Silicon spintronics

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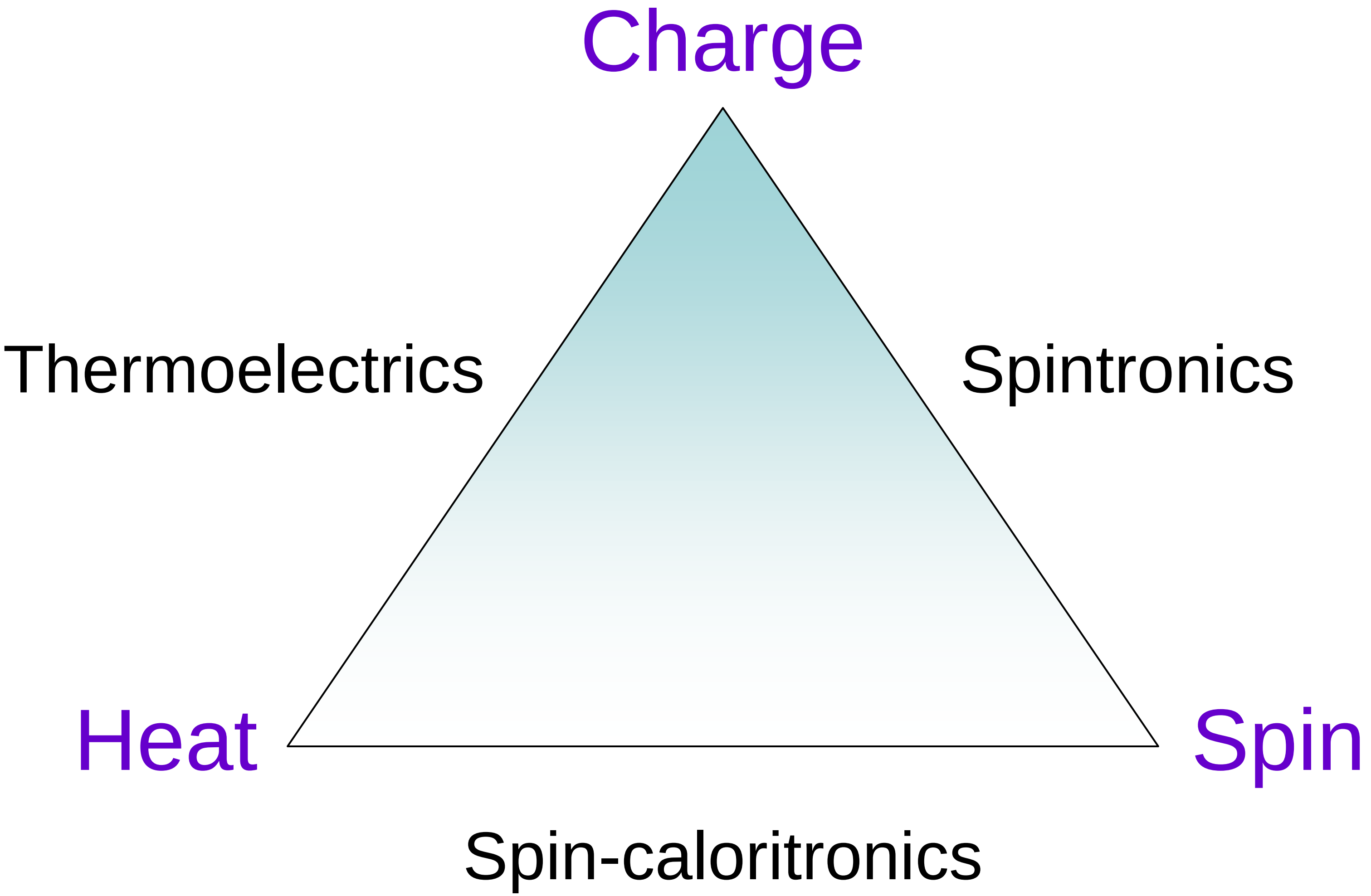
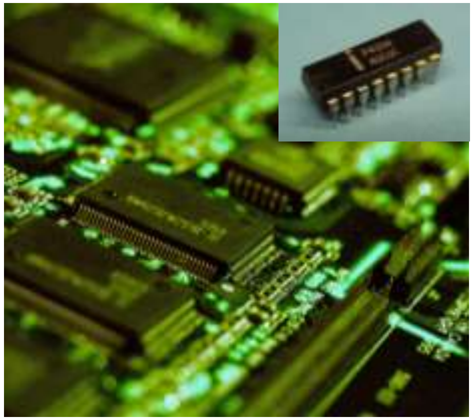

Charge
Thermoelectrics
Spintronics
Heat
Spin
Spin-caloritronics

Issues in computing based on charge



1) Concerns about continuation of scaling down

2) Heat generated by electronic components limits performance

3) Computing is increasing fraction of world's energy consumption

⇒ Need for alternative, low power solutions

Semiconductor Spintronics

a new technology based on spin

Semiconductors

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

Technology base -
(electronics)

Ferromagnets

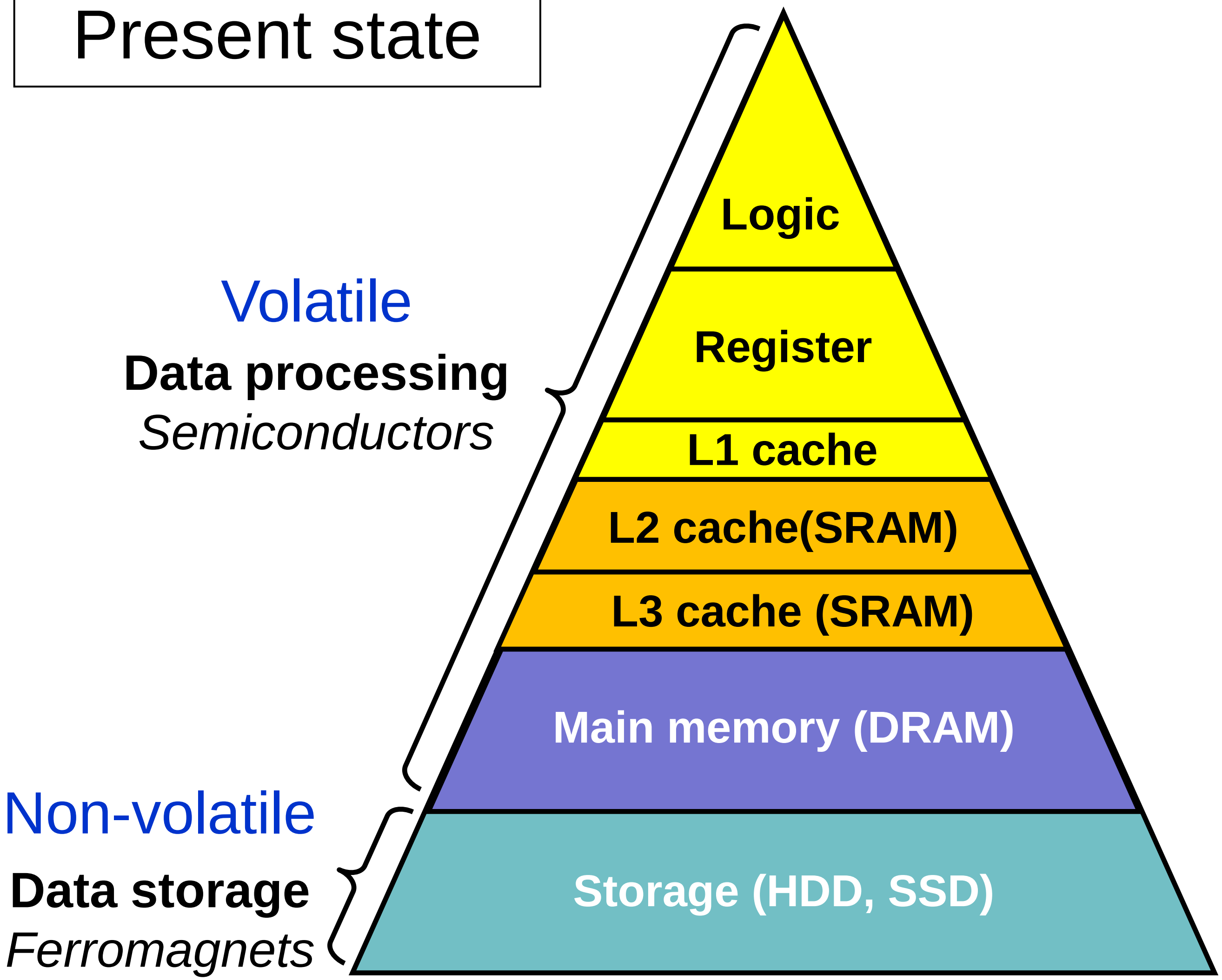
- Non-volatile memory
- Fast switching
- High ordering temp.
- Spin transport

- Technology base
(magnetic recording)

Combining the best of both worlds

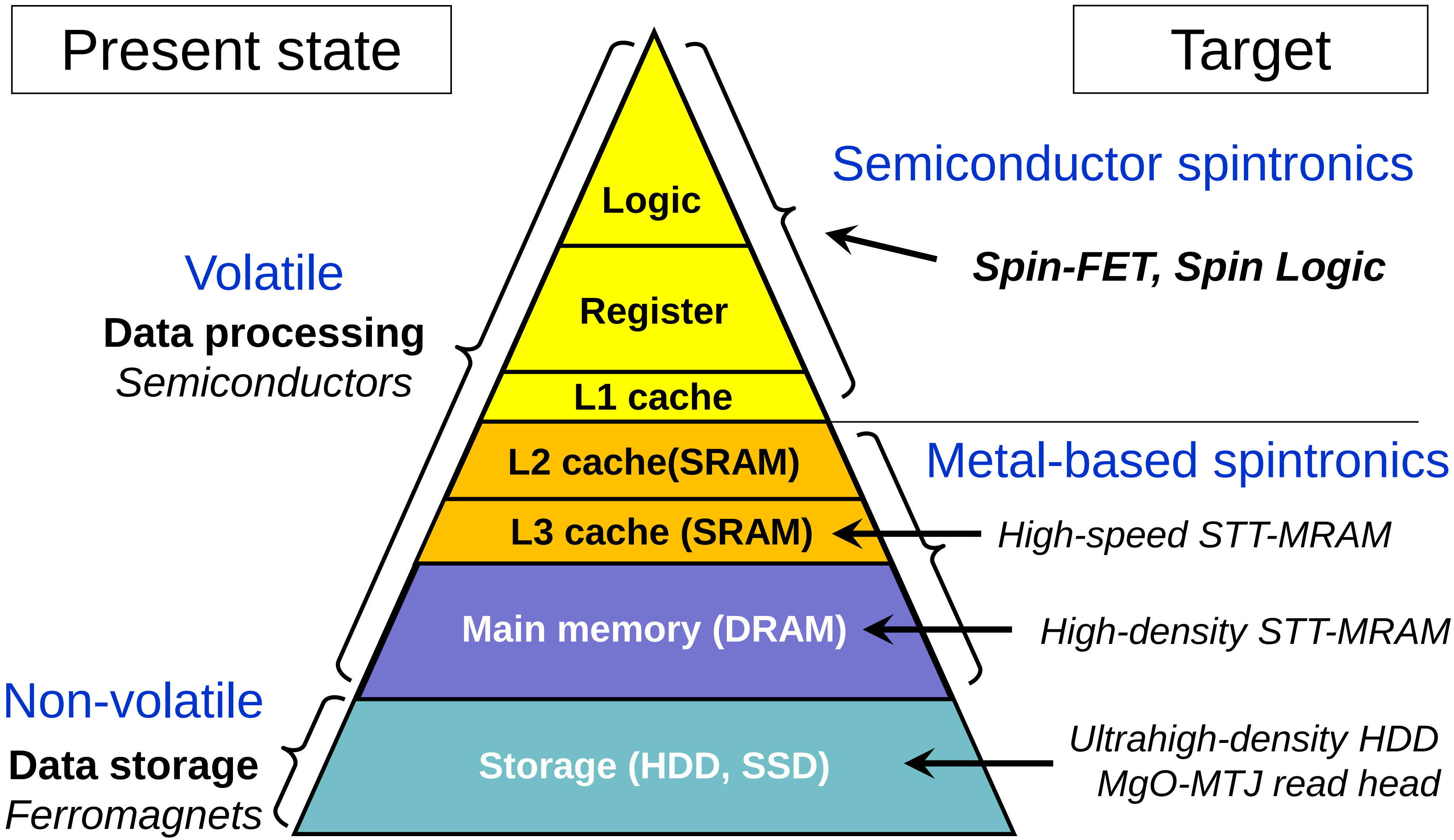
Computer hierarchy & spin

Present state



Courtesy of K. Ando

Computer hierarchy & spin



Courtesy of K. Ando

Proposed spin-based device and systems

Spin transistors

Datta, S. & Das, B. Electronic analog of the electro-optic modulator. *Appl. Phys. Lett.* **56**, 665-667 (1990).
Sugahara, S. & Tanaka, M. A spin metal-oxide-semiconductor field-effect transistor using half-metallic-ferromagnet contacts for the source and drain. *Appl. Phys. Lett.* **84**, 2307-2309 (2004).
Tanaka, M. & Sugahara, S. MOS-Based Spin Devices for Reconfigurable Logic. *IEEE Trans. Electr. Dev.* **54**, 961-976 (2007).
Sugahara, S. & Nitta, J. Spin-Transistor Electronics: An Overview and Outlook. *Proc. IEEE* **98**, 2124-2154 (2010).
Appelbaum, I. & Monsma, D. J. Transit-time spin field-effect transistor. *Appl. Phys. Lett.* **90**, 262501 (2007).
Roy, A. M., Nikonov, D.E. & Saraswat, K. C. Conductivity mismatch and voltage dependence of magnetoresistance in a semiconductor spin injection device. *J. Appl. Phys.* **107**, 064504 (2010).
Gao, Y., Low, T., Lundstrom, M. S. & Nikonov, D. E. Simulation of spin field effect transistors: Effects of tunneling and spin relaxation on performance. *J. Appl. Phys.* **108**, 083702 (2010).

Spin diodes

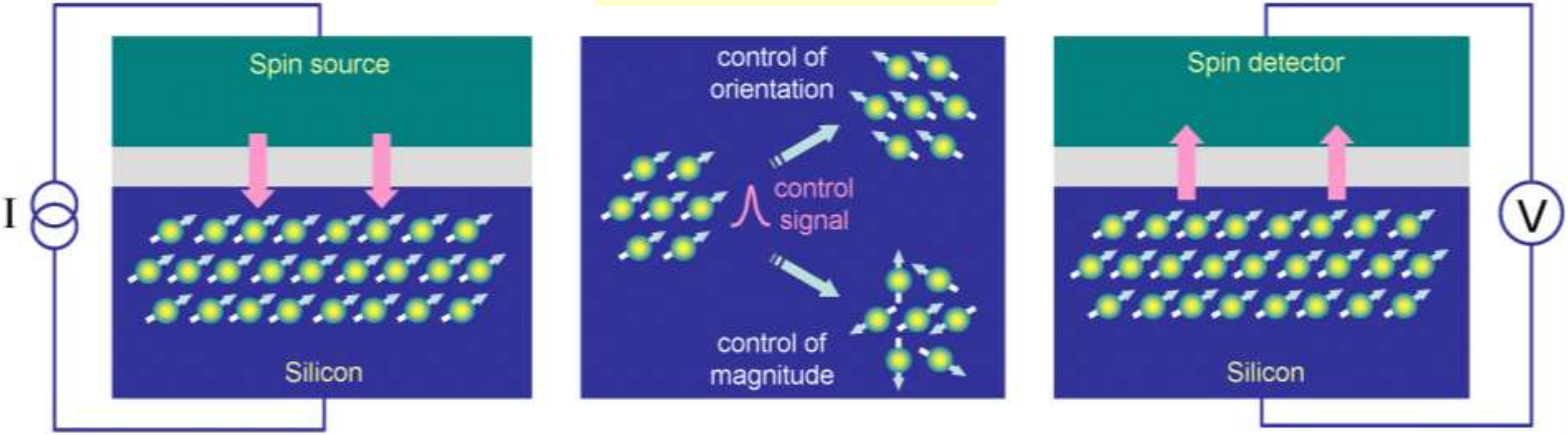
Flatté, M. E. & Vignale, V. Unipolar spin diodes and transistors. *Appl. Phys. Lett.* **78**, 1273-1275 (2001).
Flatté, M. E., Yu, Z. G., Johnston-Halperin, E. & Awschalom, D. D. Theory of semiconductor magnetic bipolar transistors. *Appl. Phys. Lett.* **84**, 4740-4742 (2003).
Castelano, L. K. & Sham, L. J. Proposal for efficient generation of spin-polarized current in silicon. *Appl. Phys. Lett.* **96**, 212107 (2010).
Rüth, M., Gould, C. & Molenkamp, L. W. Zero field spin polarization in a two-dimensional paramagnetic resonant tunneling diode. *Phys. Rev. B* **83**, 155408 (2011).

Spin circuits and spin logic

Tanamoto, T., Sugiyama, H., Inokuchi, T., Marukame, T., Ishikawa, M., Ikegami, K. & Saito, Y. Scalability of spin field programmable gate array: A reconfigurable architecture based on spin metal-oxide-semiconductor field effect transistor. *J. Appl. Phys.* **109**, 07C312 (2011).
Dery, H., Dalal, P., Cywiński, L. & Sham, L. J. Spin-based logic in semiconductors for reconfigurable large-scale circuits. *Nature* **447**, 573-576 (2007).
Behin-Aein, B., Datta, B., Salahuddin, S. & Datta, S. Proposal for an all-spin logic device with built-in memory. *Nature Nano.* **5**, 266-270 (2010).
Dery, H., Song, Y., Li, P. & Žutić, I. Silicon spin communication. *Appl. Phys. Lett.* **99**, 082502 (2011).

