Materials dependence of the spin-transfer torques on DW

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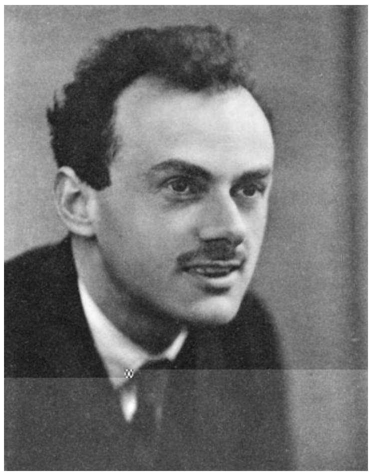
Outline

- Introduction
- Two approachs to STT
- STT in spin valves
- Gilbert Damping
- Summary

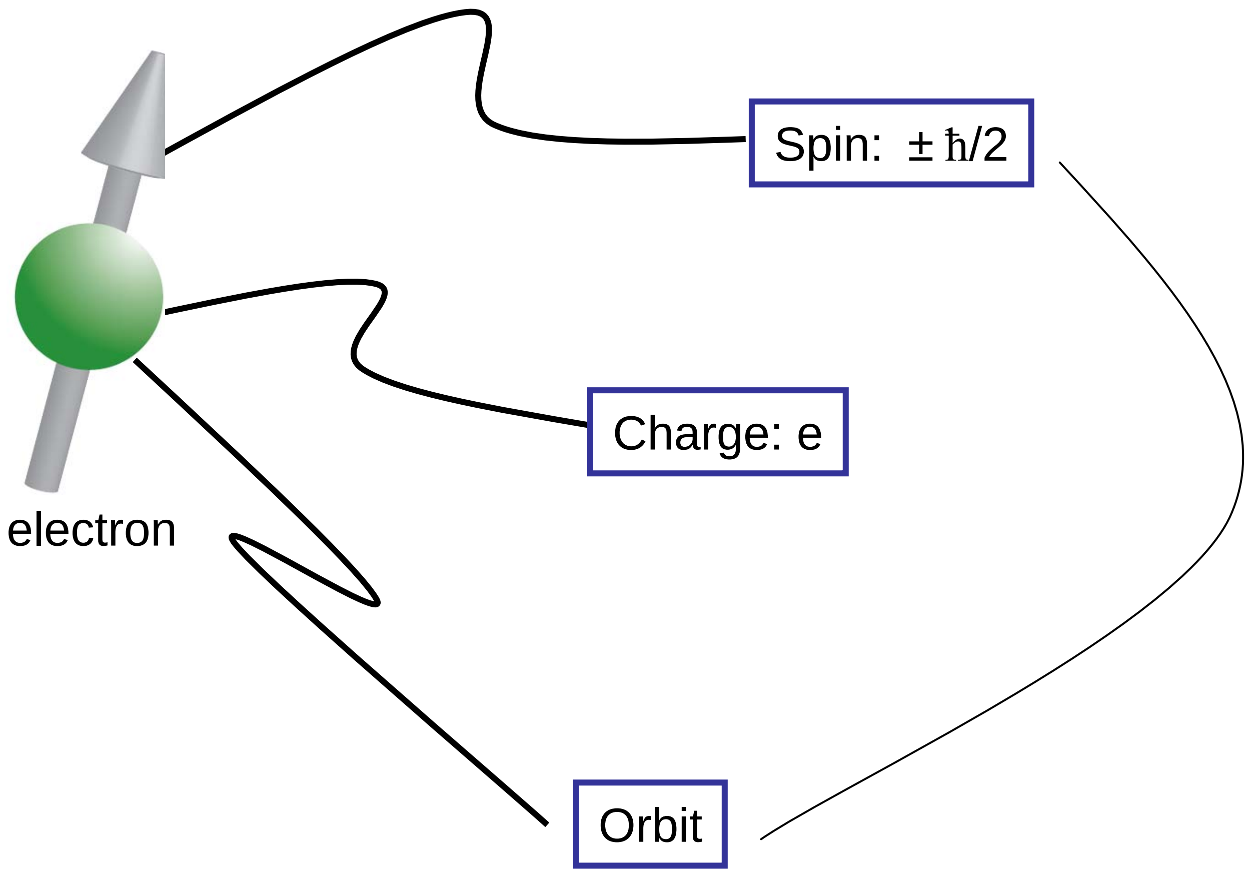
Dirac equation

Electron should have "spin."

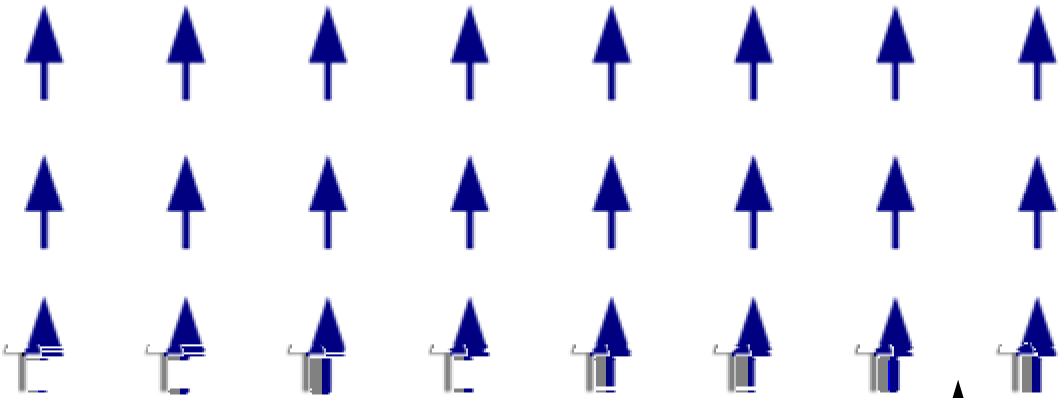
(1928)

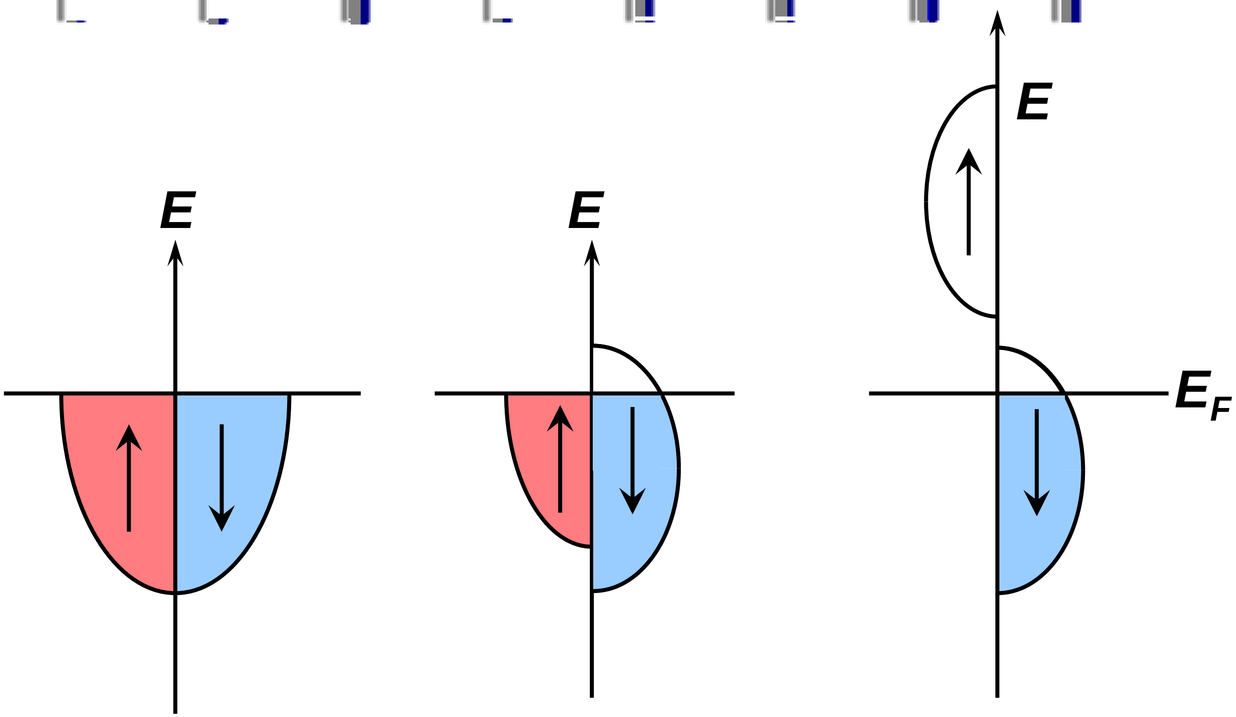


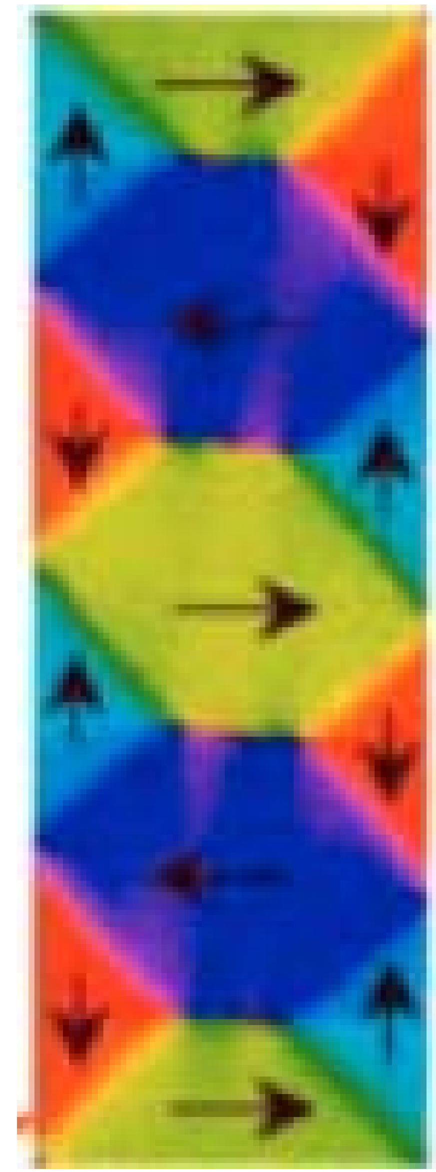
P.A.M. Dirac



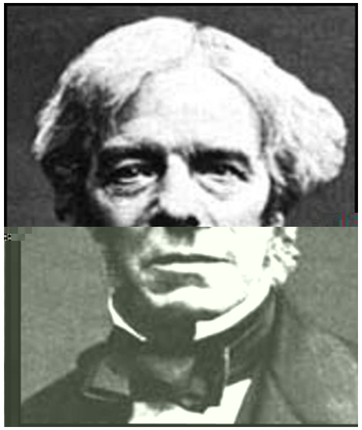
Ferromagnetism







Faraday effect---Maxwell Equation (1865)

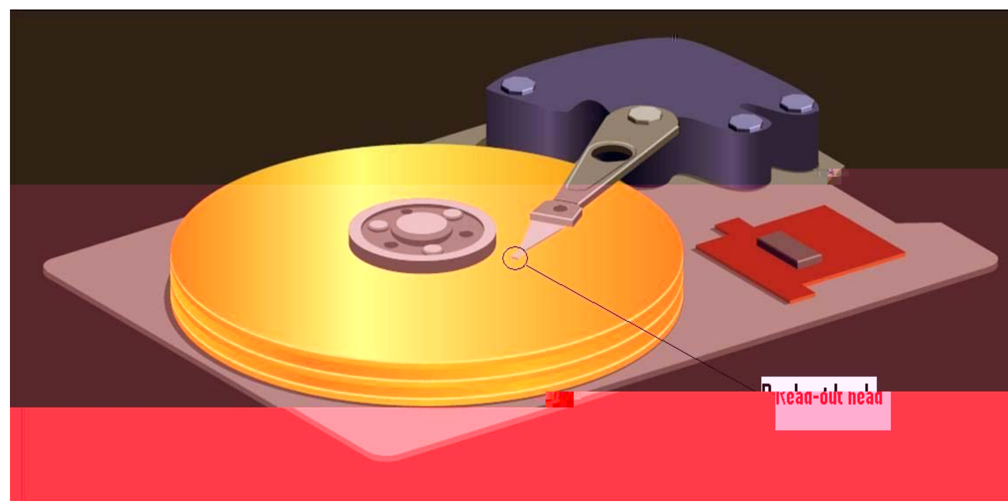


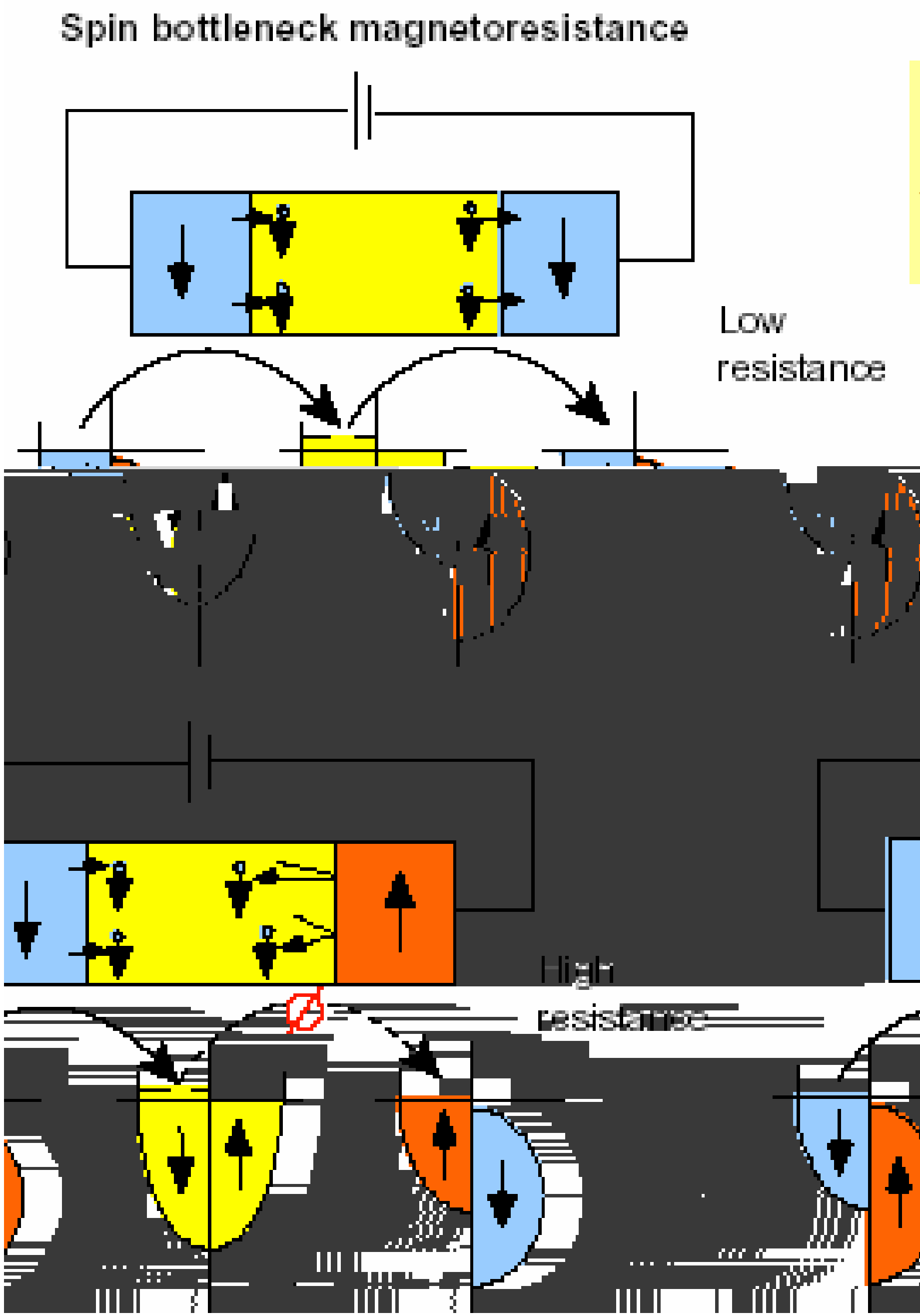
M. Faraday

Faraday's law:

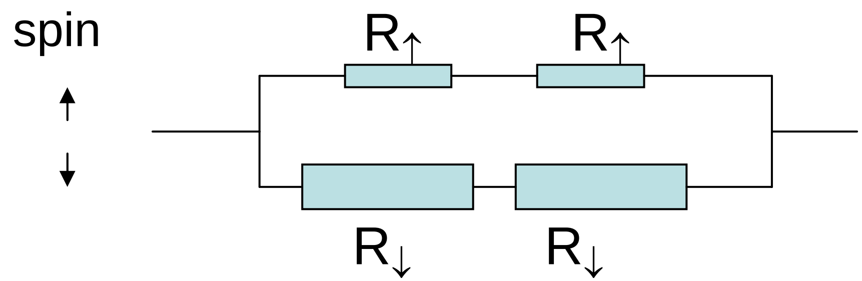
$$\mathcal{E} = -\frac{d\Phi}{dt}$$

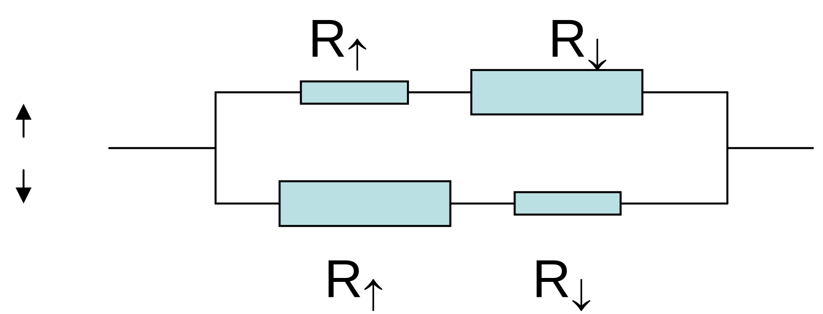
(1831)





