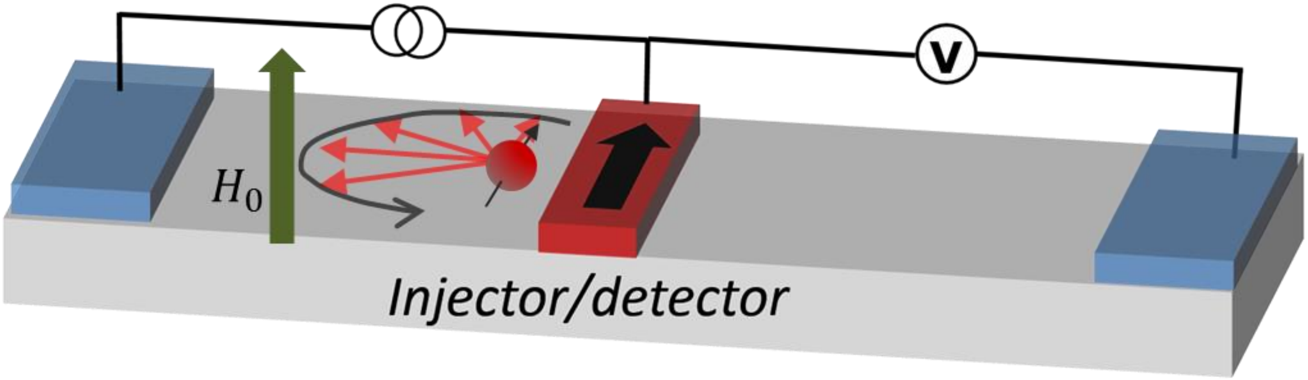
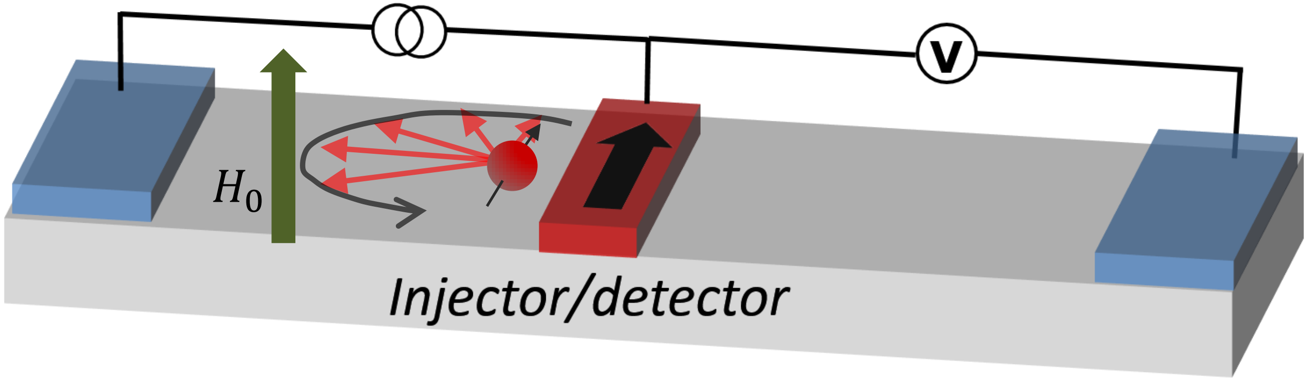
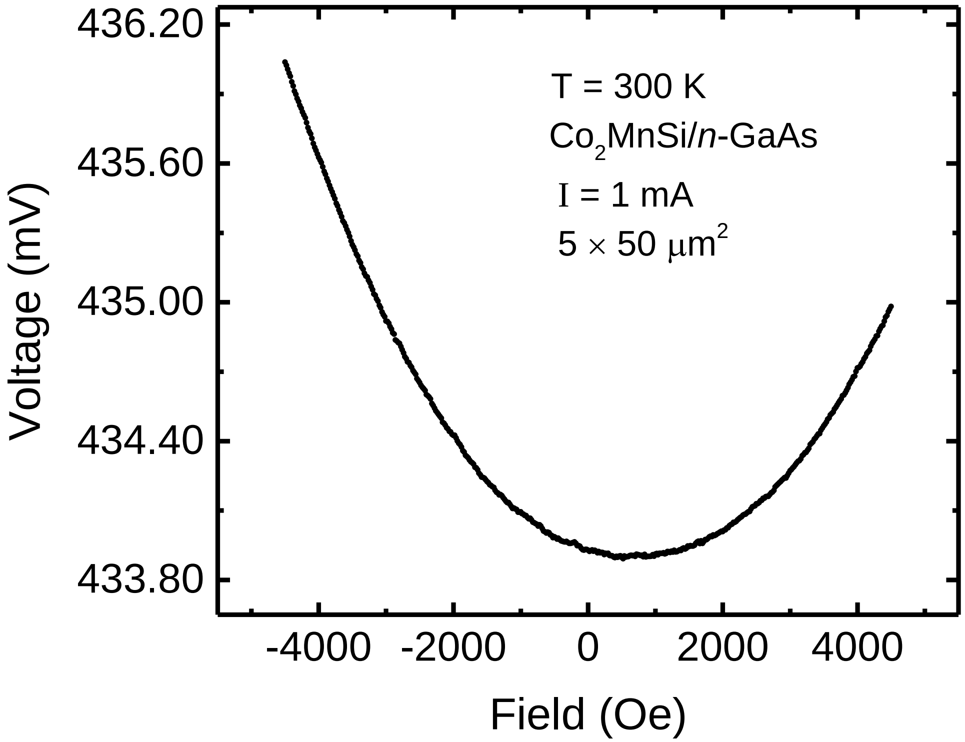
What about Hanle measurements?