Building blocks of silicon spintronics

Create spin	Manipulate spin $0 \leftrightarrow 1$	Detect spin



Ferromagnetic tunnel contact	Magnetic field Electric field	Ferromagnetic tunnel contact

Topics

Electrical creation/detection of spin polarization in Si

Creating spin polarization in silicon by heat

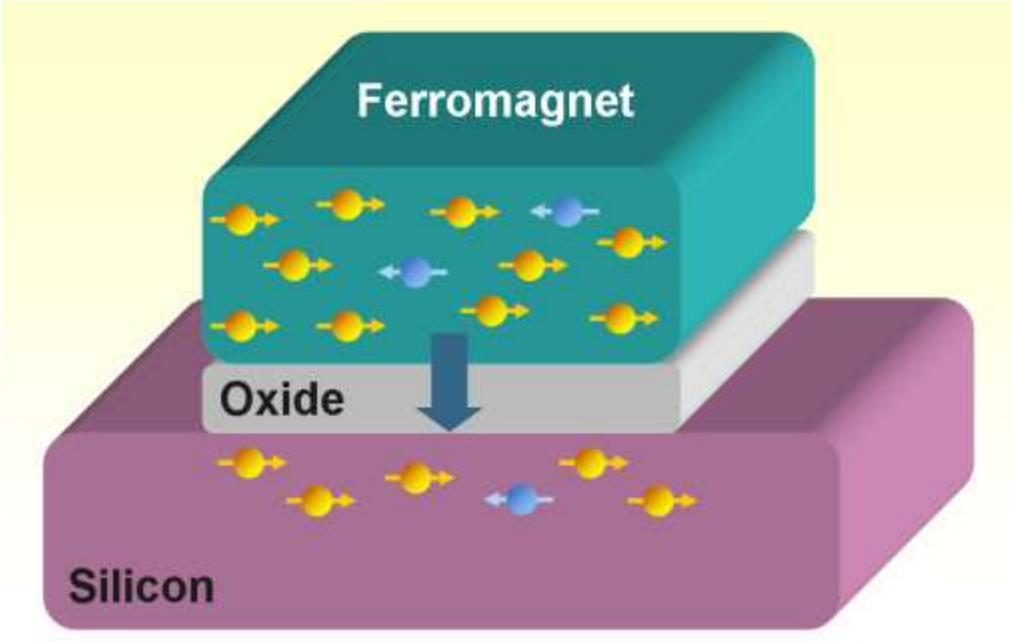
Combining electrical and thermal spin currents
&
Voltage tuning of thermal spin currents

Creation of spin polarization in semiconductors

by electrical injection from a ferromagnetic tunnel contact

Transfer of spins by spin-polarized tunneling

$$\boxed{I_T^{\uparrow} \neq I_T^{\downarrow}}$$

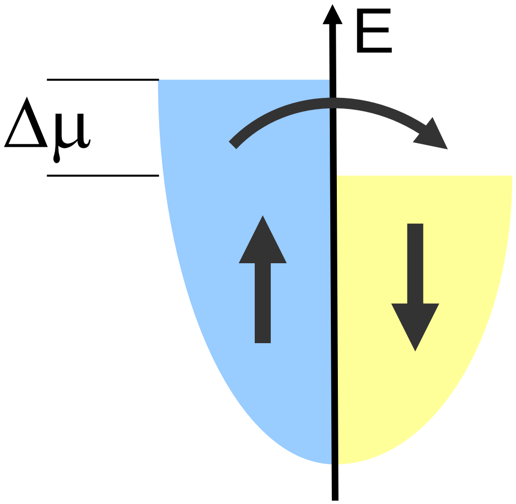


- Supply of spins by current
- Spin relaxation in semiconductor

$\Big\}\ \Delta\mu$

Creates spin accumulation

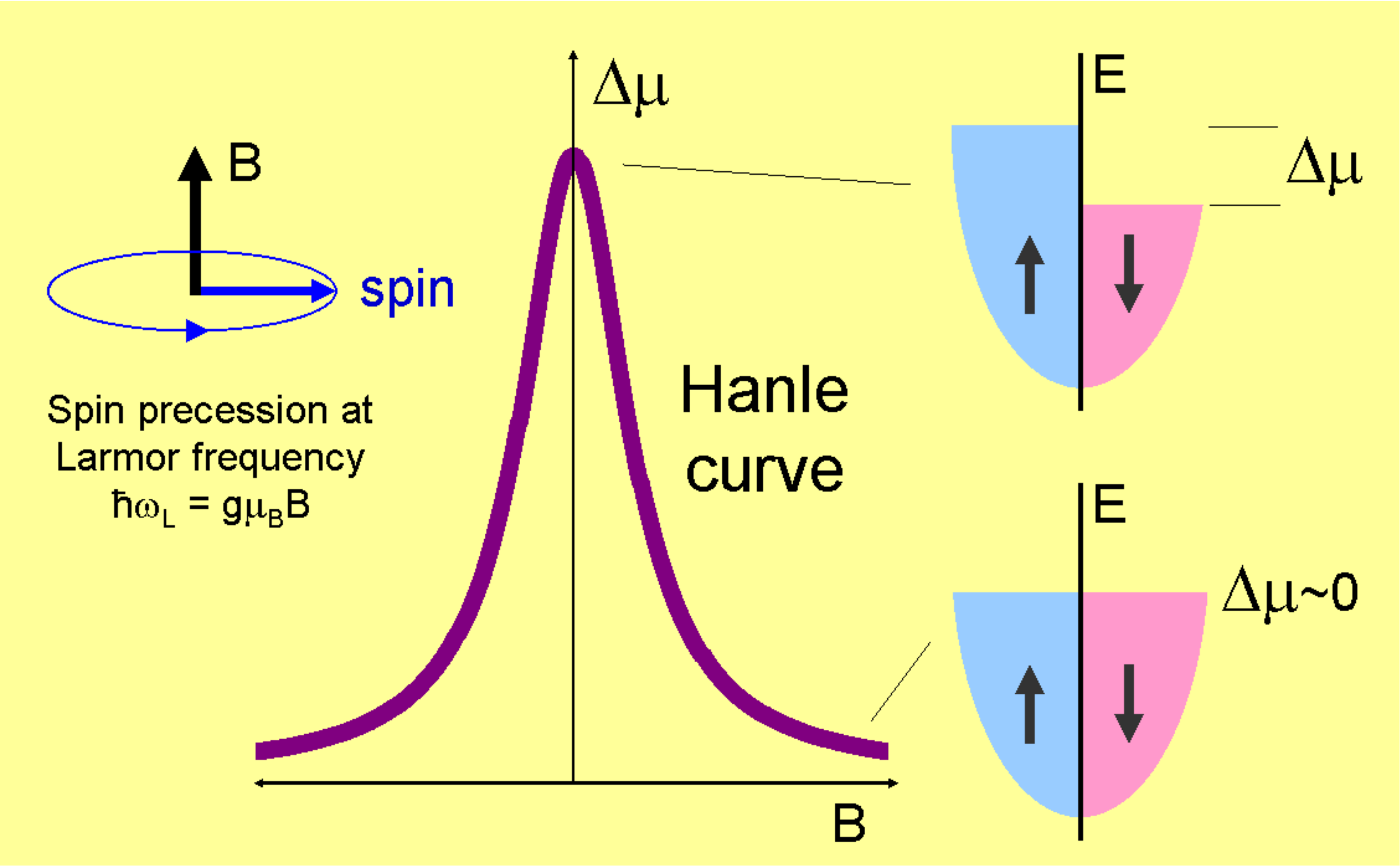
$$\boxed{\Delta\mu = \mu^{\uparrow} - \mu^{\downarrow}}$$



$$\boxed{n^{\uparrow} > n^{\downarrow}}$$

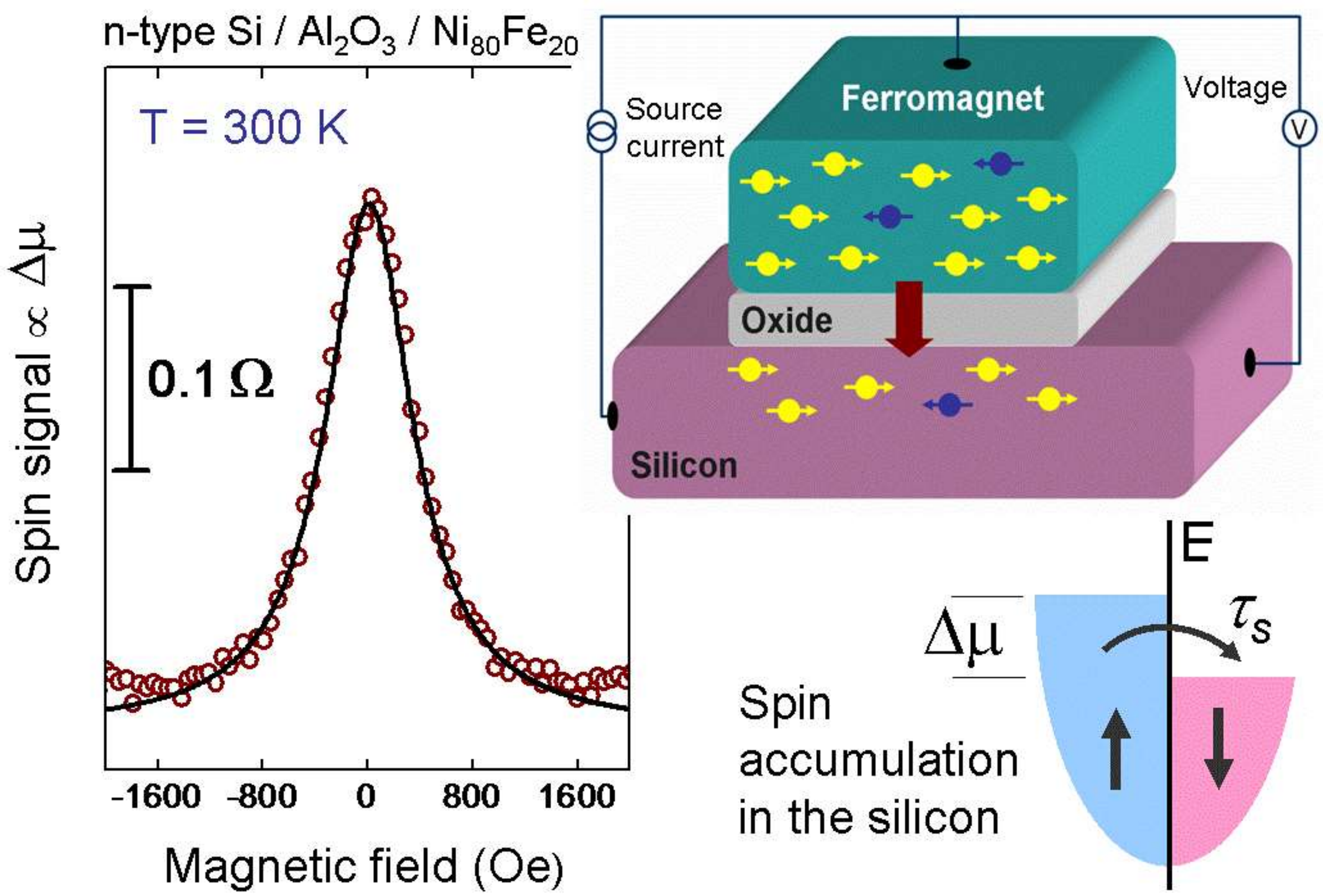
Spin manipulation & detection

Precession of spins in transverse magnetic field (Hanle effect)



Creating spin polarization in silicon at 300 K

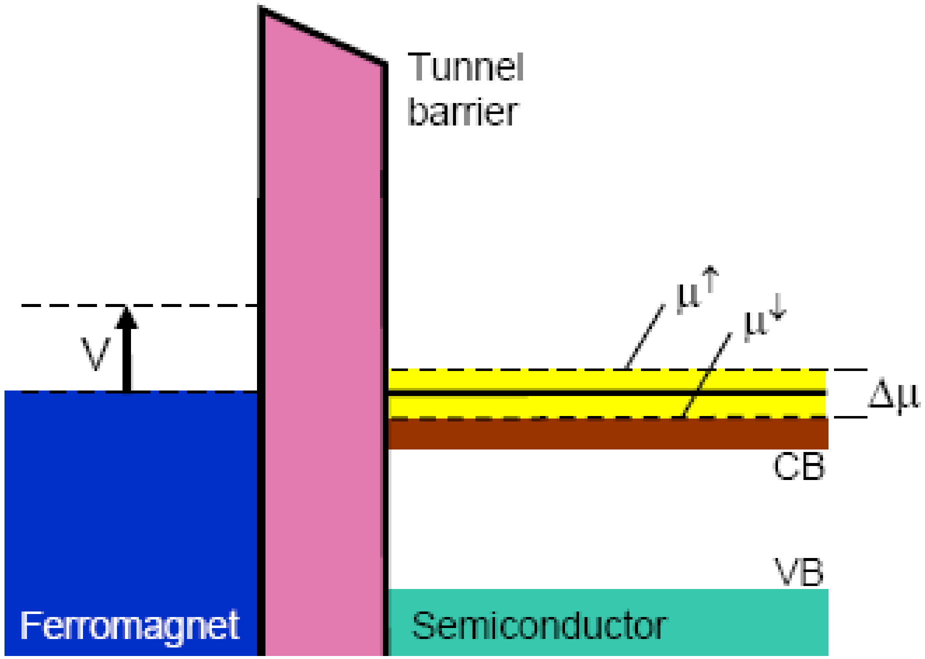
by electrical spin injection from a magnetic tunnel contact



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

Electrical detection of spin polarization

Resistance of tunnel contact is proportional to Δμ



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

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

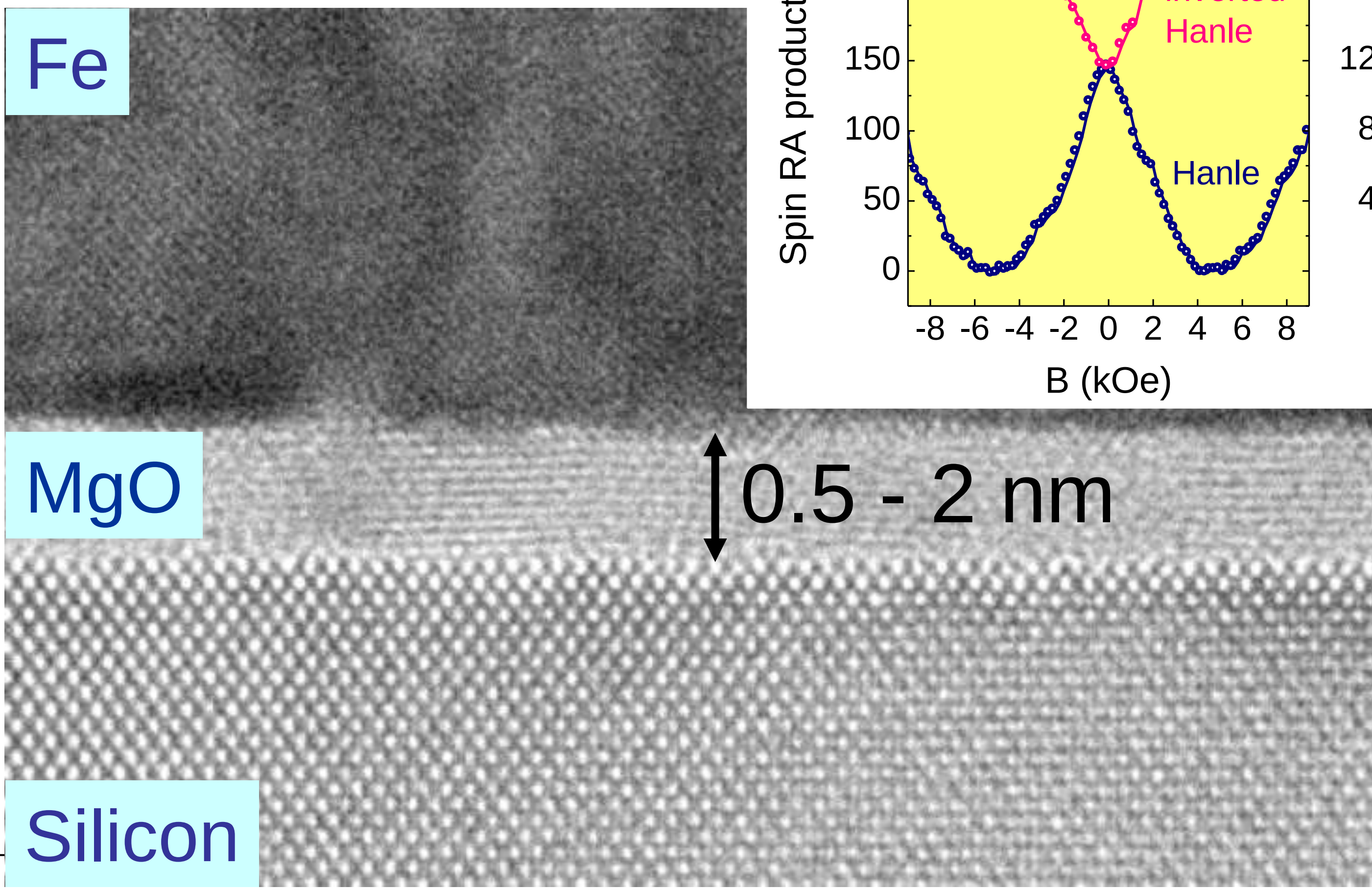
$$\boxed{V = I\,R_{tun} + P_G\left(\frac{\Delta\mu}{2}\right)}$$

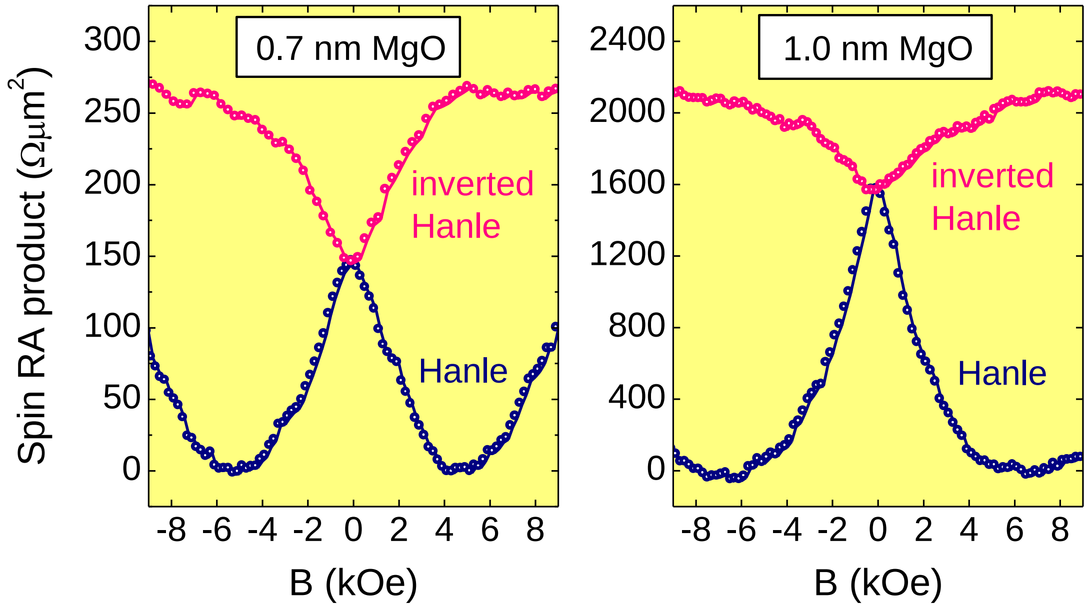
Tunnel spin polarization: $P = \dfrac{G^{\uparrow} - G^{\downarrow}}{G^{\uparrow} + G^{\downarrow}}$

Creation of spin polarization in silicon at 300 K

Crystalline Fe / MgO tunnel contact

p-type Si (Boron, p = 5 x 10^{18} cm^{-3})





