Spin injection

concept and technology

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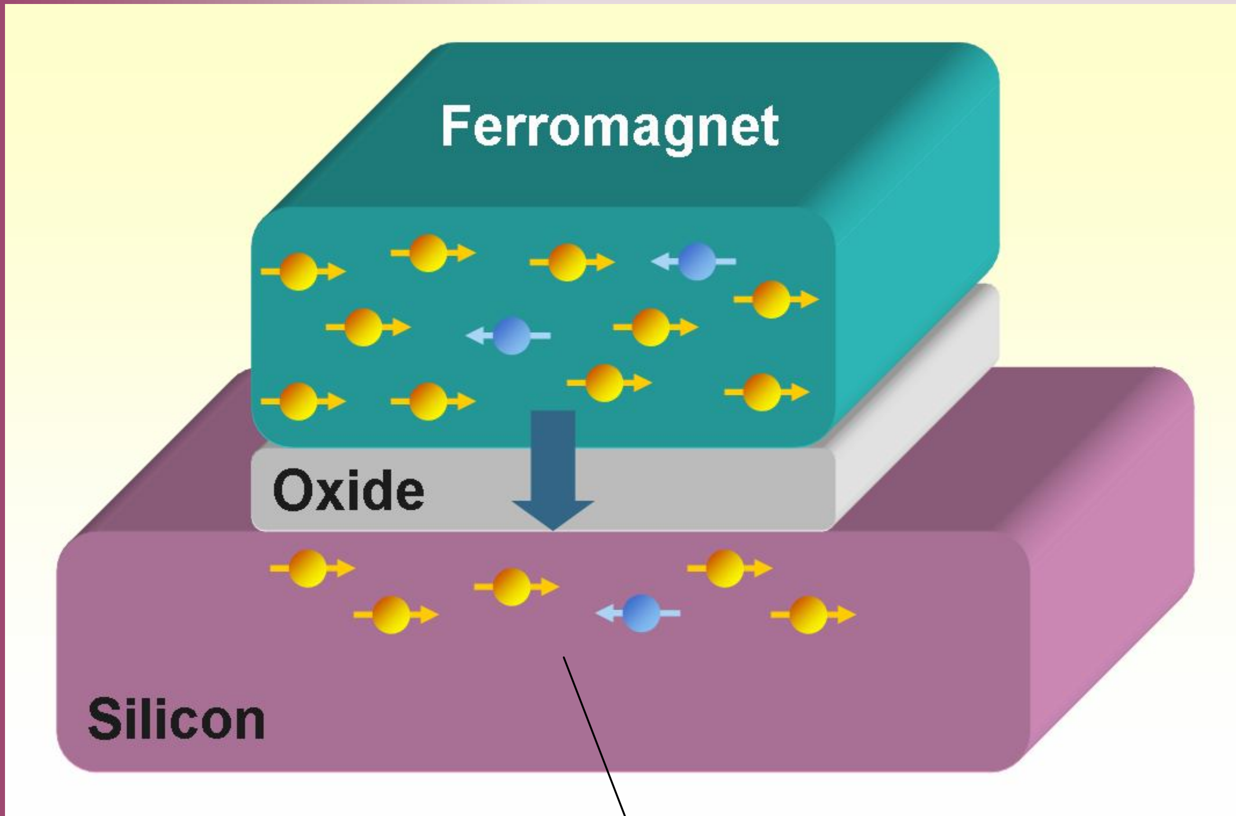
Spin injection

Transfer of spin angular momentum
from a ferromagnet to a non-ferromagnetic material



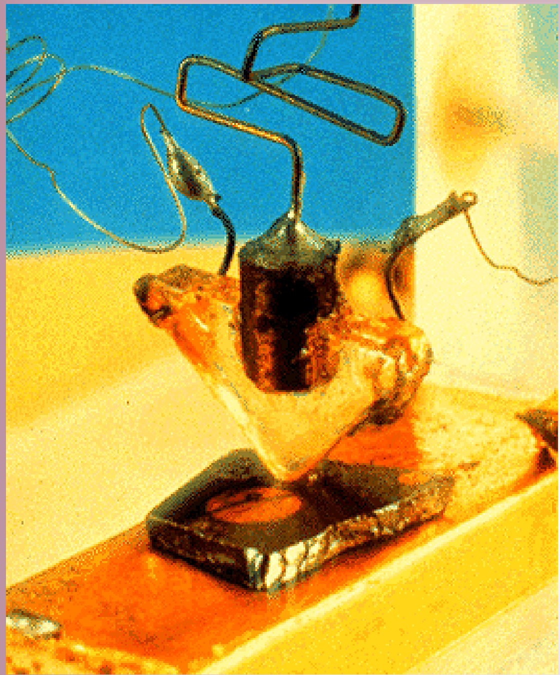
Normal metal
<u>Semiconductor</u>
Inorganic / organic
Carbon-based

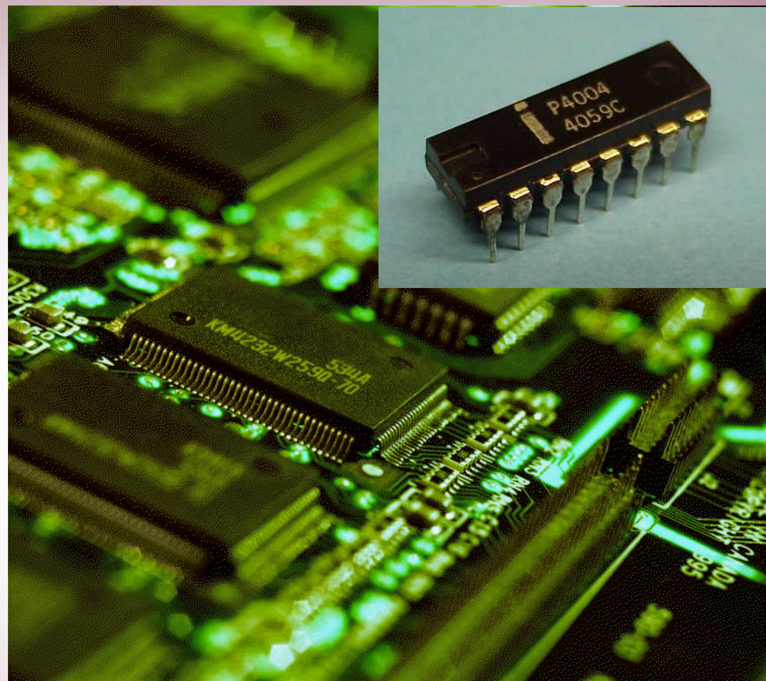
Non-equilibrium spin polarization

Semiconductors – Electronics

Computing and amplification

First transistor





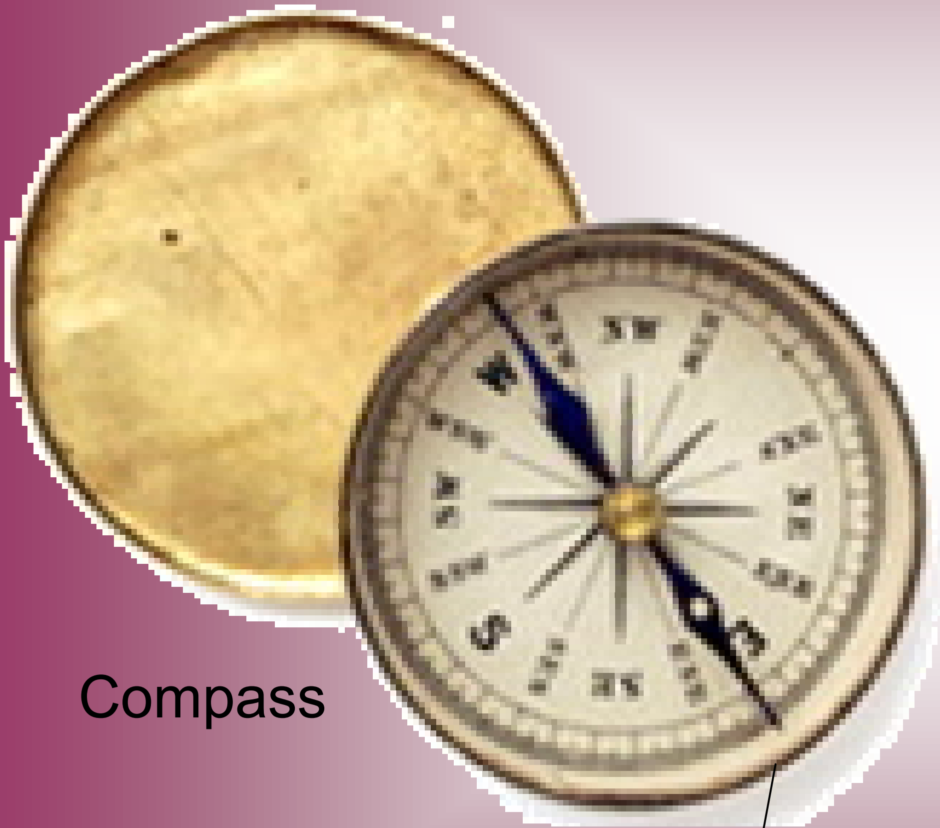
Processor chip

Very powerful technology
Present everywhere in today’s society

Workhorse – silicon field-effect transistor

Magnets – information storage

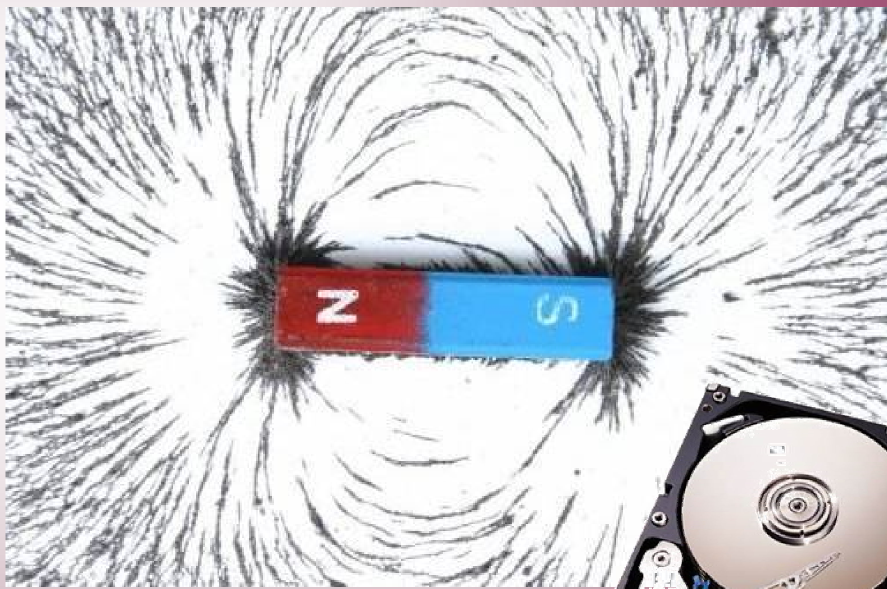
Magnetization is vector quantity



Compass

Magnetic needle

Preferred axis - binary information



Combining the best of both worlds

Ferromagnets
- Stable memory
- Fast switching
- High ordering temp.
- Spin transport

- Technology base
(magnetic recording)

Semiconductors
Bandgap engineering -
Carrier density & type -
Electrical gating -
Long spin lifetime -

Technology base -
(electronics)

Semiconductor Spintronics

Can we develop spin-based transistors, switches, and logic circuits ?

How to create, control and propagate spin information in semiconductor structures?

Outline

Part I
Introduction and brief overview
Key methods and devices for spin injection

Part II
Electrical spin devices
Injection
Detection
Transport
Manipulation

Part III
Hot topics
Spin relaxation time in Si
Magnitude spin accumulation
Interface states
Doping concentration

Creation of spin polarization in non-magnetic materials

<u>Injection of spin-polarized charge current</u>

- Hot-electron spin filtering
- From ferromagnetic tunnel contact

<u>Injection of pure spin current (no charge)</u>

- Spin pumping by magnetization dynamics
- Spin + thermoelectric effects (spin caloritronics)

<u>Optical injection</u>

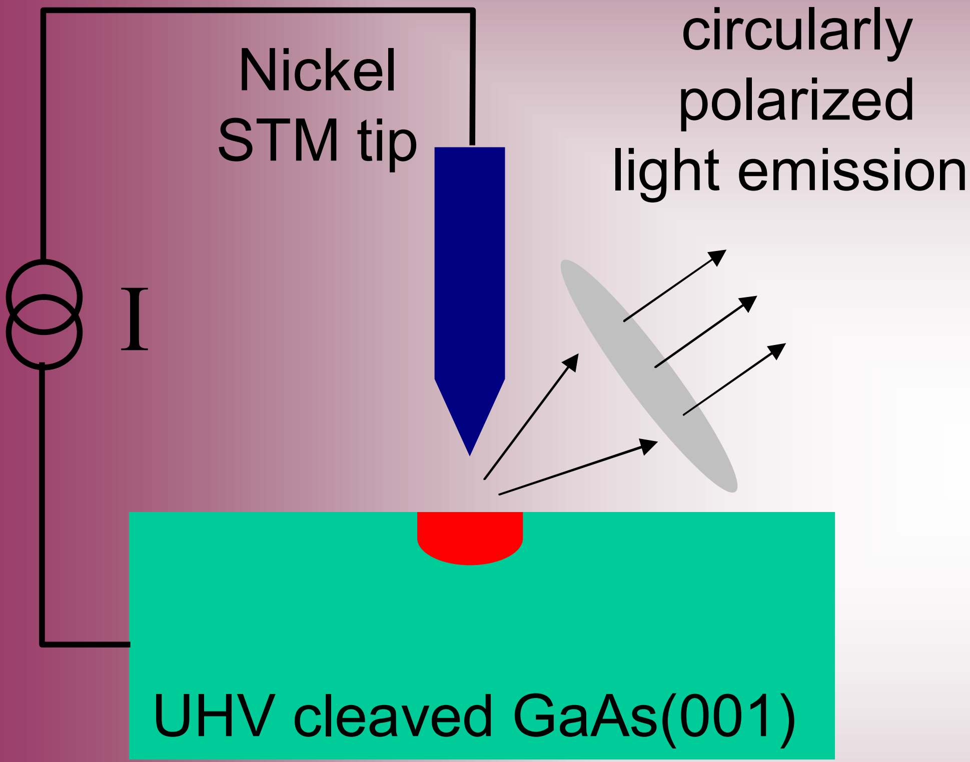
<u>Electric field + spin-orbit interaction</u>

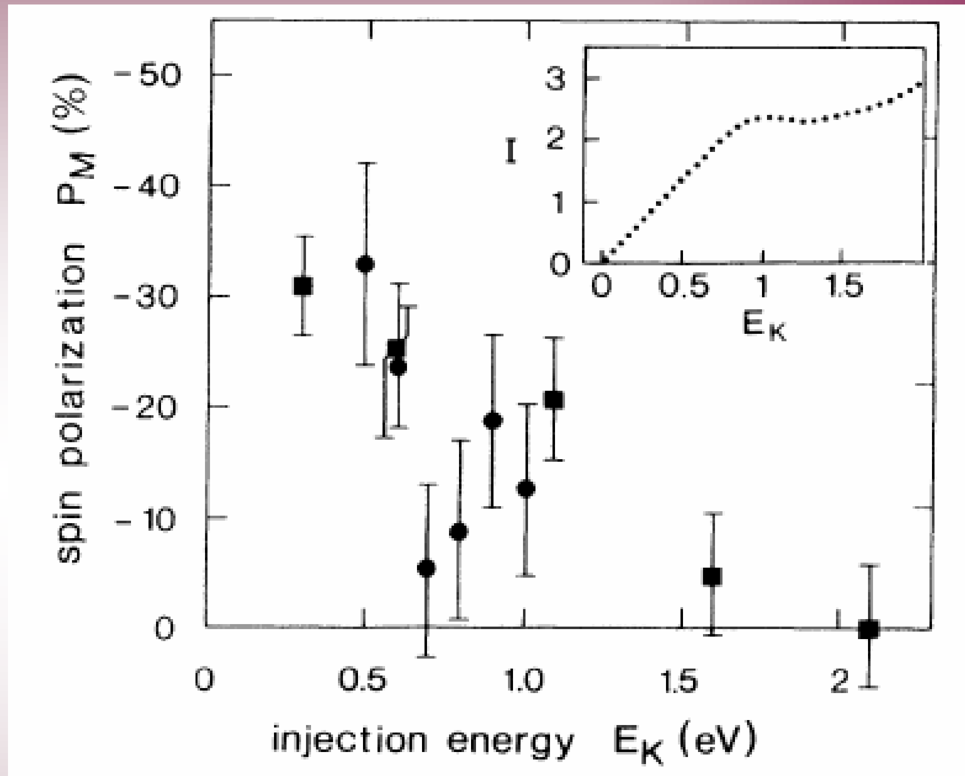
- Spin Hall effect etc.

Not in this talk

First electrical spin injection - 1992

current injection across vacuum tunnel barrier



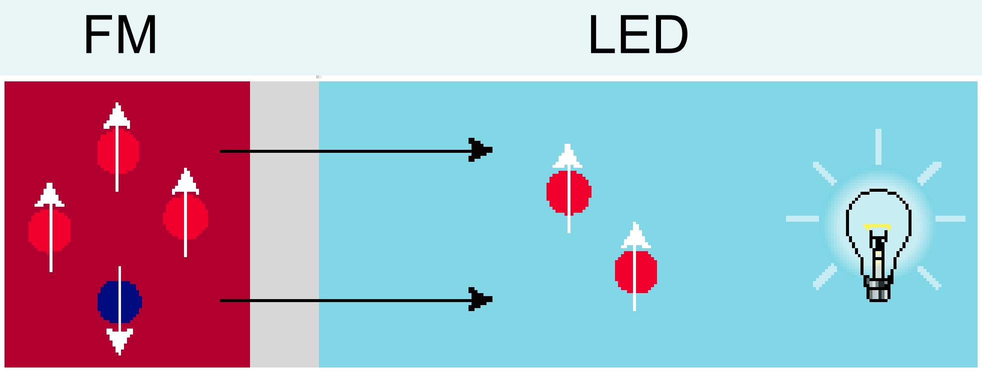


Observation of spin-polarized-electron tunneling from a ferromagnet into GaAs
S.F. Alvarado and P. Renaud, PRL 68, 1387 (1992).

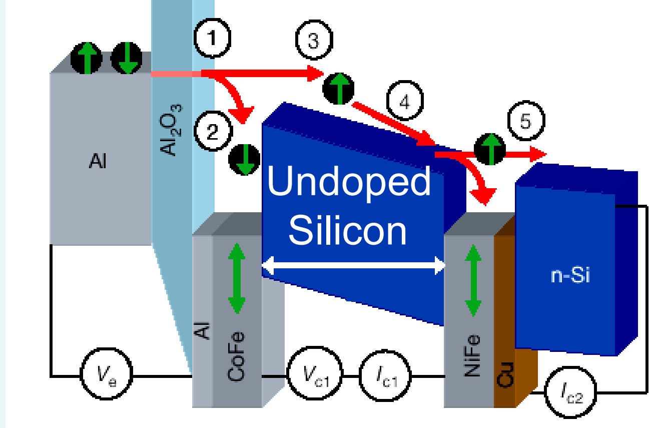
Tunneling potential barrier dependence of electron spin polarization,
S.F. Alvarado, PRL 75, 513 (1995).

Solid state devices for spin injection/detection

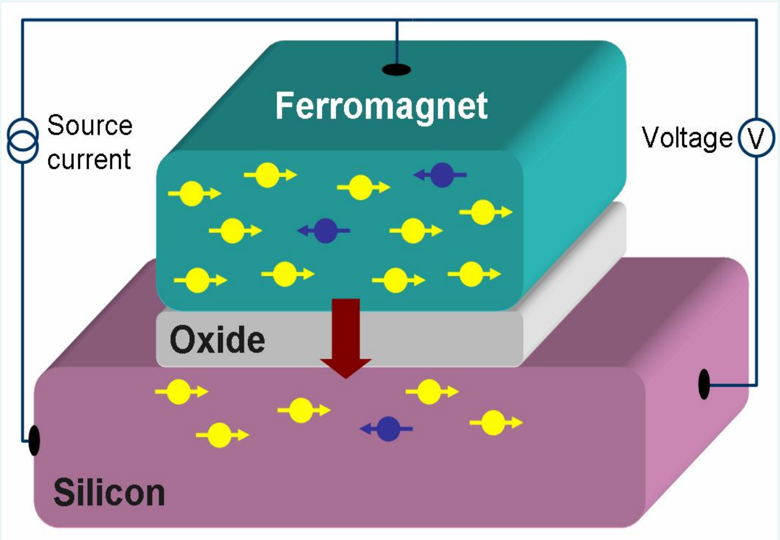
Optical detection in spin-LED



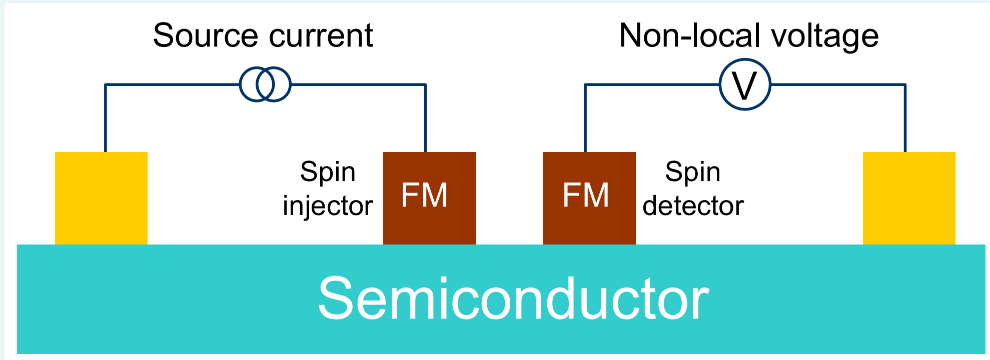
Hot-electron spin filtering



3-terminal, single interface



4-terminal, non-local



Key developments since 2007

2007

Spin transport in Si (hot electrons, low T)
Appelbaum & Co. (2007)

Electrical spin injection & detection
in GaAs (low T). Crowell & Co. (2007)

Spin injection in Si spin-LED (low T)
Jonker & Co. (2007)

2008

2009

Electrical spin injection & detection
in Si at 300 K (n- and p-type)
Jansen & Co. (2009)

2010

Electric-field control of spin in Si 2DEG
(without S-O interaction, low T, large B)
Jansen & Co. (2010)

2011

Non-local spin-valve Si channel, 300 K
TDK/Osaka group (2011)

Spin accumulation / transport in n-Ge
Shin & Co. KAIST (2011) &
Wang & Co. UCLA (2011).

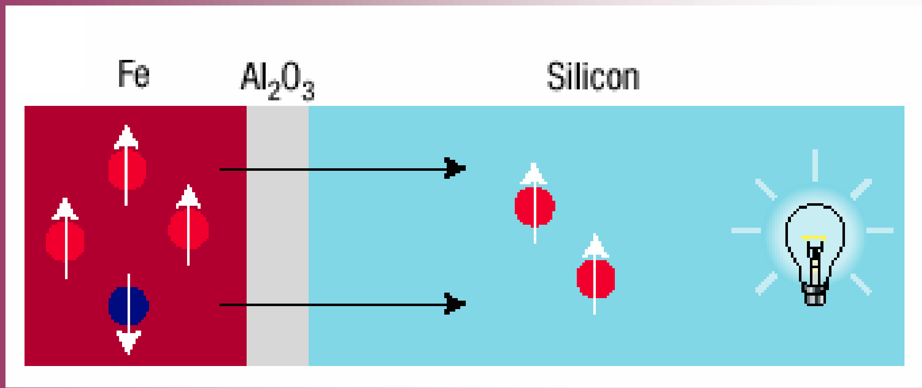
Spin injection & detection in Si at 300 K
reproduced. Jonker & Co. (2011)
(error in data interpretation)

Spin accumulation in p-Ge/MgO/Fe (low T)
Saito & Co. AIST (2011).

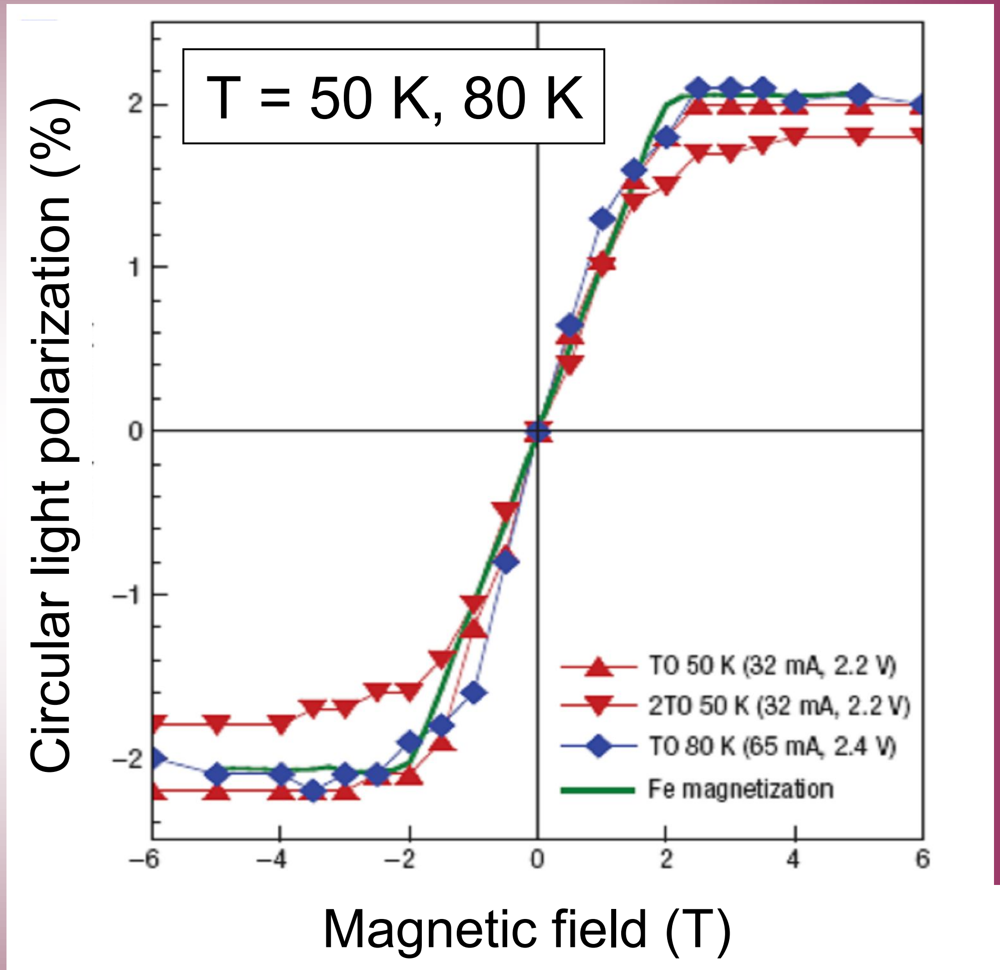
Spin injection into silicon by tunneling

Optical detection via electroluminescence

Spin-polarized electrons
Recombination with holes
$\Downarrow$
Circularly polarized emission



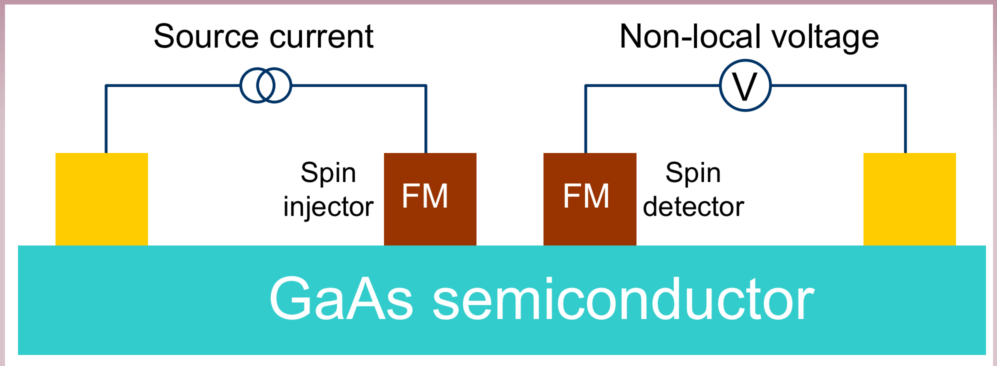
- Si n-i-p LED
- top layer 80 nm n-type Si ($2 \cdot 10^{18}$ cm^{-3})