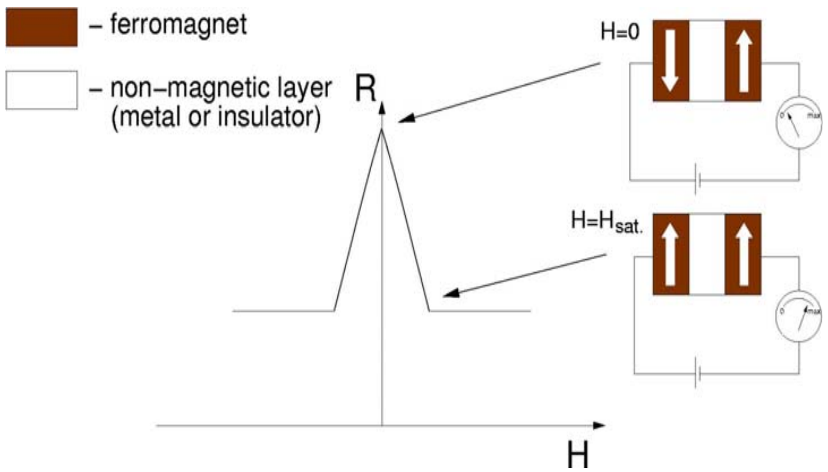
$$MR = \frac{R^{AP} - R^{P}}{R^{P}} = \frac{(R_{\uparrow} - R_{\downarrow})^2}{4R_{\uparrow}R_{\downarrow}}$$



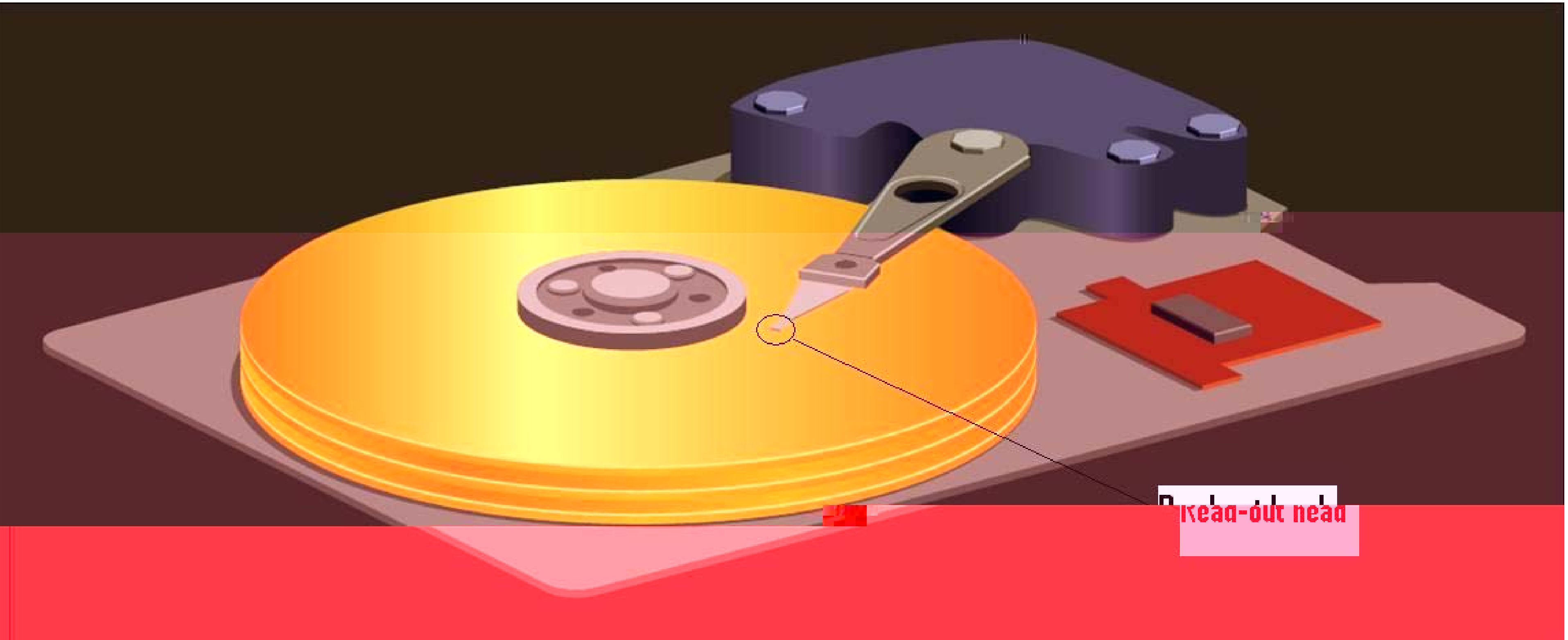


---GMR

-GMR



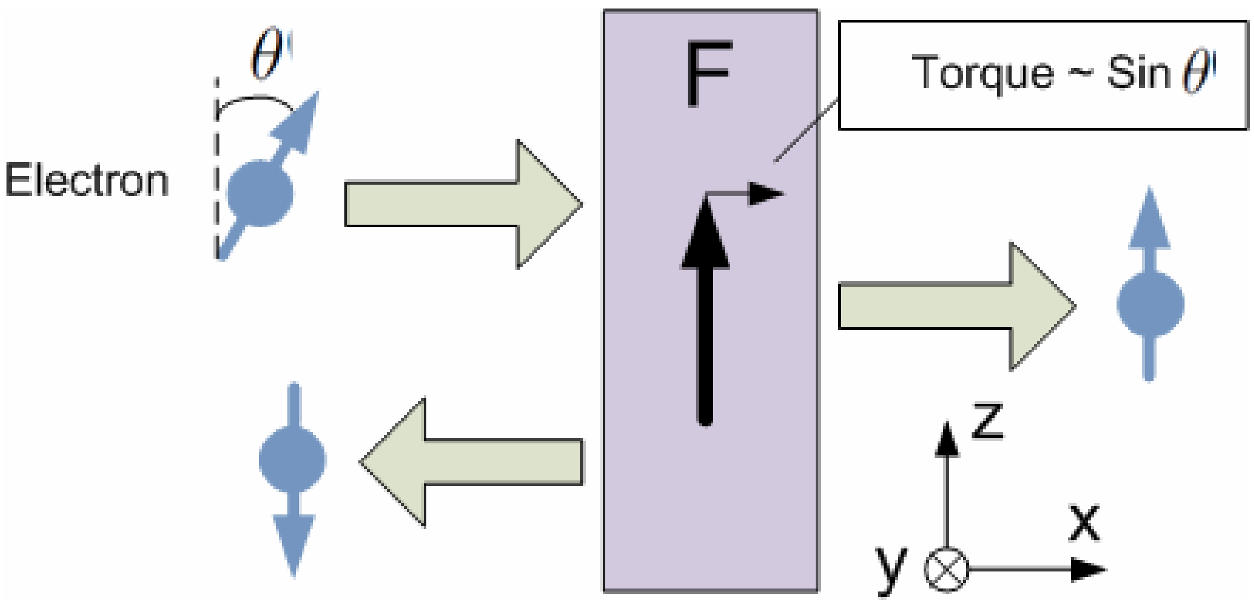
– ferromagnet
– non–magnetic layer
(metal or insulator)
R
H=0
H=H$_{sat.}$
H



Read-out head

Schematic of exchange torque generated by spin-filtering

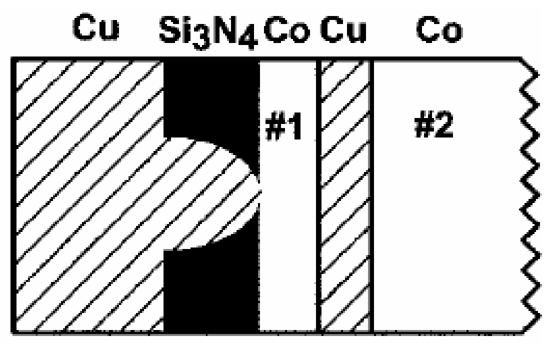
$$|\psi_{in}\rangle = \frac{e^{ik_\uparrow x}}{\sqrt{k_\downarrow}} \cos\left(\frac{\theta}{2}\right)|\uparrow\rangle + \frac{e^{ik_\downarrow x}}{\sqrt{k_\downarrow}} \sin\left(\frac{\theta}{2}\right)|\downarrow\rangle$$

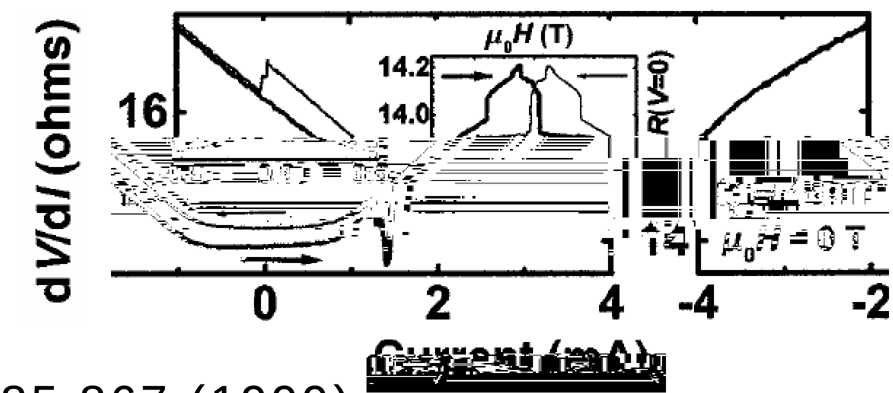


$$|\psi_r\rangle = \frac{e^{-ik_\downarrow x}}{\sqrt{k_\downarrow}} \sin\left(\frac{\theta}{2}\right)|\downarrow\rangle \qquad |\psi_t\rangle = \frac{e^{ik_\uparrow x}}{\sqrt{k_\uparrow}} \cos\left(\frac{\theta}{2}\right)|\uparrow\rangle$$

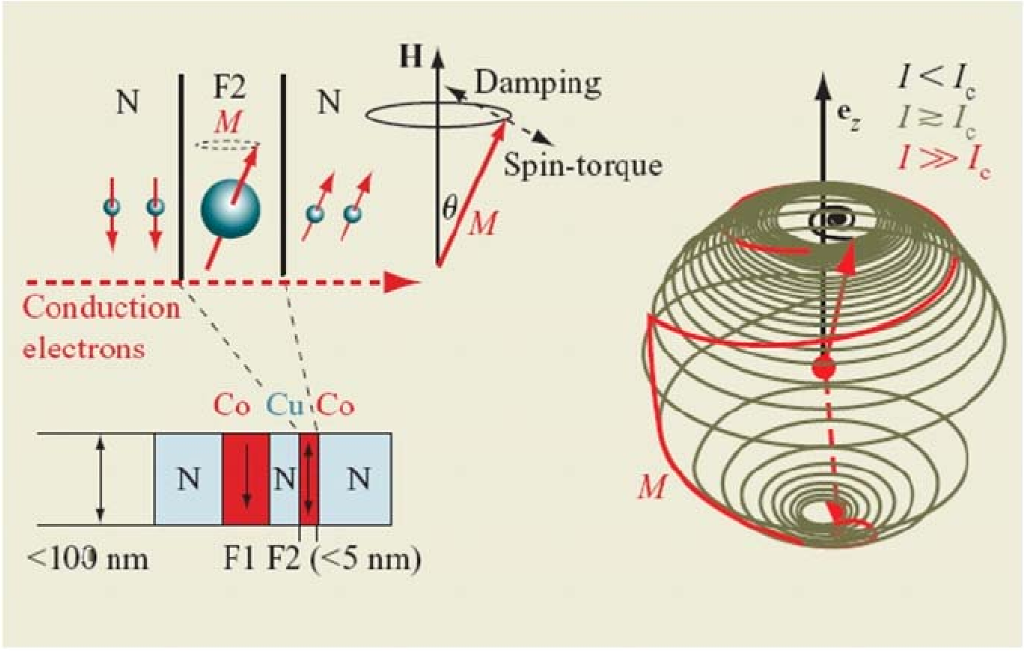
Slonczewski, J. C. (1996). Berger, L. (1996). L. Berger (1974)

Spin-transfer torques effects (1999)





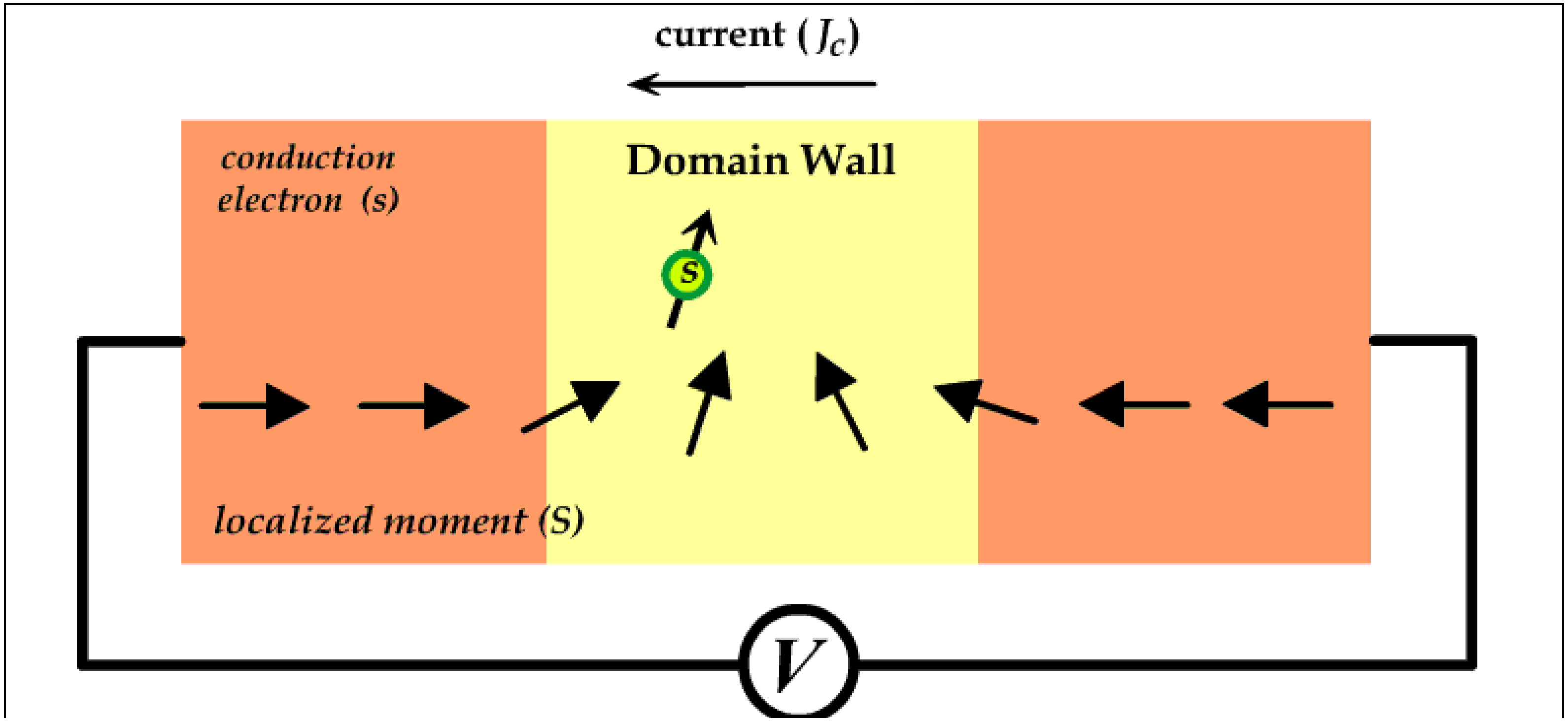
Myers, et al., Science 285,867 (1999)

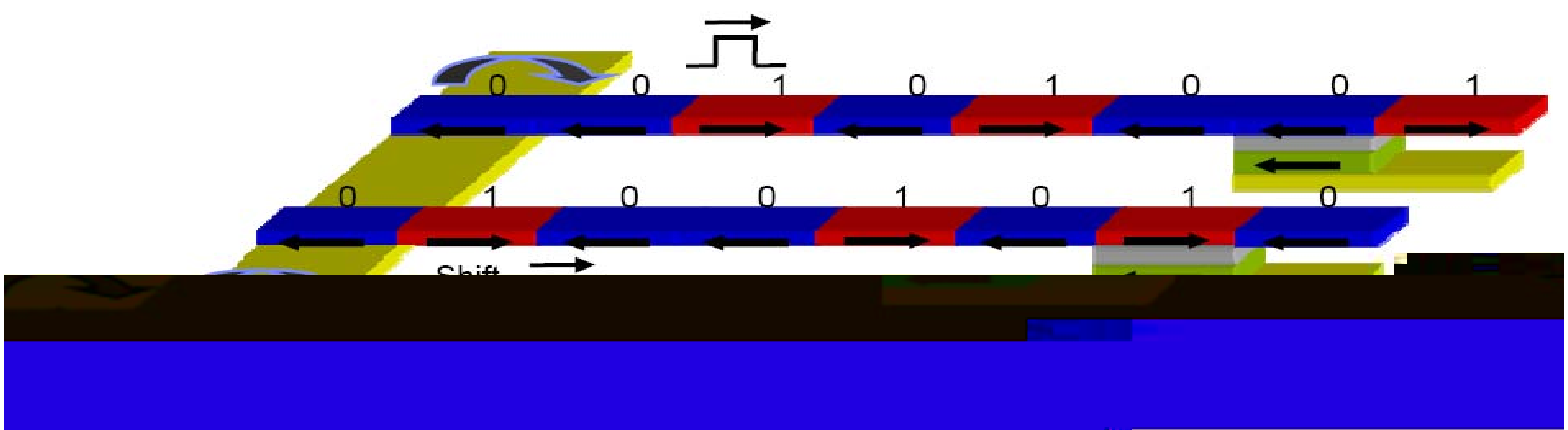


Sun, IBM J. Res. & Dev. 50, 81(2006)

