Challenges in Magnetoelectronics

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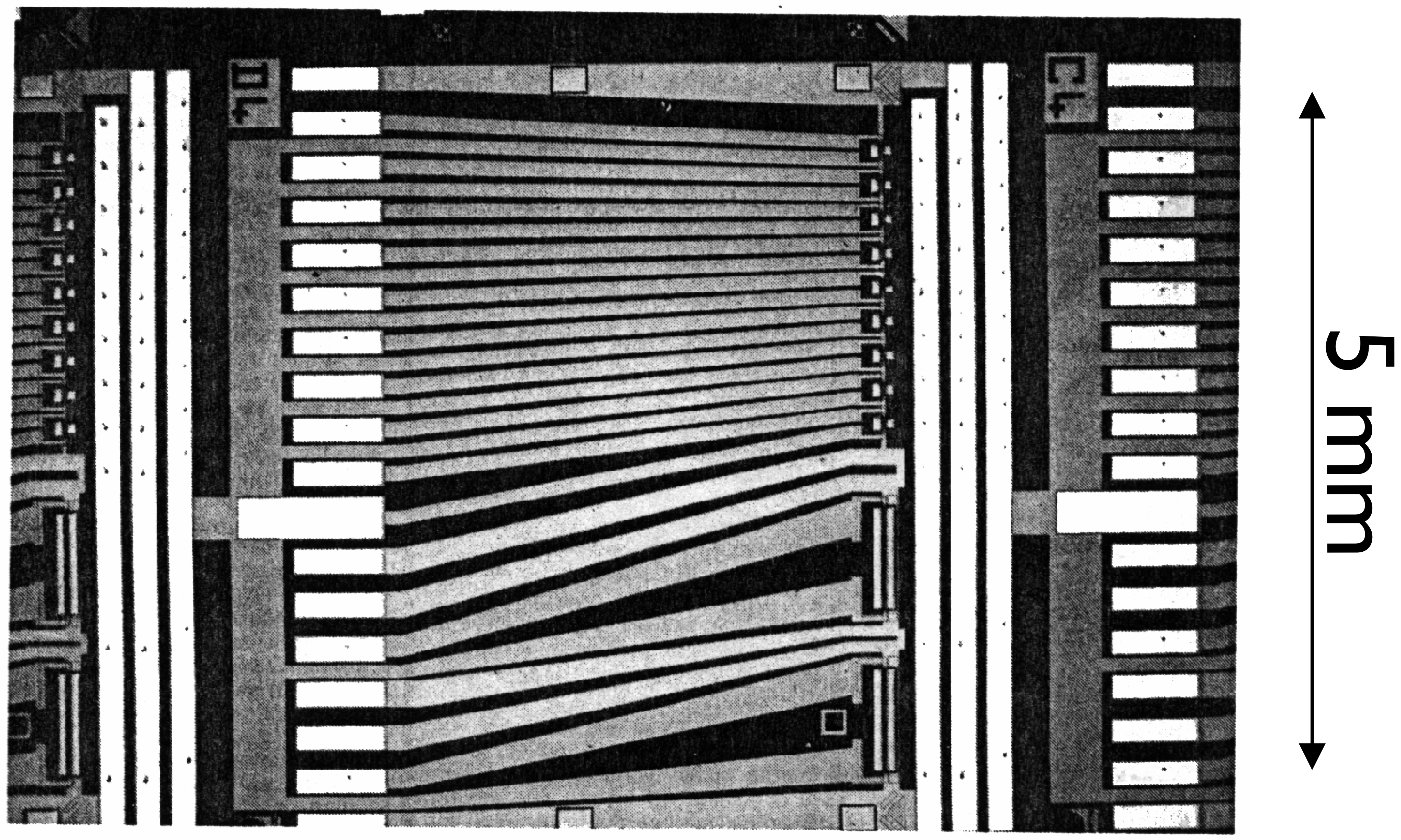
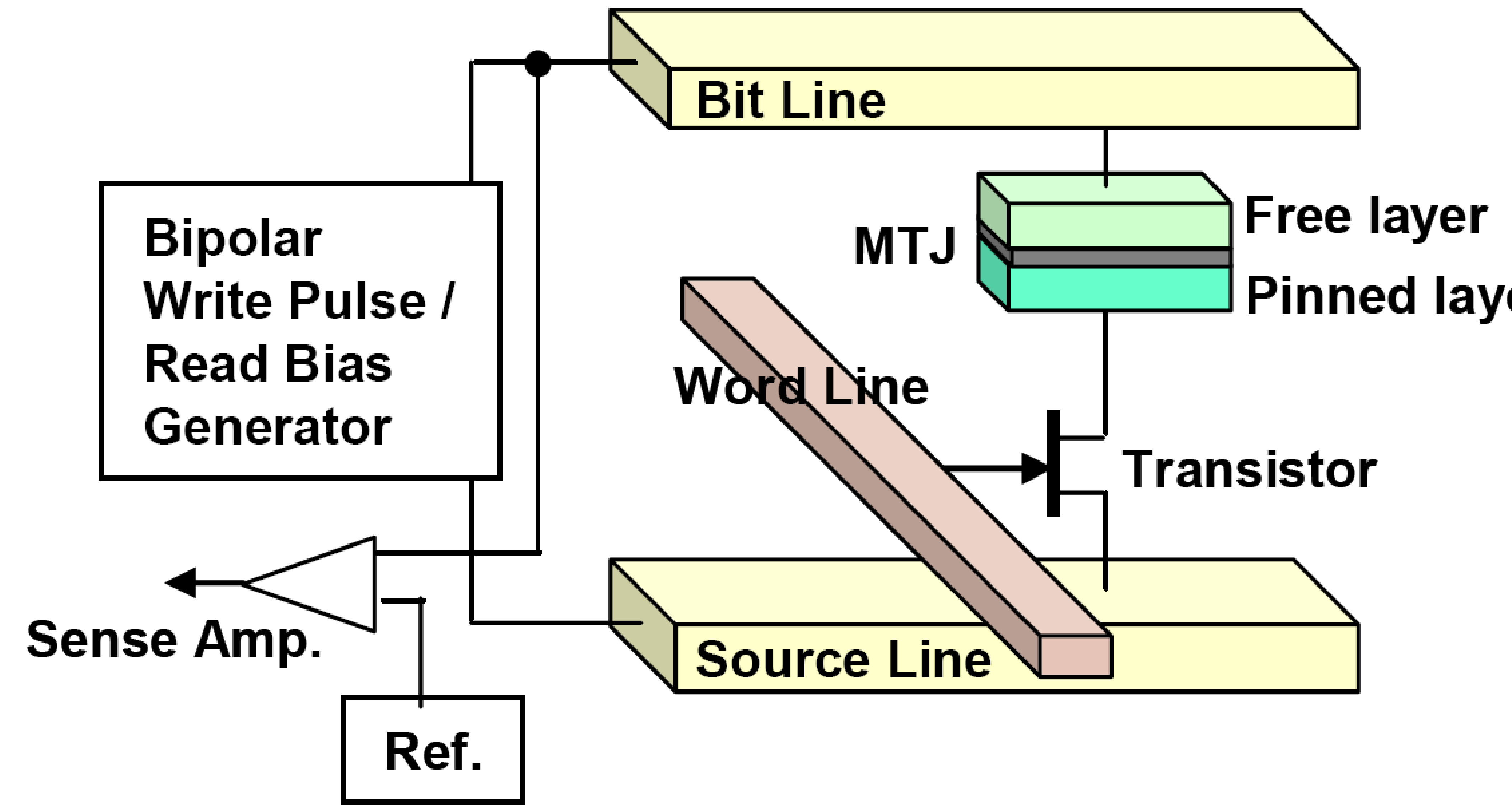
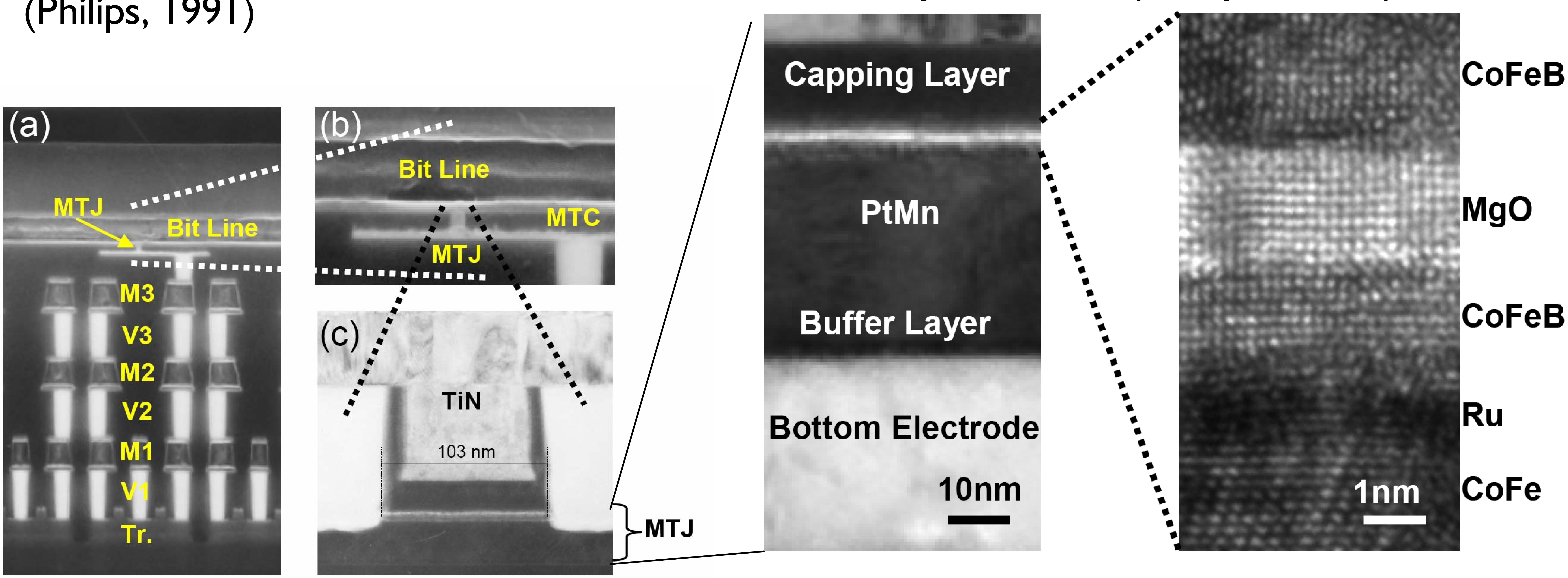
Technology





DCC Magnetoresistive read-head (Philips, 1991)

Spin-RAM (Sony, 2005)



Issues & questions

- Spin valves
- Current-induced magnetization texture
- Non-local exchange effects on transport
- Spin and magnetization noise
- F-SETs
- Electrical detection of spins in semiconductors

- Do we need first-principles calculations?
- Can we always neglect correlations?
- What's the difference between semiconductor and metal spintronics, if any?
- Do we understand transition metals?
- Novel devices or materials?

Collaborators

Arne Brataas

Yaroslav Tserkovnyak

Alex Kovalev

<u>Exp.</u>:
Bret Heinrich
Mark Covington
Bart van Wees
Teruo Ono
Axel Hoffmann

Wouter Wetzels

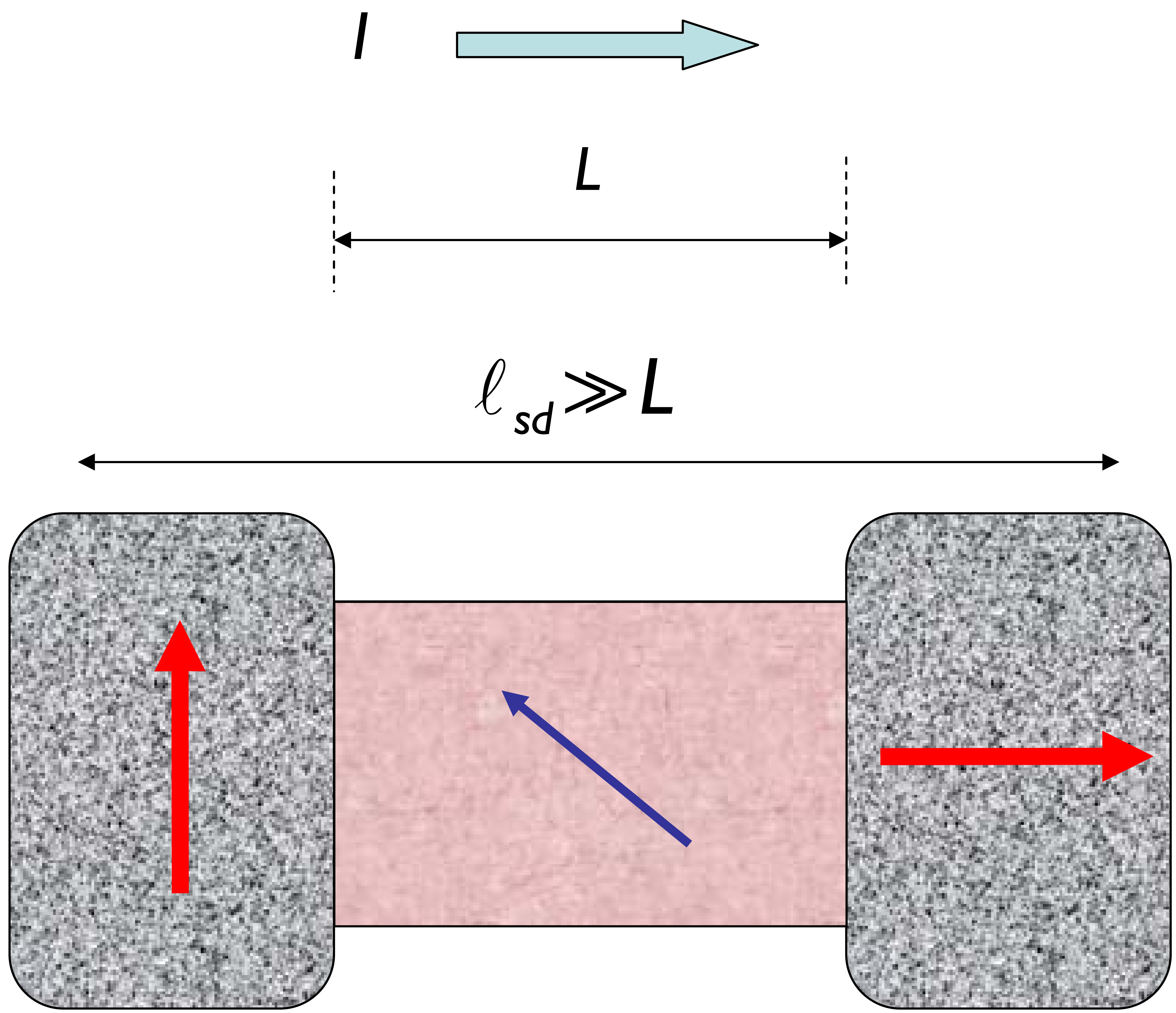
Jørn Foros

Xuhui Wang

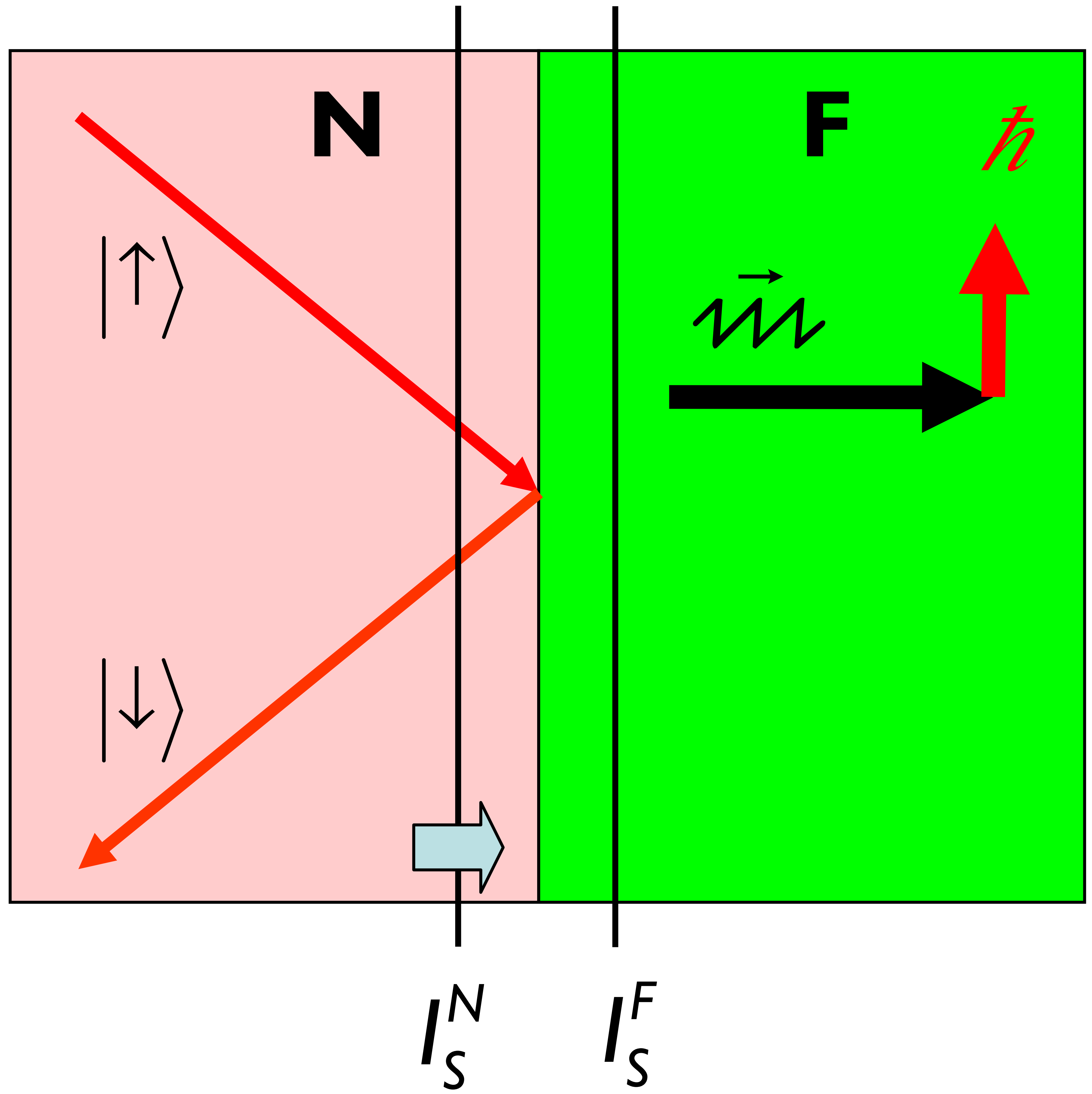
Maciej Zwierzycki

Paul Kelly

F|N|F spin valves: **non-collinear**



Slonczewski's spin-transfer torque



Charge current: $I_C = I_\uparrow + I_\downarrow = 0$

Spin current in N: $I_{S,z}^N = I_\uparrow^N - I_\downarrow^N \neq 0$

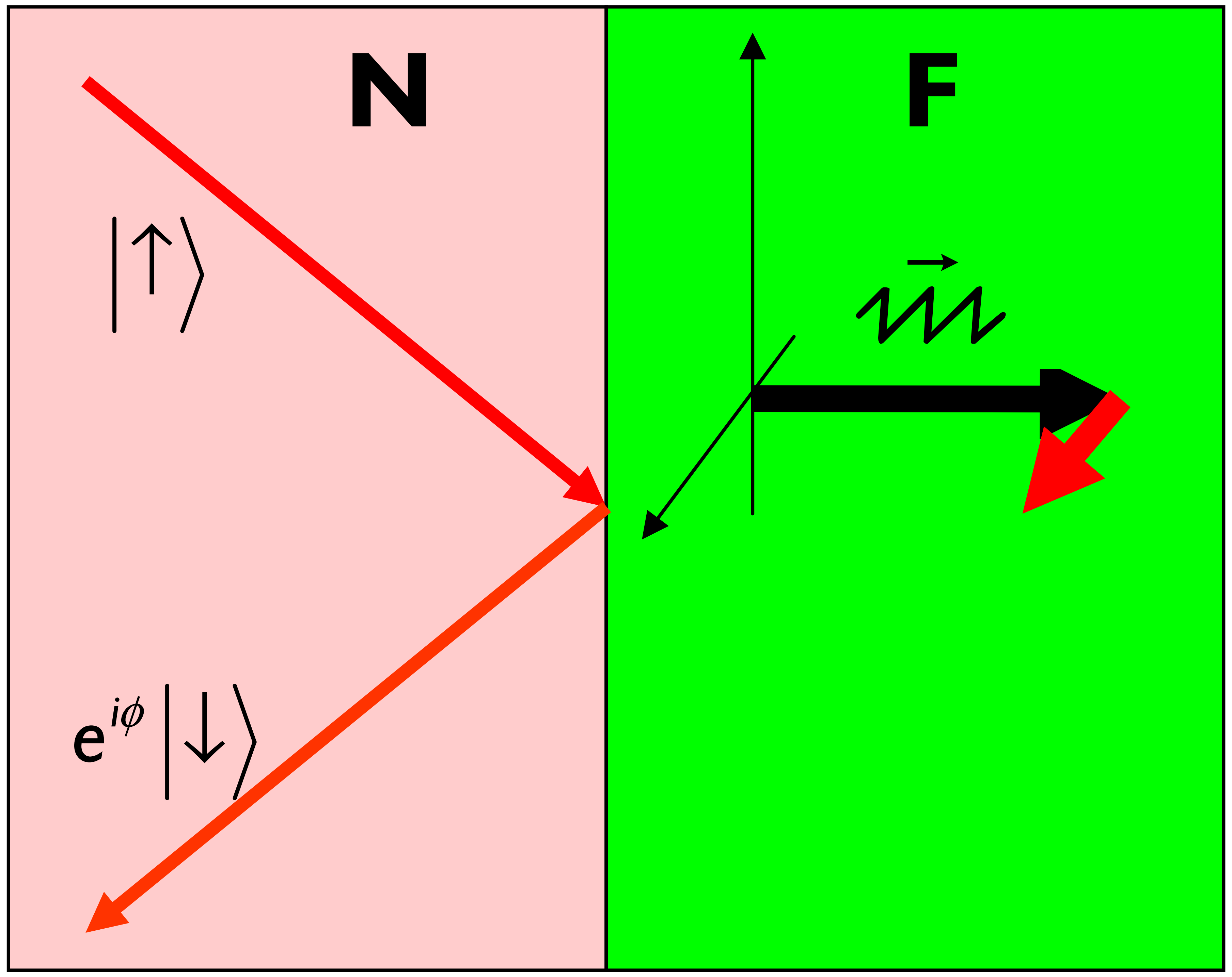
Spin current in F: $I_{S,z}^F = 0$

$$eI_{S,z}^N = \frac{e^2}{h} \mathrm{Re}\, g^{\uparrow\downarrow} \left(\mu_N^\uparrow - \mu_N^\downarrow \right)$$

real part of spin-mixing conductance (Brataas *et al.*, 2000)

Absorbed spin current = magnetization torque $L_z = \frac{I_{S,z}^N}{e} \frac{\hbar}{2}$

Non-local exchange



- effective field (Stiles, Miltat)
- spin-dependent interface phase shift (Cottet *et al*., 2005)

$$eI_{S,y}^{N} = \frac{e^2}{h} \mathrm{Im}\, g^{\uparrow\downarrow} \left(\mu_N^{\uparrow} - \mu_N^{\downarrow}\right)$$

imaginary part of spin-mixing conductance (Brataas et al., 2000)

Absorbed spin current = magnetization torque $L_y = \frac{I_{S,y}^{N}}{e}\frac{\hbar}{2}$

Spin mixing conductance

$$G_s = \frac{e^2}{h}\sum_{nm}\left|t^s_{nm}\right|^2 = \frac{e^2}{h}N - \frac{e^2}{h}\sum_{nm}\left|r^s_{nm}\right|^2$$

(normal metal)
Sharvin conductance

$s=\uparrow,\downarrow$ spin-dependent conductances for charge and collinear spin current.

