A Thermagnonic Mechanism for Spin-Transfer Torque (STT)

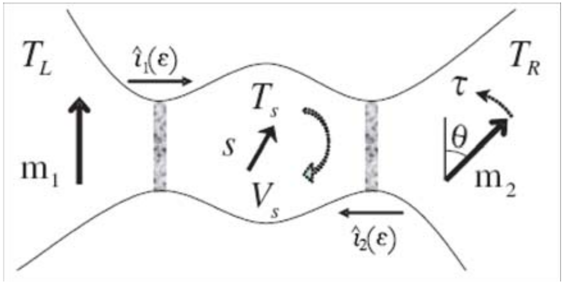
J. Slonczewski, Phys. Rev. B **82,** 054403 (2010)

Outline

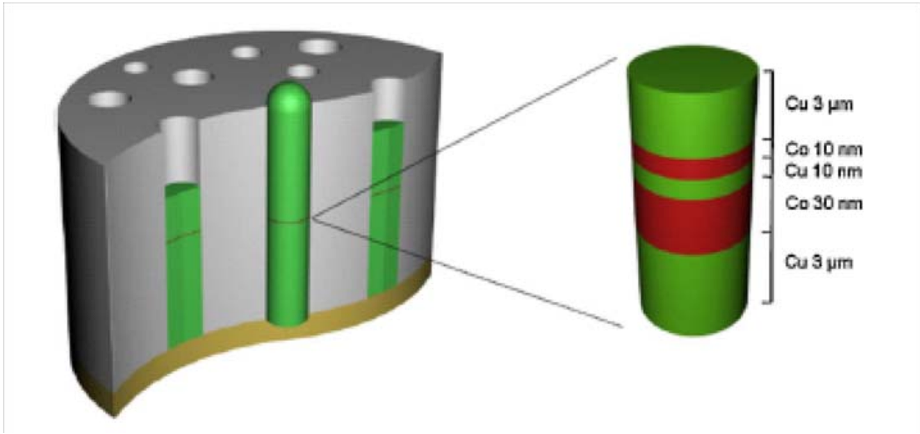
- Background of thermal STT mechanisms
- Physics of thermagnonic spin transfer
- An estimate of in-plane torque yield
- A crucial question of electron structure
- Summary

Background of spin transfer driven by heat flow

- **Theoretical prediction of spin-transfer torque driven by heat flow through an all-metallic multilayer**: M. Hatami, G. E. W. Bauer, Q. Zhang, and P. J. Kelly, Phys. Rev. Lett. **99**, 066603 (2007).



- **Observation of magnetic-field switching assisted by heat flow in an all-metallic multilayer**: H. Yu, S. Granville, D. P. Yu, and J. P. Ansermet, Phys. Rev. Lett. **104**, 146601 (2010).



