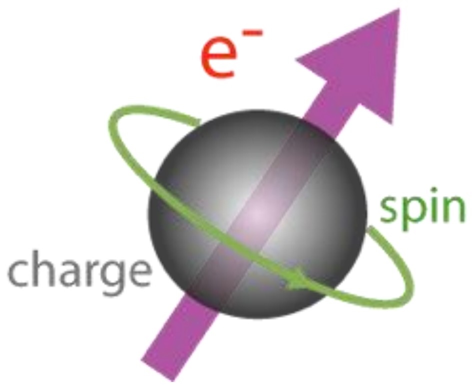
Coupling between heat transport and spin transport in metallic ferromagnets

Gyung-Min Choi

Center for Spintronics
Korea Institute of Science and Technology

Spin

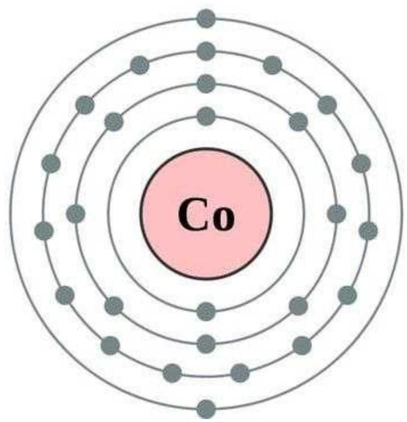
Electron



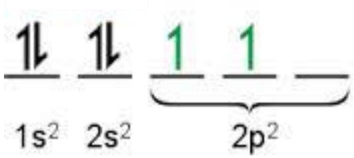
Spin angular momentum

$$\frac{1}{2}\hbar$$

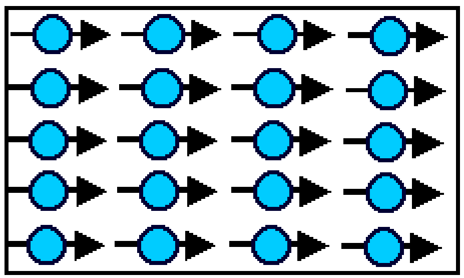
Atom



Hund's rule



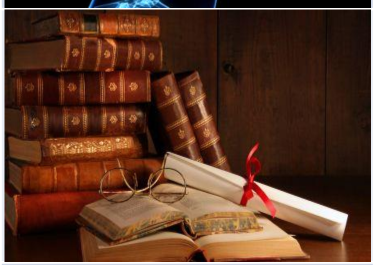
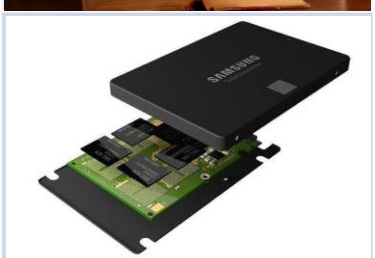
Solid



Heisenberg's exchange

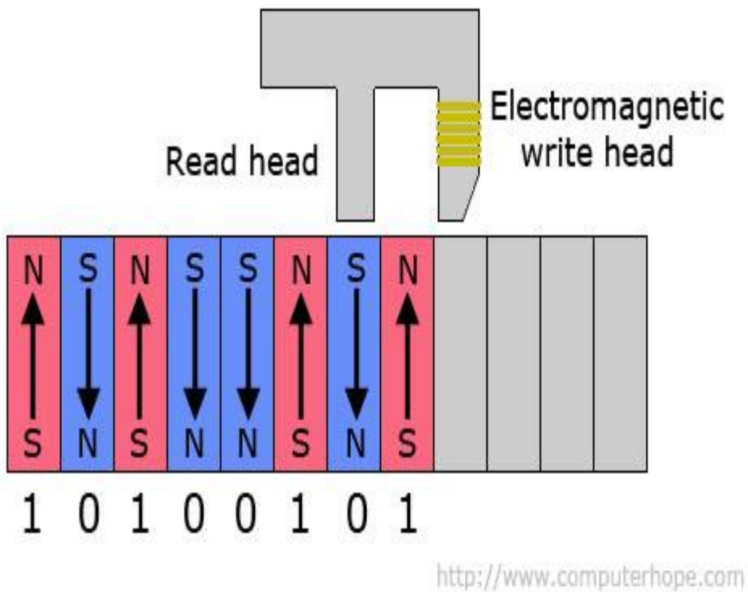
$$\hat{H}^{\text{Heis}} = -J\,\hat{\vec{S}}^{A}\cdot\hat{\vec{S}}^{B}$$

Memory

	Write	Read
	Connection of neurons	Electro-chemical
	Arrangement of ink	Optical
	Confinement of electron	Electrical
	Direction of spin	Electrical

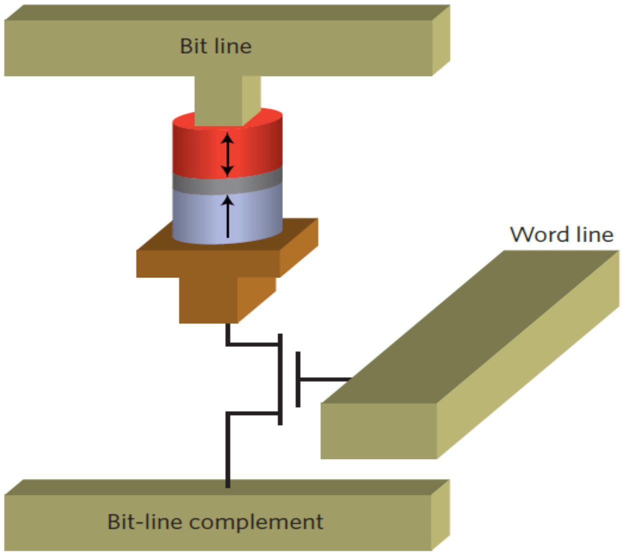
Spin Memory

Hard disk drive



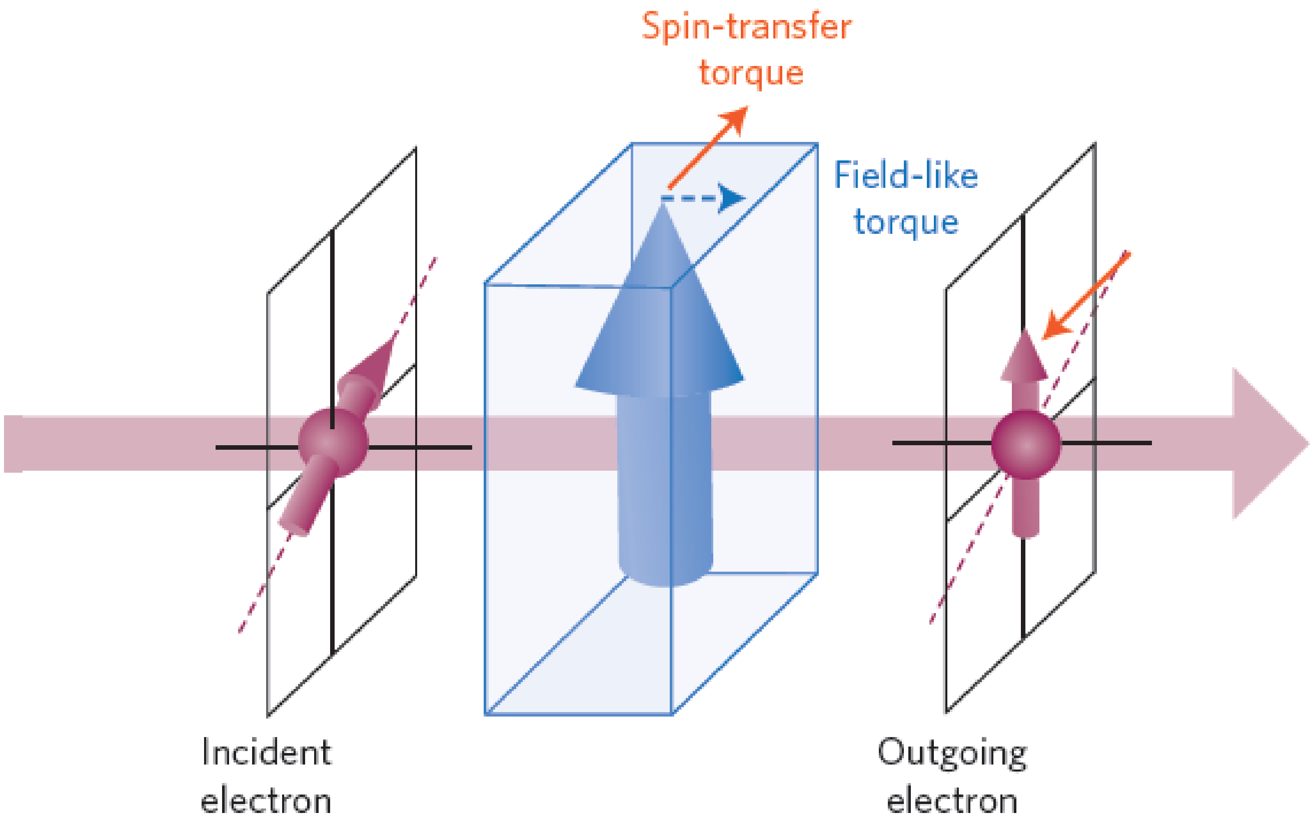
Access time: a few ms

Magnetic random access memory



Access time: a few tens of ns

Spin transfer torque

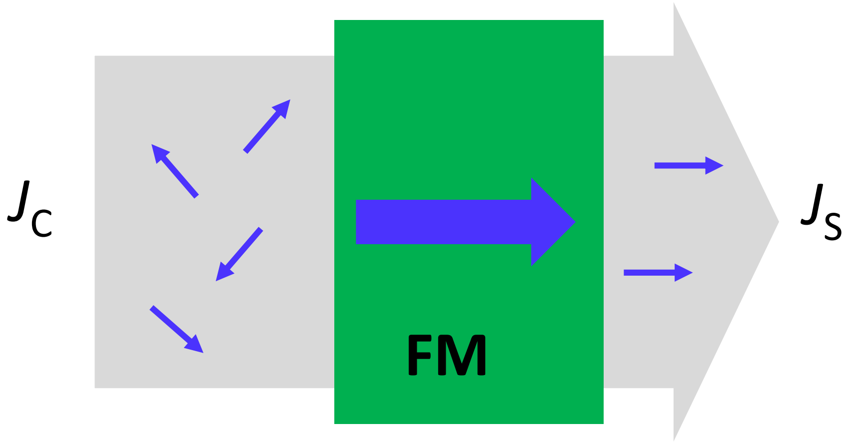


Spin current can rotation local magnetization.