- Conventional wisdom: these become difficult or impossible at high temperatures because the lifetime is “too short”
- This is reinforced by the fact that the g-factor in GaAs is so small (i.e. -0.44 insteady of 2)
- Ordinary magnetoresistance is very large

Hanle measurement at room temperature fails



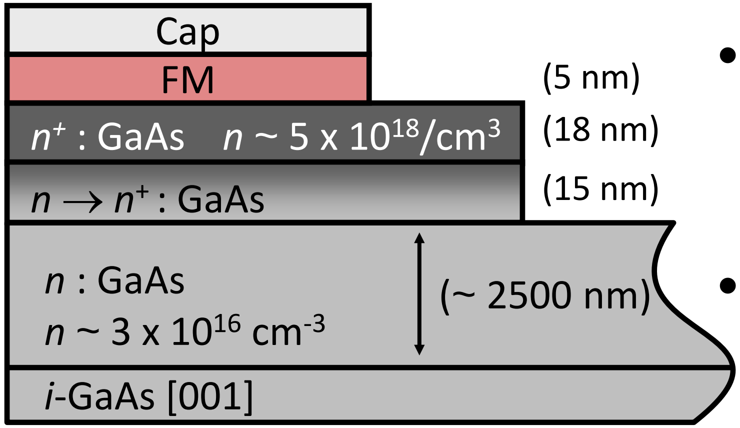


- Signal/Background $\sim 10^{-4}$
- Impossible to extract spin signal at room temperature in n-GaAs system

What about Hanle measurements?

- Conventional wisdom: these become difficult or impossible at high temperatures because the lifetime “is too short”
- This is reinforced by the fact that the g-factor in GaAs is so small (i.e. -0.44 insteady of 2)
- Ordinary magnetoresistance is very large
- Solution: use the Hanle concept (sensitivity to precession), but exploit the fact that spins can precess in the FM as well as the semiconductor.