Physics of thermagnonic spin transfer

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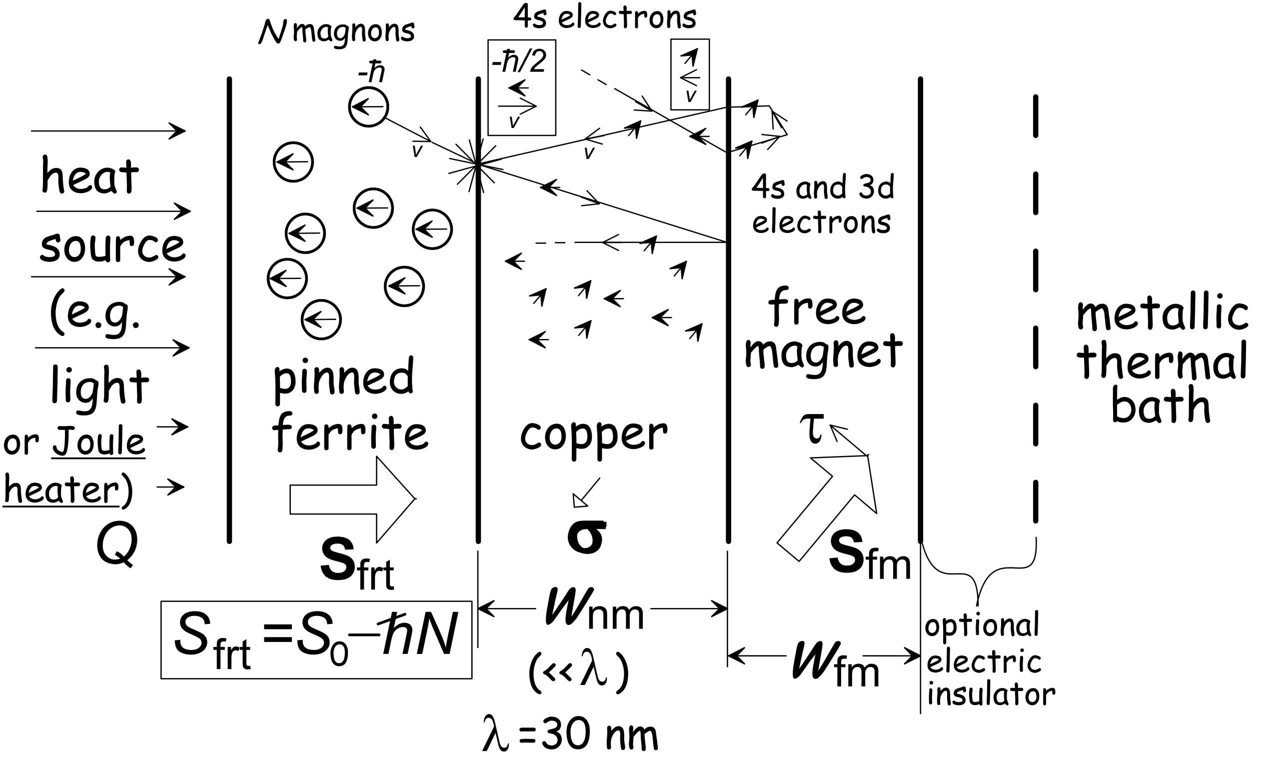
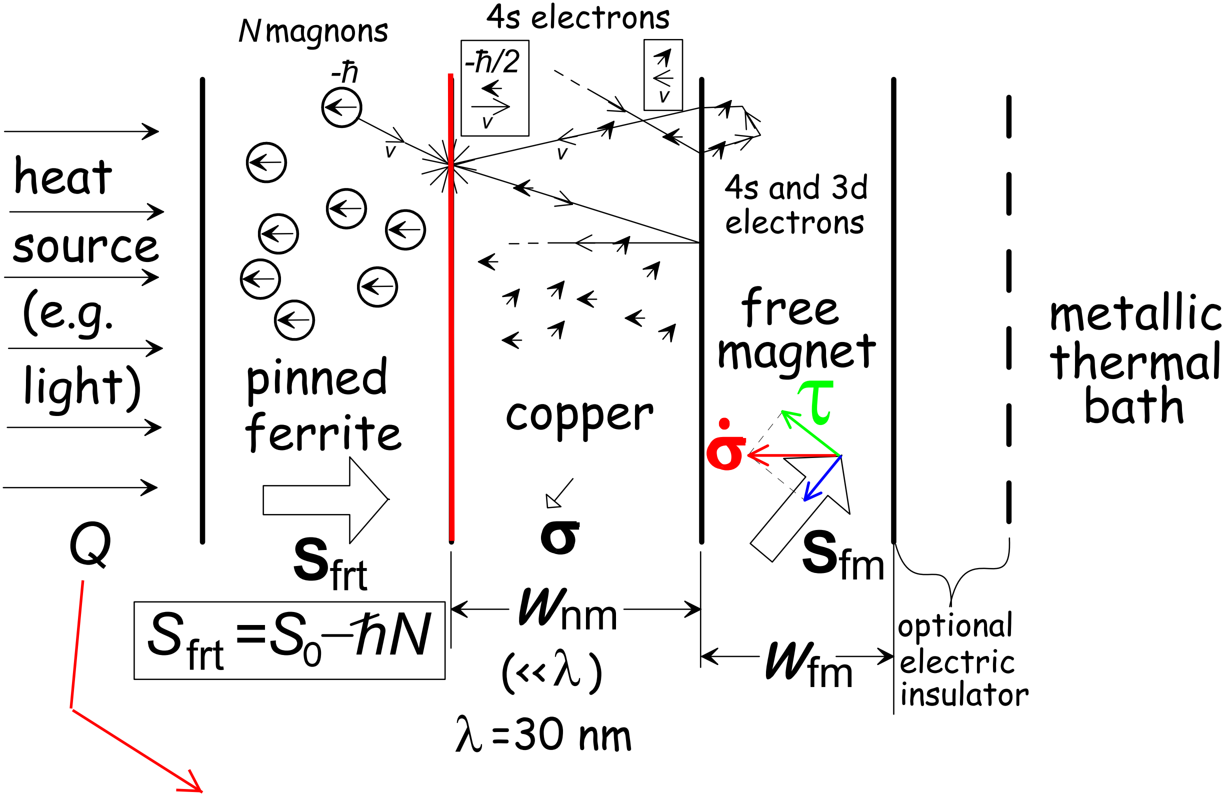