Slonczewski JMMM (1996)
Berger PRB (1996)

Quantum yield

Electrical spin generation → Spin filter effect

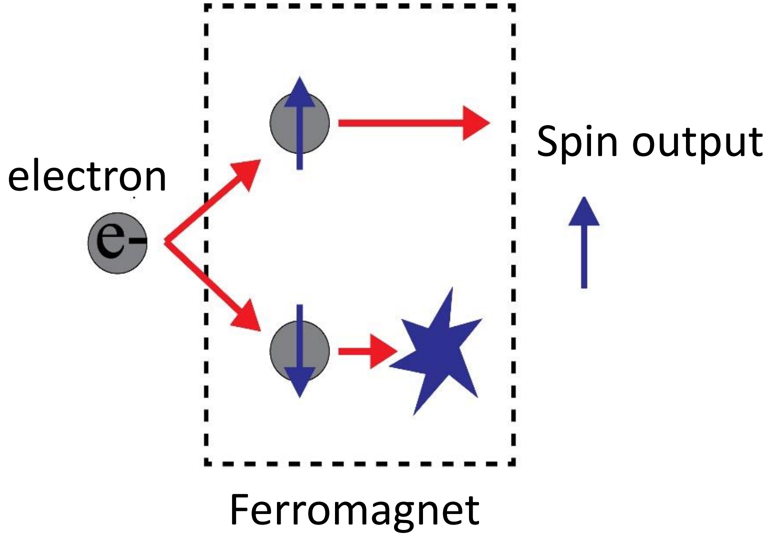


$$\varepsilon = \frac{\text{spin}}{\text{electron}} = \frac{\text{spin angular momentum}/\hbar}{\text{electric charge}/e} = \frac{1}{2}$$

Slonczewski PRB (2010)

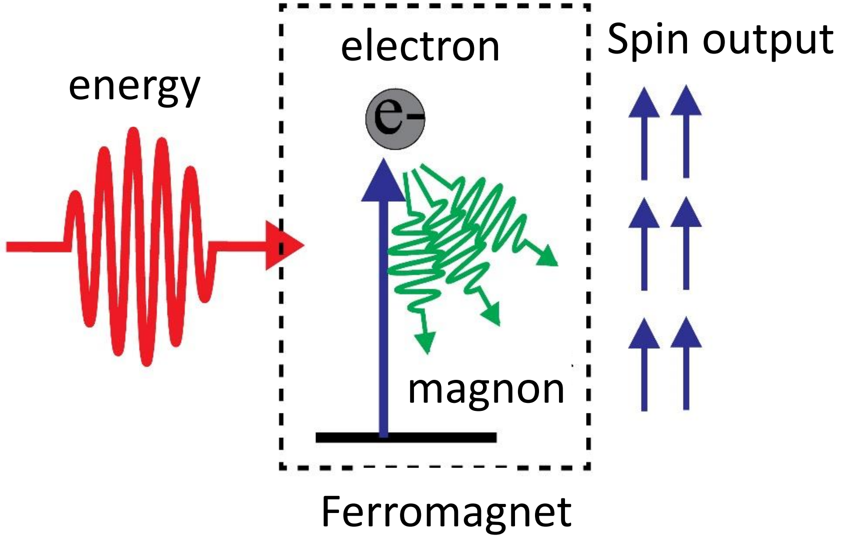
Quantum yield for thermal spin

Electrical spin generation



$$\varepsilon < \frac{1}{2}$$

Thermal spin generation



$$\varepsilon >? \frac{1}{2}$$

Slonczewski PRB (2010)

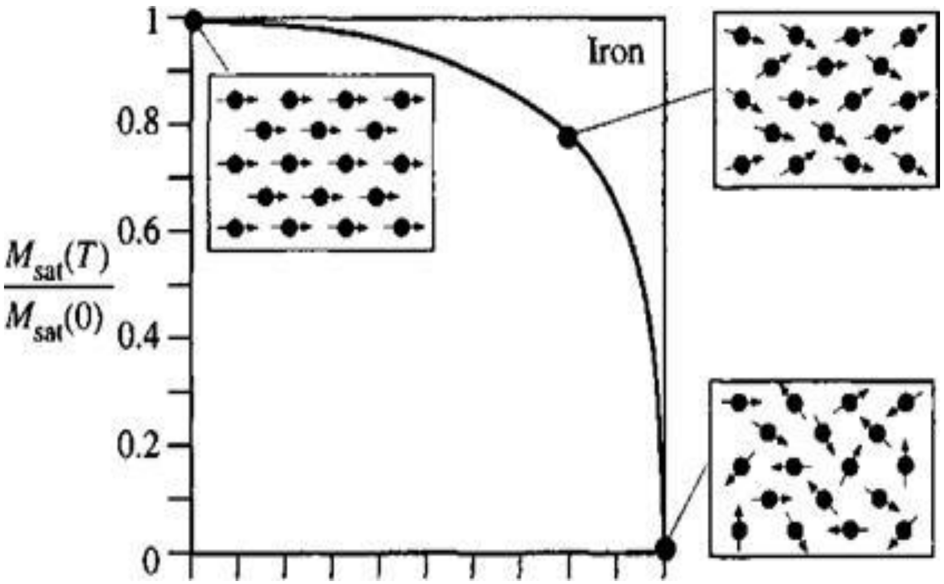
Thermal spin generation in metallic ferromagnet

Part 1: Ultrafast demagnetization

Part 2: Spin-dependent Seebeck effect

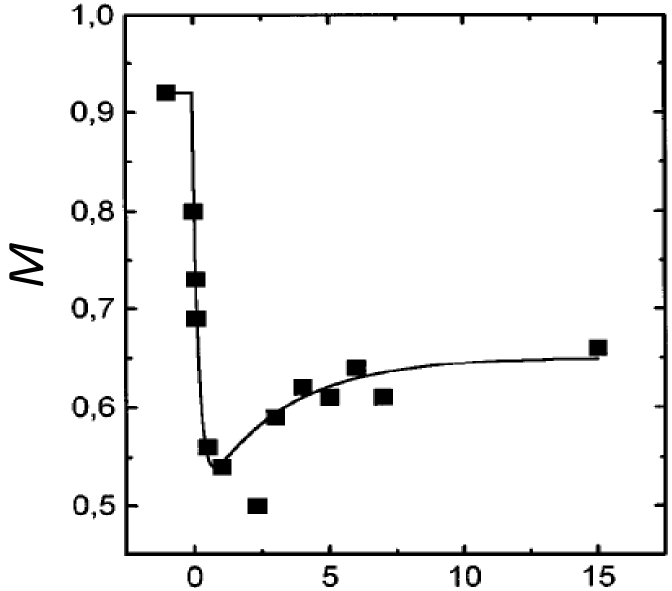
Ultrafast demagnetization

Slow heating



Temperature

Ultrafast heating

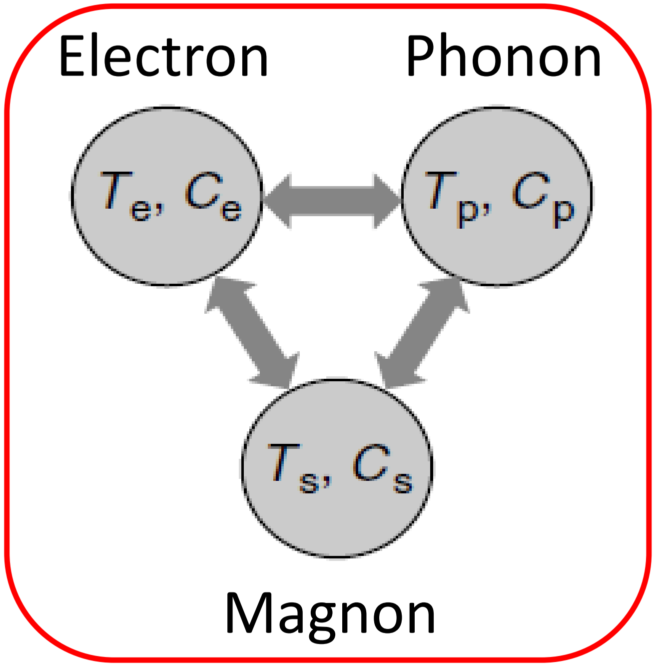


Time (ps)

Beaurepaire *et al.* PRL (1996)