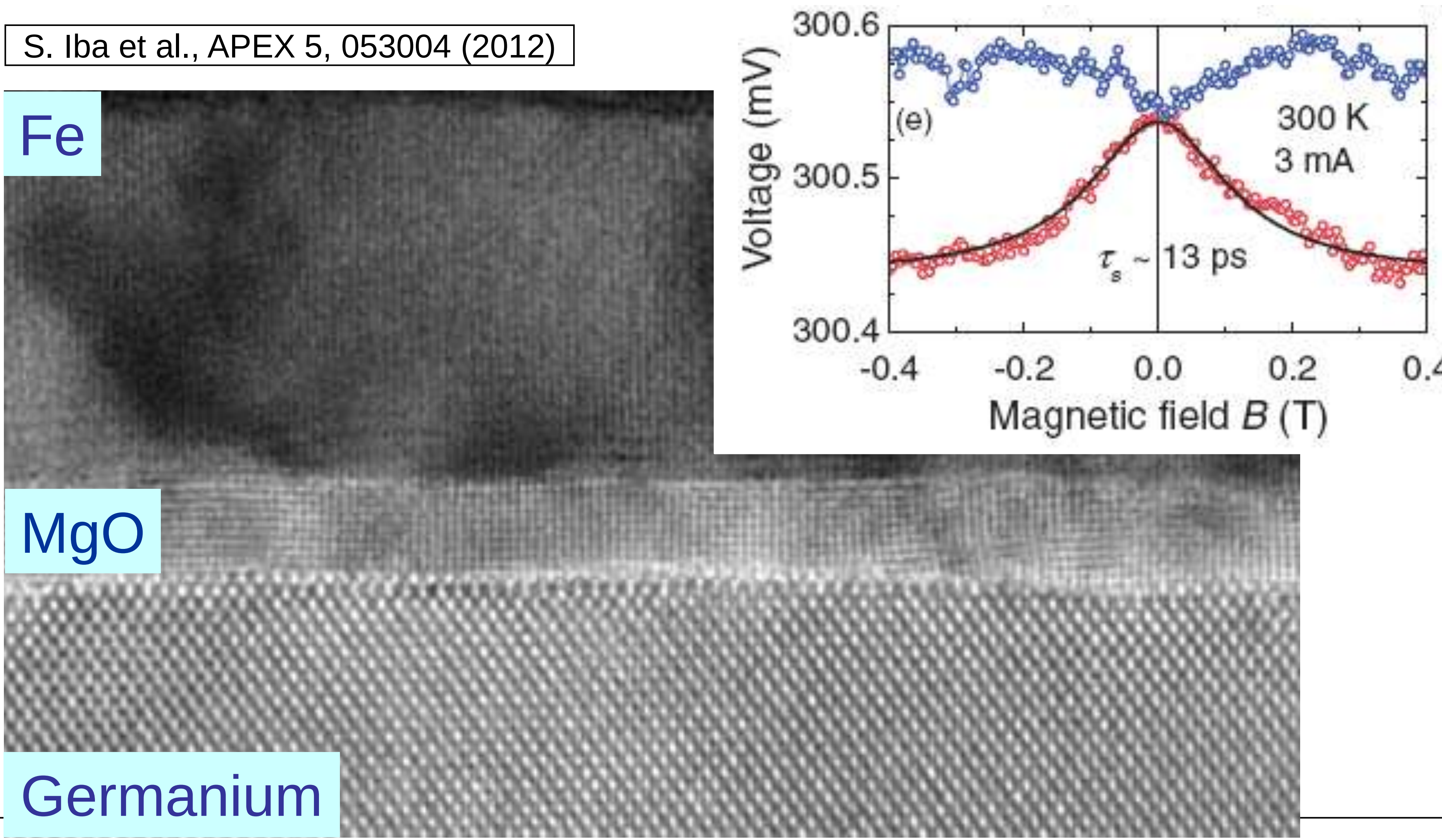
S. Sharma et al. PRB 89, 075301 (2014)

A. Spiesser et al. Proc. SPIE 8461, 84610K (2012)

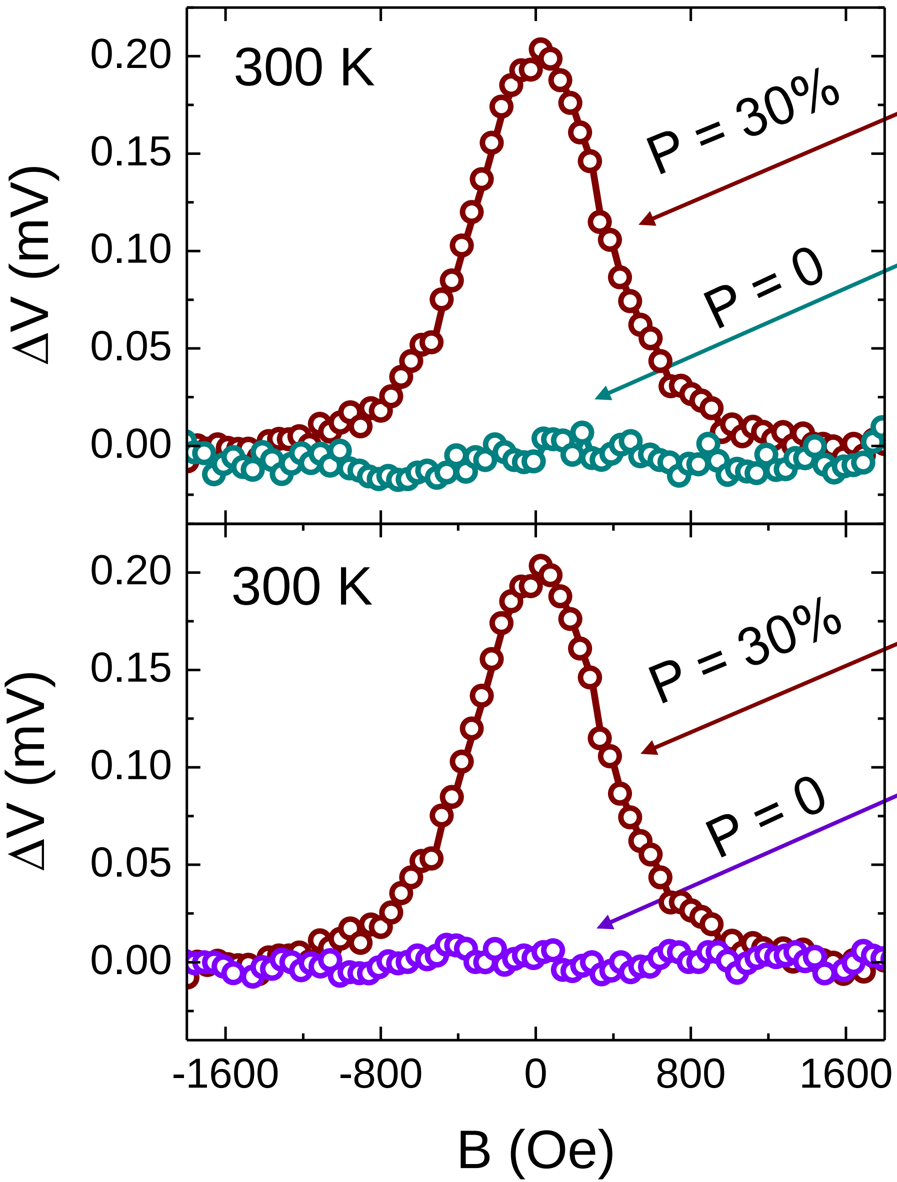
Spintronics with p-type germanium at 300 K

Crystalline and Schottky free contacts

S. Iba et al., APEX 5, 053004 (2012)



Control experiment with Yb or Au nanolayer



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

Control device
Silicon / Al_2O_3 / Yb (2 nm) / $Ni_{80}Fe_{20}$

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

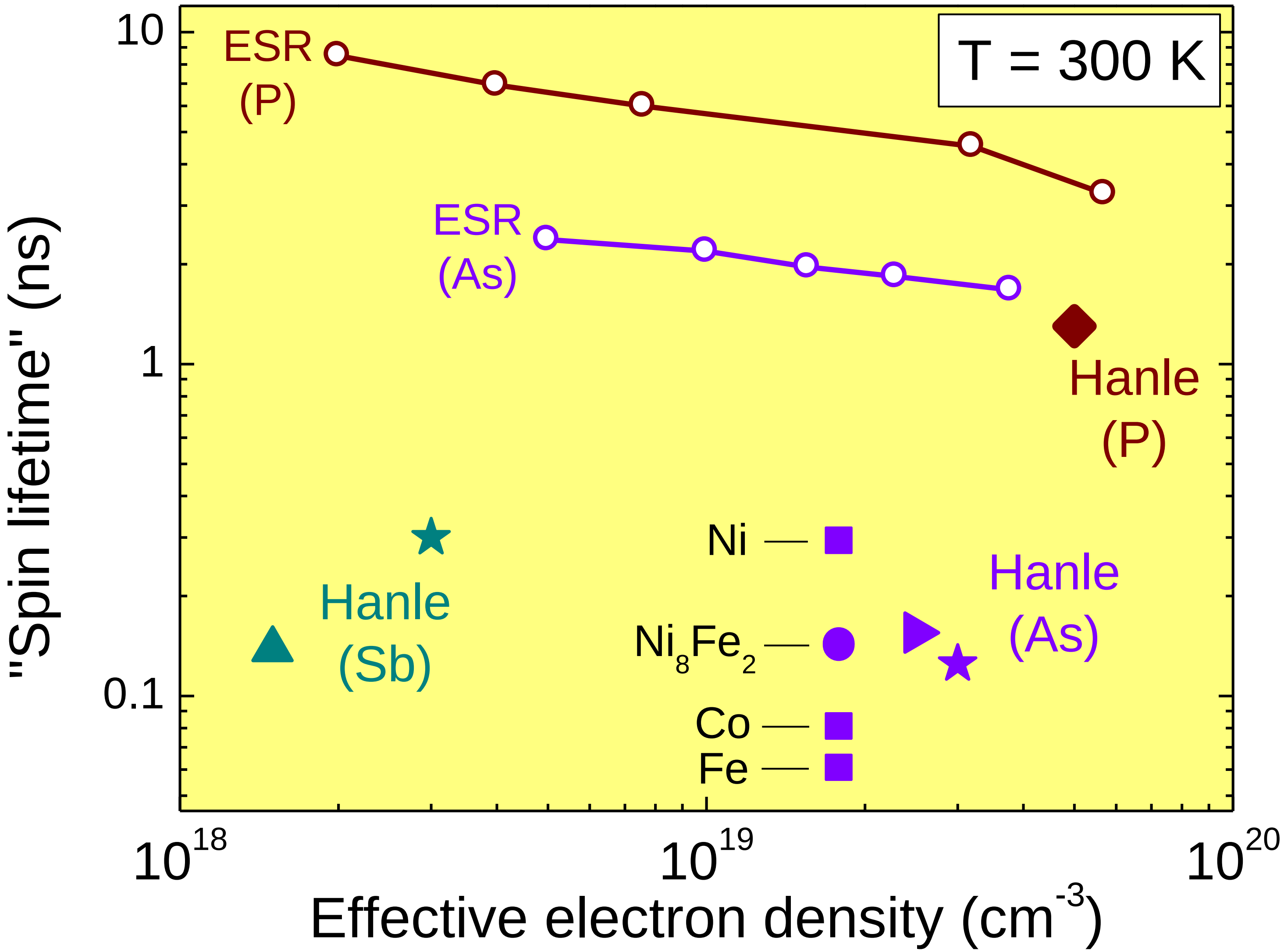
Control device
Silicon / Al_2O_3 / Au (3 nm) / $Ni_{80}Fe_{20}$

Proof that signal is due to spin injection by tunneling

Electrical creation of spin polarization in silicon

Spin lifetime and spin precession near a tunnel interface

Spin lifetime in n-type silicon - Hanle vs. ESR



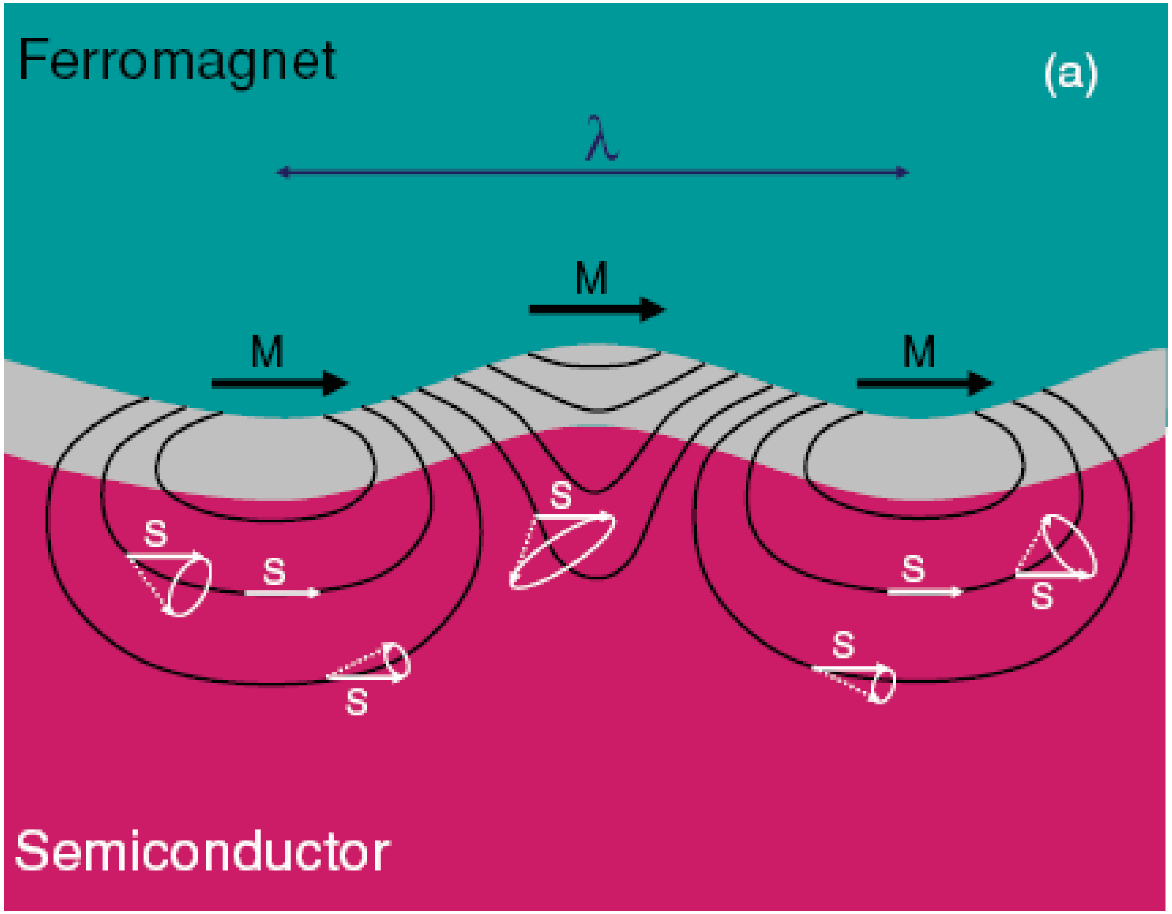
See reviews on Silicon Spintronics:

R. Jansen, Nature Materials 11, 400 (2012)

R. Jansen et al. Semicon. Sci. Technol. 27, 083001 (2012)

Extrinsic contributions to spin relaxation

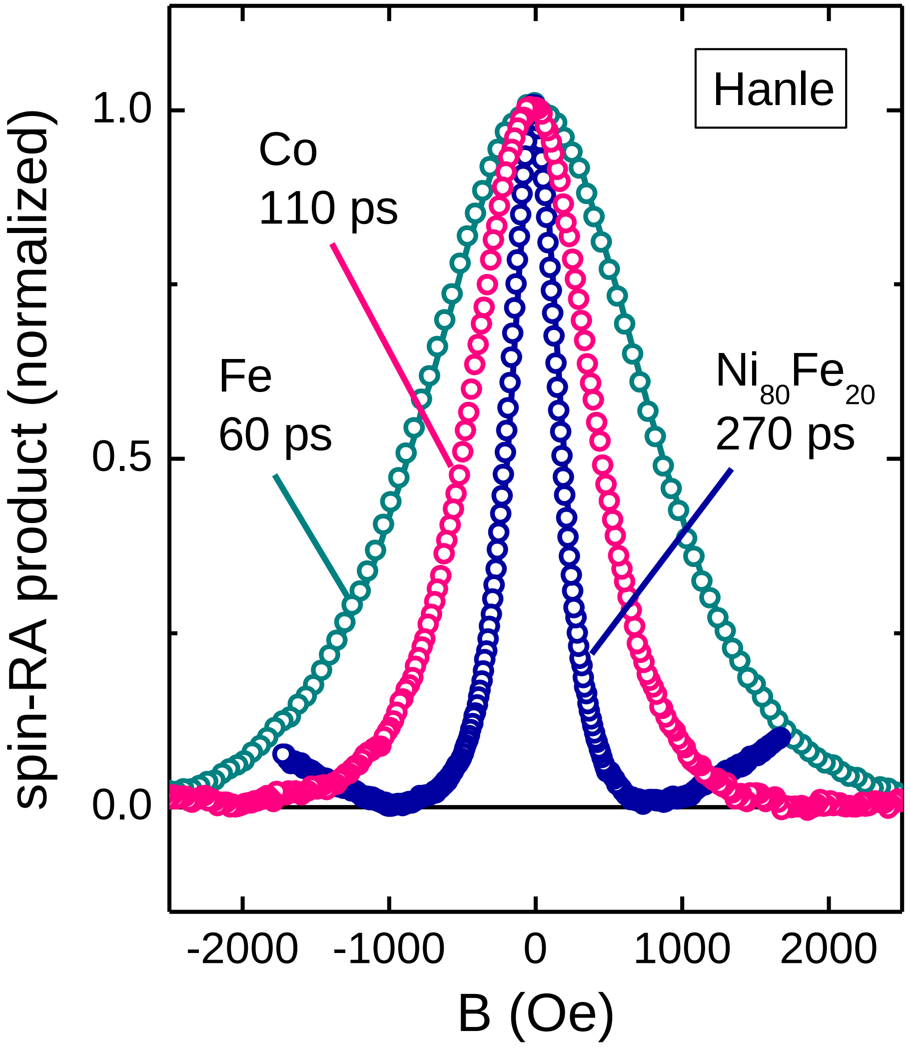
spin precession in local magnetostatic fields



Inhomogeneous spin precession axis and frequency

Spin relaxation near magnetic tunnel interface

role of ferromagnetic electrode



Injected spins feel presence of the ferromagnet !