heat flow from Joule heater: Q = IV

$\boldsymbol{\sigma}$ = spin moment of 4s (free) electrons

$\dot{\boldsymbol{\sigma}}$ = spin current at ferrite/copper interface

$$\tau = \dot{\sigma} \sin\theta$$

Quantum torque yield

Define a numerical quantum yield ε of current-driven spin-transfer torque by the output-to-input ratio

$$\varepsilon = \left| \frac{\text{transferred spin momentum}}{\hbar} \div \frac{\text{spent electric charge}}{e} \right|$$

for $\sin\theta = \pi/2$. For a magnetic tunnel junction (MTJ), $\varepsilon_{\text{mtj}} \leq 1/2$.

Quantum yield permitted by ferrite/noble-metal interface

Assume the presence of an octahedral-site magnetic monolayer with 3d spins $\mathbf{S}_j$ at the ferrite/noble-metal interface.

Spin operator is $\hbar\mathbf{S}_j$ ($j = 1, 2, ..N_\mathrm{d}$),

Effective molecular-field exchange energy is $-\underline{\mathbf{F}(T)\ \cdot\mathbf{S}_j}$.

The system includes the magnetic monolayer and conduction electrons of the noble-metal film. The hamiltonian is

$$H = -\underline{\mathbf{F}}\cdot\sum_{j=1}^{N}\mathbf{S}_j-(\underline{J_\mathrm{sd}}/n)\sum_{i,j}\mathbf{s}_i\cdot\mathbf{S}_j+\sum_{i=1}^{n}(\mathbf{p}_i^2/2m_e).$$

The transition $\Delta m_j = \pm 1$ in the magnetic energy $-Fm_j$ $(m_j = -S, -S+1, \dots S)$ of the j-th interfacial atomic moment determines the inherent quantum yield. This inherent yield amounts to

$$\varepsilon_\mathrm{inh} = |eV/F| \approx 10^2\,V$$

Thus the interface permits a large inherent yield.

Useful quantum yield

But alas, in practice the inherent yield $\varepsilon_{\text{inh}} = e|V|/F$ is not available. The interfacial heat flow via phonons (Kapitza) exceeds that via magnons. The *useful* quantum yield is reduced in proportion to the respective interfacial thermal conductances:

$$\varepsilon_{\text{us}} = |eV/F|[1 + (G_{\text{Kap}}/G_{\text{fs}})]^{-1}, \; G_{\text{fs}} = (G_{\text{fd}}^{-1} + G_{\text{ds}}^{-1})^{-1}$$

Define the thermal s-electron spin moment: $\boldsymbol{\sigma} = \left\langle \sum_i^{N_s} \mathbf{s}_i \right\rangle$