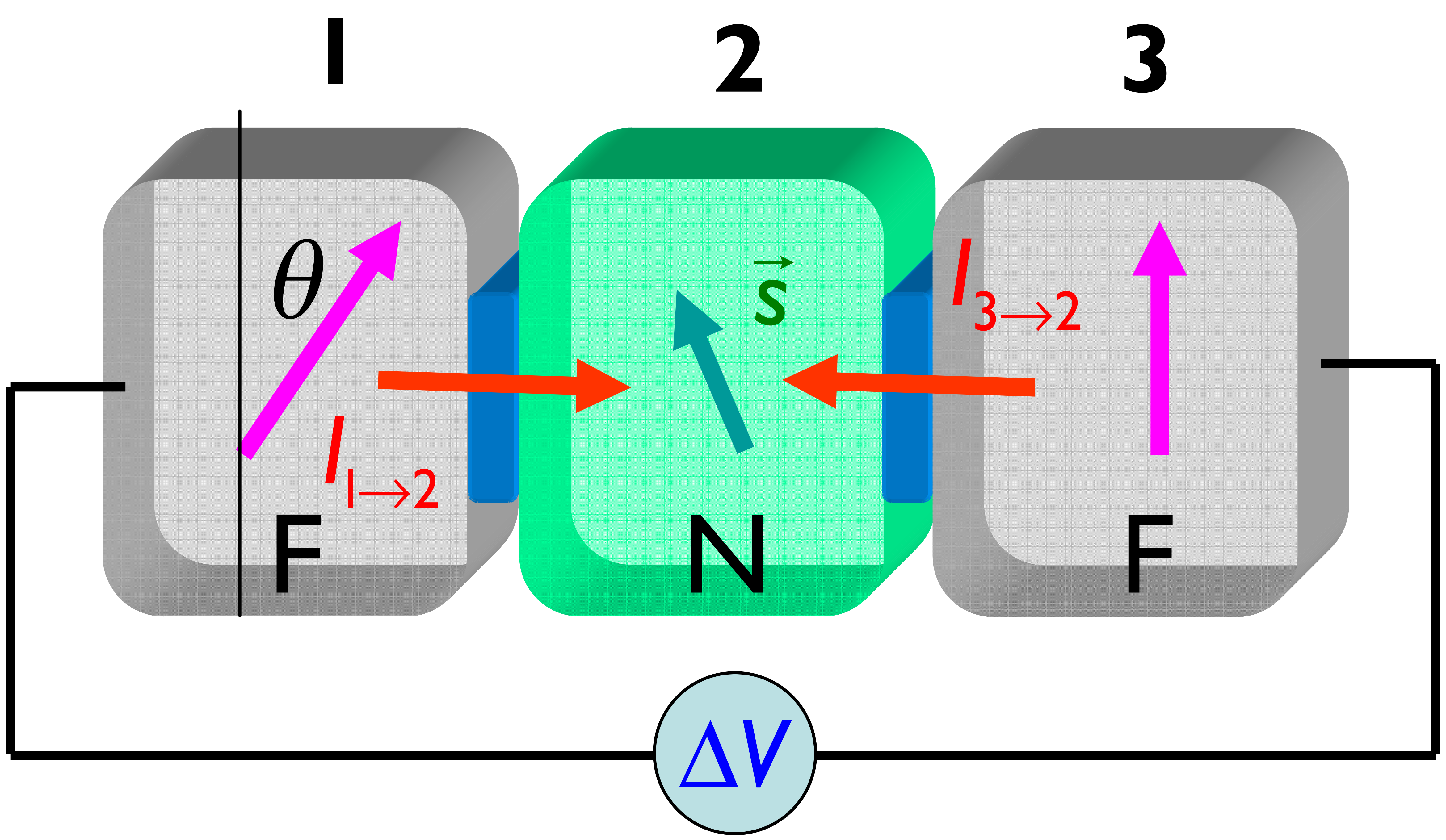
$$G^{\uparrow\downarrow} = \frac{e^2}{h}N - \frac{e^2}{h}\sum_{nm}\left(r^{\uparrow}_{nm}\right)^* r^{\downarrow}_{nm}$$

complex spin-mixing conductance for transverse spin current/spin-transfer torque.

Xia *et al*. (2002), Zwierzycki *et al*. (2005) $10^{15}\Omega^{-1}m^{-2}$

System	Interface	$G^{\uparrow}$	$G^{\downarrow}$	$\mathrm{Re}G^{r}_{\uparrow\downarrow}$	$\mathrm{Im}G^{r}_{\uparrow\downarrow}$	G_N^{Sh}
Au/Fe	clean	0.40	0.08	0.466	0.005	0.46
(001)	alloy	0.39	0.18	0.462	0.003	
Cu/Co	clean	0.42	0.38	0.546	0.015	0.58
(111)	alloy	0.42	0.33	0.564	−0.042	

Circuit theory of spin valves



$$I^c_{1\to2} = I^c\left(V_1,\theta,V_2,\vec{s}_2;G_\uparrow,G_\downarrow\right)$$

$$\vec{I}^{\,s}_{1\to2} = \vec{I}_s\left(V_1,\theta,V_2,\vec{s}_2;G_\uparrow,G_\downarrow,G_{\uparrow\downarrow}\right)$$

Self consistent solution of charge and spin current conservation:

$$I^c_{3\to2} + I^c_{1\to2} = 0$$

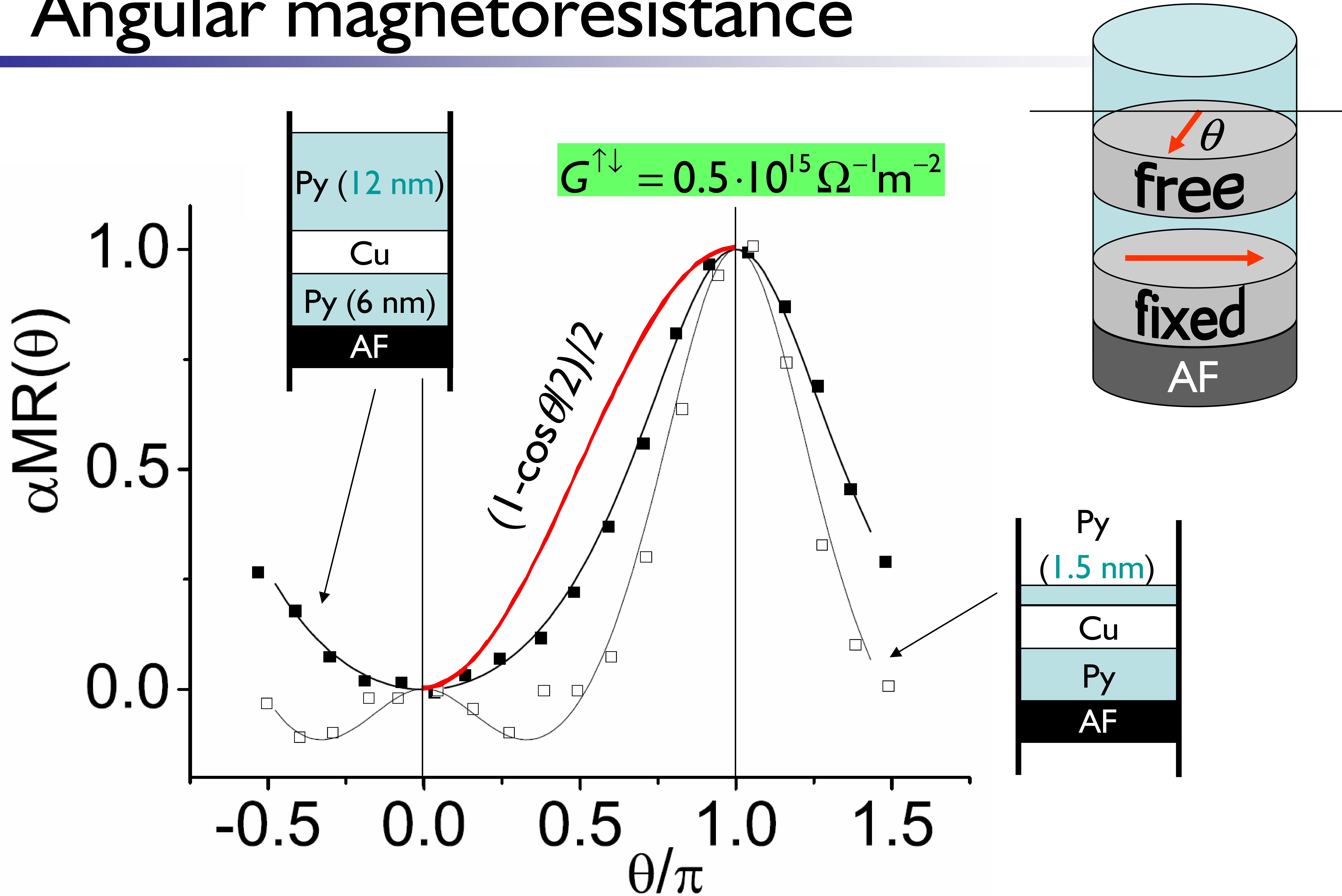
$$\vec{I}^{\,s}_{3\to2} + \vec{I}^{\,s}_{1\to2} = \vec{s}/\tau_{sf}$$

Results:

$$R(\theta) = I^c_{1\to2}/\Delta V$$ angular magnetoresistance

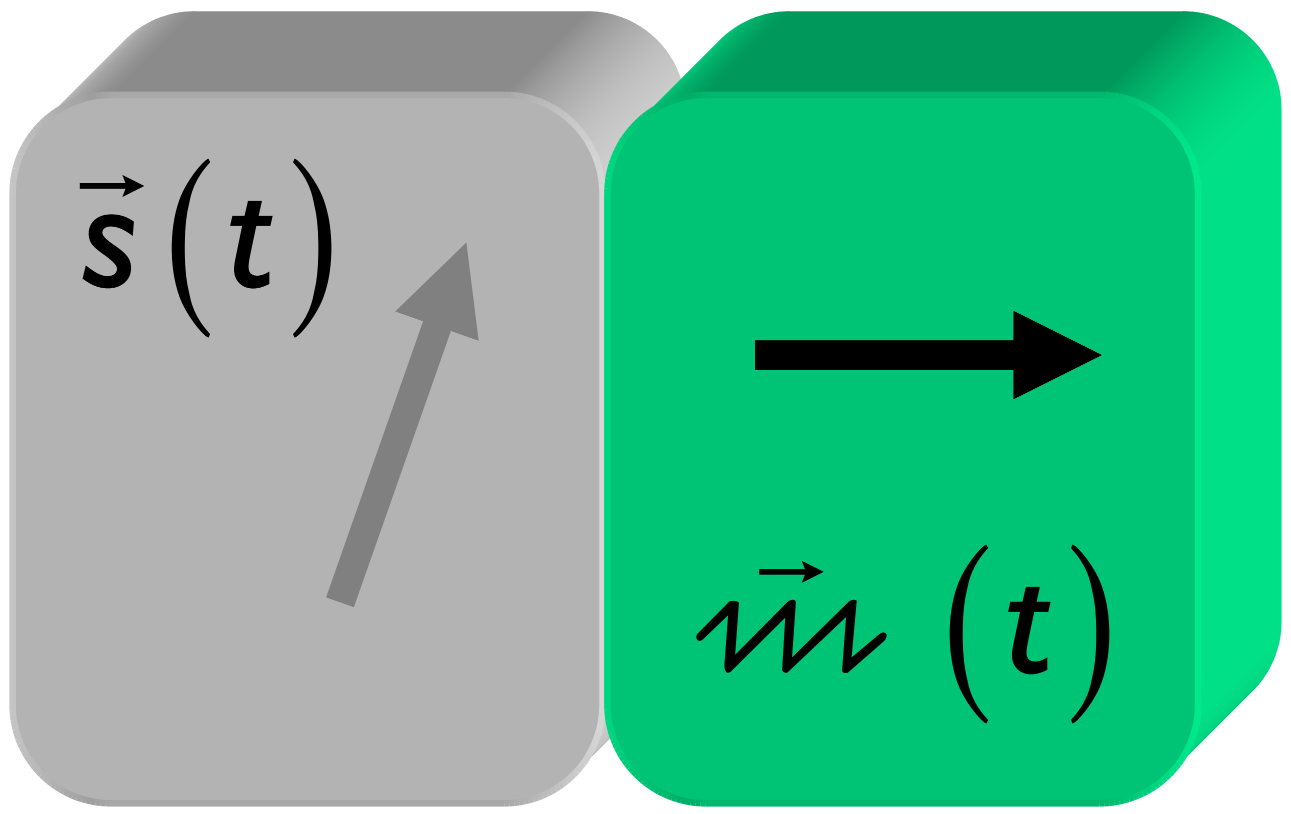
$$\vec{L}(\theta) = -\frac{\hbar}{2e}\left(\vec{I}^{\,s}_{1\to2}\right)_\perp$$ torque on left magnet

Angular magnetoresistance

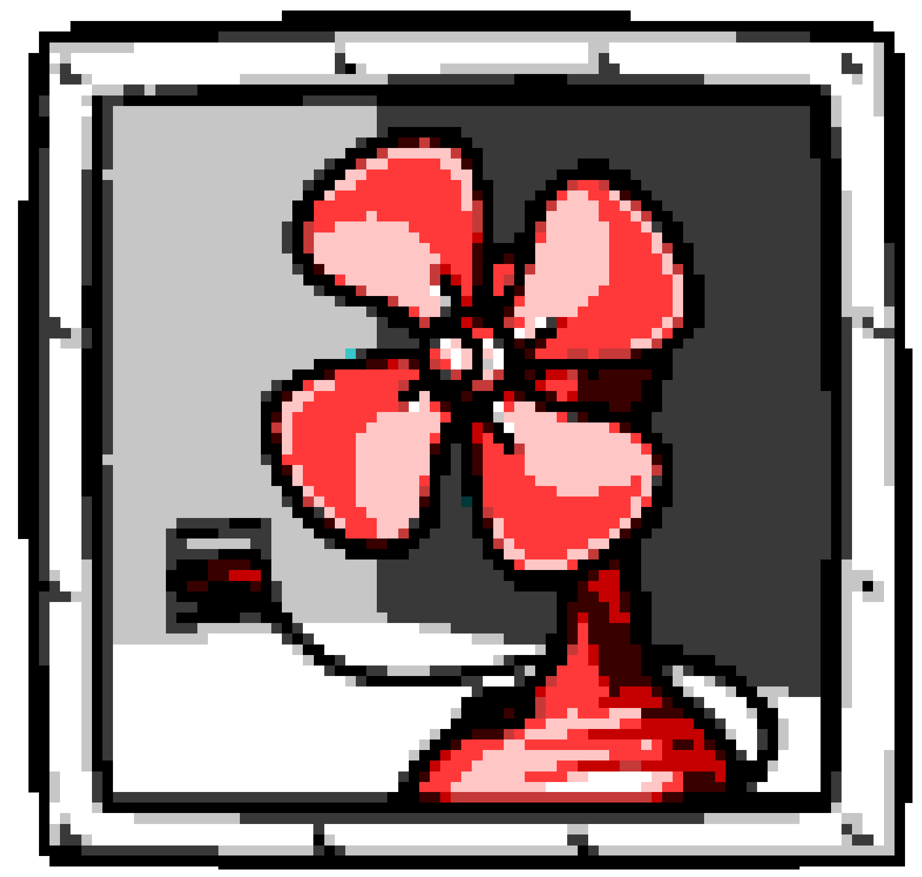


Exp: S. Urazhdin *et al*. (2005), th. Kovalev et al. (2006)

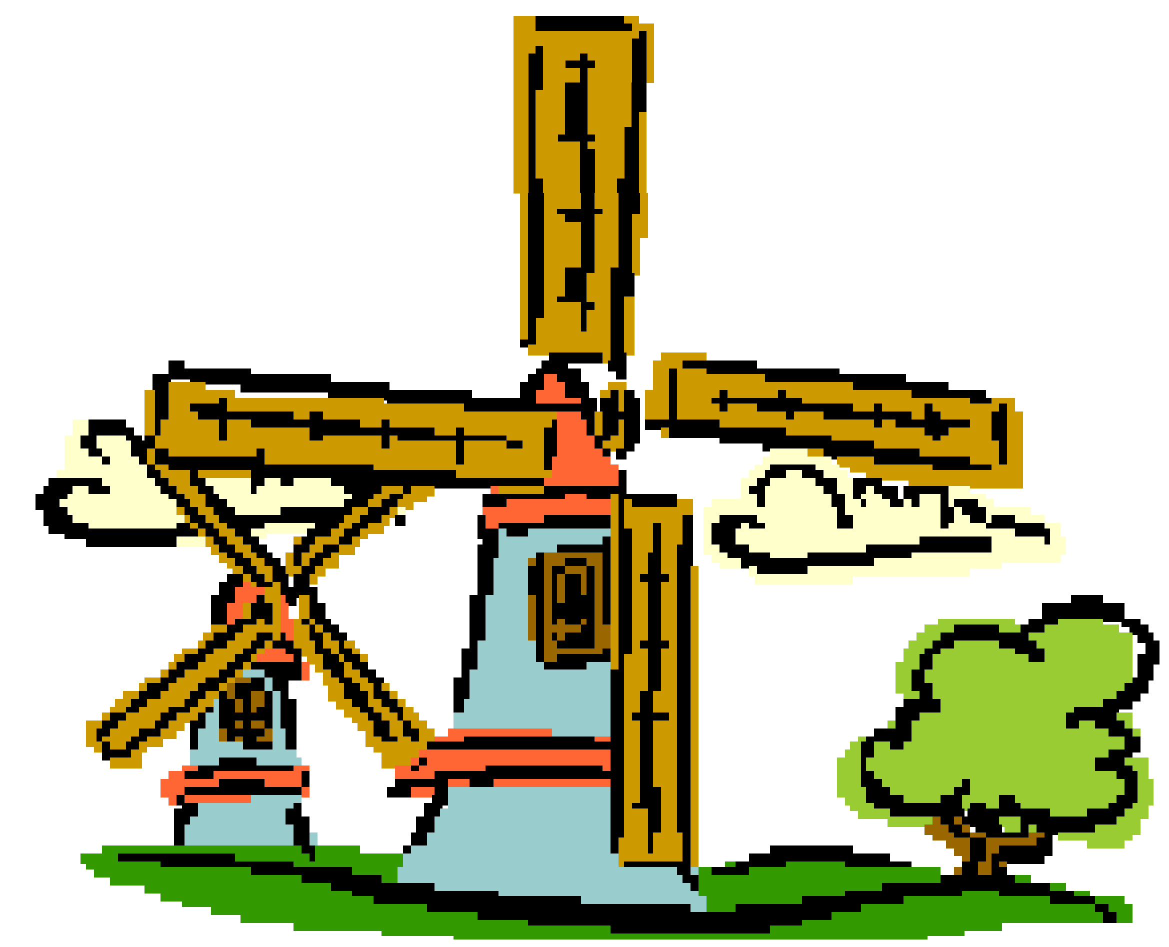
Magnetization dynamics



spin pumping
(Tserkovnyak *et al*.,2002)



spin-transfer torque

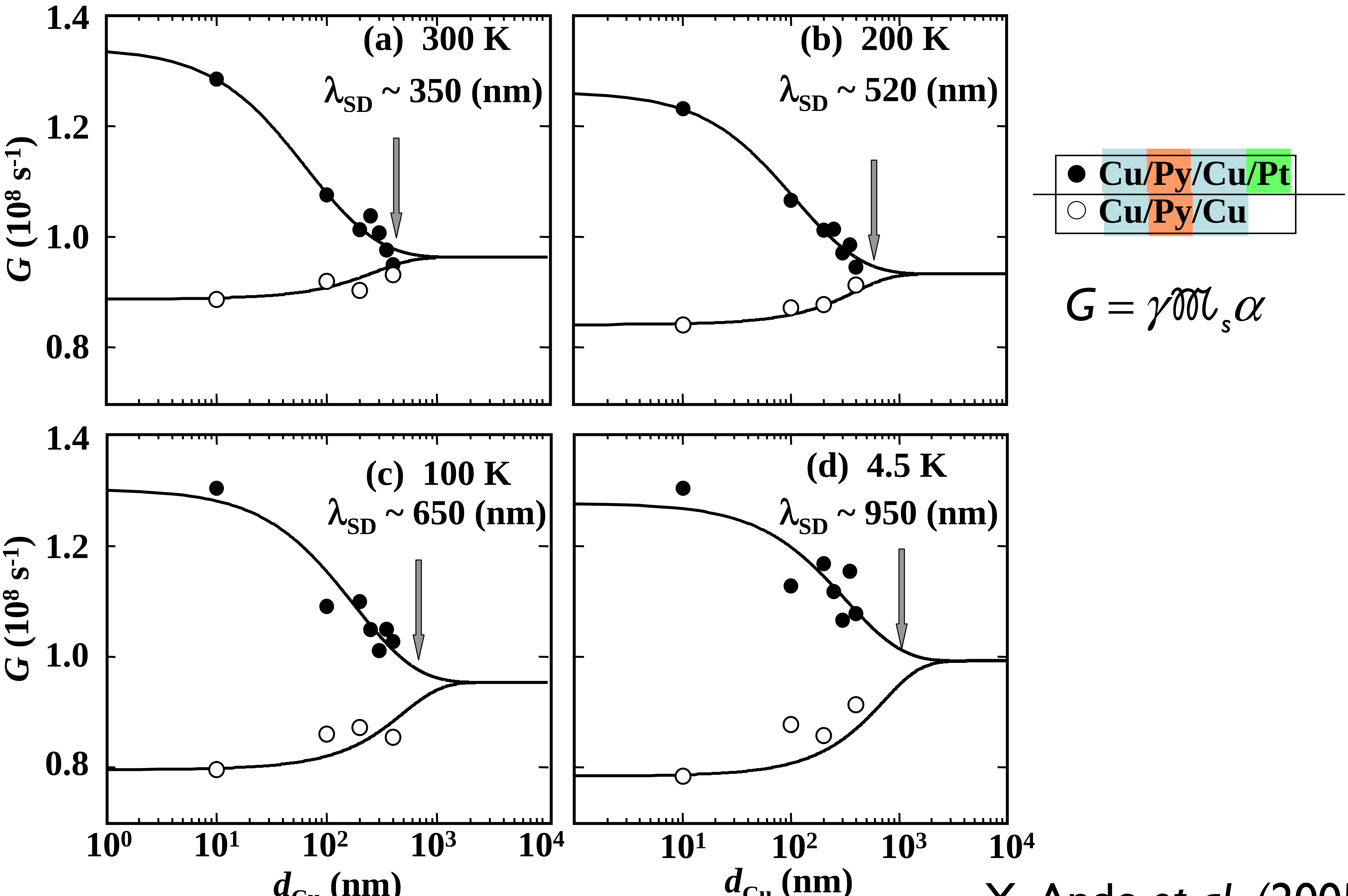


Macrospin
Landau-Lifshitz-Gilbert equation:

$$\frac{\partial \vec{m}}{\partial t} = -\gamma \vec{m}\times\vec{B} + \alpha_0 \vec{m}\times\frac{\partial \vec{m}}{\partial t} - \frac{\hbar\gamma}{4\pi\mathfrak{M}}\vec{m}\times\left(\vec{I}_s^{pump}+\vec{I}_s^{bias}\right)\times\vec{m}$$

$$= -\gamma \vec{m}\times\vec{B} + \left(\alpha_0 + \frac{\hbar\gamma}{4\pi\mathfrak{M}} g_{\uparrow\downarrow}\right)\vec{m}\times\frac{\partial\vec{m}}{\partial t} + \frac{\hbar\gamma}{4\pi\mathfrak{M}} g_{\uparrow\downarrow}\vec{m}\times\vec{s}\times\vec{m}$$

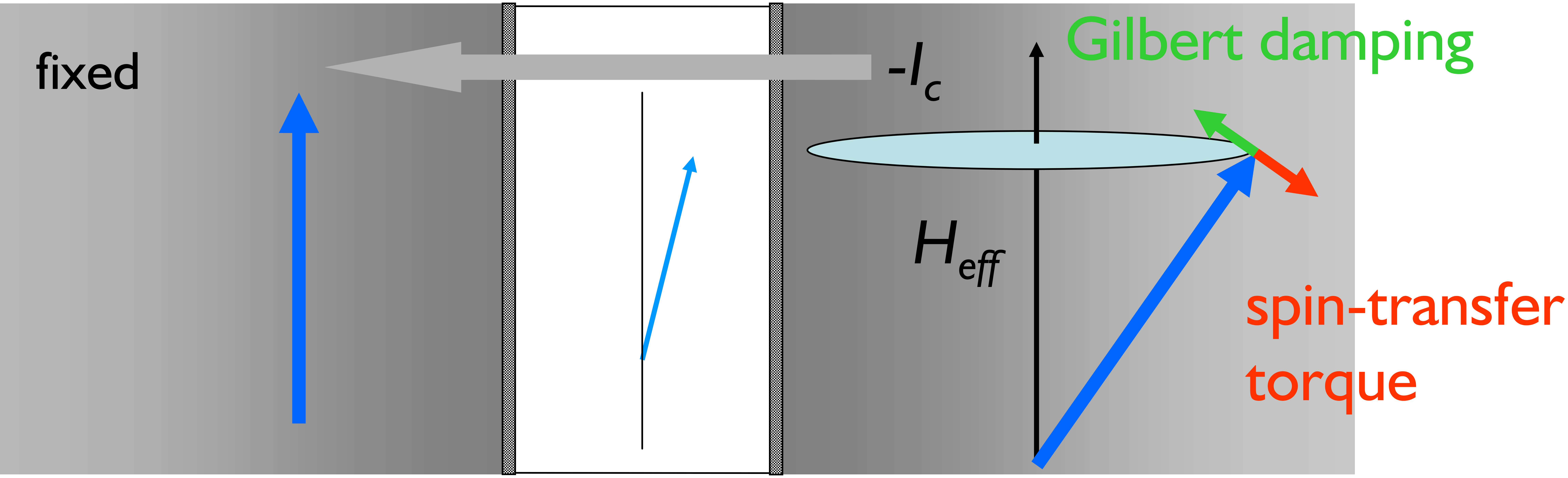
Gilbert damping in multilayers



$$G = \gamma \mathfrak{M}_s \alpha$$

Y. Ando *et al*. (2005)

Onset of instability (macrospin model)



Onset to magnetization reversal when Gilbert damping is canceled by spin transfer torque for small fluctuations around the collinear configuration.