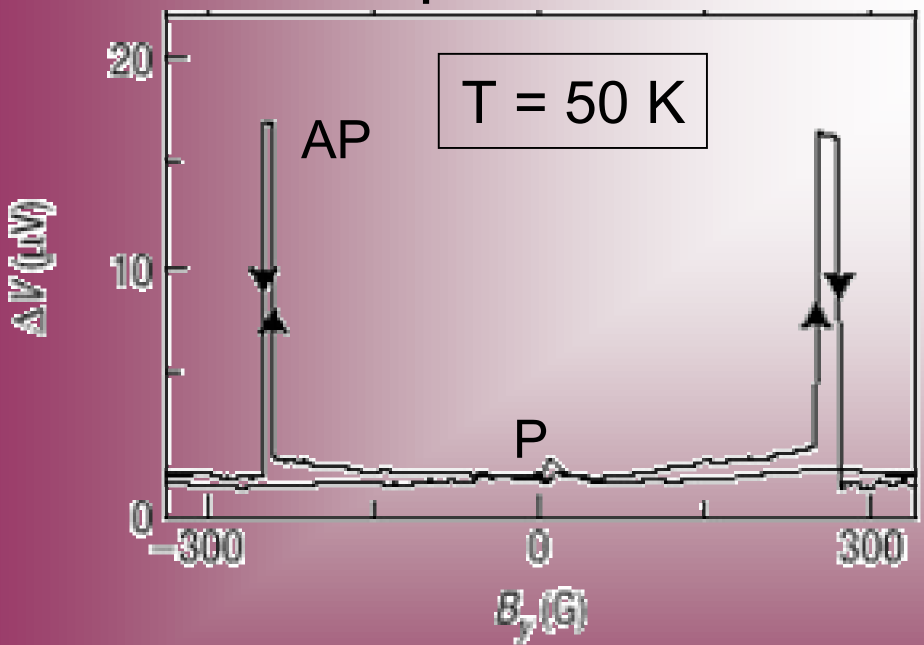


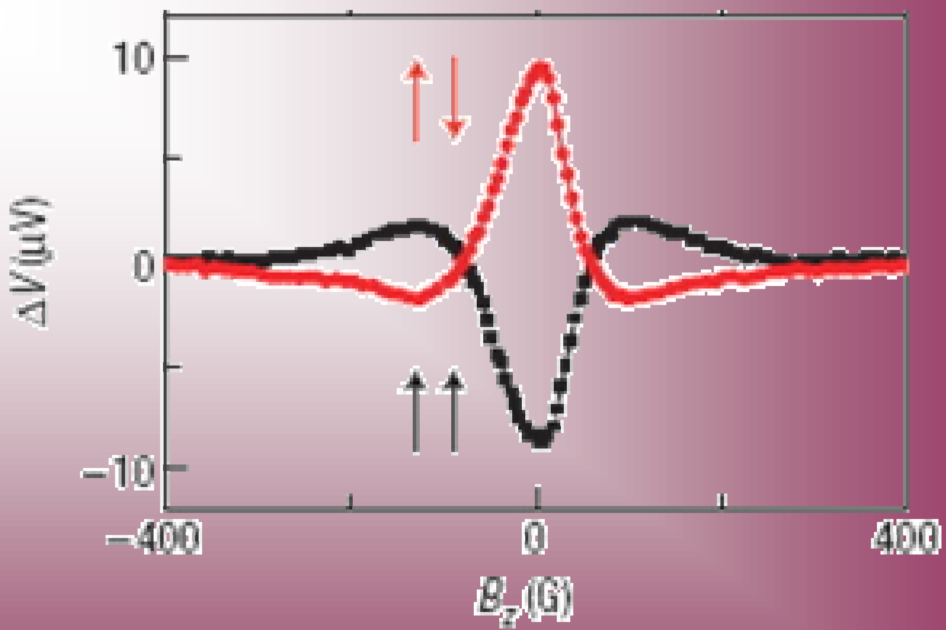
Jonker et al., Nature physics **3**, 542 (2007), see also
Li & Dery, PRL **105**, 037204 (2010) for theory of spin-dependent optical transitions in Si

Electrical spin injection & detection in GaAs

non-local geometry



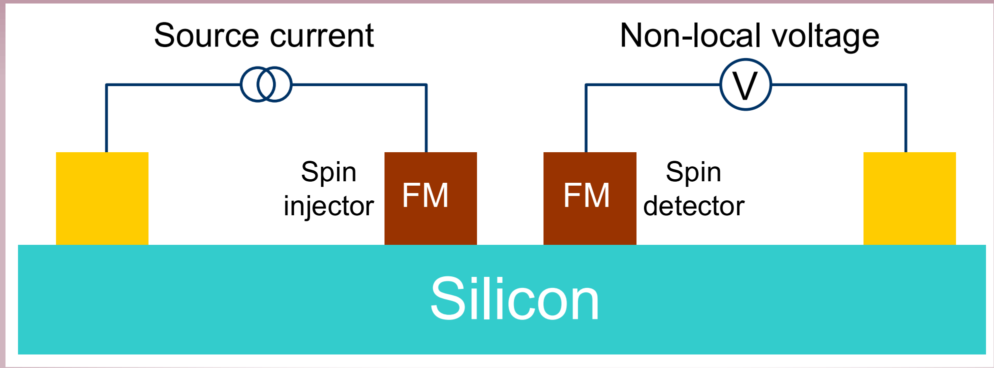




Lou *et al.* Nature Physics **3**, 197 (2007)

Electrical spin injection & detection in Si

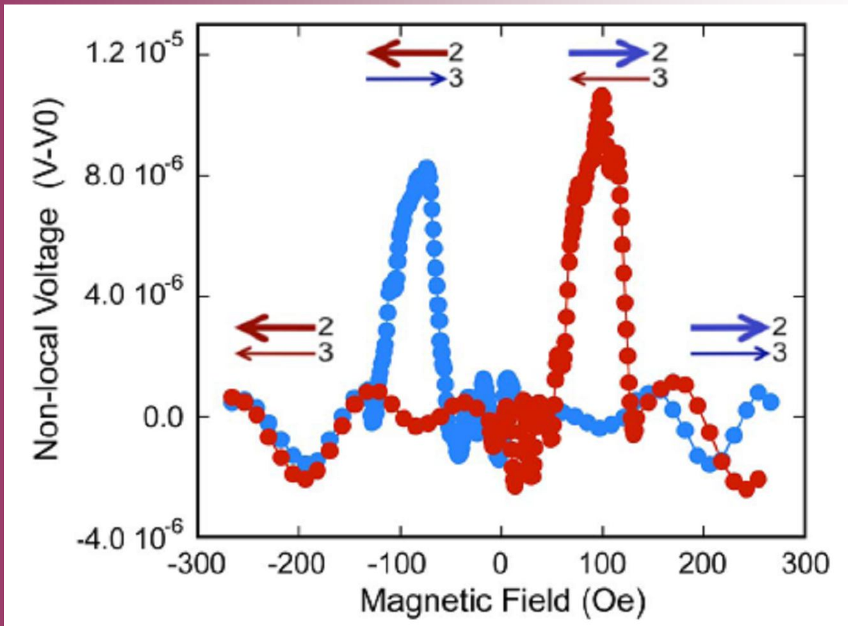
non-local geometry

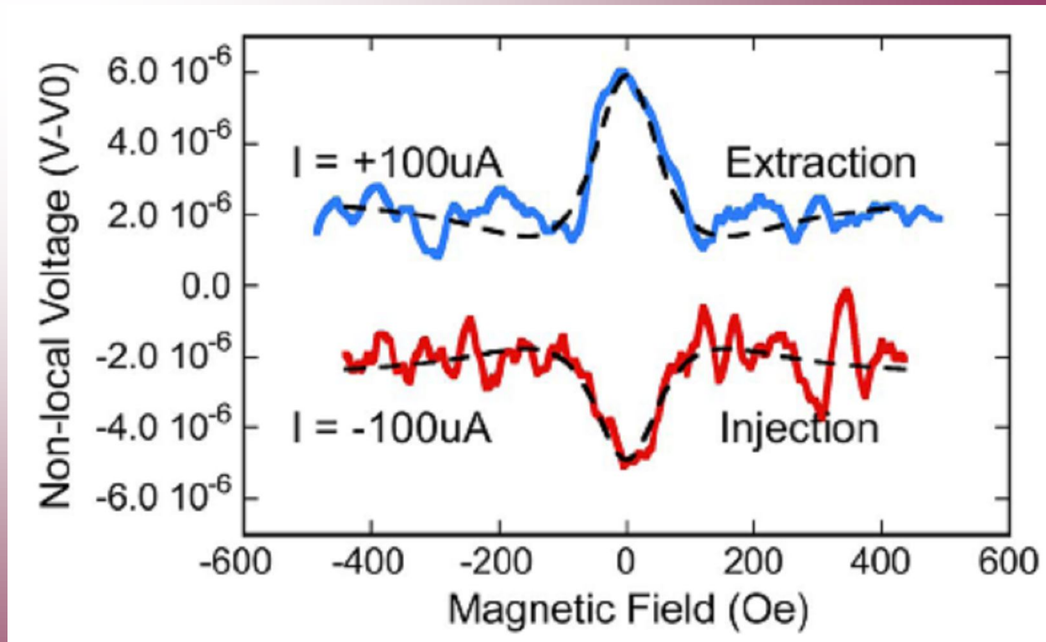


T = 10 K
n-Si ($3\cdot10^{18}$ cm^{-3})

Spin-valve response

Hanle spin precession





van ‘t Erve et al. APL **91**, 212109 (2007)

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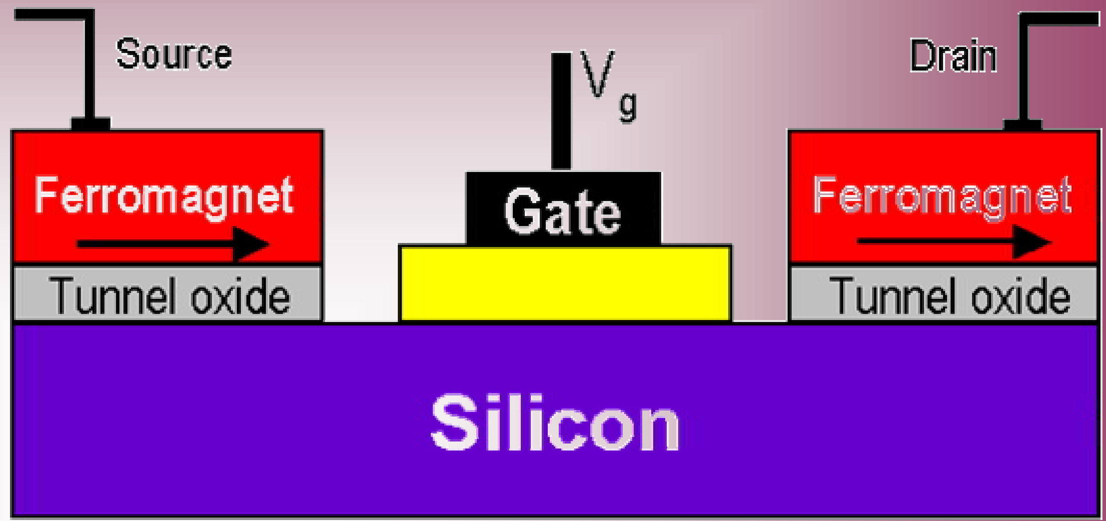
Building blocks for electrical spin devices

Example: the canonical spin-FET



Building blocks:

1) Injection of spin-polarized electrons into semiconductor

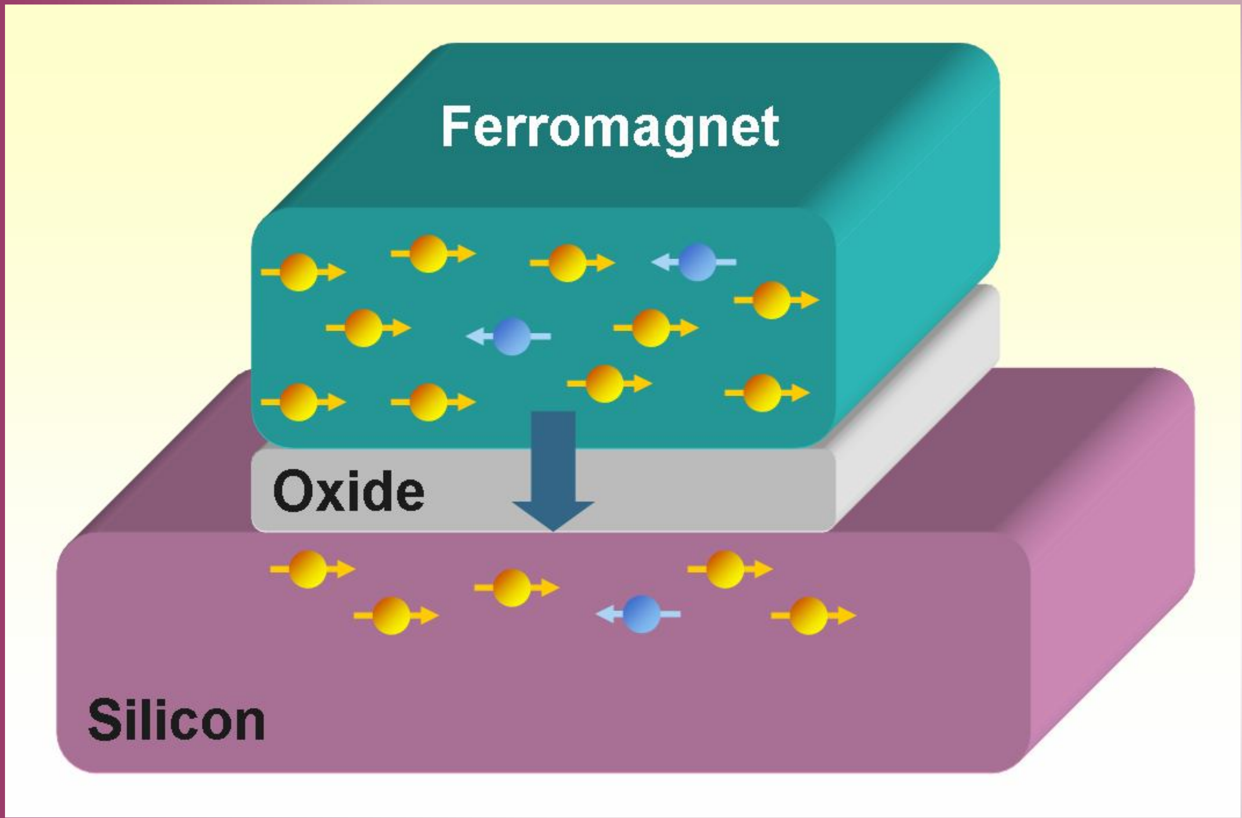
2) Transport spin information through the semiconductor

3) Detection of spin polarization

4) Control of spin polarization by gate electric field

Creation of spin polarization

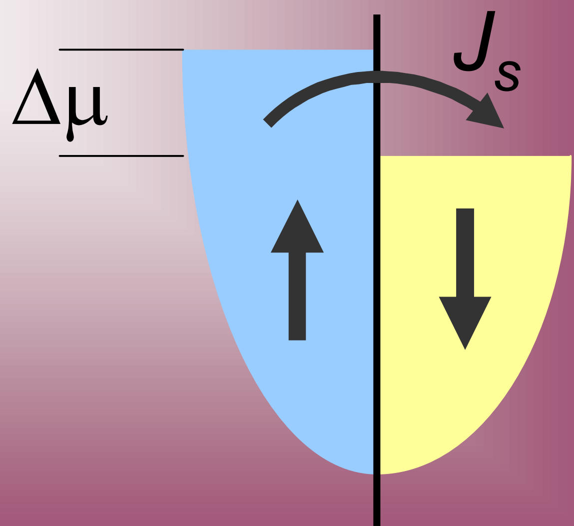
by electrical injection from a ferromagnetic tunnel contact



Transfer of spin information by spin-polarized tunneling

Creates spin accumulation

$$\boxed{\Delta\mu = \mu^{\uparrow} - \mu^{\downarrow}}$$

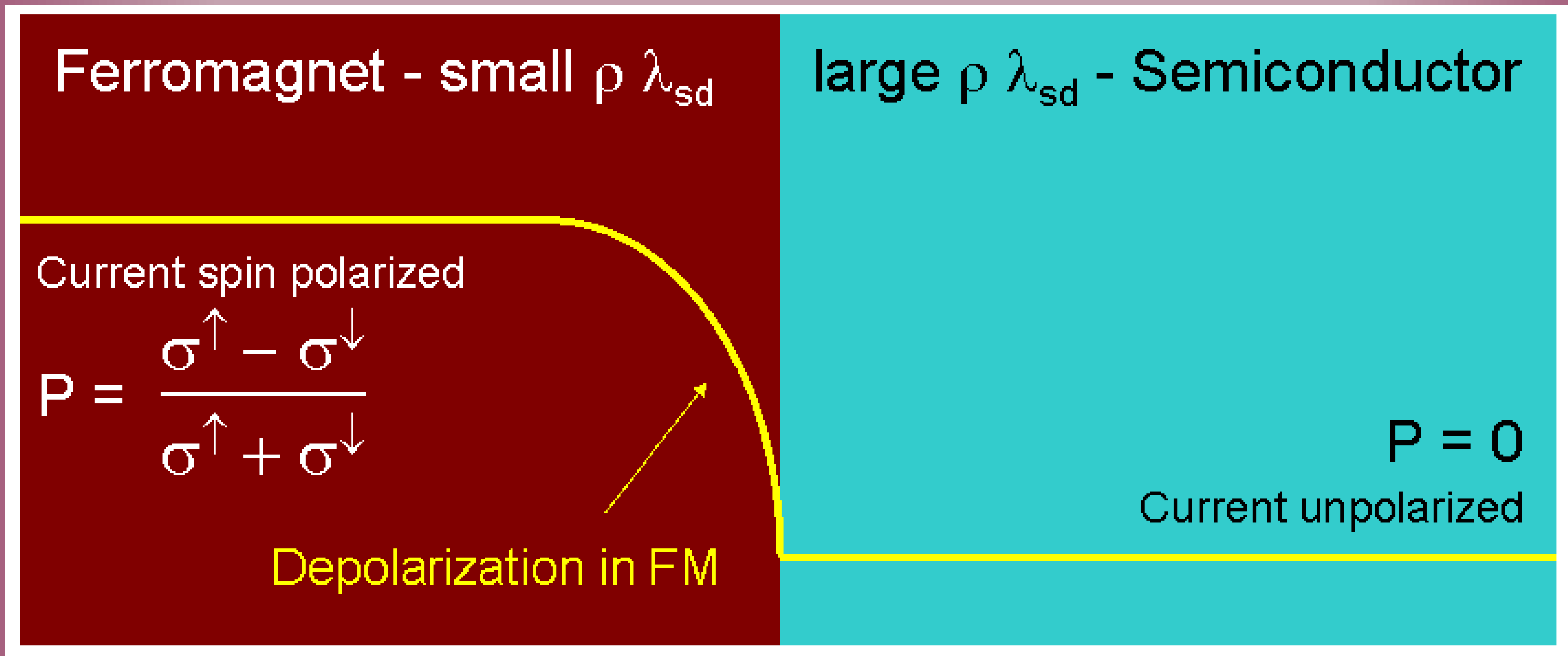


- Supply of spins by current
- Spin relaxation in Si

$\Big\}\ \Delta\mu$

Conductivity mismatch in direct contact

fundamental obstacle for diffusive spin injection ….



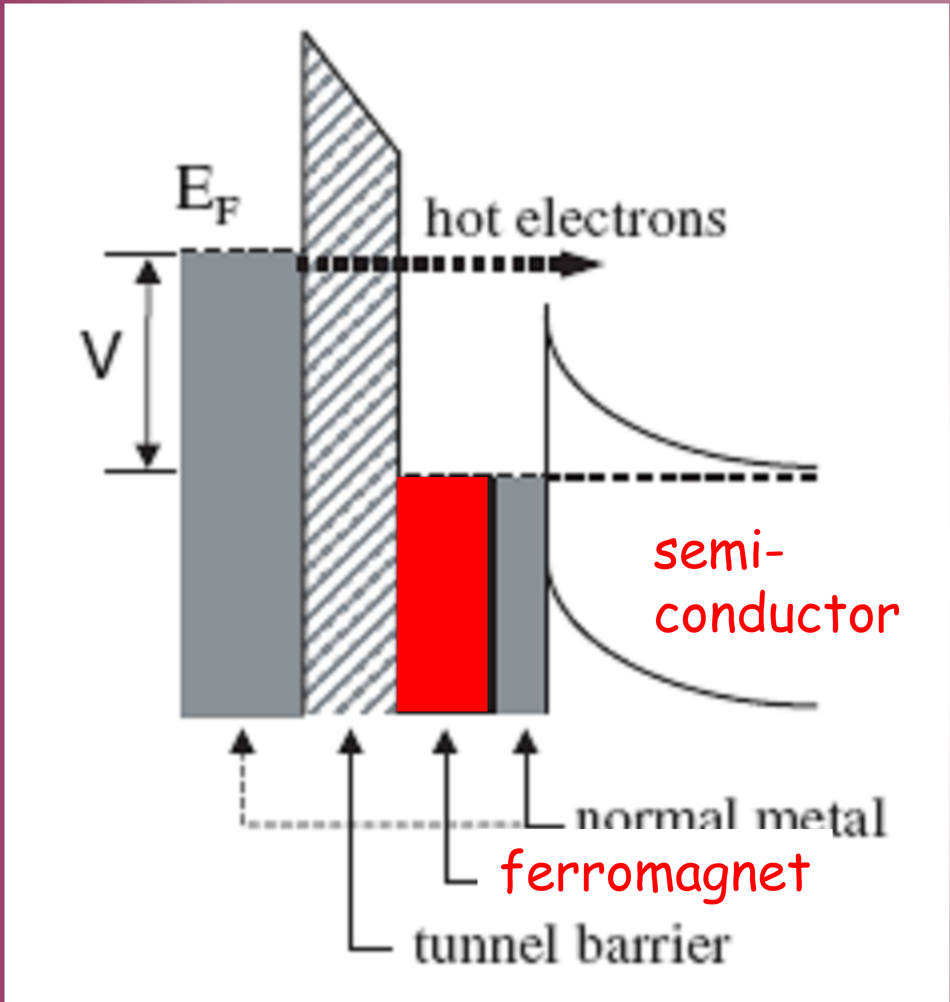
Depolarization of spin current predominantly in ferromagnet
Almost no spin accumulation in semiconductor

ρ resistivity

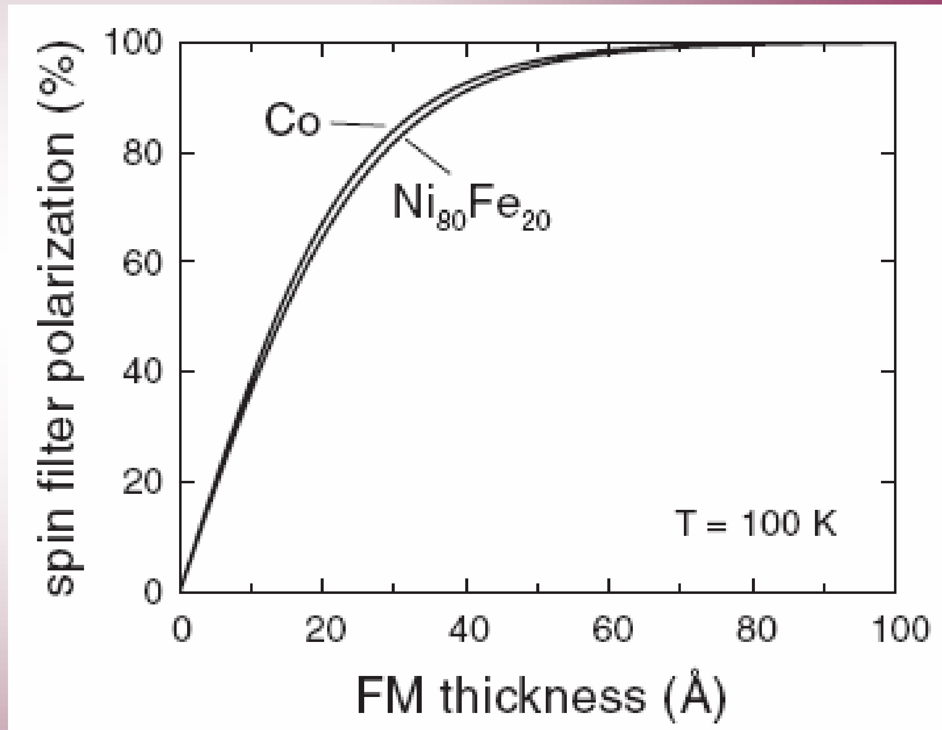
λ_{sd} spin-diffusion length

Schmidt et al. PRB 62, R4790 (2000).

Spin injection using hot-electron spin filtering



Hot-electron transport driven by electron kinetic energy.
No conductivity mismatch !!

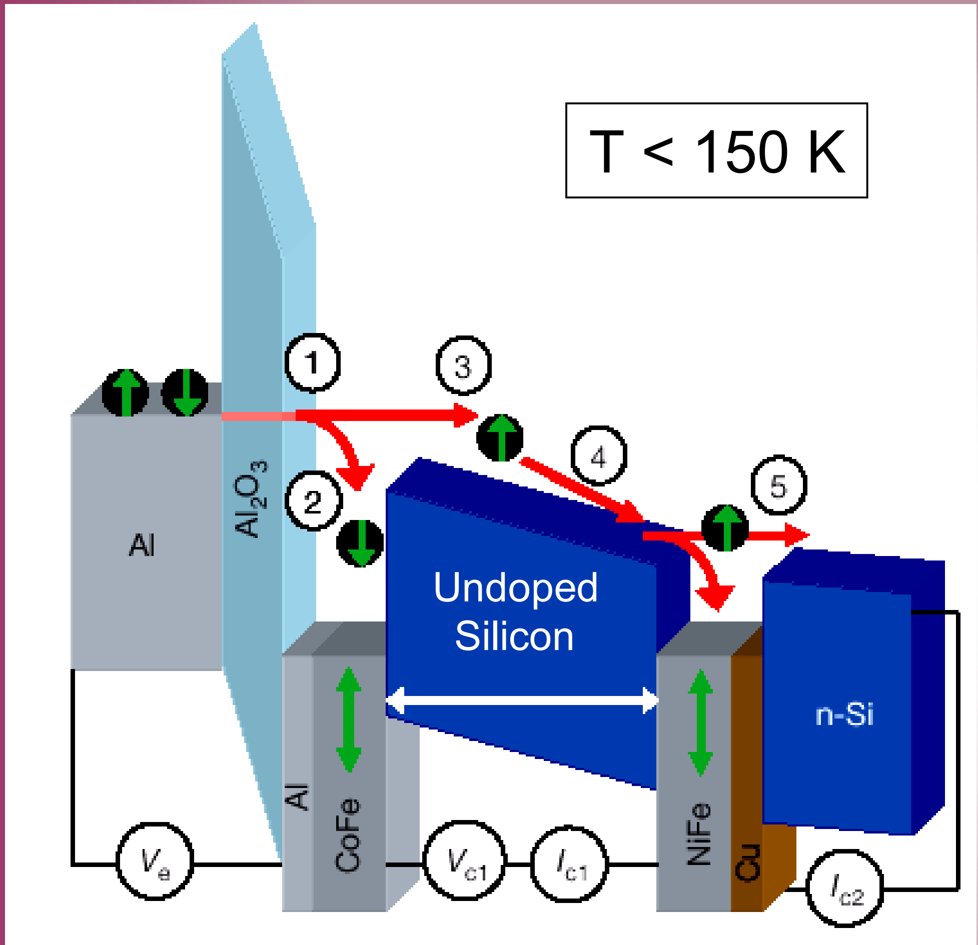


Proposed in 2003 as a way to circumvent the conductivity mismatch
R. Jansen, J. Phys. D **36**, R289 (2003).

Experimental demonstration in 2007 by Appelbaum *et al.* Nature 447, 295 (2007).