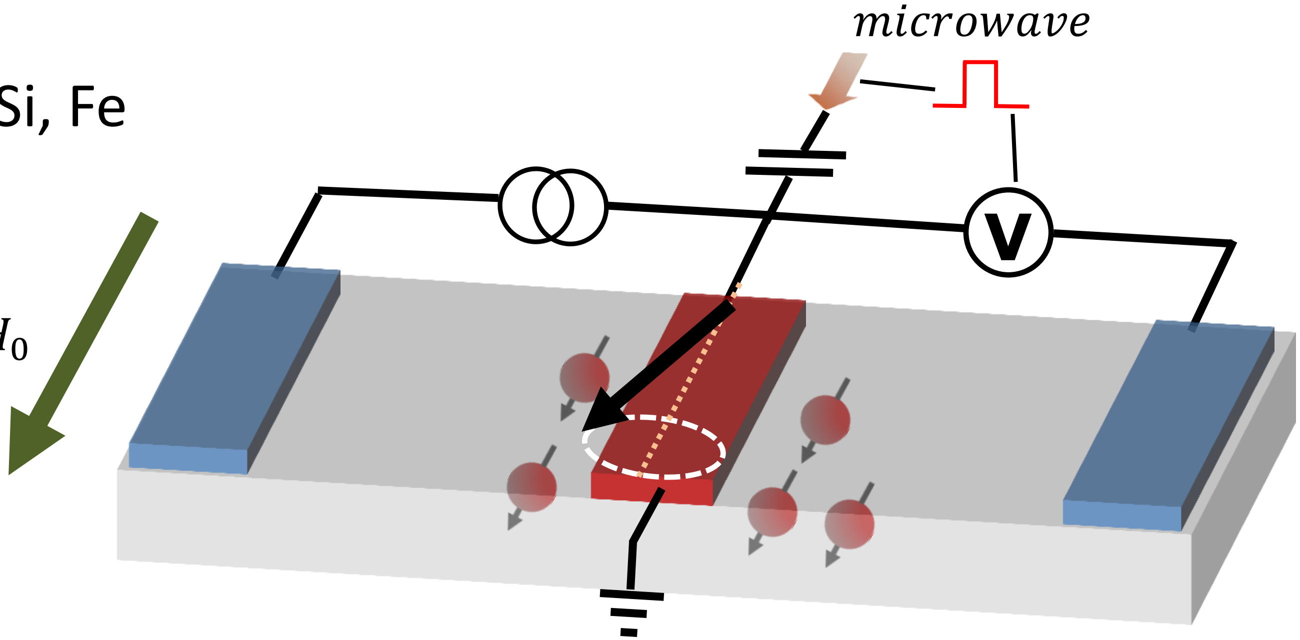
Solution: modulate the injector with FMR



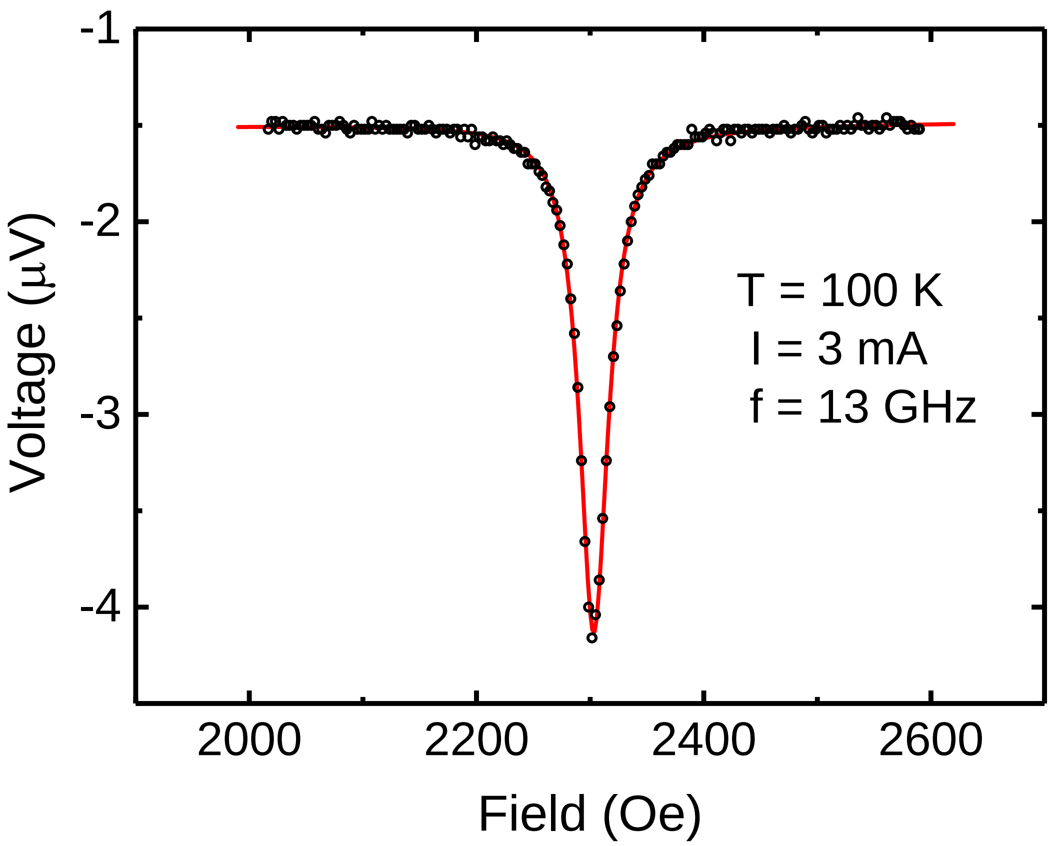
- This is a three-terminal measurement with microwave excitation
- Signal is the difference of the 3T signal with and without microwave field