Dynamic stiffness in symmetric spin valves (Tserkovnyak, 2003):

$$\alpha \vec{m} \times \frac{\partial \vec{m}}{\partial t} + \frac{\hbar \gamma}{4\pi \mathfrak{M}} g_{\uparrow\downarrow} \vec{m} \times \vec{s} \times \vec{m} = 0$$

$$\frac{I_{s,c}^{bias}}{\hbar \gamma B_{eff}} = \frac{2\mathfrak{M}\alpha_0}{\hbar \gamma} + \frac{\operatorname{Re} g_{\uparrow\downarrow}}{4\pi}$$

Published extensions

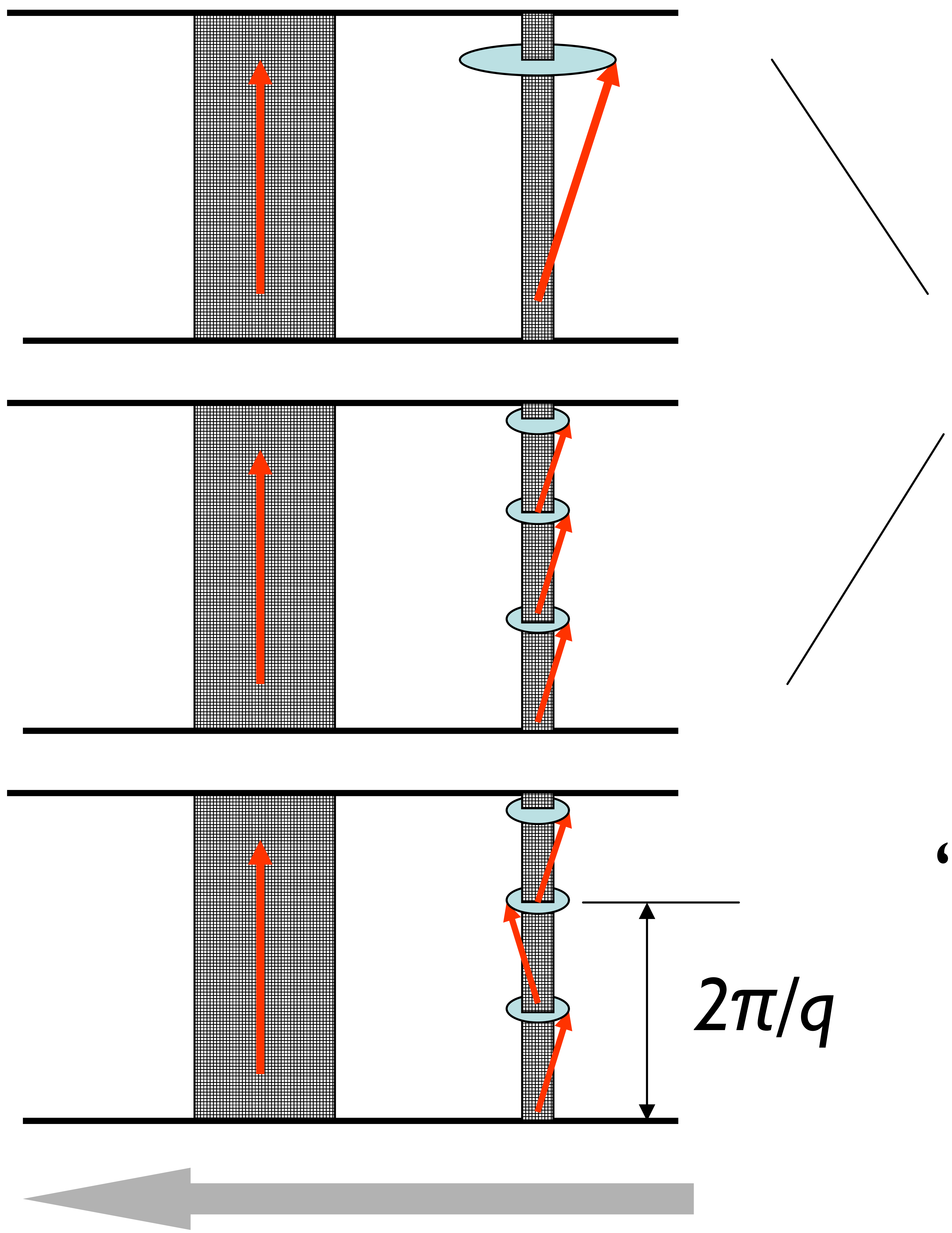
Non-linear large-angle dynamics of macrospin model:

- Non-linear system theory (Valet, Visscher, Bertotti)
- Numerical simulation incl. pulses (Kiselev)

Numerical micromagnetics with Slonczewski torque (Miltat, Lee, Zhang, Berkov).

Spin waves in magnetization and spin currents (Brouwer, Brataas).

Macrospin vs. spin wave

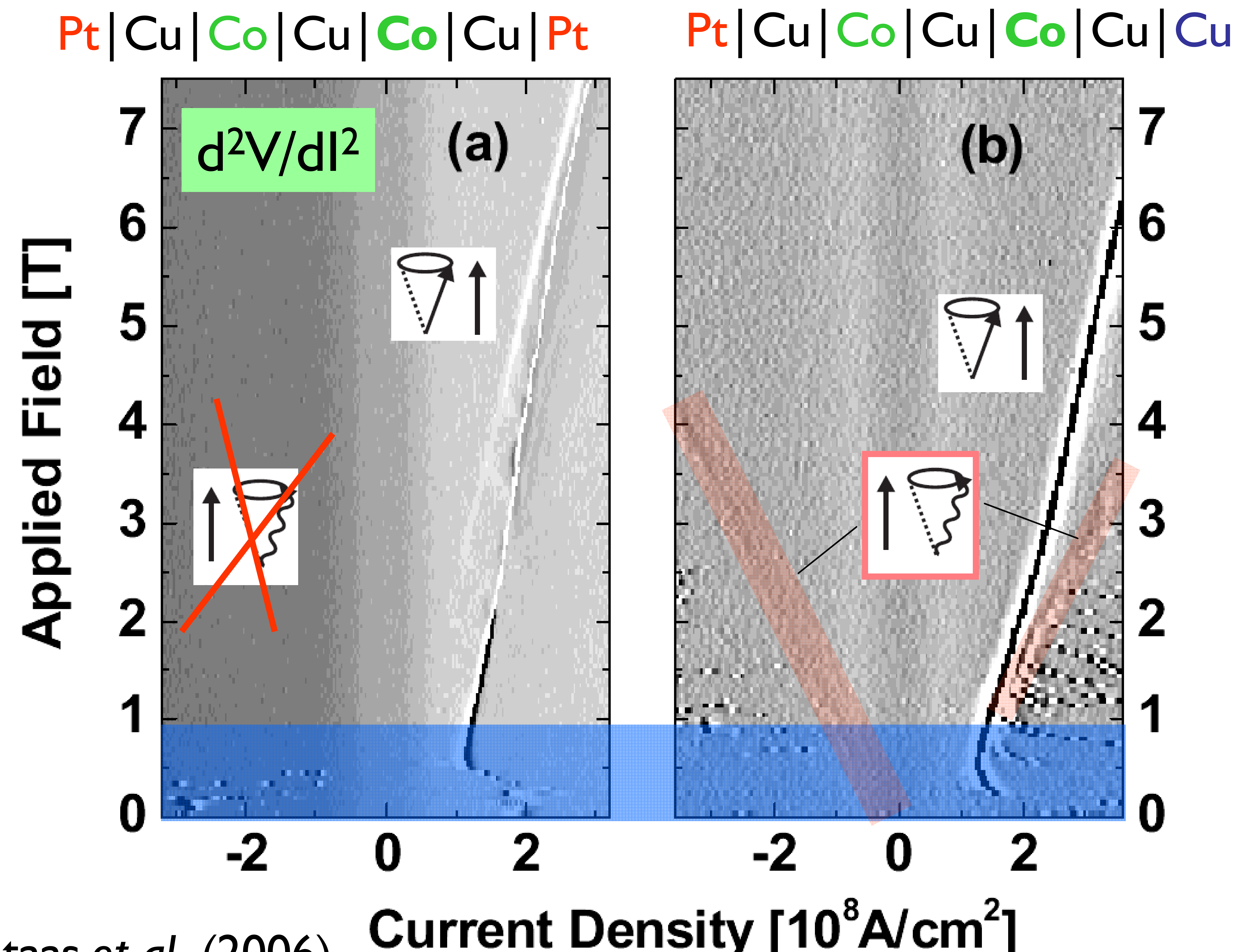


"macrospin" excitation

"spin wave" excitation

(Polianski & Brouwer, 2004
Brataas et al., 2006)

Exp. NYU/IBM (2005)



Brataas *et al*. (2006)

Spin *vs.* magnetization noise

Foros *et al*. (2005)

$$\vec{L}(t) = -\vec{m}\times\gamma\left(\vec{h}^{(\text{thermal})}(t)+\vec{h}^{(\text{shot})}(t)\right)$$

$$\frac{\partial\vec{m}}{\partial t} = -\vec{m}\times\gamma\left(\vec{H}+\vec{h}^{(0)}(t)+\vec{h}^{(\text{thermal})}(t)+\vec{h}^{(\text{shot})}(t)\right)+\left(\alpha_0+\alpha'\right)\vec{m}\times\frac{\partial\vec{m}}{\partial t}$$

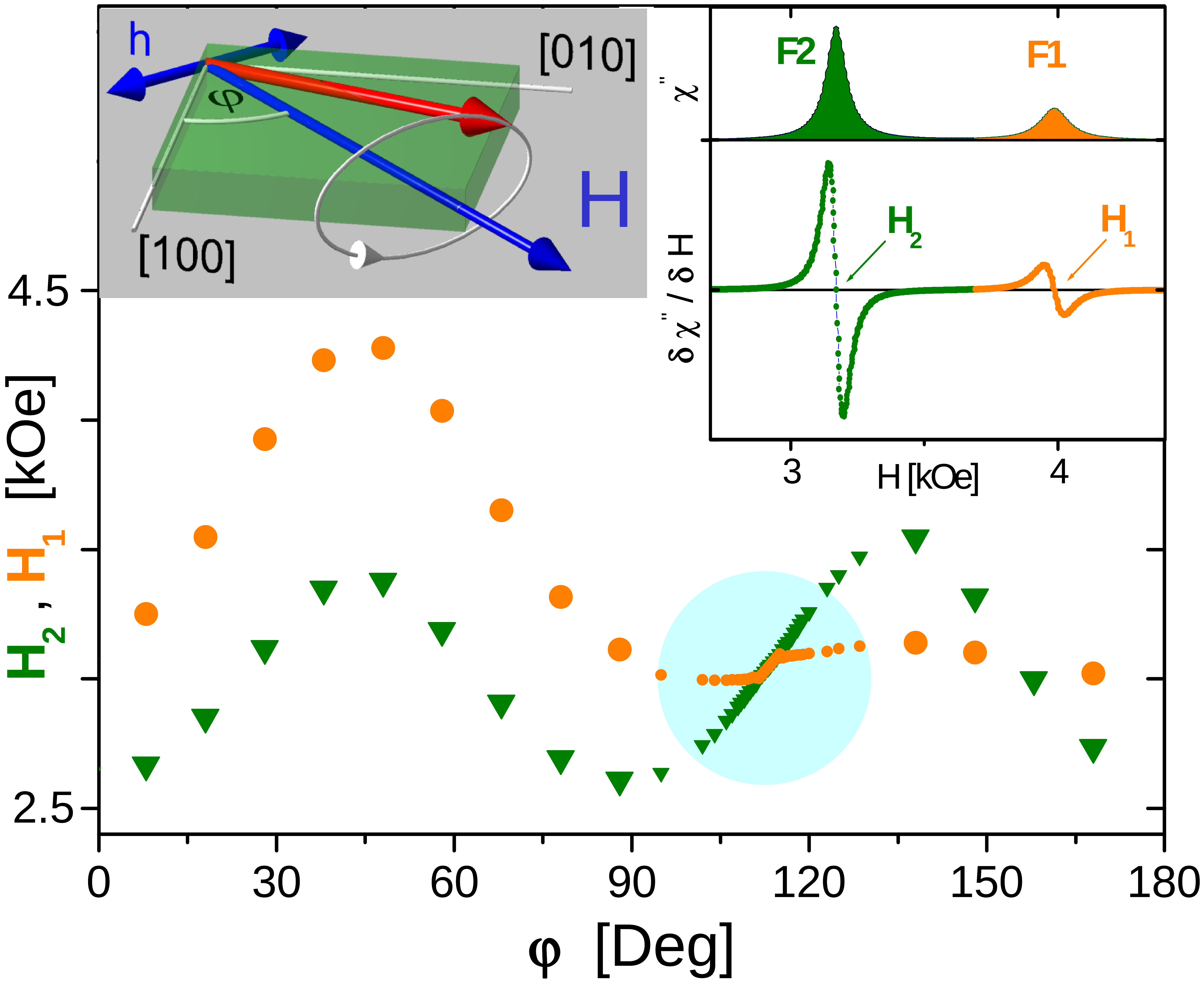
$$\left\langle h_i^{(\text{thermal})}(t)\,h_j^{(\textit{thermal})}(t')\right\rangle = 4k_BT\frac{\alpha'}{\gamma\mathfrak{M}}\delta_{ij}\delta(t-t')$$

$$\alpha' = \frac{\gamma\hbar}{4\pi\mathfrak{M}}\mathrm{Re}\left(g_L^{\uparrow\downarrow}+g_R^{\uparrow\downarrow}\right)$$

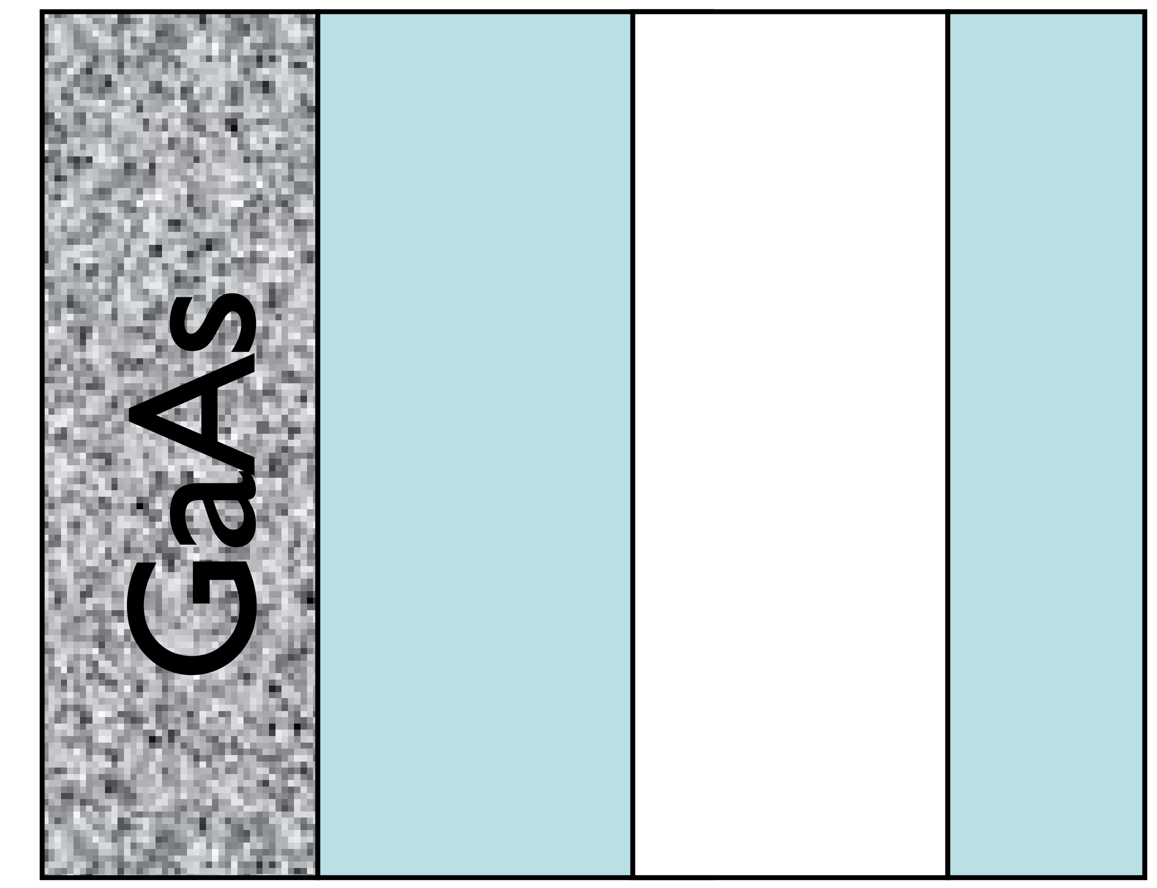
Thermal spin current noise ↔ spin pumping dissipation.

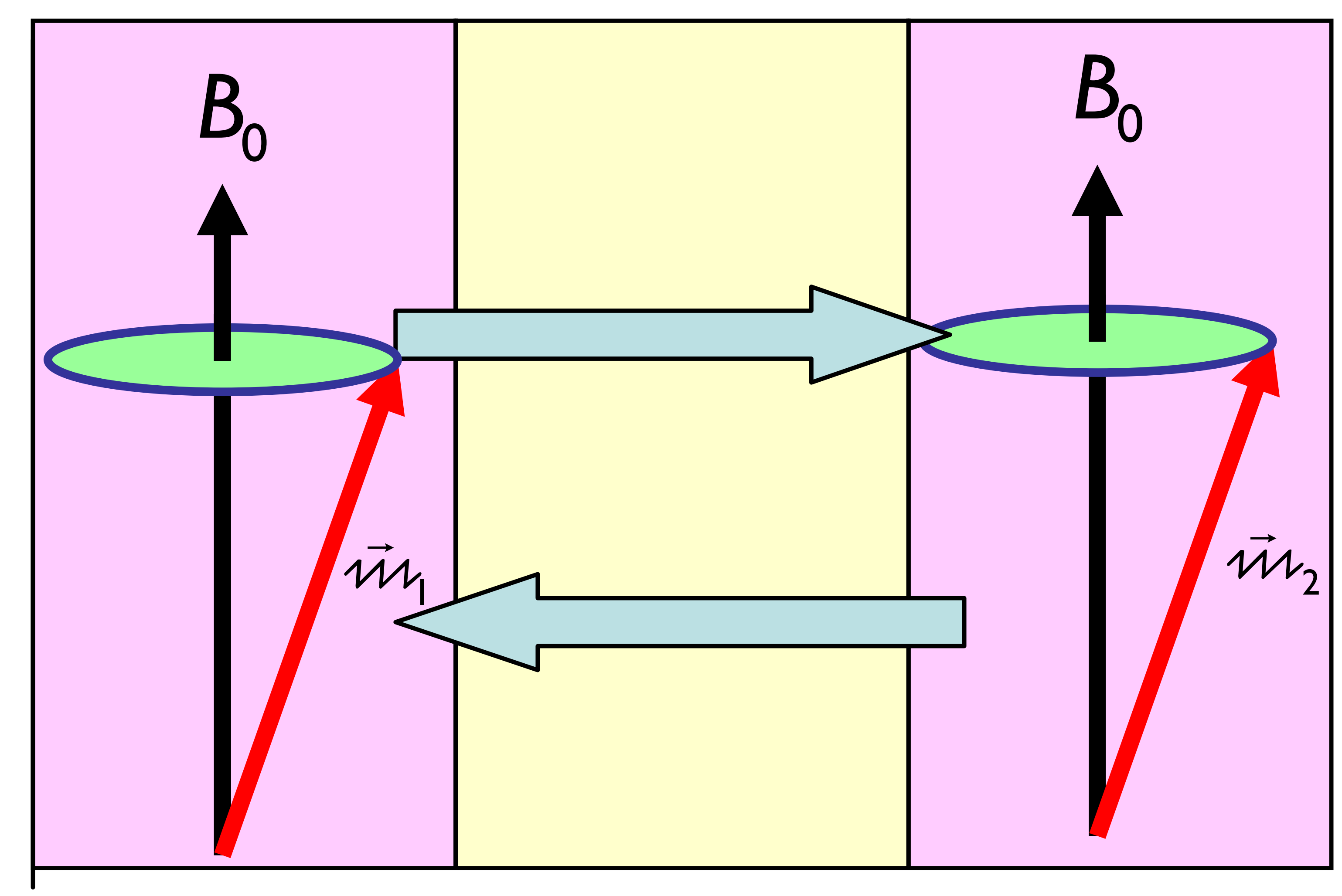
$$\left\langle h_i^{(\text{shot})}(t')\,h_j^{(\text{shot})}(t)\right\rangle = \frac{\hbar}{4\pi}\frac{\left|\Delta\mu_c\right|}{\mathfrak{M}^2}\delta_{ij}\delta(t-t')\,\mathrm{Tr}\left[\mathbf{r}_\uparrow\mathbf{r}_\uparrow^\dagger\mathbf{t}'_\downarrow\mathbf{t}'^\dagger_\downarrow+\mathbf{r}'_\downarrow\mathbf{r}'^\dagger_\downarrow\mathbf{t}_\uparrow\mathbf{t}_\uparrow^\dagger\right]$$

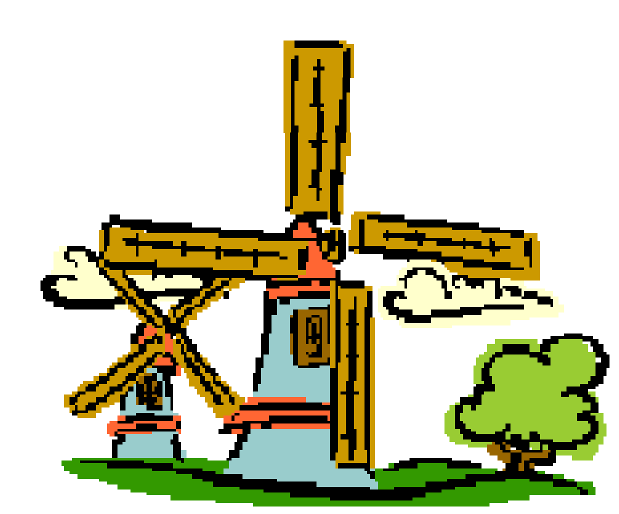
FMR spectra of spin valves (Heinrich *et al.*, 2003)