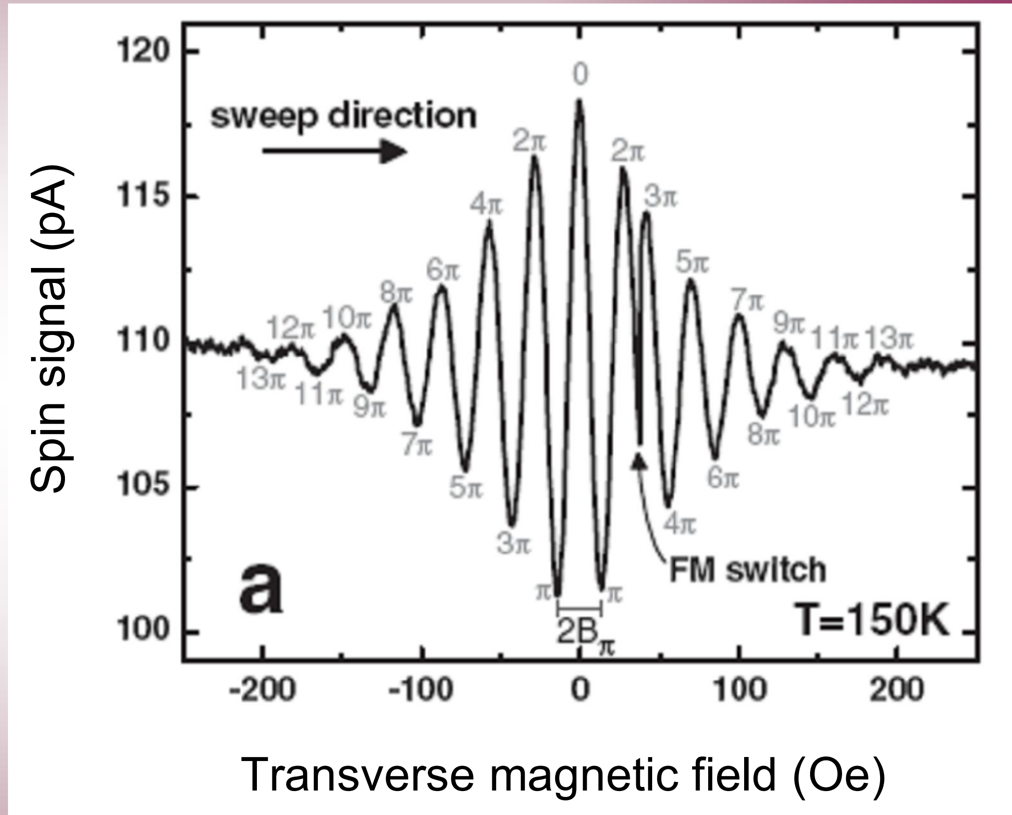
Spin transport in silicon using "hot" electrons

undoped Si, low T



FM 1 FM 2

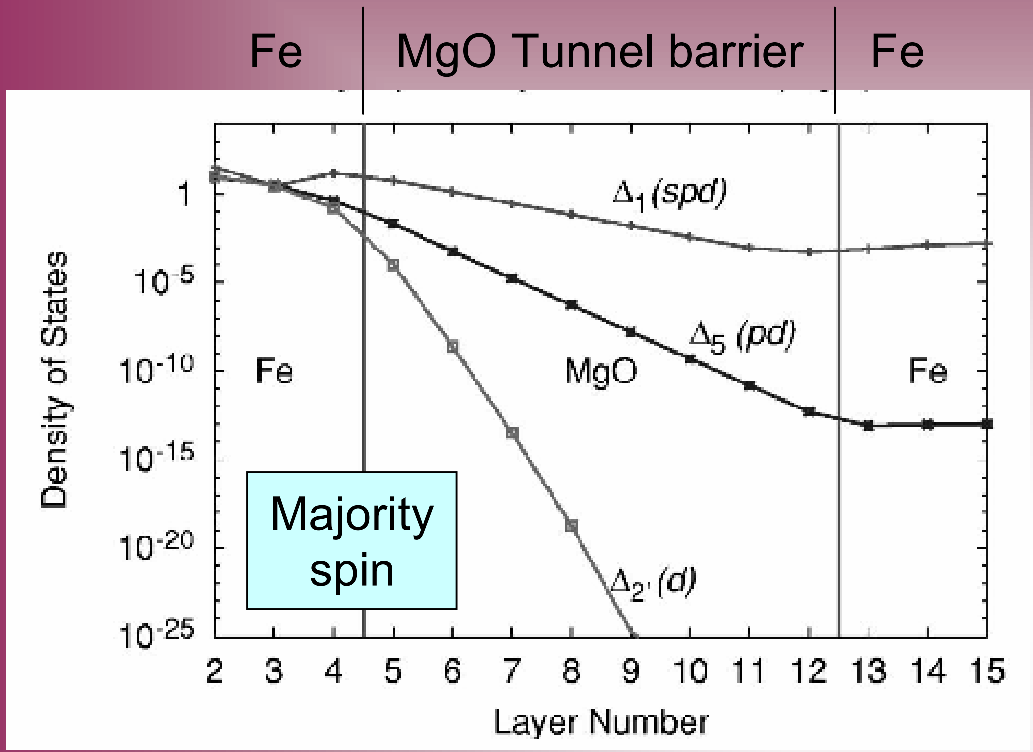
Very long spin coherence time (undoped Si at low T)

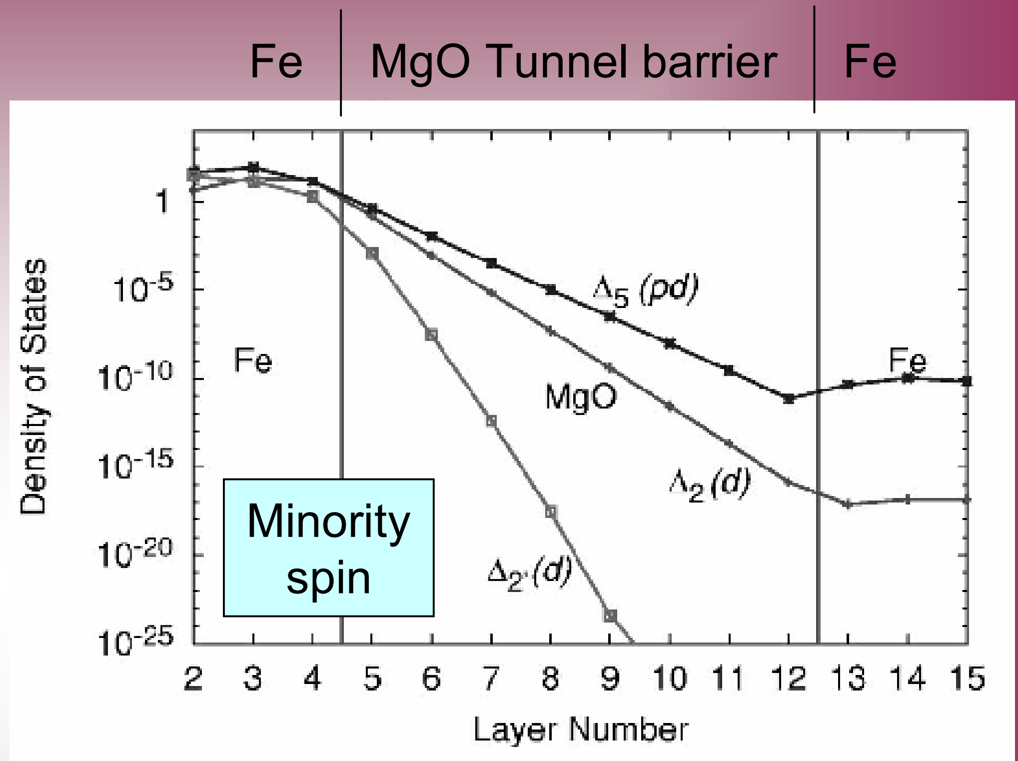


- not a very practical geometry
- small current levels

Appelbaum *et al.* Nature **447**, 295 (2007) & PRL **99**, 177209 (2007).

Intermezzo: Spin-polarized tunneling



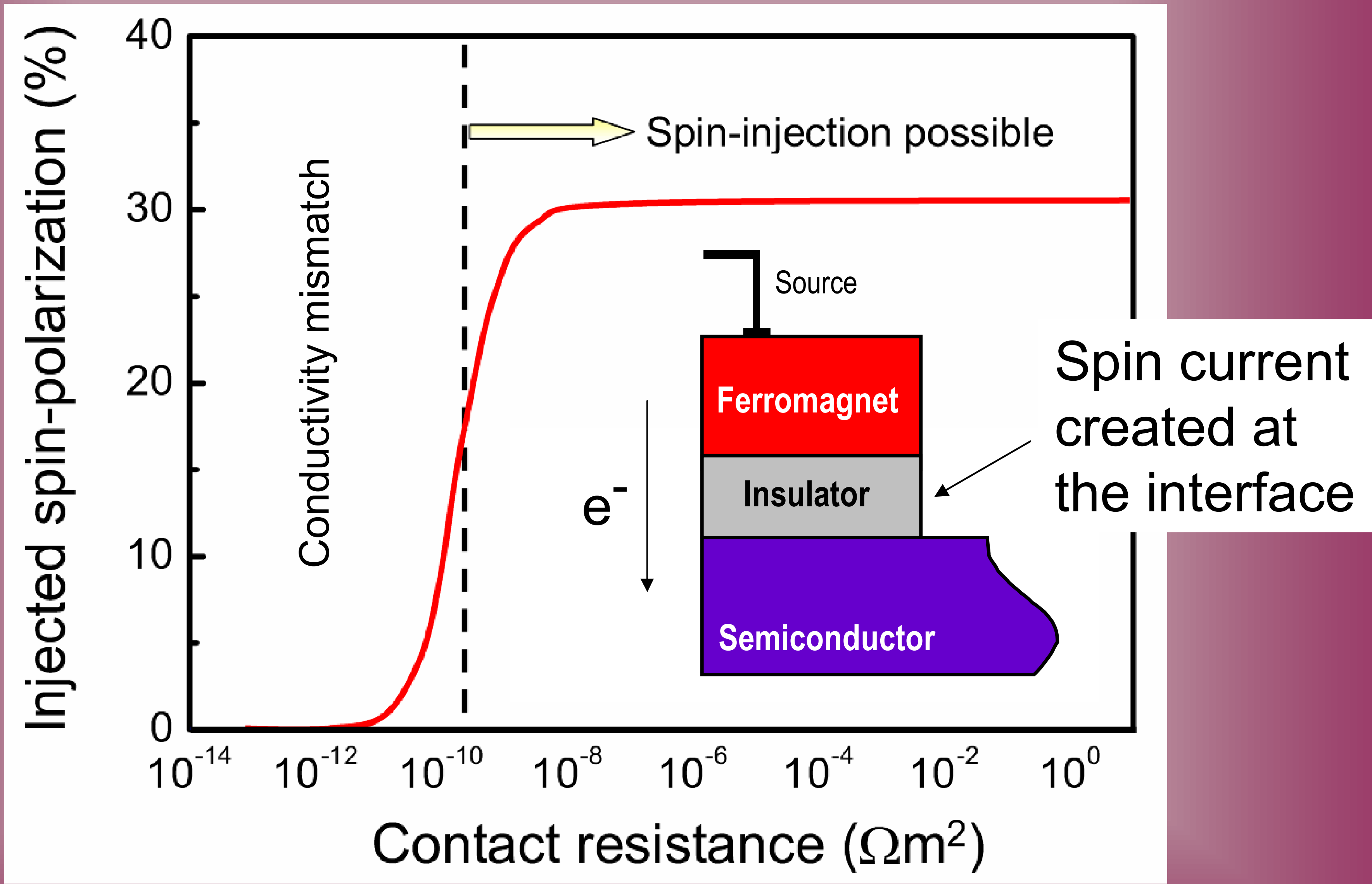


Minority spin states of Fe decay much faster into the MgO barrier:

⇒ Tunnel current from the ferromagnet across the thin insulator is highly spin-polarized

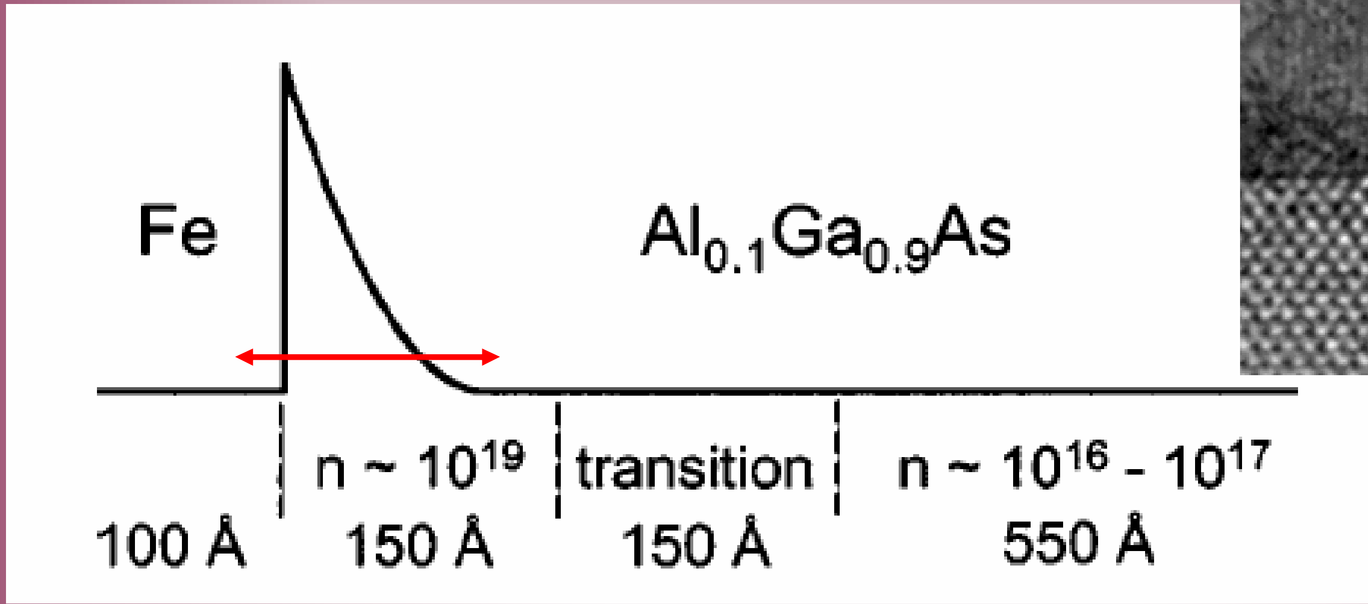
Spin injection by tunneling

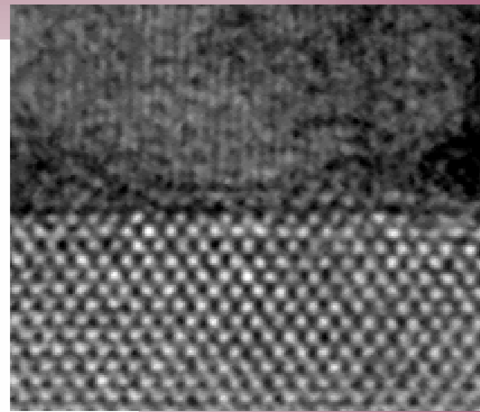
spin-dependent interface resistance



Spin injection into a semiconductor

Schottky tunnel contacts





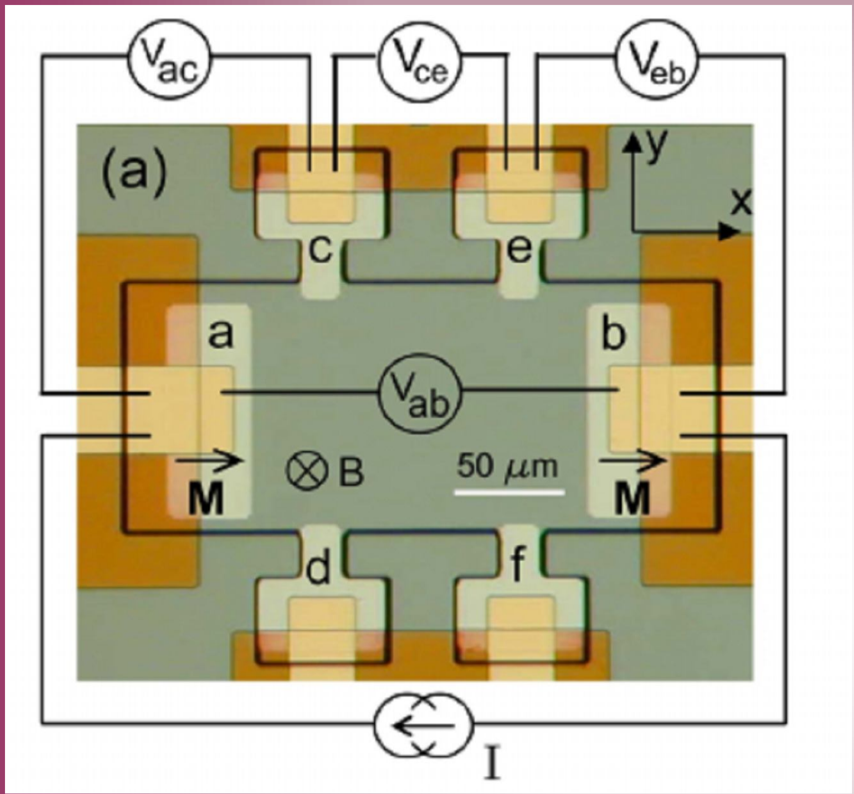
Grown by MBE

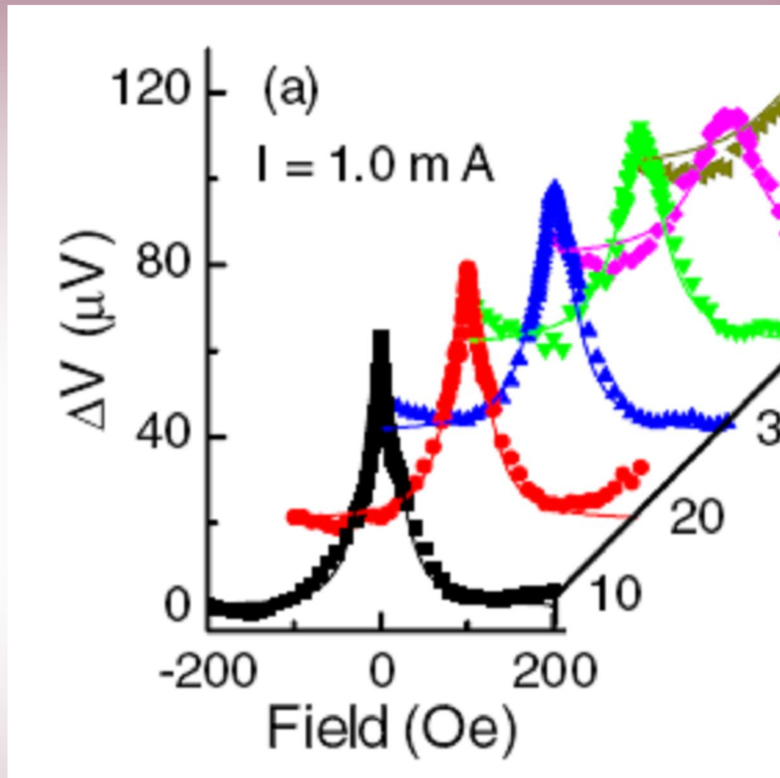
Tunneling across the narrow Schottky energy barrier between metal (Fe) and semiconductor (AlGaAs)

Optical spin detection: Hanbicki et al. APL **80**,1240 (2002)

Spin injection via Schottky tunnel contact

three-terminal geometry, single contacts





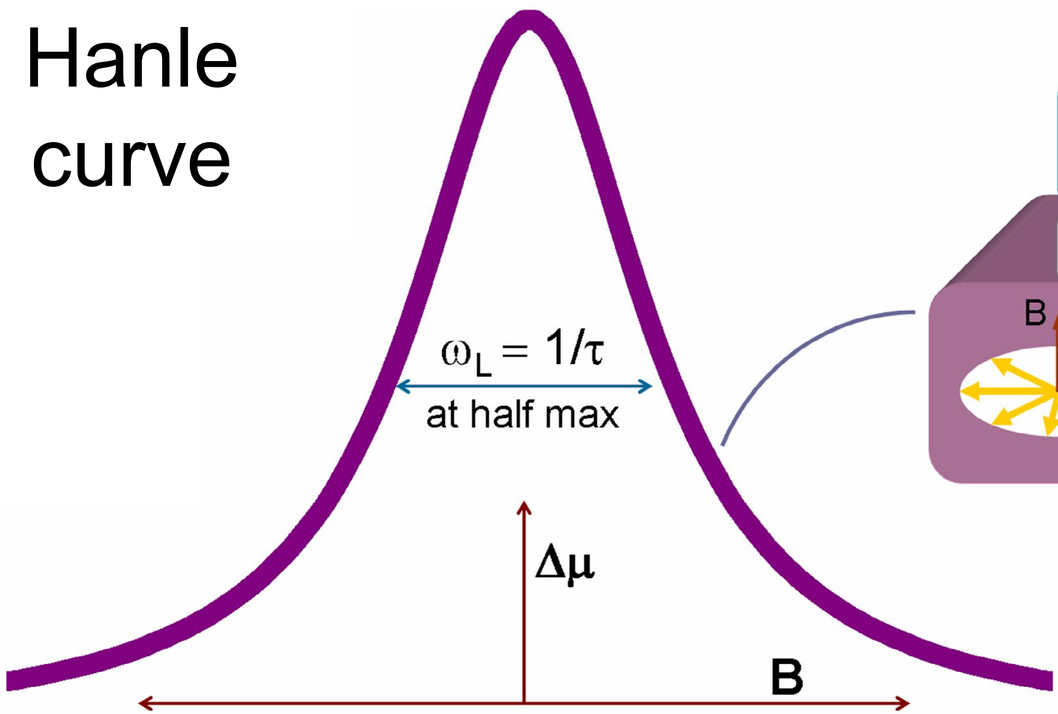
Spin polarization detected via Hanle effect

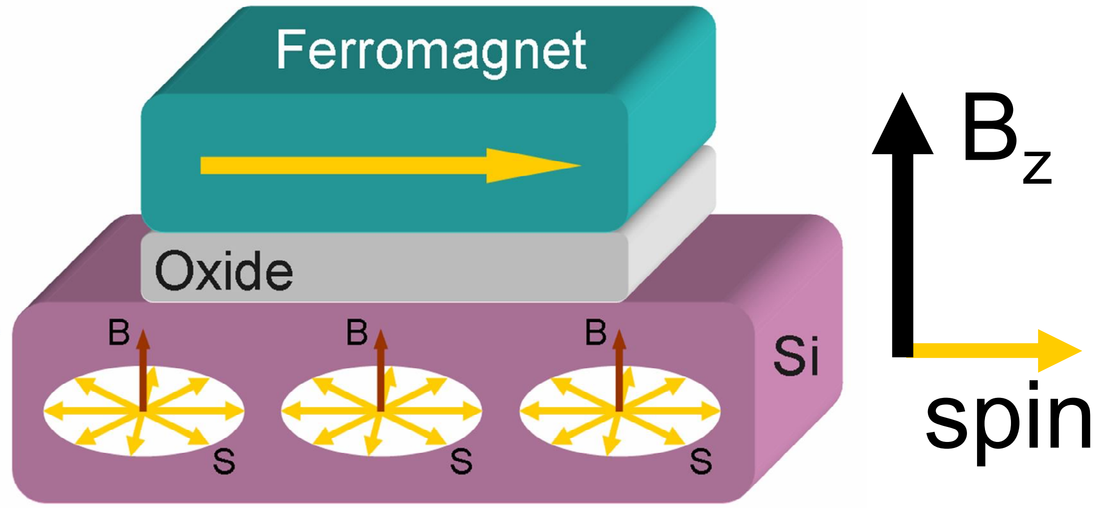
Three-terminal measurement
Probes spins under a
<u>single</u> magnetic contact

n-type GaAs,
Lou et al. PRL 96, 176603 (2006)

Spin manipulation by the Hanle effect

Precession of spins in transverse magnetic field





Transverse magnetic field B_z

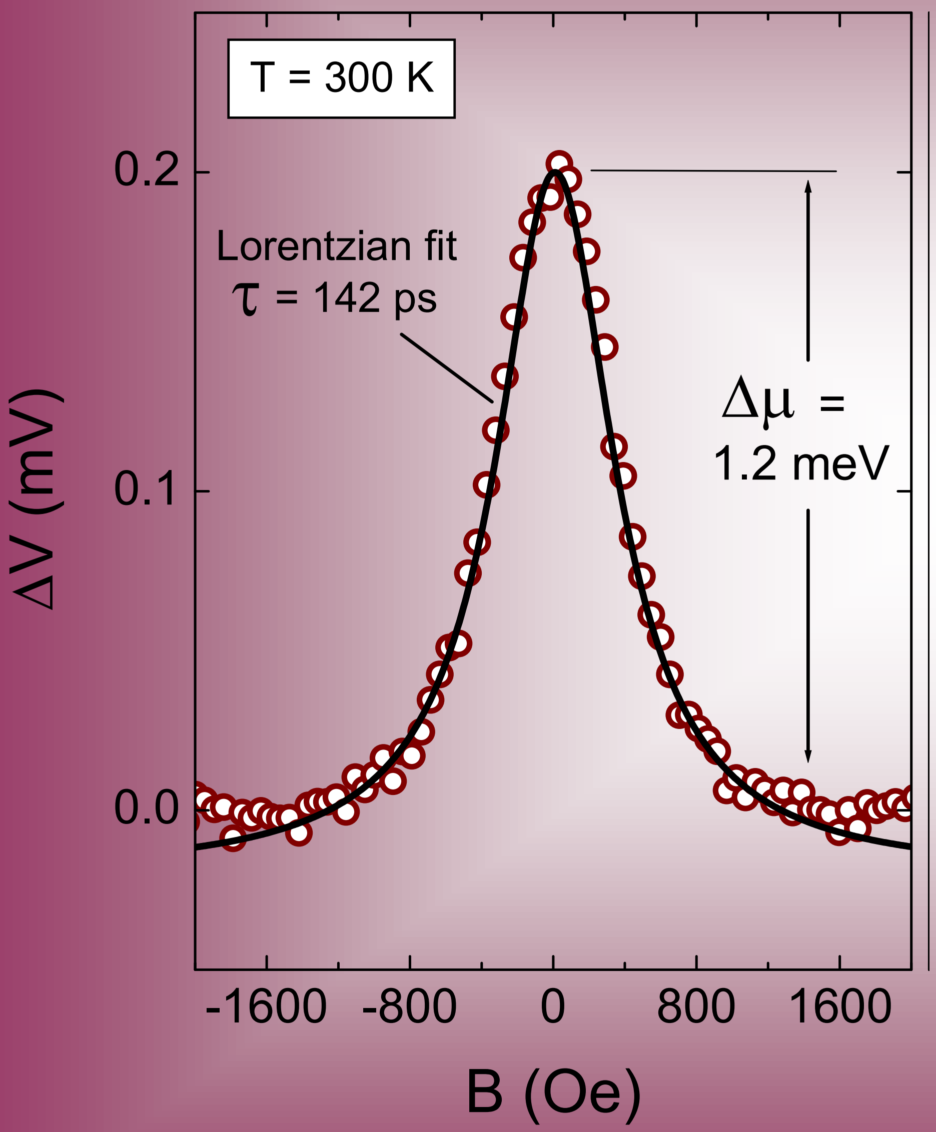
$\Rightarrow$ Spin precession

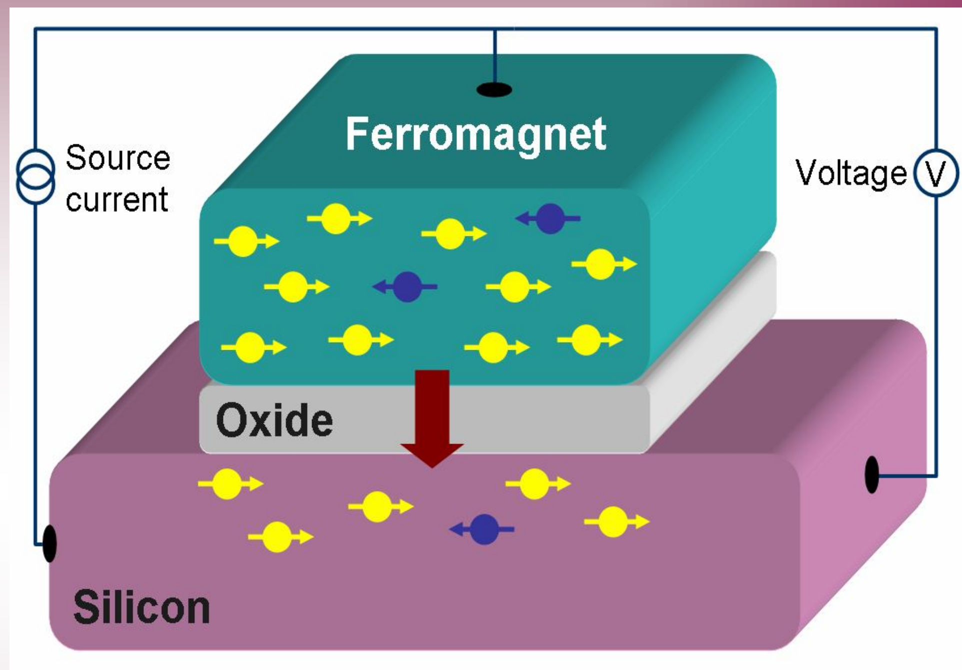
$\Rightarrow$ Suppression of spin accumulation

Hanle line-width inversely proportional to spin lifetime

Spin polarization in n-type silicon at 300 K

Silicon / Al_2O_3 / $Ni_{80}Fe_{20}$





$n = 1.8 \cdot 10^{19}$ cm^{-3}

100 x 200 μm^2 contacts

3-terminal geometry

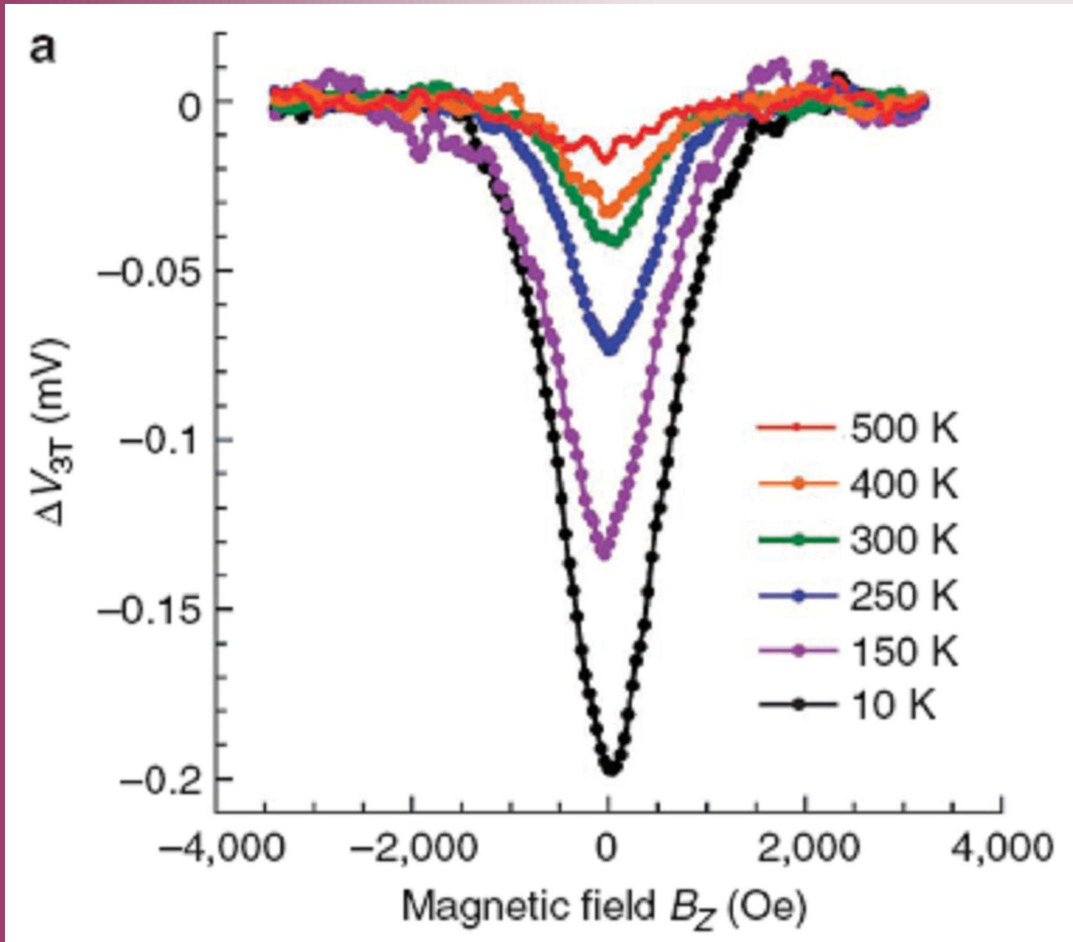
S.P. Dash et al.
Nature 462, 491 (2009)