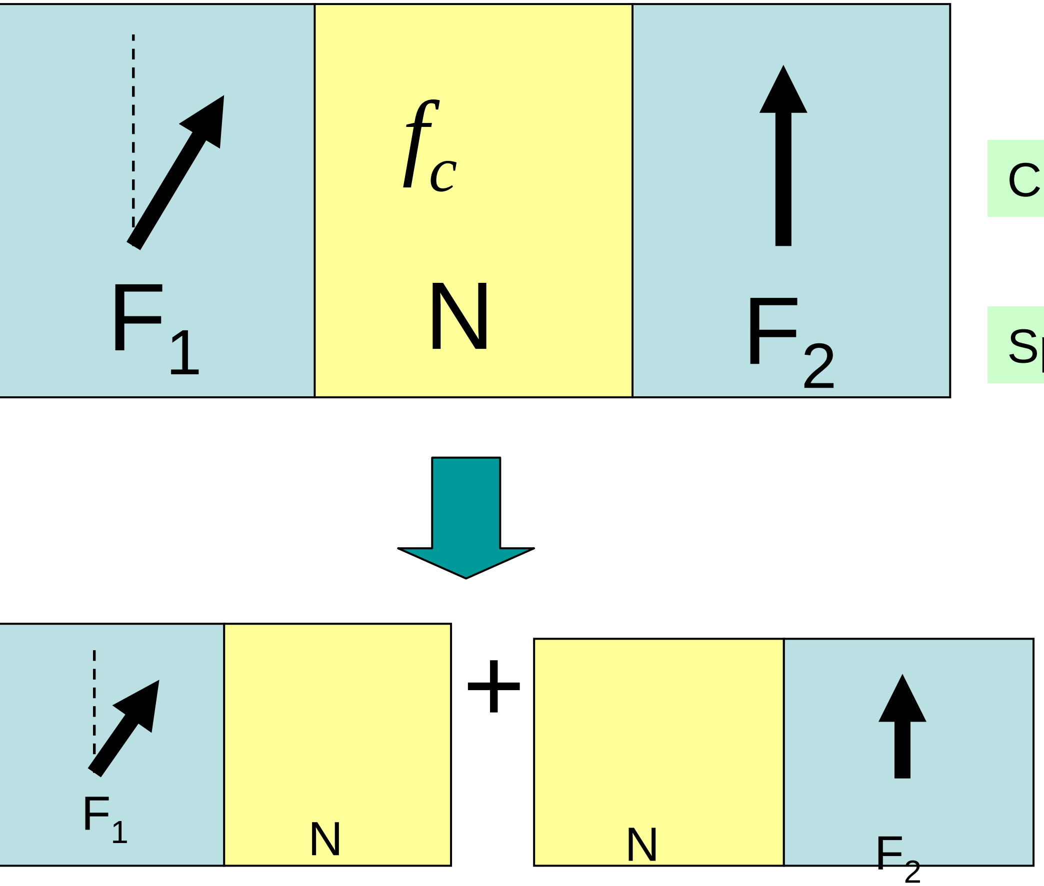
Current-driven domain wall motion:

$$\theta = 2\cot^{-1} e^{-(z-z_0)/w}$$





Circuit theory(Batraas2001)



Boundary condition

Charge current I_1 I_2

Spin current $\mathbf{I}_s$ $\mathbf{I}_s$

Charge accumulation f_c

Spin accumulation

In-plane torque $\tau = \frac{\hbar}{2e}\left(\mathrm{I}_{s1} - \mathrm{I}_{s1}\cdot \mathrm{m}_2\right)$

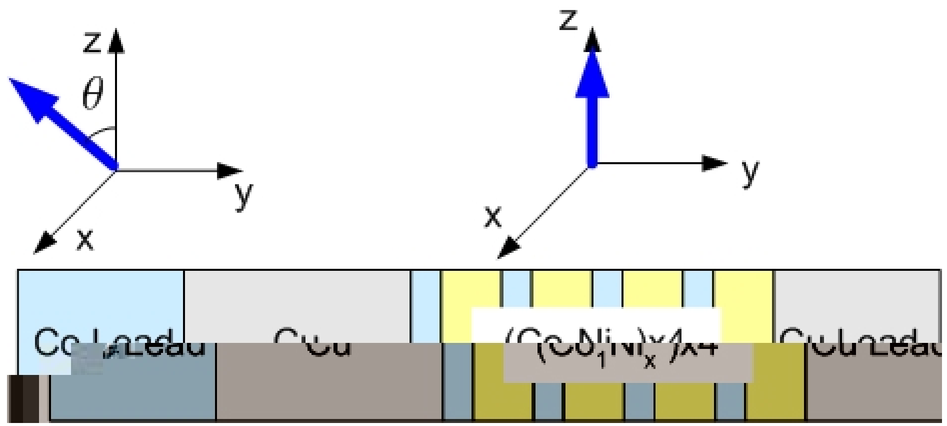
Current and spin current for F_1/N

$$I_1 = \left(G^{\uparrow} + G^{\downarrow}\right)\left(f_c^{F1} - f_c^{N}\right) + \left(G^{\uparrow} - G^{\downarrow}\right)\left(f_s^{F1} - \mathbf{m}_1 \cdot \mathbf{s} f_s^{N}\right)$$

$$\mathbf{I}_{s1} = \left(G^{\uparrow} + G^{\downarrow}\right)\left(f_c^{F1} - f_c^{N}\right)\mathbf{m}_1 + \left(2\mathrm{Re}G^{\uparrow\downarrow} - G^{\uparrow} - G^{\downarrow}\right)\mathbf{m}_1 \cdot \mathbf{s} f_s^{N} \mathbf{m}_1 - 2\mathrm{Re}G^{\uparrow\downarrow}\mathbf{s} f_s^{N} + 2\mathrm{Im}G^{\uparrow\downarrow} f_s^{N} \mathbf{m}_1 \times \mathbf{s}$$

Methods

First principles approach to spin transfer torques



- First-principles tight-binding LMTO
- Green function method for layered systems.
- Large system with the number of atoms > 1000

Spin current:

$$\hat{\mathcal{J}} \equiv \frac{1}{2}\left[\hat{\sigma} \otimes \hat{\mathbf{V}} + \hat{\mathbf{V}} \otimes \hat{\sigma}\right]$$

Spin torque from one lead:

$$\left\langle \hat{\mathbf{T}}^{s}_{\mathbf{R}}\left(\mathbf{k}_{\|}\right)\right\rangle = \sum_{\mathbf{R}' \in I-1, I} \left\langle \hat{\mathcal{J}}^{s}_{\mathbf{R}',\mathbf{R}}\left(\mathbf{k}_{\|}\right)\right\rangle - \sum_{\mathbf{R}' \in I, I+1} \left\langle \hat{\mathcal{J}}^{s}_{\mathbf{R},\mathbf{R}'}\left(\mathbf{k}_{\|}\right)\right\rangle$$

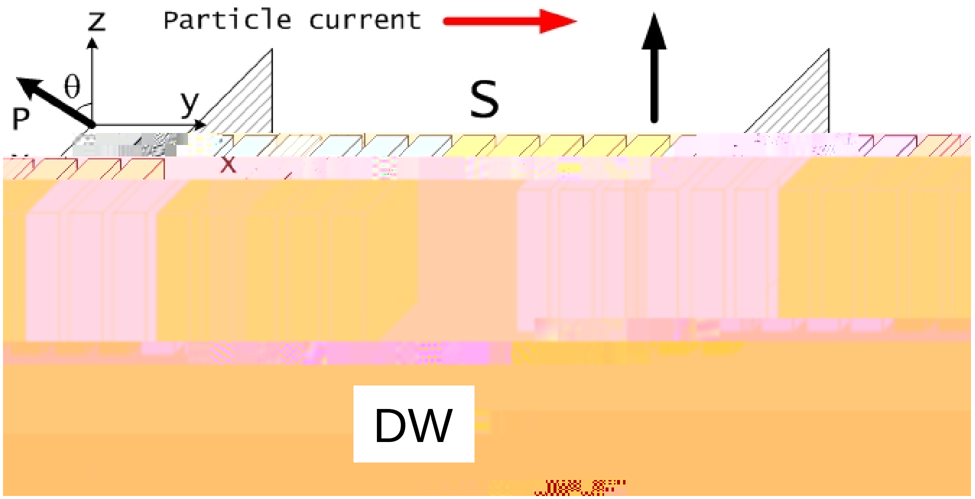
Spin torque on atom R:

$$\mathbf{T}_{\mathbf{R}} = \left(\frac{\hbar}{2}\right)\frac{e}{2h}\frac{1}{N_{\|}}\sum_{s,\mathbf{k}_{\|}}\left[\left\langle \hat{\mathbf{T}}^{s}_{\mathbf{R}}\left(\mathbf{k}_{\|}\right)\right\rangle_{\mathcal{L}} - \left\langle \hat{\mathbf{T}}^{s}_{\mathbf{R}}\left(\mathbf{k}_{\|}\right)\right\rangle_{\mathcal{R}}\right] V_b$$

S Wang , Y Xu, Ke Xia, (2008).

First principles approach to spin transfer torques

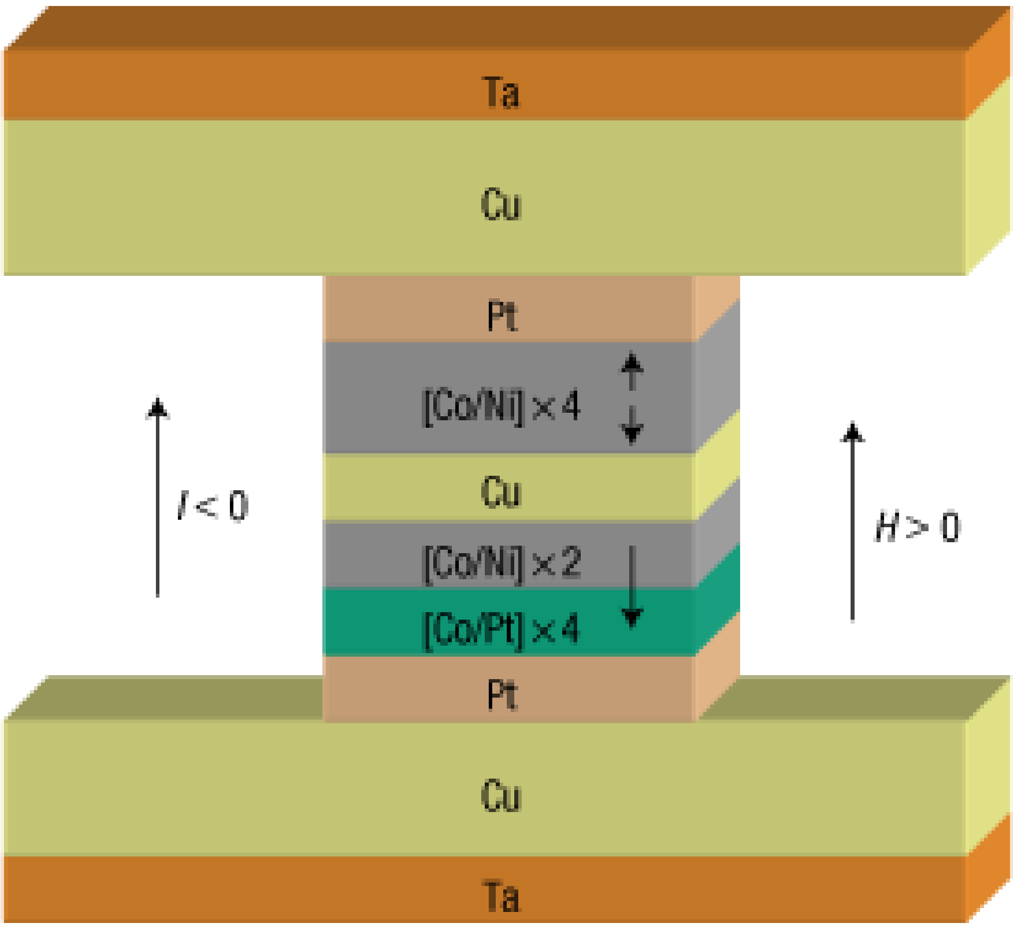
$$\tau \propto \langle \vec{s} \rangle \times \vec{M}$$

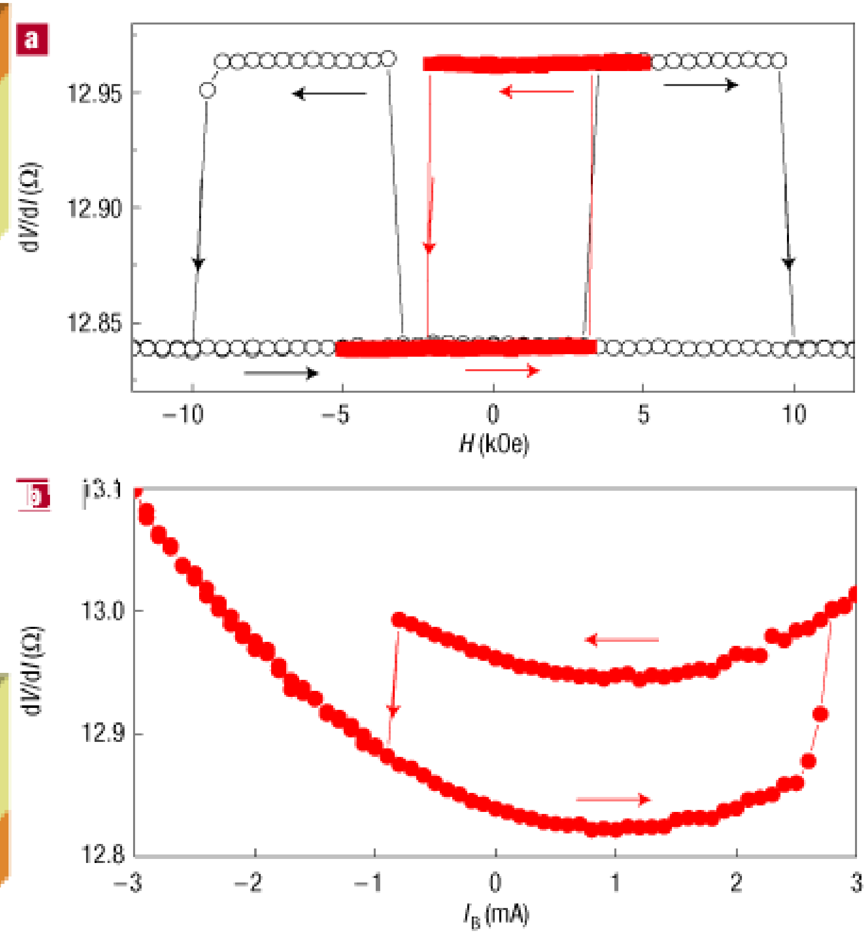


- TB LMTO
- Green function method
- NEGF if necessary
- Order& disorder

Linear equations of system

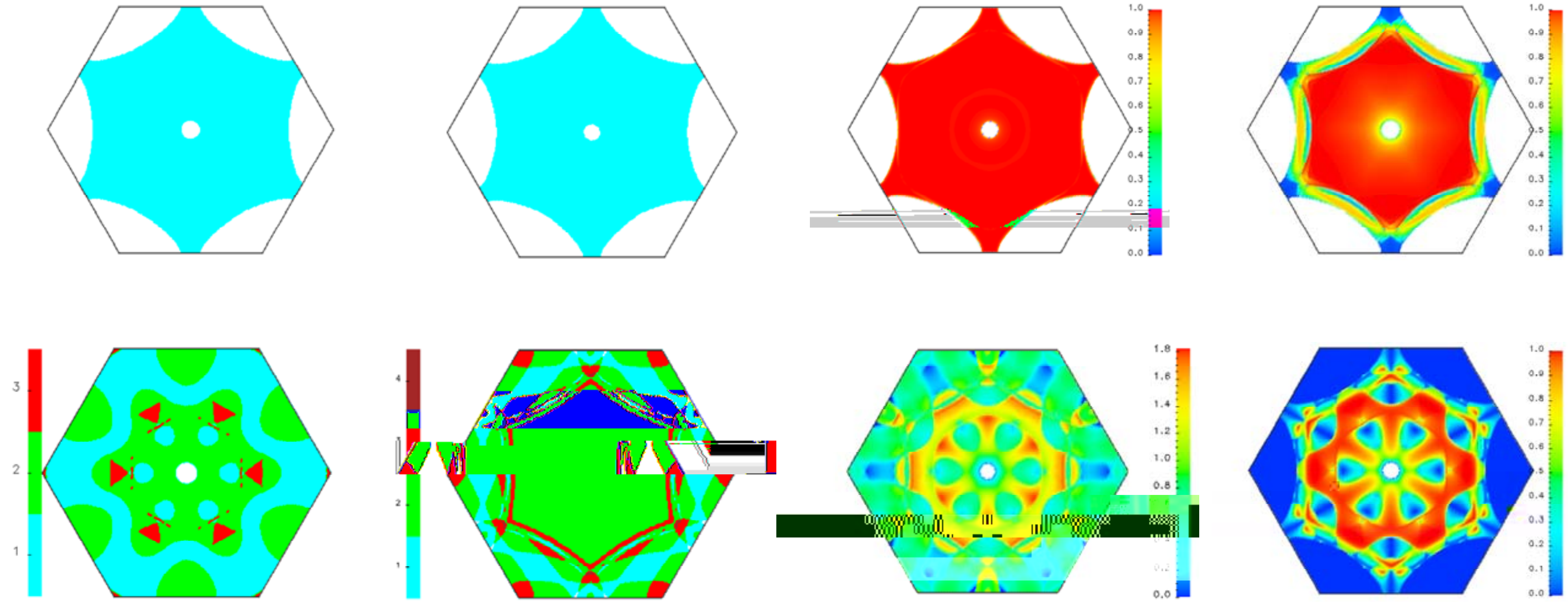
$$\begin{pmatrix} \mathbf{C}_0 \\ \mathbf{C}_1 \\ \mathbf{C}_2 \\ \cdots \\ \mathbf{C}_N \\ \mathbf{C}_{N+1} \end{pmatrix} = (\mathbf{UPU}^+ - \tilde{\mathbf{S}})^{-1} \begin{pmatrix} \mathbf{S}_{0,-1}[\mathbf{F}_L^{-1}(+) - \mathbf{F}_L^{-1}(-)]\mathbf{C}_0(+) \\ 0 \\ 0 \\ \cdots \\ 0 \\ 0 \end{pmatrix}$$