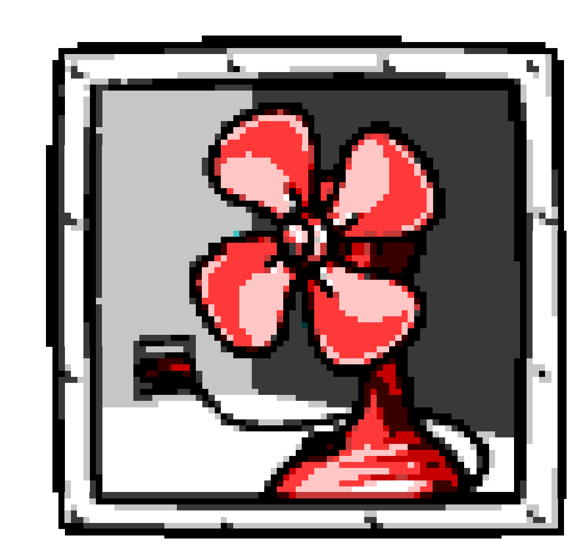


Py|Au |Py



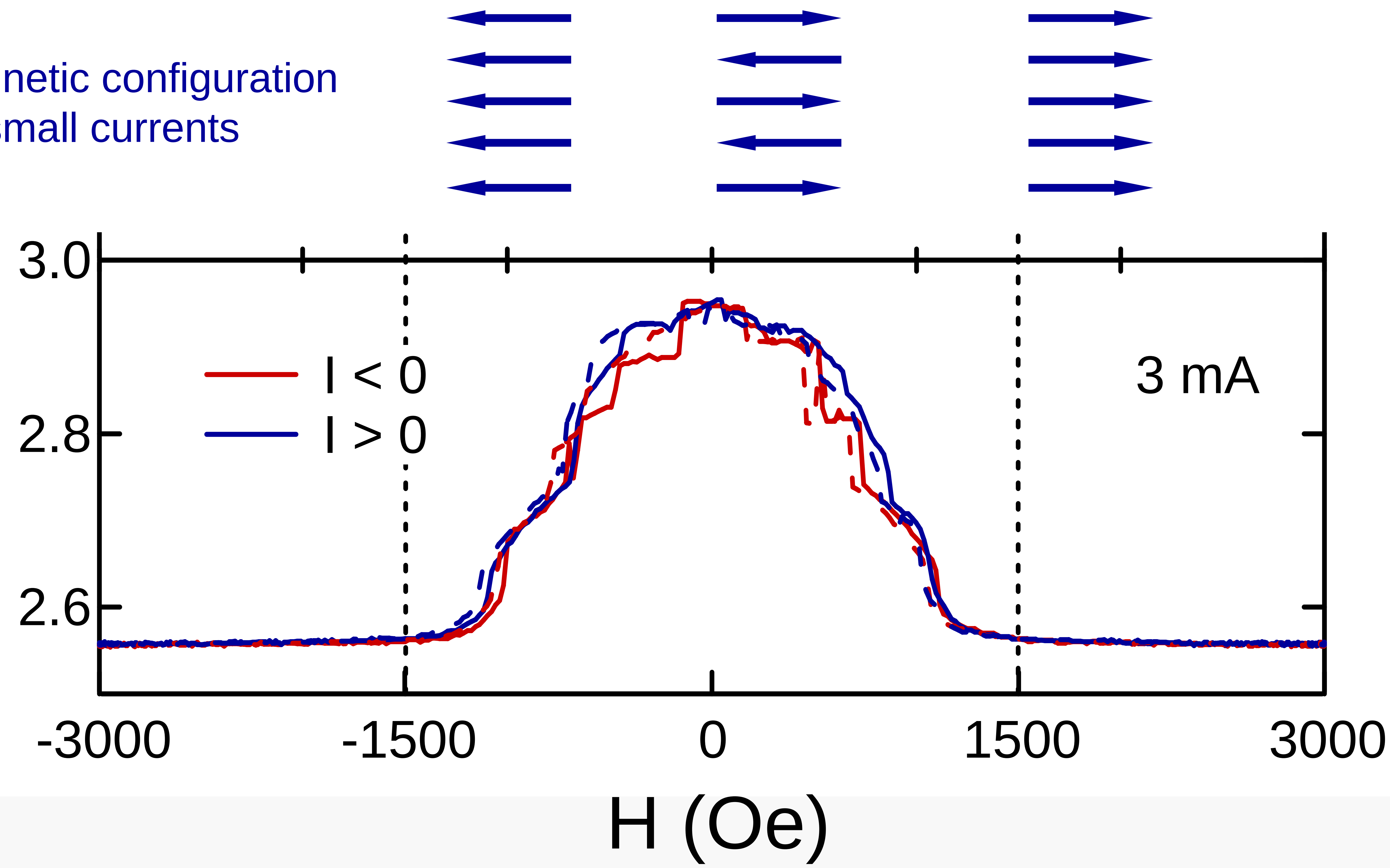




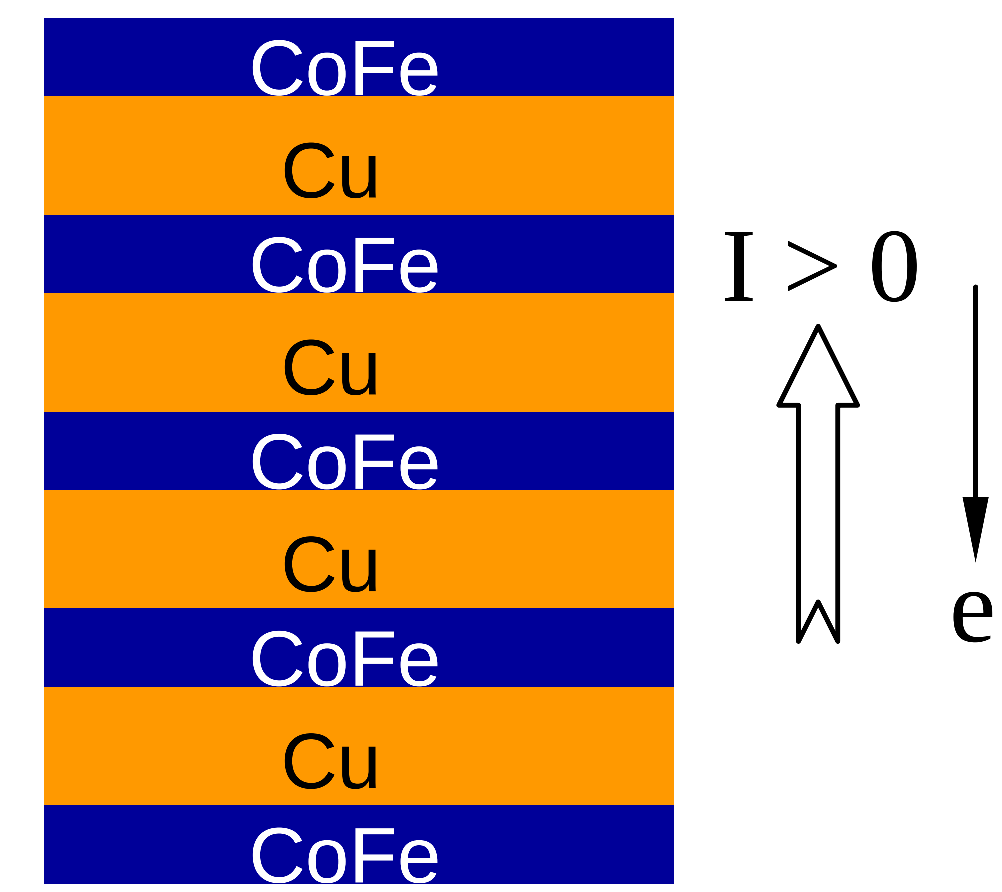


CPP multilayer nanopillars -- Resistance vs. field

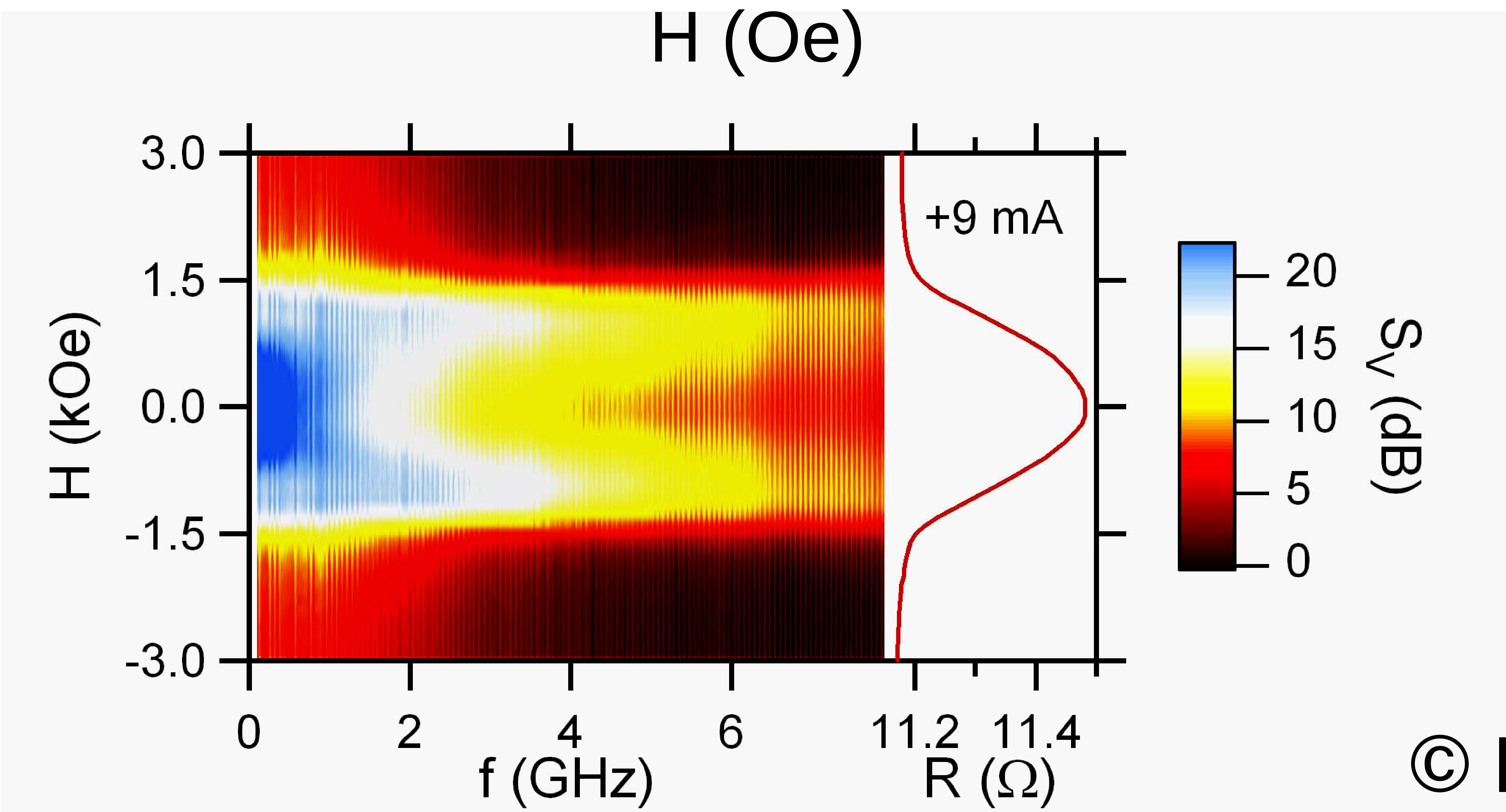
Magnetic configuration
for small currents



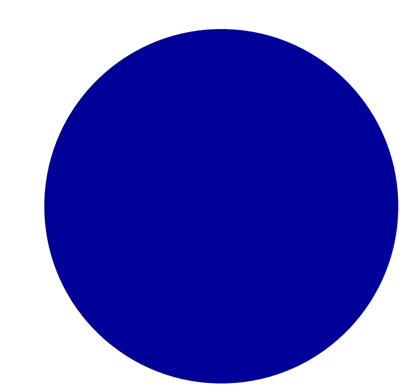
multilayer



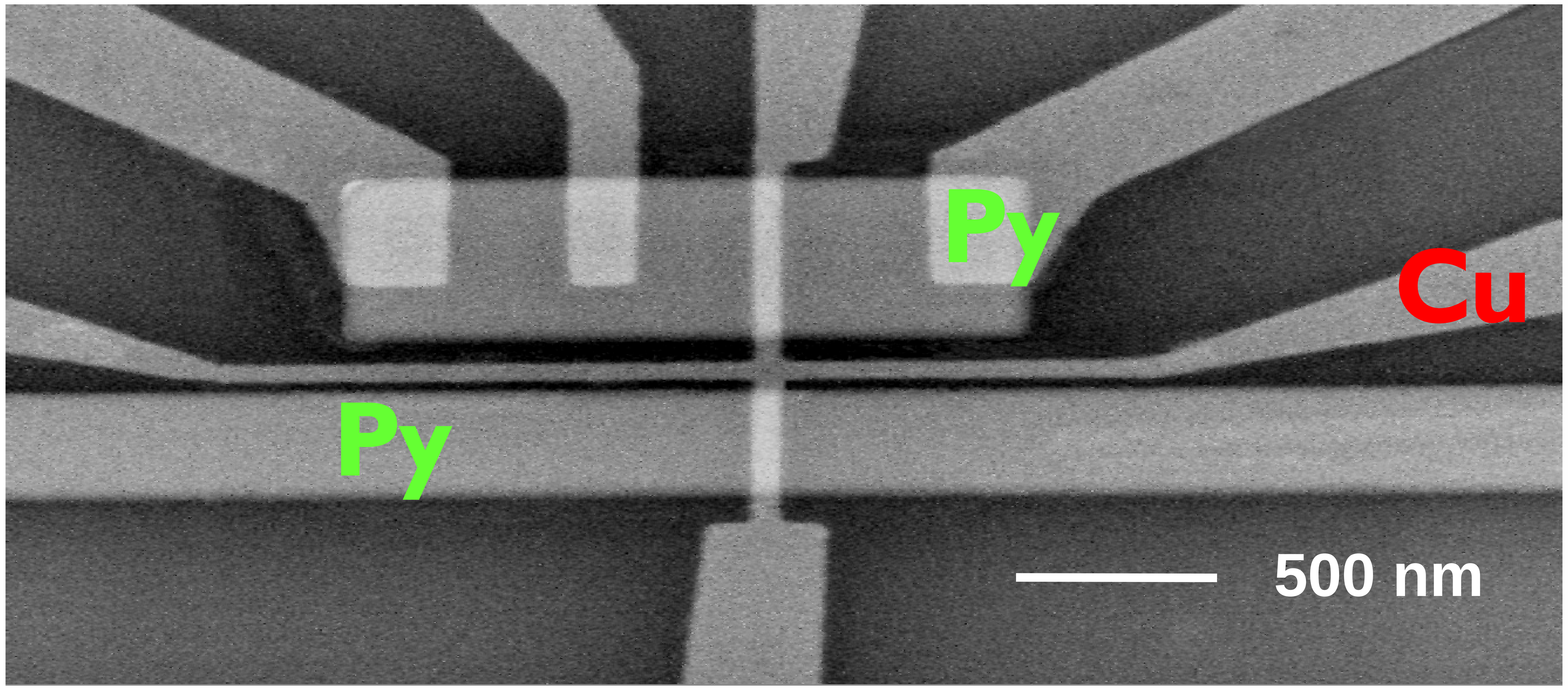
[CoFe-20 Å/Cu-19 Å]x10

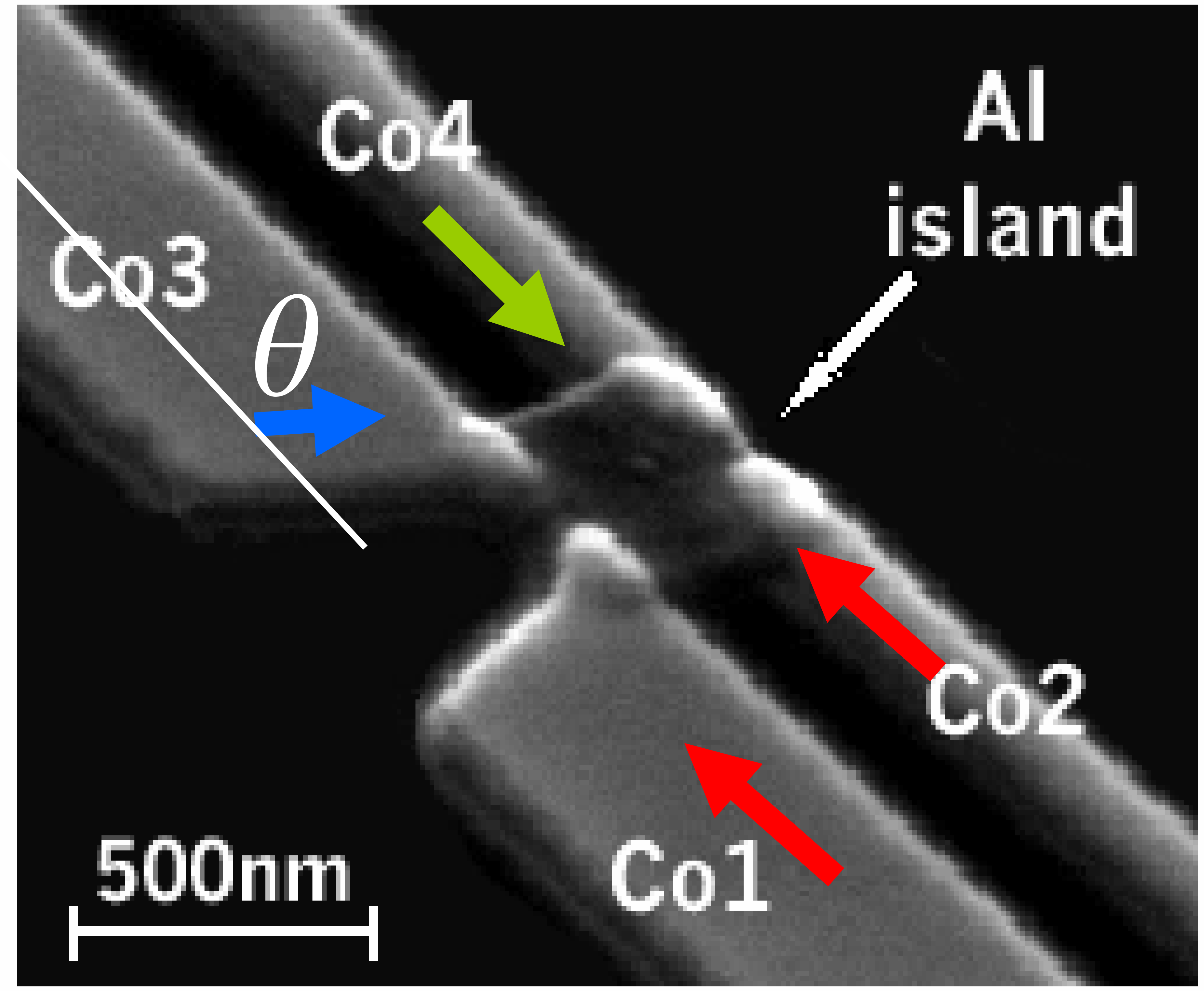


75 to 150 nm dia.

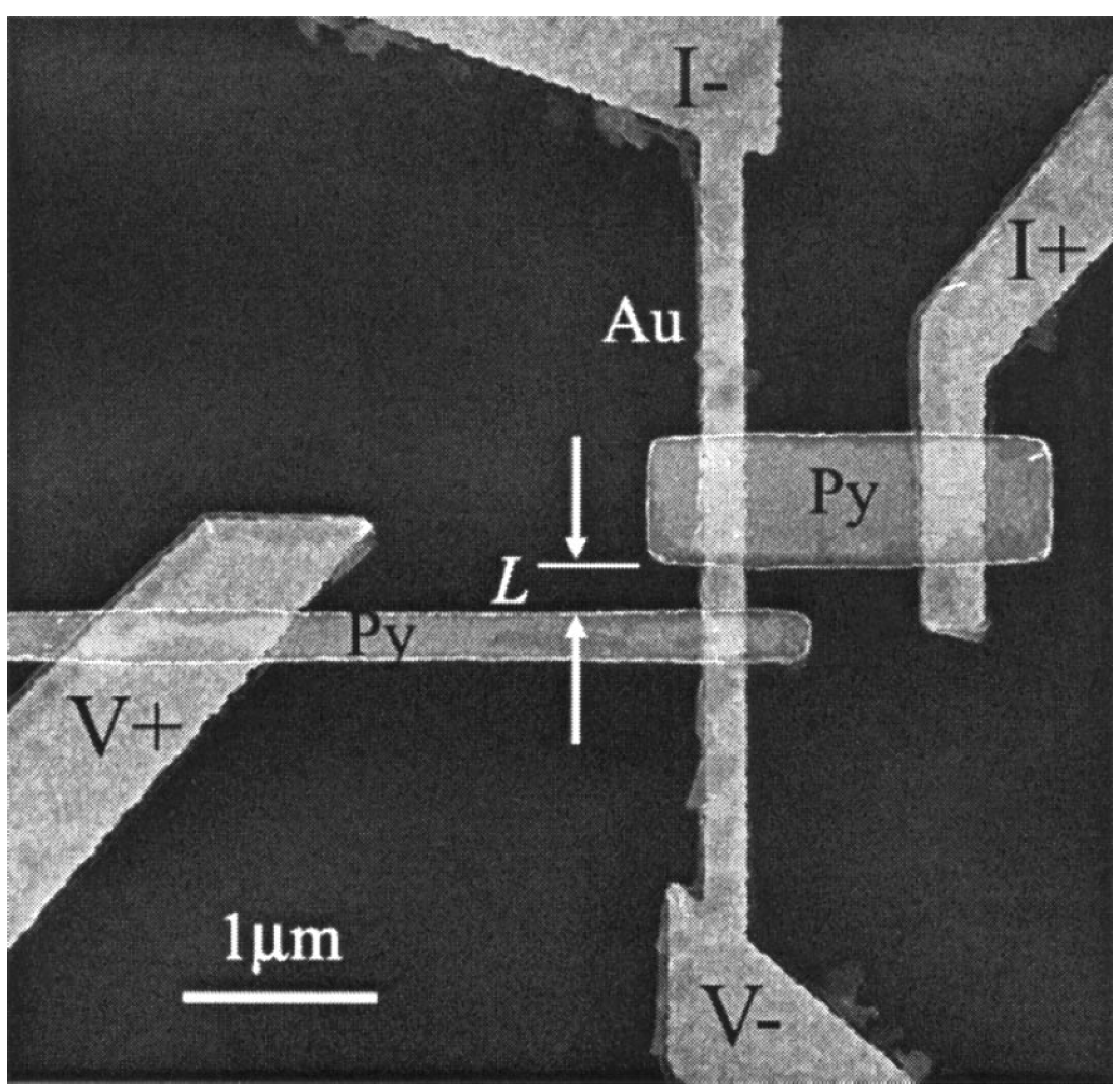


Thin film magnetoelectronic nanostructures



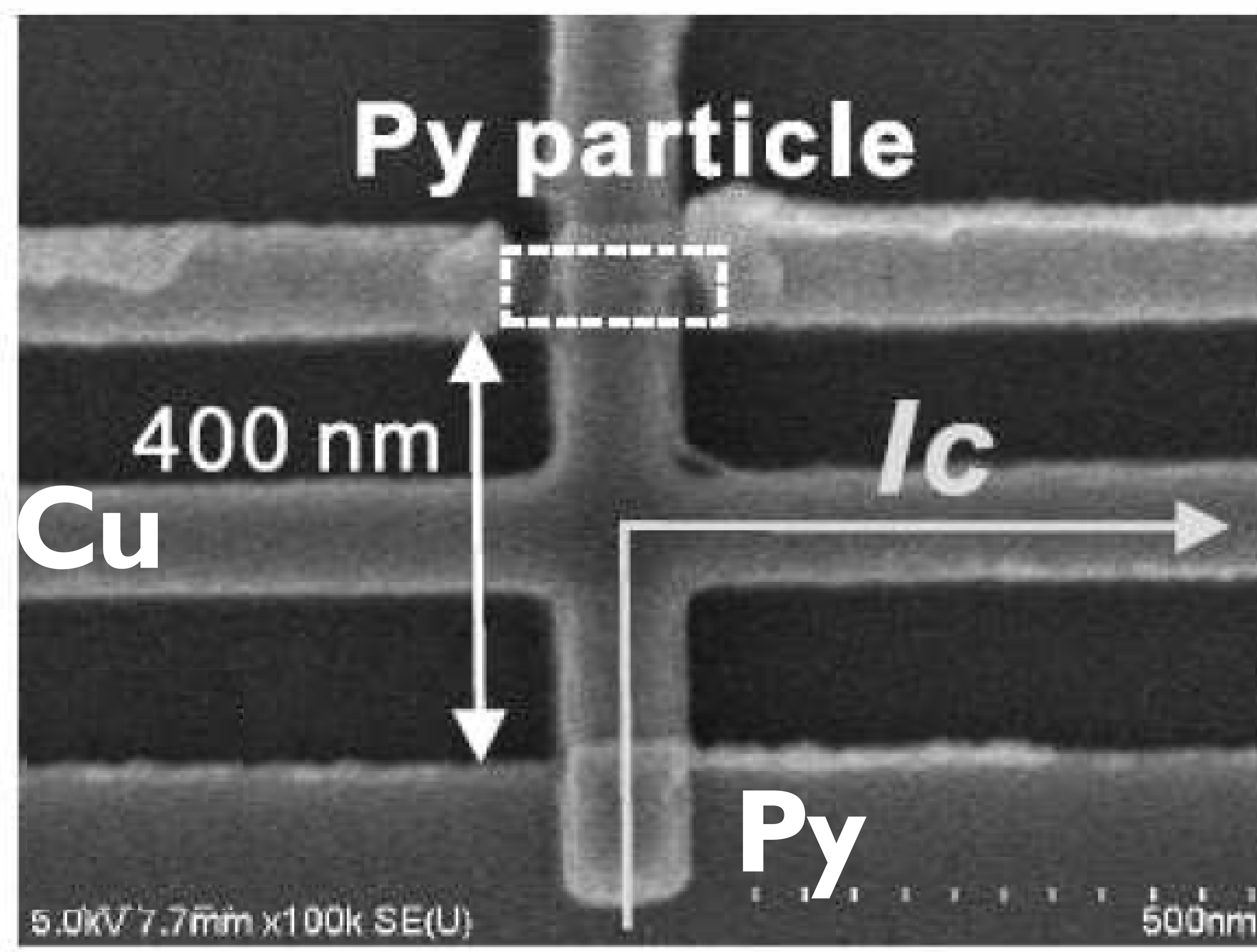


Groningen (2001-2005)

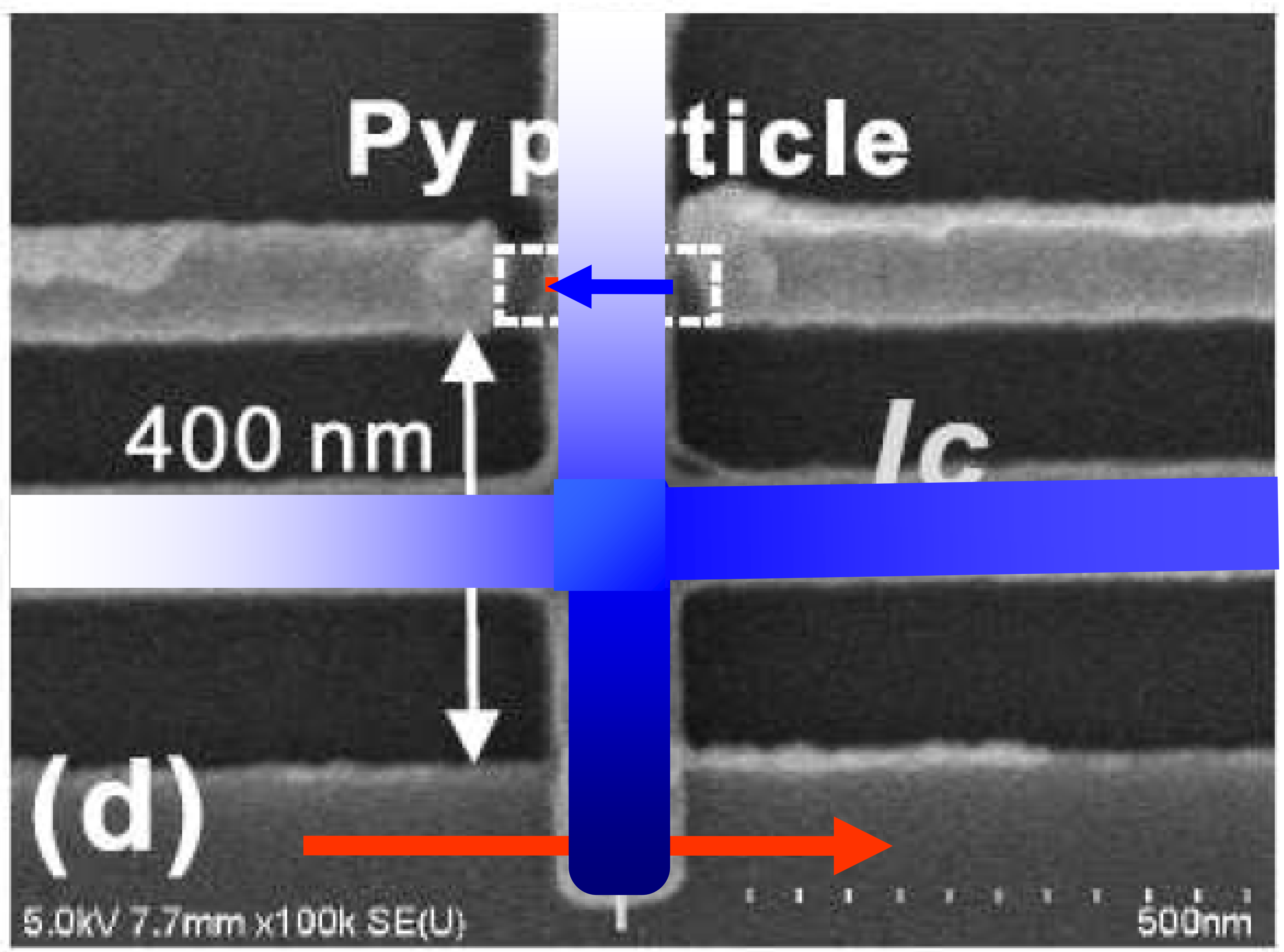


ANL (2005)

Riken (2006)