FM: Co_2MnSi, Co_2FeSi, Fe

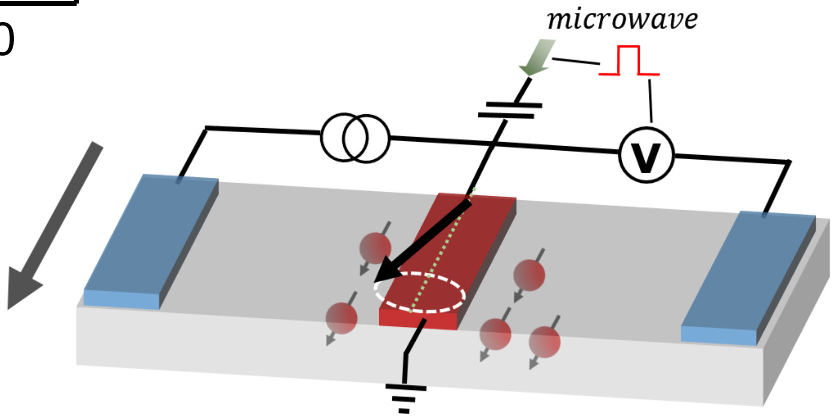
Skipping details...



Spin accumulation leads to an FMR peak in ΔV

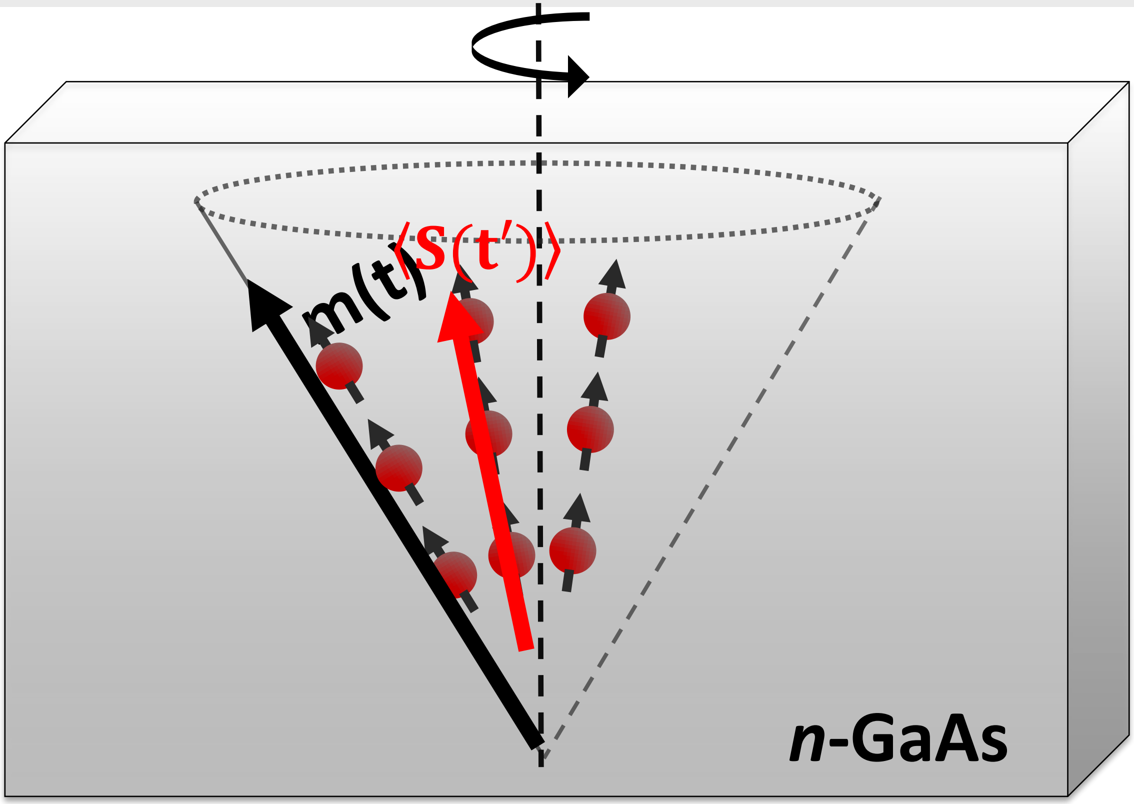


- A strong resonance peak is observed (note the sign is negative)
- The peak position is well described by the Kittel's formula