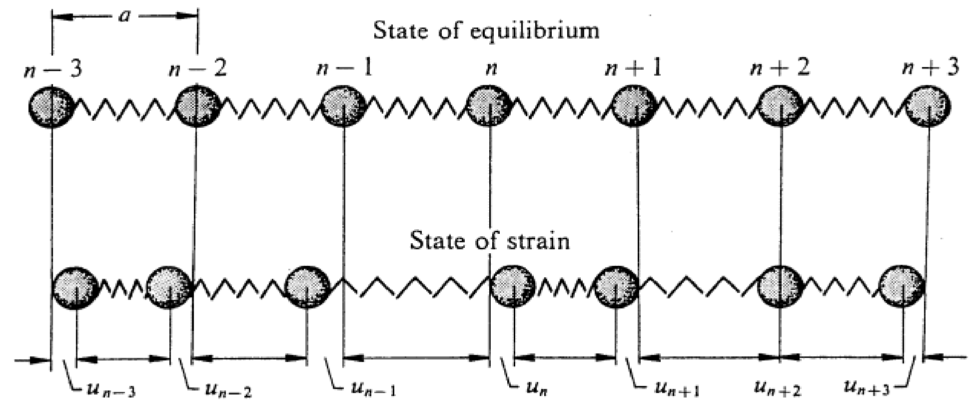
Three temperature model

Three heat reservoir

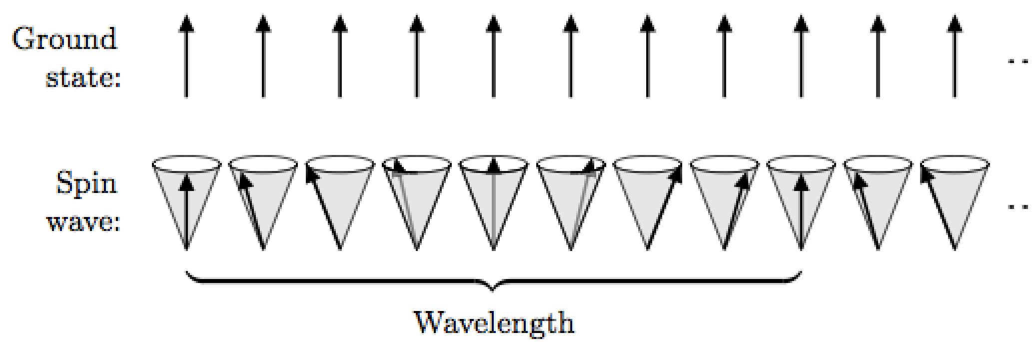


Beaurepaire *et al.* PRL (1996)

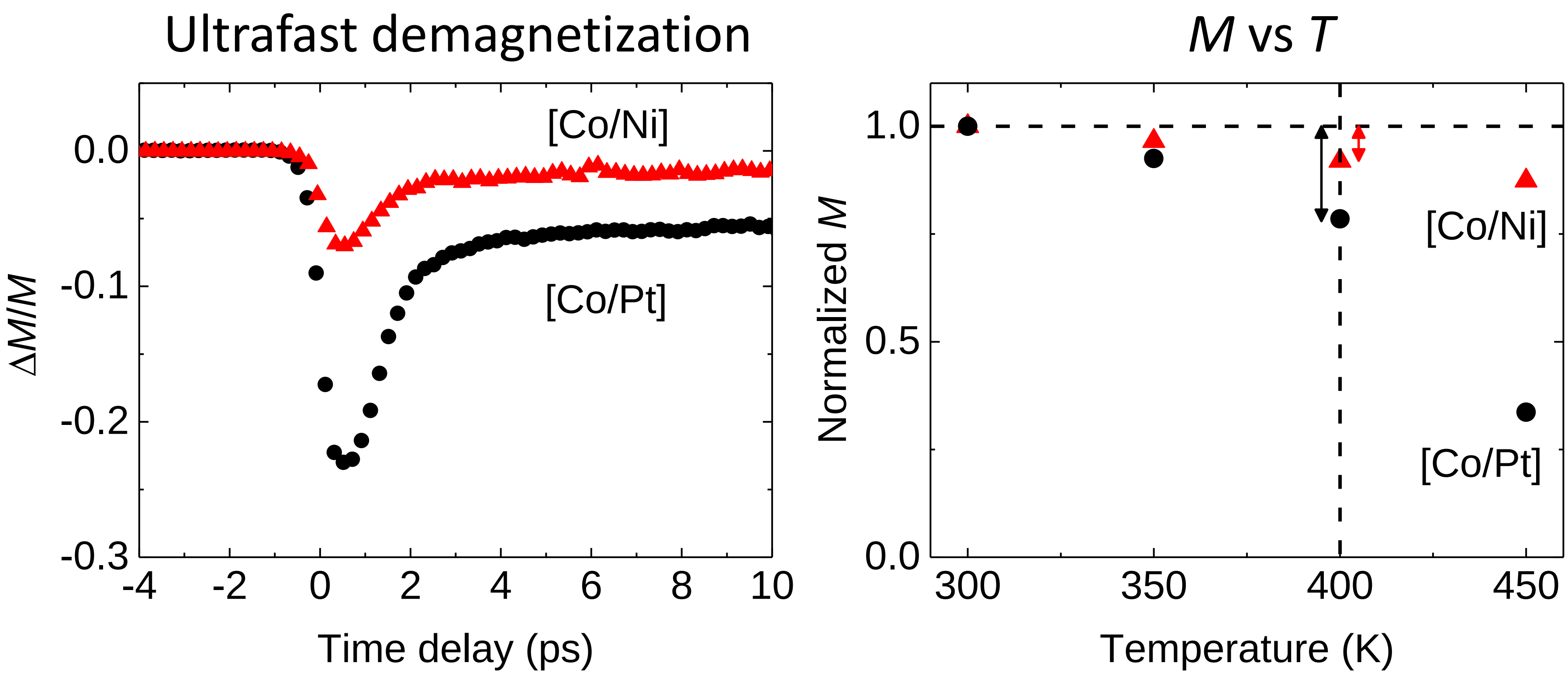
Phonon



Magnon



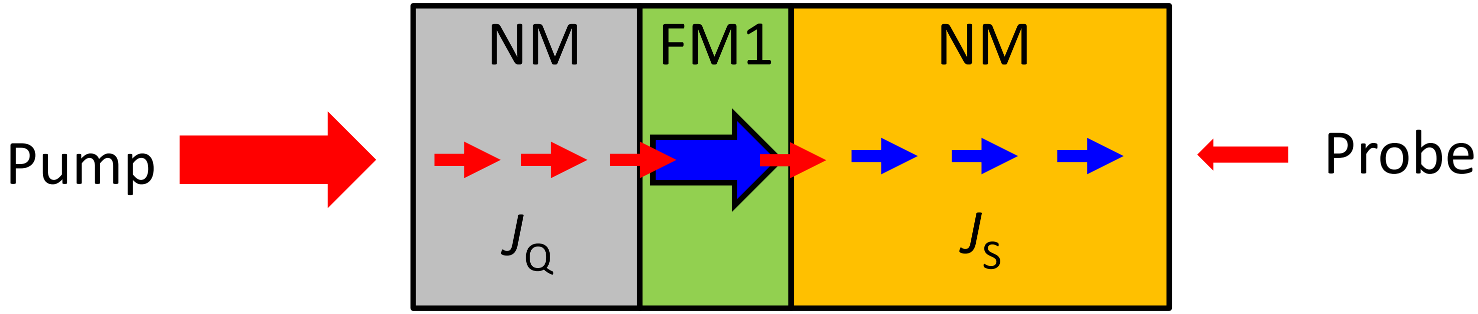
Effect of Curie temperature



$$\Delta M \approx \Delta T_{\mathrm{m}} \times \frac{\Delta M}{\Delta T_{\mathrm{m}}} = \Delta T_{\mathrm{m}} \times f\left(\frac{T_{\mathrm{m}}}{T_C}\right)$$