S.MANGIN et.al, Nature materials vol5,210, (2006) , D.Ravelosona, et.al, APL 90,072508 (2007),D.Ravelosona, et.al, PRL 96,186604(2006), D.Ravelosona, et.al,J.Phys.D: Appl.Phys.40,1253(2007)

Co|Ni interface



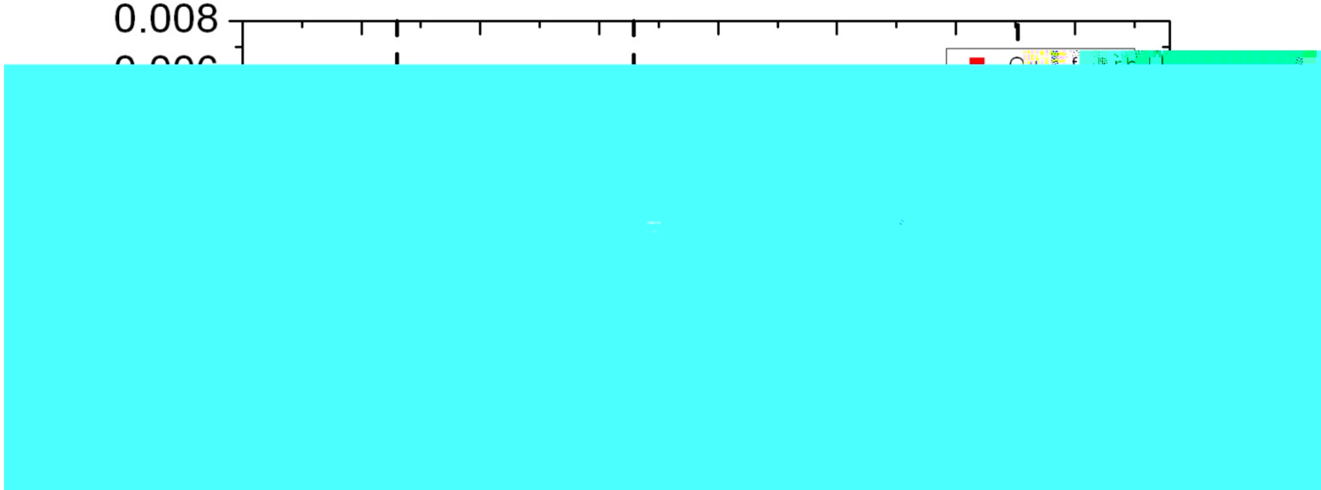
Interface resistance for Co|Ni(111)

AR unit $\mathbf{f}^{-1}\Omega^{-1}\mathbf{m}^{-2}$

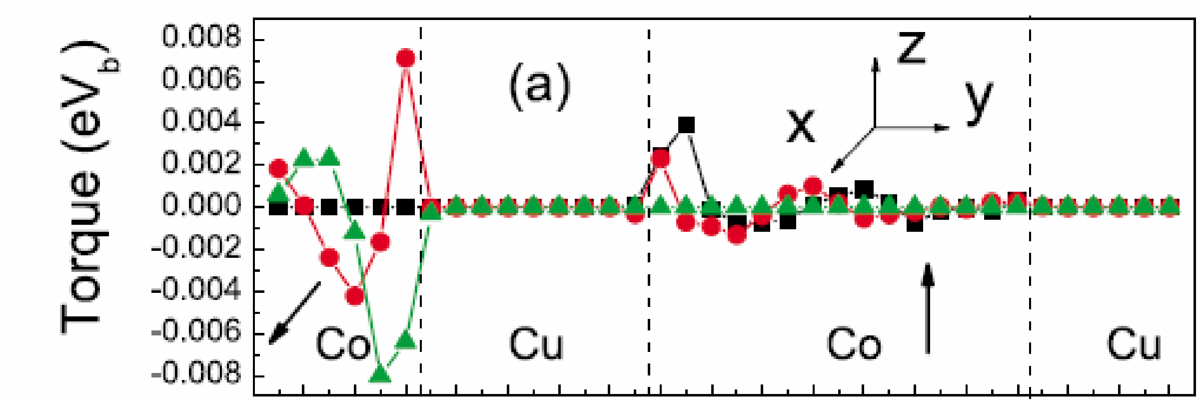
$$\mathrm{ia} = \frac{AR_{\downarrow} - AR_{\uparrow}}{AR_{\uparrow} + AR_{\downarrow}} \quad \mathrm{Gamm}$$

Lattice constant		AR(maj.)	AR(min.)	Gamma
Co	3.549	0.014664	0.725067	0.960353
Ni	3.524	0.0241504	0.727603	0.935749
½(Co+Ni)	3.537	0.0186835	0.730984	0.950155

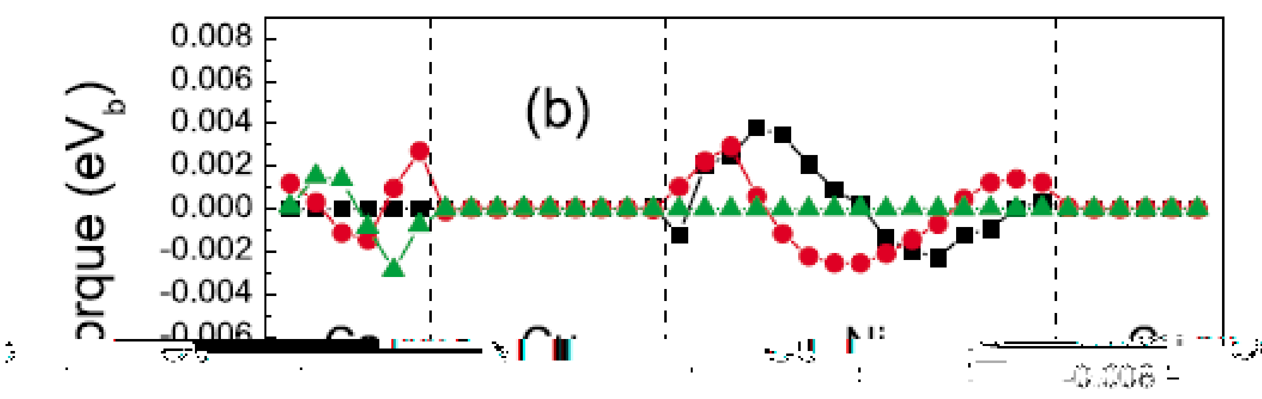
Co_1Ni_3


0.008

Co

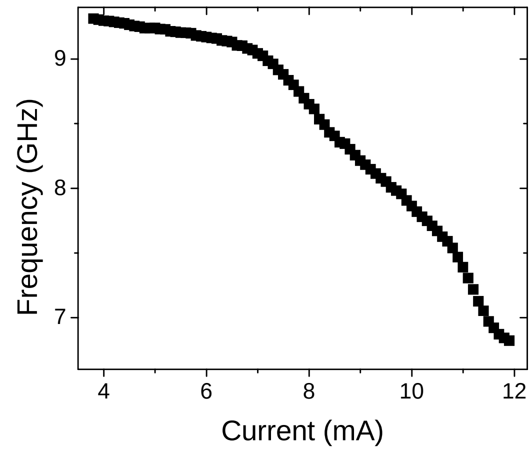

Torque (eV$_b$)
0.008
0.006
0.004
0.002
0.000
-0.002
-0.004
-0.006
-0.008
(a)
z
y
x
Co
Cu
Co
Cu

Ni

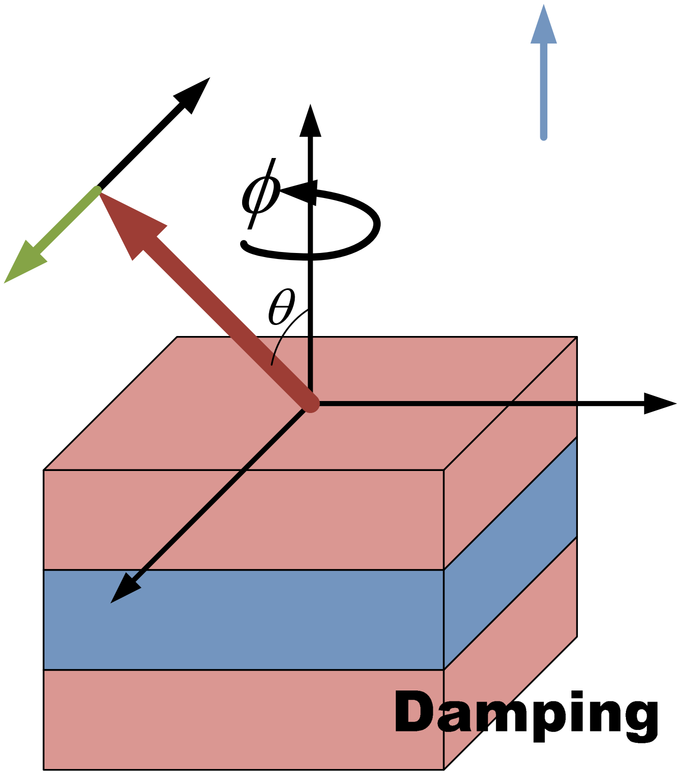

0.008
0.006
0.004
0.002
0.000
-0.002
-0.004
(b)

substrate|Ta(3)|Cu(15)|$Co_{90}Fe_{10}$(20)

|Cu(4.5)|[Co(0.2)|Ni(0.4)]^{x5}|Co(0.3)|Cu(3)|Ta(3)



Spin transfter nanocontact oscillator devices(STNO)



LLG equation

Damping

z

H

M

g factor [1]

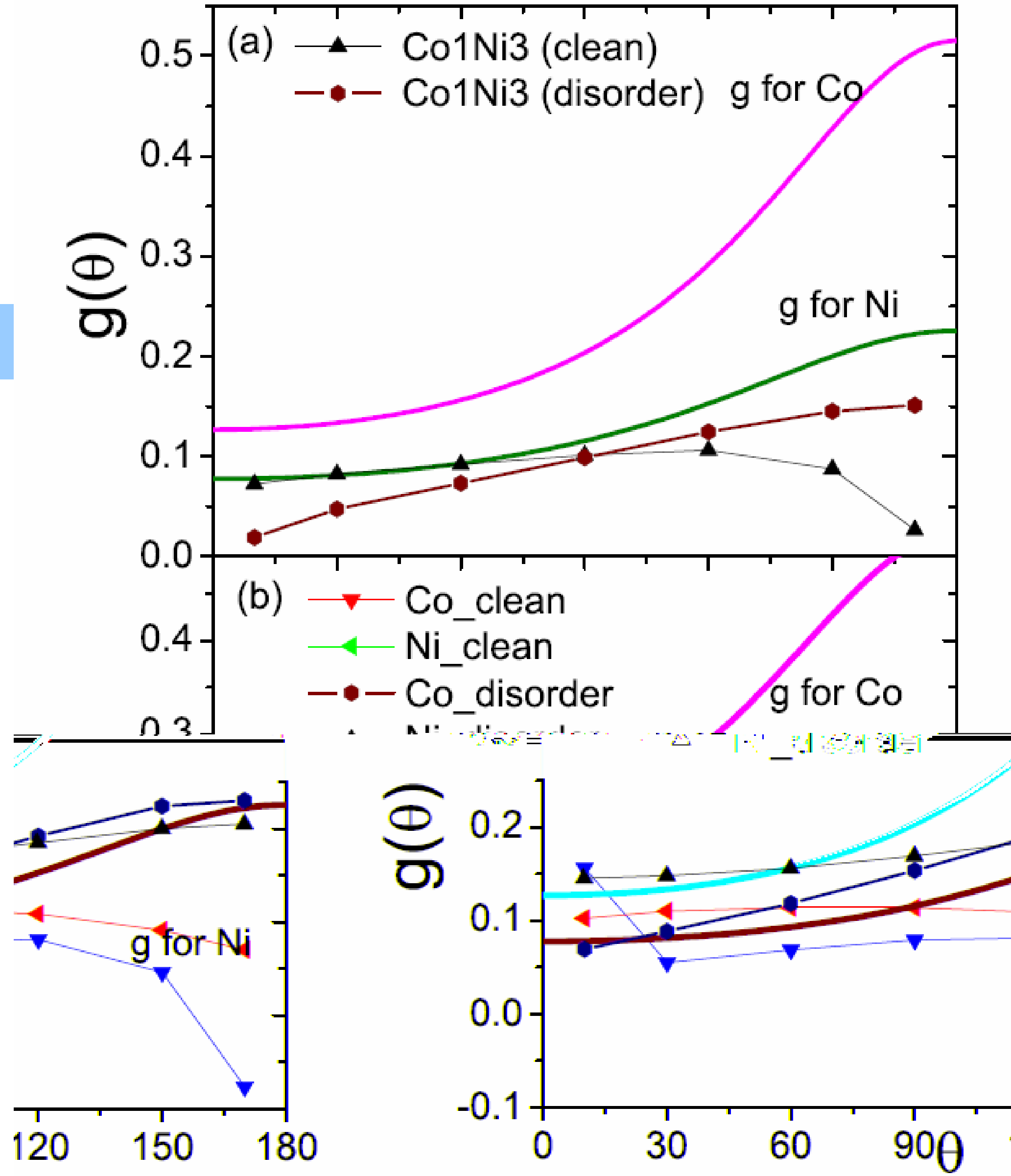
G factor

$$g = \left[-4 + \frac{(1+P)^3 (3 + \hat{s}_1 \cdot \hat{s}_2)}{4P^{3/2}} \right]^{-1}$$

Here Co P=0.35 Ni P=0.23

$$\mathbf{g}(\theta) = \frac{\text{torque}(\theta)}{\mathbf{I}(\theta)\sin(\theta)}$$

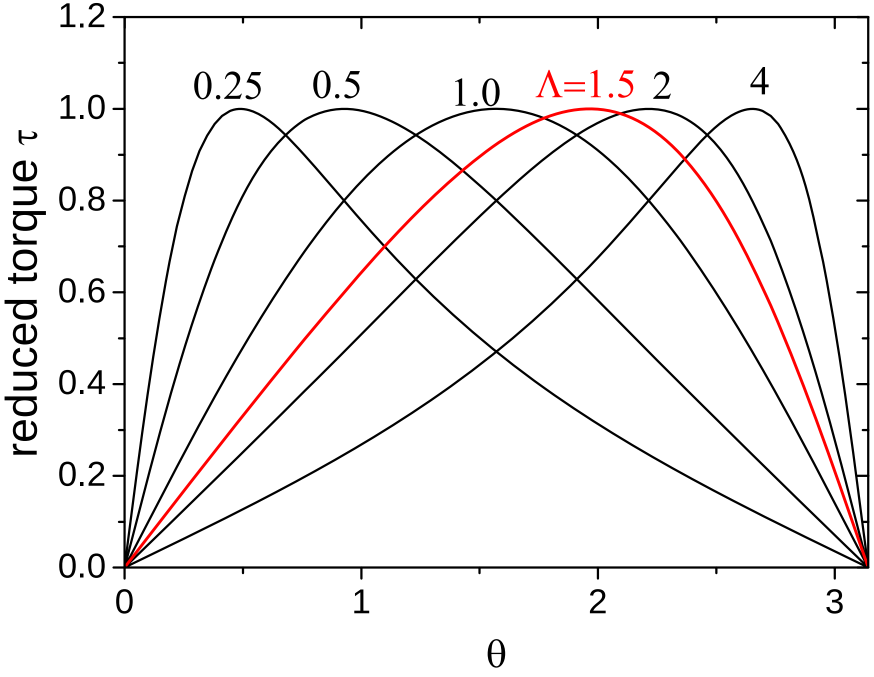
G factor can be enhanced by disorder effect.