- At forward bias, the FMR signal is dominated by spin accumulation
- Linewidth determined by $\alpha \sim 0.003$ for Co_2MnSi at room temperature

Modeling FMR spin detection



I_s: Spin injection current

η: Detection efficiency

D: Spin diffusion constant

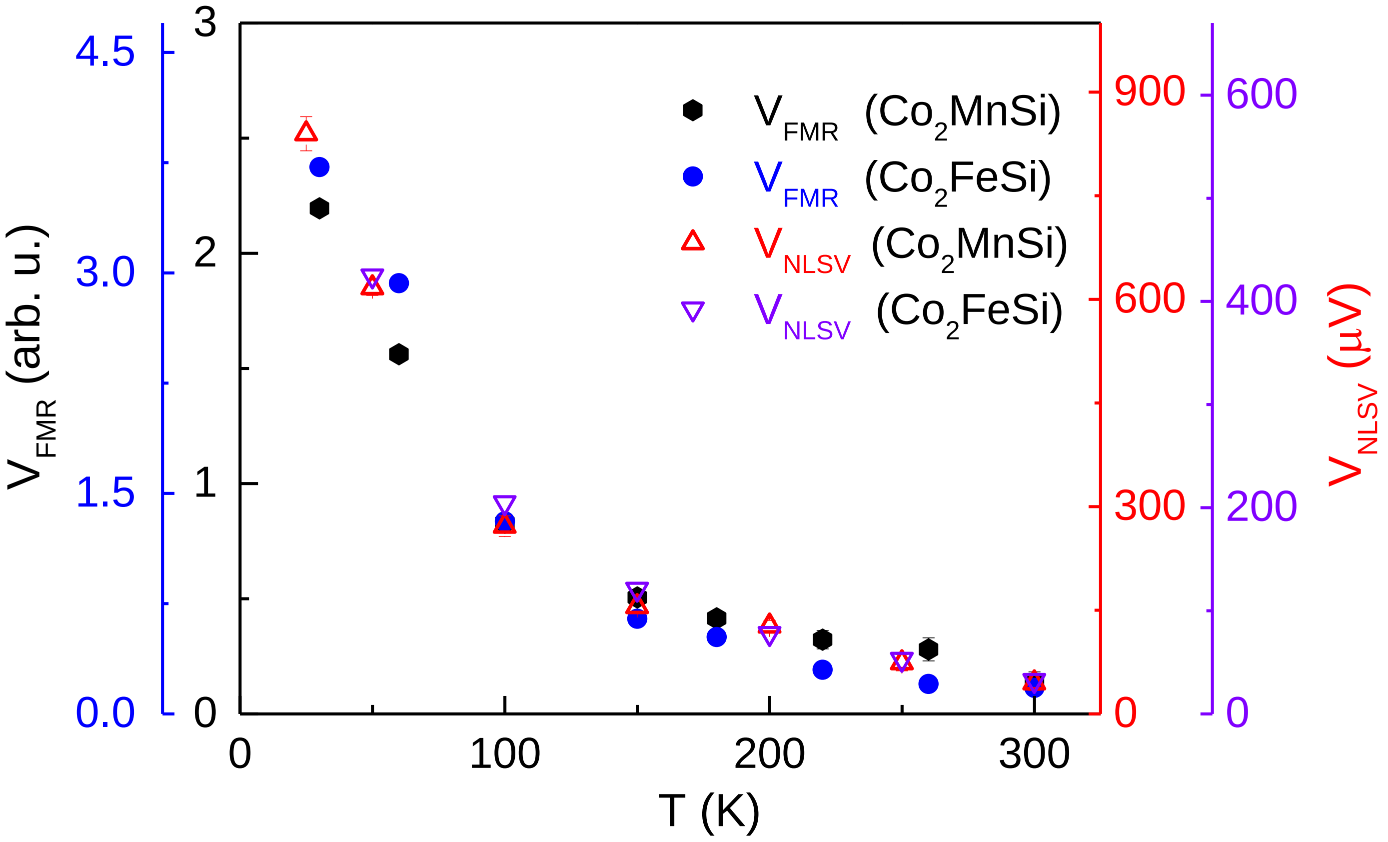
τ_s: Spin lifetime

$\varphi_{in}\ \ \varphi_{out}$: Precession cone angles

$$V = \eta I_s \int_{-\infty}^{t} \hat{\boldsymbol{m}}(t) \cdot \hat{\boldsymbol{s}}(t') \frac{1}{\sqrt{2\pi D(t-t')}} e^{-\frac{t-t'}{\tau_s}} dt'$$