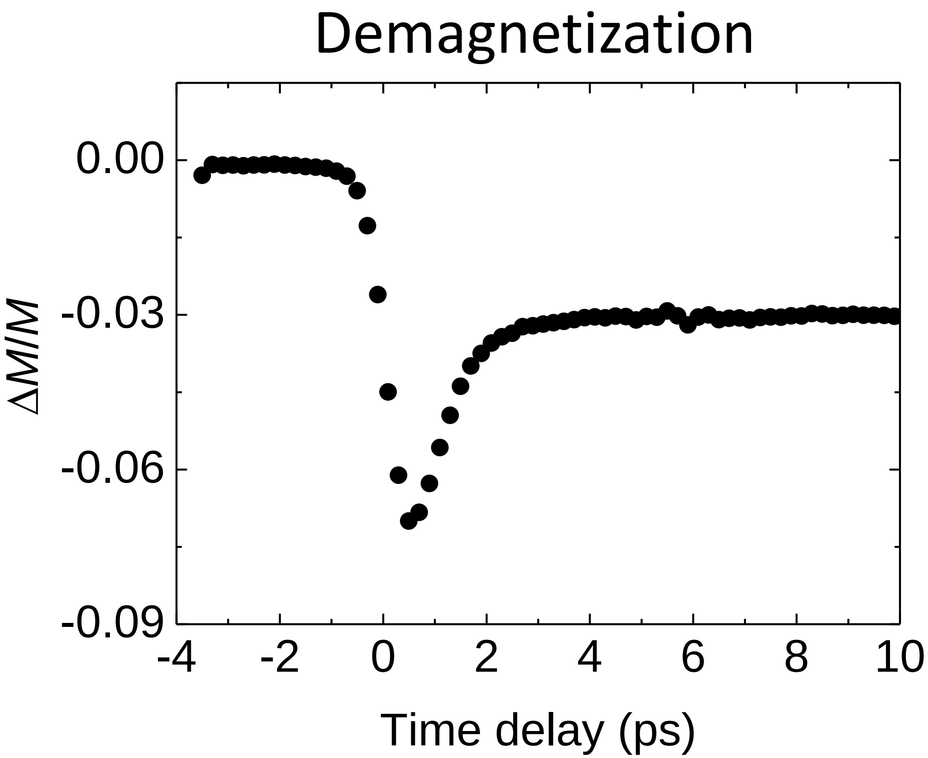
Spin accumulation

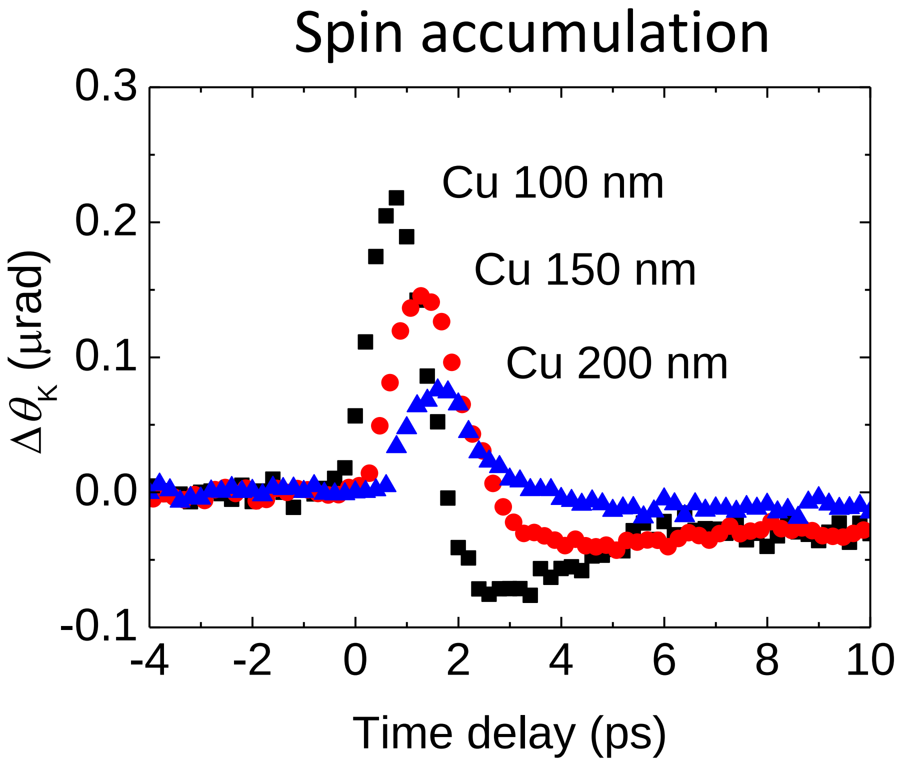
Measure spin accumulation on Cu



Spin accumulation

Pt (30)/ [Co/Pt] (6.5)/ **Cu (100~200)**



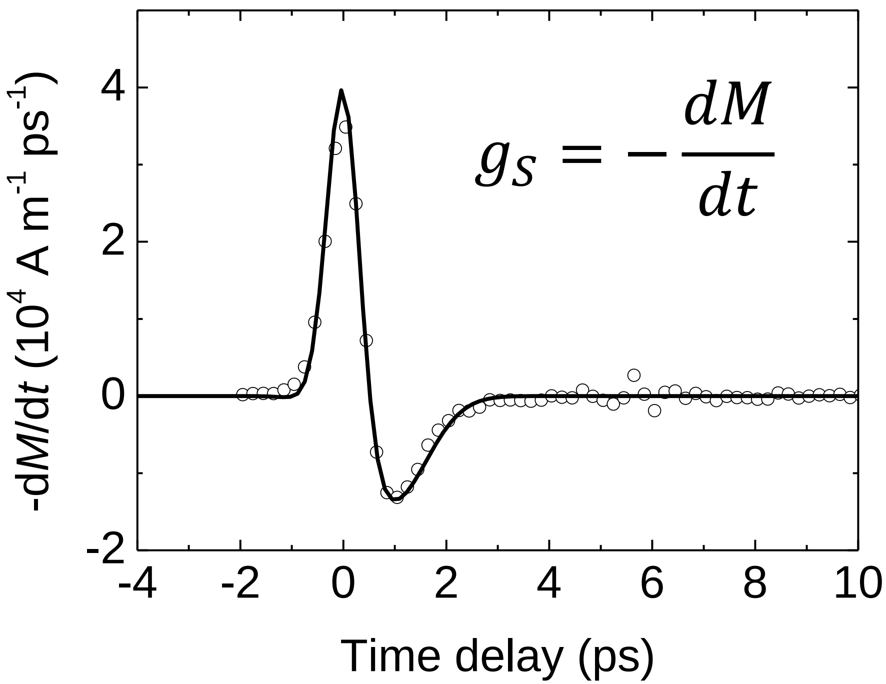


Choi *et al.* Nature Commun. 5, 4334 (2014)

Demagnetization-spin generation

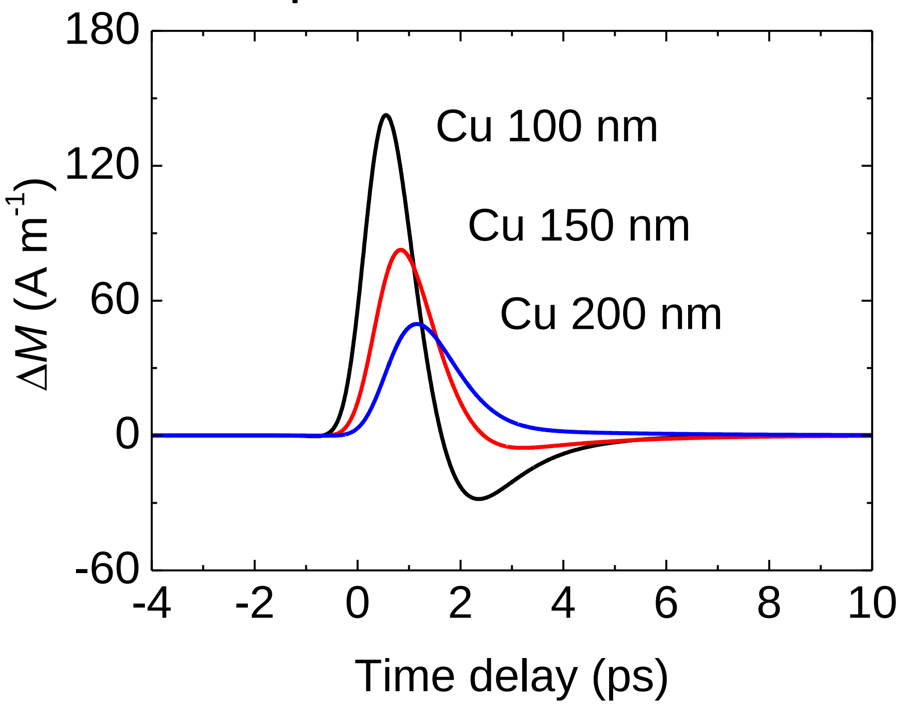
$$\frac{\partial \mu_S}{\partial t} = D\frac{\partial^2 \mu_S}{\partial^2 z} - \frac{\mu_S}{\tau_S} + \left(\frac{g_S}{N_S}\right)$$

Spin generation rate



$$g_S = -\frac{dM}{dt}$$

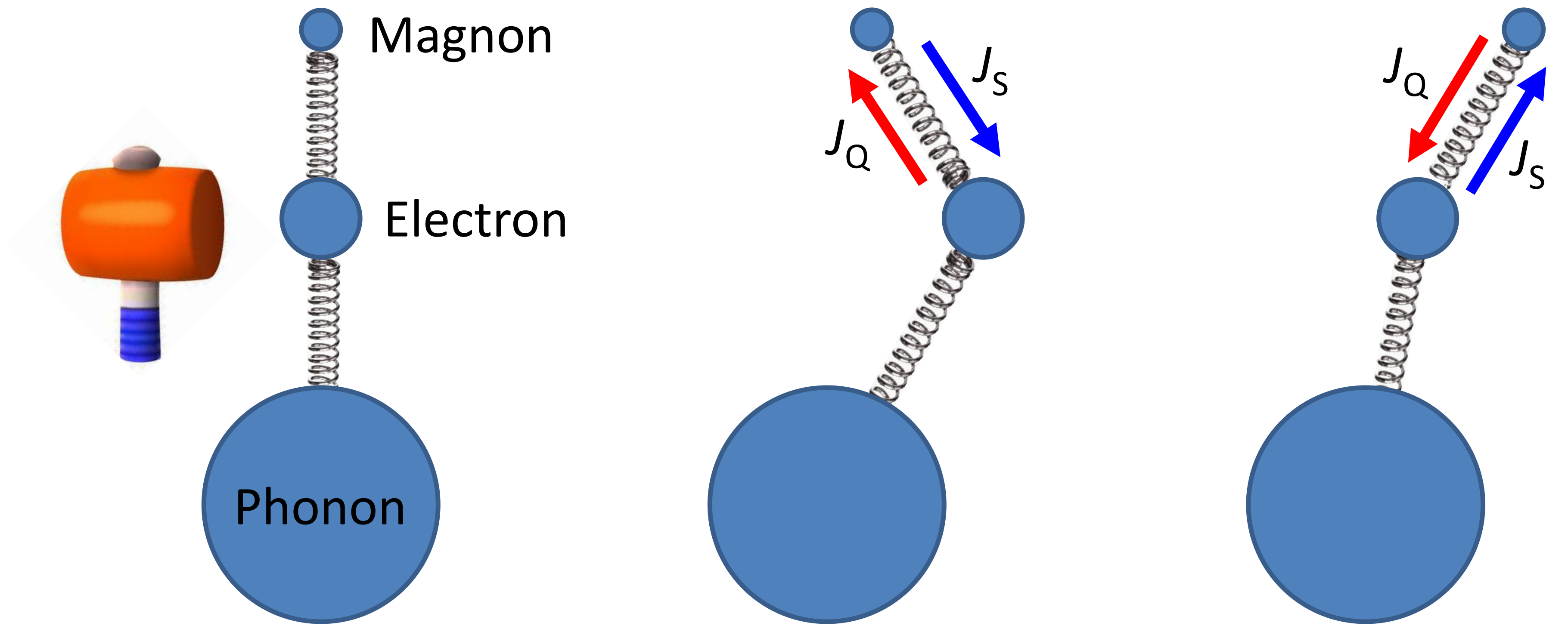
Spin accumulation



Choi *et al.* Nature Commun. 5, 4334 (2014)

Conclusion

$$\frac{dM}{dt} = \frac{dT_\mathrm{m}}{dt} \times f\left(\frac{T_\mathrm{m}}{T_C}\right), \qquad g_S = -\frac{dM}{dt}$$



Electron-magnon scattering conserve angular momentum.