$\Rightarrow$ Apparent reduction of spin lifetime

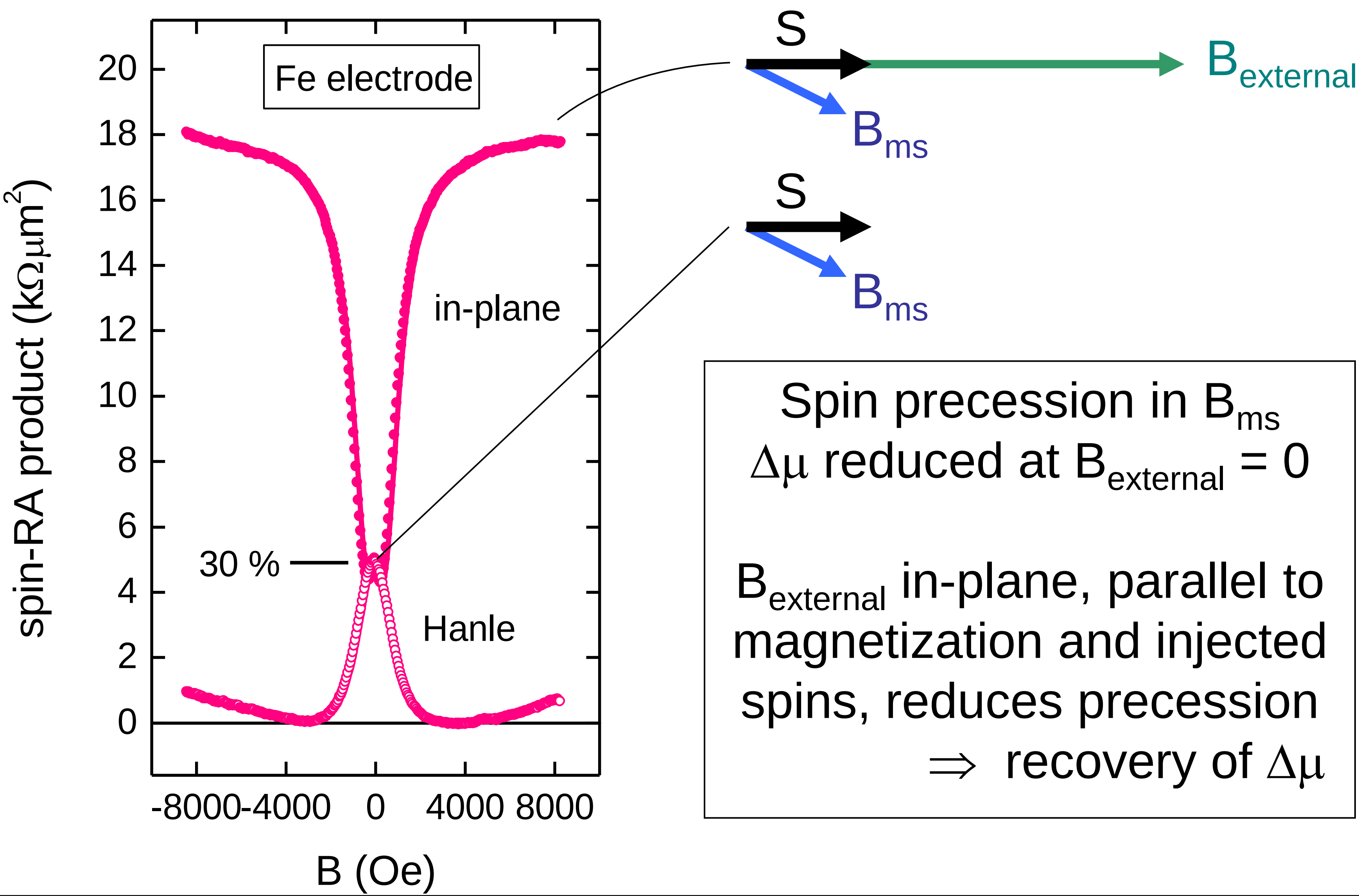
$Ni_{80}Fe_{20} \rightarrow \mu_0 M_{sat} = 0.9$ T

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

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

T = 300 K
p-Si = $4.8 \cdot 10^{18}$ cm^{-3} (B)

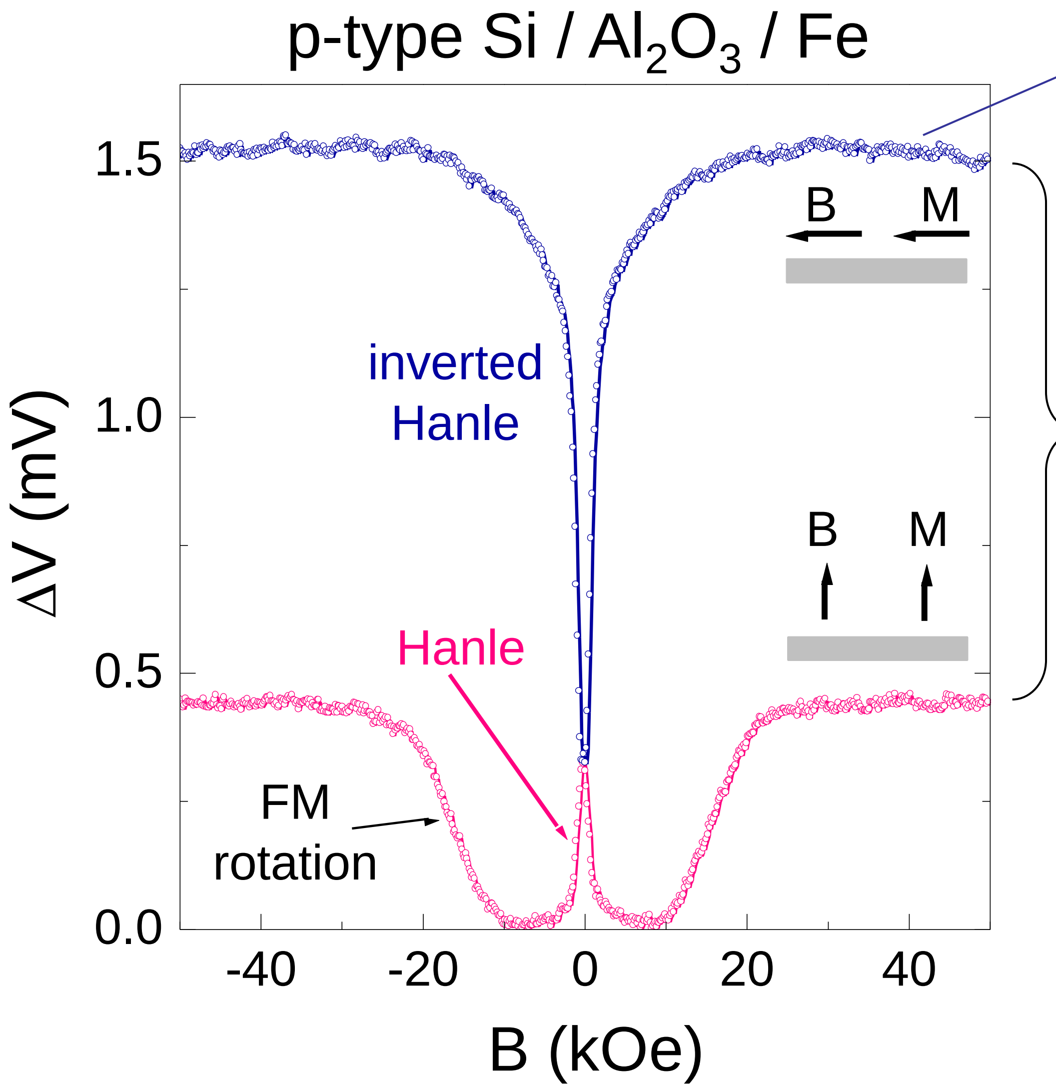
Hanle effect and inverted Hanle effect



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 $\Delta\mu$

Hanle, inverted Hanle & anisotropy



Inverted Hanle effect:
spin precession modified by
inhomogeneous magnetic fields
(roughness, nuclear spins)

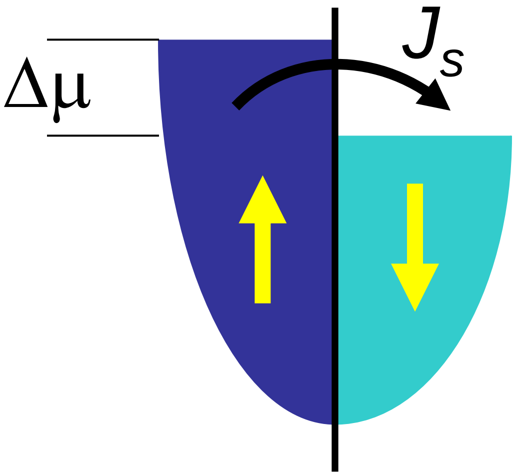
Anisotropy

All characteristic features of
spin precession and
spin accumulation

Magnitude and scaling of the spin signal

Magnitude of the spin accumulation

Expectation based on standard model for 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:

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

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

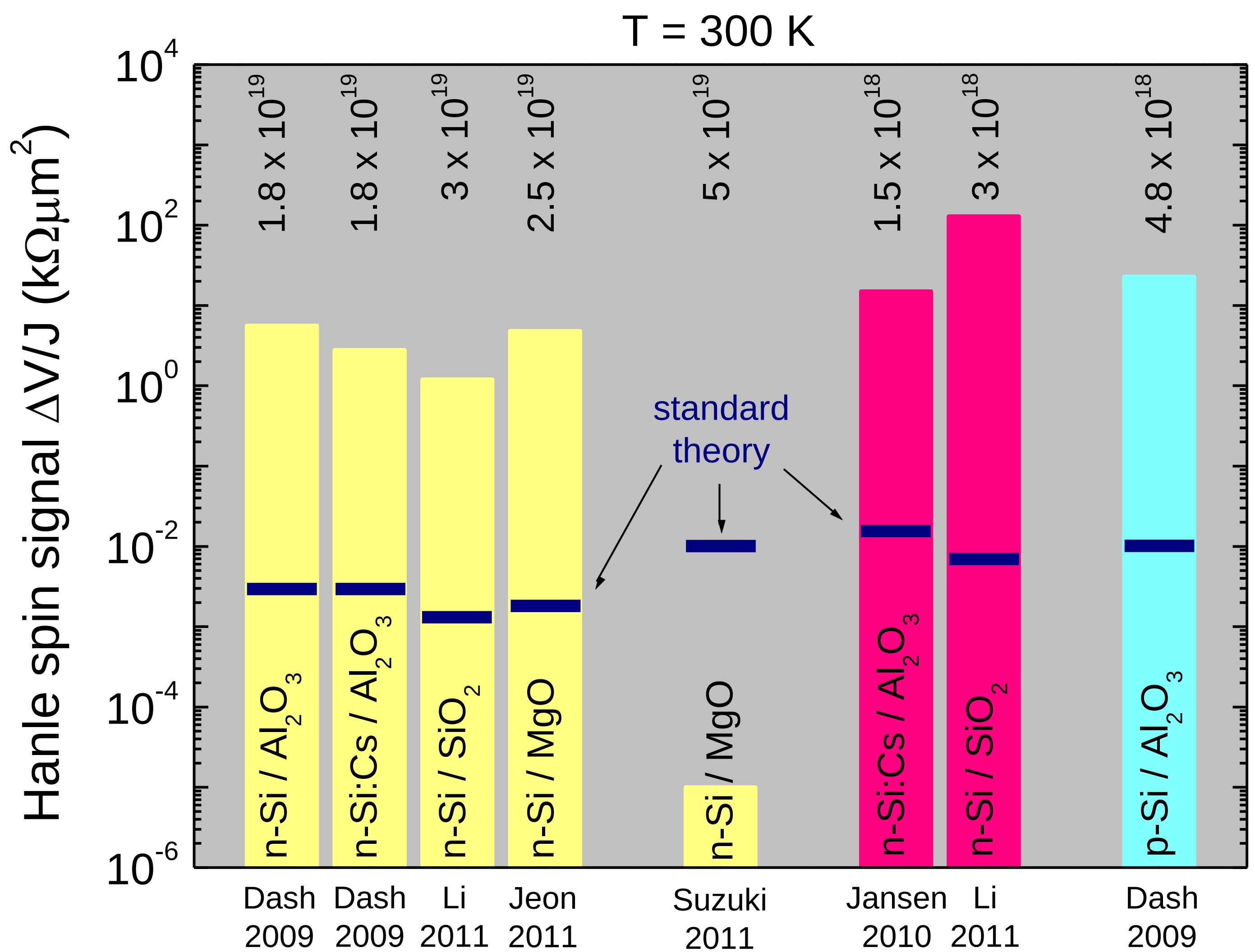
in Ωm^2

Resistivity

spin-diffusion length

Magnitude of the spin accumulation

disagreement between experiment and theory



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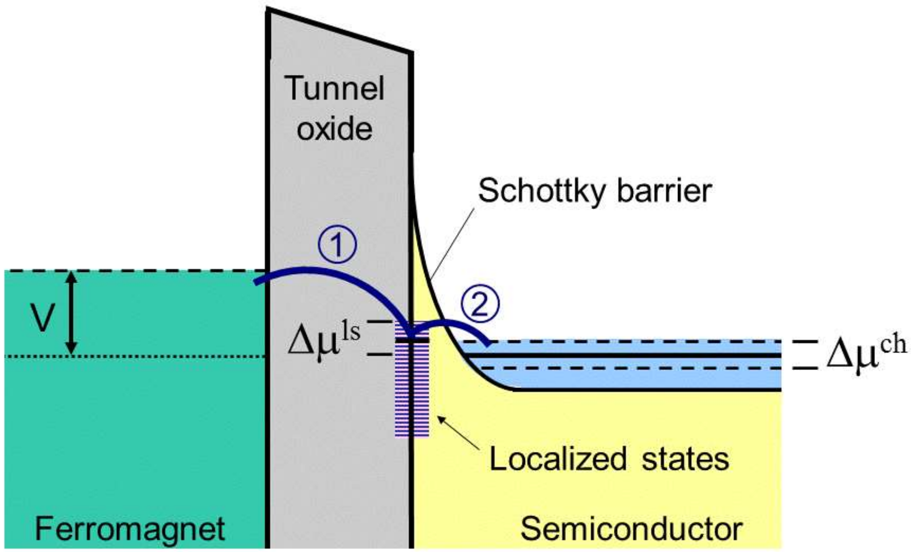
R. Jansen, Nature Materials 11, 400 (2012)

R. Jansen et al. Semicon. Sci. Technol. 27, 083001 (2012)

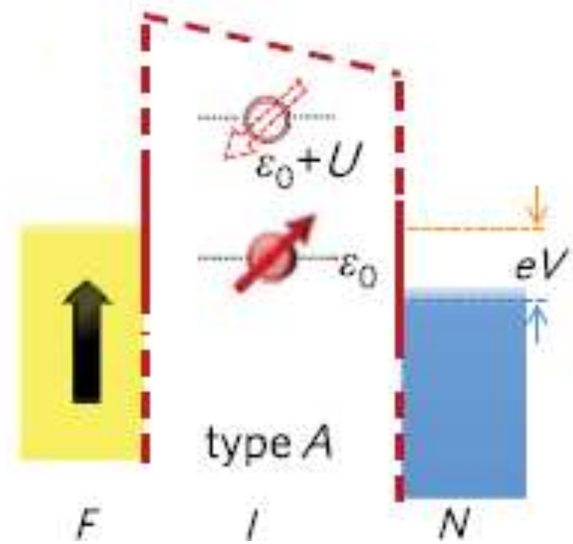
Theory proposals to explain the disagreement

Localized states in the oxide barrier or at the oxide/semiconductor interface

First proposal by Tran et al. PRL 102, 036601 (2009)	Recent extension by Song and Dery PRL 113, 047205 (2014)



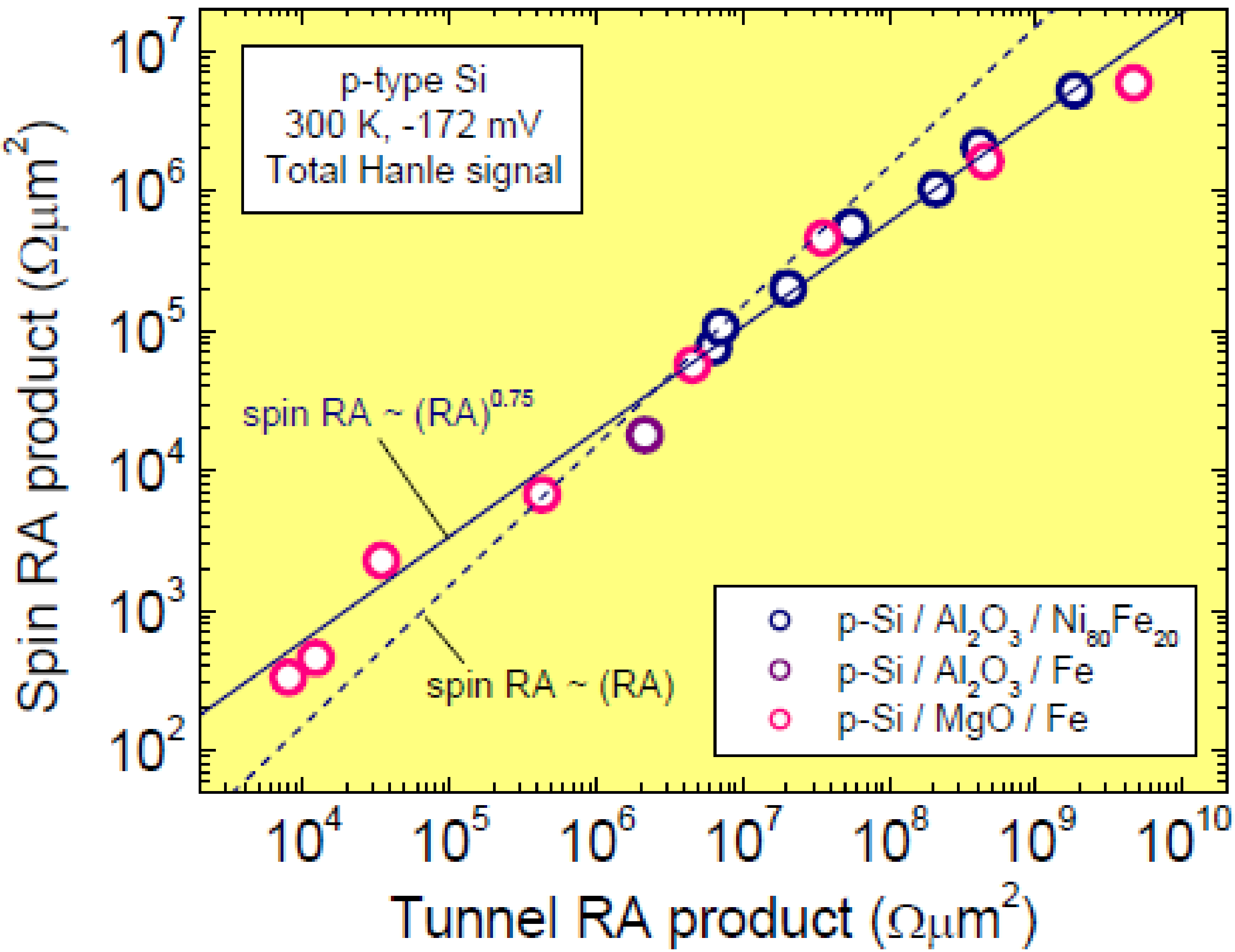
- Two-step tunneling
- spin accumulation in localized states
- Hanle spin precession



- Same as Tran's model, but
- added Coulomb repulsion energy U
- spin-dependent blocking for eV >> kT

But, experiments ………..