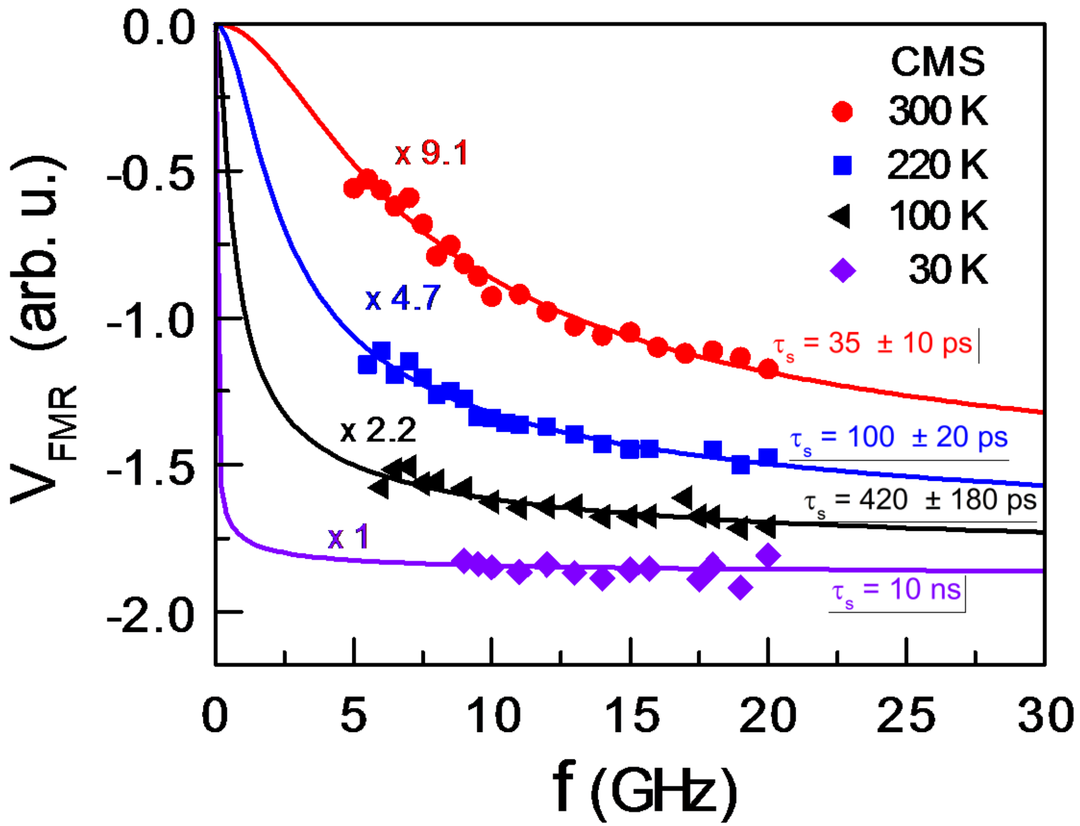
$$V_{FMR} = \eta I_s \frac{1}{2} ({\varphi_{in}}^2 + {\varphi_{out}}^2) \sqrt{\frac{\tau_s}{2D}} \left(\sqrt{\frac{1}{2\sqrt{1+\omega^2\tau_s^2}} + \frac{1}{2(1+\omega^2\tau_s^2)}} - 1 \right)$$

Temperature dependence (comparison with NLSV)



- Agreement with spin-valve data for both Co_2FeSi and Co_2MnSi

Frequency dependence



- Spin lifetime extracted agrees with those obtained from spin-valve measurements
- At high temperatures, this technique is much more sensitive than the conventional spin valve approach

Summary

- $Co_2Mn_{1-x}Fe_xSi$ is a very effective spin injector/detector for GaAs
- The high polarization helps, although in our case the highest polarizations *measured* are about 70%
- There are other features of these materials that are as "useful" as the high polarization
- Lateral spin valves useful as quantitative tools up to room temperature
- Microwave detection of spin accumulation is a complementary technique, particularly when τ_s is *short*.