Thermal spin generation in metallic ferromagnet

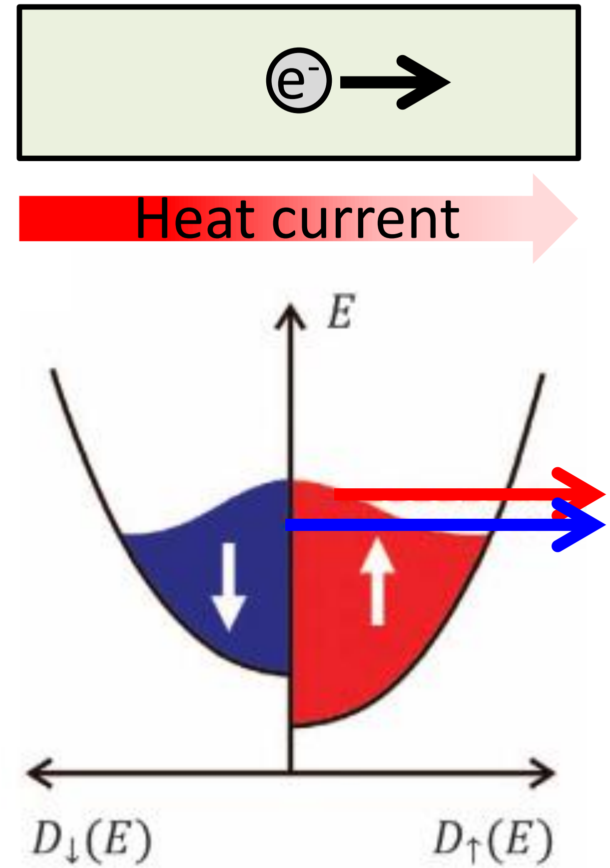
Part 1: Ultrafast demagnetization

Part 2: Spin-dependent Seebeck effect

Spin-dependent Seebeck effect

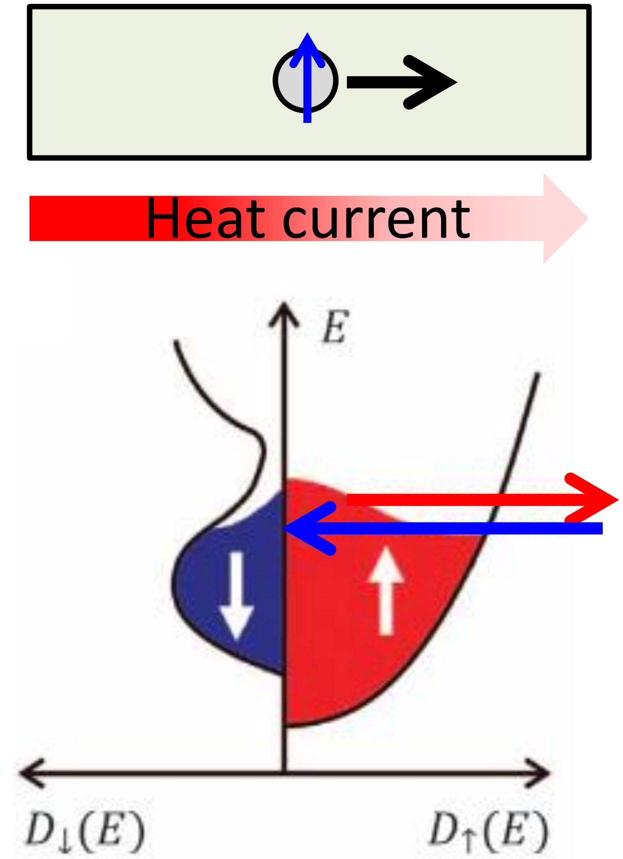
Seebeck effect

Charge



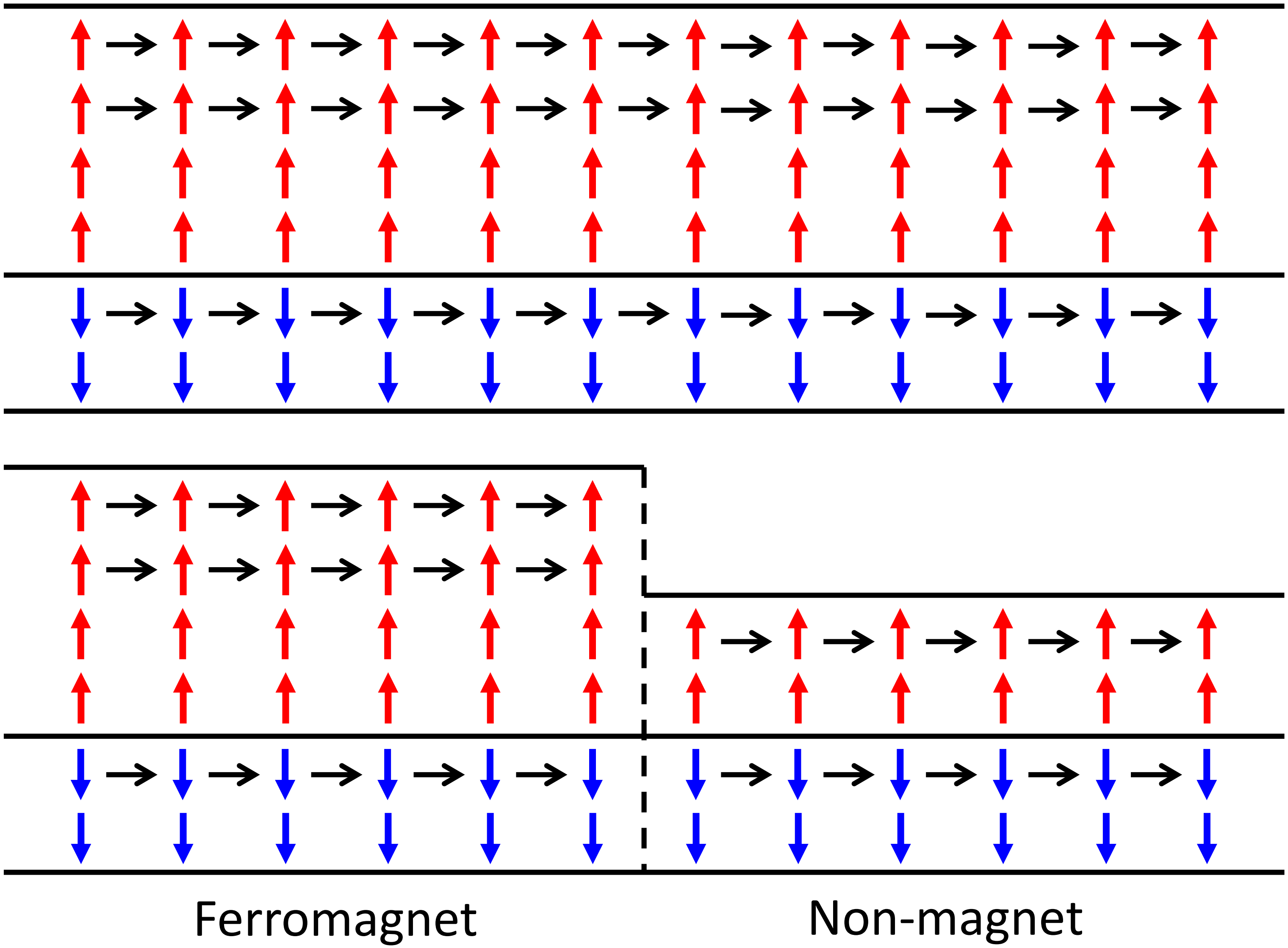
Spin-dependent Seebeck effect

Spin



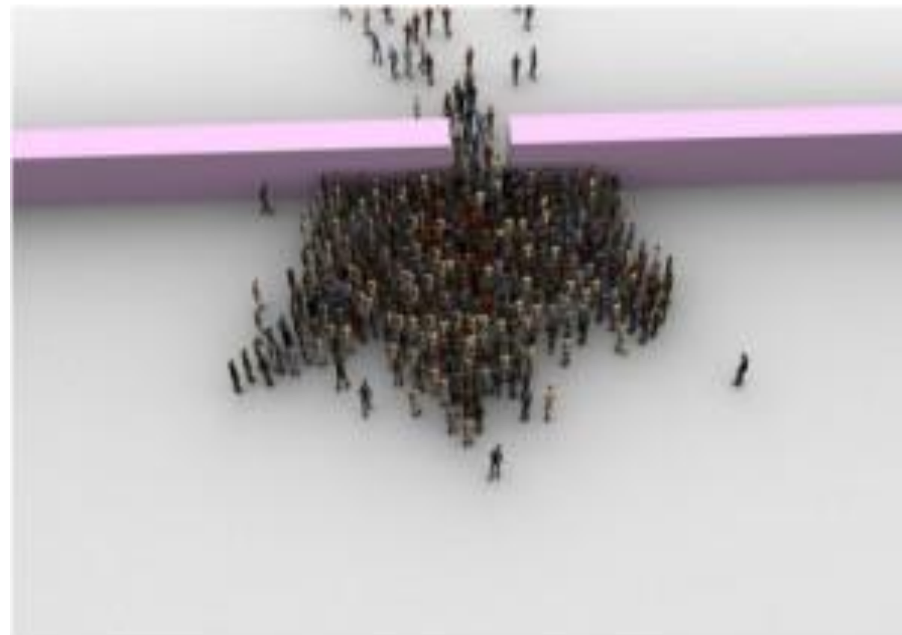
Hu *et al.* NPG Asia Mater. (2014)