J.C.Slonczewski (1996)

Reduced torque

$$\Lambda = 1.5$$



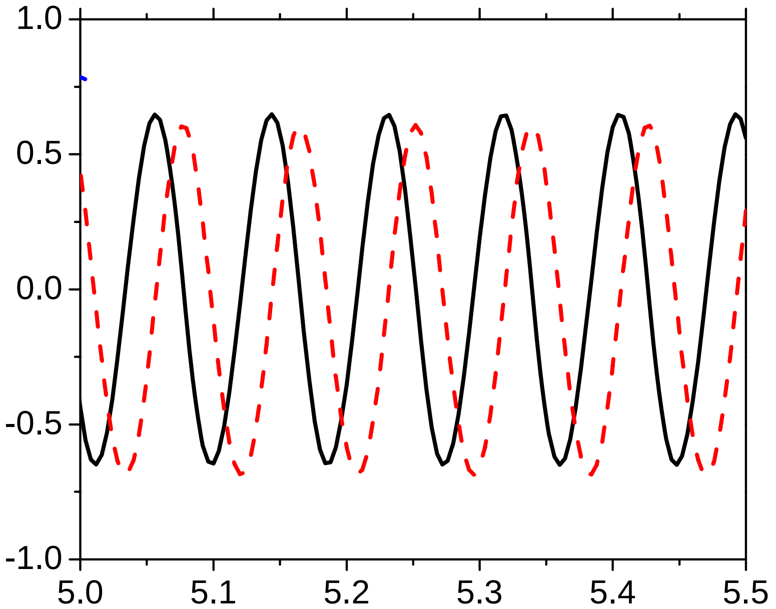
Torques

$$L = \hbar I P_r \Lambda \tau(\theta) / 4Ae$$

Reduced torques

[redacted]

J.C. Slonczewski (2002)

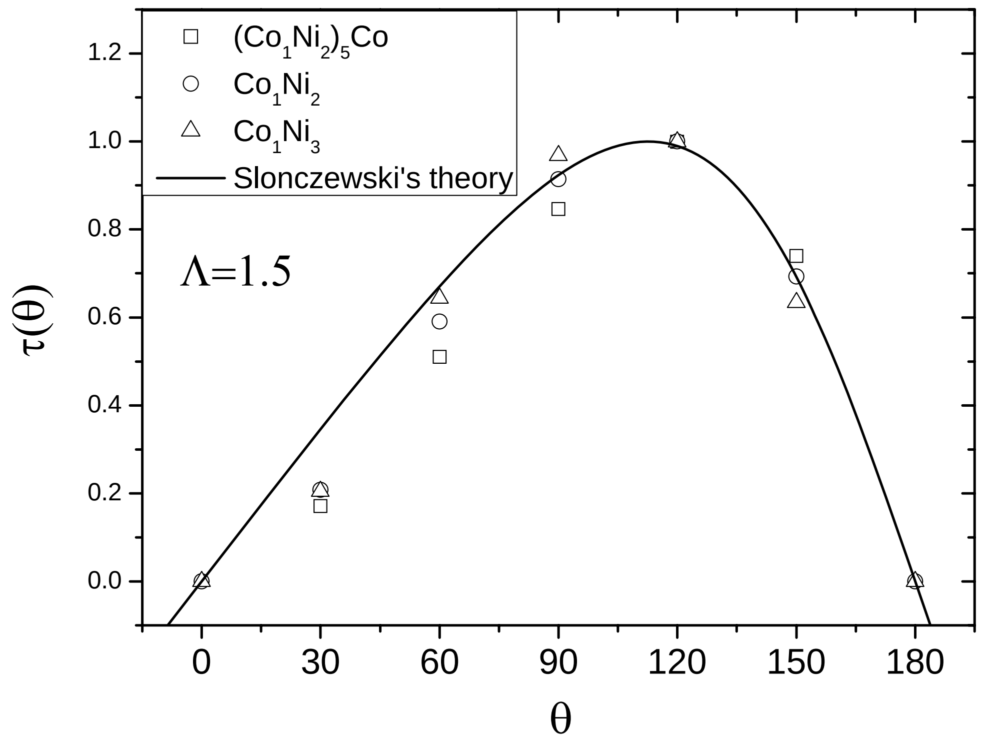


1.0
0.5
0.0
-0.5
-1.0
5.0
5.1
5.2
5.3
5.4
5.5

$Cu/Co/Cu/(Co_1Ni_2)_5Co/Cu$

Reduced torque

$$\tau(\theta) = \frac{t(\theta)/I(\theta)}{(t/I)_{max}}$$



Experiment $\Lambda = 1.5$

Gilbert Damping In the Presence of Andreev Reflection

Spin Current Induced Dynamics

$$\dot{\vec{m}} = \gamma_0 \vec{H}_{eff} \times \vec{m} + \alpha_0 \dot{\vec{m}} \times \vec{m} + \left.\frac{\partial \vec{m}}{\partial t}\right|_{torque}$$

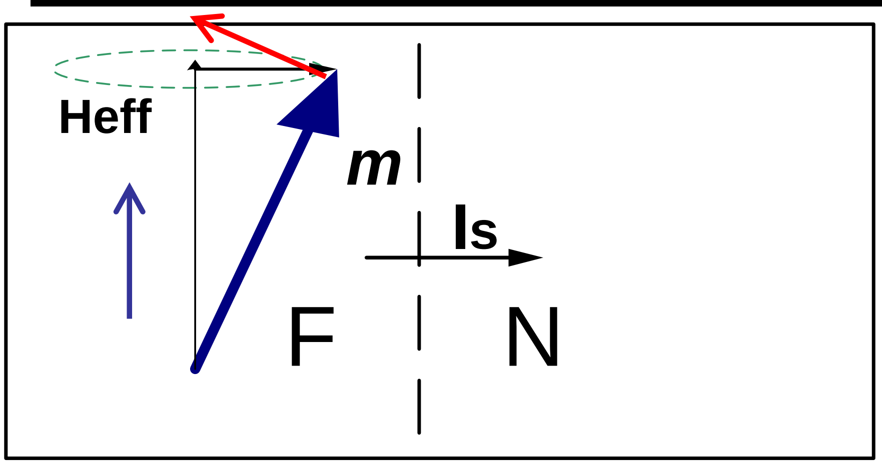
Precession **Damping**

Spin Transfer Torque from current Is

$$\mathbf{I}_s = \frac{\hbar}{4\pi}\left(\mathrm{Re}\, A_{\mathrm{eff}}^{\uparrow\downarrow} \mathbf{m} \times \frac{d\mathbf{m}}{dt} + \mathrm{Im}\, A_{\mathrm{eff}}^{\uparrow\downarrow} \frac{d\mathbf{m}}{dt}\right)$$

$A^{\uparrow\downarrow}{}_{eff}$

Ferromagnet/Normal Metal



Tserkovnyak,Y. *et al Phys. Rev. B* **66**, 224403 (2002)

Spin Dependent Scattering Matrix

$$\hat{S} = S^{\uparrow} u^{\uparrow} + S^{\downarrow} u^{\downarrow} \qquad u^{\uparrow/\downarrow} = \frac{1}{2}(\hat{I}_0 \pm \hat{\sigma} \cdot \vec{m})$$

$$\hat{S} = \frac{S^{\uparrow} + S^{\downarrow}}{2} \hat{I}_0 + \frac{S^{\uparrow} - S^{\downarrow}}{2} \hat{\sigma} \cdot \vec{m}$$

$$\frac{\partial \hat{S}}{\partial X} = S^{\uparrow} \frac{\partial u^{\uparrow}}{\partial X} + S^{\downarrow} \frac{\partial u^{\downarrow}}{\partial X} = (S^{\uparrow} - S^{\downarrow}) \hat{\sigma} \cdot \frac{\partial \vec{m}}{\partial X}$$

EMISSIVITY

$$\frac{d\hat{n}_l}{dX} = \left(\frac{1}{4\pi i} \sum_{nn'l'} \frac{\partial \hat{s}_{nn',ll'}}{\partial X} \hat{s}^{\dagger}_{nn',ll'} \right) + \mathrm{H.c.}$$

Tserkovnyak,Y. *et al Phys. Rev. Lett, 88,117601(2002)* *Buttiker et al. (1994)*

F/N Spin Pump

$$\text{Current } \hat{I}_{F/N} = e\frac{\partial \hat{N}_{F/N}}{\partial X}\frac{\partial X}{\partial t} = \frac{1}{2} I_C \cdot \hat{i}_0 - \frac{e}{\hbar}\hat{\sigma}\cdot \hat{I}^S_{F/N}$$

$$\text{Precession induced current } \hat{I}^S_{F/N} = \frac{\hbar}{4\pi}\left(\operatorname{Re} A^{\uparrow\downarrow}\vec{m}\times\frac{\partial \vec{m}}{\partial t} + \operatorname{Im} A^{\uparrow\downarrow}\frac{\partial \vec{m}}{\partial t}\right),$$

$$I_C = 0.$$

Mixing Conductance (One Interface)

[illegible]

LLG equation in the presence of spin current pump

$$\frac{\partial \vec{m}}{\partial t} = \gamma_0 \vec{H}_{eff}\times\vec{m} + \alpha_0\frac{\partial \vec{m}}{\partial t}\times\vec{m} + \frac{\gamma\hbar}{4\pi M_S V}\left(A_r^{\uparrow\downarrow}\vec{m}\times\frac{\partial \vec{m}}{\partial t} + A_i^{\uparrow\downarrow}\frac{\partial \vec{m}}{\partial t}\right)$$

Effective Damping Enhancement

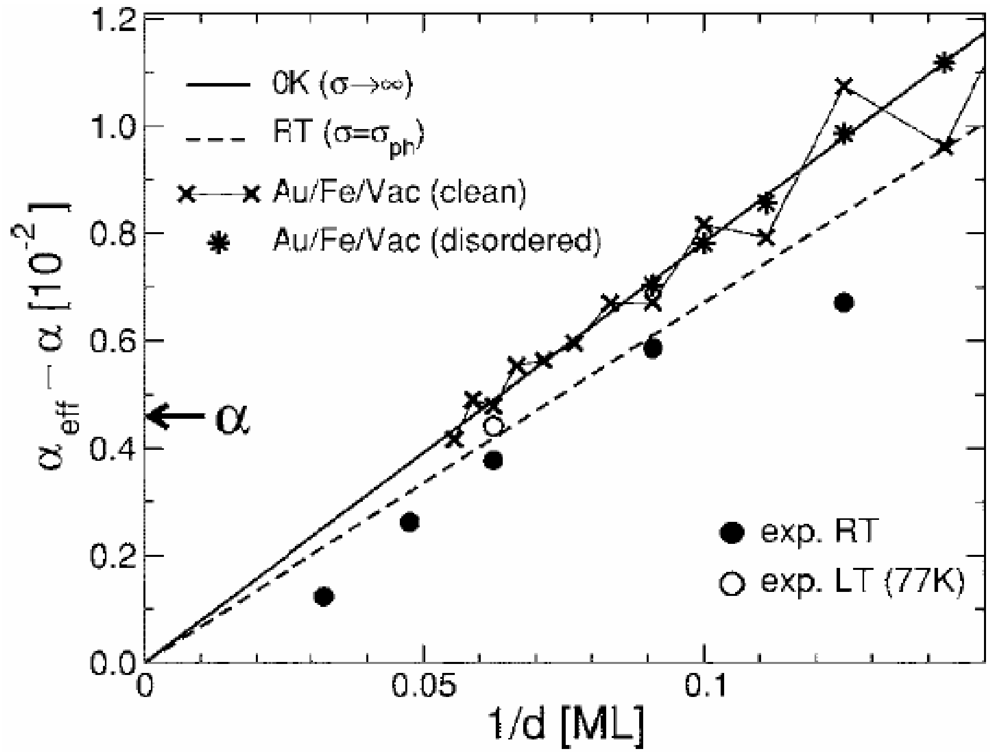
$$\frac{\partial}{\partial t}\overrightarrow{m} = -\gamma_{eff}\overrightarrow{m} \times \overrightarrow{H_{eff}} + \alpha_{eff}\overrightarrow{m} \times \frac{\partial}{\partial t}\overrightarrow{m}$$

$$\frac{\gamma}{\gamma_{eff}} = 1 - \frac{\gamma\hbar}{4\pi M_s V} A_i^{\uparrow\downarrow}$$

$$\alpha_{eff} = \frac{\alpha + \frac{\gamma\hbar}{4\pi M_s V} A_r^{\uparrow\downarrow}}{1 - \frac{\gamma\hbar}{4\pi M_s V} A_i^{\uparrow\downarrow}}$$

Tserkovnyak,Y. *et al*

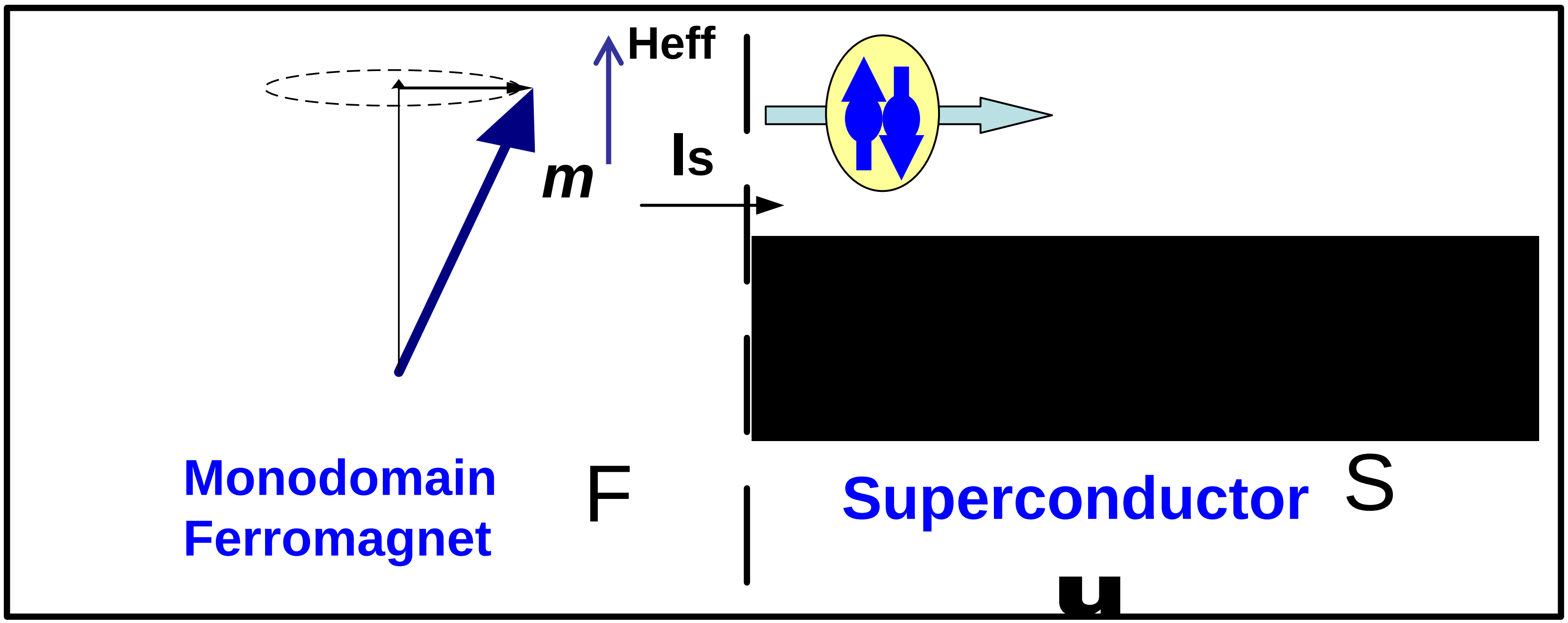
Rev. Mod. Phys. ,77 ,4(2005)



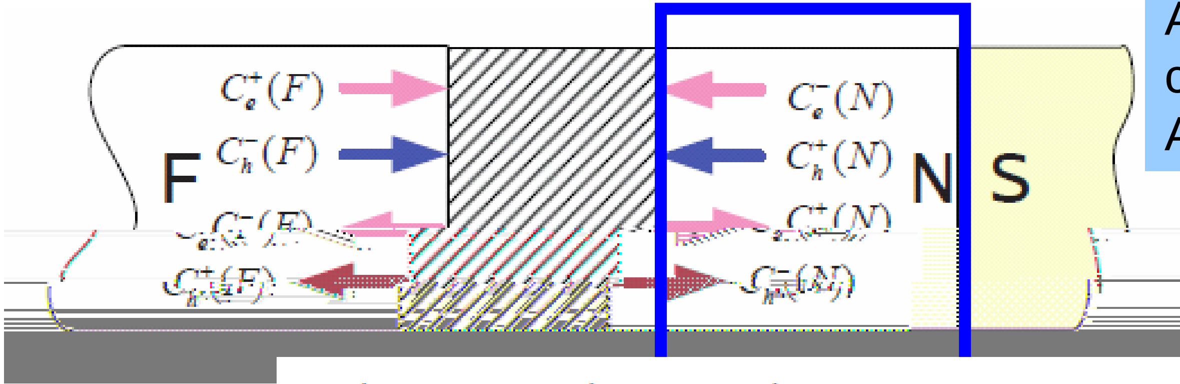
Urban. R *et al Phys. Rev. Lett. 87, 217204*(2001)

Heinrich, B. *et al, J. Appl. Phys. 93,7545(2003)*

Spin Pump at F/S Contacts



F/N/S Interface Approach



At N|S interface we consider there is only Andreev reflection.