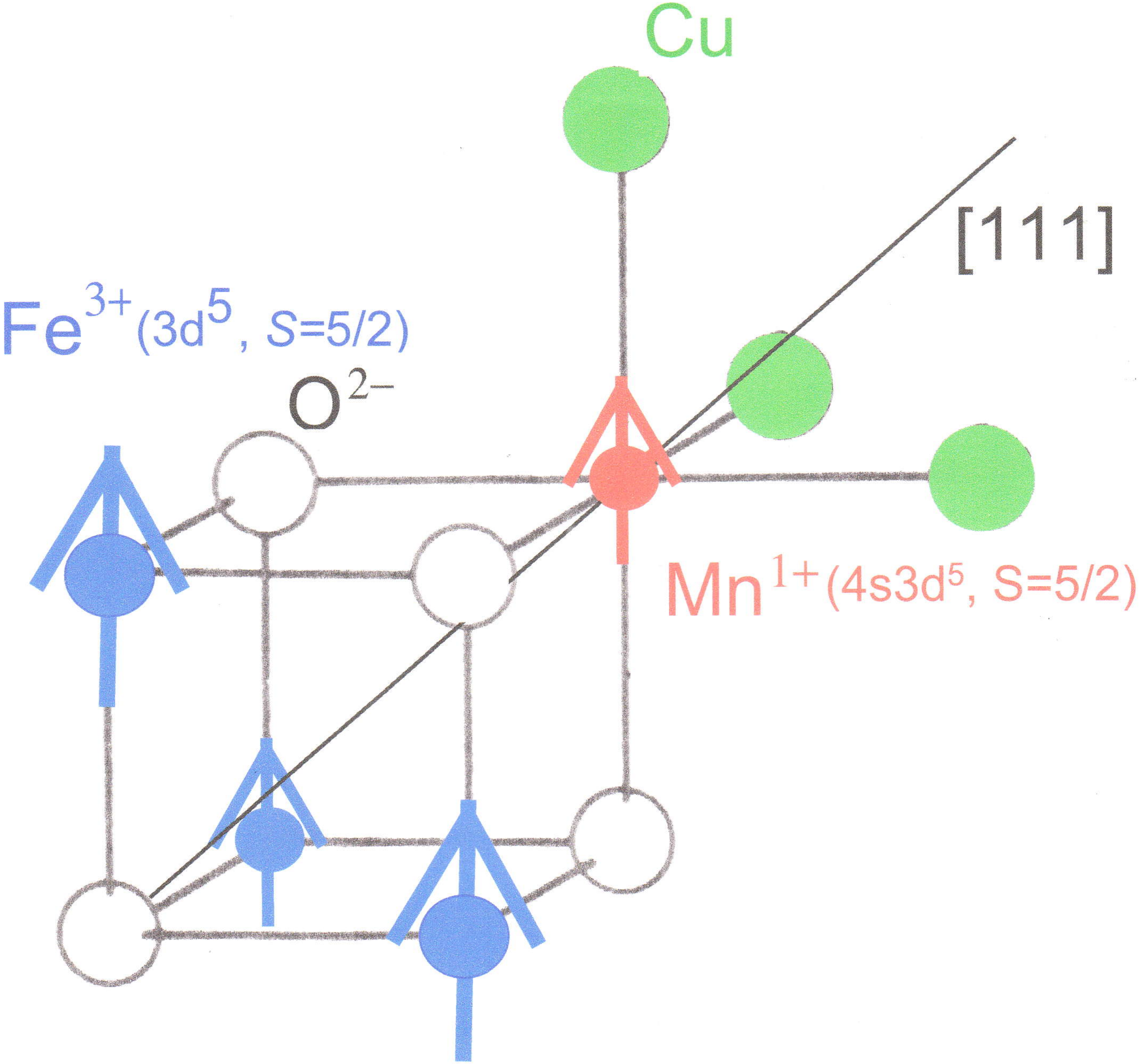
Bloch-type dynamic equation (Hasegawa, 1959):

$$\dot{\boldsymbol{\sigma}} + \lambda \left\langle \sum_j \mathbf{S}_j \right\rangle \times \boldsymbol{\sigma} = \nu_{\text{ds}} \left(\left\langle \sum_j \mathbf{S}_j \right\rangle - \left\langle \sum_j \mathbf{S}_j \right\rangle_{\text{equil}} \right) - \nu_{\text{s}} \boldsymbol{\sigma}.$$