Interfacial effect

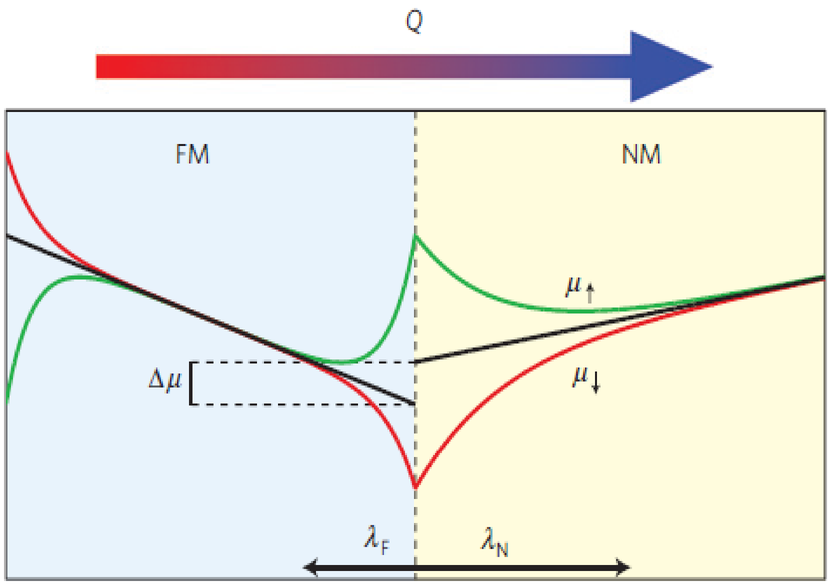


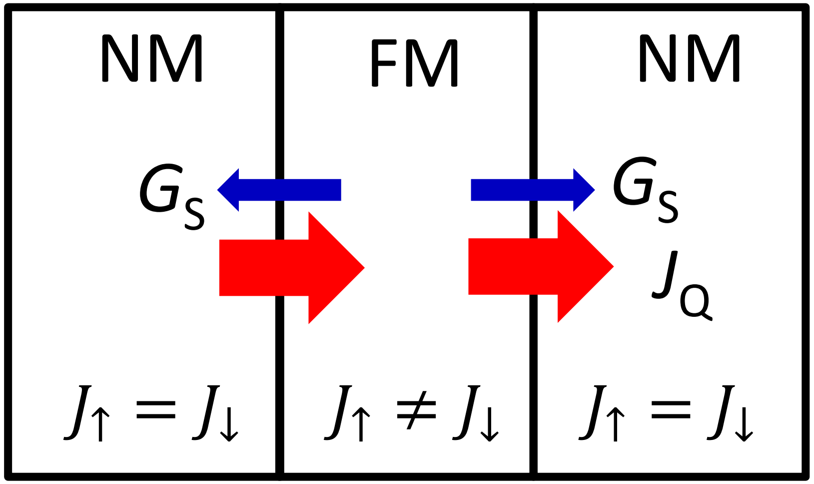
Interfacial effect

병목현상



Interfacial effect





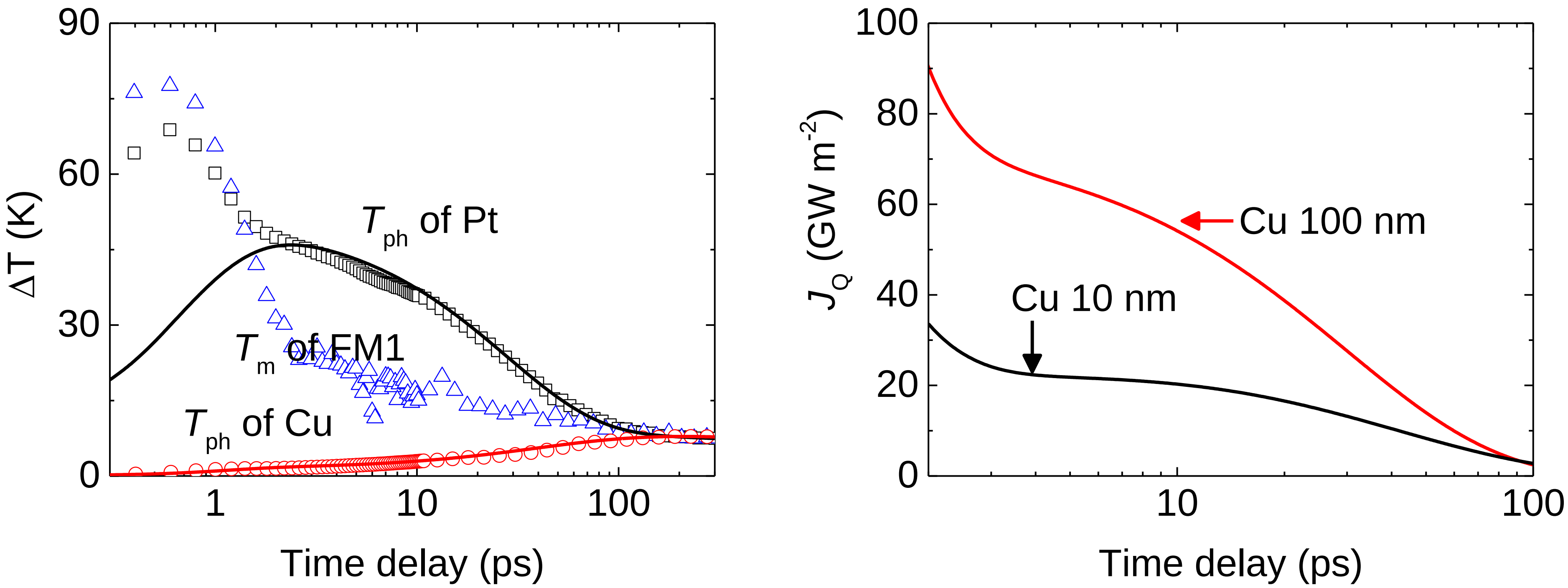
$$G_S = -\left(\frac{\mu_B}{eLT}\right)\frac{1-P^2}{2}(S_\uparrow - S_\downarrow)\,J_Q \qquad S_{\uparrow,\downarrow} = -eLT\frac{1}{\sigma_{\uparrow,\downarrow}}\frac{\partial\sigma_{\uparrow,\downarrow}}{\partial E}\bigg|_{E_F}$$

Slachter *et al.* Nature Phys. (2010)

Hatami *et al.* Phys. Rev. Lett. (2007)

Thermal analysis

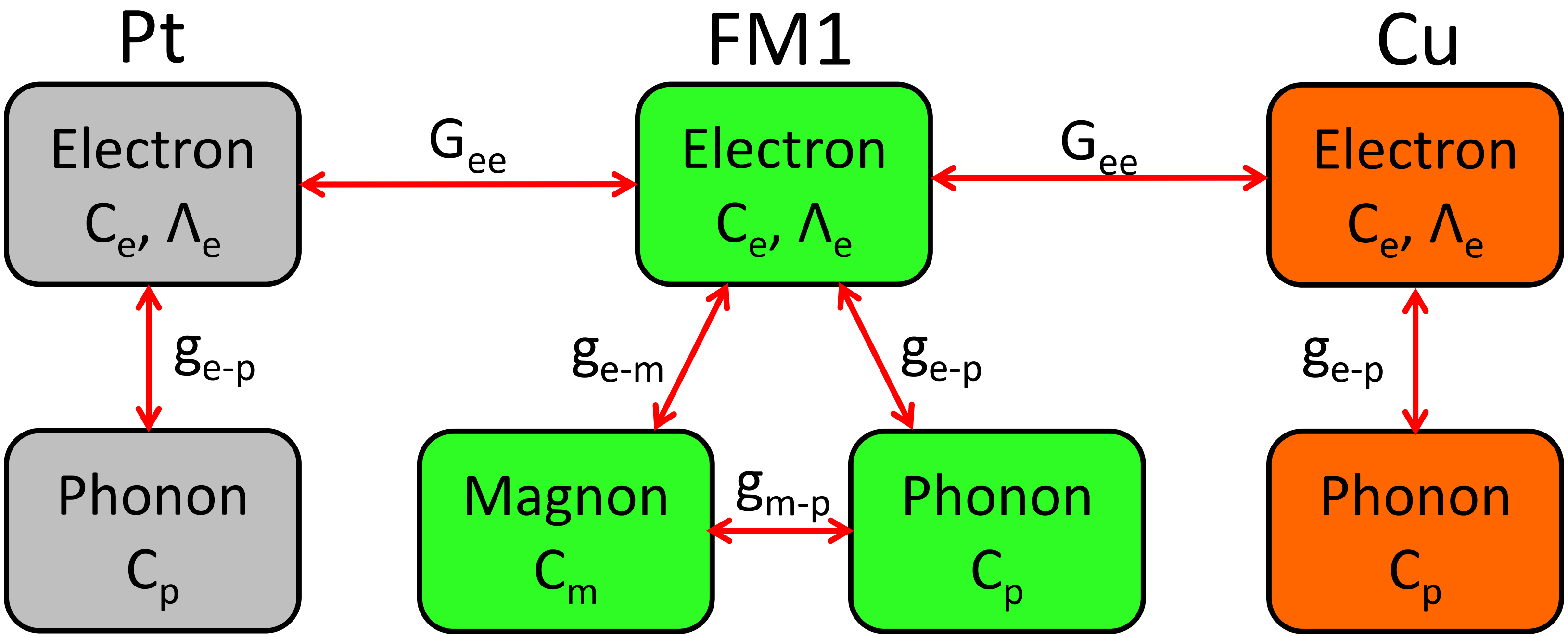
Pt (20)/ FM1 (3)/ Cu (10 or 100)/ FM2 (2) (in nm)



$$J_Q = \frac{E_{abs}}{\tau} \times \frac{C_{Cu} h_{Cu}}{C_{Pt} h_{Pt} + C_{Cu} h_{Cu}} \times e^{-t/\tau}$$

Choi *et al.* Nature Phys. 11, 576 (2015)