Spin polarization in n-type Si at 300 K

Reproduced with different barrier materials

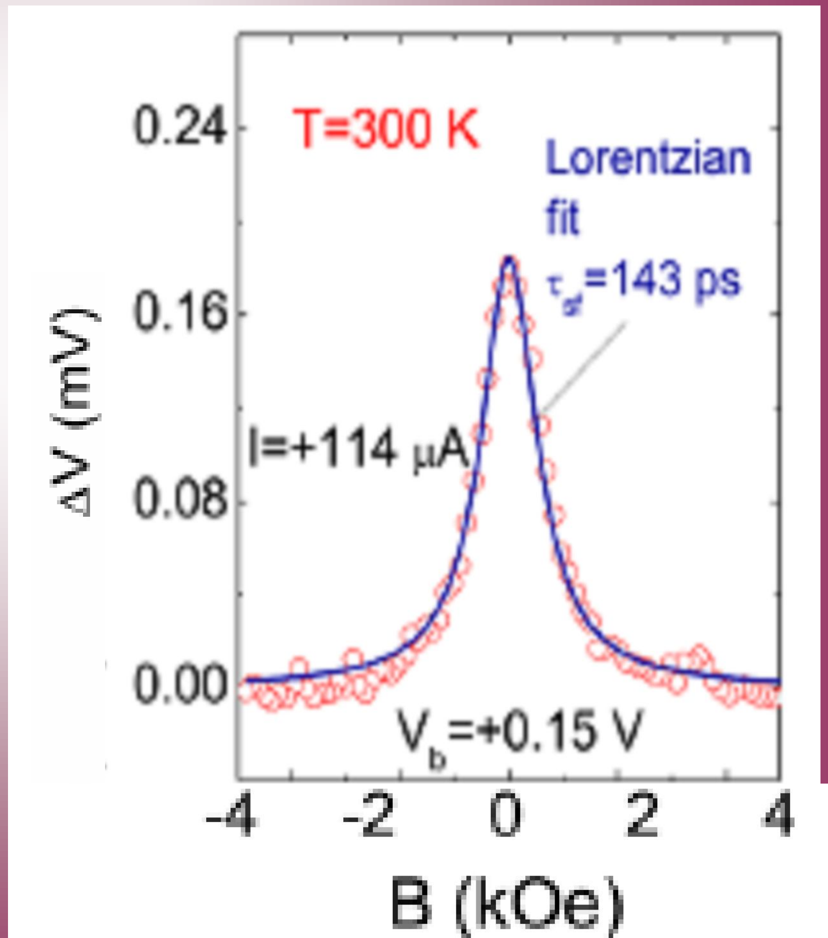
NiFe / SiO_2 / n-Si

Li / Erve / Jonker, Nat. Comm. 2, 245 (2011)



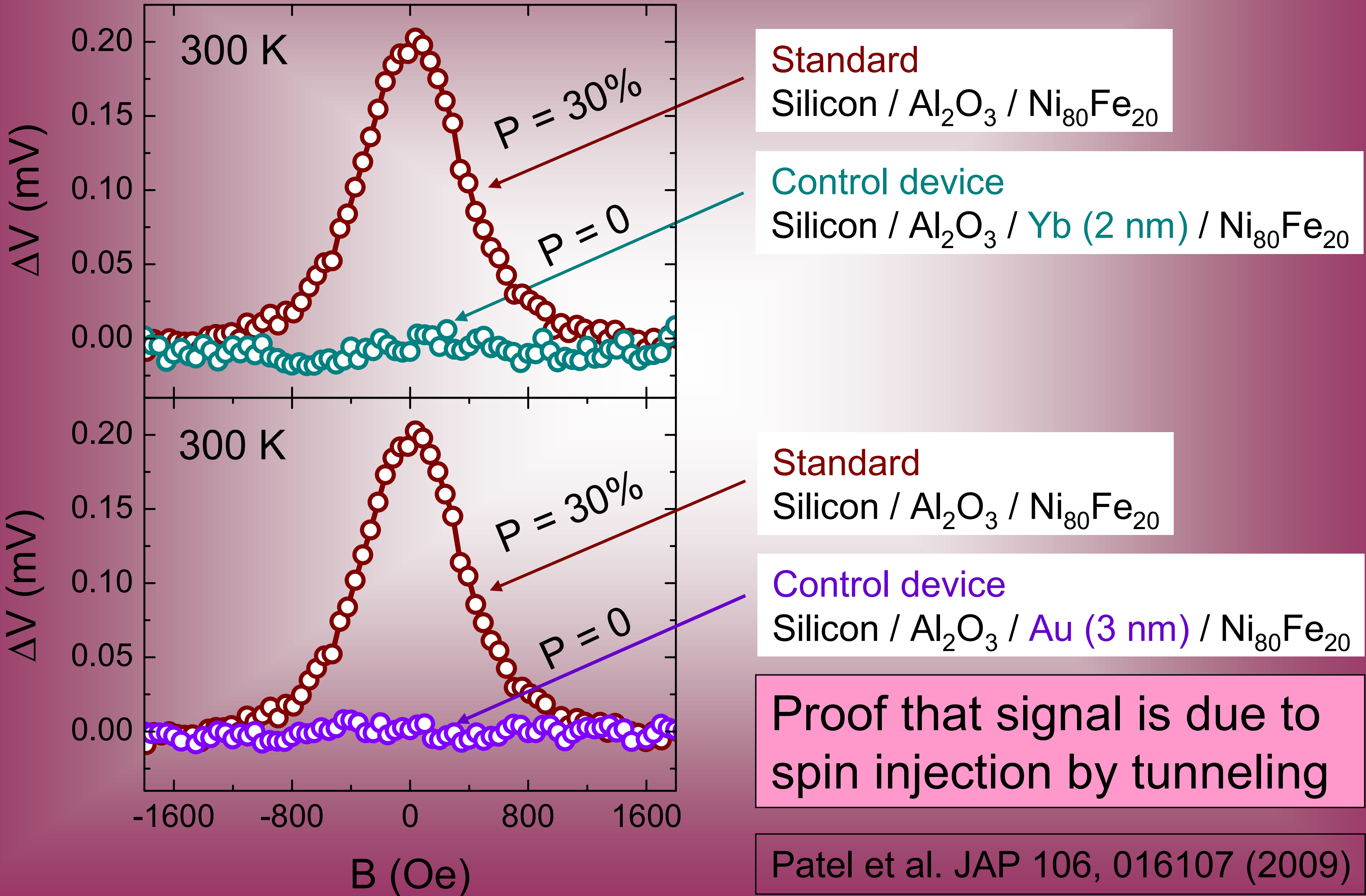
CoFe / MgO / n-Si

Jeon et al. APL 98, 262102 (2011)



Spin polarization in n-type silicon

Control experiment with Yb or Au nanolayer



Proof that signal is due to spin injection by tunneling

Patel et al. JAP 106, 016107 (2009)

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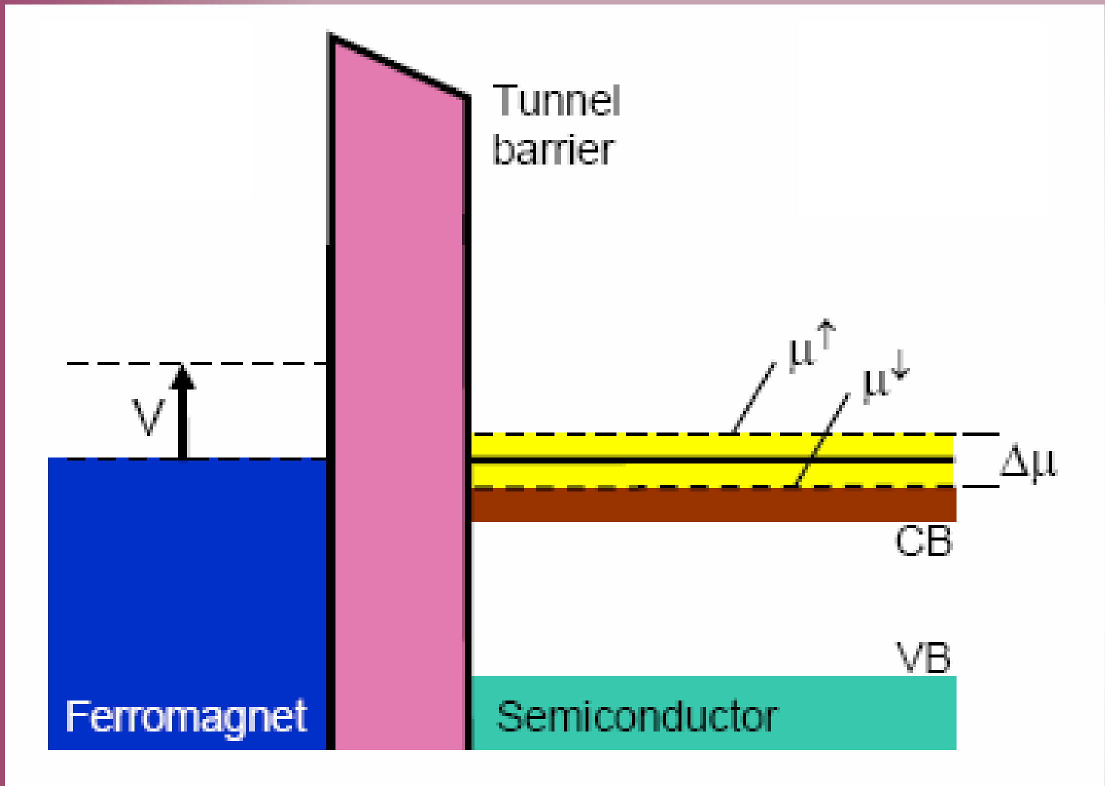
Electrical detection of spin polarization

Ferromagnetic tunnel contact - resistance is proportional to $\Delta\mu$



$$I^{\uparrow} = G^{\uparrow}\left(V - \frac{\Delta\mu}{2}\right)$$

$$I^{\downarrow} = G^{\downarrow}\left(V + \frac{\Delta\mu}{2}\right)$$

Hanle signal at constant tunnel current:

$$\boxed{\Delta V = P * \Delta\mu/2}$$

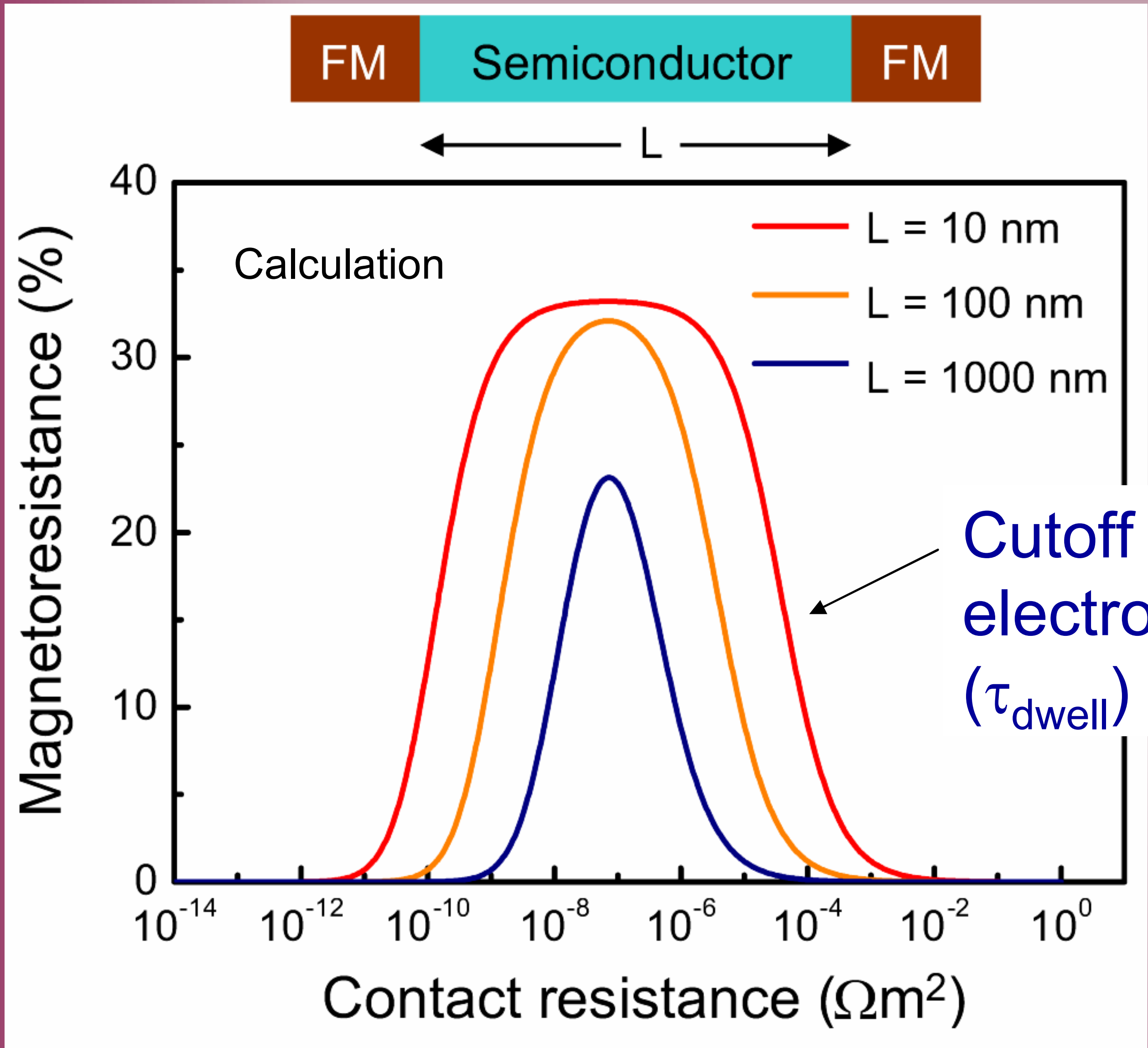
Tunnel spin polarization:

$$P = \frac{G^{\uparrow} - G^{\downarrow}}{G^{\uparrow} + G^{\downarrow}}$$

p.s.
Applies to non-local detection (I = 0)
and to 3-terminal detection ($I \neq 0$)

Spin detection in two-terminal geometry

criteria for observing magnetoresistance



$MR = R^P/R^{AP} - 1$

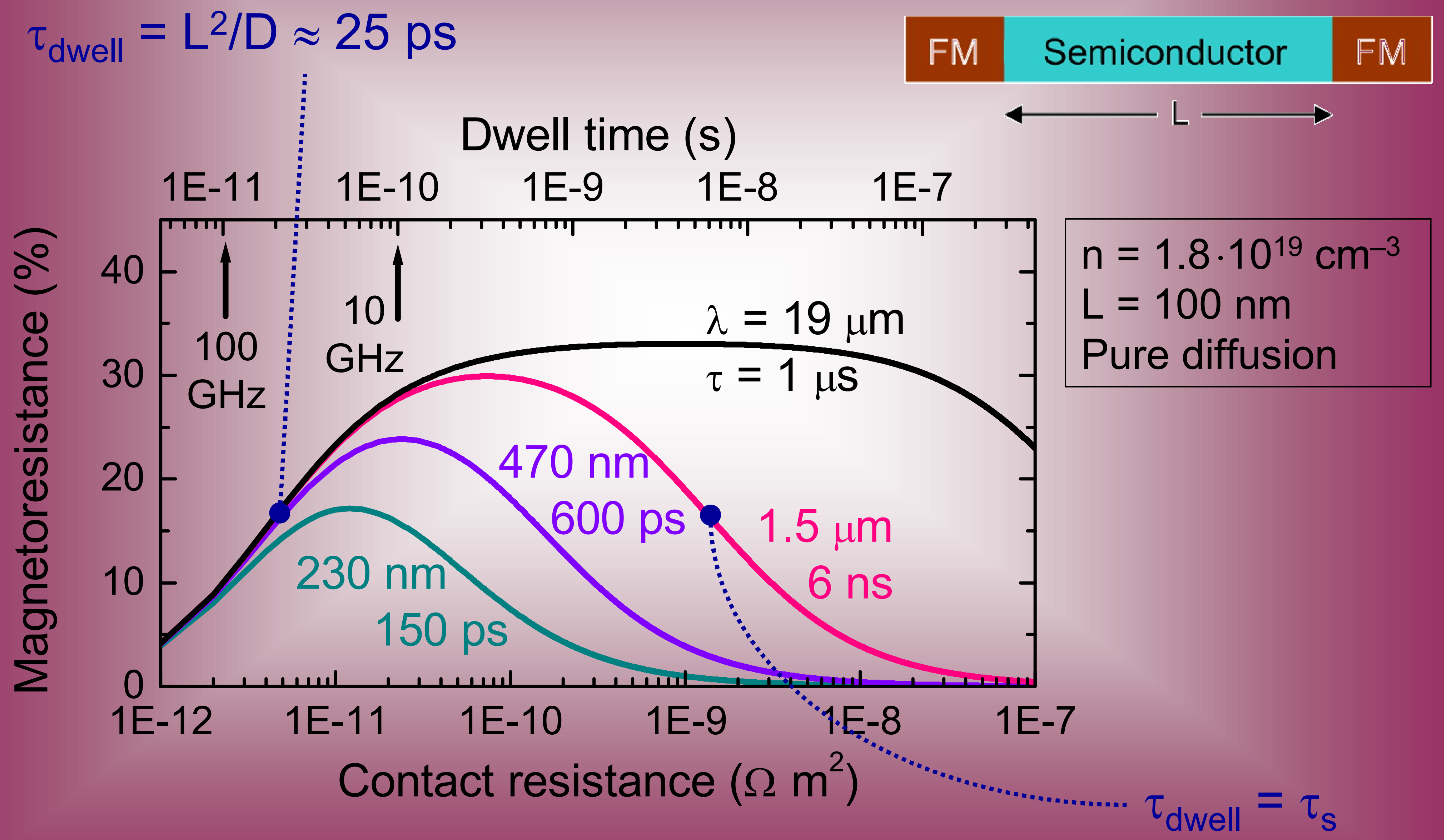
After Fert and Jaffrès
PRB **64**, 184420 (2001)

Cutoff when average time electron spends in channel (τ_{dwell}) becomes > τ_s

Determined by:
- spin relaxation time
- channel length
- mobility

Spin lifetime and high-frequency operation

Two-terminal MR device



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Spin transport

Diffusion, drift, relaxation and precession of spin

Time evolution of spin density S

$$\frac{\delta \overrightarrow{\mathbf{S}}}{\delta t} = \overrightarrow{\mathbf{S}} \times \overrightarrow{\omega_L} + D\nabla^2 \overrightarrow{\mathbf{S}} + \mu E \nabla \overrightarrow{\mathbf{S}} - \frac{\overrightarrow{\mathbf{S}}}{\tau_s}.$$

spin precession — spin diffusion — spin drift — spin relaxation

$$\overrightarrow{\omega_L} = (\omega_x, \omega_y, \omega_z) = (g\mu_B/\hbar)\,(B_x, B_y, B_z)$$

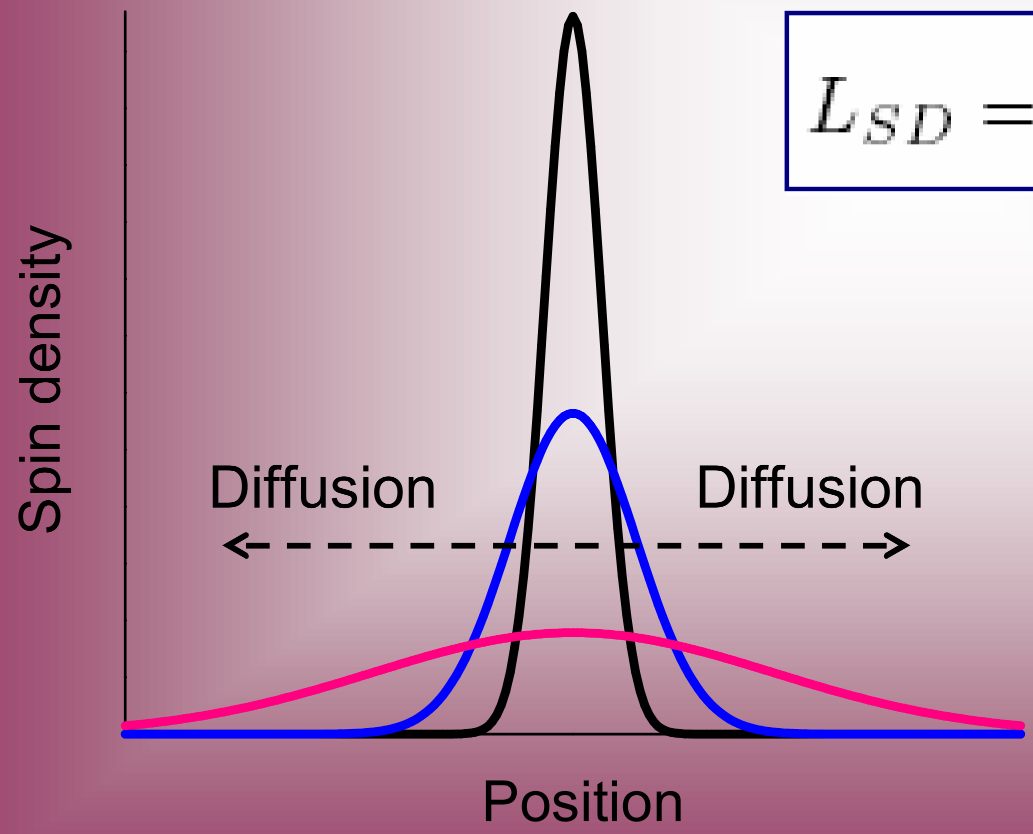
Larmor precession frequency

Spin transport

Spin-diffusion and spin-diffusion length

<u>Spin-diffusion length</u> (L_{SD}):

Distance spin polarization can diffuse during spin lifetime



$$L_{SD} = \sqrt{D\tau_s}$$

Spin lifetime

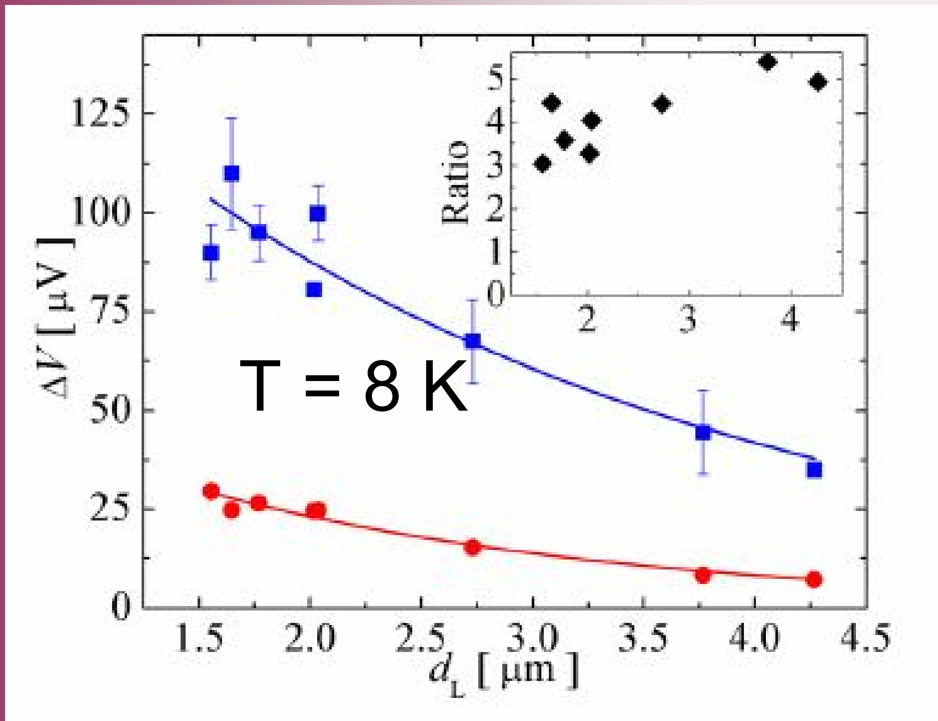
Diffusion constant

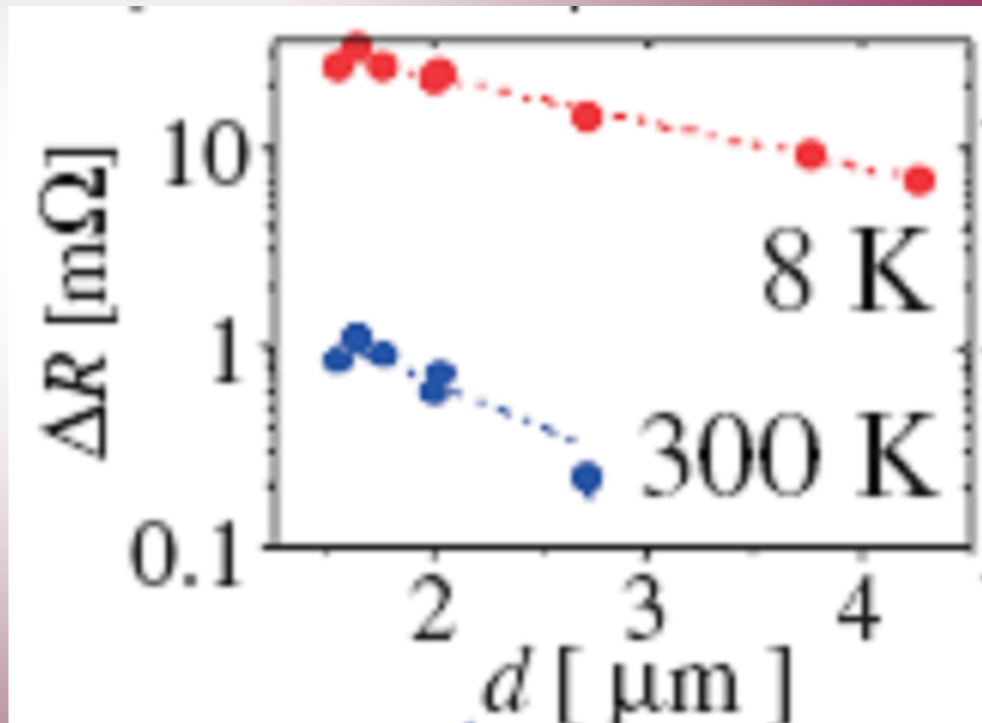
p.s.
diffusion constant for spin and charge can be different
see Yu and Flatte,
PRB 66, 235302 (2002).

Spin transport

Measurement of spin-diffusion length – (1) direct

Direct: measure spin signal as a function of <u>separation</u> d between 2 FM contacts (multiple devices needed).