At F/N Interface

$$\begin{pmatrix} c_e^-(F) \\ c_e^+(N) \\ c_h^-(F) \\ c_h^+(N) \end{pmatrix} = \begin{pmatrix} r_{11}^e & t_{12}^e & 0 & 0 \\ t_{21}^e & r_{22}^e & 0 & 0 \\ 0 & 0 & r_{11}^h & t_{12}^h \\ 0 & 0 & t_{21}^h & r_{22}^h \end{pmatrix} \begin{pmatrix} c_e^+(F) \\ c_e^-(N) \\ c_h^+(F) \\ c_h^-(N) \end{pmatrix}$$

We are interested in wave functions in the *F layer*

C.W.J. Beenakker, Rev. Mod. Phys. 69, 731 (1997).
K. Xia *et al*., PRL89, 166603(2002)

Spin Current in the Presence of Andreev Reflection

Linear Response & Circuit Theory

Spin current and Damping

$$\text{Current } \hat{I}_{F/S} = \frac{1}{2} I_C \cdot \hat{i}_0 - \frac{e}{\hbar}\hat{\sigma}\cdot \hat{I}^S_{F/S} \quad \mathrm{I}_C = 0,$$

$$\hat{I}^S_{F/S} = \frac{\hbar}{4\pi}\int d\varepsilon \left(-\frac{\partial f}{\partial \varepsilon}\right)\left(\mathrm{Re}\, G^{\uparrow\downarrow}(\varepsilon)\vec{m}\times\frac{\partial \vec{m}}{\partial t} + \mathrm{Im}\, G^{\uparrow\downarrow}(\varepsilon)\frac{\partial \vec{m}}{\partial t}\right)$$

Effective Damping

$$\alpha_{eff} = \frac{\alpha_0 + \frac{\gamma\hbar}{4\pi M_S V}\int d\varepsilon\left(-\frac{\partial f}{\partial \varepsilon}\right)\mathrm{Re}\, G_{F/S}^{\uparrow\downarrow}(\varepsilon)}{\gamma_0 - \frac{\gamma\hbar}{4\pi M_S V}\int d\varepsilon\left(-\frac{\partial f}{\partial \varepsilon}\right)\mathrm{Im}\, G_{F/S}^{\uparrow\downarrow}(\varepsilon)}$$

Mixing Conductance and Andreev Reflection

$$G^{\uparrow\downarrow}(\varepsilon) \equiv \left(N_{Sharvin} - \left|R_{he}^{\uparrow\uparrow}(\varepsilon)\right|^2 - \left|R_{he}^{\uparrow\downarrow}(\varepsilon)\right|^2 - \left|R_{he}^{\downarrow\uparrow}(\varepsilon)\right|^2 - \left|R_{he}^{\downarrow\downarrow}(\varepsilon)\right|^2 \right) - R_{ee}^{\uparrow\uparrow}(\varepsilon) R_{ee}^{\downarrow\downarrow\dagger}(\varepsilon)$$

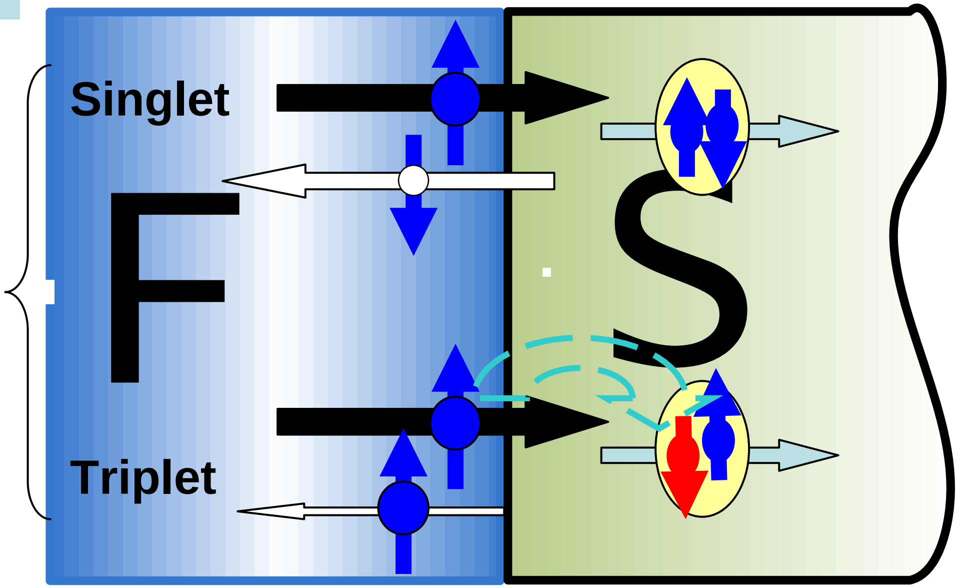
Normal Reflection

$$+R_{he}^{\downarrow\uparrow}(\varepsilon) R_{he}^{\uparrow\downarrow\dagger}(\varepsilon) + R_{he}^{\uparrow\uparrow}(\varepsilon) R_{he}^{\downarrow\downarrow\dagger}(\varepsilon)$$

Singlet

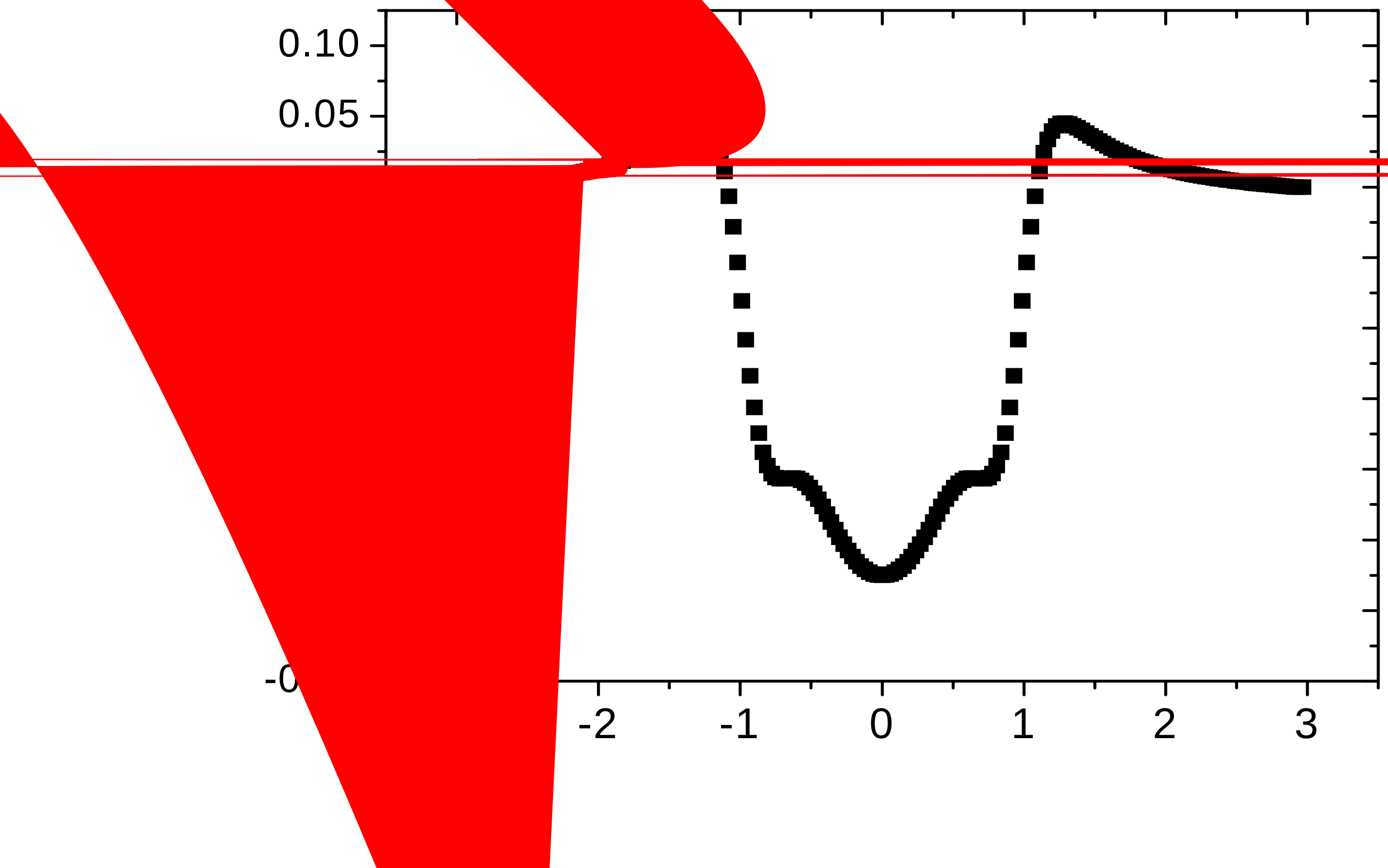
Triplet

Rhe



Andreev Reflection

Charge Conductance Spectrum



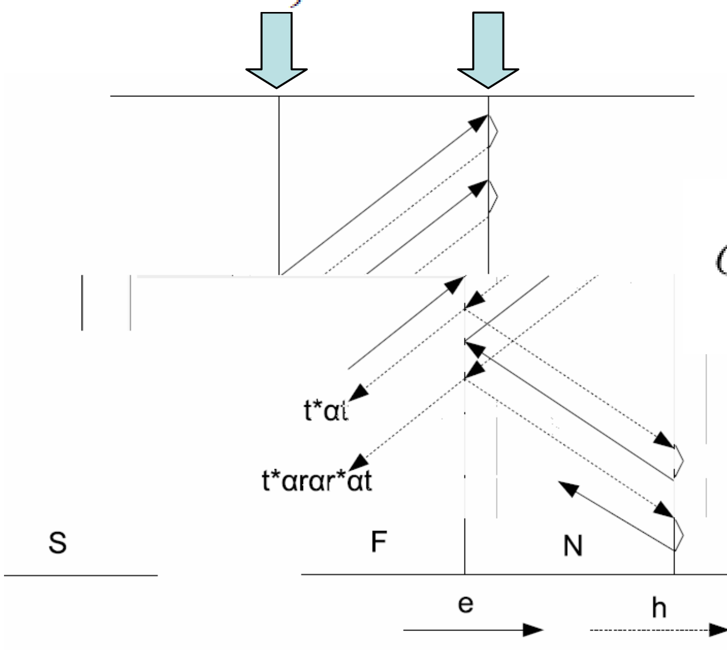
$$r'_{\uparrow(\downarrow)} = |r'_{\uparrow(\downarrow)}| e^{i\phi_{\uparrow}(\phi_{\downarrow})}$$

$$\hat{t}, \hat{r} \quad \alpha = e^{-i \arccos(\varepsilon / \Delta_0)}$$

[1]

$$r_{he} = t^* \alpha t + t^* \alpha r \alpha r^* \alpha t + t^* \alpha \left[r \alpha r^* \alpha \right]^2 t + \cdots$$

$$= t^* \alpha \left[1 - r \alpha r^* \alpha \right]^{-1} t$$



$$G_{FS}(\varepsilon) = \frac{G_0}{1 + R^4 - 2R^2 \cos\left(-2 \arccos \frac{\varepsilon}{\Delta_0} + \phi_{\uparrow} - \phi_{\downarrow}\right)}$$

$$\varepsilon / \Delta_0 = \cos \frac{\phi_{\uparrow} - \phi_{\downarrow}}{2}$$

F/N

$$\langle G_{FS}(\varepsilon) \rangle = \frac{G_0}{\left| \frac{1}{2\varphi} \int_{-\varphi}^{\varphi} \left(1 - R^2 e^{-i2 \arccos \frac{\varepsilon}{\Delta_0}} e^{i\delta}\right) d\delta \right|^2}$$

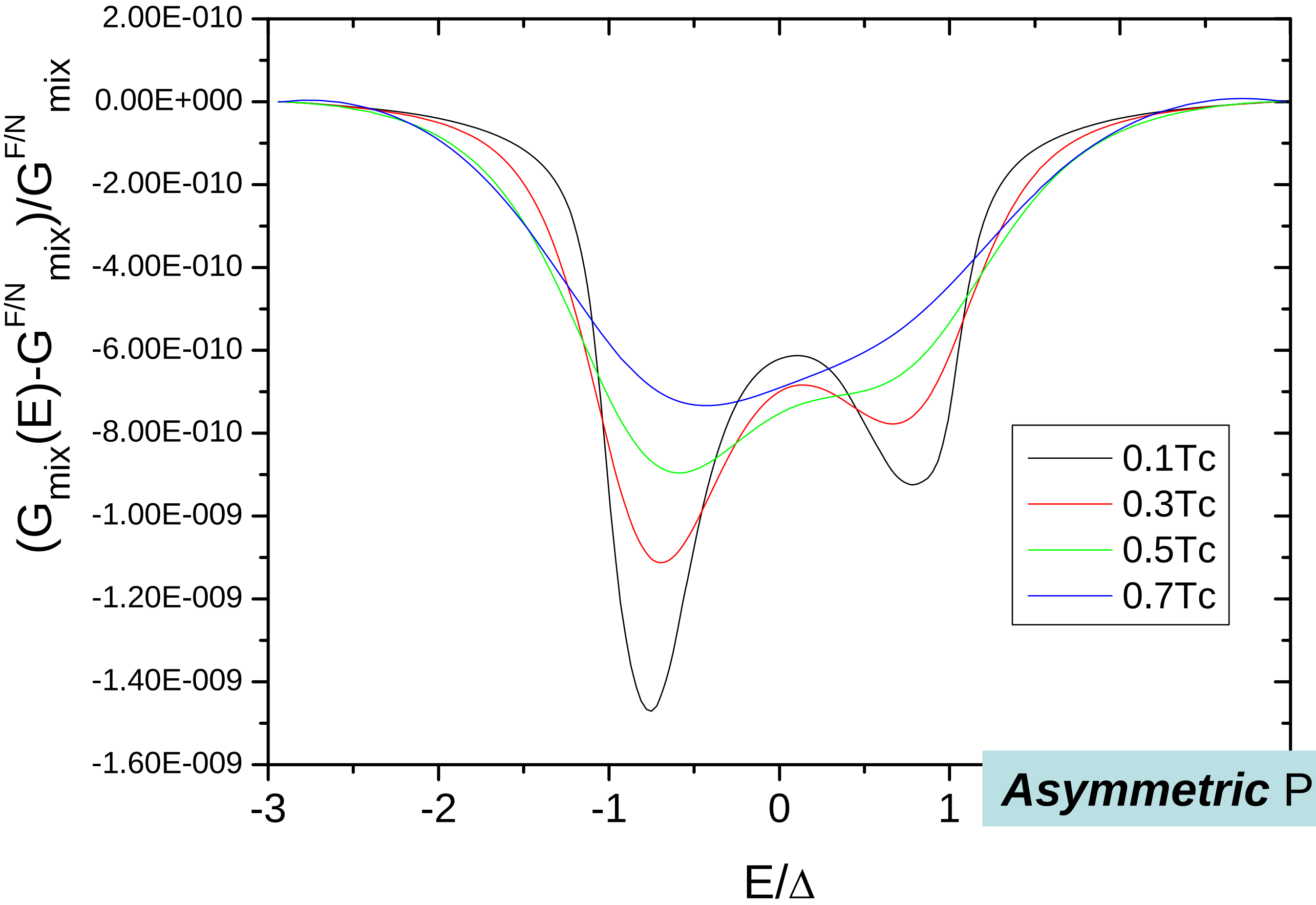
$$G_0 = \frac{2e^2}{h} |t_{\uparrow}|^2 |t_{\downarrow}|^2, \quad R^2 = |r'_{\uparrow}| |r'_{\downarrow}|$$

$$\delta = \phi_{\uparrow} - \phi_{\downarrow}$$

[1] C.W.J. Beenakker, Quantum Mesoscopic Phenomena and Mesoscopic Devices in Microelectronics, edited by I.O. Kulik and R. Ellialtioglu, pp. 51-60, (NATO Science Series, Dordrecht, 2000)