Thermal analysis

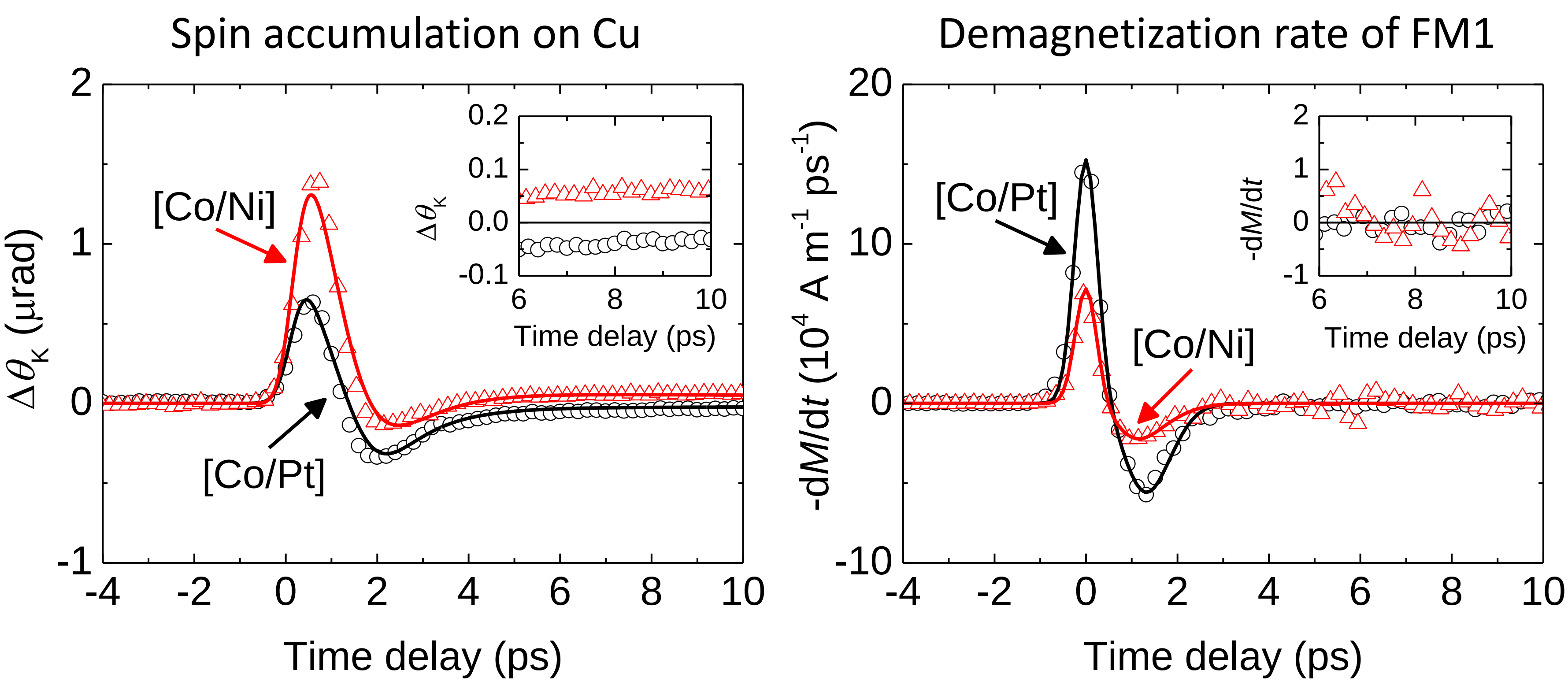


Energy transport among different heat reservoirs of different layers

$$\tau = \left(\frac{1}{C_{\mathrm{Pt}} h_{\mathrm{Pt}}} + \frac{1}{C_{\mathrm{Cu}} h_{\mathrm{Cu}}}\right)^{-1} \times \left(\frac{h_{\mathrm{Pt}}}{\Lambda_{\mathrm{Pt}}} + \frac{h_{\mathrm{FM1}}}{\Lambda_{\mathrm{FM1}}} + \frac{1}{g_{\mathrm{Cu}} h_{\mathrm{Cu}}}\right)$$

SDSE-spin accumulation

Pt (20)/ FM1 (3)/ Cu (100) (in nm)

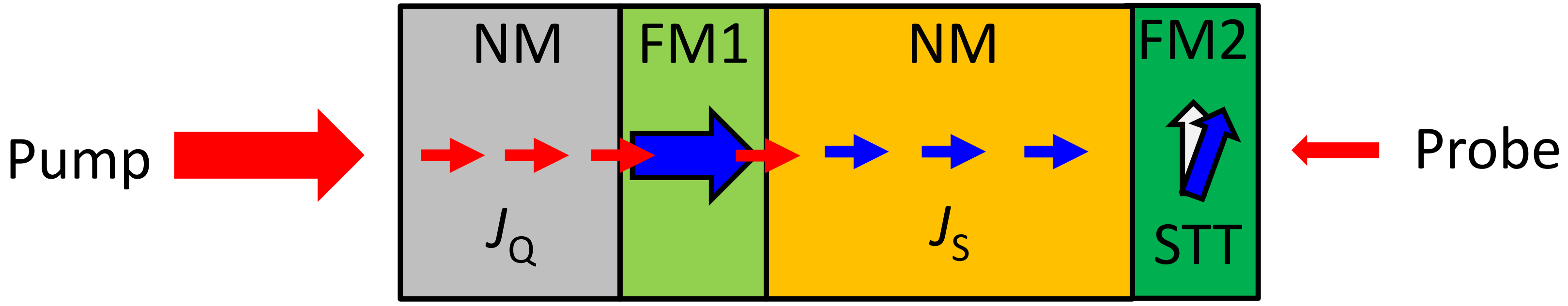


Offset in spin accumulation on Cu is due to SDSE.

Choi *et al.* Nature Phys. 11, 576 (2015)

SDSE-spin torque

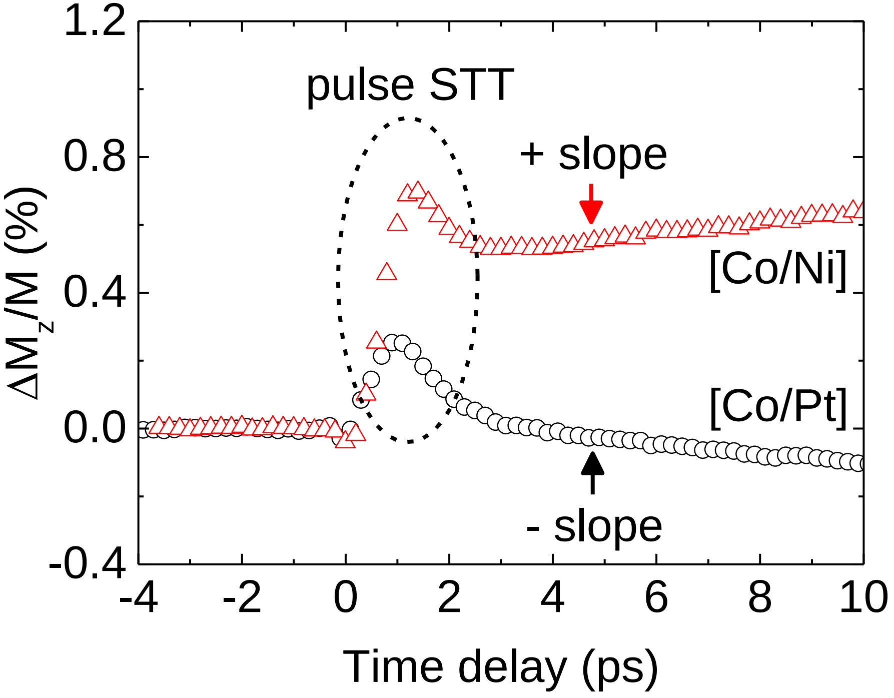
Measure STT on FM2



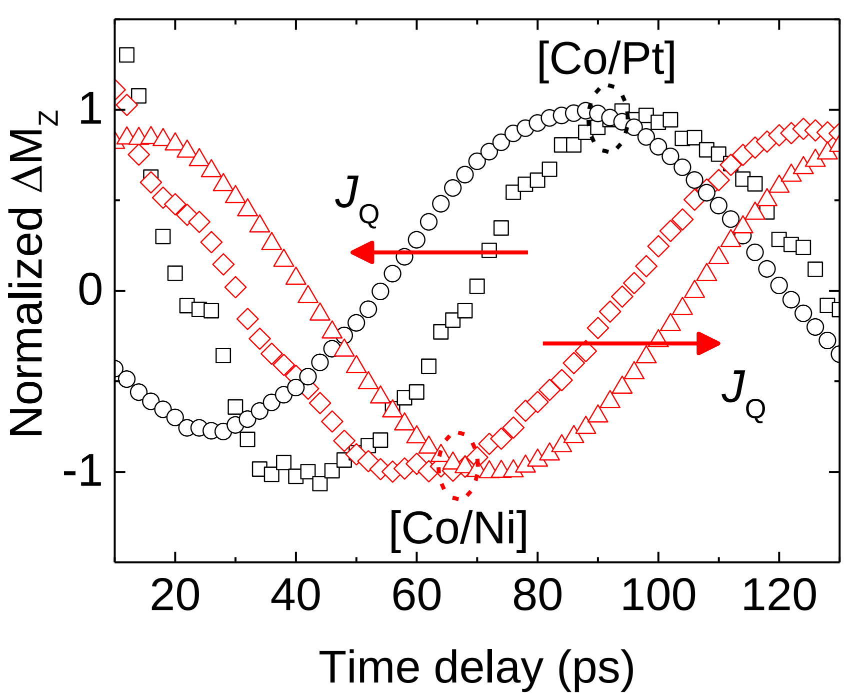
SDSE-spin torque

Pt (20)/ FM1 (3)/ Cu (10 or 100)/ FM2 (2) (in nm)

Initial slope of $M(t)_{FM2}$



Phase delay of $M(t)_{FM2}$



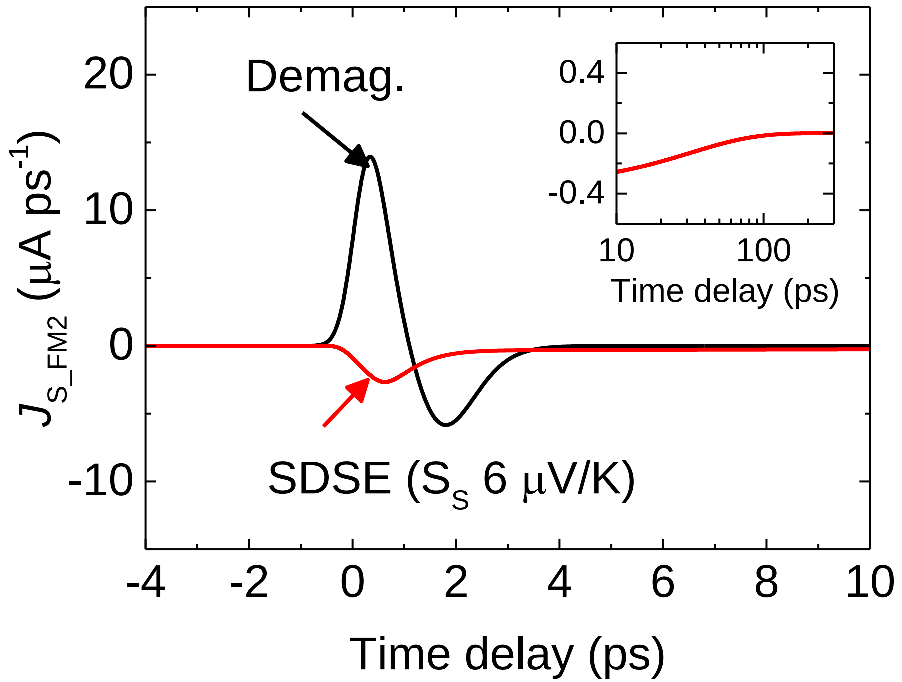
SDSE → initial slop → overall phase delay