Suzuki et al.
APEX 4, 023003 (2011)

n-type Si
$\sim 10^{19}$ cm^{-3}

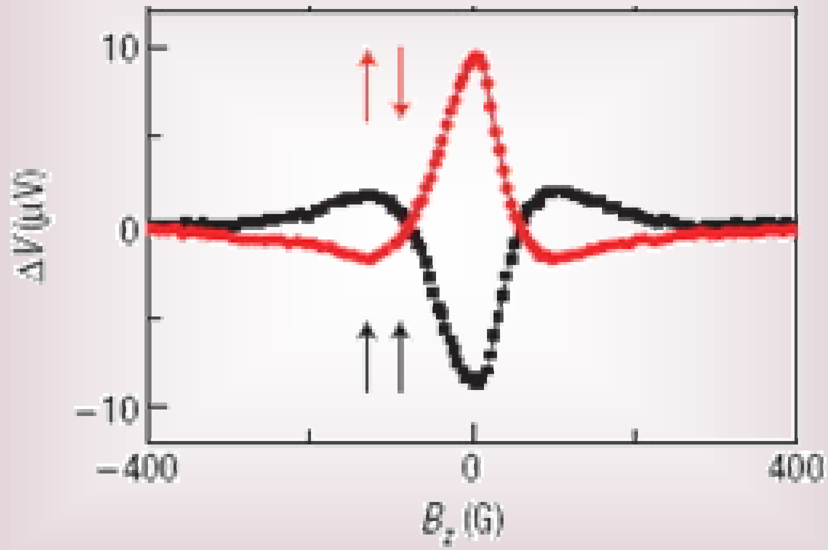
Sasaki et al.
APL 98, 012508 (2011)

Spin transport

Measurement of spin-diffusion length – (2) indirect

Indirect: Measure the Hanle curve in a transport configuration
Fit with equation for spin-precession/diffusion

Lou *et al.*
Nat. Physics **3**,
197 (2007)



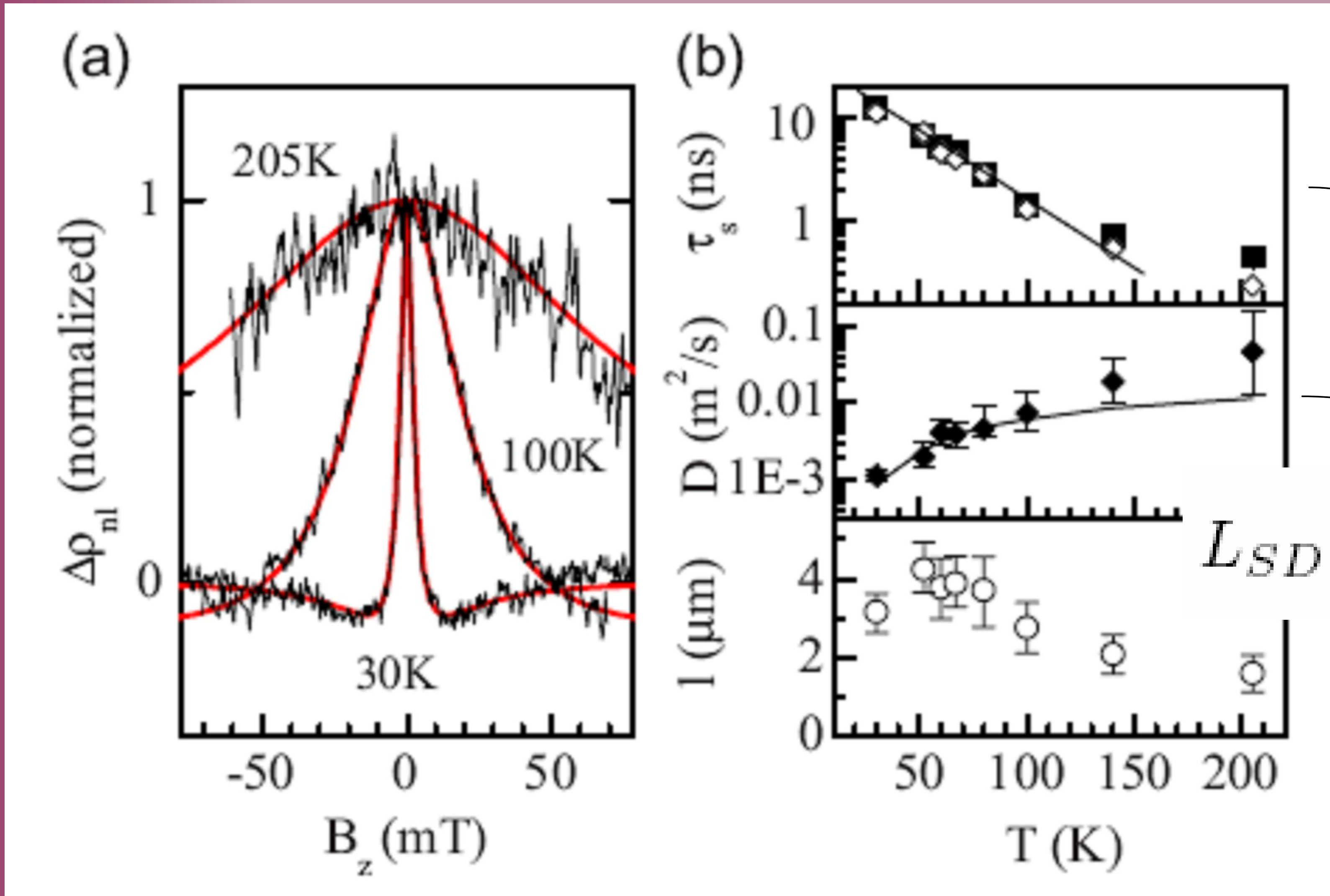
Hanle
non-local device
n-type GaAs

$$S_y(x_1, x_2, B) = S_0 \int_0^\infty \frac{1}{\sqrt{4\pi D t}} e^{-(x_2 - x_1 - v_d t)^2 / 4Dt} \times \cos(g \mu_B B t / \hbar) e^{-t/\tau_s} dt,$$

+ integration over width of injector and detector (x_1, x_2)

Spin transport

Measurement of spin-diffusion length – (2) indirect



$$L_{SD} = \sqrt{D\tau_s}$$

Salis et al. PRB 81, 205323 (2010)

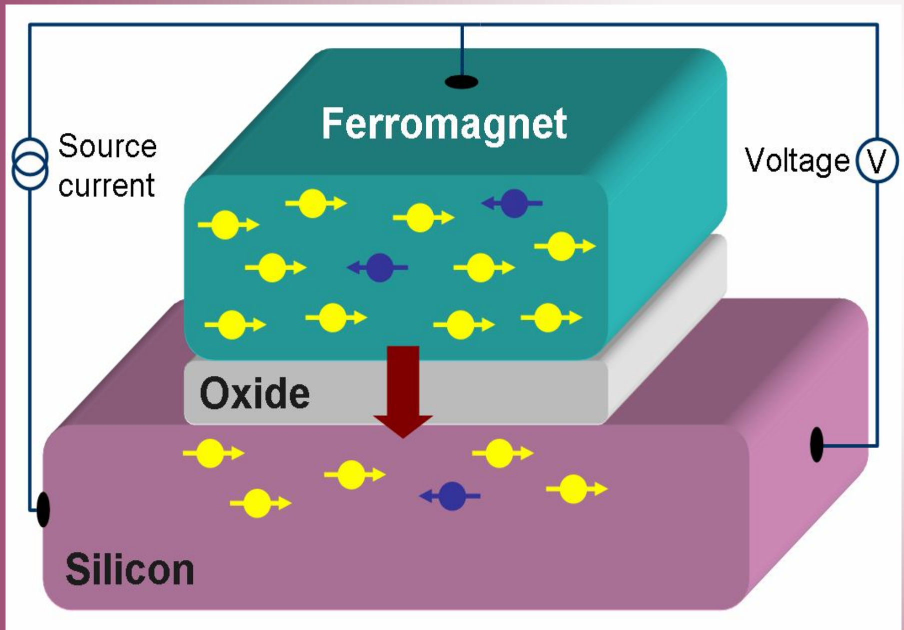
n-type GaAs

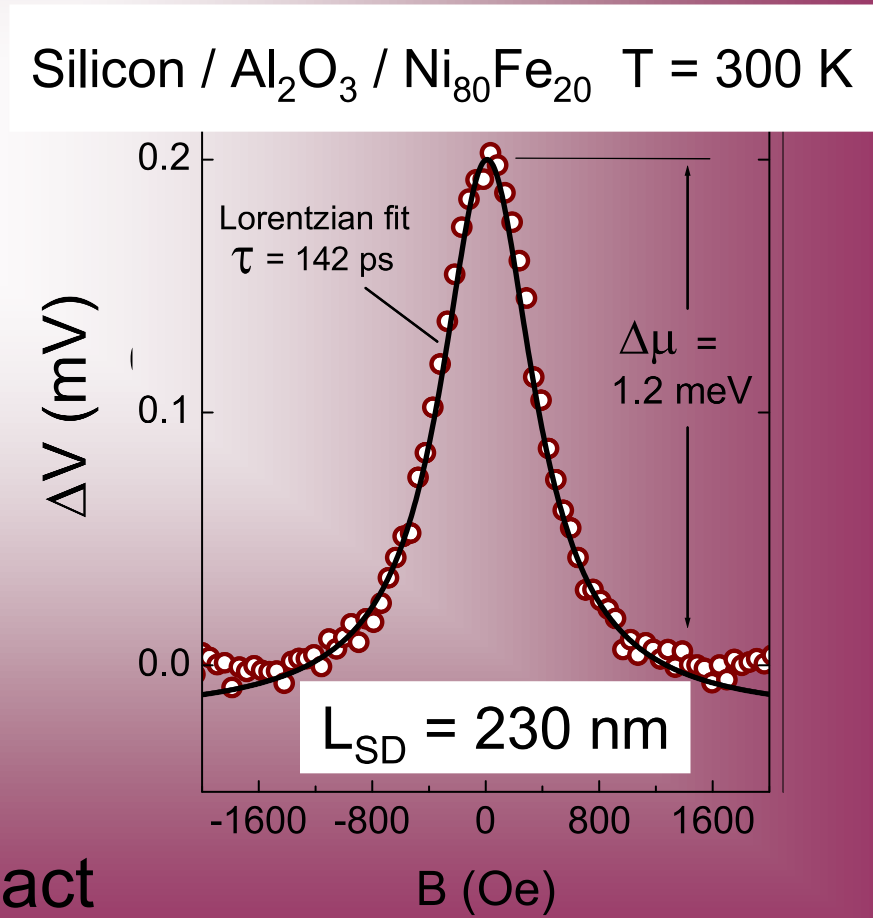
Spin transport

Measurement of spin-diffusion length – (3) indirect

Indirect:

- Measure Hanle curve in 3-terminal device $\Rightarrow \tau_s$
- Measure charge mobility + use Einstein relation $\Rightarrow$ D





- Fast (single device)
- Good SNR (large area contact)
- Probes spin-diffusion under contact

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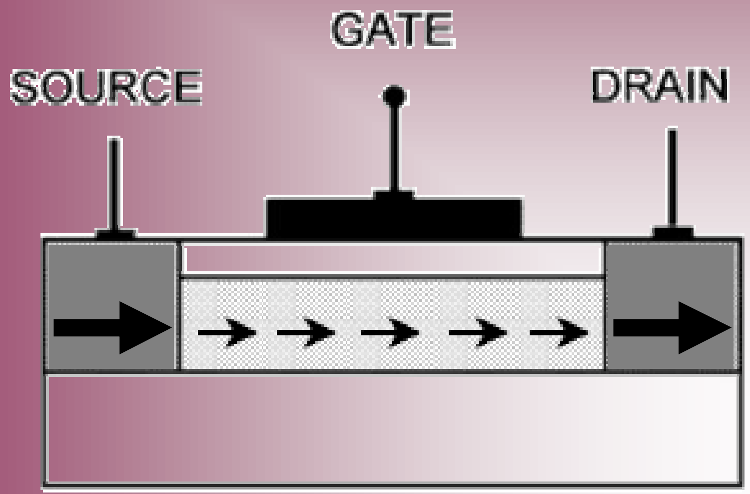
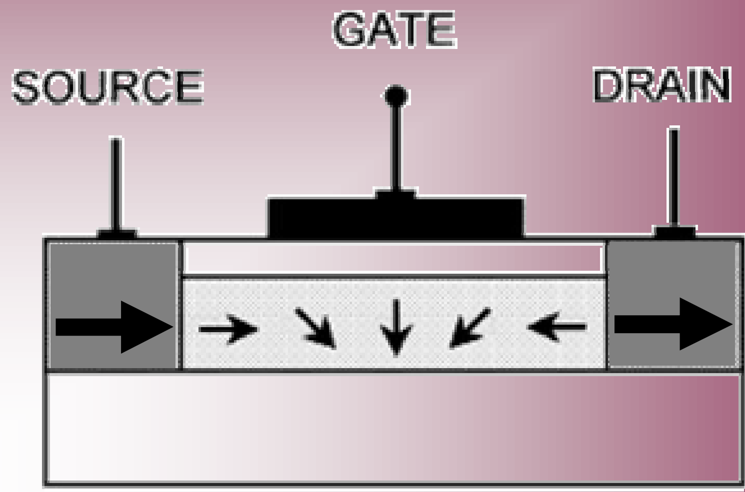
Magnitude spin accumulation
Interface states
Doping concentration

Operation of the spin-FET

Datta and Das



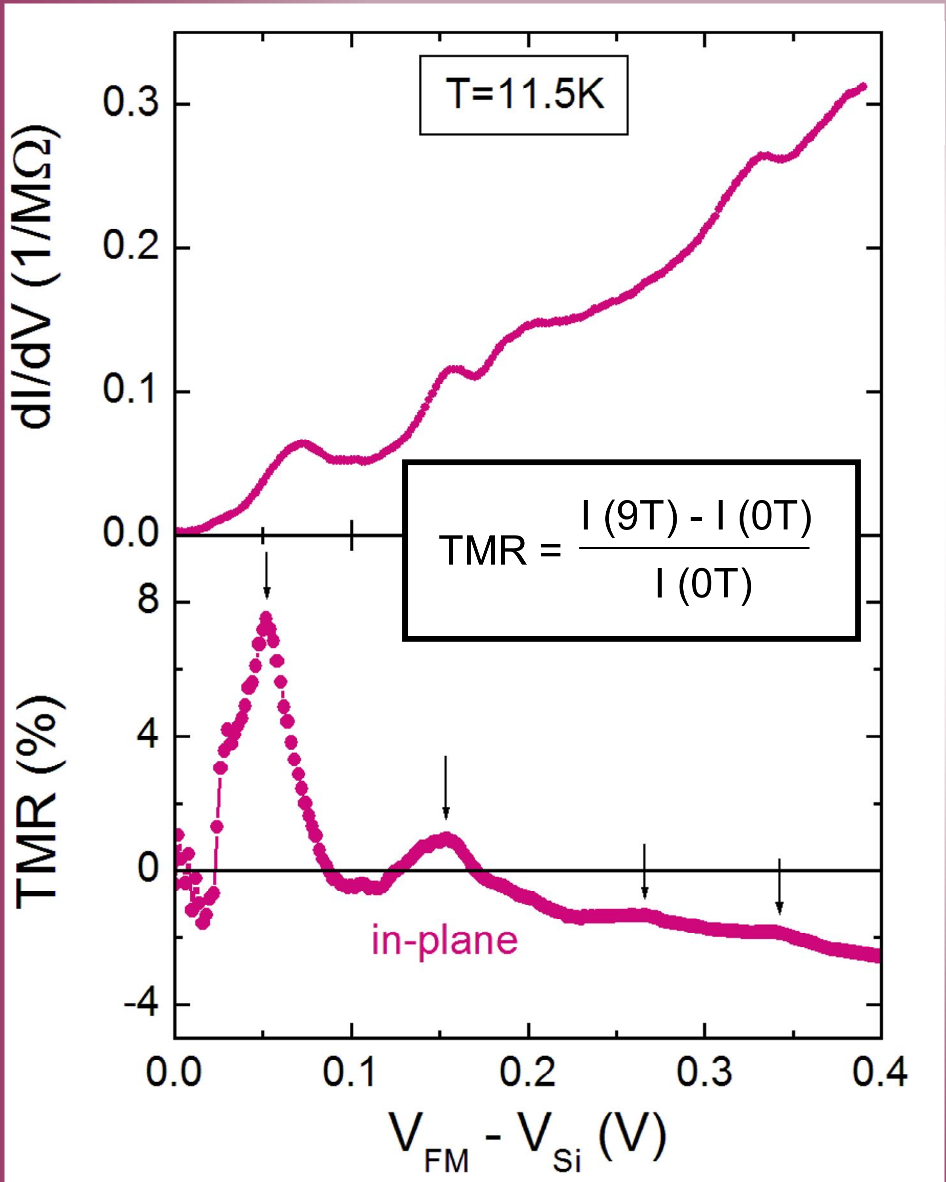


No rotation of spin ⇓ Large conductance	Spin rotation by 180 degrees ⇓ Small conductance
On-state	Off-state

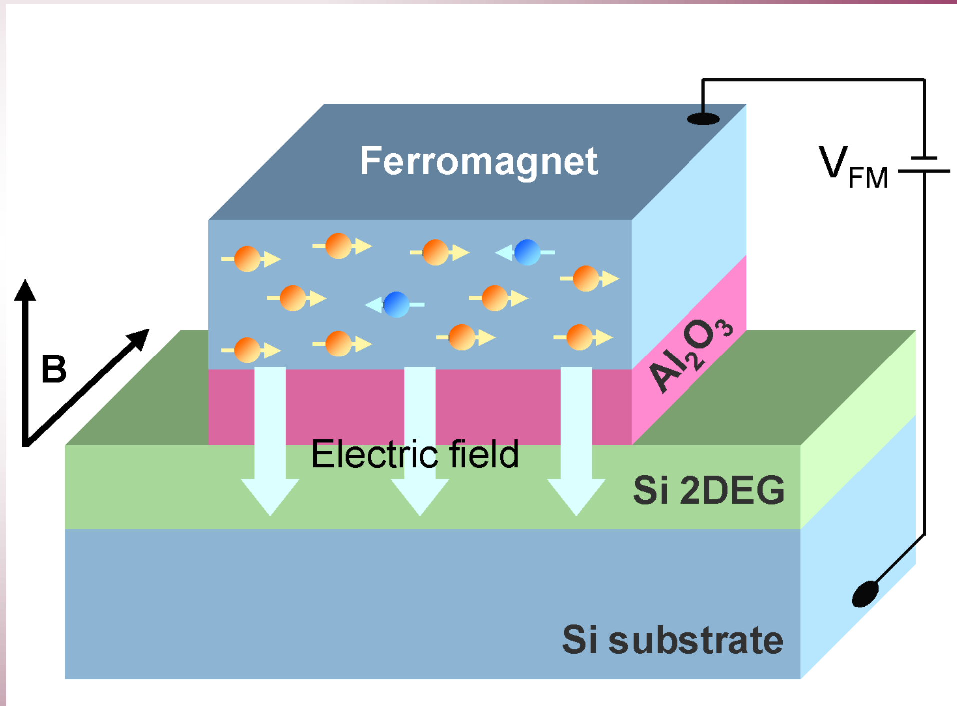
This gate action requires spin-orbit interaction

- Too weak in silicon, organics, graphene etc.
- Doesn't scale well (precession angle per unit length, given by spin-orbit strength)

Electric field control of spin polarization in silicon quantum wells



- Control spin polarization magnitude
- No spin-orbit interaction involved



R. Jansen et al.
Nature Materials 9, 133 (2010)

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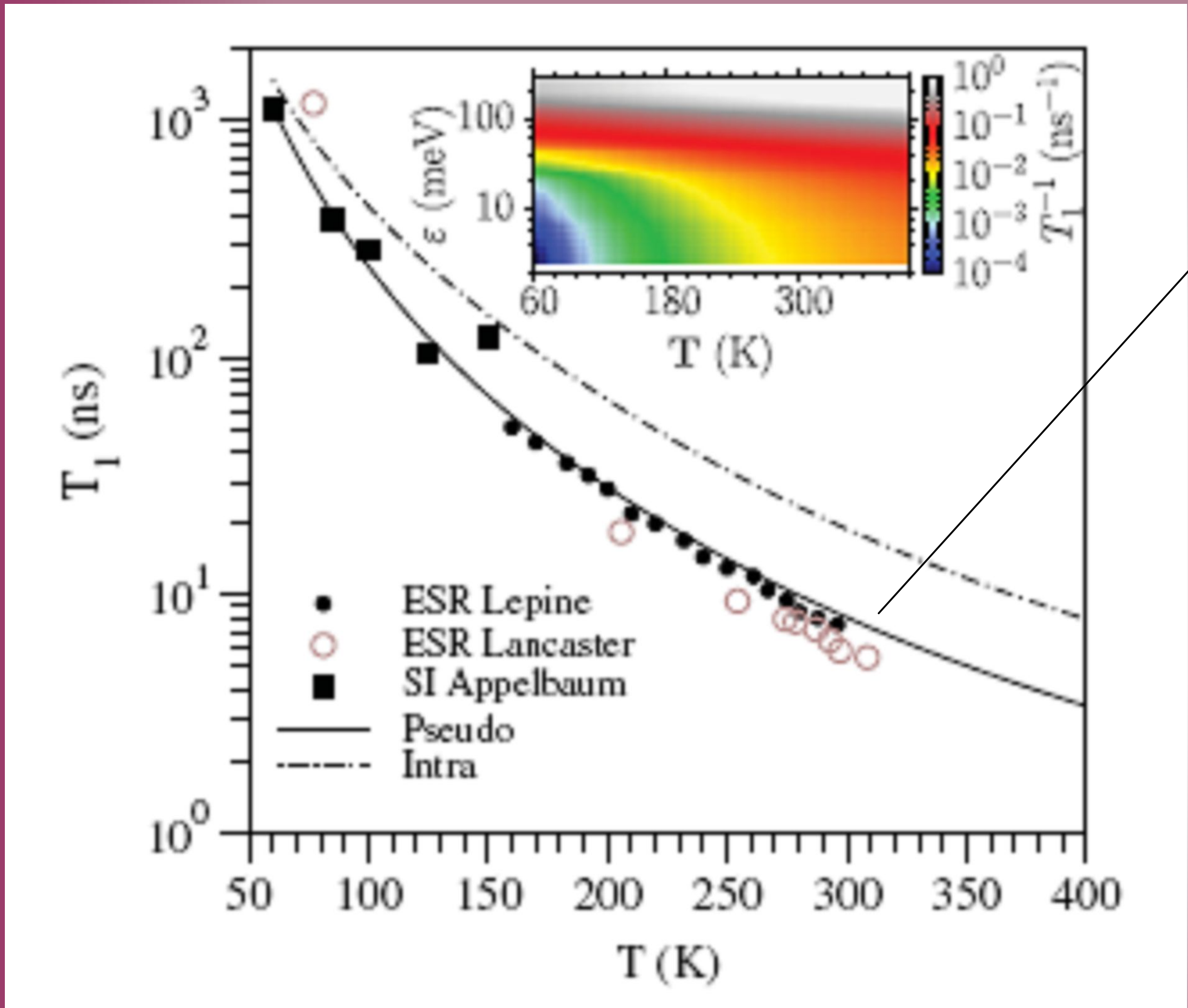
Spin lifetime in n-type Si at room temperature



Cheng, Wu, Fabian, PRL 104, 016601 (2010).

No or very low doping

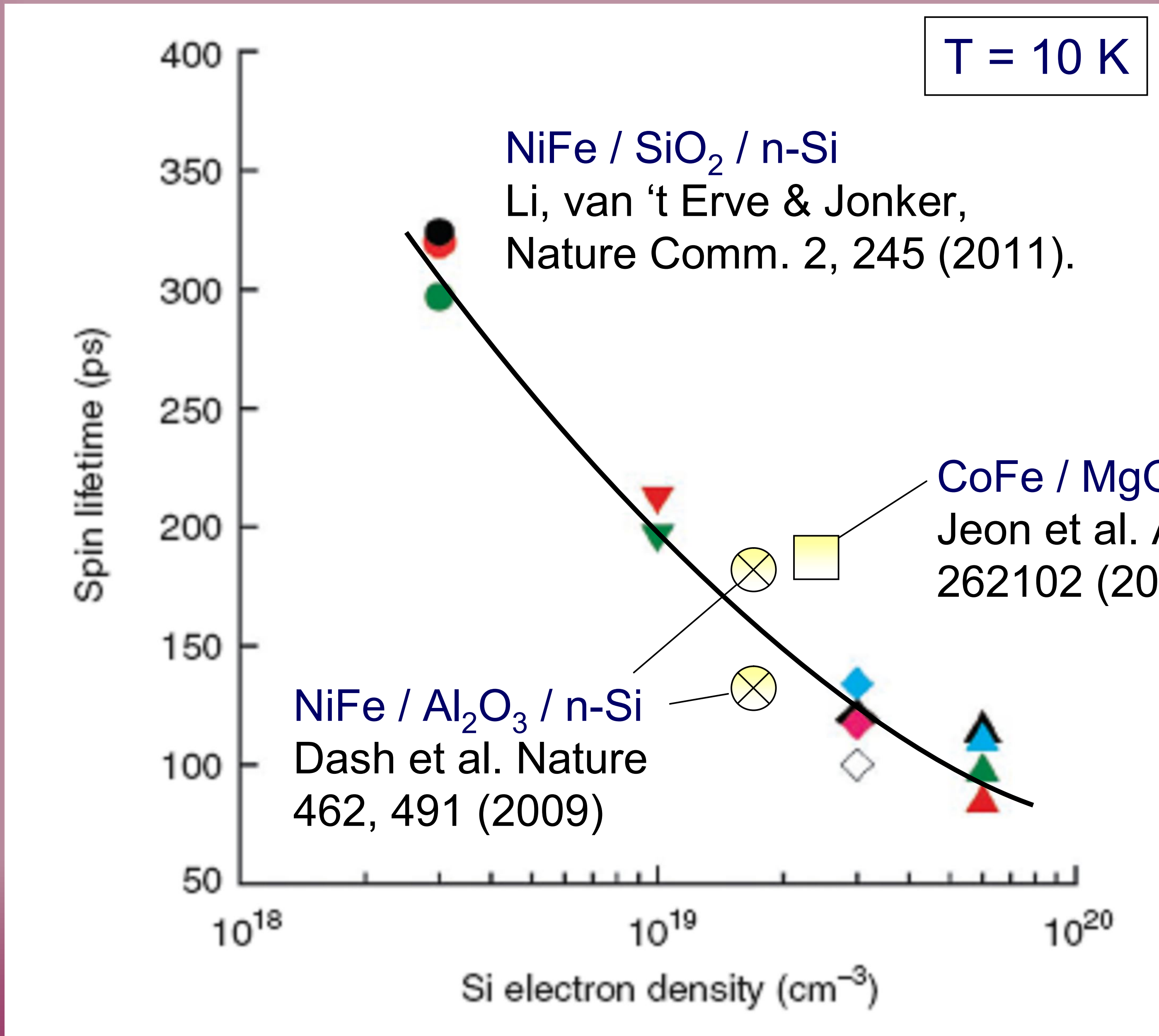
7 – 10 ns at 300 K
Elliott-Yafet mechanism
Spin-orbit + phonons

heavily doped (10^{19} cm^{-3})

1 ns at 300 K (ESR),
Elliott-Yafet mechanism
Spin-orbit + impurity scattering

Spin lifetime in n-type Si from Hanle effect

Consistent results for different tunnel barriers



Spin lifetime extracted from Hanle effect

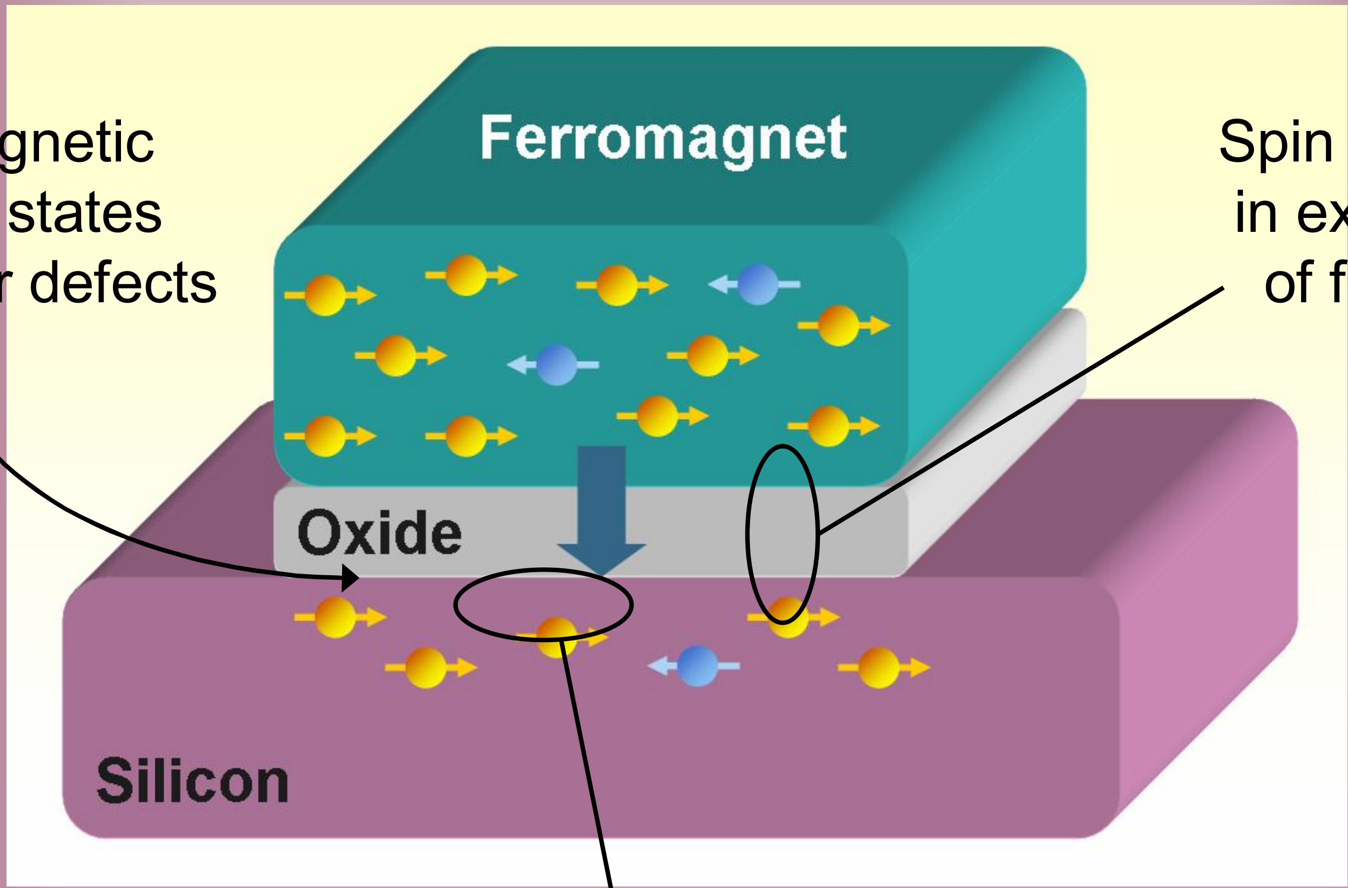
3-terminal (3T) and non-local (NL) devices

spin lifetime	T	FM	tunnel oxide	semiconductor	carrier density at 300 K	technique	reference
140 ps	300 K	Ni_8Fe_2	Al_2O_3	n-type Si	1.8×10^{19} cm^{-3}	3T	Dash et al. Nature 462, 491 (2009)
140 ps	300 K	Ni_8Fe_2	Al_2O_3	n-Si with Cs	1.8×10^{19} cm^{-3}	3T	Dash et al. Nature 462, 491 (2009)
290 ps	300 K	Ni	Al_2O_3	n-type Si	1.8×10^{19} cm^{-3}	3T	Dash et al. ArXiv:1101.1691 (2011)
80 ps	300 K	Co	Al_2O_3	n-type Si	1.8×10^{19} cm^{-3}	3T	Dash et al. ArXiv:1101.1691 (2011)
60 ps	300 K	Fe	Al_2O_3	n-type Si	1.8×10^{19} cm^{-3}	3T	Dash et al. ArXiv:1101.1691 (2011)
125 ps	300 K	Ni_8Fe_2	SiO_2	n-type Si	3×10^{19} cm^{-3}	3T	Li/Erve/Jonker, Nat. Comm. 2, 245 (2011)
155 ps	300 K	CoFe	MgO	n-type Si	2.5×10^{19} cm^{-3}	3T	Jeon et al. APL 98, 262102 (2011)
1.3 ns	300 K	Fe	MgO	n-type Si	5×10^{19} cm^{-3}	NL	Suzuki et al. APEX 4, 023003 (2011)
135 ps	10 K	Ni_8Fe_2	Al_2O_3	n-type Si	1.8×10^{19} cm^{-3}	3T	Dash et al. Nature 462, 491 (2009)
185 ps	10 K	Ni_8Fe_2	Al_2O_3	n-Si with Cs	1.8×10^{19} cm^{-3}	3T	Dash et al. Nature 462, 491 (2009)
125 ps	10 K	Ni_8Fe_2	SiO_2	n-type Si	3×10^{19} cm^{-3}	3T	Li/Erve/Jonker, Nat. Comm. 2, 245 (2011)
100 ps	10 K	Co_9Fe_1	SiO_2	n-type Si	3×10^{19} cm^{-3}	3T	Li/Erve/Jonker, Nat. Comm. 2, 245 (2011)
190 ps	10 K	CoFe	MgO	n-type Si	2.5×10^{19} cm^{-3}	3T	Jeon et al. APL 98, 262102 (2011)
3.1 ns	25 K	Co_6Fe_4	Schottky	n-type Si	2×10^{18} cm^{-3}	3T	Ando et al. APL 99, 012113 (2011)
0.9 ns	5 K	Fe	Al_2O_3	n-type Si	2×10^{18} cm^{-3}	NL	Erve et al. IEEE Tr. Elec. Dev. 56, 2343 (2009)
10 ns	10 K	Fe	MgO	n-type Si	5×10^{19} cm^{-3}	NL	Suzuki et al. APEX 4, 023003 (2011)
9 ns	8 K	Fe	MgO	n-type Si	1×10^{19} cm^{-3}	3T	Sasaki et al. APL 98, 012508 (2011)