Mixing Conductance Spectrum

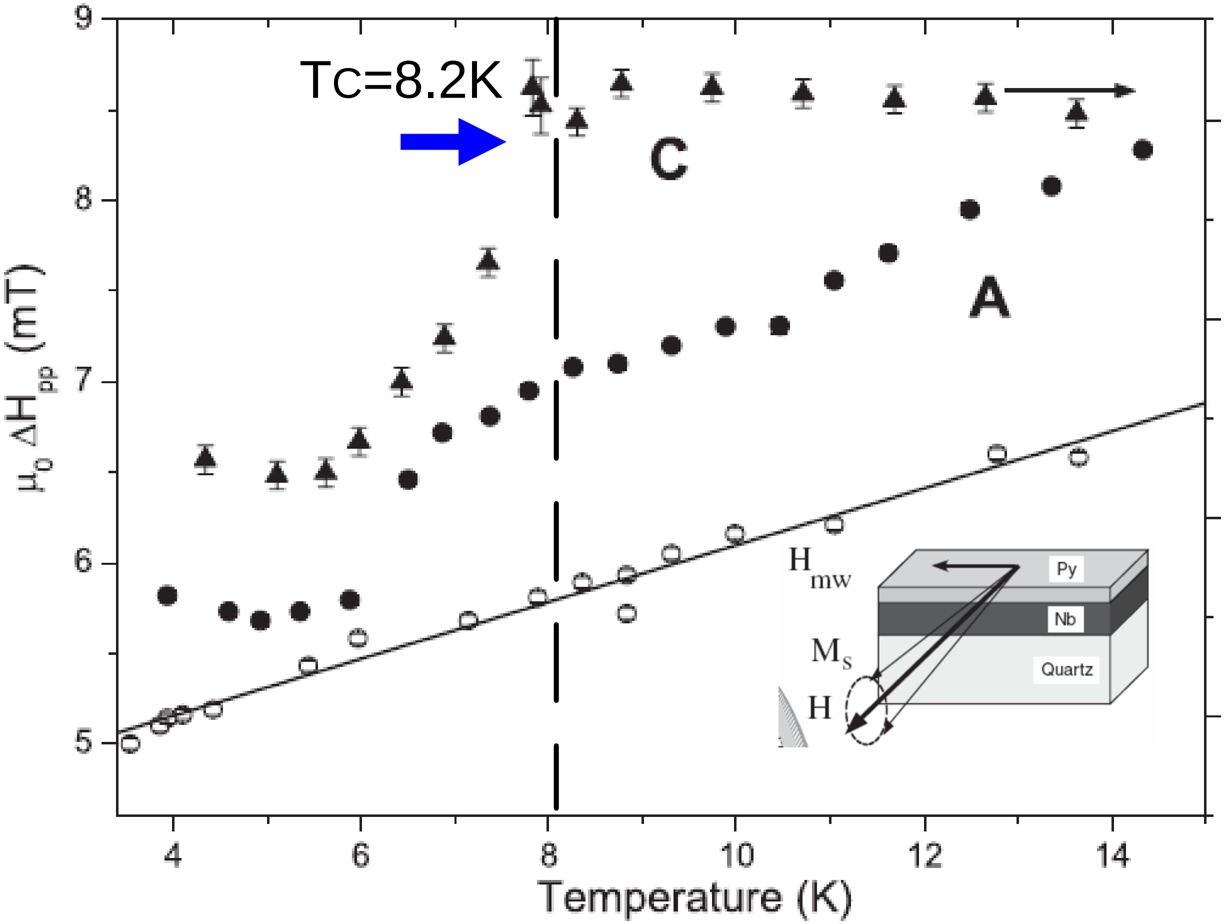
$$G^{\uparrow\downarrow}_{ee} = G^{\uparrow\downarrow}_{ne} + G^{\uparrow\downarrow\text{singlet}}_{ne} + G^{\uparrow\downarrow\text{triplet}}$$



Asymmetric Peaks below the gap

Temperature Dependence of Gilbert Damping Enhancement

Experiment: FMR linewidth



Sample A,C
Superconductor

Sample B

Non-superconductor

C. Bell J. Aarts *et al*
Phys.Rev.Lett.100,047002(2008)

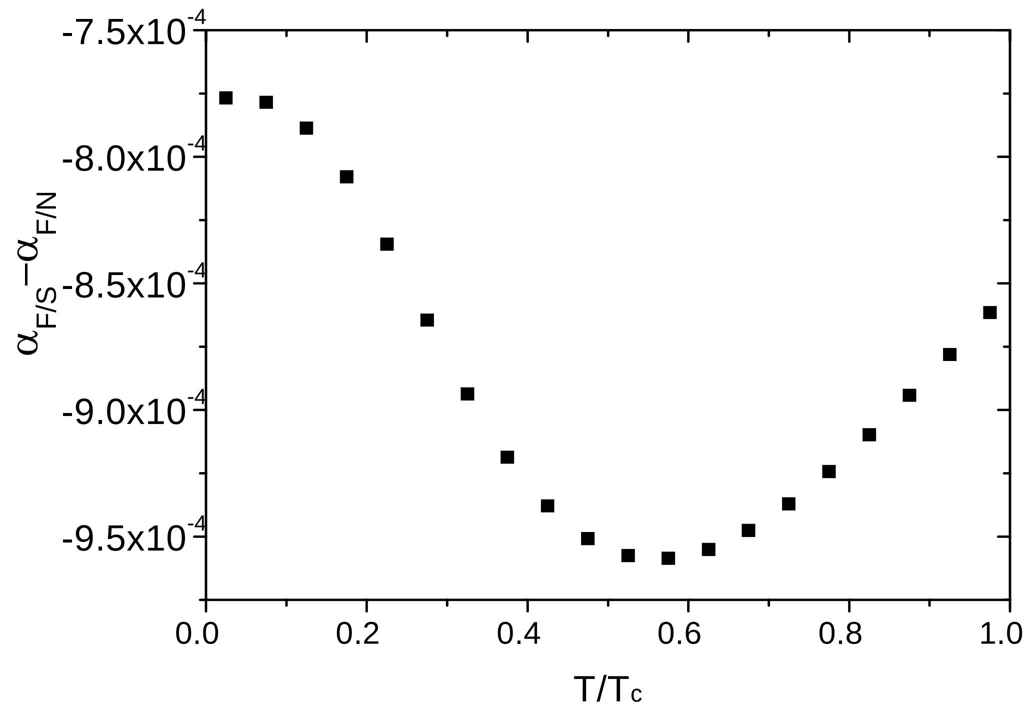
Temperature Dependence of Gilbert Damping Enhancement

T→ Tc, Δ (T) →0, $R_{he} \to 0,\ \delta\alpha_{F/S}(T)$ reduces to

$$\delta\alpha_{F/S} = \frac{\gamma\hbar}{4\pi M_s V}\int d\varepsilon \left(-\frac{\partial f}{\partial \varepsilon}\right)\left[N - \mathrm{Re}\,Tr\left(R^{\uparrow\uparrow}R^{\downarrow\downarrow\dagger}\right)\right]$$

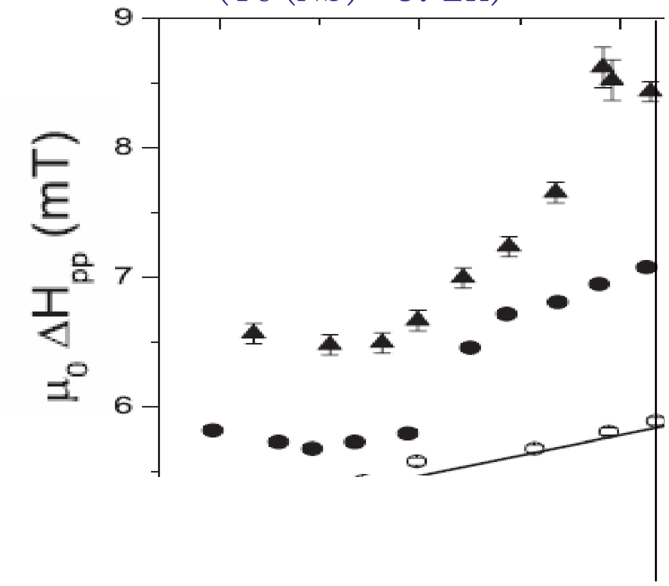
For $\mu_{Fe}=2.2\mu_B$

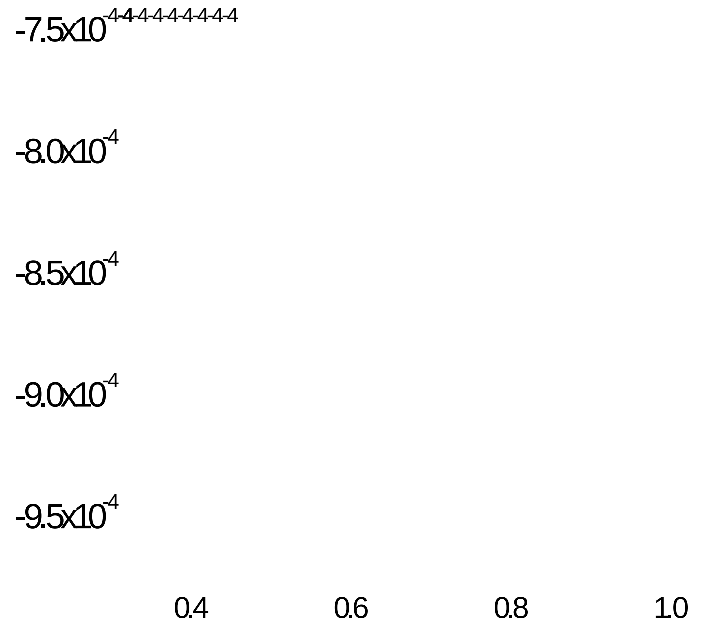
(Thickness of F layer is 10ML)



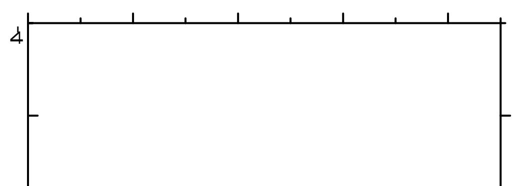
Temperature Dependence of Gilbert Damping Enhancement

FMR Experiment
(Tc(Nb)=8.2K)

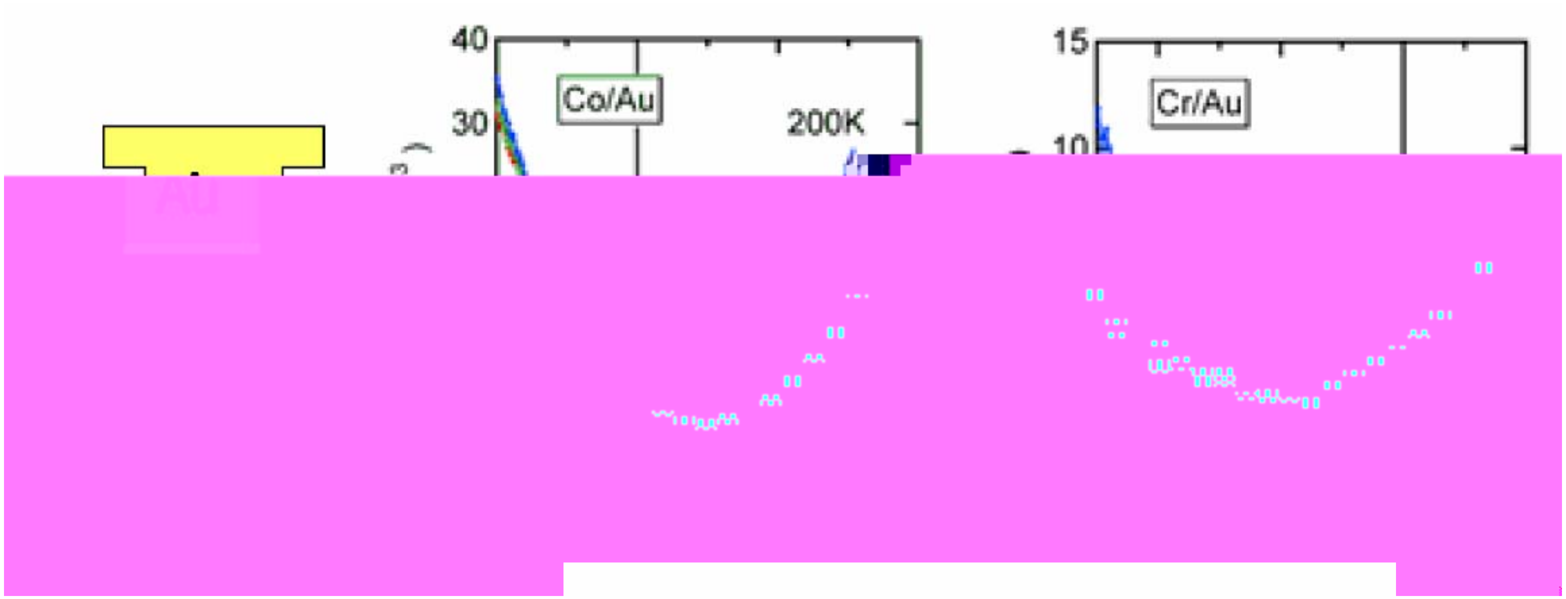


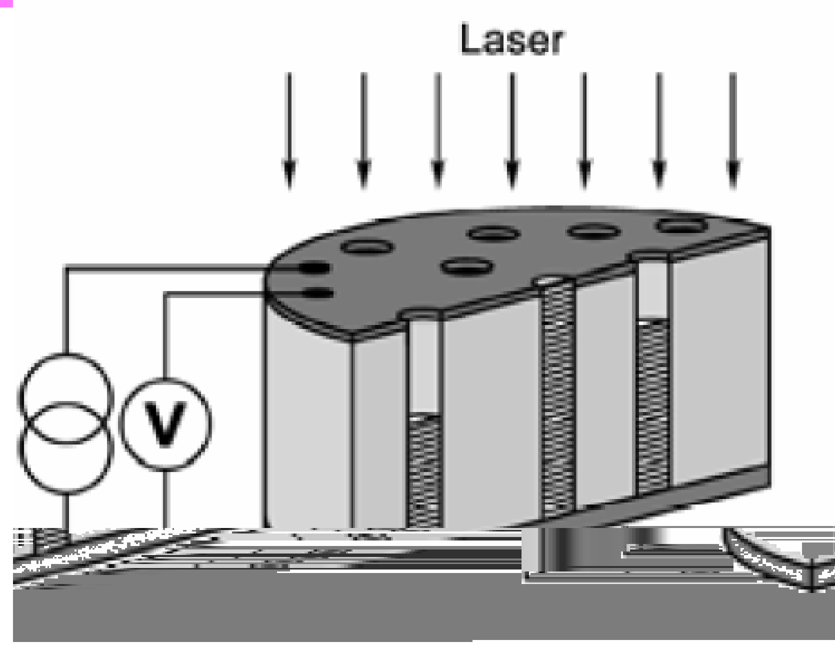


T/K



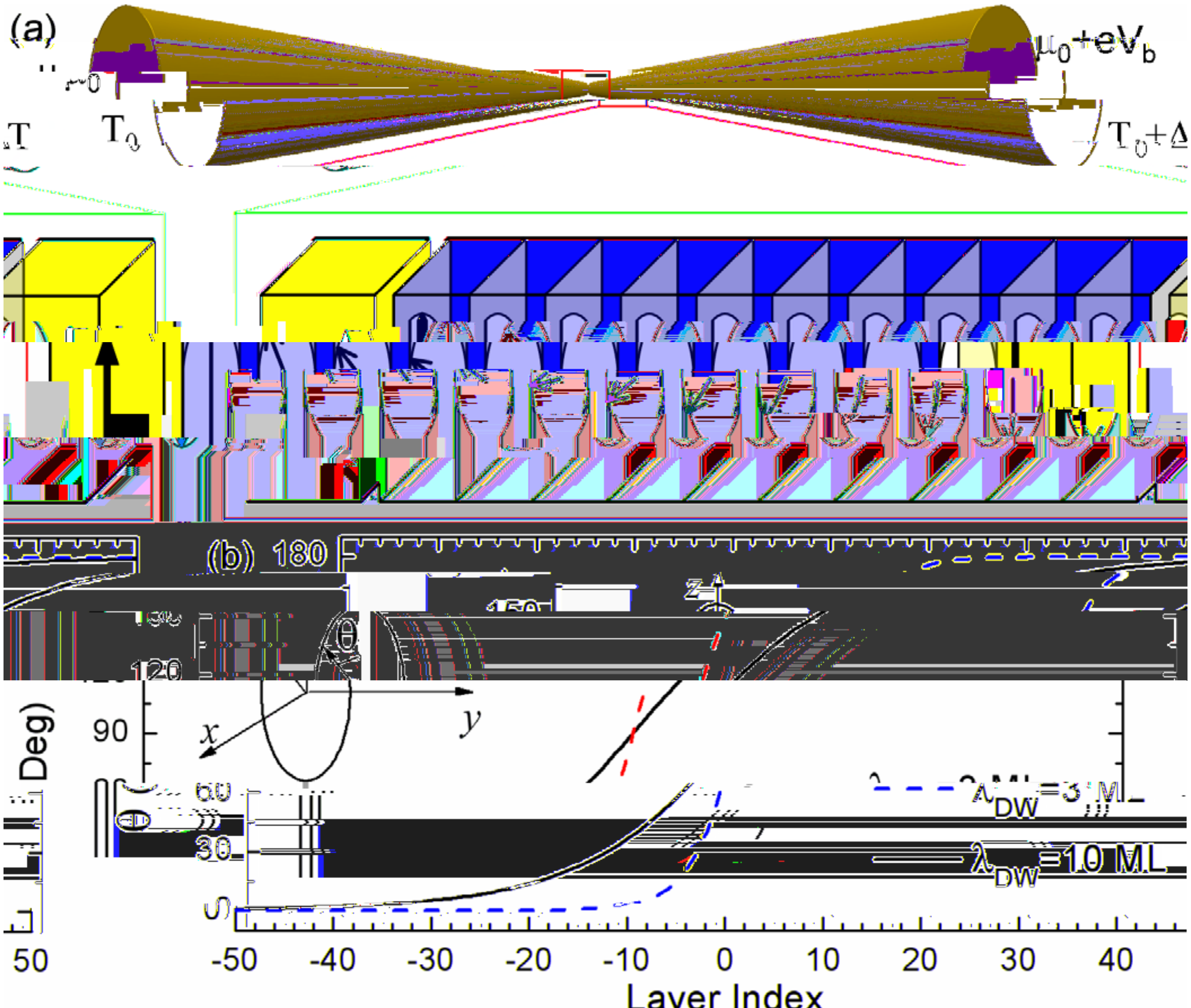
Metallic nanopillars (Fukushima et al., 2005)