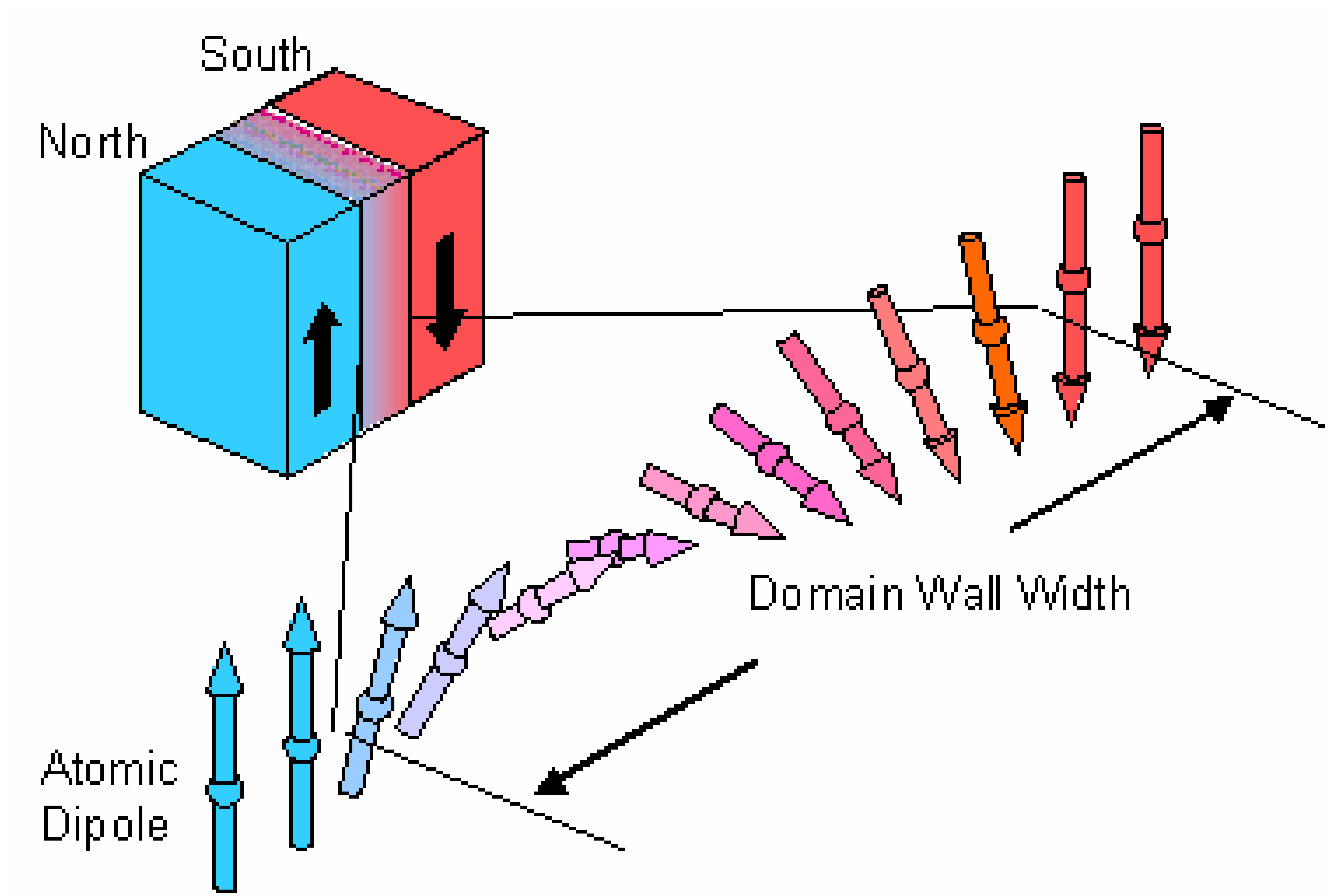


Accumulation-driven magnetization reversal



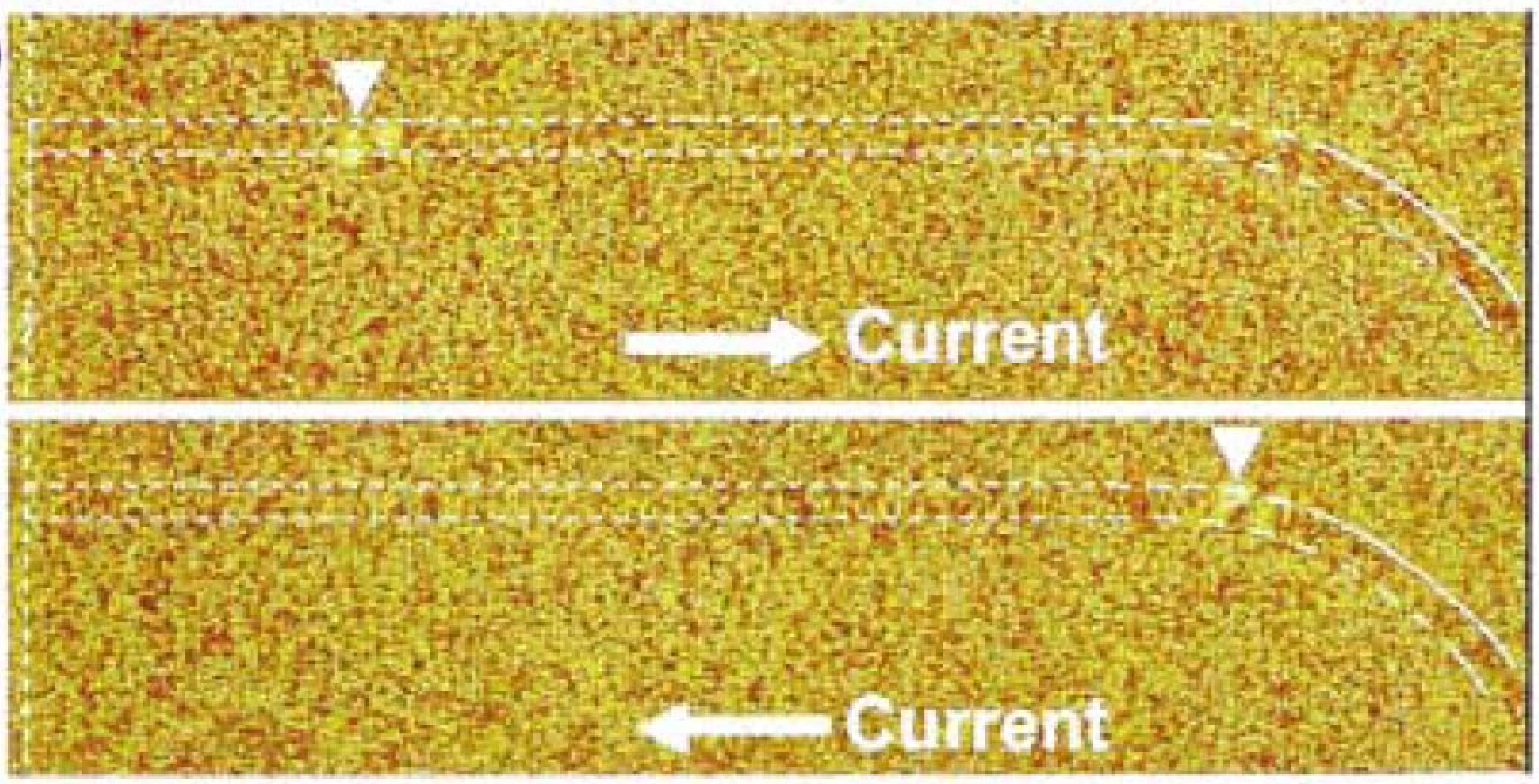
Kimura *et al*. (2006)

Magnetic domain walls

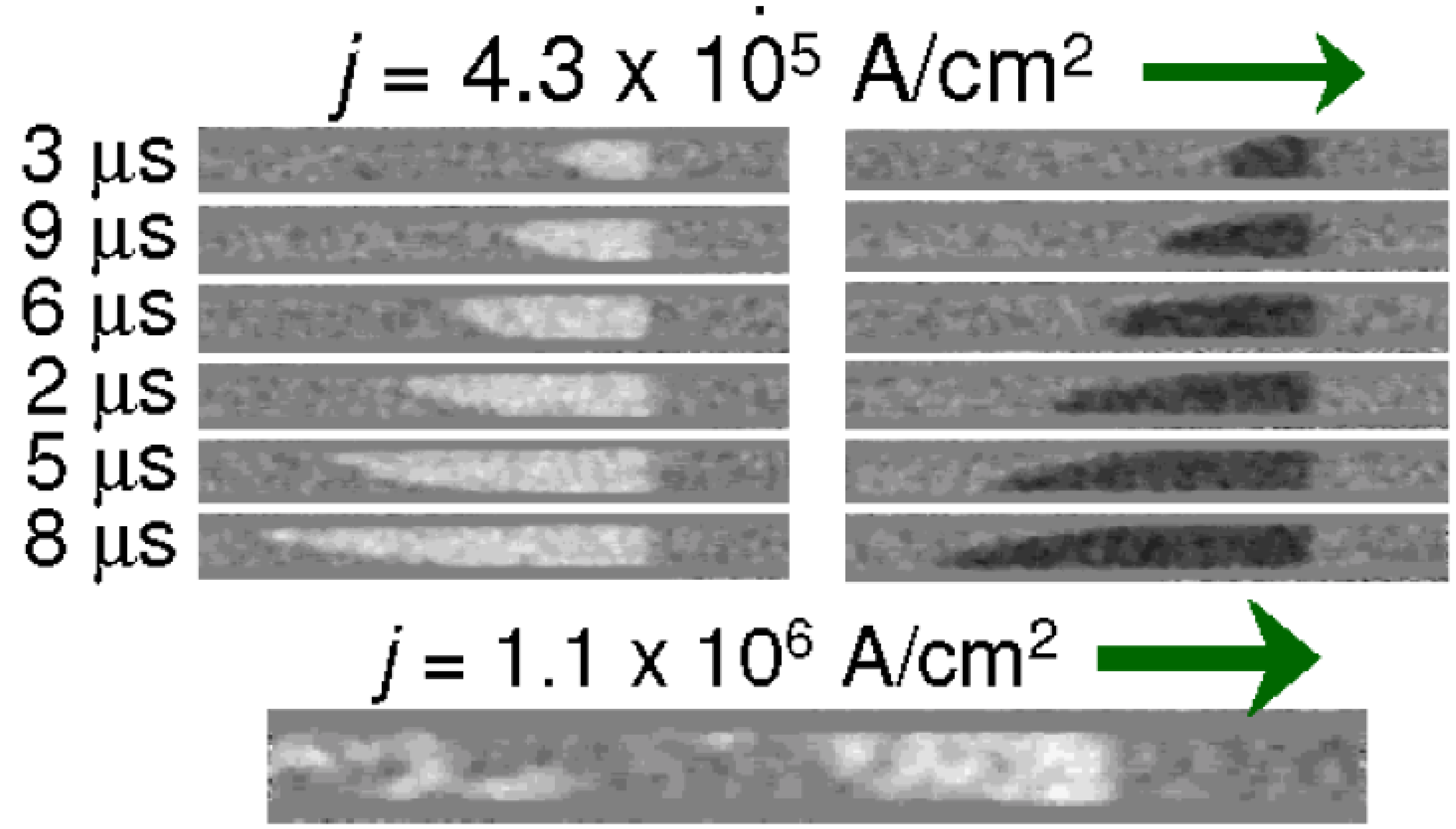


Current-induced domain wall motion

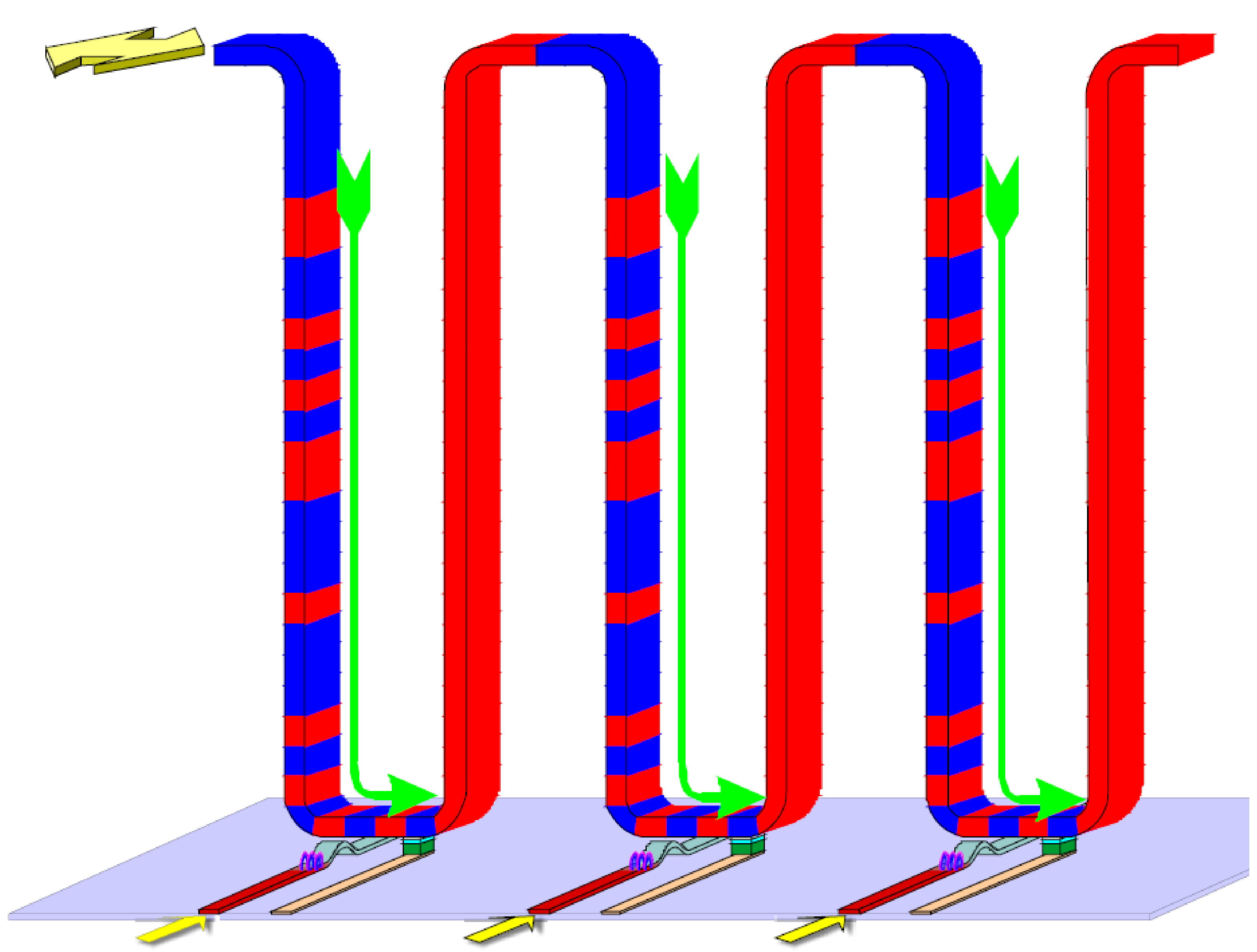
Experiments:



Yamaguchi *et al*. (2004)



Yamanouchi *et al*. (2006)



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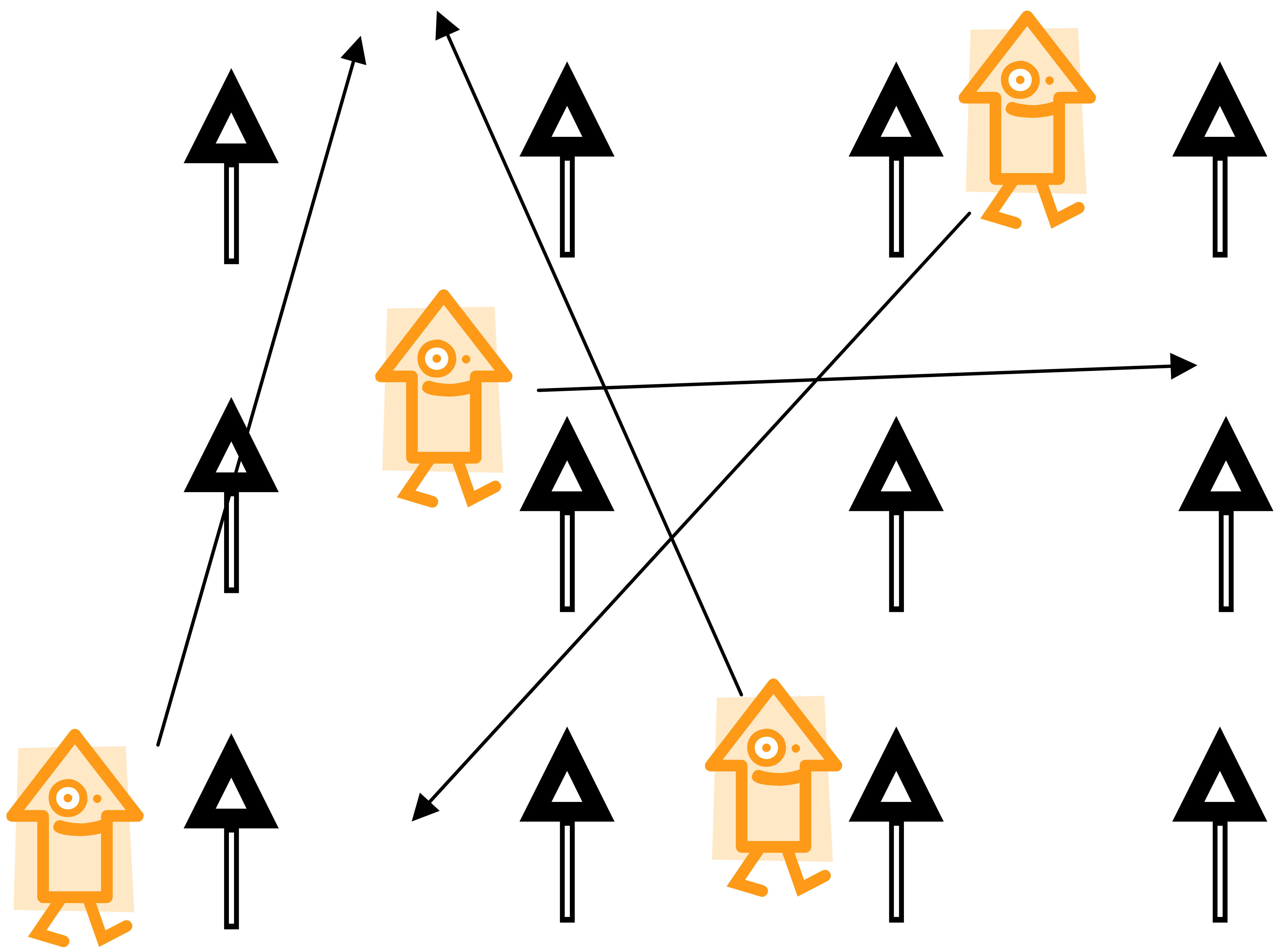
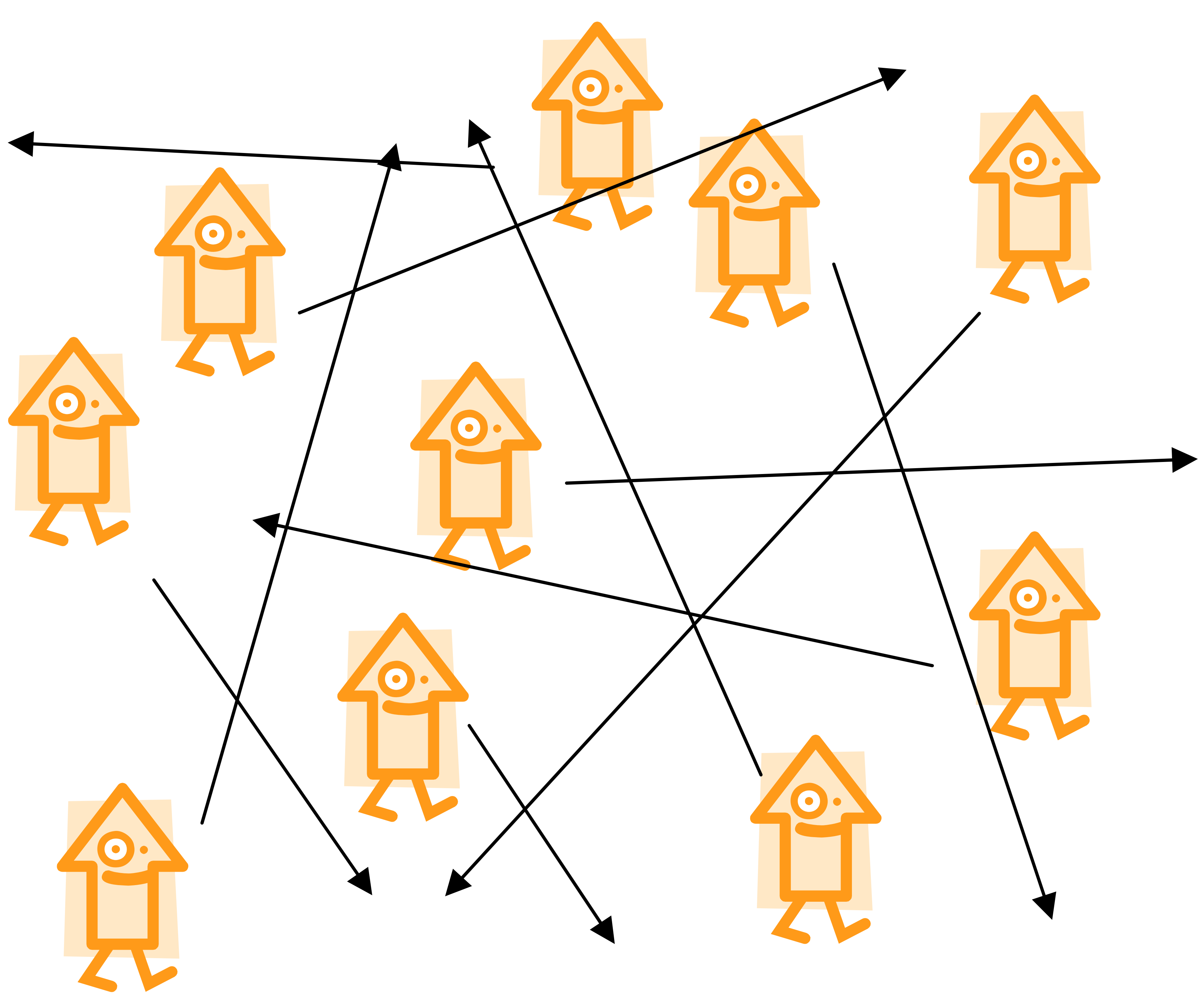
Theory: Berger (1979)
Tatara & Kohno (2004)
Li & Zhang (2004)
Barnes & Maekawa (2005)
Xiao *et al*. (2006)
Tserkovnyak *et al*. (2006)