Magnitude and scaling of spin signal



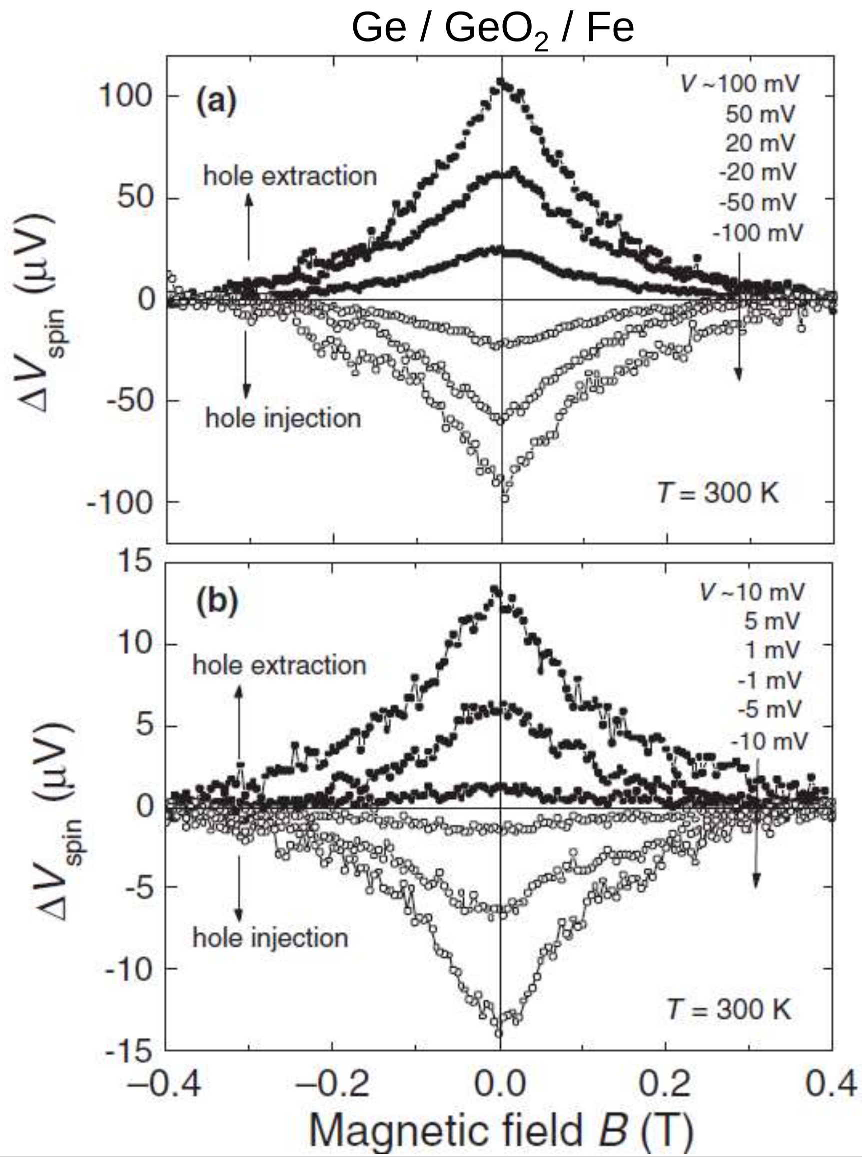
Theory:
ΔV should be proportional to J, thus ΔV / J is a constant

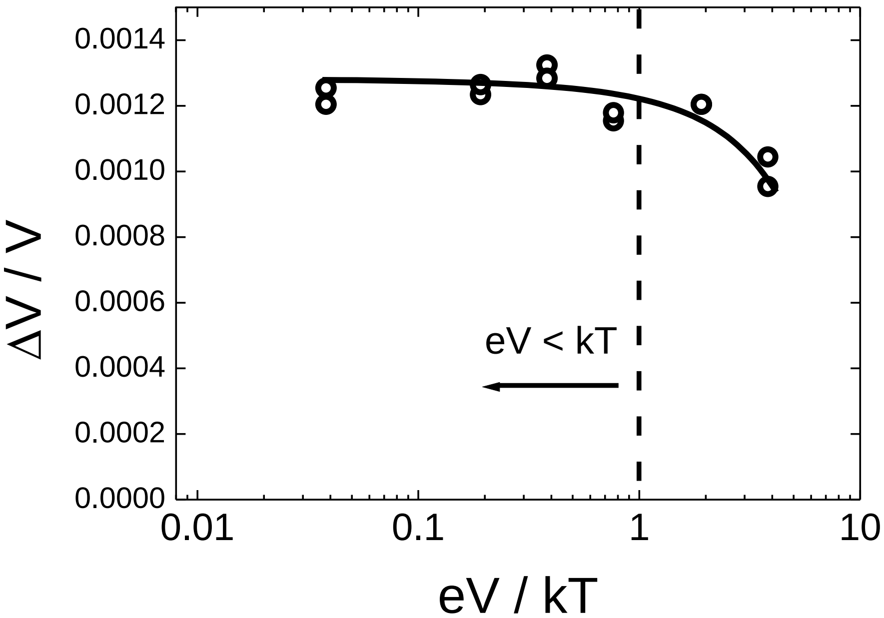
Experiment:
spin-RA = ΔV / J scales with the tunnel resistance

Not understood

S. Sharma et al.
PRB 89, 075301 (2014)

Magnitude of the spin signal for eV < kT



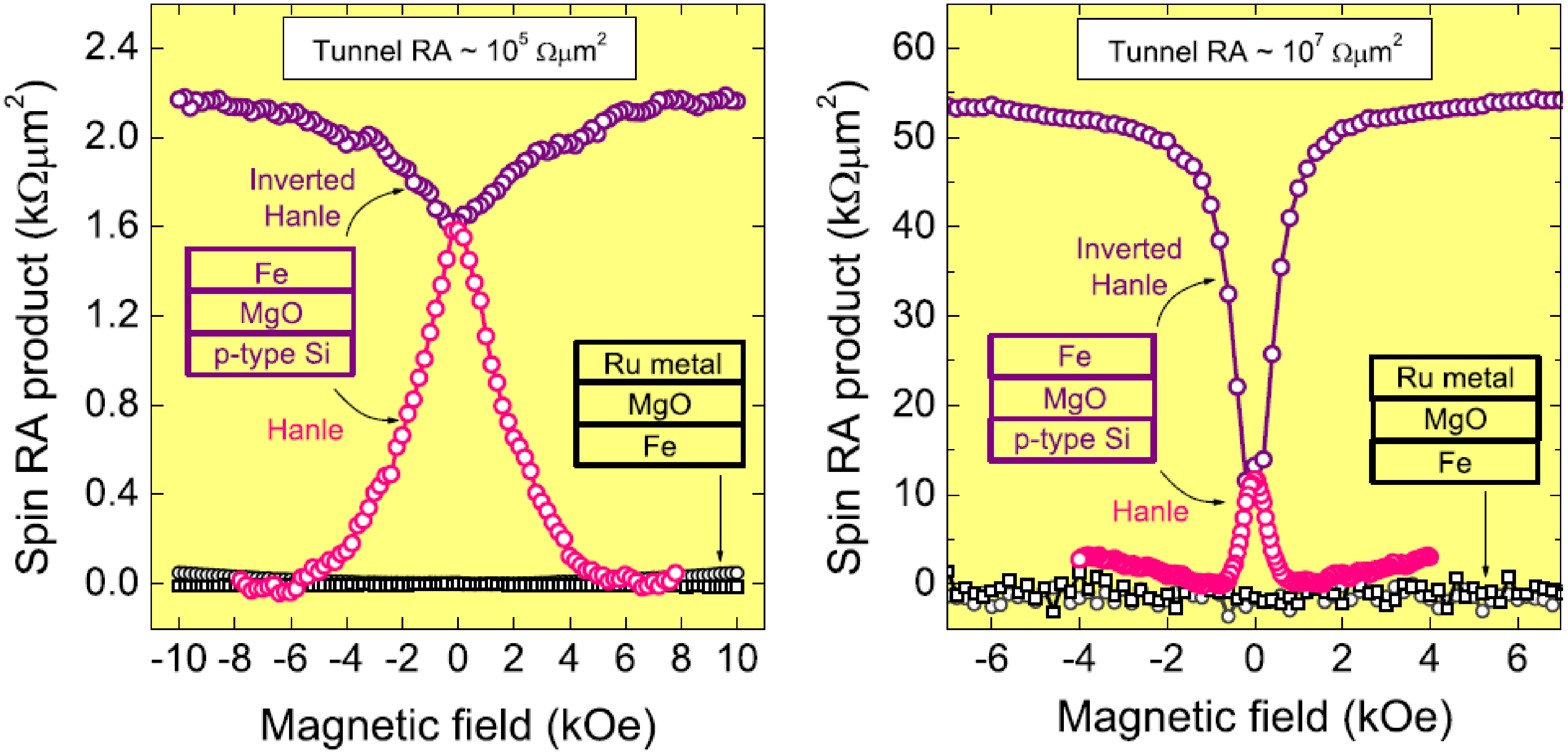


No spin signal reduction in the regime eV < kT,
⇒ inconsistent with the theory of Song and Dery

Data from S. Spiesser et al,
Jap. J. Appl. Phys. 52, 04CM01 (2013)

Control experiment with Ru metal instead of Si

S. Sharma et al. PRB 89, 075301 (2014)



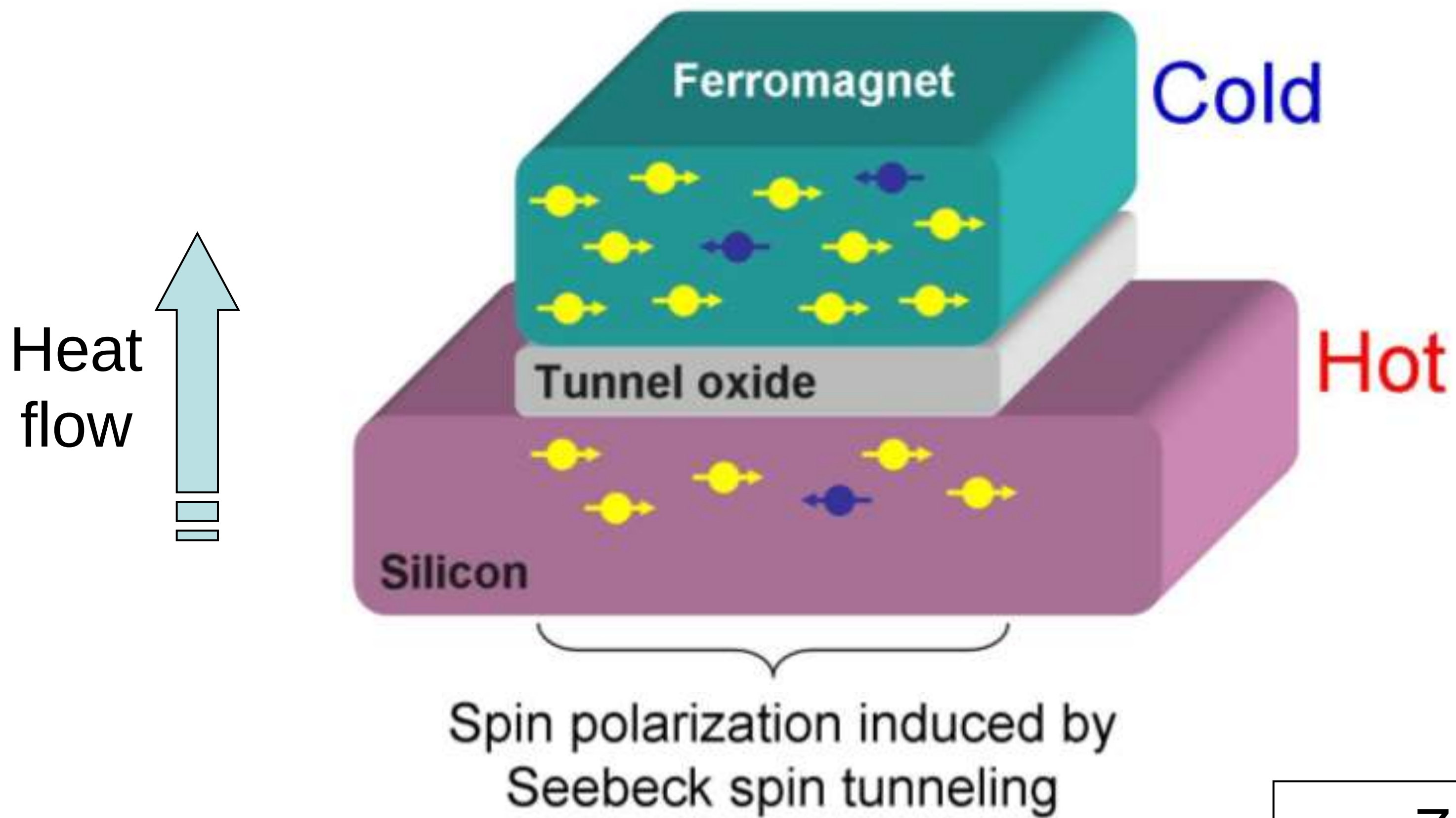
Oxide but no semiconductor ⇒ no Hanle signal

Thus, signal does not originate from the tunnel oxide

Can we create spin polarization in silicon by heat, instead of charge current ?

Thermal creation of spin polarization in Si

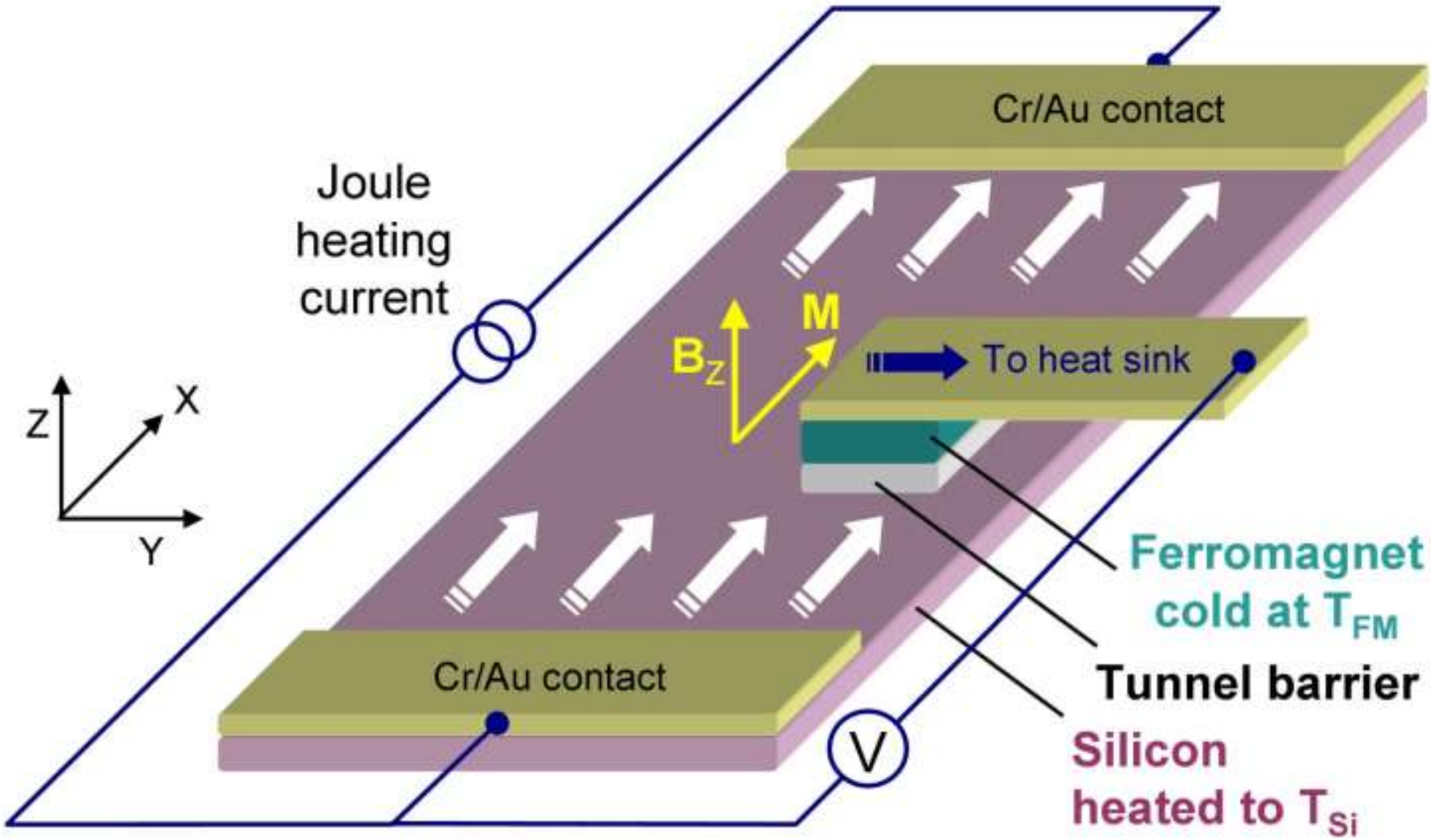
New phenomenon: Seebeck spin tunneling



p.s. Zero charge tunnel current !!