L. Gravier et al. (2005).

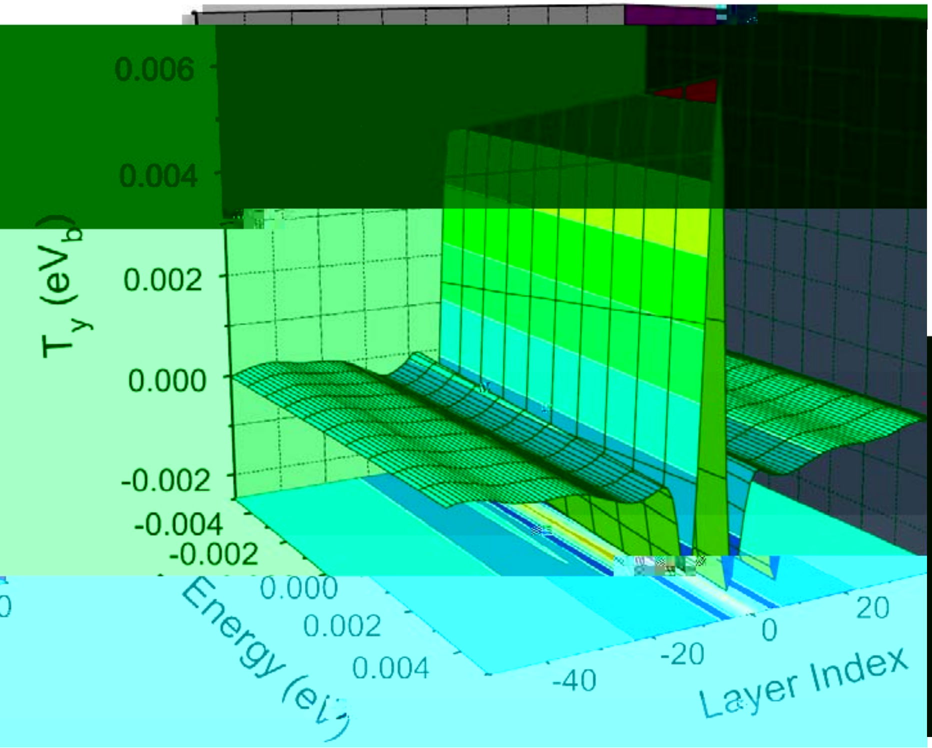
Model

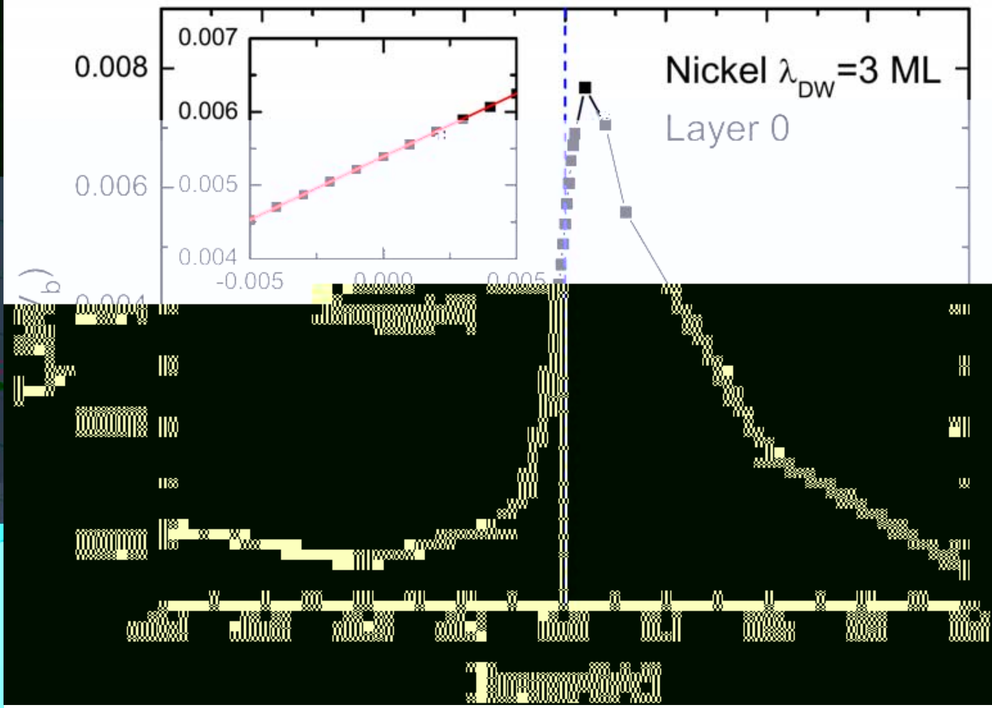

(a)
μ_0+eV_b
T_0
(b) 180
90
θ
x
y
λ_{DW}=10 ML
-50
-40
-30
-20
-10
0
10
20
30
40
50
Layer Index

First-principles spin-transfer torque

$$\hat{\mathcal{J}} \equiv \frac{1}{2}\left[\hat{\sigma} \otimes \hat{\mathbf{V}} + \hat{\mathbf{V}} \otimes \hat{\sigma}\right]$$

$$\mathbf{T}_{\mathbf{R}}(\mathbf{k}_{\parallel}, \epsilon) = \sum_{\mathbf{R}' \in I-1, I} \mathcal{J}_{\mathbf{R}',\mathbf{R}}(\mathbf{k}_{\parallel}, \epsilon) - \sum_{\mathbf{R}' \in I, I+1} \mathcal{J}_{\mathbf{R},\mathbf{R}'}(\mathbf{k}_{\parallel}, \epsilon)$$

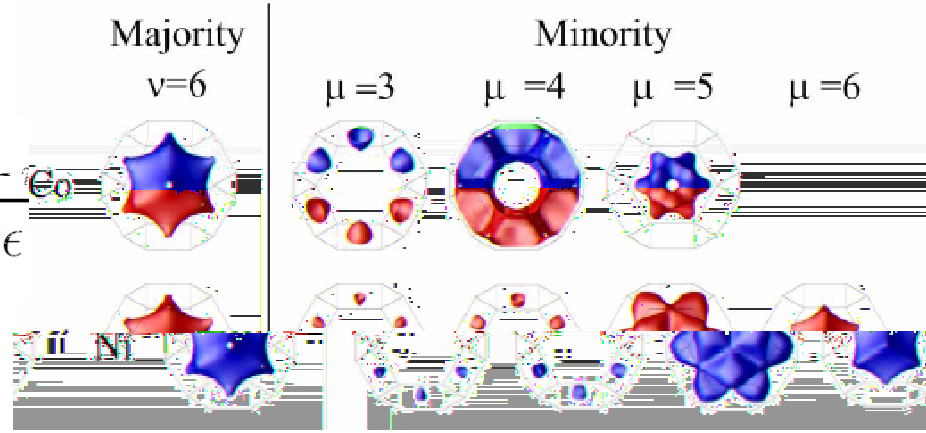


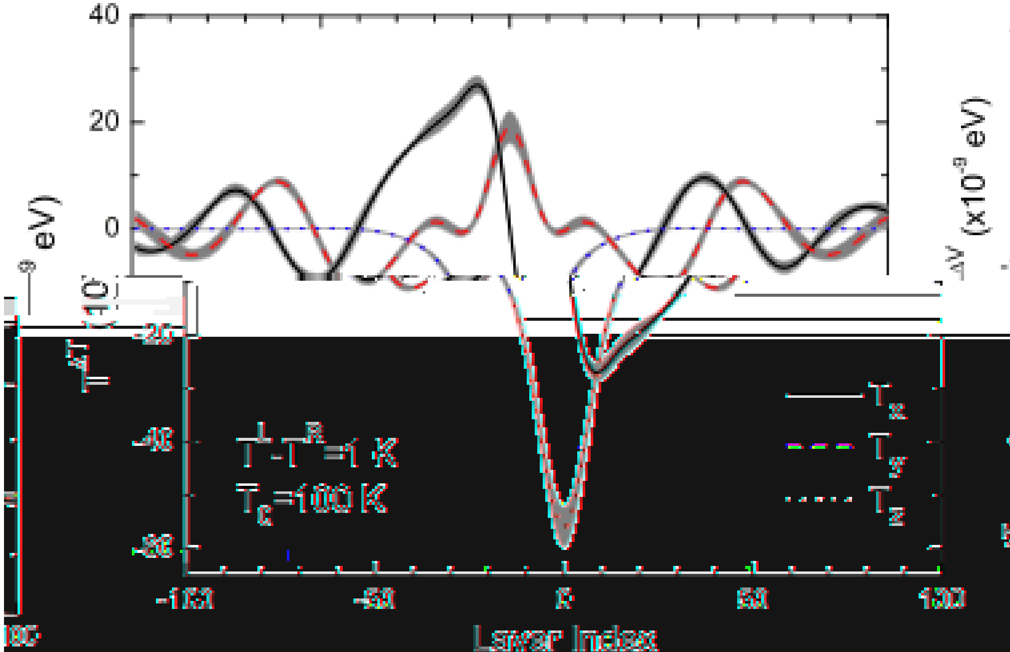


Z. Yuan,S. Wang, KX, Solid State Communication(Spin Caloritronics) (2009).

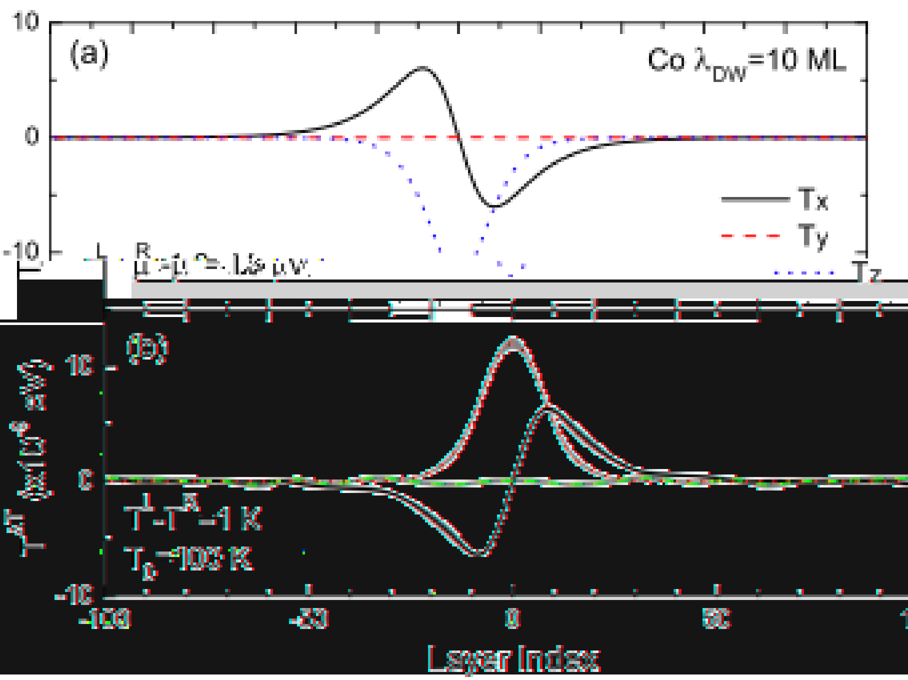
Bias- and temperature-STT

$$\mathbf{T}_n = \cdot \Big|_{\epsilon=\mu_0} \tilde{\mathbf{T}}_n e V_b + \frac{\pi^2 k_B^2 T \Delta T}{3} \frac{\partial \tilde{\mathbf{T}}}{\partial \epsilon}$$





Ni:



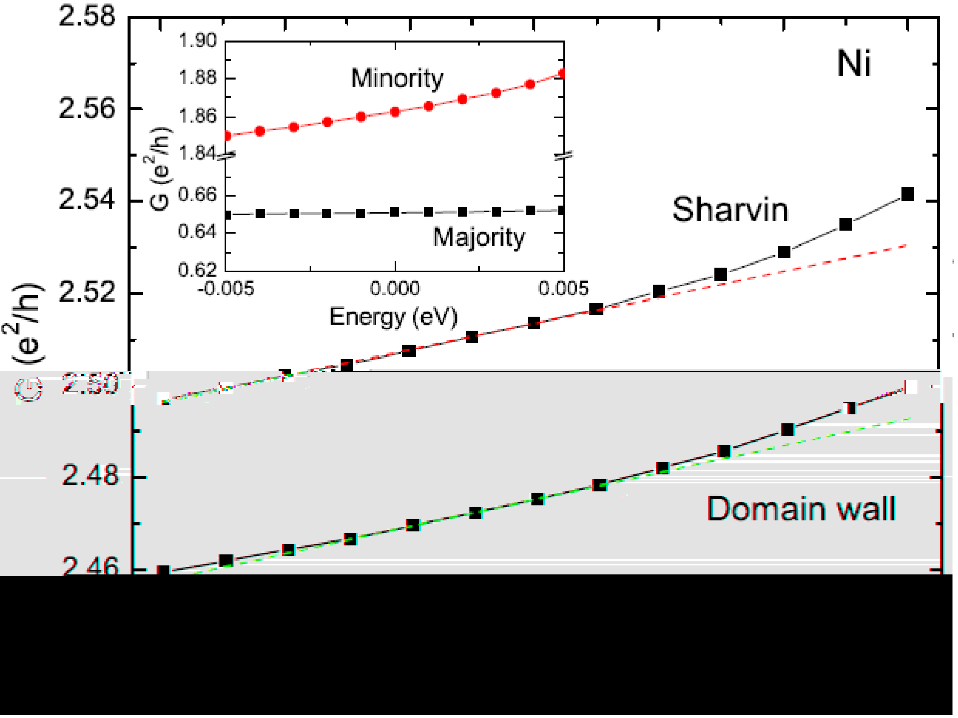
Co:

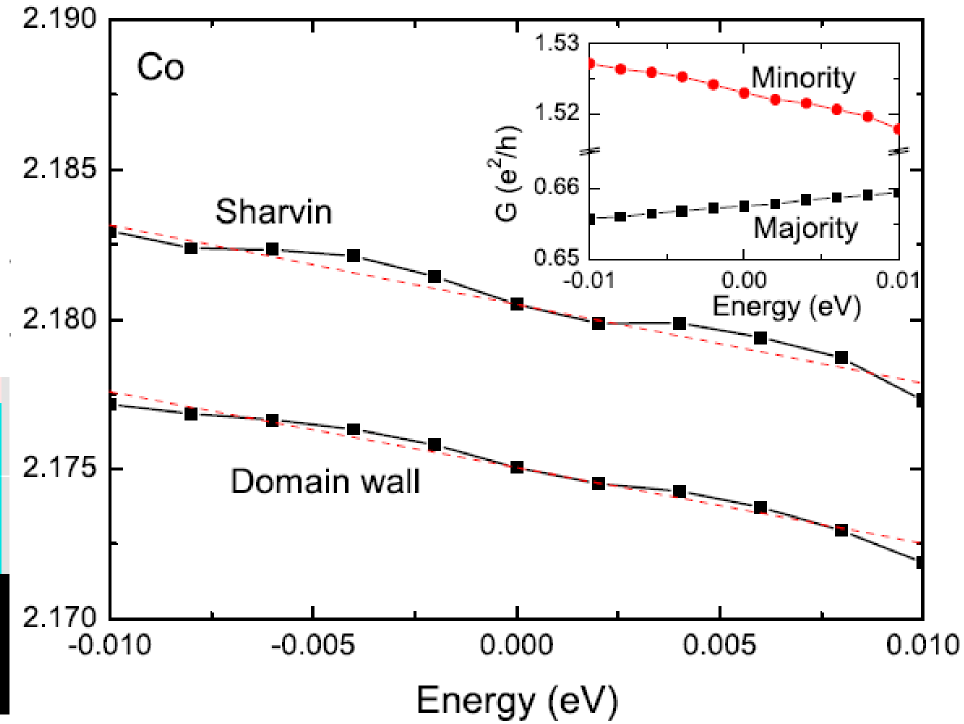
Peltier and Seebeck coefficients

	G' (e/hV)	G (e^2/h)	$\partial_\epsilon \ln G|_{\epsilon_F}$ (eV^{-1})	S/T (nV/K^2)
Ni domain wall	2.94	2.48	1.19	-28.9
Ni Sharvin	2.84	2.51	1.13	-27.5
Polarized Sharvin	–	–	0.57	-13.9
Co domain wall	-0.253	2.175	-0.116	2.83
Co Sharvin	-0.264	2.181	-0.121	2.95
Polarized Sharvin	–	–	0.184	-4.50

$$P \equiv \frac{w_\uparrow G_\uparrow - w_\downarrow G_\downarrow}{w_\uparrow G_\uparrow + w_\downarrow G_\downarrow}$$

$$\bar{S} = w_\uparrow S_\uparrow + w_\downarrow S_\downarrow$$





Messages

Spin-dependent transport properties of interfaces govern many magnetoelectronic phenomena.

Agreement between interface-dominated transport properties calculated by first principles and the isotropy assumption with experimental values is (semi)-quantitative for itinerant systems like transition metals.

Mixing conductance and spin-torque can be calculated and measured accurately.

Computational Material Science

The End