Itinerant ferromagnetism



s-d model:

$$H_{s-d} = J_x \vec{s} \cdot \left\langle \vec{S} \right\rangle$$

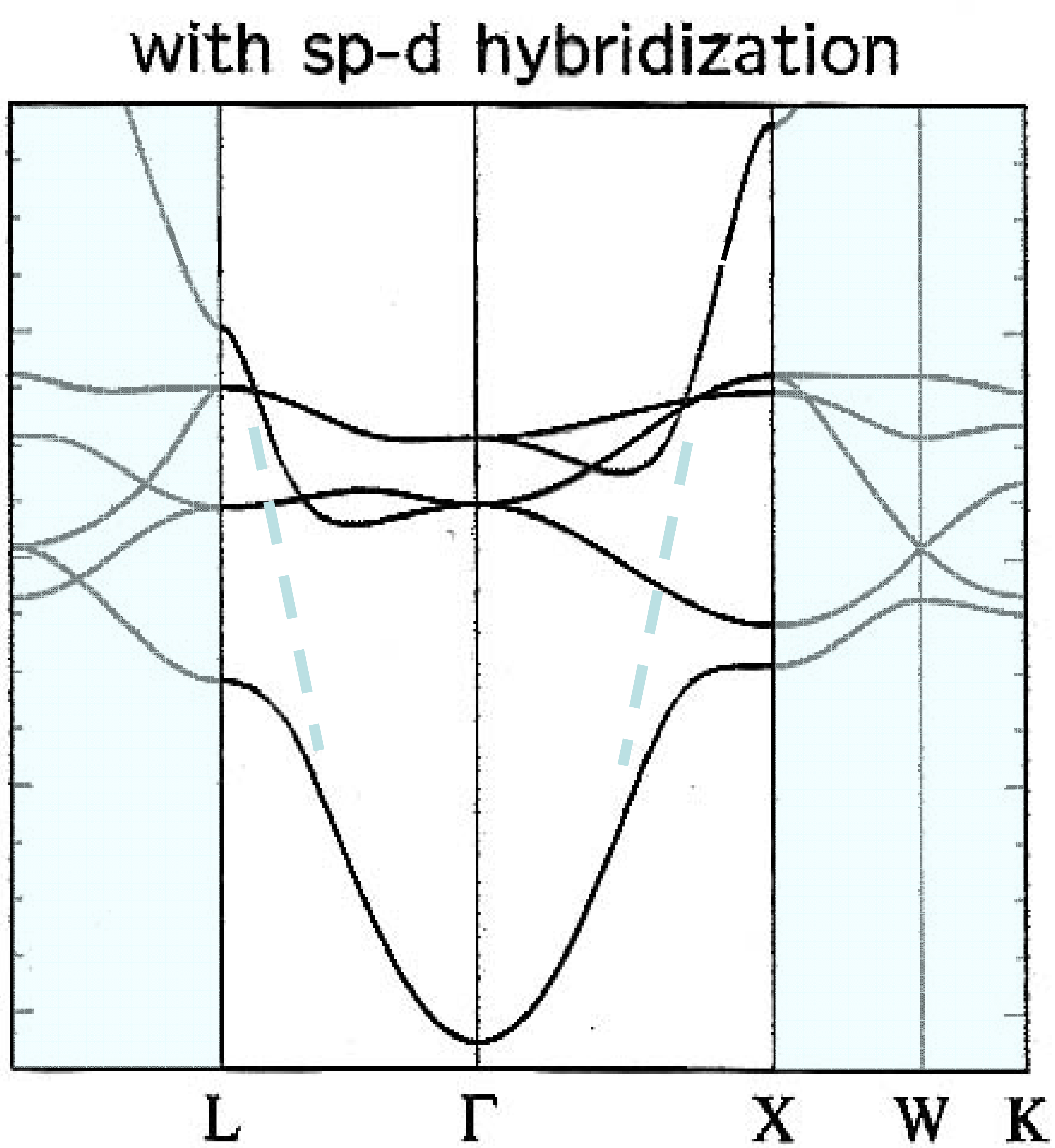


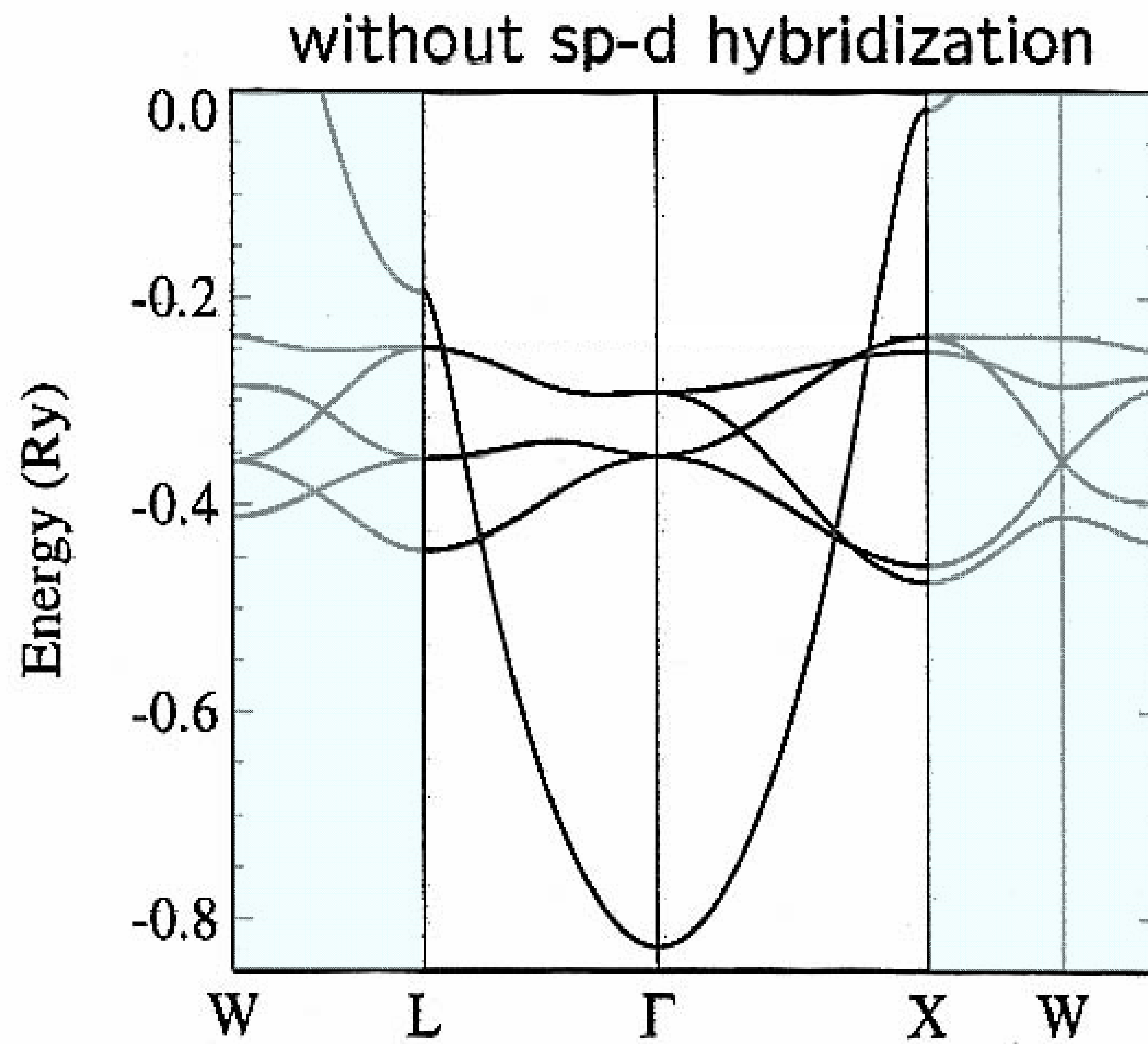
Stoner model:

$$H_{Stoner} = J_x \vec{s} \cdot \left\langle \vec{s} \right\rangle$$

$$H_{SDFT} = \vec{s} \cdot \vec{H}_{xc}\left[\rho, \left\langle \vec{s} \right\rangle\right](\vec{r})$$

Transition metals as Stoner magnets





$$\Delta E_{sd} \sim 10\,eV \triangleq \Delta t_{sd} \sim \frac{\hbar}{\Delta E_{sd}} \sim fs$$

s and d- electrons are strongly hybridized and cannot be distinguished on electron transport time scales.

Magnetization texture dynamics of transition metals

Tserkovnayk *et al*. (2006)

Philosophy:

(1) Stoner model (local spin-density functional theory) is more appropriate than s-d model

(2) In transition metals impurity and spin-flip scattering are very important

(3) The exchange interaction is very large.

Approach:

(1) Quasiclassical kinetic equation to lowest order in electric, magnetic, and exchange field gradients (similar to dirty superconductors).

(2) Born approximation for spin (non)-conserving impurity scattering, for the time being treated as phenomenological relaxation times, but amenable to microscopic calculations.

Magnetization texture dynamics

Consequences:

(1) In spite of the different model results are similar to that of previous ones, **but**

(2) There is no transverse spin accumulation.

(3) There is an extra time-dependent torque ("spin pumping").

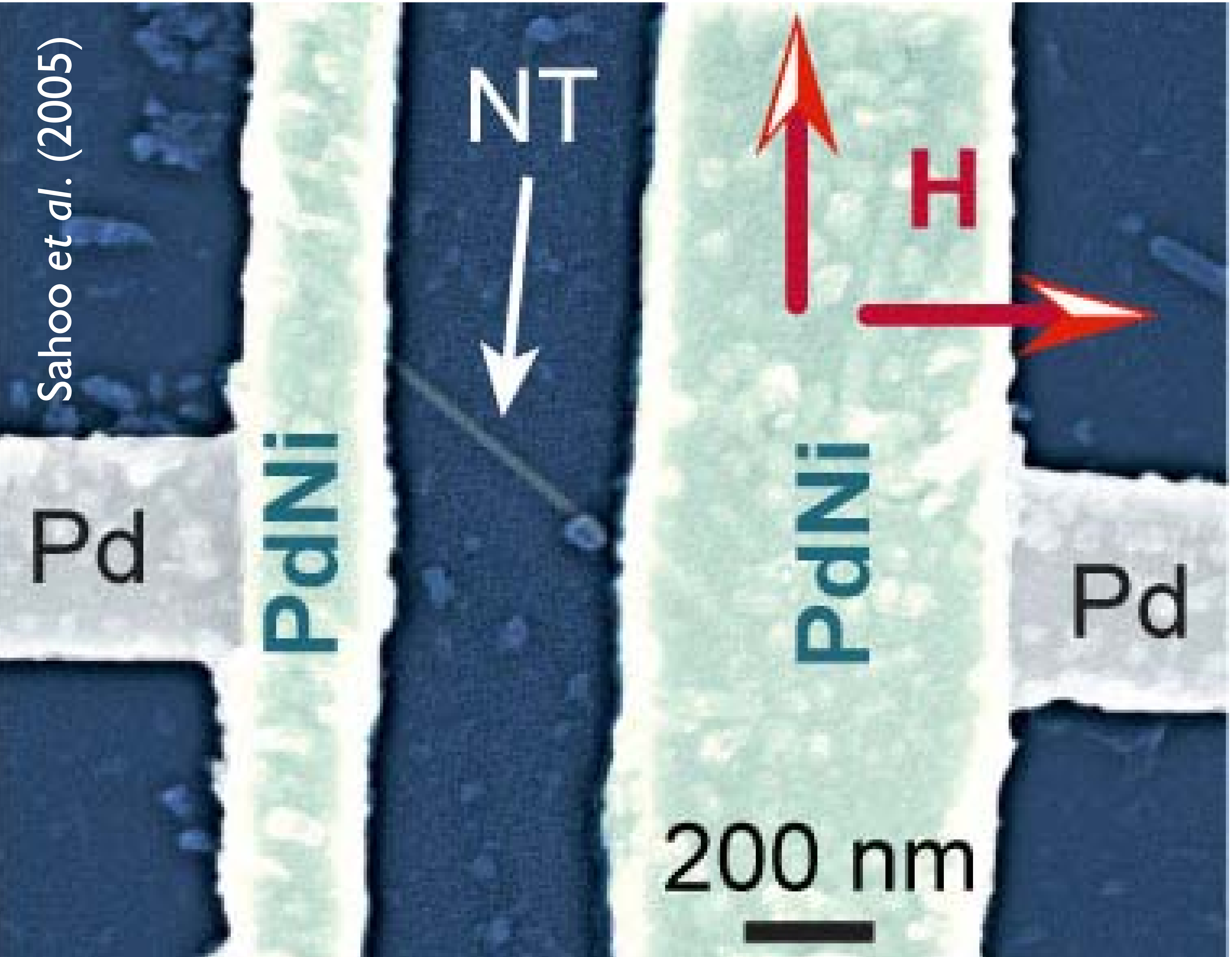
(4) $\alpha = \beta = \hbar / \left(\tau_{s\phi} \Delta_{xc} \right)$

$$\partial_t \mathbf{m} = \partial_t \mathbf{m}|_{\mathrm{LLG}} + \partial_t \mathbf{m}|_j$$

$$\partial_t \mathbf{m}|_{\mathrm{LLG}} = -\gamma \mathbf{m} \times \mathbf{H} + \beta \mathbf{m} \times \partial_t \mathbf{m}$$

$$\partial_t \mathbf{m}|_j = \mathcal{P} \left[1 - \mathbf{m} \times \left(\beta + \frac{\hbar \partial_t}{\Delta_{\mathrm{xc}}} \right) \right] (\mathbf{j} \cdot \partial_{\mathbf{r}}) \, \mathbf{m}$$

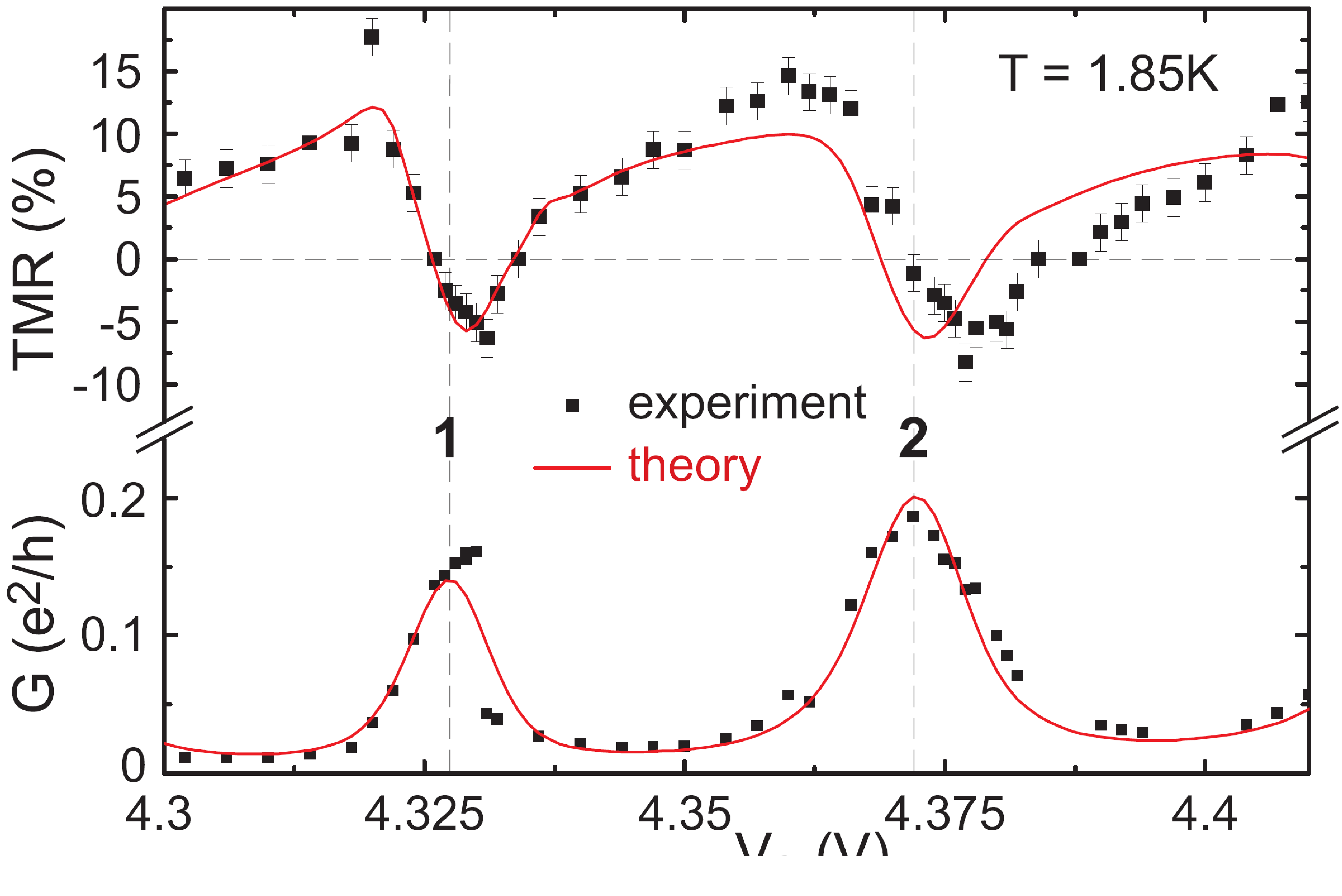
Single nanotube spin-valve



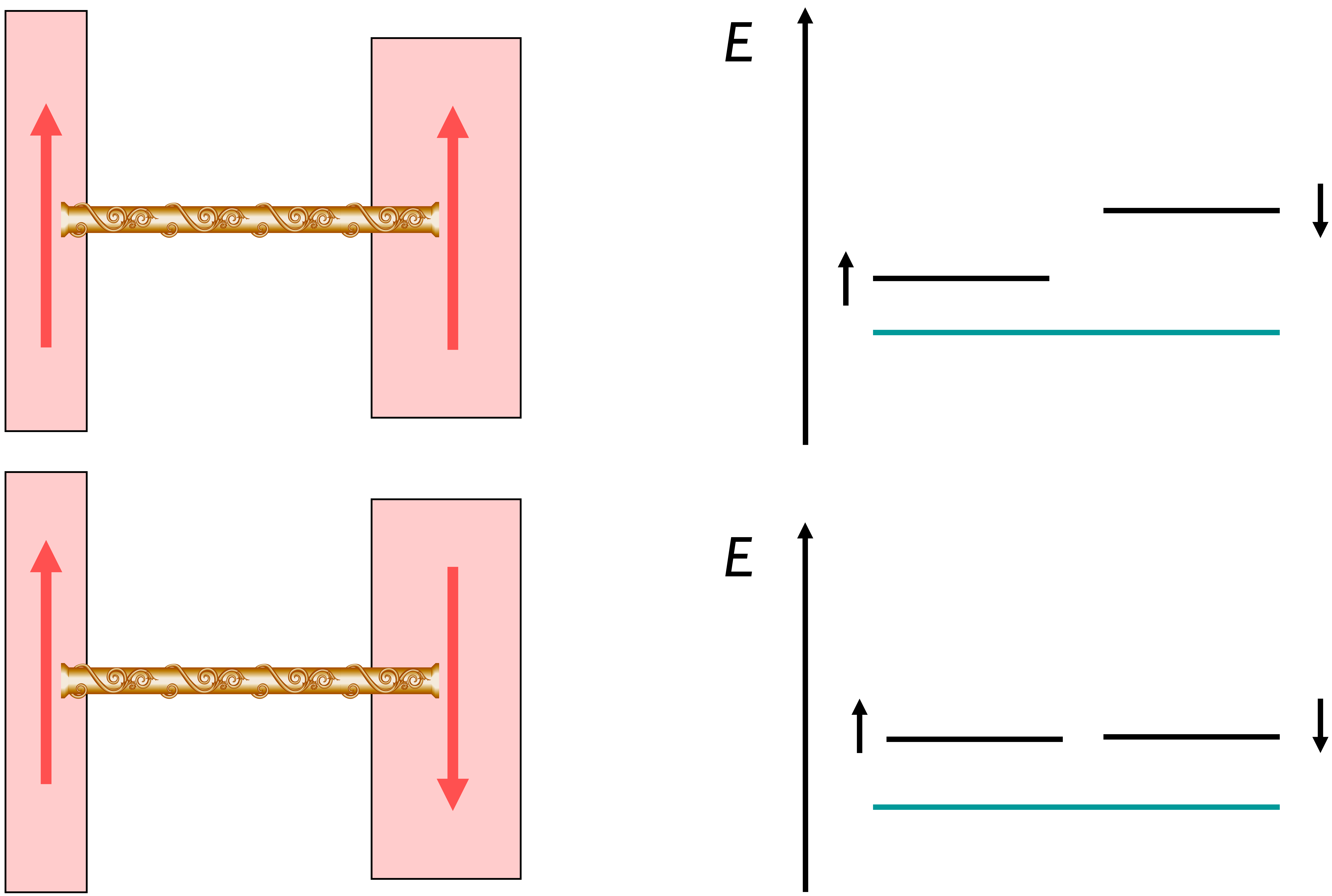
Sahoo *et al*. (2005)

Tombros *et al*. (2005)
Man *et al*. (2006)

Non-local exchange in single quantum states

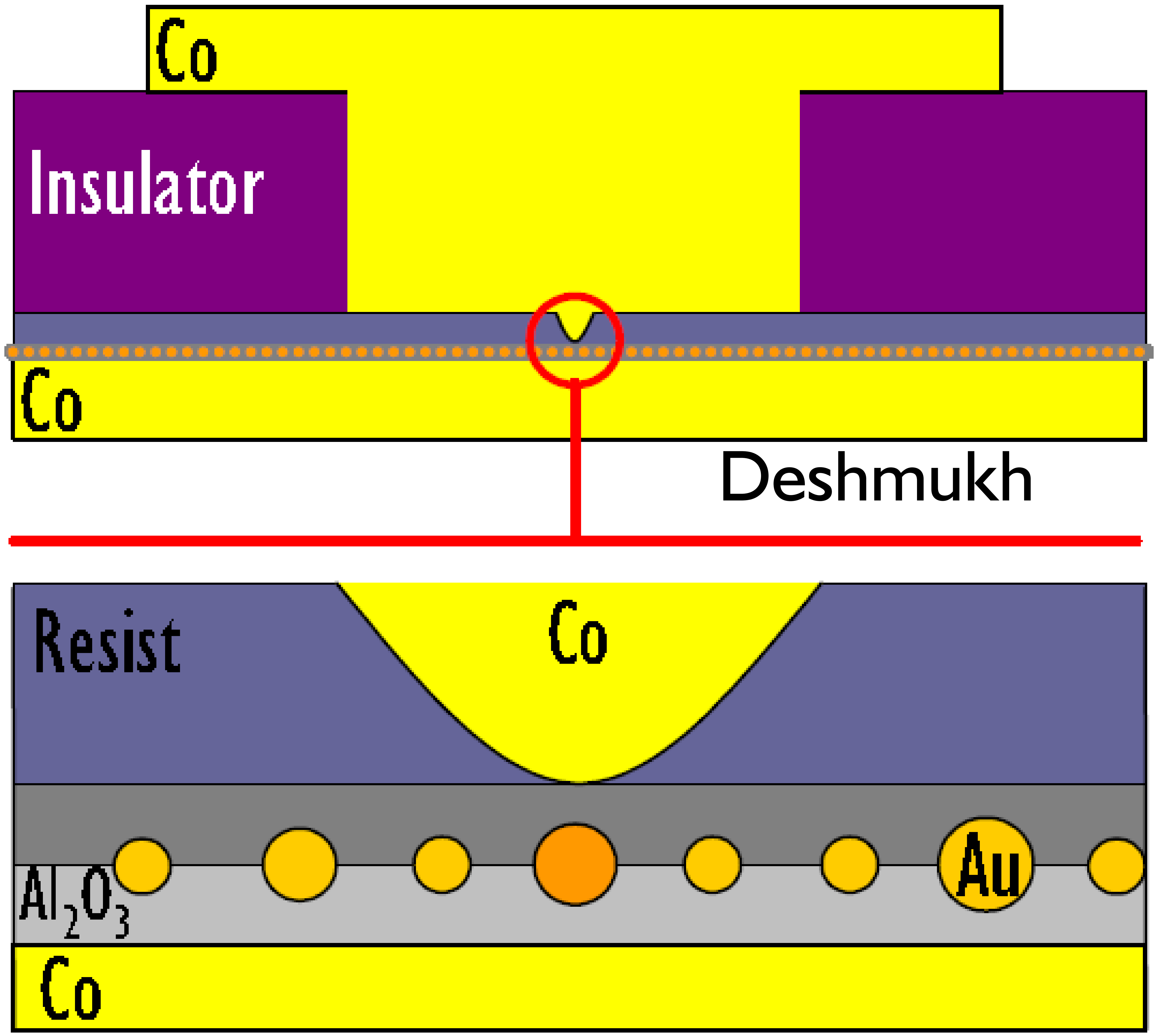


Single quantum state MR



Cottet *et al*. (2006)

F-SET



F|F|F

Ono *et al*. (1997)

Yakushiji *et al*. (2003)

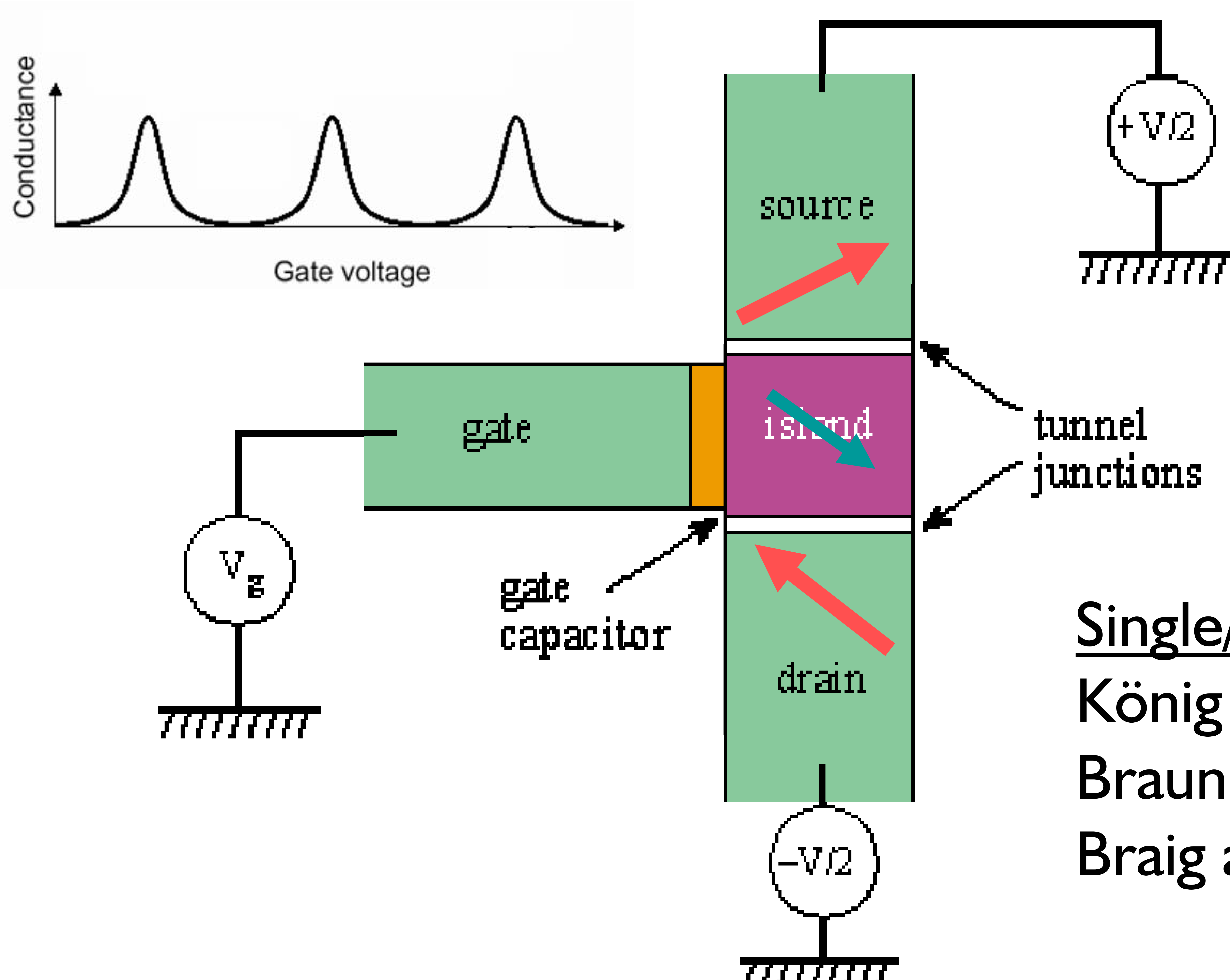
N|F|N

Deshmukh *et al*. (2001)

Bernand-Mantel *et al*. (2006)

$\tau_{sf}^{Au} \sim 1$ ns

Coulomb blockade and F-SET



<u>Single/few quantum levels</u>

König & Martinek (2003)

Braun *et al*. (2004)