Thermal spin current from ferromagnet to Si

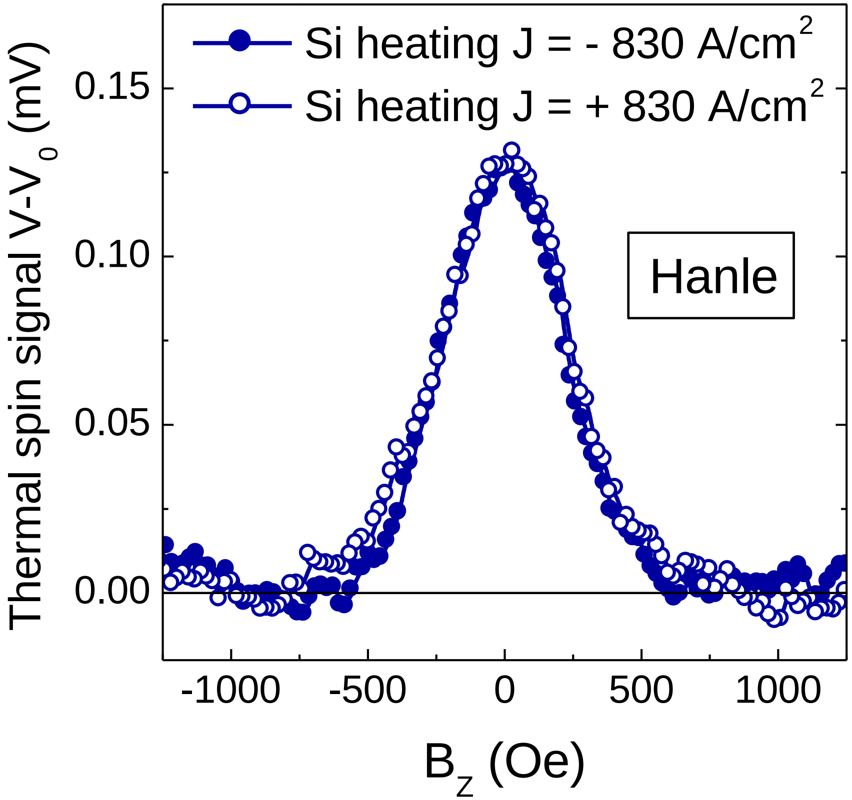
Joule heating of Si

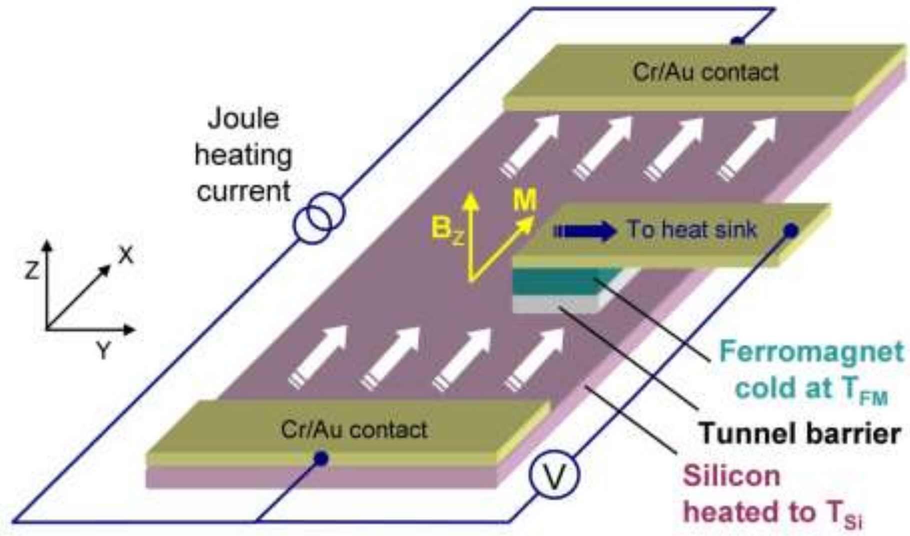


p-type Si / Al_2O_3 / $Ni_{80}Fe_{20}$, T_{base} = 300 K, Si strip: 4000 x 800 x 3 μm^3

Thermal spin current from ferromagnet to Si

Observation of Seebeck spin tunneling





J.C. Le Breton et al., Nature 475, 82 (2011)

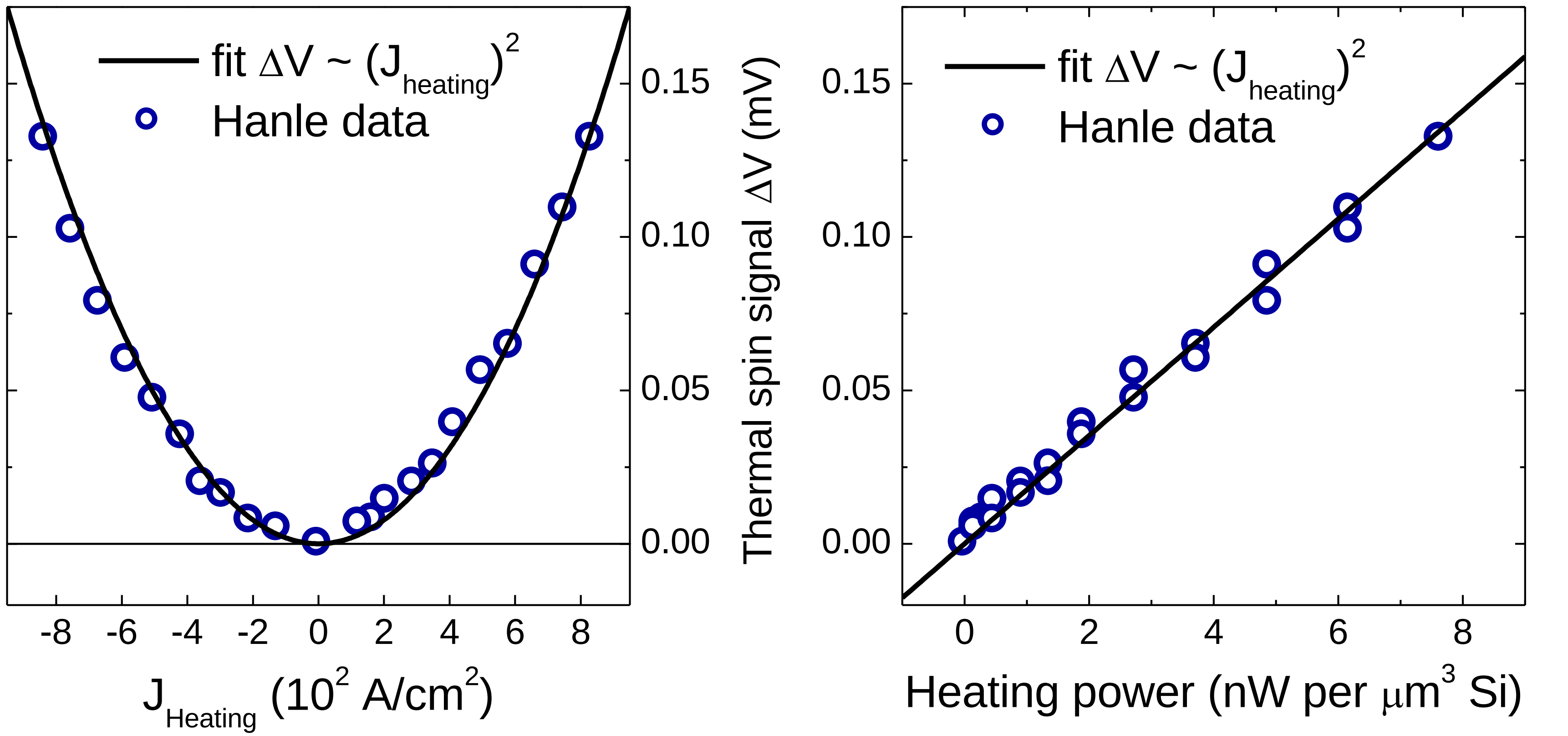
Spin polarization induced by temperature difference only

No charge tunnel current

Thermally-induced spin accumulation in Si

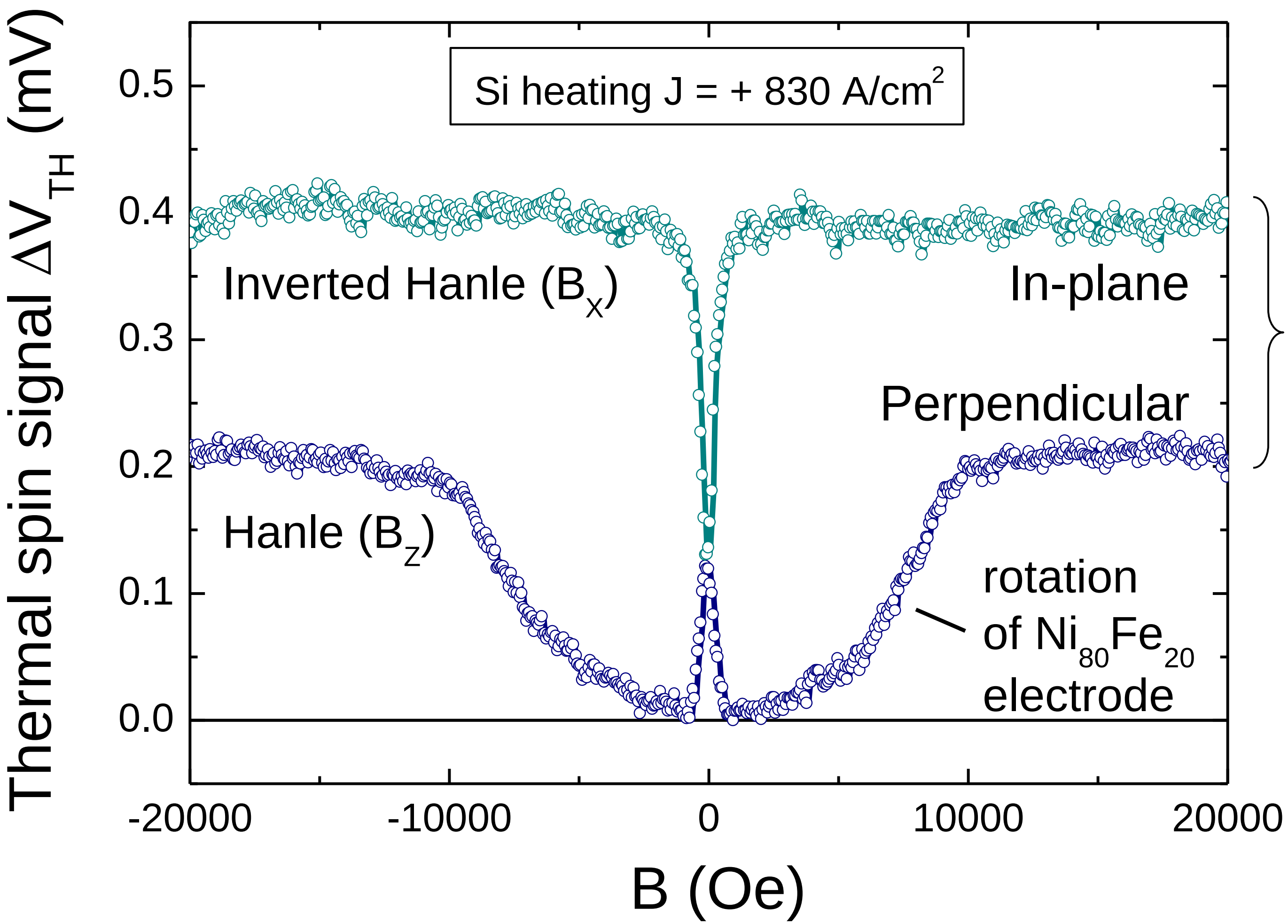
Scaling with Joule heating power

p-type Si / Al_2O_3 / $Ni_{80}Fe_{20}$ T_{base} = 300 K



J.C. Le Breton et al., Nature 475, 82 (2011)

Anisotropy of the Seebeck coefficient



Anisotropy of S

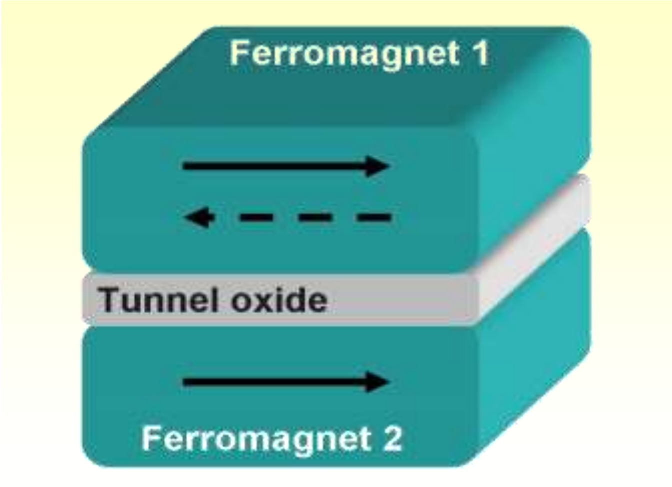
J.C. Le Breton et al., Nature 475, 82 (2011), supplement
R. Jansen, Proc. SPIE 8813, 88130A (2013)

Origin of the thermal spin current

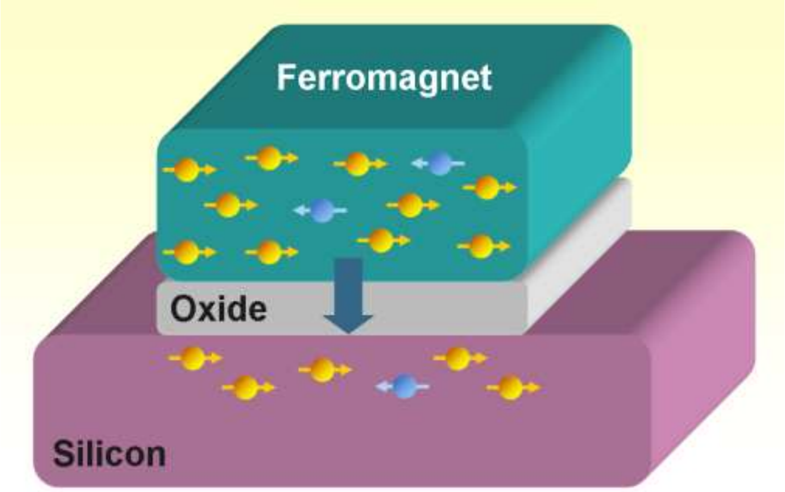
Spin-polarized tunneling

$$\boxed{G^{\uparrow} \neq G^{\downarrow}}$$

Tunnel conductance is spin dependent
(1971)



Tunnel magnetoresistance
at 300 K (1995)

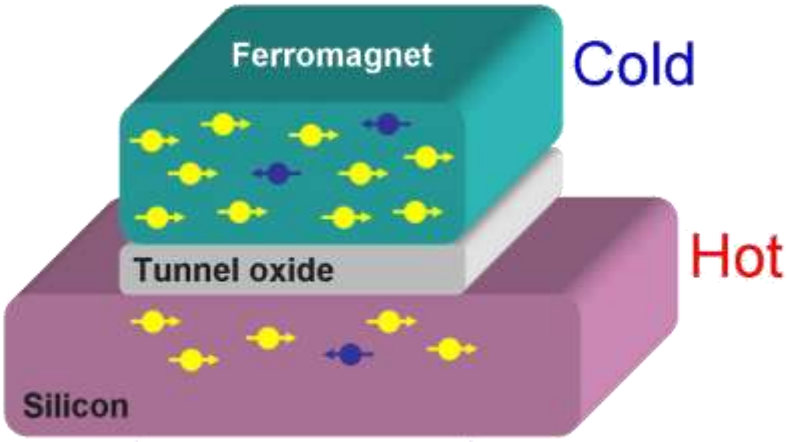


Electrical spin injection
(1999 - ……)

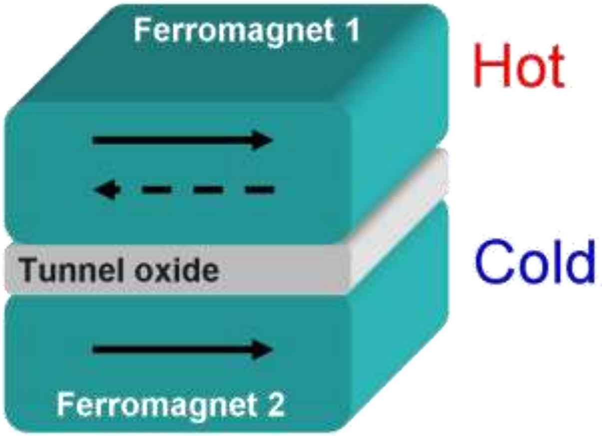
Seebeck spin tunneling

$$\boxed{S^{\uparrow} \neq S^{\downarrow}}$$

Seebeck coefficient of tunnel contact is spin dependent
(Le Breton et al. 2011)

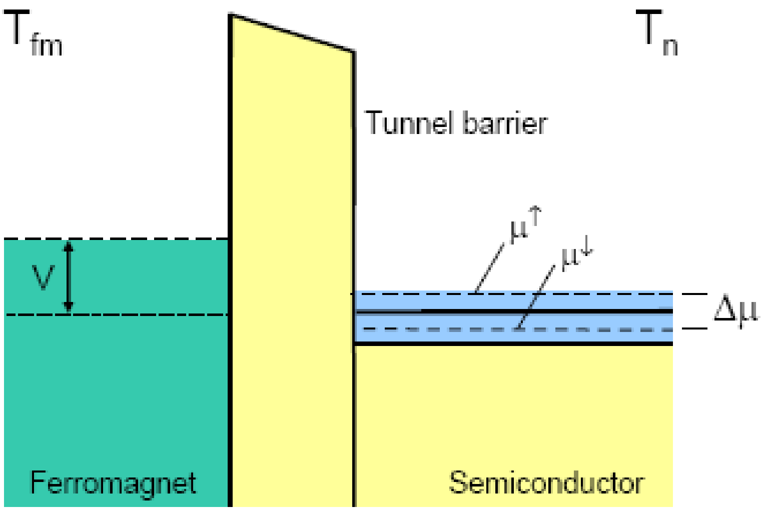


Thermal spin injection
(Le Breton et al. 2011)



Tunnel magneto-thermopower
(Walter et al. / Liebing et al. 2011)

Electrical detection of Seebeck spin tunneling



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

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

Thermally-induced spin accumulation

$$\boxed{V = \cancel{I R_{tun}} + P_G\left(\frac{\Delta\mu}{2}\right) + S_0\,\Delta T}$$

$$\underbrace{P_G\left(\frac{\Delta\mu}{2}\right)}_{\Delta V_{\text{Hanle}}} \qquad \underbrace{S_0\,\Delta T}_{\text{Charge thermopower}}$$