Extrinsic contributions to spin relaxation

proximity of magnetic tunnel contact

Paramagnetic interface states and barrier defects

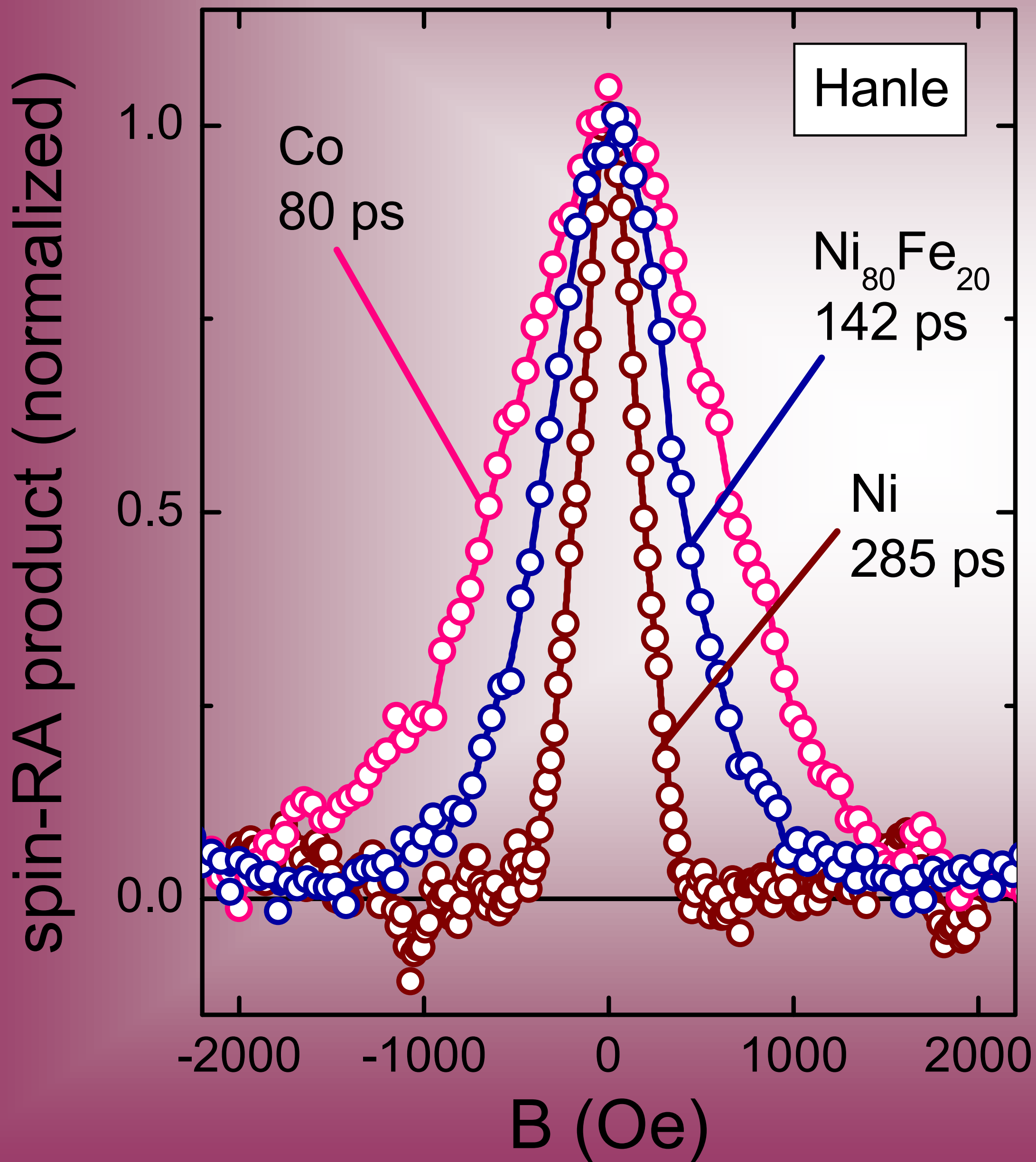


Spin decoherence in exchange field of ferromagnet

Spin precession in local magnetostatic fields arising from roughness

Spin relaxation near magnetic tunnel interface

role of ferromagnetic electrode



Injected spins feel presence of the ferromagnet !

⇒ Apparent reduction of spin lifetime

$Ni_{80}Fe_{20} \rightarrow \mu_0 M_{sat} = 0.9$ T

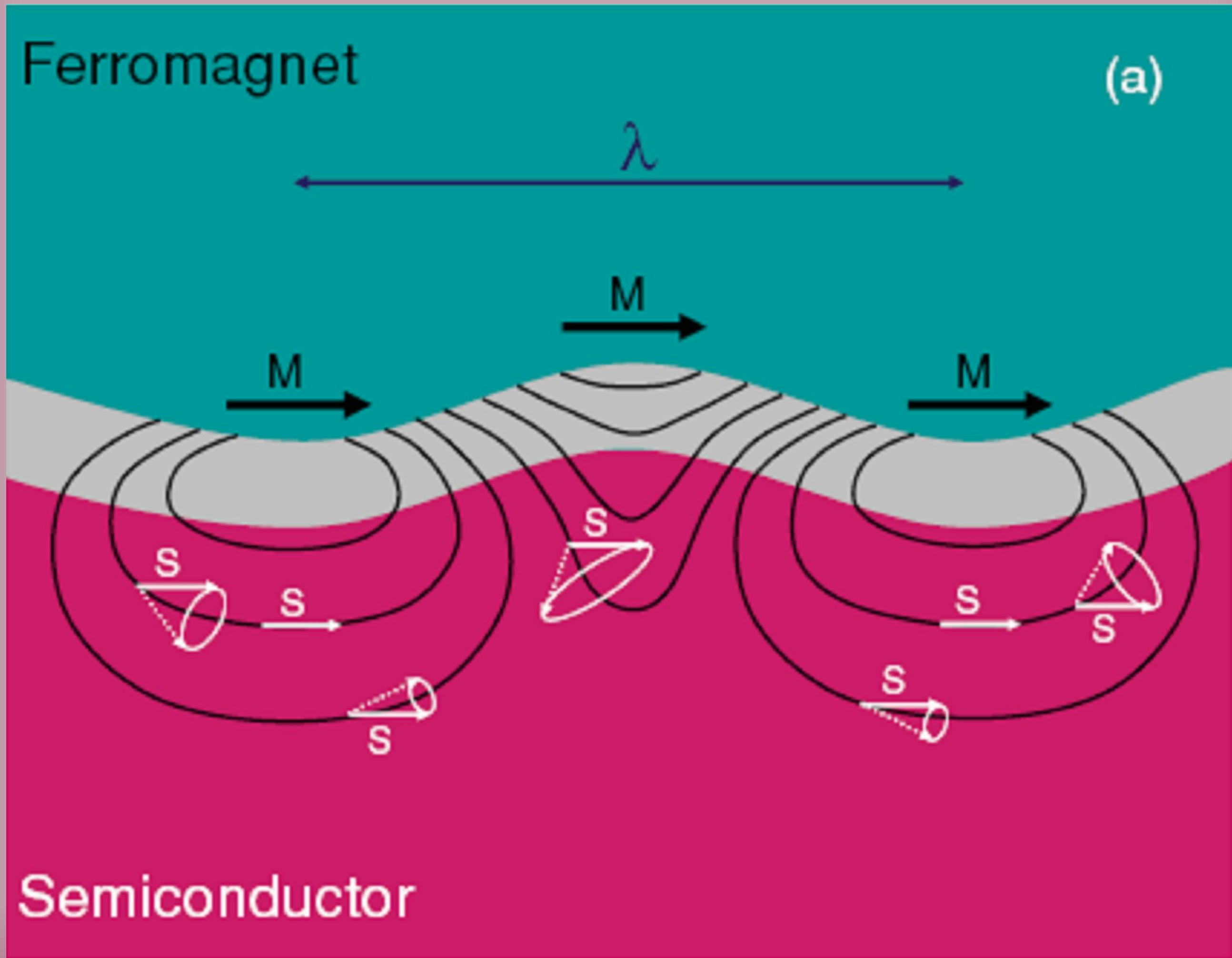
Co $\rightarrow \mu_0 M_{sat} = 1.8$ T

Fe $\rightarrow \mu_0 M_{sat} = 2.2$ T

T = 300 K
n-Si = $1.8 \cdot 10^{19}$ cm^{-3} (As)

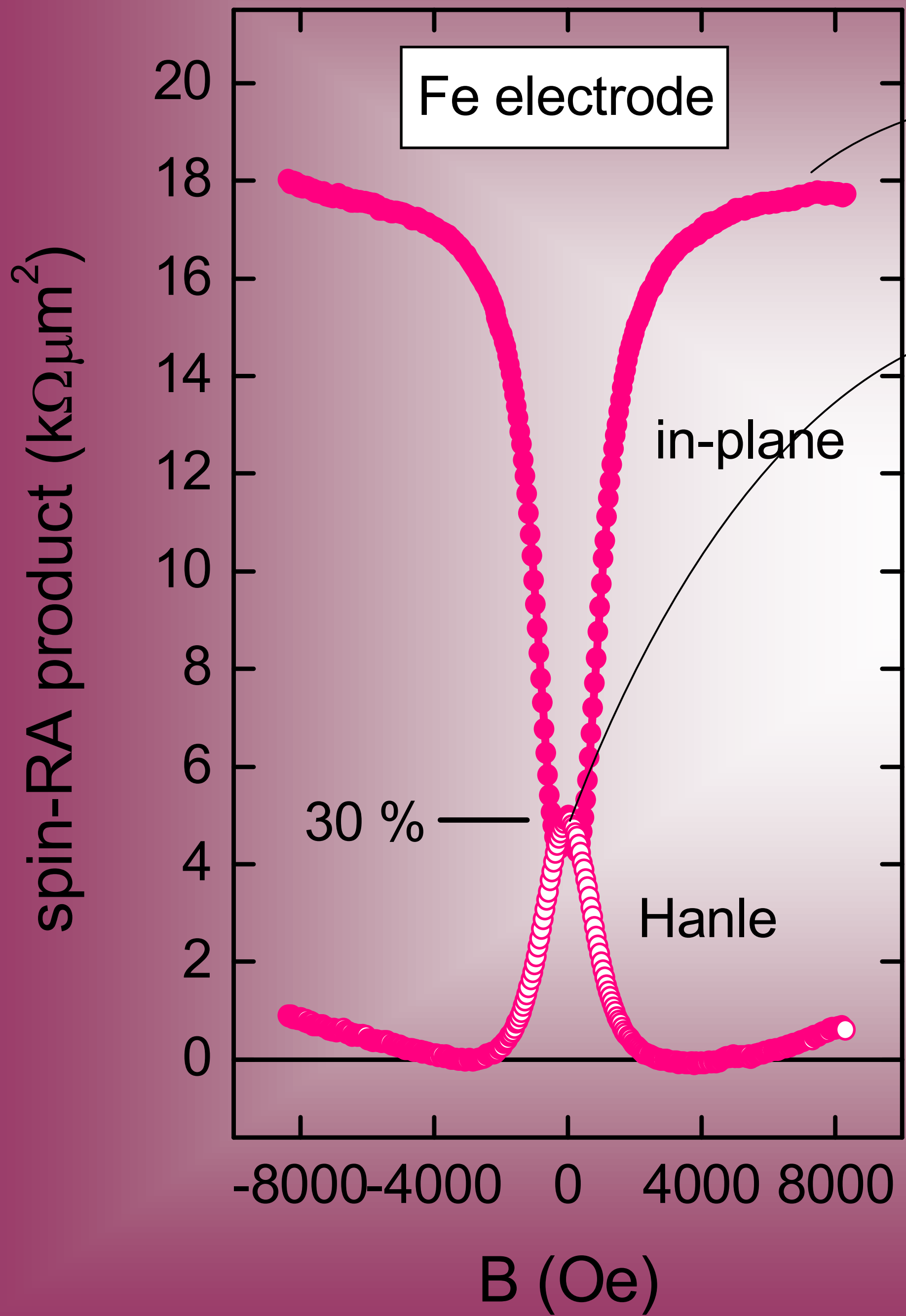
Extrinsic contributions to spin relaxation

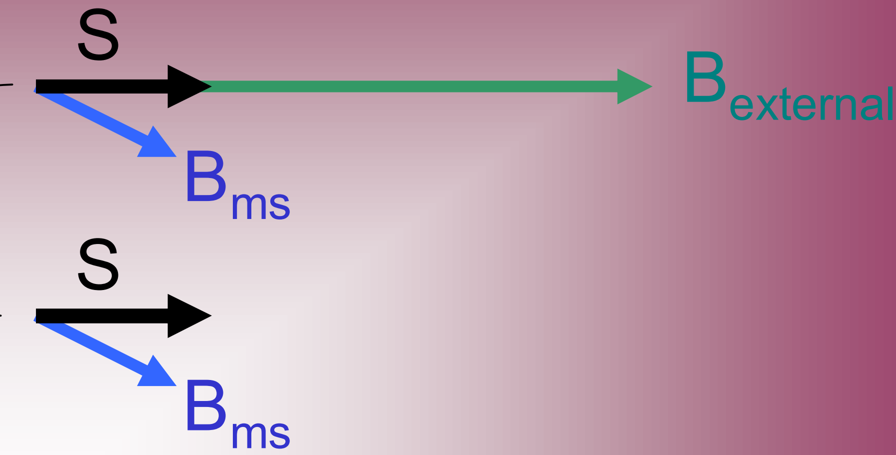
spin precession in local magnetostatic fields



Inhomogeneous spin precession axis and frequency

Hanle effect and inverted Hanle effect





Spin precession in B_{ms}

$\Delta\mu$ reduced at $B_{external} = 0$

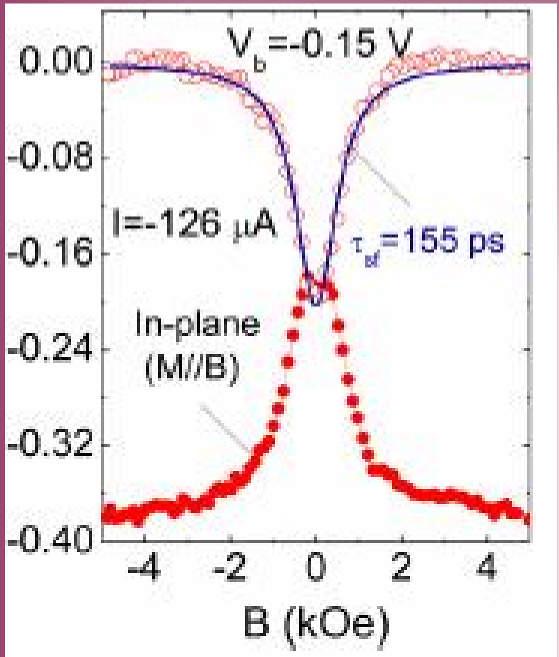
$B_{external}$ in-plane, parallel to magnetization and injected spins, reduces precession

$\Rightarrow$ recovery of $\Delta\mu$

http://arxiv.org/abs/1101.1691

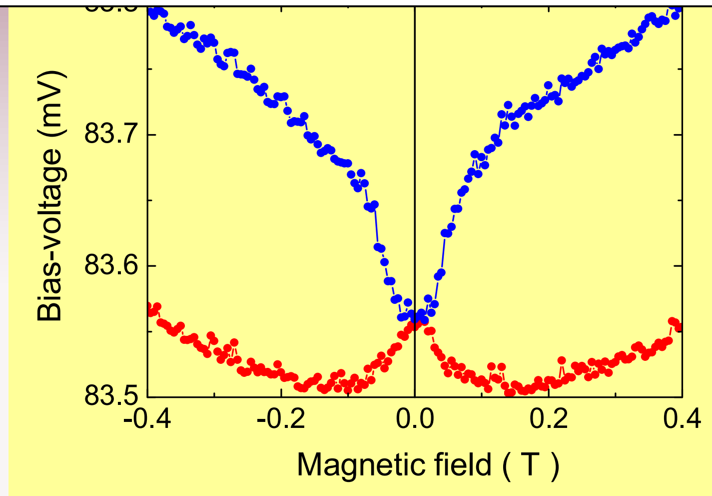
Poster WP – 52 (Wednesday)

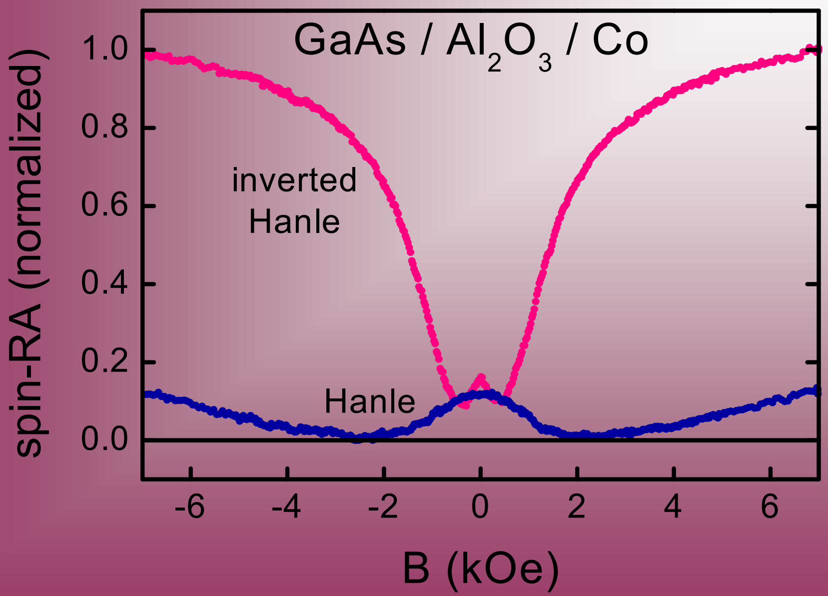
Inverted Hanle effect – a generic feature



n-Si / MgO / CoFe
T = 300 K
APL 98,
262102 (2011)

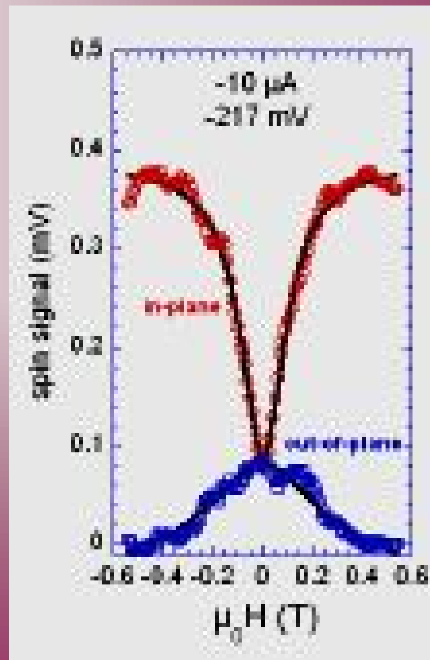
p-Ge / MgO / Fe, 10 K
Sol. St. Comm. 151, 1159 (2011)





Arxiv:1101.1691

n-Ge / Al_2O_3 / NiFe
T = 10 K
ArXiv:1107.3510



Extracting spin lifetime from Hanle effect

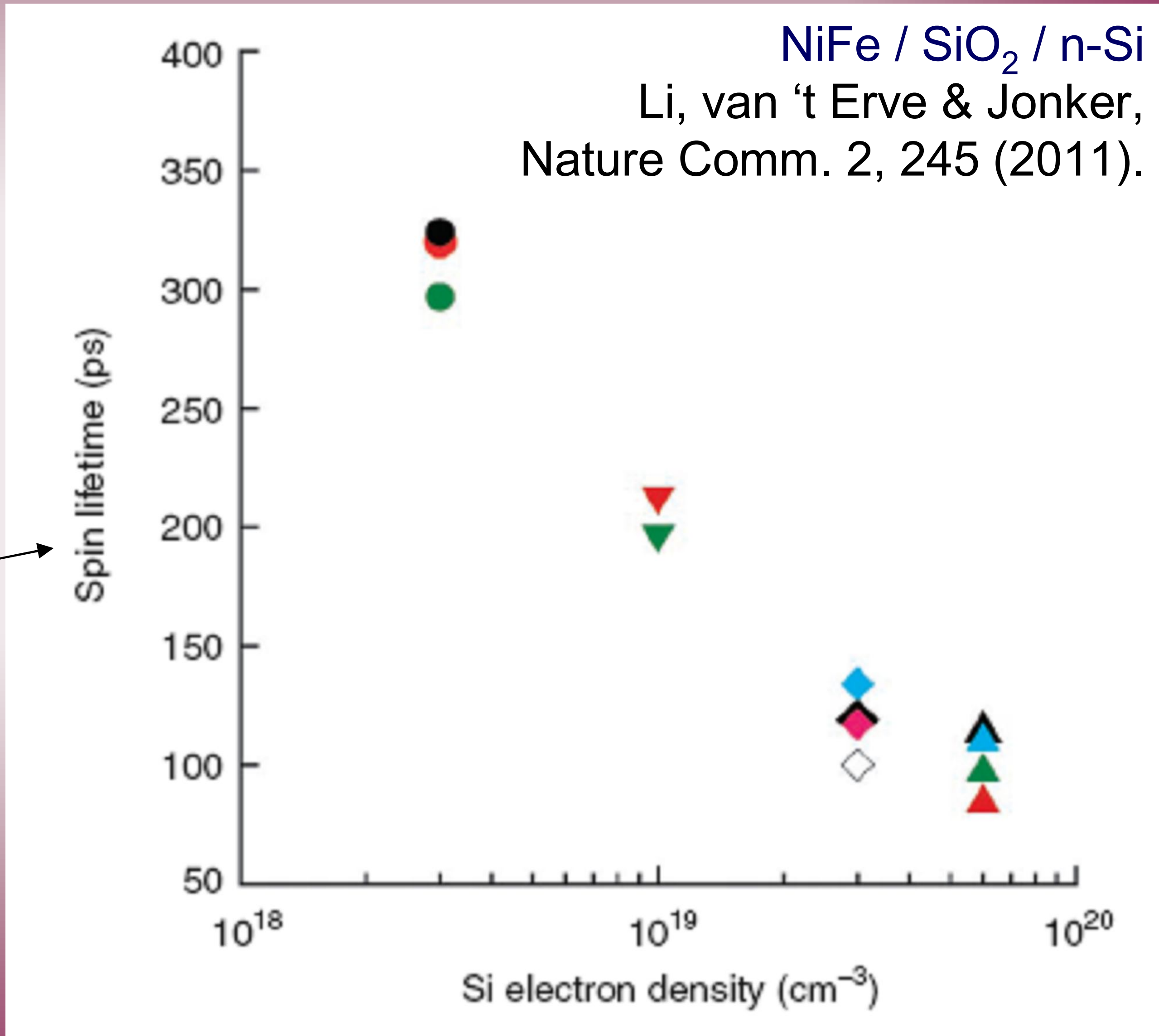
Be careful !

Concluded that trend of spin lifetime vs. doping density is as expected.

Or……

What if this is not the spin lifetime,

but just a lower limit ?