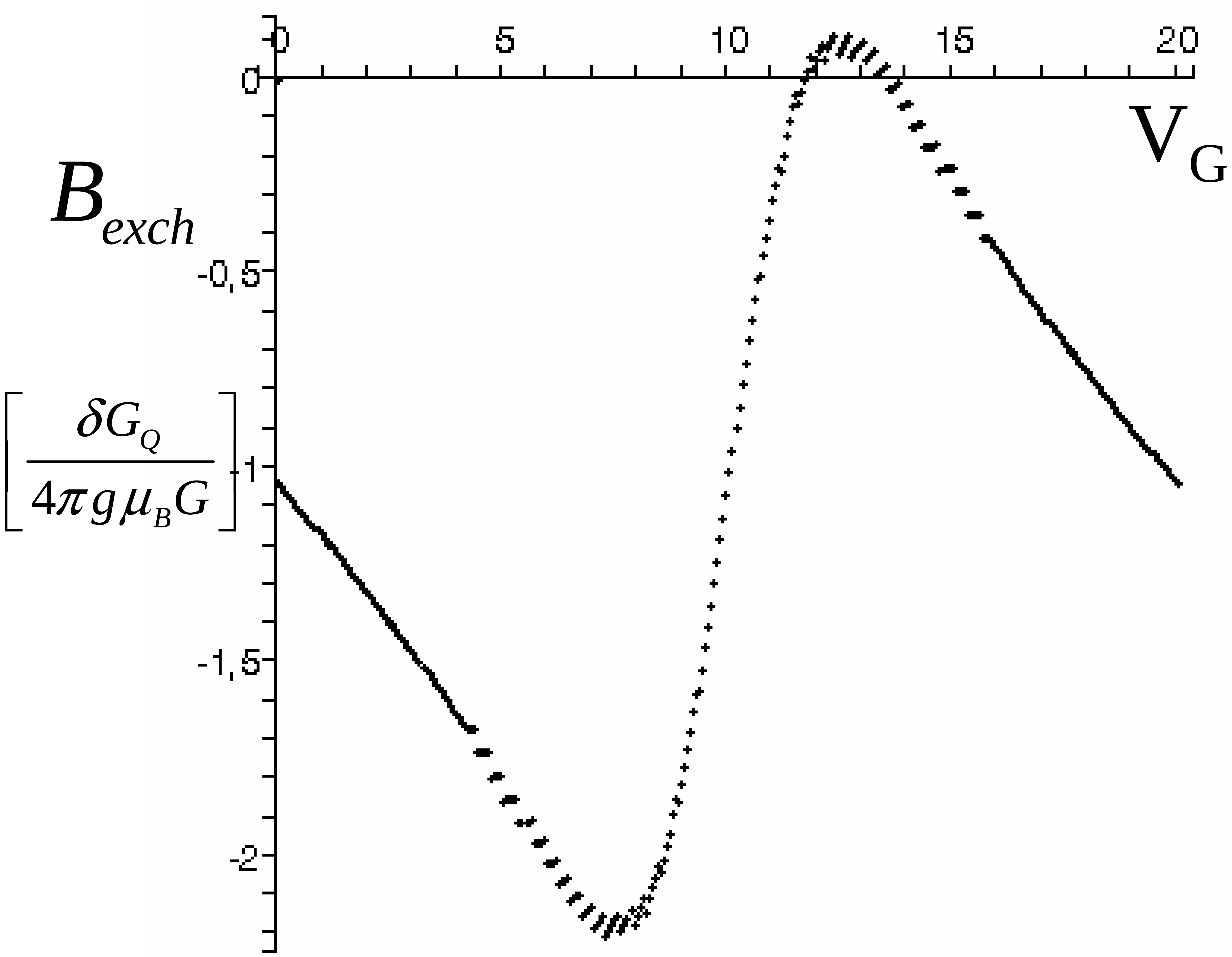
Braig and Brouwer (2005)

<u>Classical dot</u>

Wetzels *et al*. (2005)

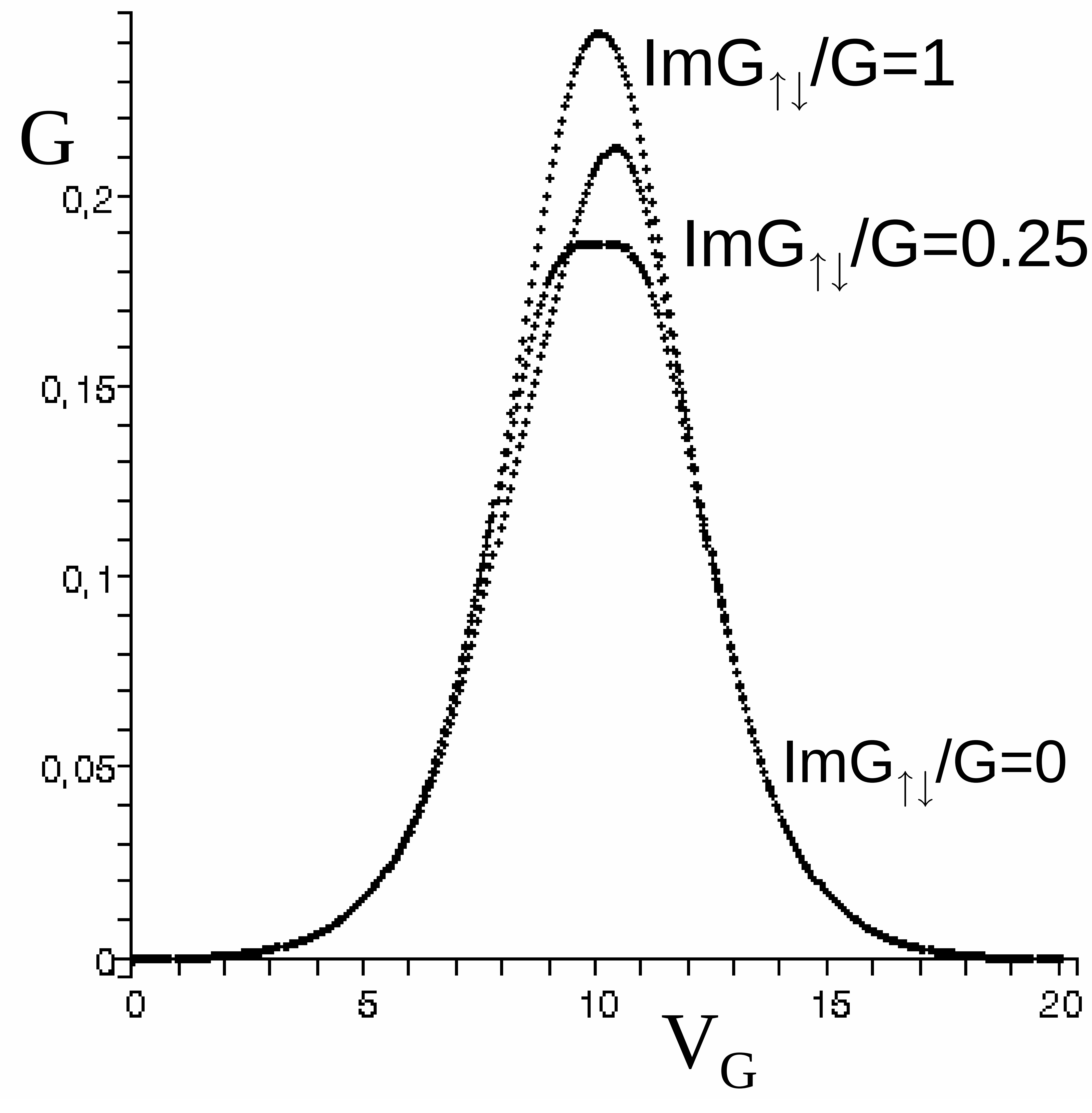
Non-local exchange coupling

Total exchange field vs. gate voltage



$\mathrm{Im}G_{\uparrow\downarrow}/G=-0.26$

Conductance vs. gate voltage (a Coulomb oscillation)



Open questions

Nature of the exchange effect?

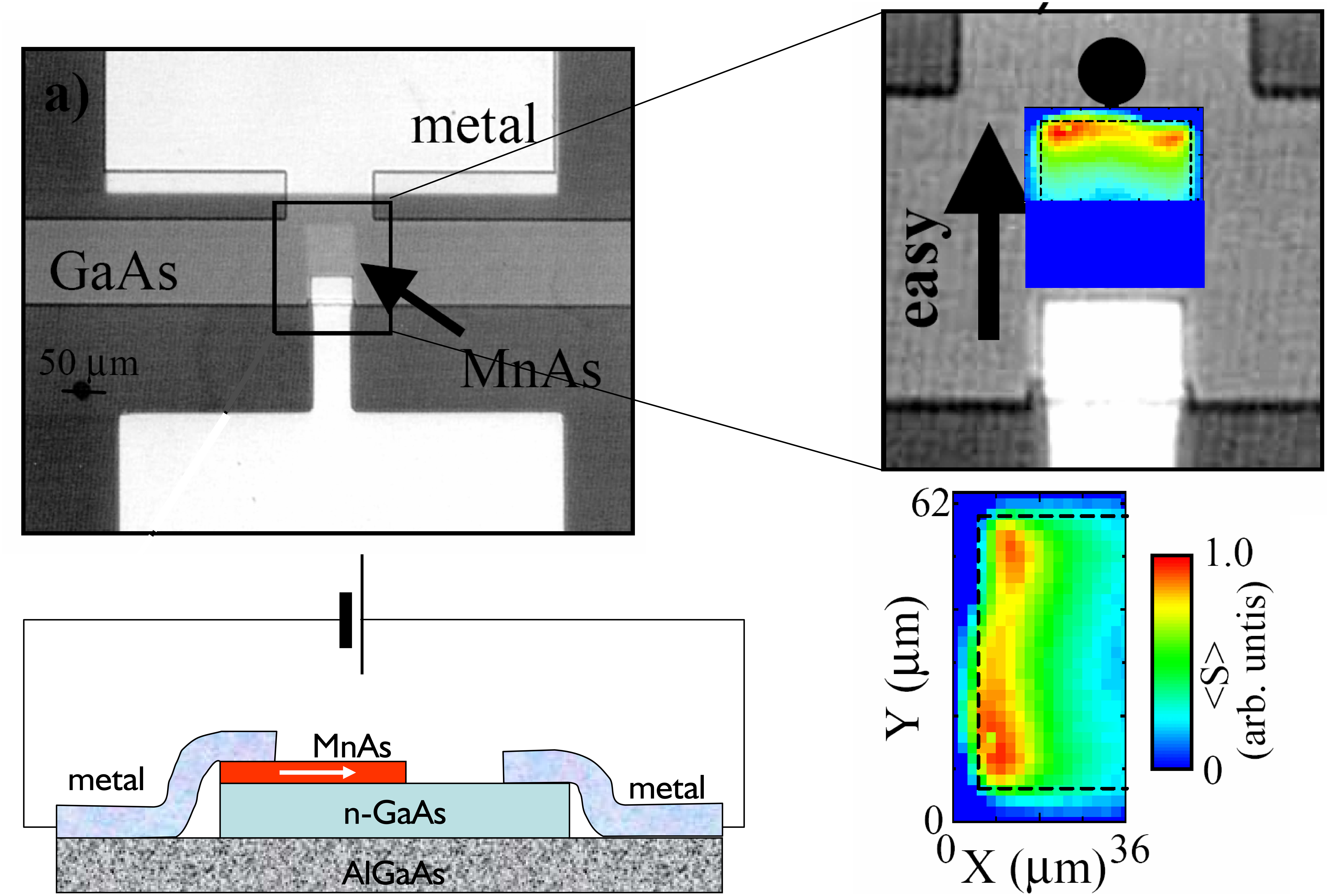
- interface
- gate voltage modulated virtual exchange

Correlation effects?

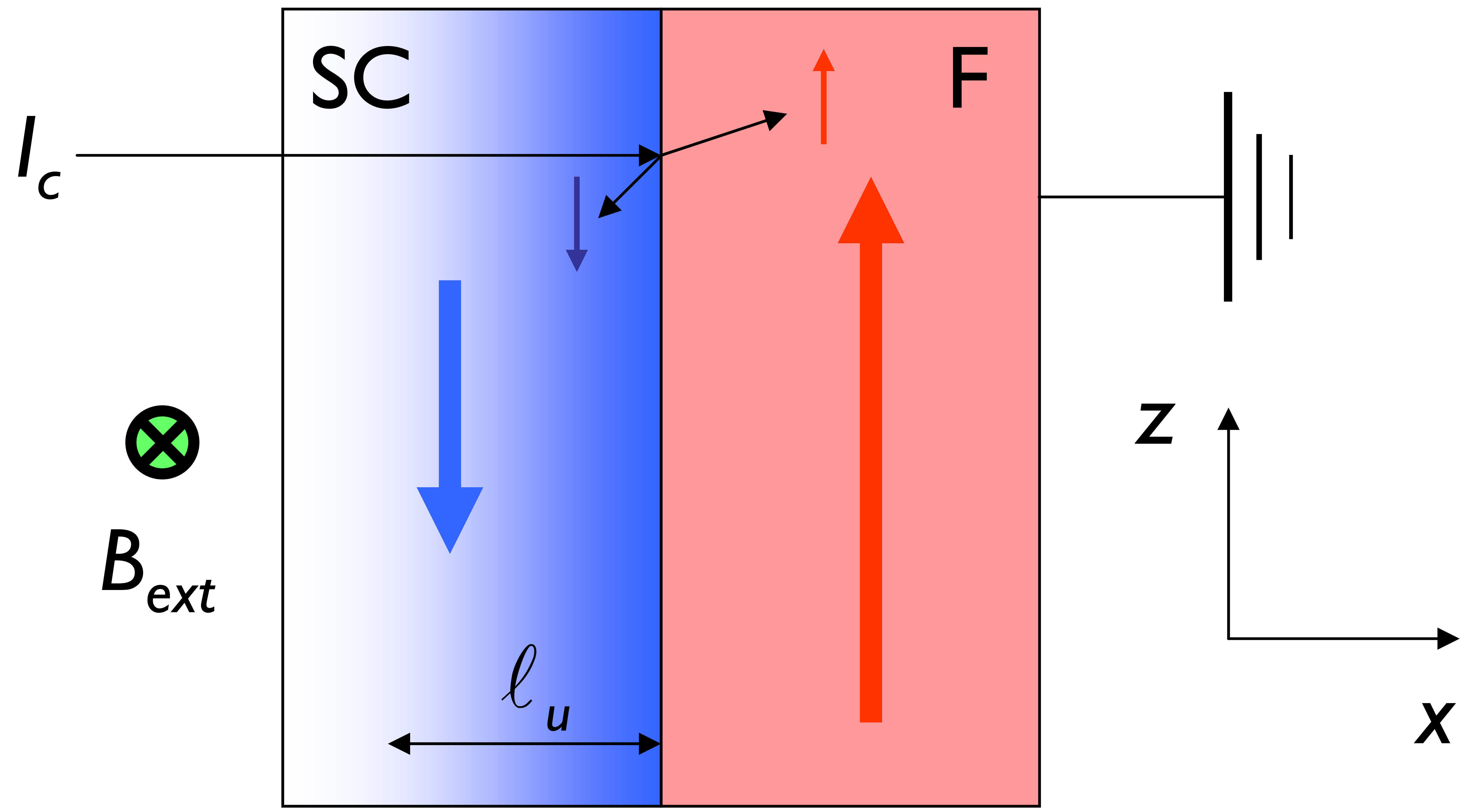
Balents & Egger (2000)
Bena &Balents (2004)

- Luttinger liquid vs. Coulomb blockade

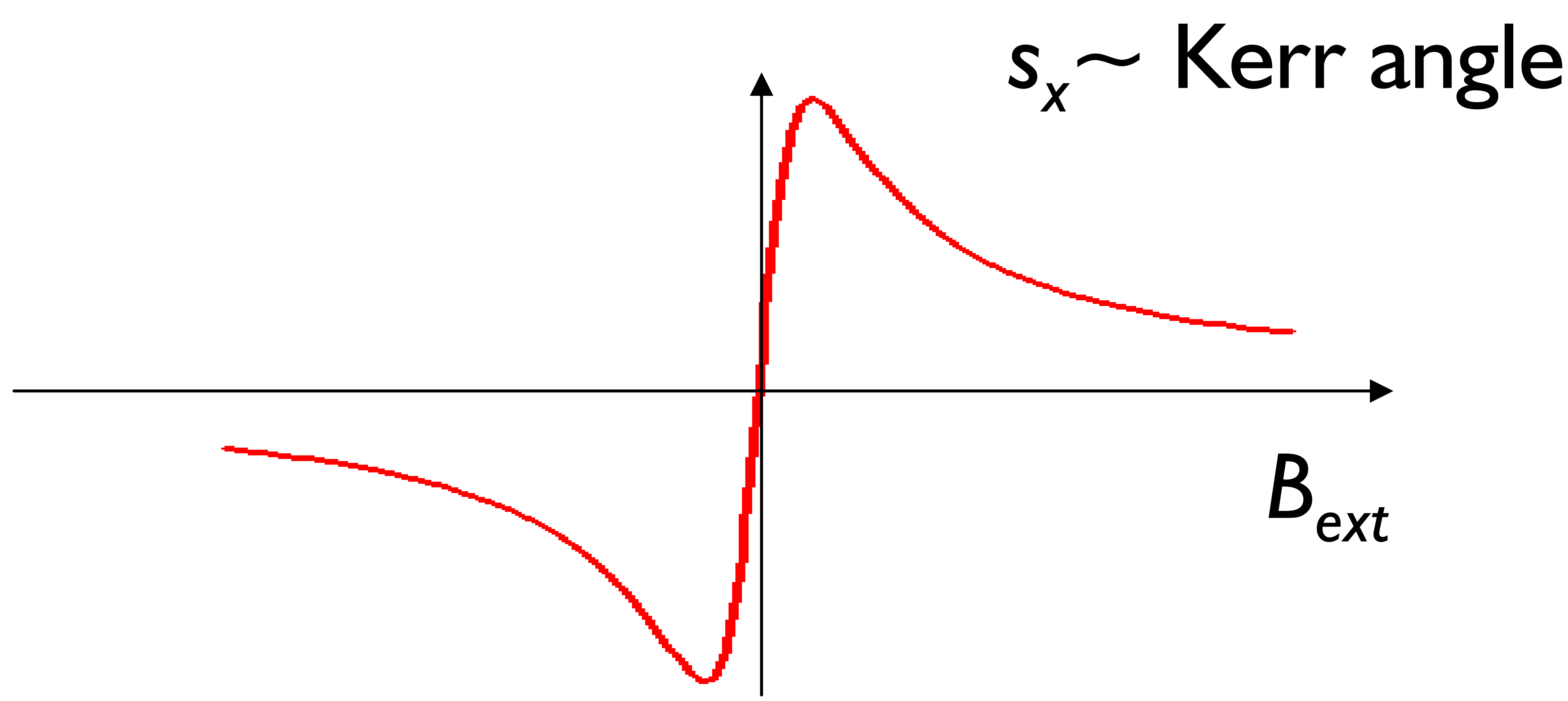
J. Stephens *et al*. (2004)



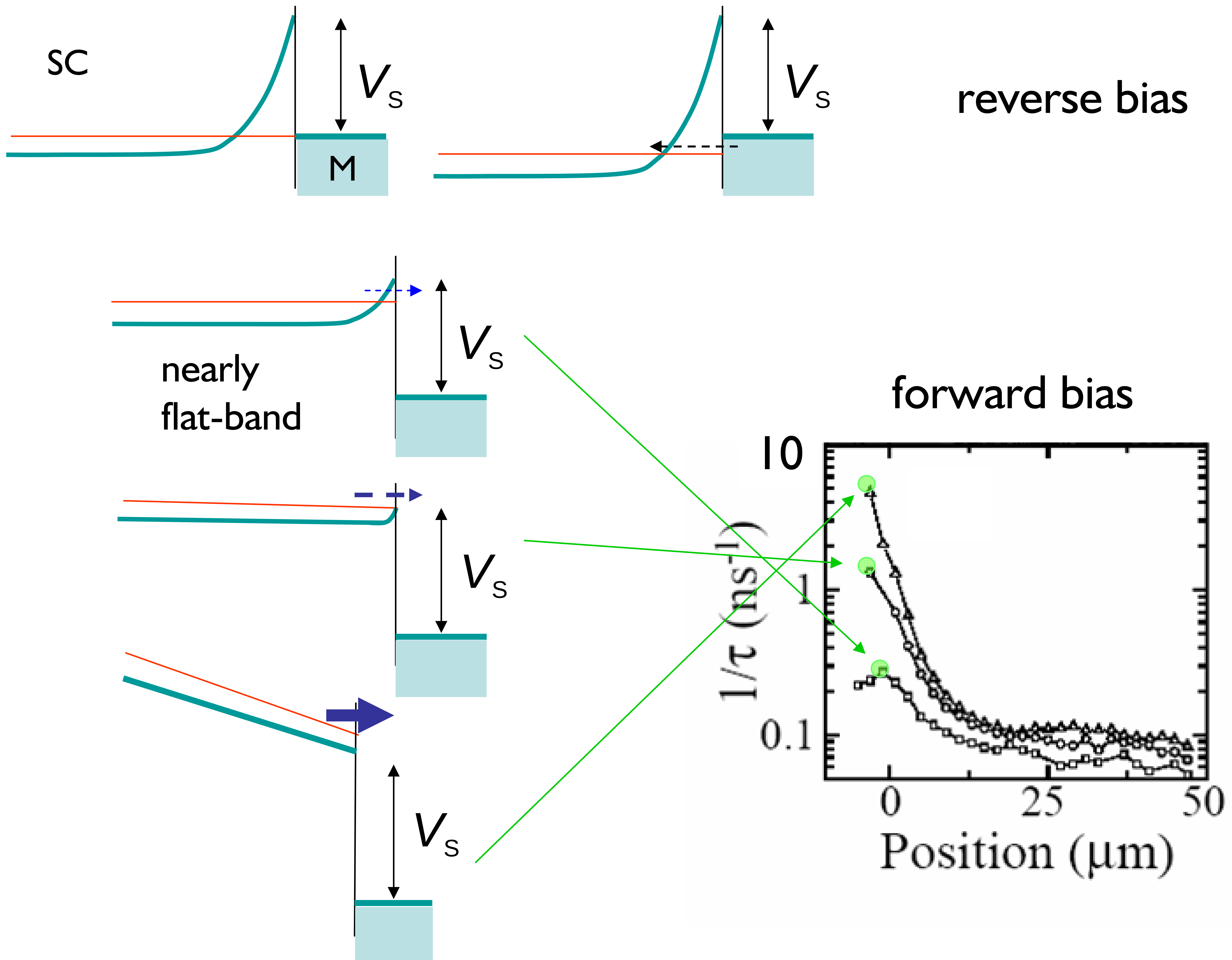
Hanle effect



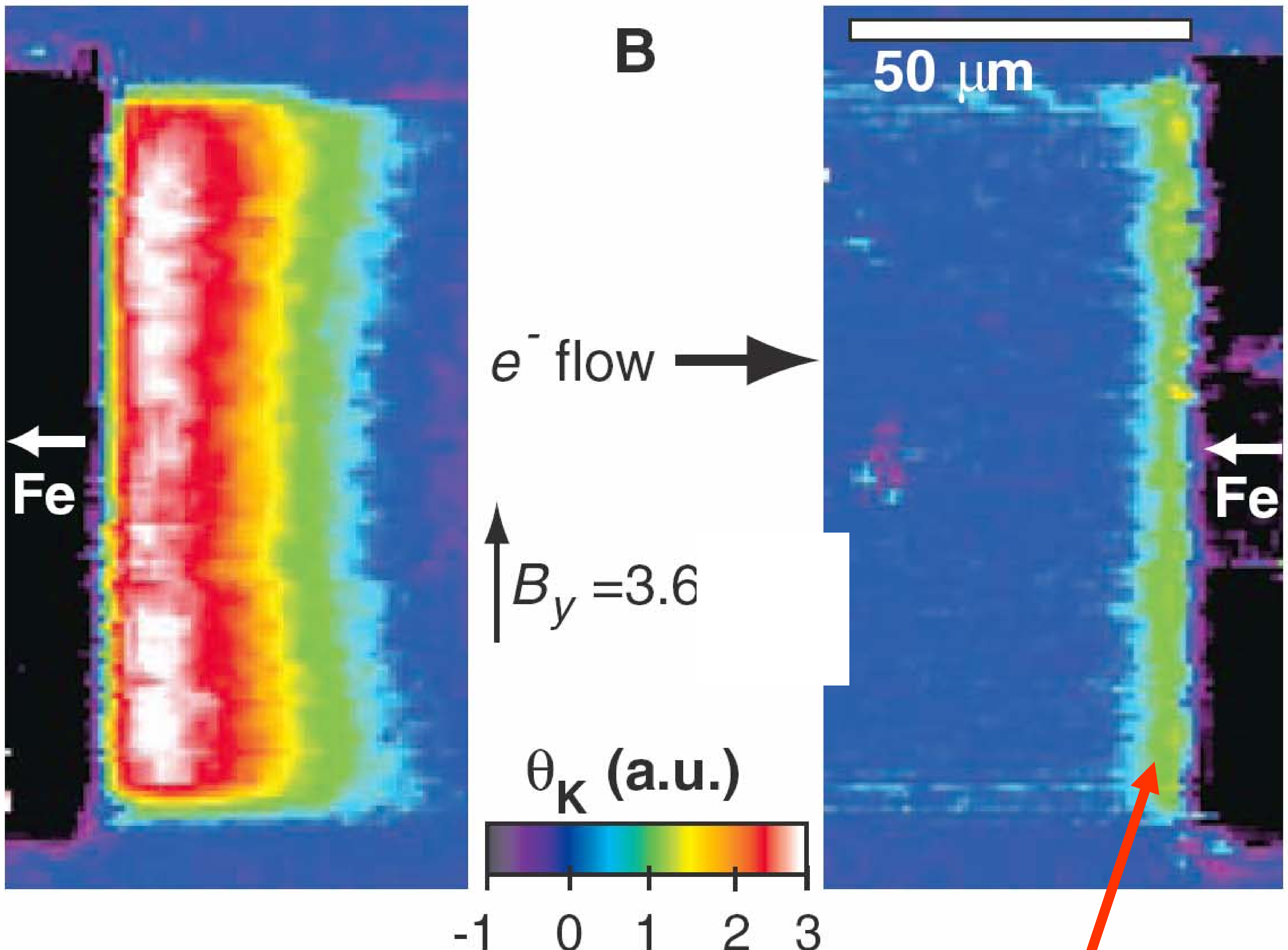
$$s_x = \frac{A\omega_L}{\omega_L^2 + \frac{1}{\tau^2}}$$