Seebeck spin tunneling coefficient

spin resistance
of semiconductor

$$\Delta\mu = \left\{ \frac{2\,r_s}{R_{tun} + (1 - P_G^2)\,r_s} \right\} [\,\underbrace{(P_G)\,R_{tun}\,I}_{\text{electrical}} - \underbrace{(P_L - P_G)\,S_0 \Delta T}_{\text{thermal}}\,]$$

electrical

thermal

$$\boxed{S_{st} = \frac{\Delta\mu}{\Delta T} = \left\{ \frac{(1 - P_G^2)\,r_s}{R_{tun} + (1 - P_G^2)\,r_s} \right\} (S_{st}^{\uparrow} - S_{st}^{\downarrow})}$$

$$S_{st}^{\uparrow} = -L^{\uparrow}/G^{\uparrow}$$

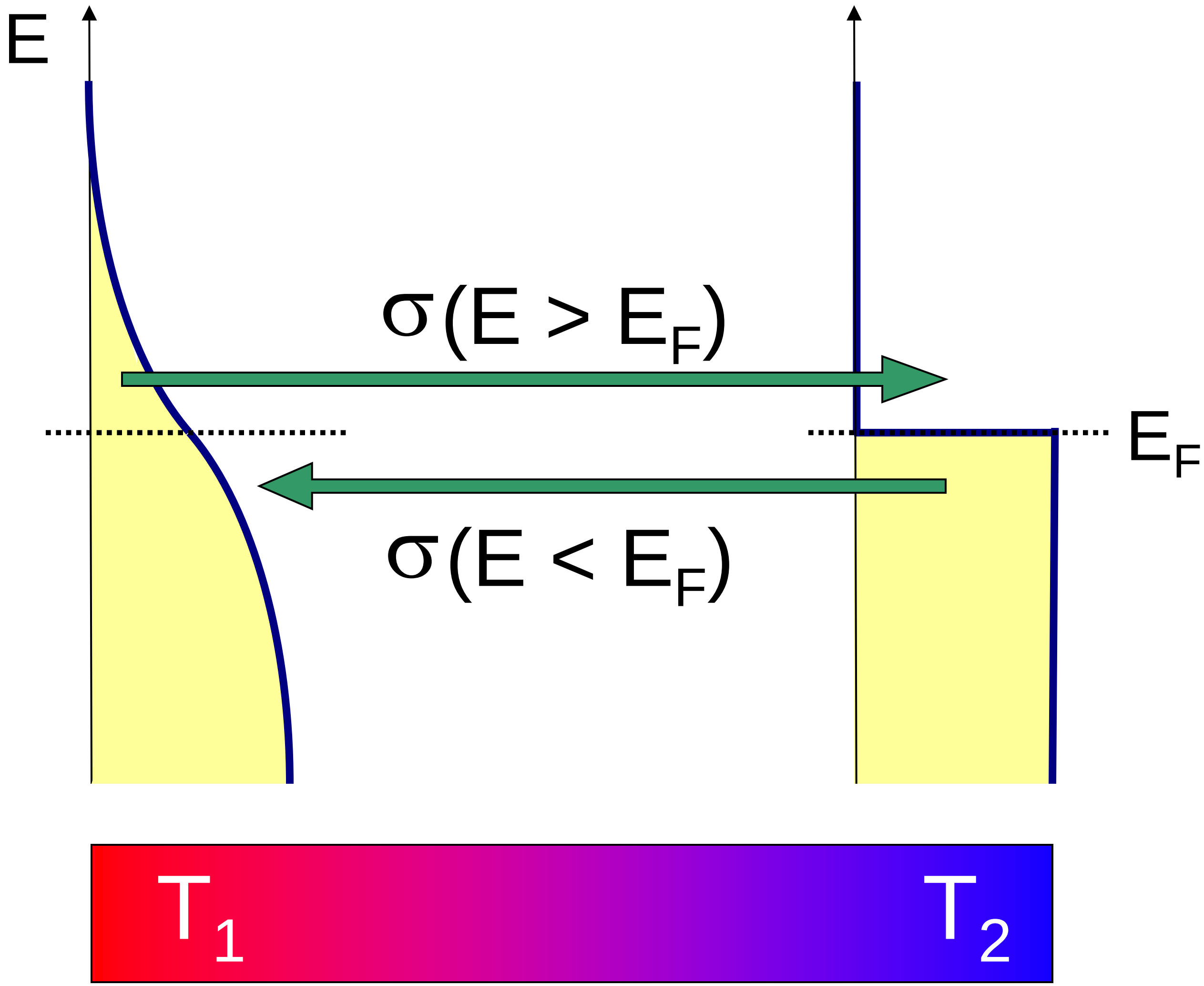
$$S_{st}^{\downarrow} = -L^{\downarrow}/G^{\downarrow}$$

Spin-dependent
Seebeck coefficient

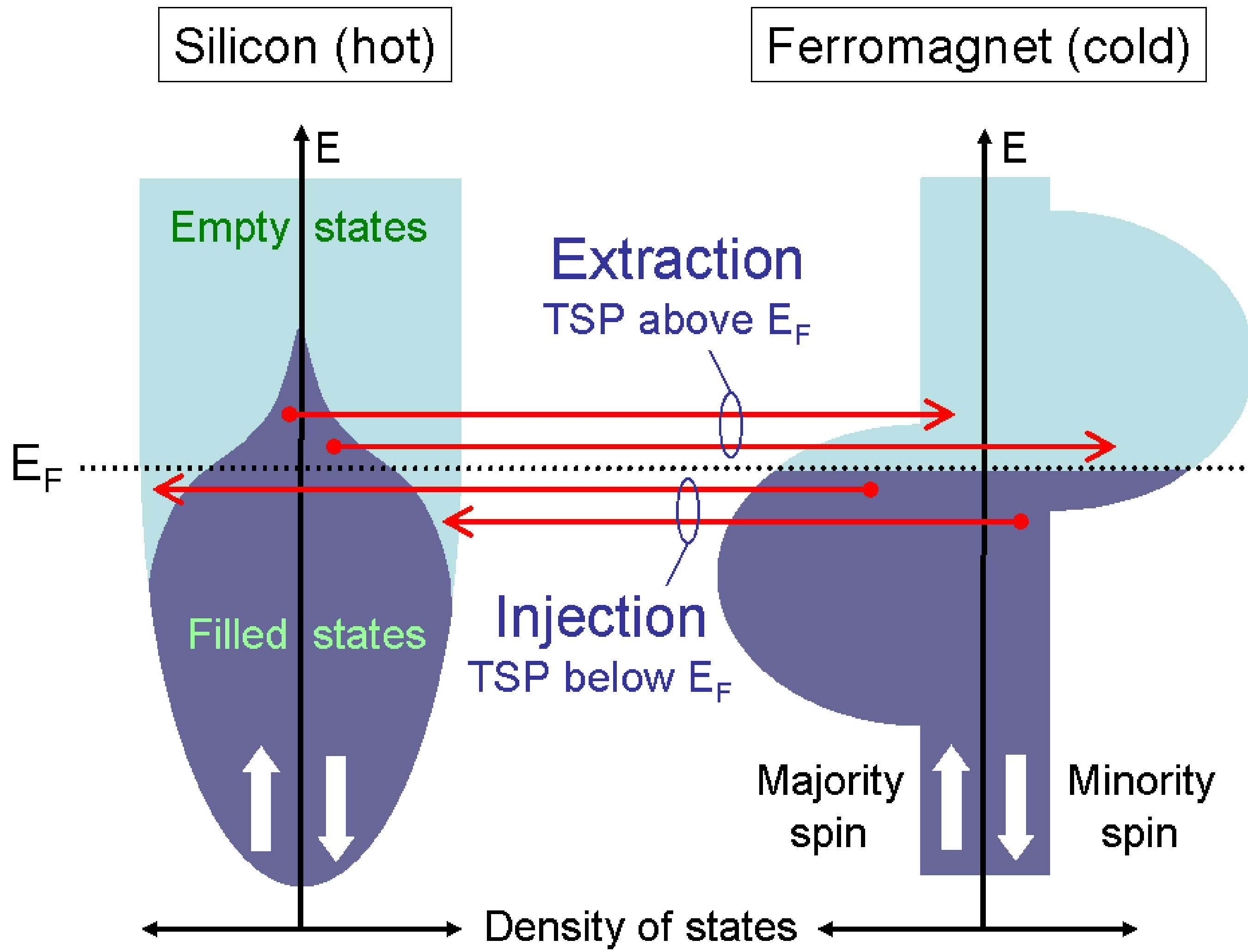
Jansen, Deac et al.
PRB 85, 094401 (2012)

Charge Seebeck effect

governed by energy derivative of charge conductivity



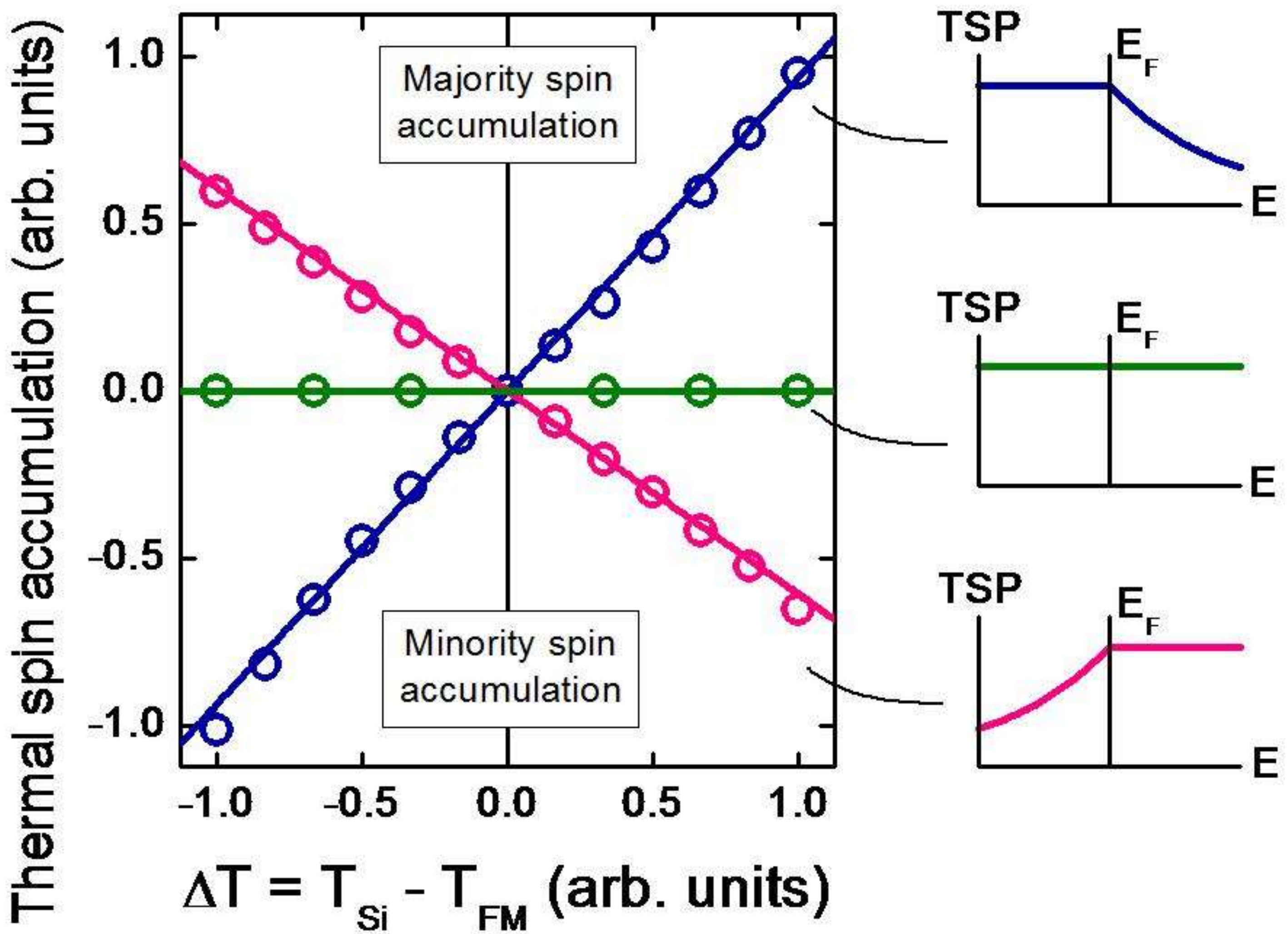
Seebeck spin tunneling (SST)



J.C. Le Breton et al., Nature 475, 82 (2011)

Seebeck spin tunneling

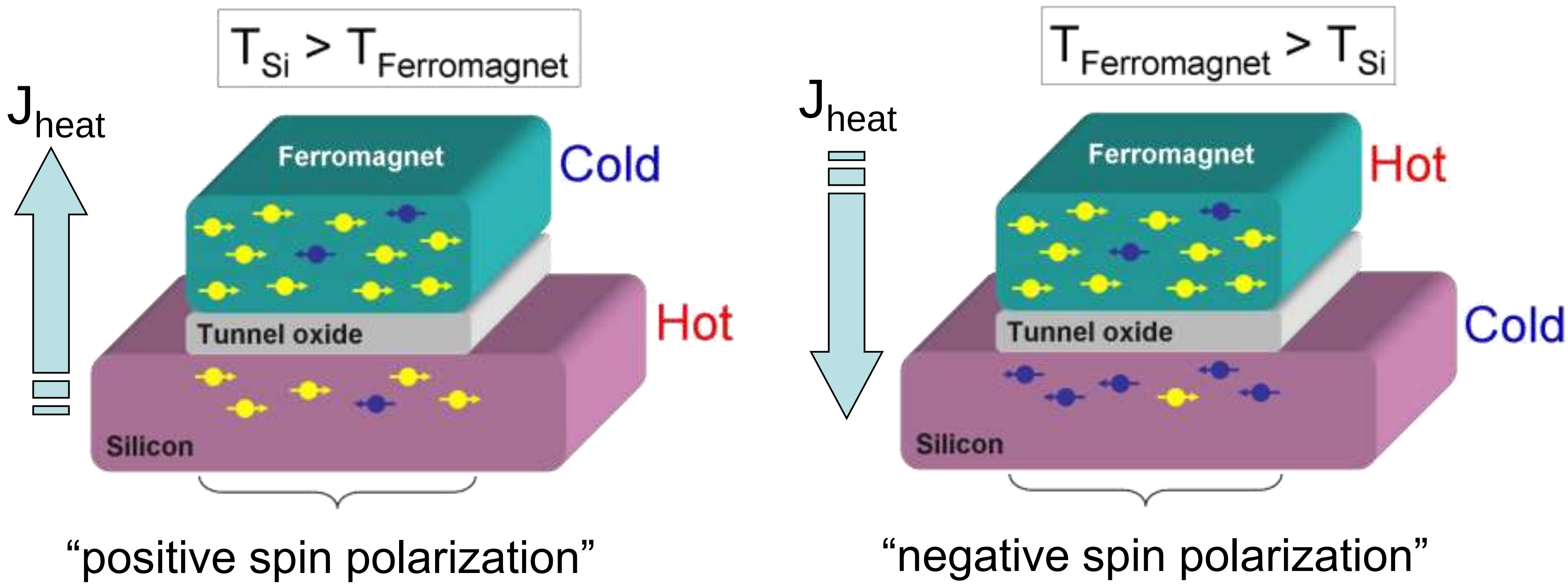
Governed by energy derivative of tunnel spin polarization



Sign of the thermal spin current

Control of the sign of the spin polarization

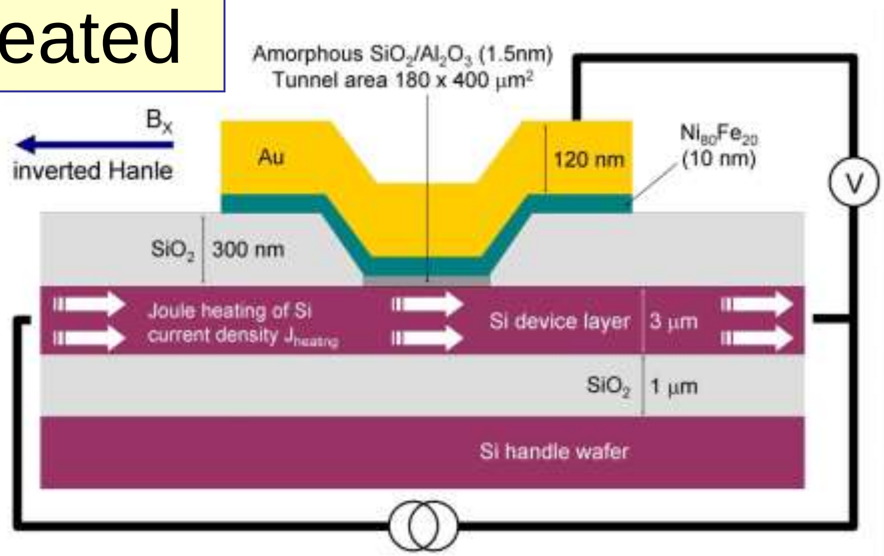
by direction of heat flow

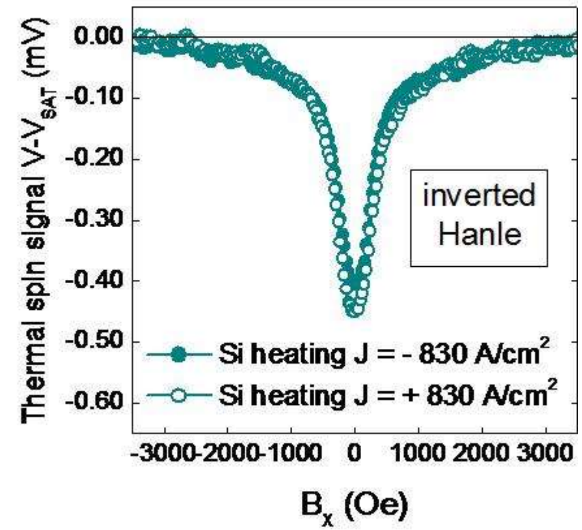


Reversing the heat flow $\Rightarrow$ Opposite spin polarization

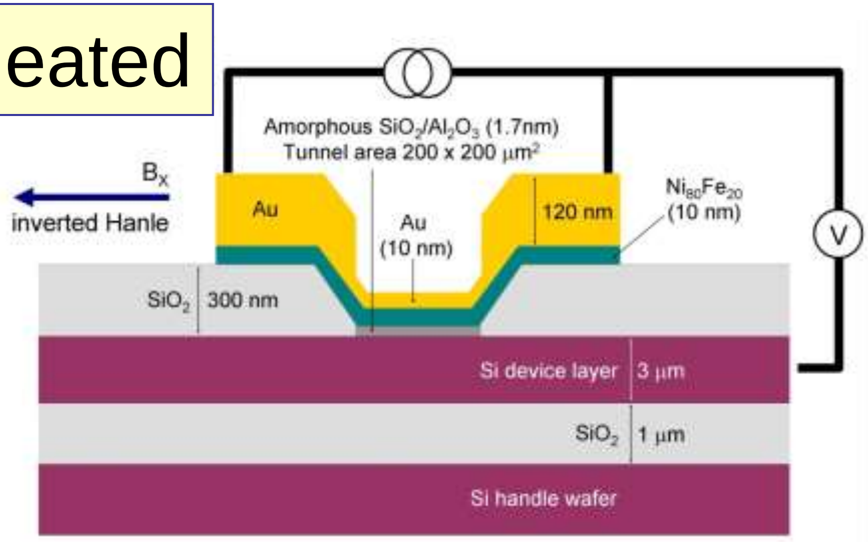
Sign reversal of thermal spin accumulation