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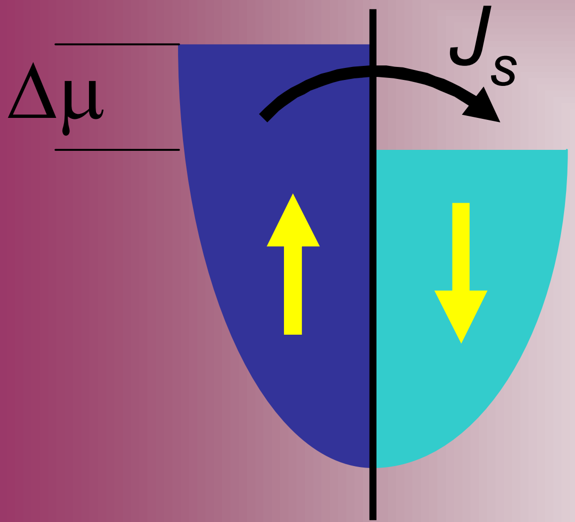
Magnitude of the spin accumulation

spin resistance



Spin current:

$$J_s = \frac{e(n^{\uparrow} - n^{\downarrow})}{\tau_s}$$

Spin resistance:

$$r_s = \frac{\Delta\mu}{J_s} = \frac{\tau_s}{e^2\left(\frac{\partial n}{\partial E_F}\right)}$$

Use Einstein relation:

$$D = \frac{\mu_e n}{e\left(\frac{\partial n}{\partial E_F}\right)}$$

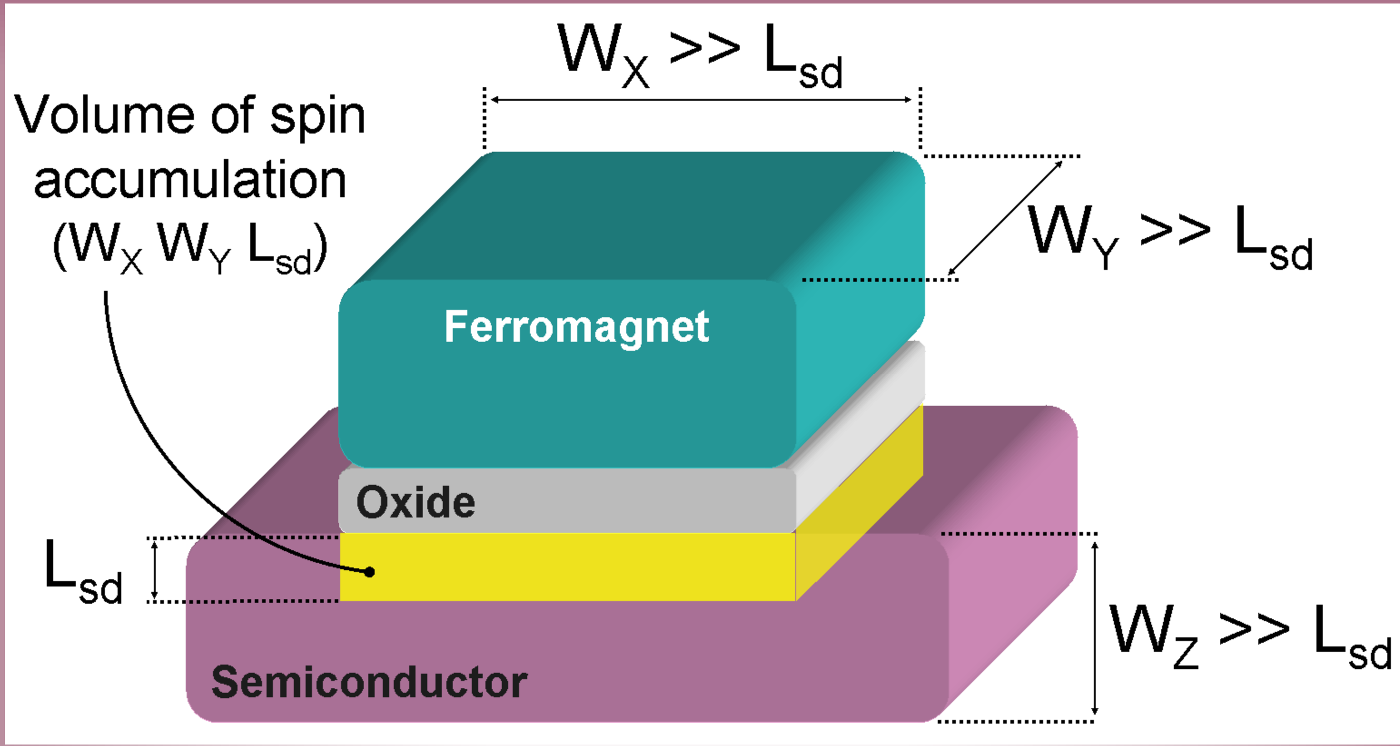
$$\boxed{r_s = \rho\, L_{sd}^2}$$

in Ωm^3

Resistivity

spin-diffusion length

Spin resistance of semiconductor – large contact



Spin resistance:

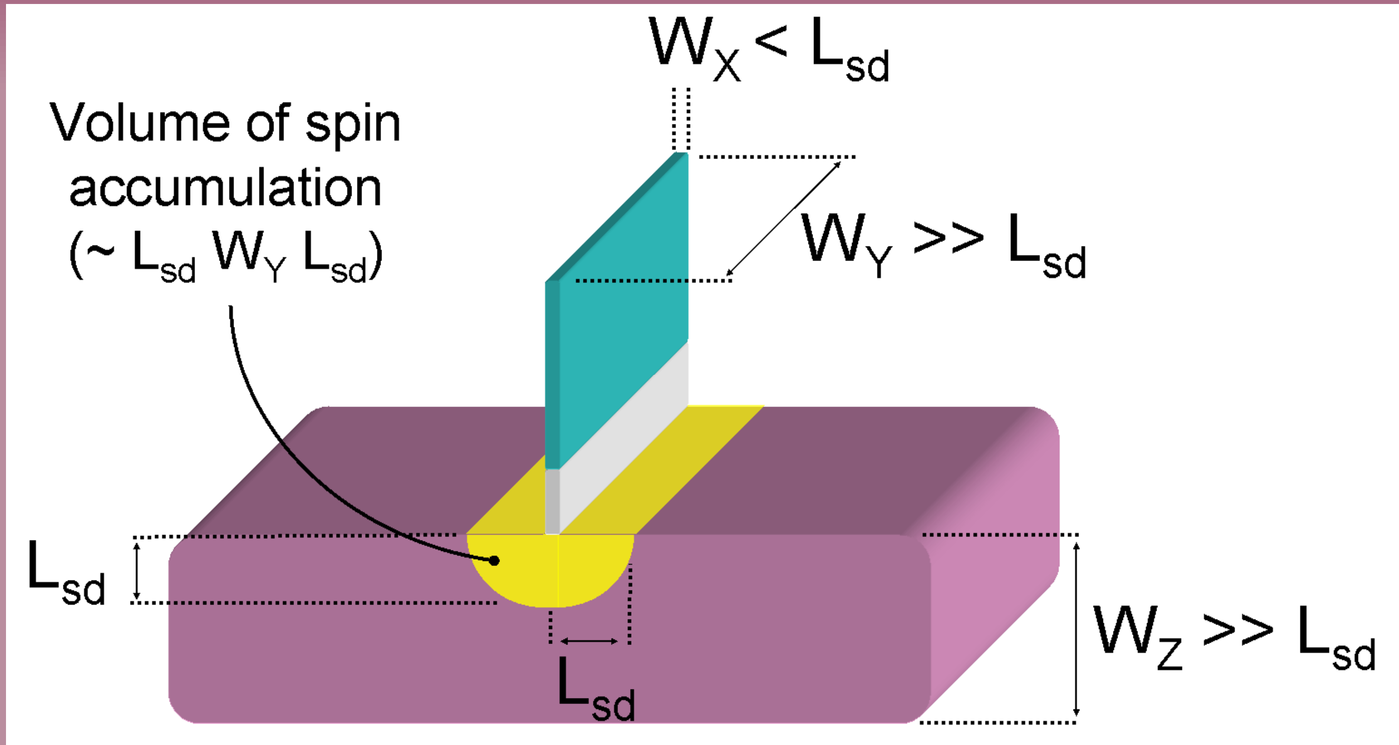
$$r_S = \frac{\rho L_{sd}^2}{W_X W_Y L_{sd}} \quad (\text{in } \Omega)$$

Areal spin resistance:

$$\boxed{r_S = \rho L_{sd}} \quad (\text{in } \Omega m^2)$$

× contact area $W_X W_Y$

Spin resistance of semiconductor – small contact



Spin resistance:

$$r_S = \frac{\rho L_{sd}^2}{L_{sd} W_Y L_{sd}} \quad (\Omega)$$

Areal spin resistance:

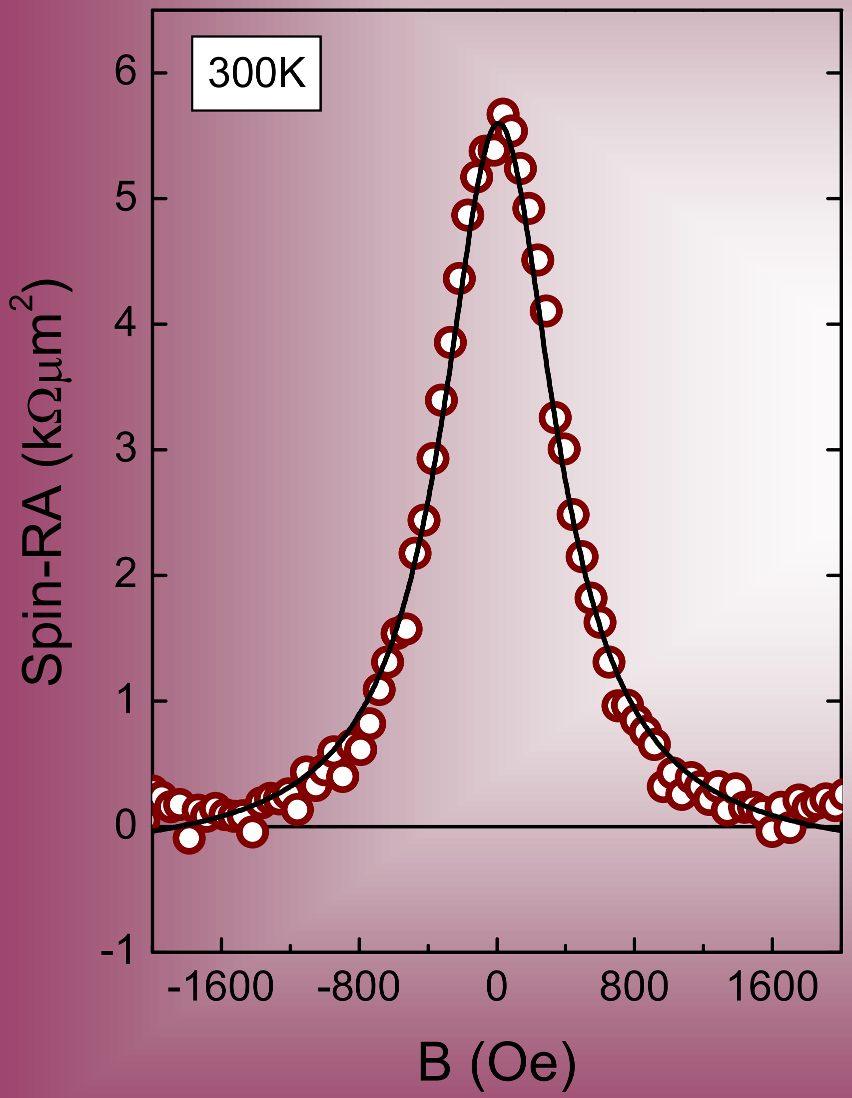
$$\boxed{r_S = \rho L_{sd} \frac{W_X}{L_{sd}}} \quad (\Omega m^2)$$

Large contact

Geometric correction < 1

Magnitude of the spin accumulation

Comparison with standard model for spin resistance



Area spin resistance in standard model

$r_s = \rho \, L_{sd} \sim 0.01 \text{ k}\Omega\mu\text{m}^2$

3 mΩcm

> 230 nm

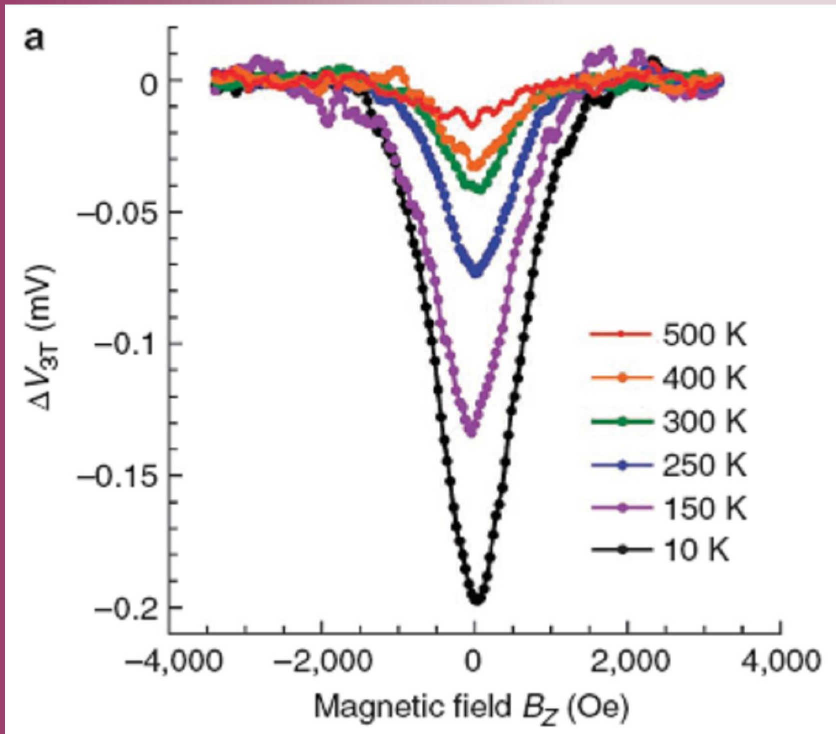
Standard model does not match with the experimental data

Magnitude of the spin accumulation

Reproduced in different systems

NiFe / SiO_2 / n-Si

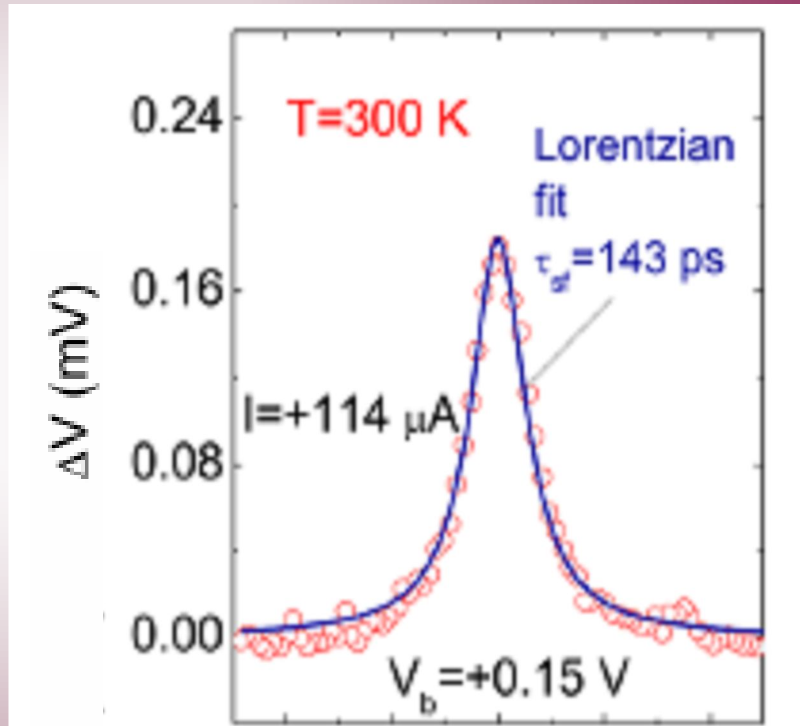
Li / Erve / Jonker, Nat. Comm. 2, 245 (2011)



Spin-RA ~ 1.2 kΩμm^2

CoFe / MgO / n-Si

Jeon et al. APL 98, 262102 (2011)



Spin-RA ~ 4 - 5 kΩμm^2

Also larger than theory: $r_s = \rho\, L_{sd} \sim 0.01$ kΩμm^2

Size of spin accumulation – experiment vs theory

From: Li / Erve / Jonker, Nature Comm. 2, 245 (2011)

Comparison of Hanle signal amplitude with theory. The amplitude of the Hanle signal agrees well with that expected from the theory of spin injection into a semiconductor channel in the diffusive regime[13,14], indicating that spin accumulation occurs in the semiconductor channel rather than in localized interface states. The amplitude of the Hanle signal at 300 K for sample A, $\Delta V_{3T}(B_z=0)\sim 0.04$ meV, corresponds to a spin resistance $R_s=\Delta V_{3T}(B_z=0)/I\sim 0.08\,\Omega$, or equivalently a spin resistance–area product $R_s{\cdot}A\sim 1{,}200\,\Omega\,\mu m^2$ for the $150\times 100\,\mu m^2$ contact. The value at 10 K is $R_s{\cdot}A\sim 6{,}000\,\Omega\,\mu m^2$. These are in excellent agreement with the value predicted by theory[12,13,14] as given by $r_1=(\rho L_{SD})\boxed{(W/w)}\sim 3{,}000\,\Omega\,\mu m^2$ using parameters meas-

Geometric correction (750 !) cannot be used for large area contact with W_x, W_y >> L_{SD}.

Correct value $r = \rho L_{sd} \sim 10\ \Omega\mu m^2$

Theory and experiment not in agreement !

Large spin accumulation - possible explanations

1) Local magnetostatic fields (roughness)

$\Rightarrow$ *Hanle data underestimates* τ_s *and thus* L_{sd}

2) Inhomogeneous tunnel current density

$\Rightarrow$ *real tunnel area << geometric area*

3) Two-step tunneling via localized interface states

- *proposed by Tran et al. -* PRL 102, 036601 (2009)
- *already ruled out in Dash et al. Nature 462, 491 (2009)*

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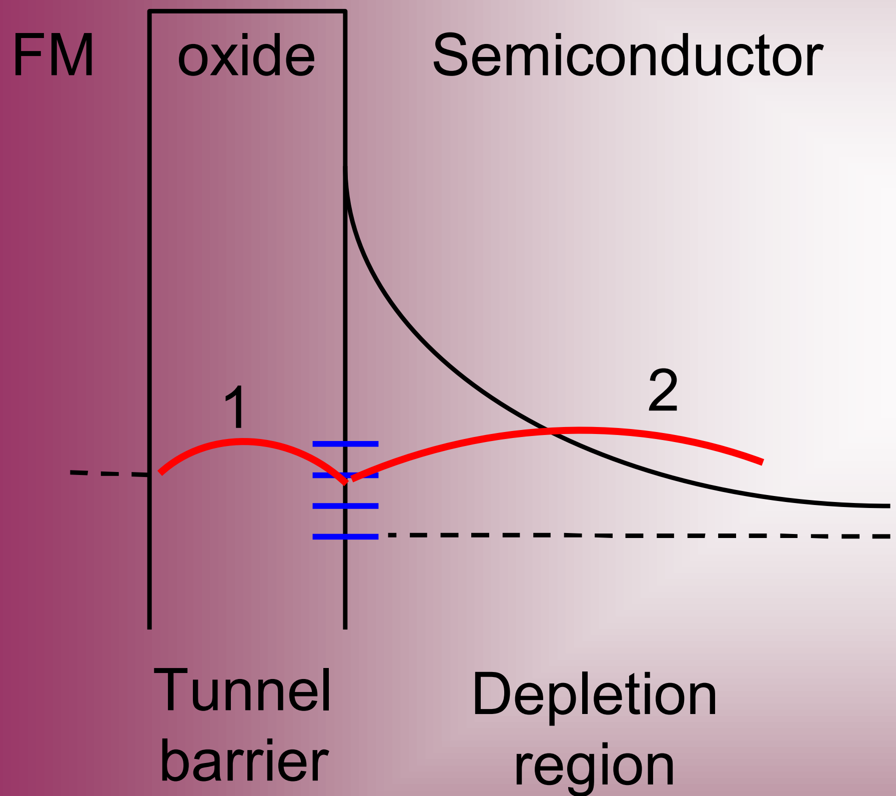
Two-step tunneling via localized interface states

Potential source of enhanced spin accumulation



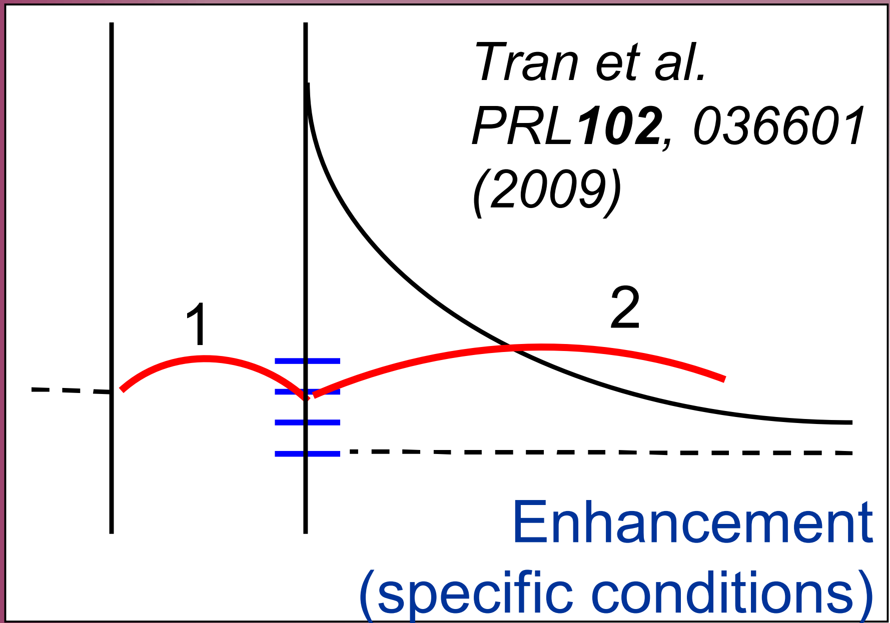
Proposal by Tran et al.
PRL 102, 036601 (2009):

- Two-step (sequential) tunneling via localized interface states
- Spin accumulation in localized states can be larger than in semiconductor channel
- Only if bulk bands and interface states are well separated by a large resistance (Schottky) barrier

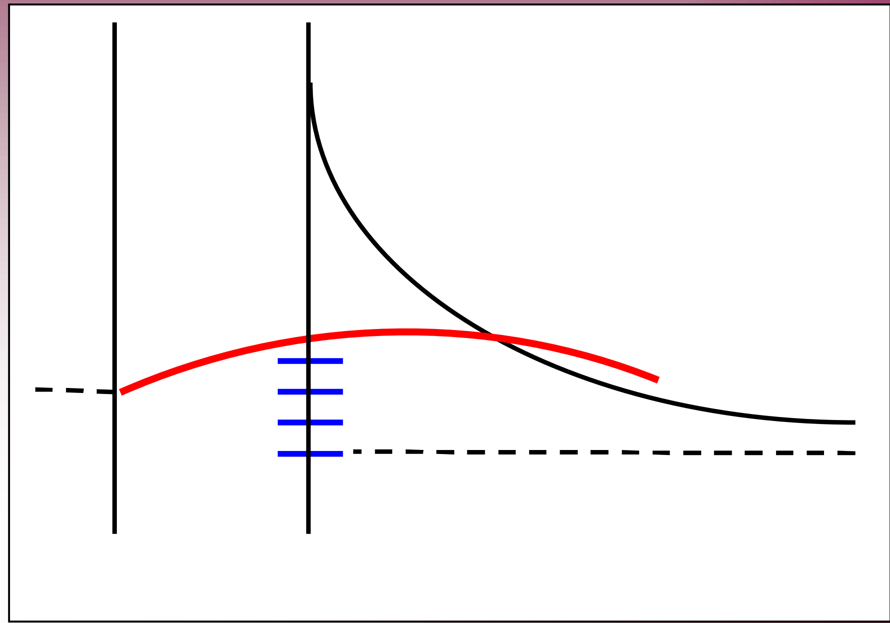
p.s. to date no experimental confirmation of this mechanism in spin injection

Transport and localized states

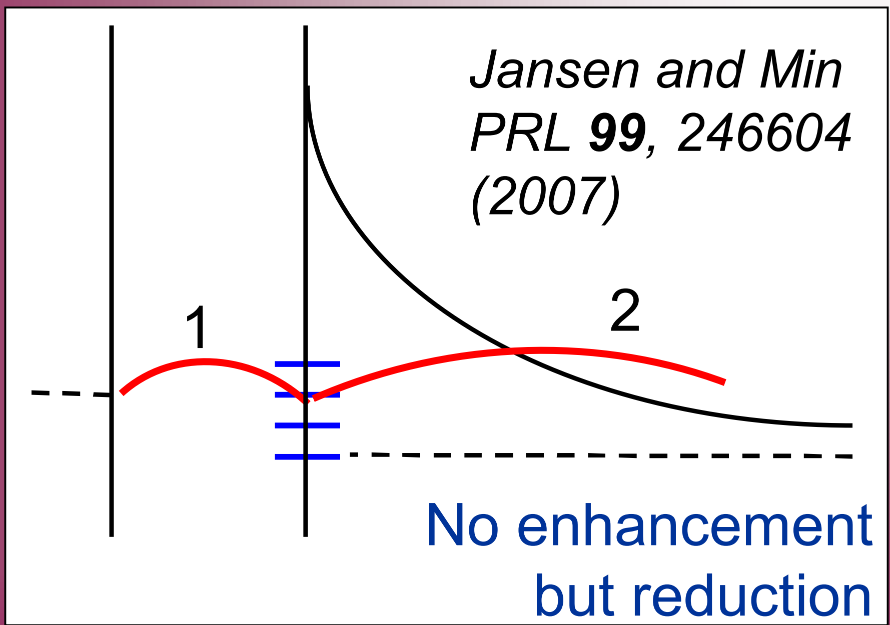
Two-step tunneling



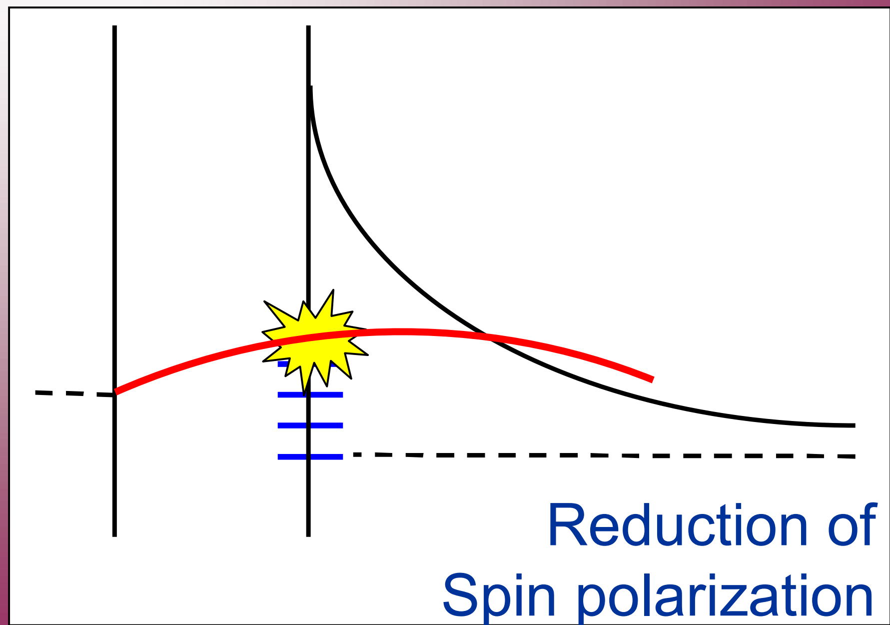
Direct tunneling



Thermionic emission



Resonant / off-resonant tunneling



Two-step tunneling via localized interface states

Basic equations and parameters

$$\Delta\mu^{ls} = \Bigg\{ \underbrace{\frac{r_{ls}\,(r_b + r_{ch})}{r_{ls} + r_b + r_{ch}}}_{\boxed{\leq r_b}} \Bigg\}\, 2\, P_G\, I$$

r_{ls} Spin resistance of localized states

r_{ch} Spin resistance of semiconductor channel

r_b Resistance between localized states and semiconductor

$$\Delta\mu^{ls} = \Delta\mu^{ch} \left\{ 1 + \frac{r_b}{r_{ch}} \right\}$$

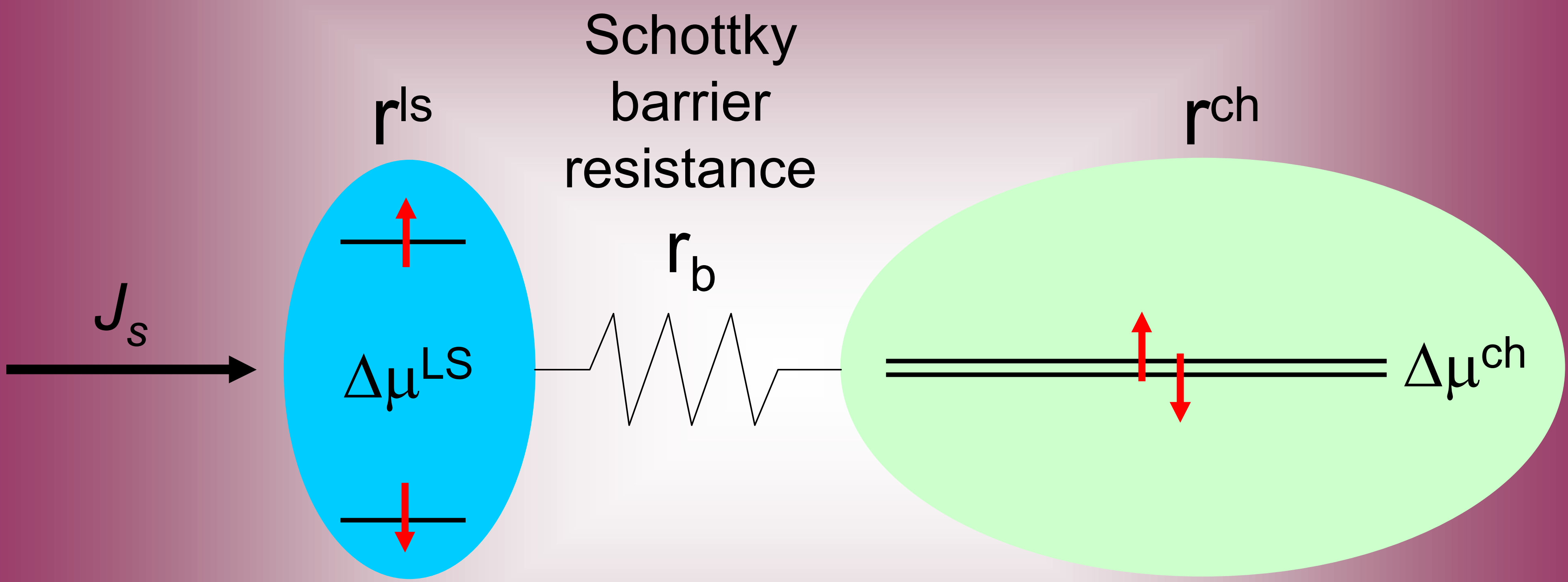
Enhancement factor: spin accumulation in localized states (ls) can be larger than in semiconductor channel (ch)

$$I_s^{ch} = \left\{ \frac{r_{ls}}{r_{ls} + r_b + r_{ch}} \right\} P_G\, I$$

No detrimental effect on spin current into semiconductor if r_{ls} is larger than Schottky barrier resistance r_b.