What F giveth F taketh away

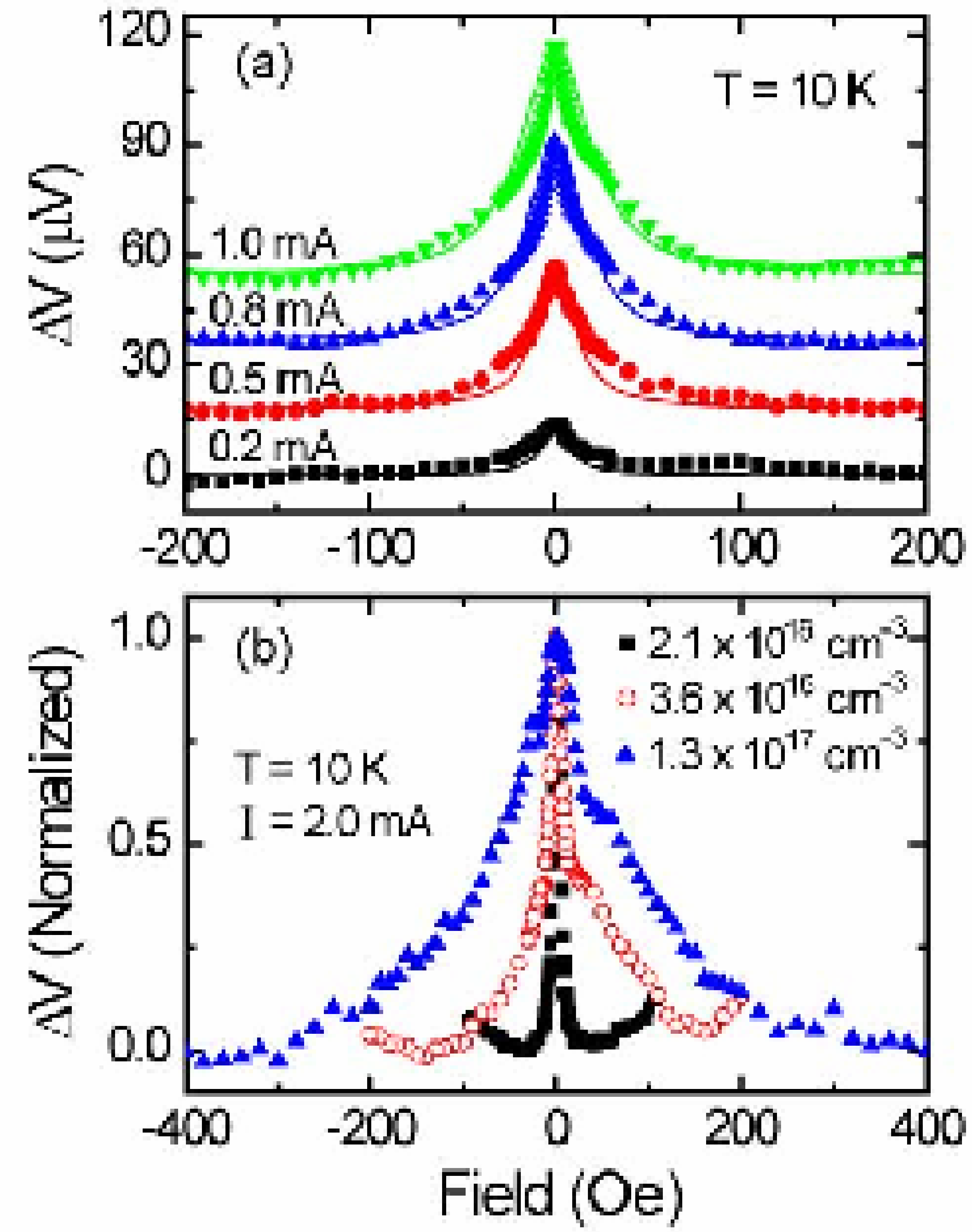


Injection and detection



Crooker *et al*. (2005)

?????

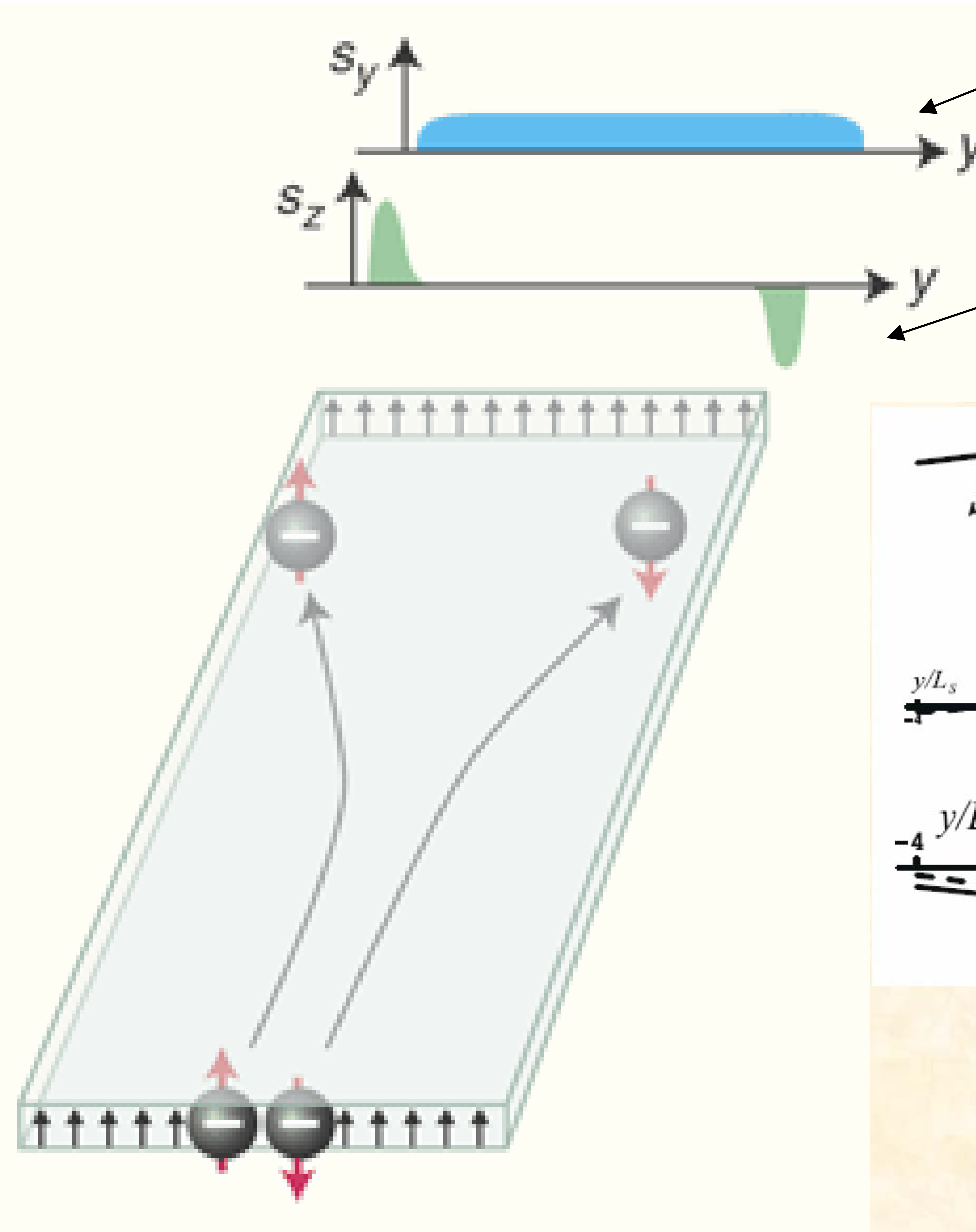


Lou *et al*. (2006)

Workshop on SHE

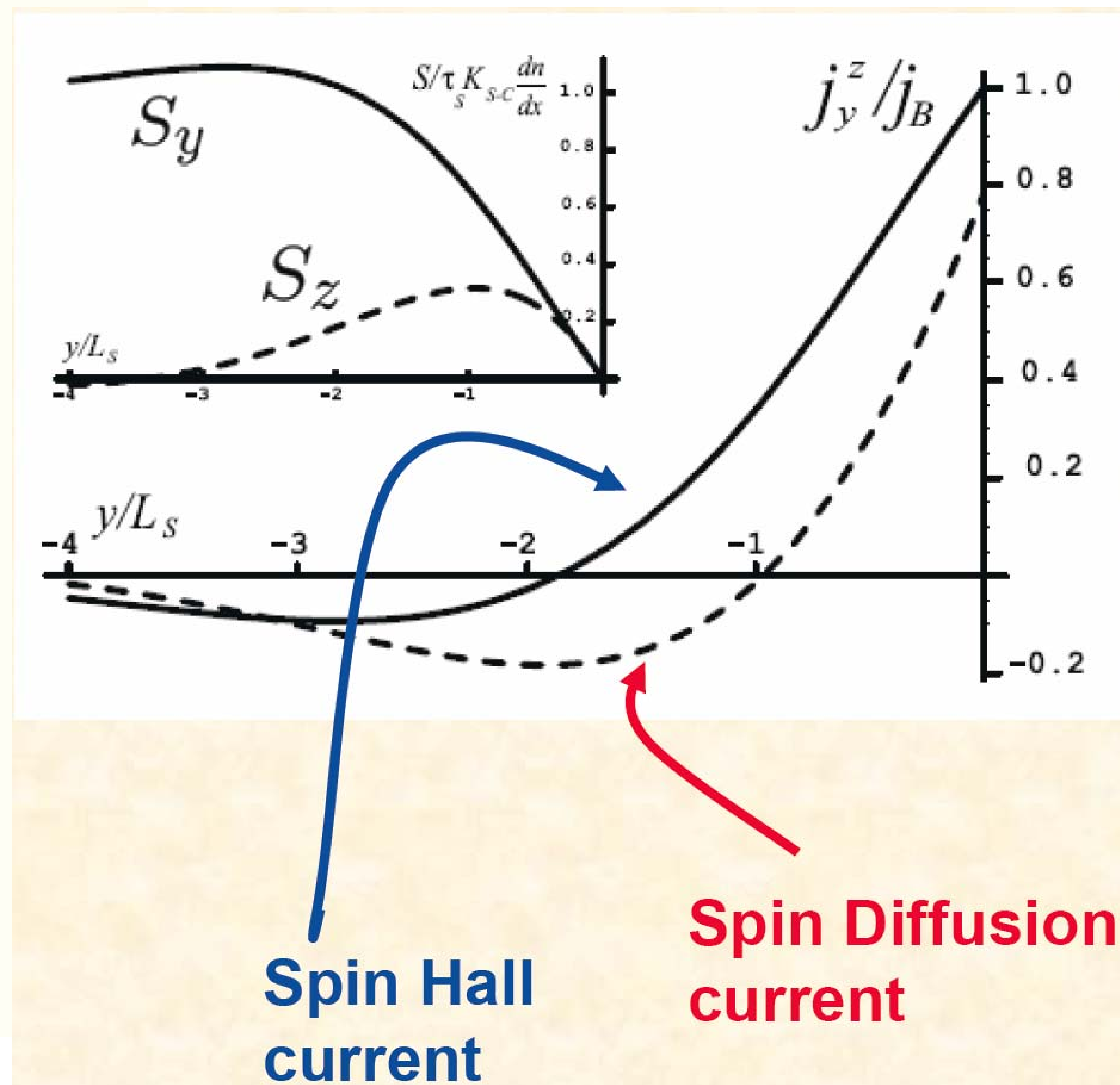
Asia Pacific Center for Theoretical Physics

Current-induced spin accumulation



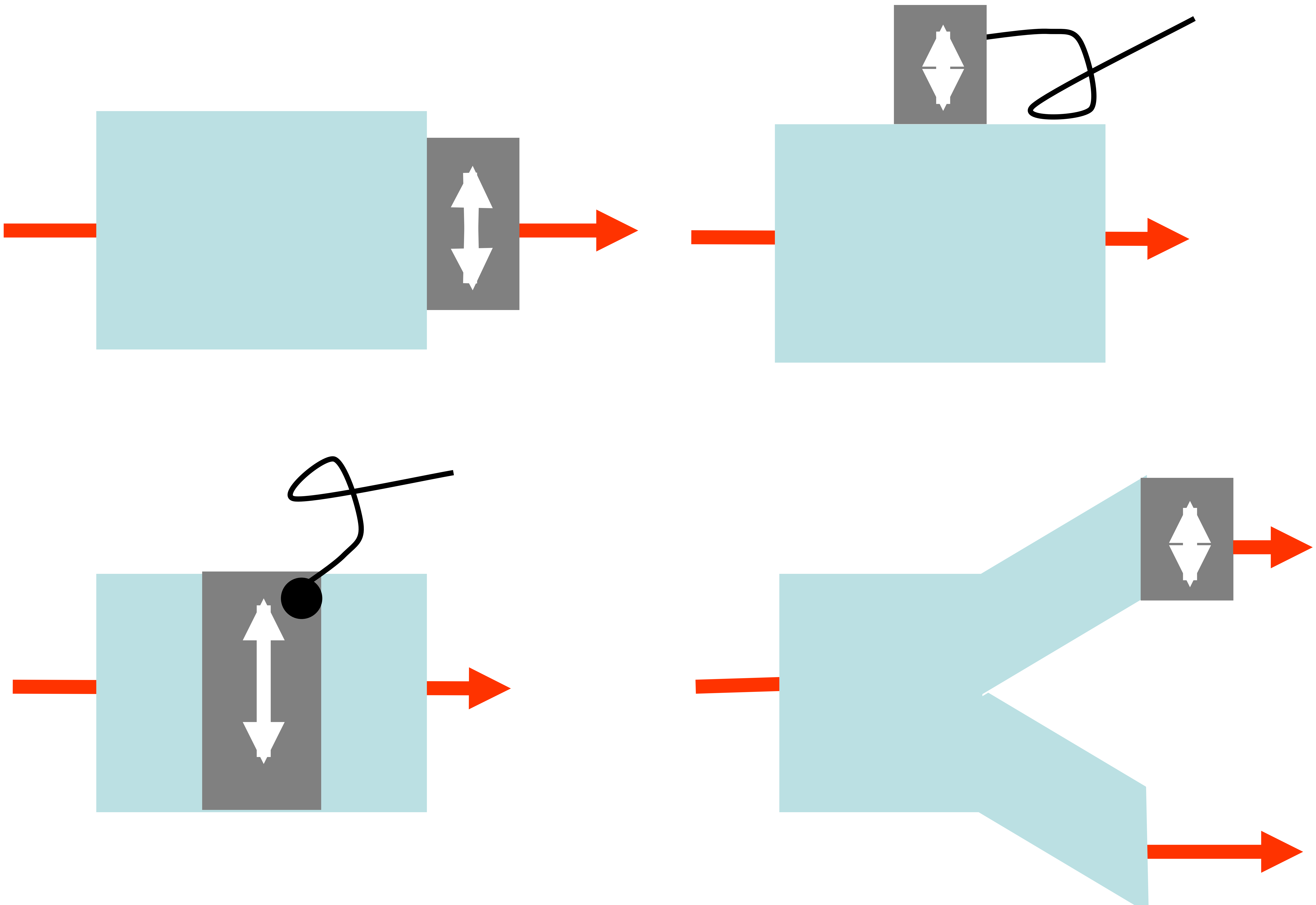
in-plane
spin accumulation

spin Hall spin accumulation
normal to plane



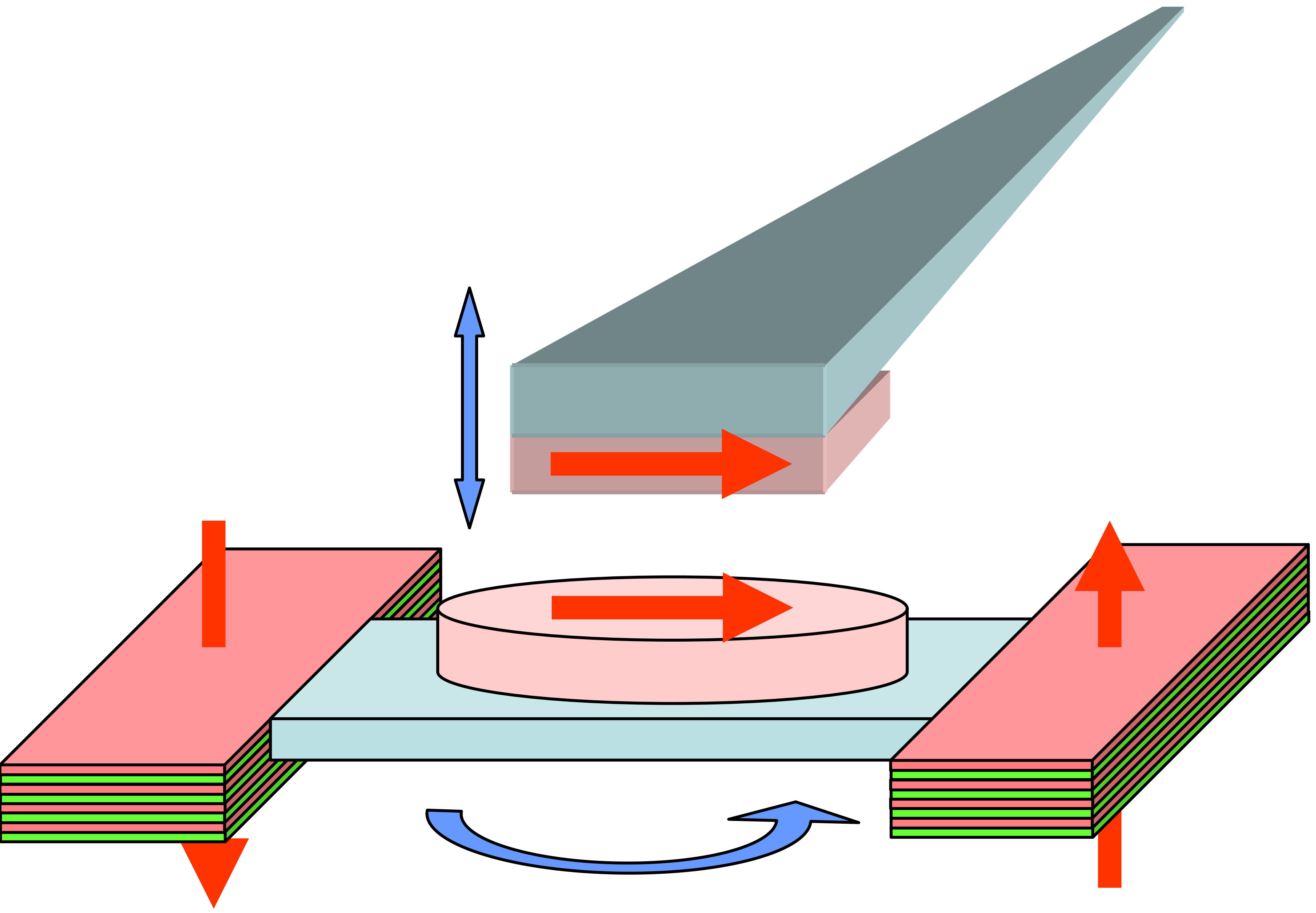
Adagideli *et al.* (2005)

Detecting current-induced spin accumulation

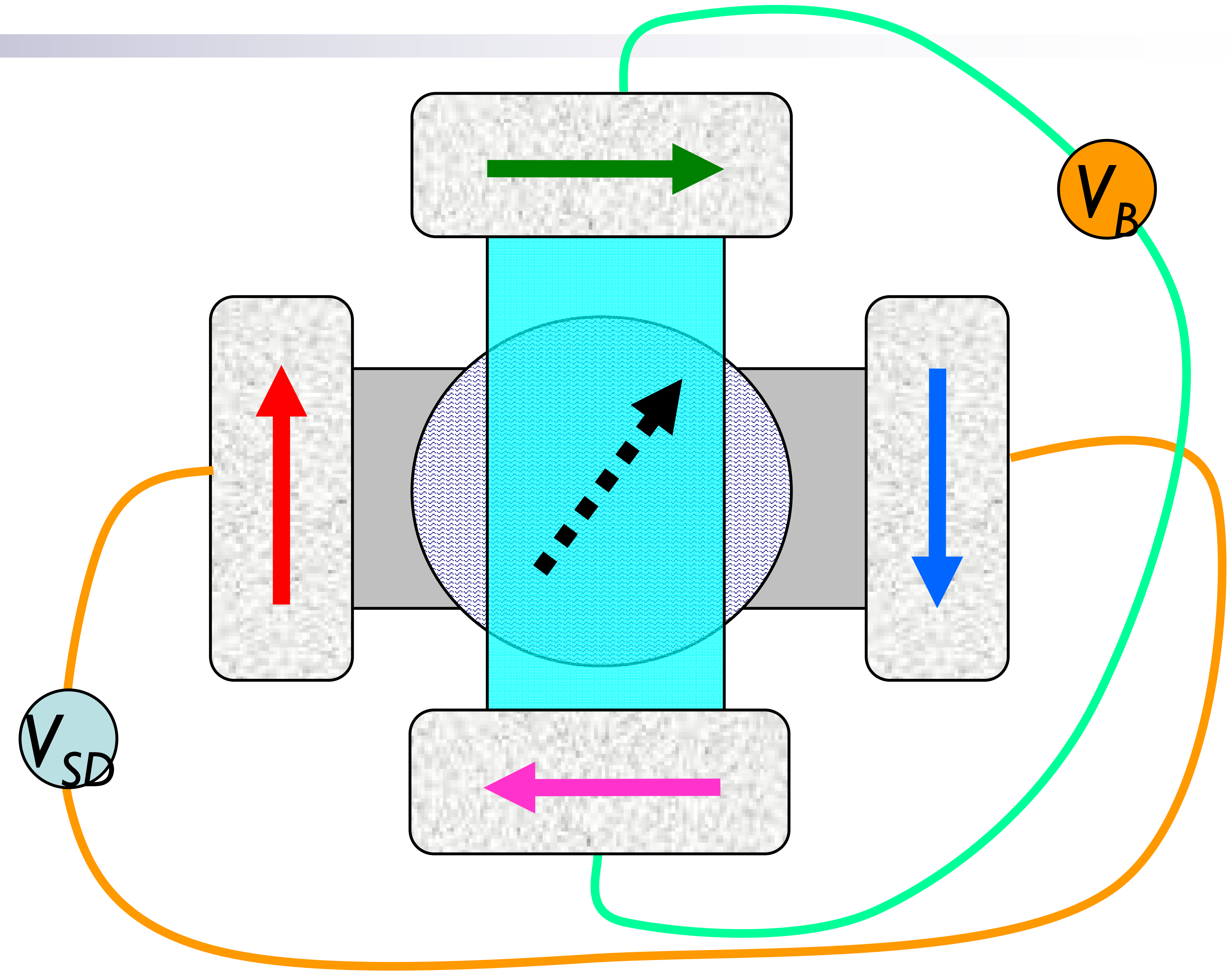


Adagideli *et al*. (2006)

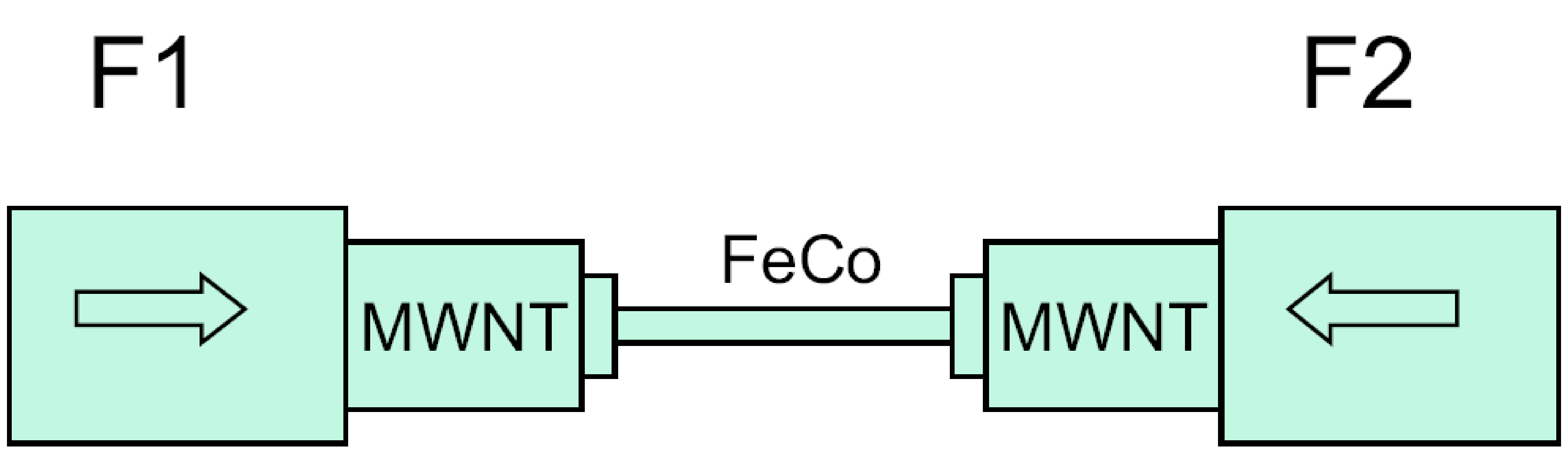
New devices



Wang *et al*. (2006):
cantilever actuation



Bauer *et al*. (2003):
Spin torque transistors



Spin torque motor

Mohanty *et al*. (2004)
Mal'shukov *et al*. (2005)
Kovalev *et al*. (2004,2006)

Issues & questions

- Transport and micromagnetism
- Current-induced magnetization texture
- Non-local exchange effects on transport
- Electrical detection of spins in semiconductors
- Spin and magnetization noise

- Do we need first-principles calculations?
- Can we always neglect correlation?
- What's the difference between semiconductor and metal spintronics?
- What is a transition metal ferromagnet?
- Novel devices or materials?