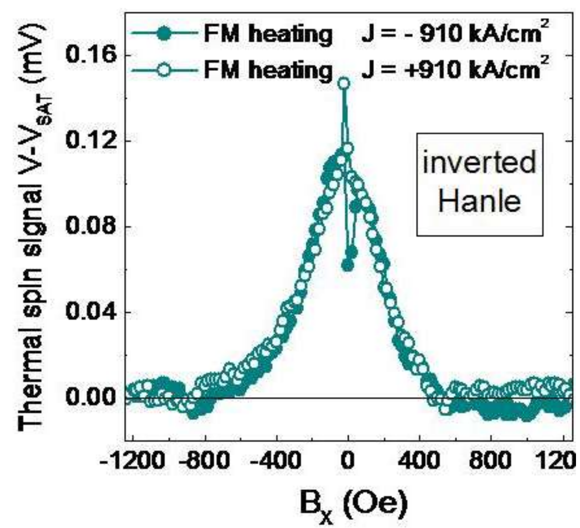
Si heated





FM heated

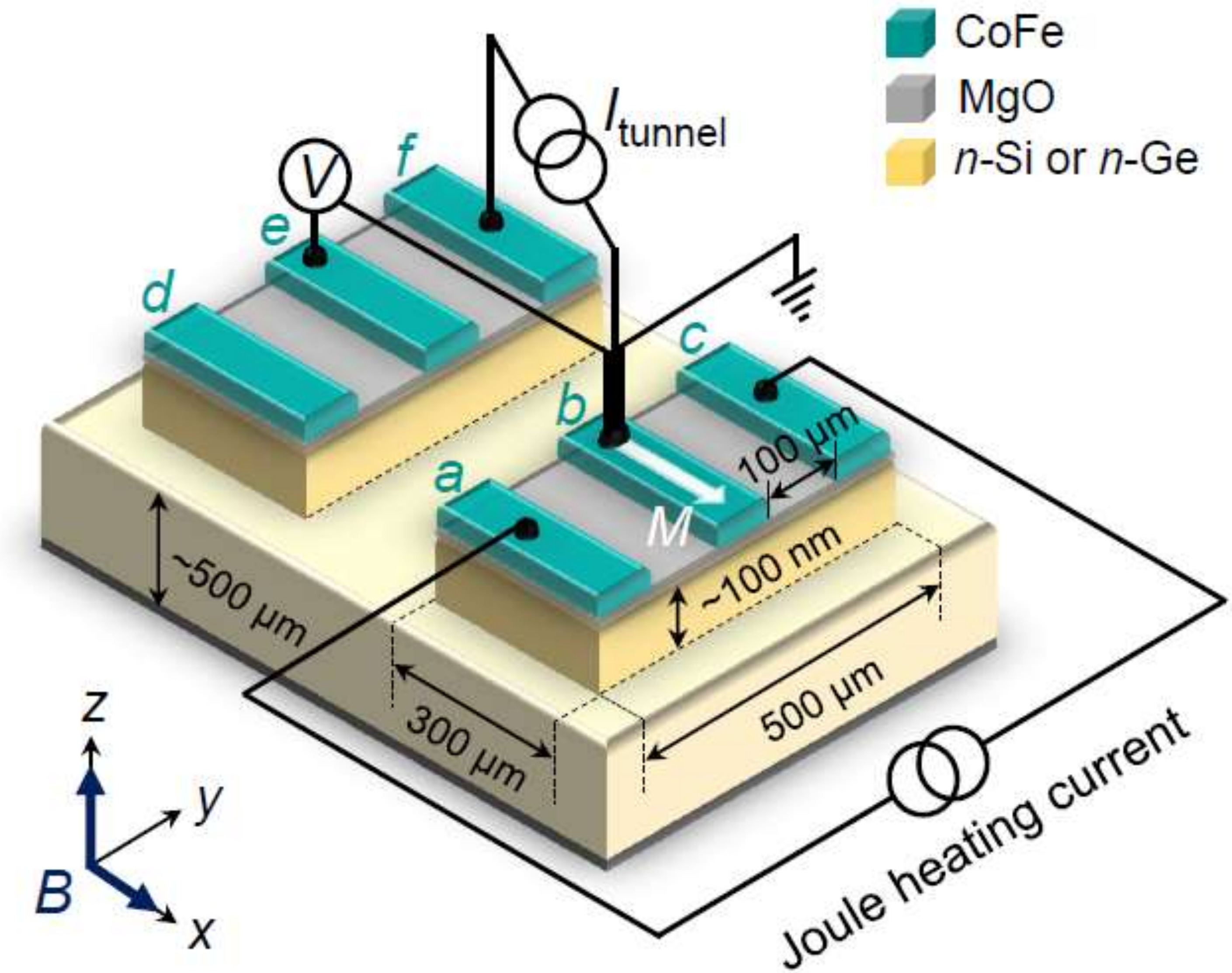




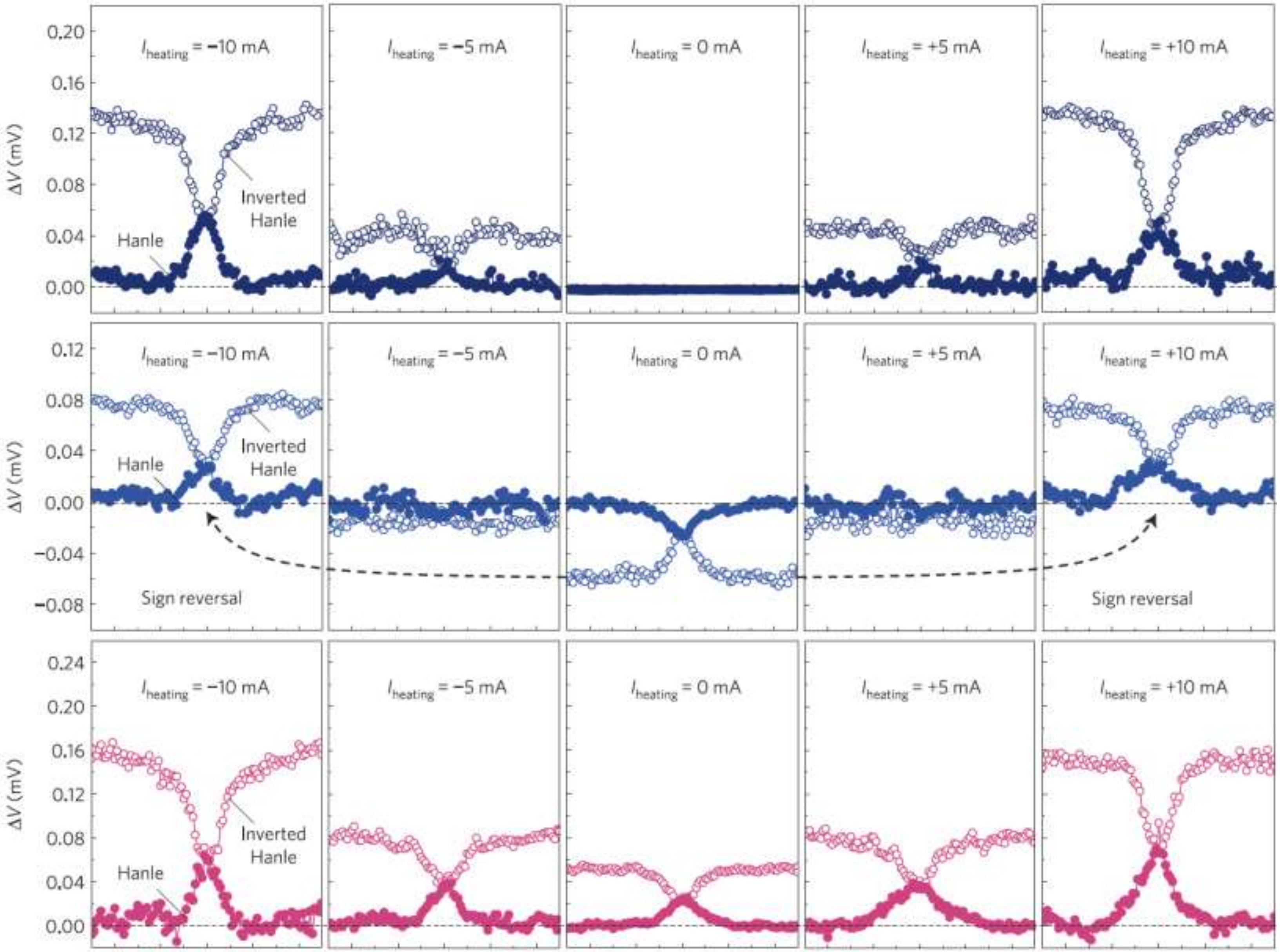
Thermal + electrical spin currents

K.R. Jeon et al.
Nature Materials 13,
360 (2014)

Simultaneous thermal & electrical driving force



Thermal & electrical spin current together



Thermal only

Thermal + electrical spin <u>extraction</u>

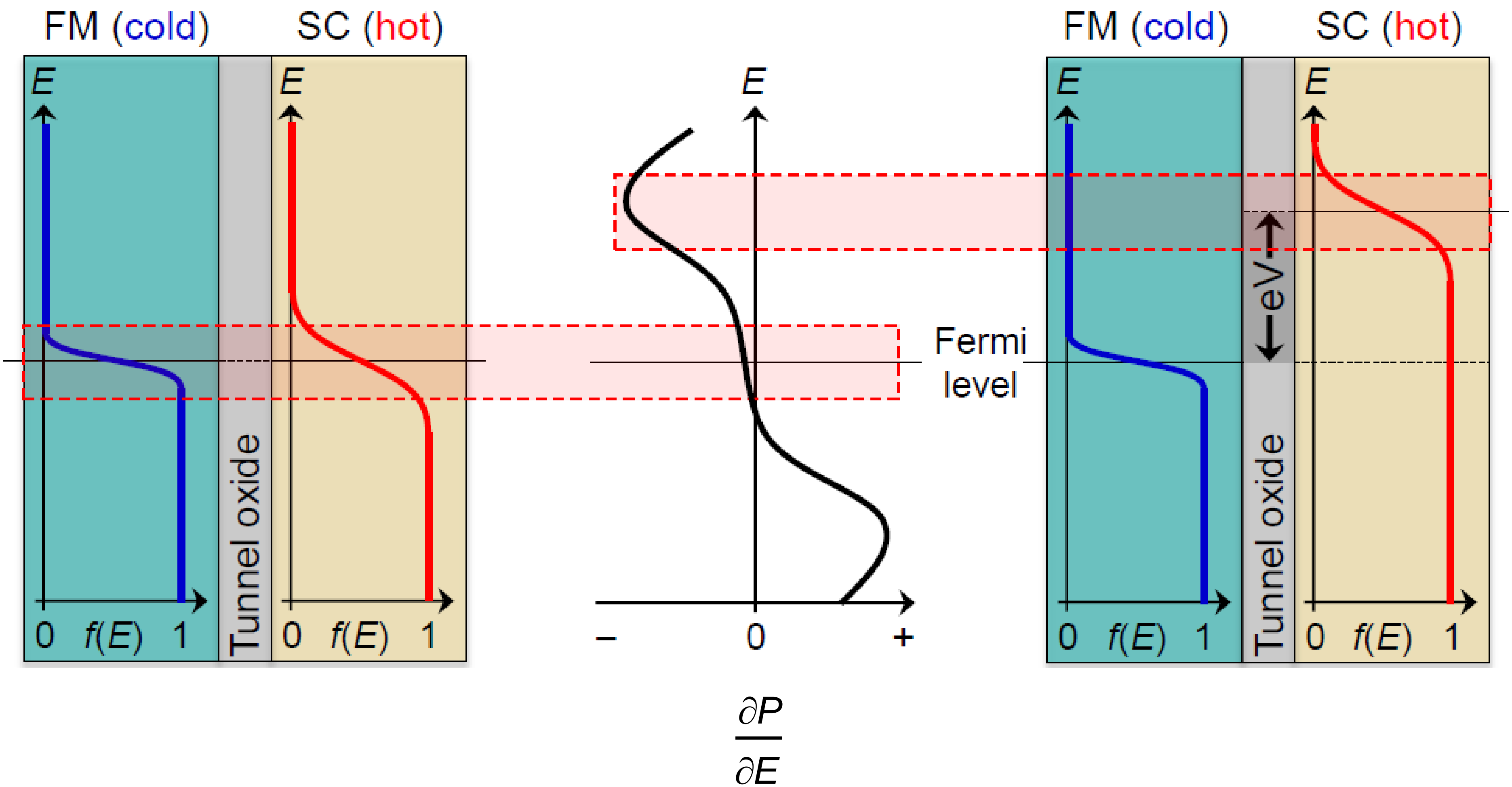
Thermal + electrical spin <u>injection</u>

Voltage tuning of the thermal spin current

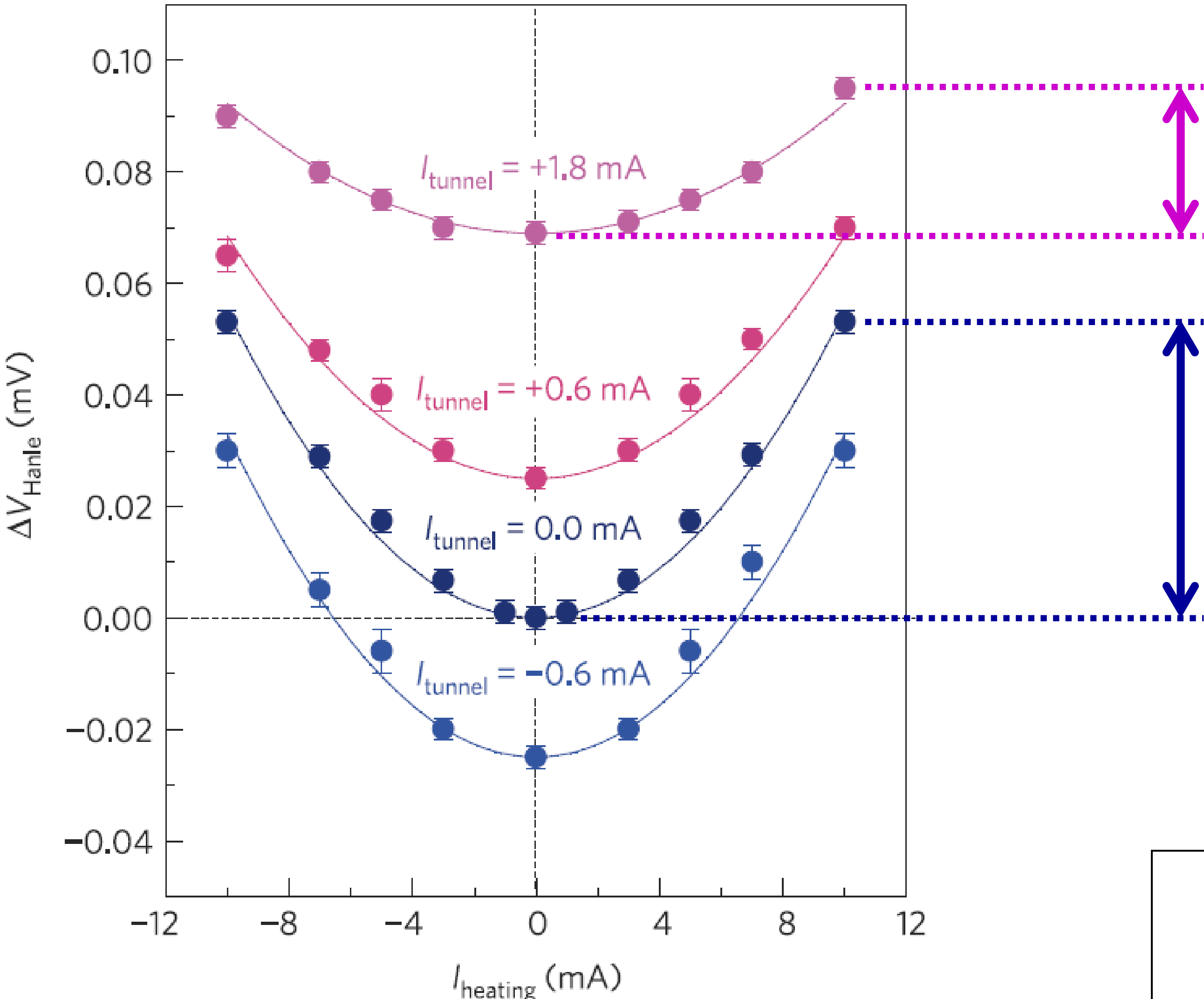
Spin thermoelectrics away from Fermi energy

Conventional thermal spin current near Fermi energy

Thermal spin current at finite bias voltage



Tuning of thermal spin current with voltage

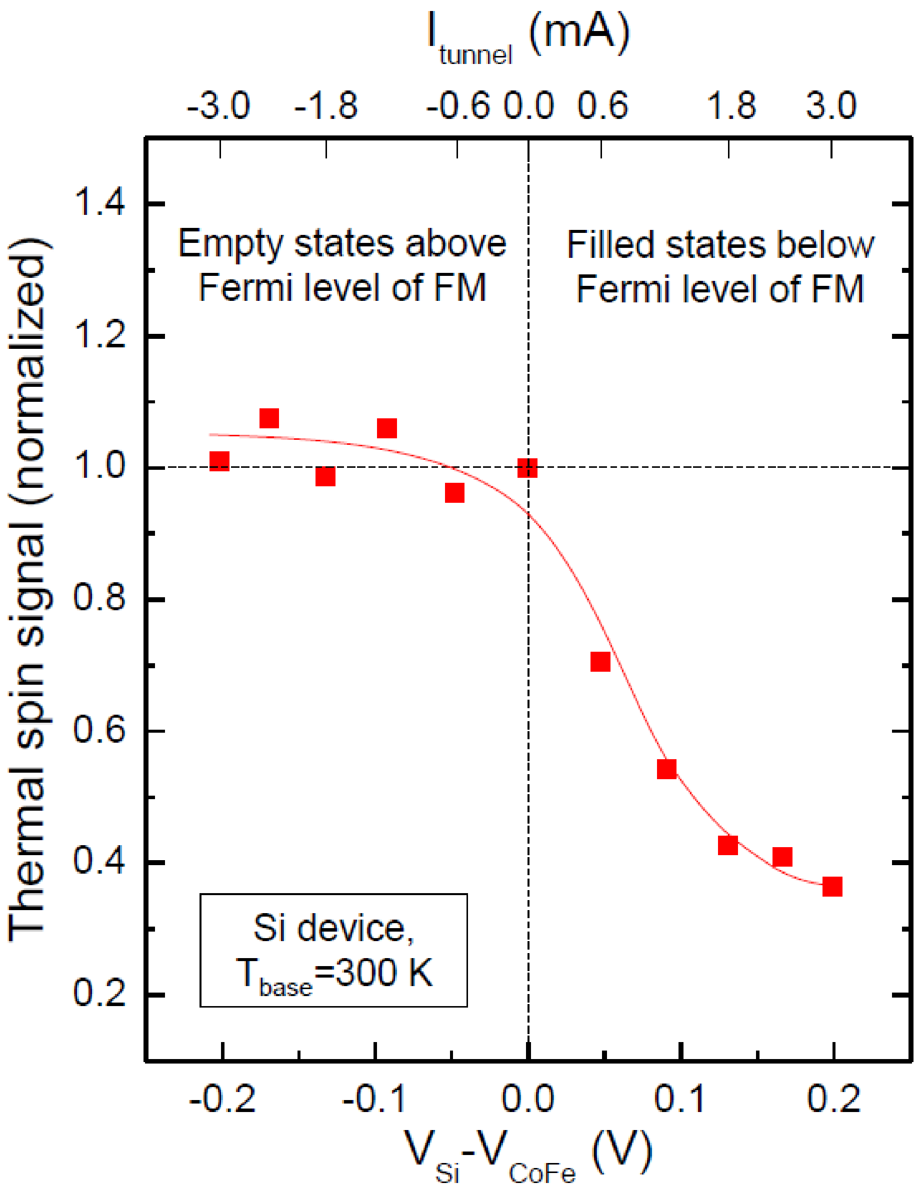


Thermal spin current with positive bias

Thermal spin current at zero bias

K.R. Jeon et al. Nature Materials 13, 360 (2014)

Voltage tuning of thermal spin current



Magnitude of thermal spin current is tuned by bias voltage

Tunneling states with a different

$$\frac{\partial P}{\partial E}$$

n-type Si / MgO / $Co_{70}Fe_{30}$

Electrical creation & detection of spin polarization in Si using magnetic tunnel contacts

Thermal spin current into Si without a charge tunnel current, by Seebeck spin tunneling

For recent reviews of silicon spintronics, see

R. Jansen, Nature Materials 11, 400 (2012)
R. Jansen et al. Semicon. Sci. Technol. 27, 083001 (2012).

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