The d-to-s spin-relaxation rate (Korringa) is

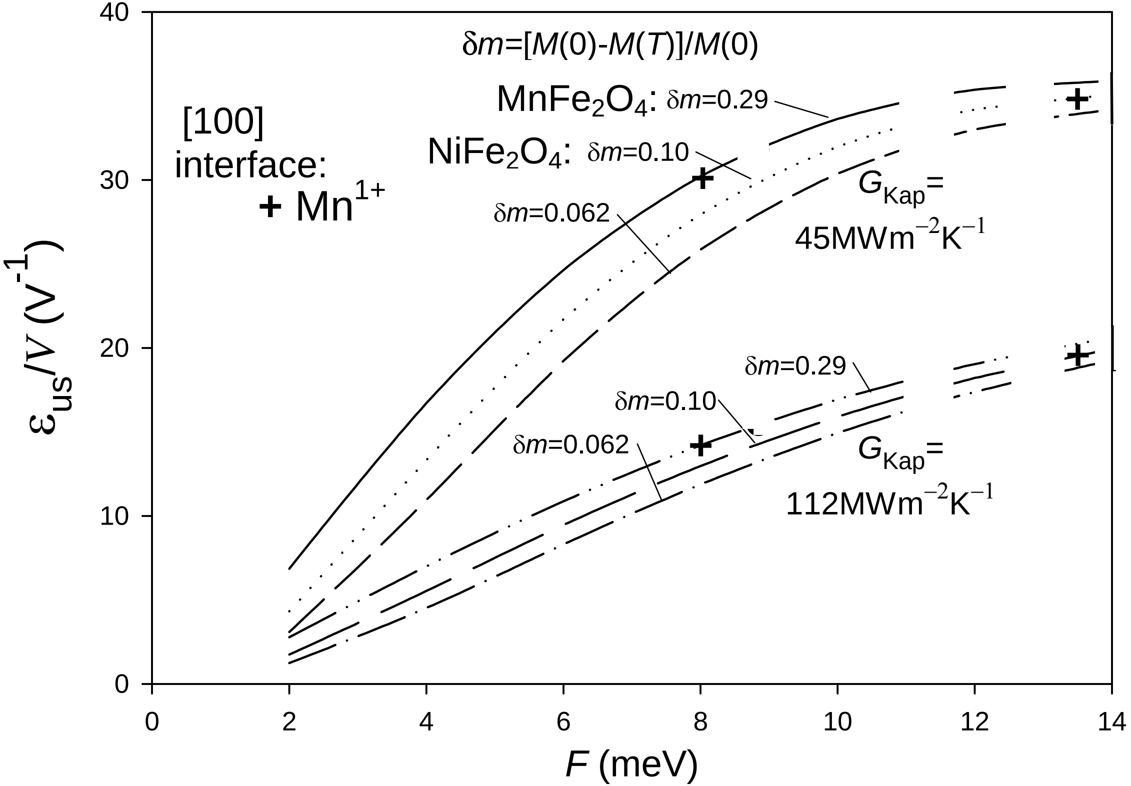
$$\nu_{\text{ds}} = (\pi/\hbar)(J_{\text{sd}}\rho)^2 k_{\text{B}} T,$$

interface: $MnFe_2O_4|Mn|Me$



Electron Structure of Mn

known	known	plausibly inferred
in ionic ferrite	impurity in metal	in interface
Mn^{2+}, $3d^5$	Mn^0, $(4sp)^2\ 3d^5$	Mn^{1+}, $(4sp)^1 3d^5$
$S = 5/2$	5/2	5/2
electrons = 5	7	6


δm=[M(0)-M(T)]/M(0)
MnFe₂O₄: δm=0.29
NiFe₂O₄: δm=0.10
δm=0.062
[100] interface:
+ Mn¹⁺
G_Kap= 45MWm⁻²K⁻¹
δm=0.29
δm=0.10
δm=0.062
G_Kap= 112MWm⁻²K⁻¹
ε_us/V (V⁻¹)
F (meV)
0
10
20
30
40
0
2
4
6
8
10
12
14

Summary and discussion

- For thermagnonic spin transfer one must make two replacements:

  pinned magnet: metallic ⇒ ferrimagnetic
  driving flow: electricity ⇒ heat

- In-plane torque for thermagnonic spin transfer:

$$\boldsymbol{\tau}_{\text{tmg}} = \pm\varepsilon_{\text{us}}\hbar|I/e|(\mathbf{m}_{\text{ref}} \times \mathbf{m}_{\text{fm}}) \times \mathbf{m}_{\text{fm}}. \quad (\varepsilon_{\text{us}} \propto V)$$

- Thermagnonic spin transfer may provide a significant increase of available torque in nano devices: $\varepsilon_{\text{us}} \gg \varepsilon_{\text{mtj}}$
- One disadvantage for MRAM and storage devices is that the torque does not reverse with the sign of the driving current.
- A time delay (perhaps 1 ns per nm of ferrite thickness) needs investigation.