Spin accumulation in interface states

Upper limit to the enhancement set by Schottky barrier



If there is enhancement ($r^{LS} >> r^{ch}$)
then:

$$r_s = \frac{\Delta\mu^{ls}}{J_s} \leq r_b$$

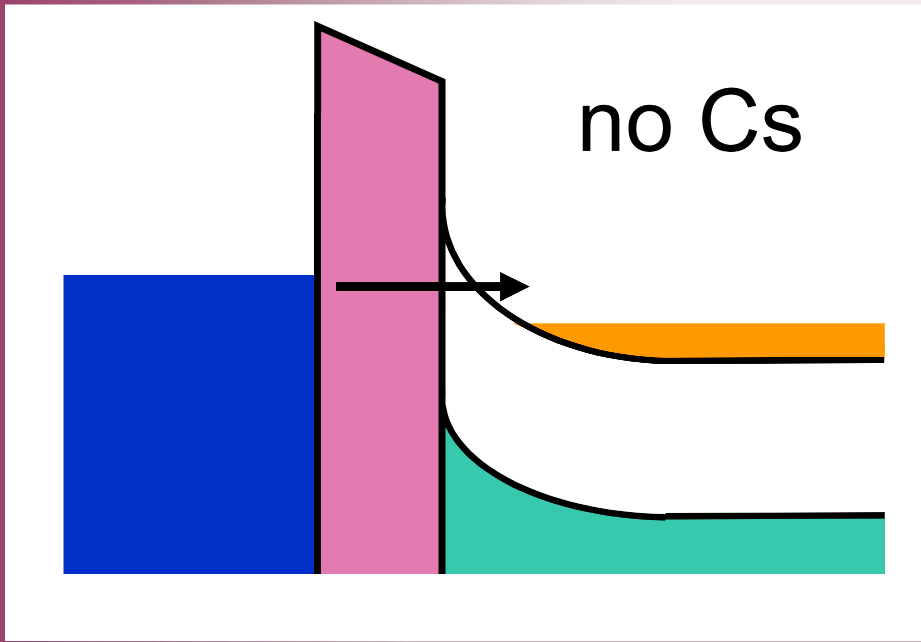
Tran et al. PRL ***102****, 036601 (2009)*

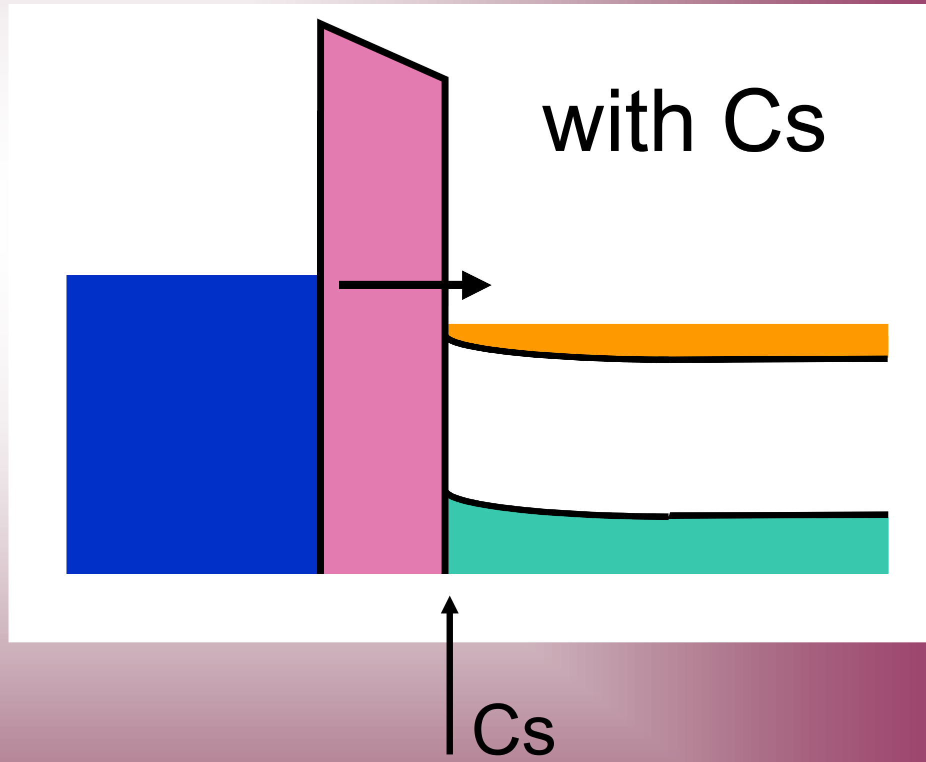
Test of spin accumulation in interface states

Schottky barrier reduction by Cs

Schottky barrier
$\Phi_B \sim 0.7 - 0.8$ eV
Narrow width (heavily doped Si)

Strongly reduced Schottky barrier
$\Phi_B \sim 0.2 - 0.3$ eV
Width reduced correspondingly

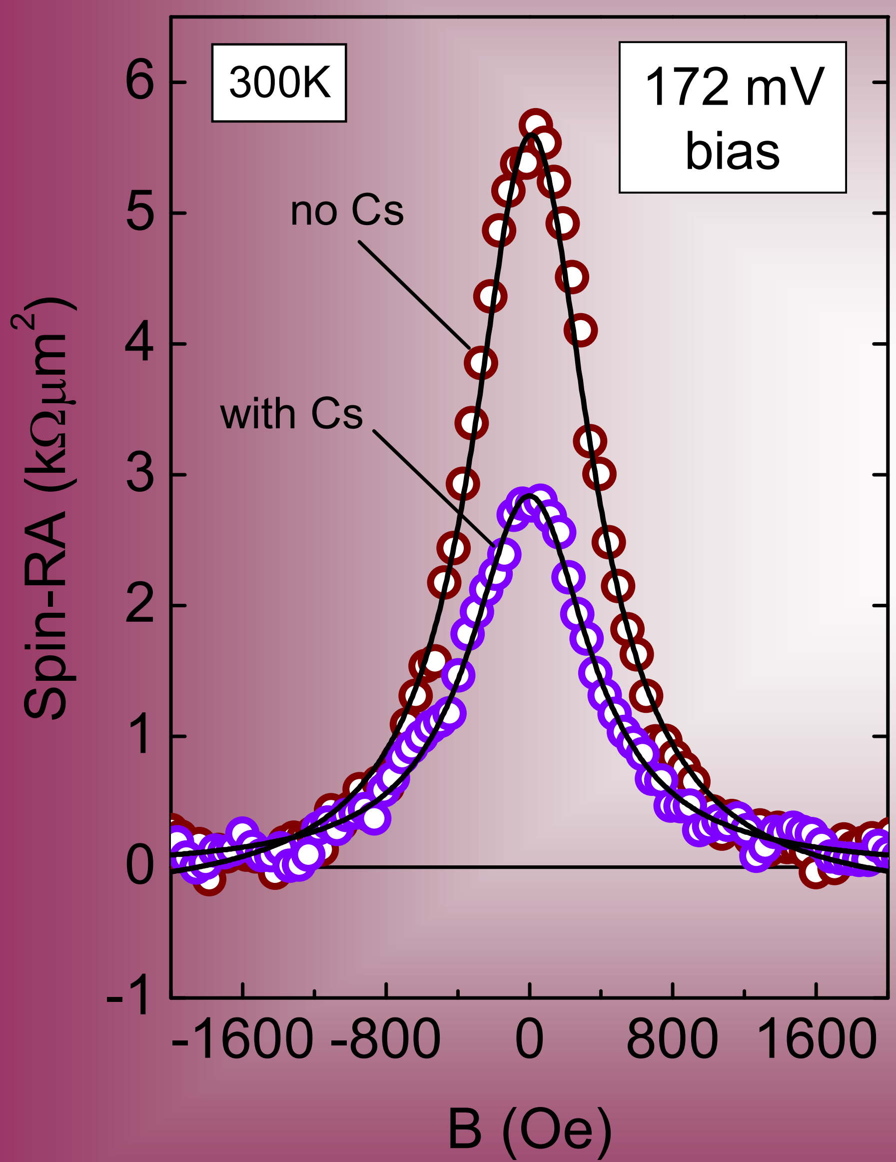




Effect of Cs: see R. Jansen et al., PRB 82, 241305(R) (2010).

Ruling out spin accumulation in interface states

Dash et al. Nature 462, 491 (2009)



1) No significant change with Cs

2) With Cs still large spin-RA in 1-10 kΩμm^2 range.

But with Cs the r_b is much smaller than this (r_b should be 40 Ωμm^2 at best)

Data with Cs cannot be explained by enhancement due to surface states

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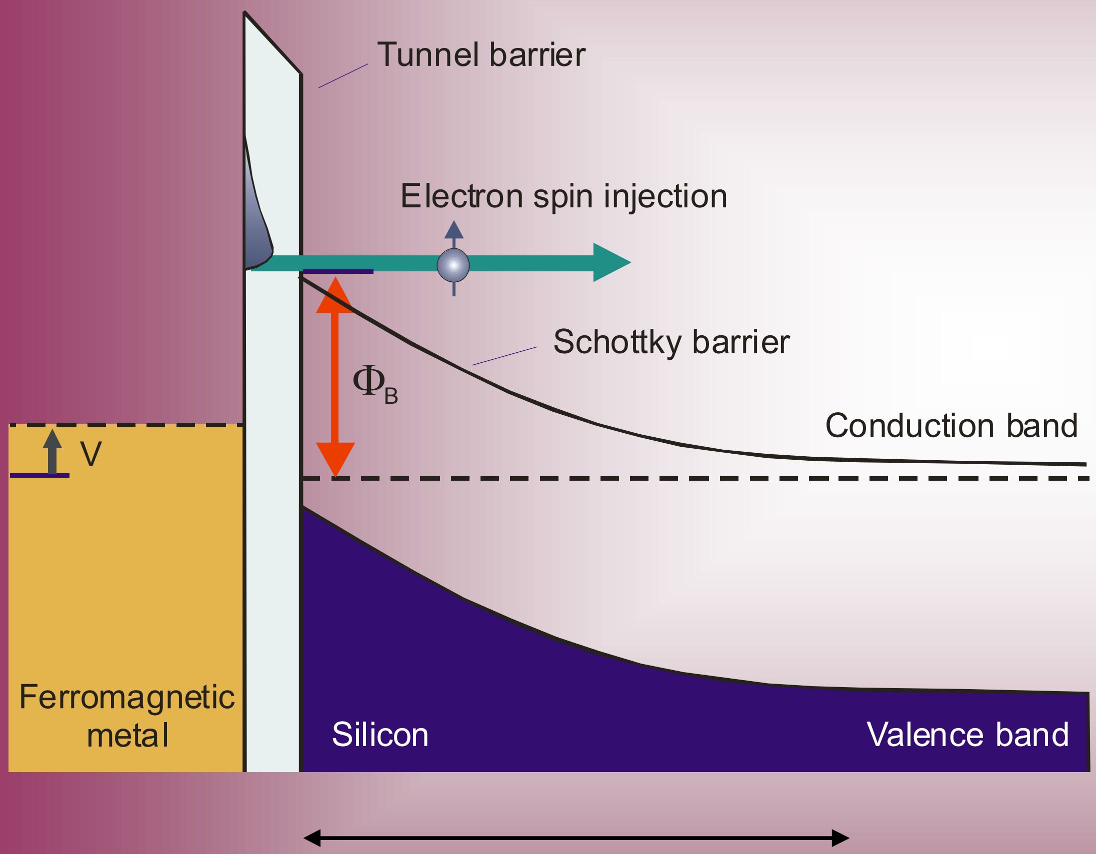
The carrier depletion issue

Metal / Semiconductor contact



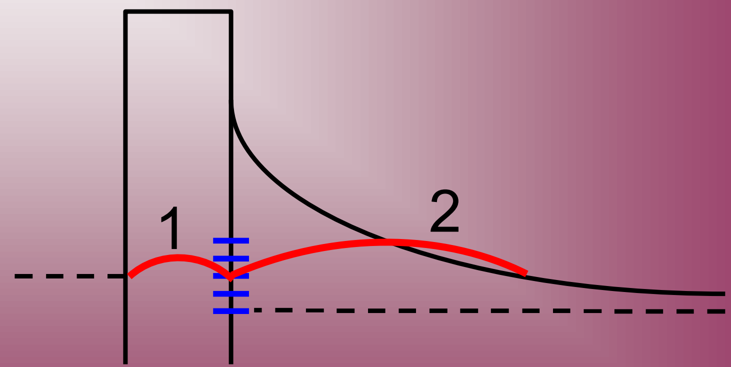
Depletion region
10 – 1000 nm

Depletion region:

1) Diode – small current
   – large dwell time
   Min et al. Nature Mater 5, 817 (2006)

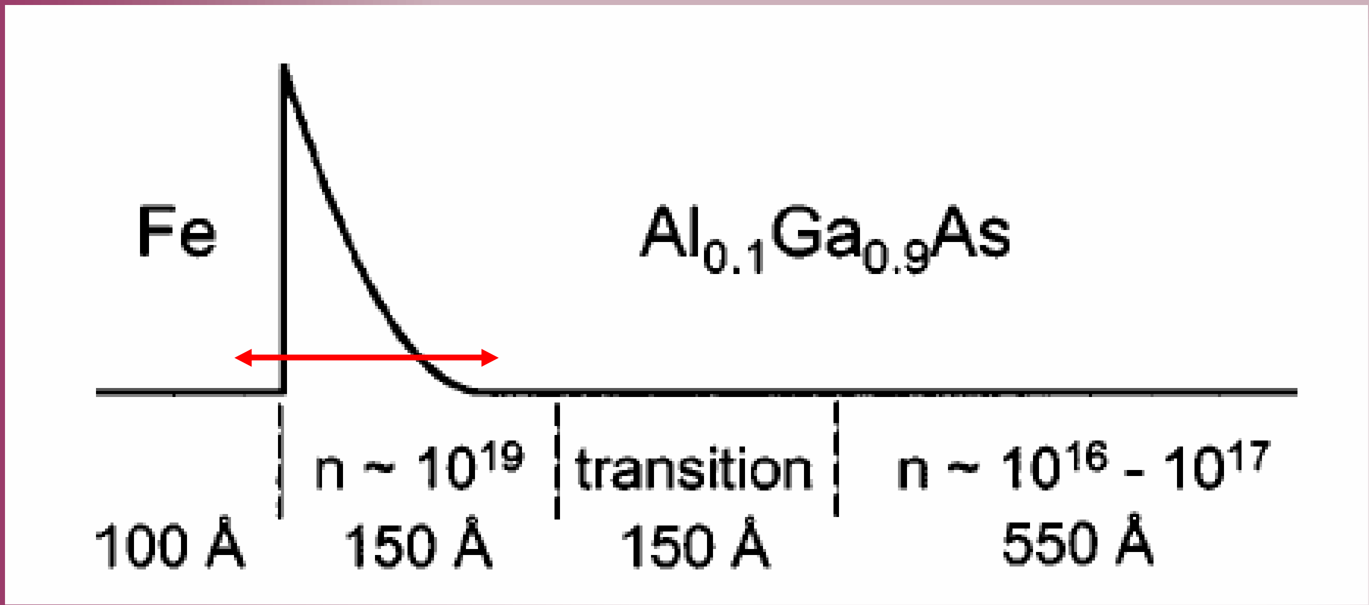
2) Spin transport → tunneling & thermionic emission
   Jansen et al. PRL 99, 246604 (2007)

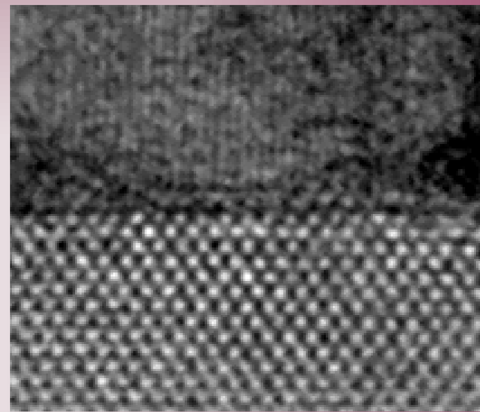
3) Two-step tunneling via interface states
   Tran et al. PRL 102, 036601 (2009)



Reduced depletion in FM/Semiconductor contacts

heavily doped surface region



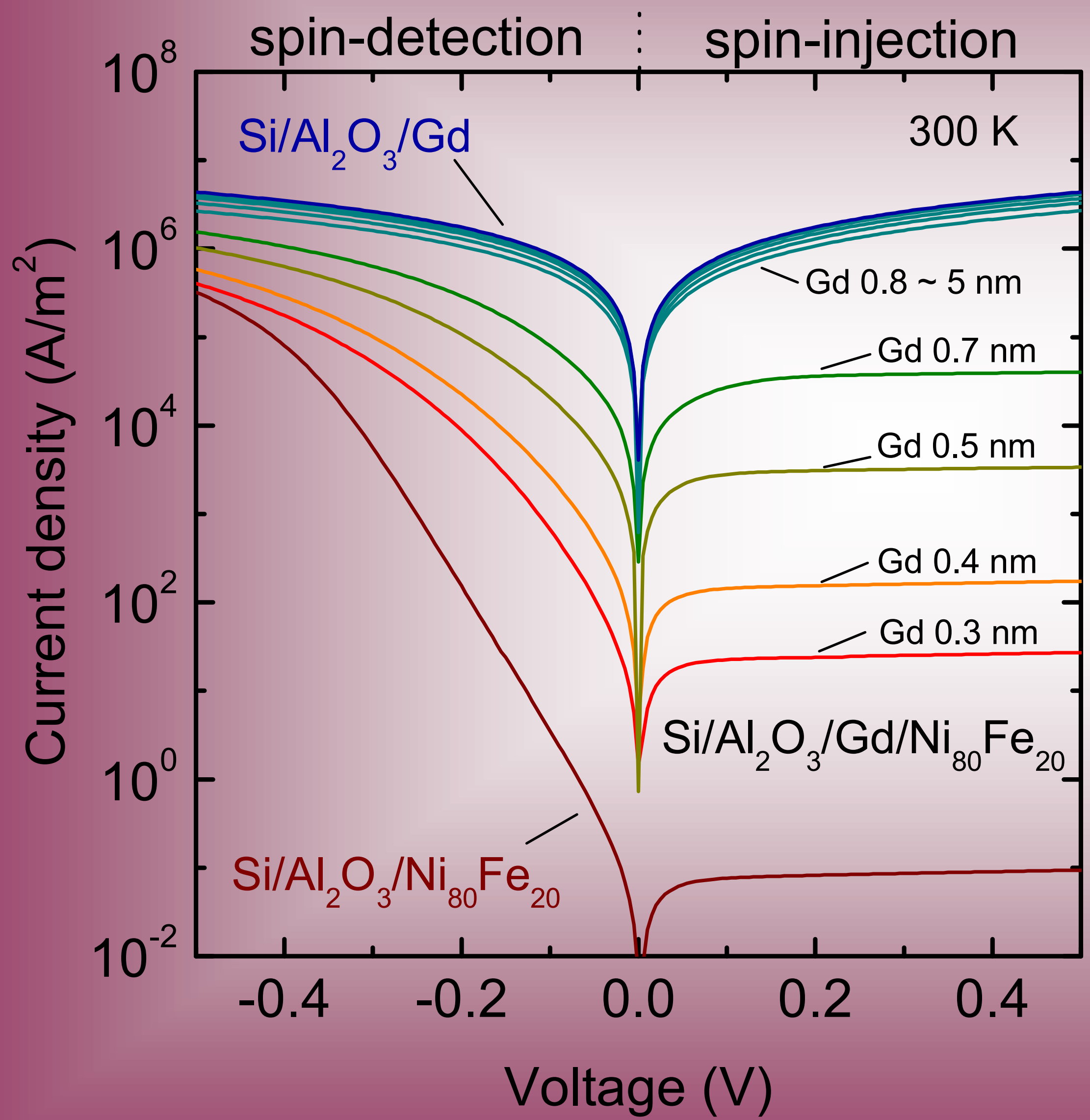


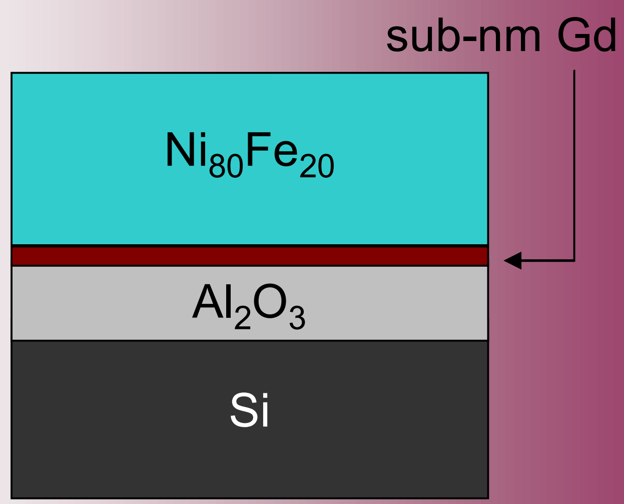
Grown by MBE

Used by many groups
for GaAs and more recently for Si.

Tuning of the FM/Si tunnel contact resistance

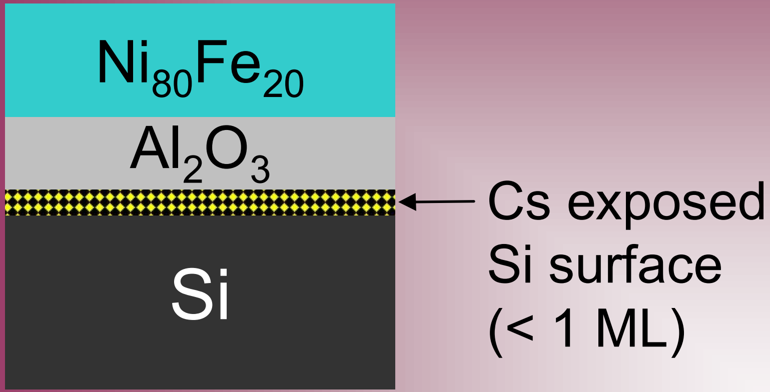
with low work function ferromagnets

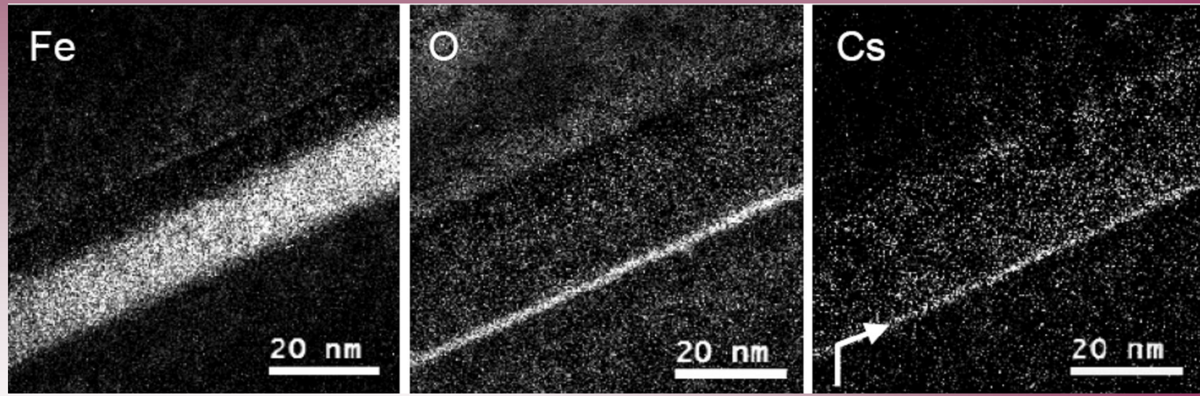




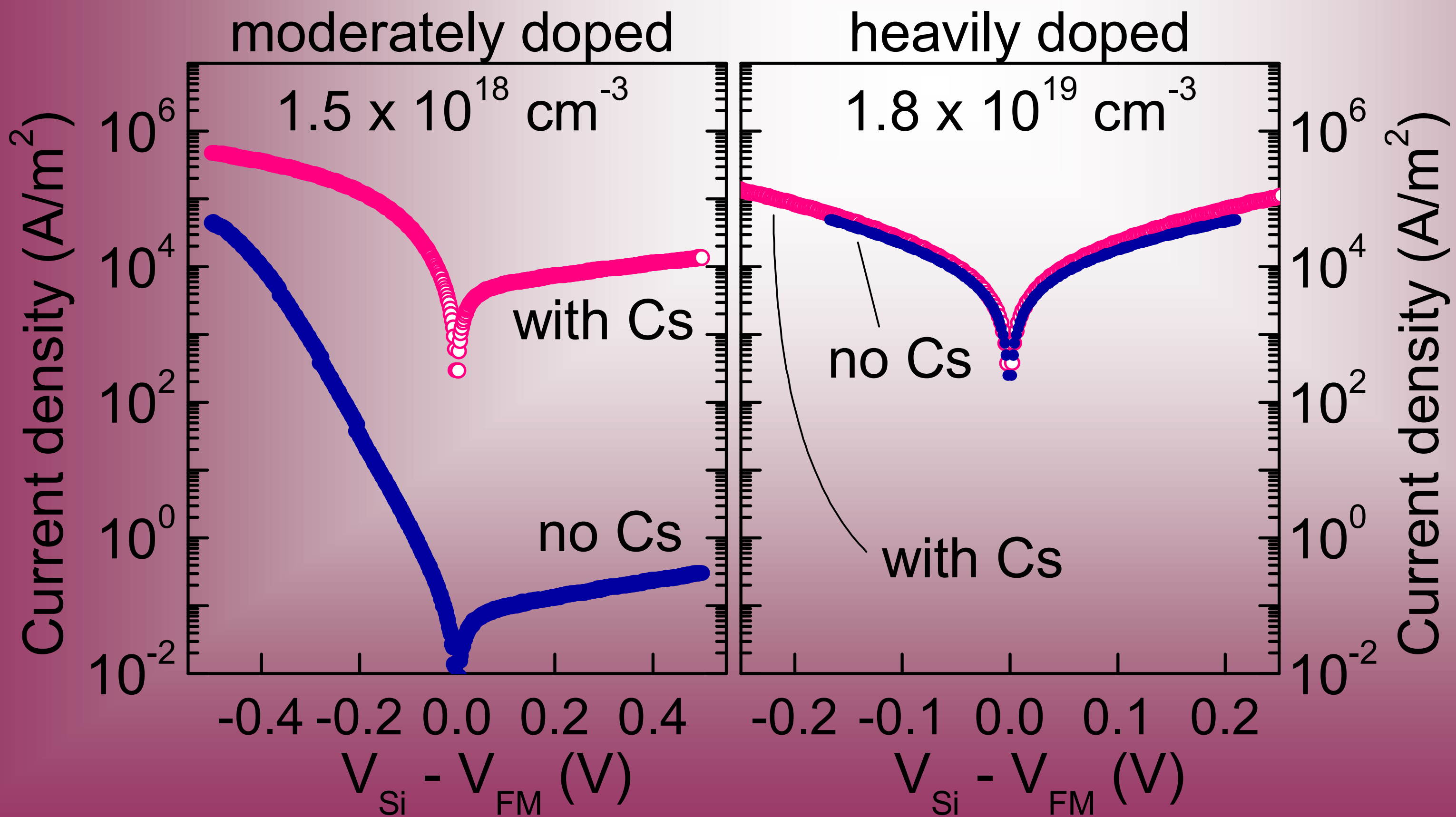
B.C. Min et al,
Nature Materials **5**, 817 (2006)

Engineering spin tunnel contacts to silicon by Cs





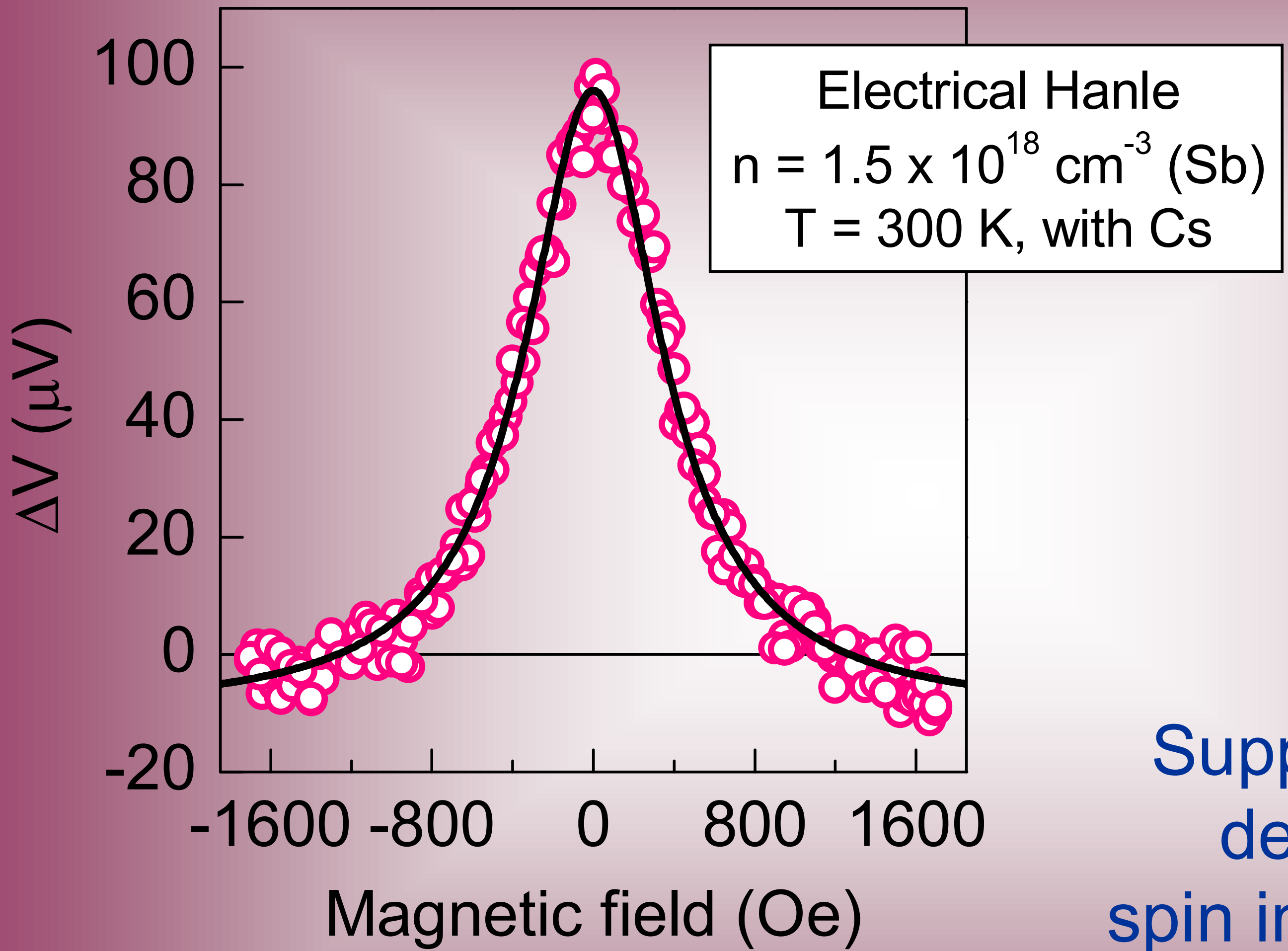
EF-TEM



R. Jansen et al., PRB 82, 241305(R) (2010).

Electrical creation of spin polarization in Si

medium donor impurity concentration



Without Cs:
- Strong diode
- No Hanle signal

With Cs:
- Schottky barrier suppressed
- Hanle signal !

Suppression of carrier depletion enables spin injection & detection

R. Jansen et al., PRB 82, 241305(R) (2010).

Summary

Exciting progress

- In GaAs, recently also in Si & Ge and at 300 K

Basic understanding of spin injection, but

- Many aspects poorly or not understood
- Theories not yet confirmed experimentally

Outlook

Challenges:

- Electric field control without spin-orbit
- Device design

Opportunities by new approaches to spin injection

- Spin pumping from magnetization dynamics
- Thermal spin current (spin caloritronics)