Choi *et al.* Nature Phys. 11, 576 (2015)

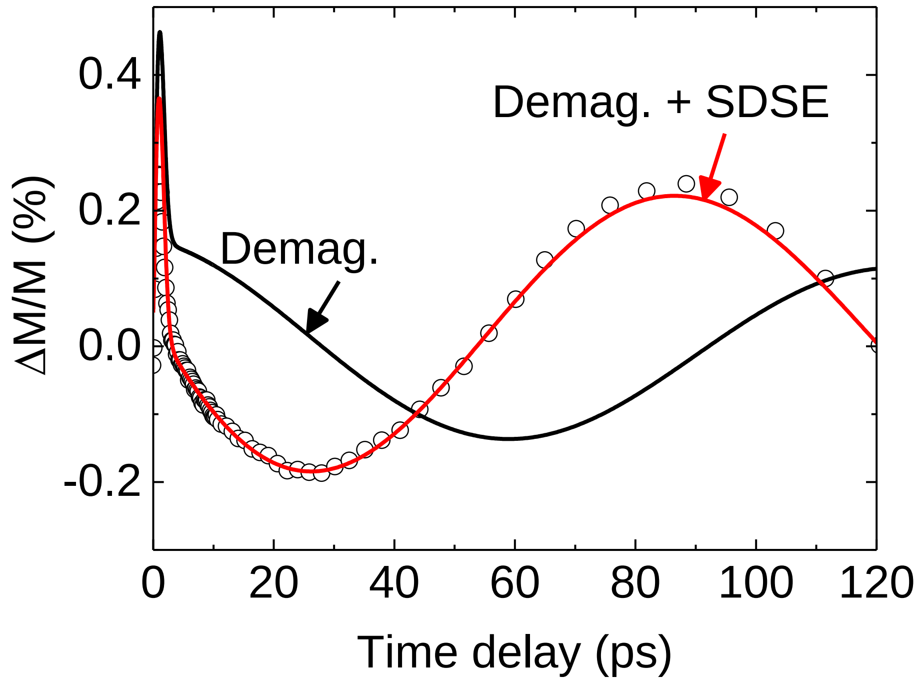
SDSE-coefficient

Pt (20)/ **[Co/Pt]** (3)/ Cu (100)/ CoFeB (2) (in nm)

Input (J_S to FM2)



Output (FM2 dynamics)

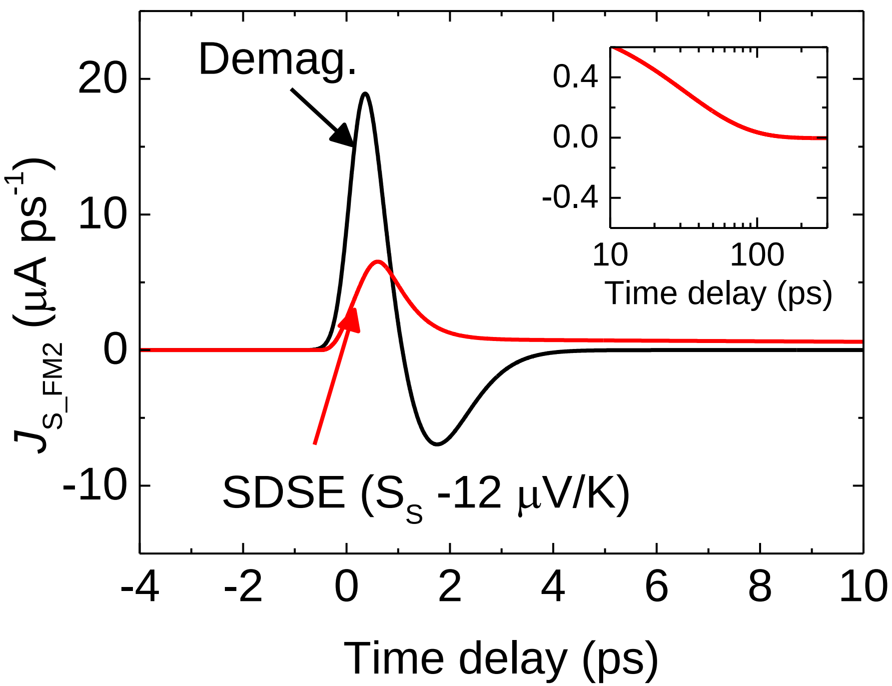


$$\dot{\mathrm{m}} = -\gamma_e \mathrm{m} \times \mathrm{H}_{\mathrm{eff}} + \alpha \mathrm{m} \times \dot{\mathrm{m}} + \frac{J_S}{M_S h} \mathrm{m} \times (\mathrm{m} \times \mathrm{m}_{\mathrm{fixed}})$$

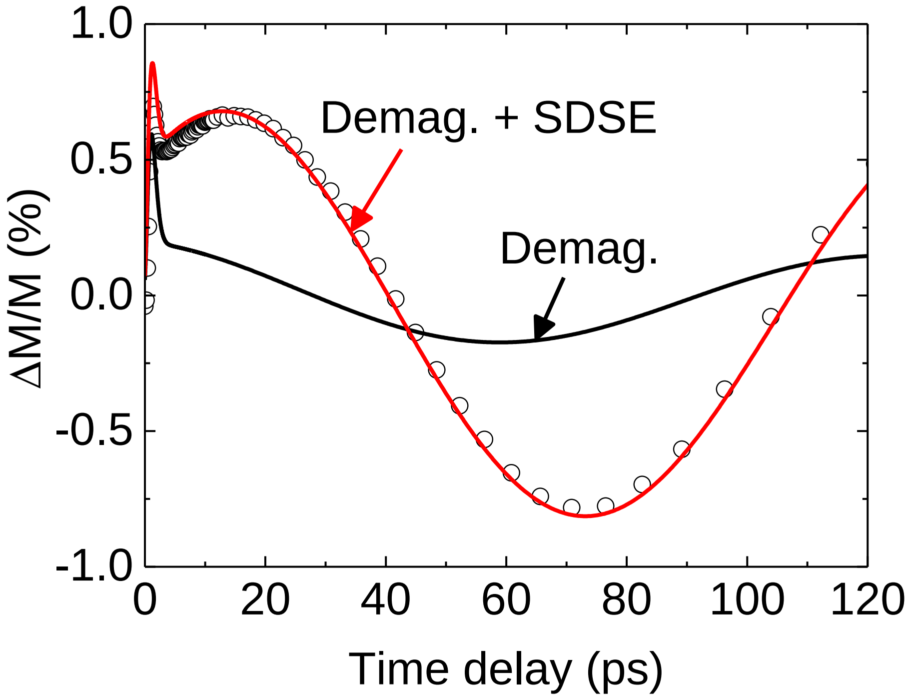
SDSE-coefficient

Pt (20)/ **[Co/Ni]** (3)/ Cu (100)/ CoFeB (2) (in nm)

Input (J_S to FM2)

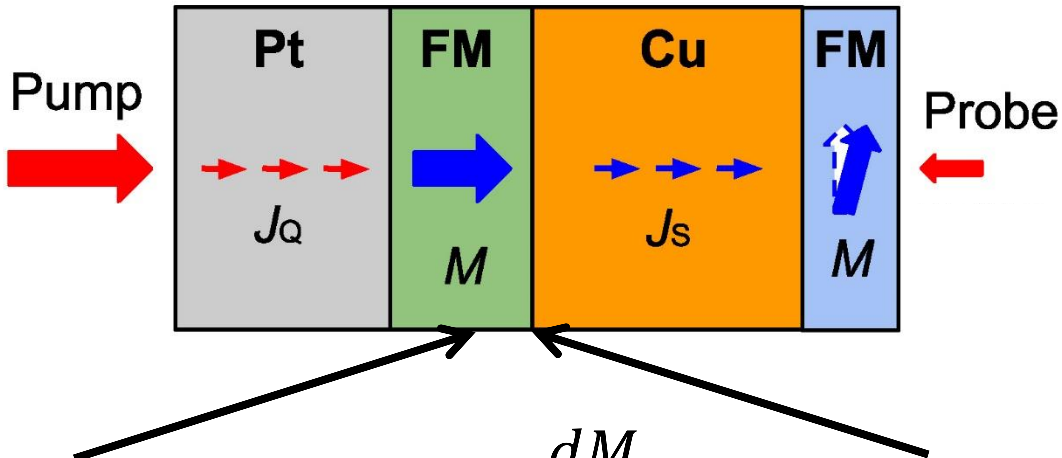


Output (FM2 dynamics)



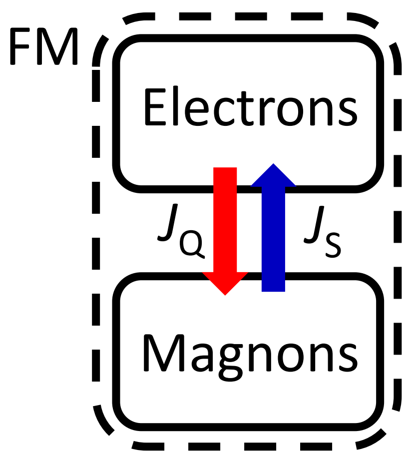
$$\dot{\mathrm{m}} = -\gamma_e \mathrm{m} \times \mathrm{H_{eff}} + \alpha \mathrm{m} \times \dot{\mathrm{m}} + \frac{J_S}{M_S h} \mathrm{m} \times (\mathrm{m} \times \mathrm{m_{fixed}})$$

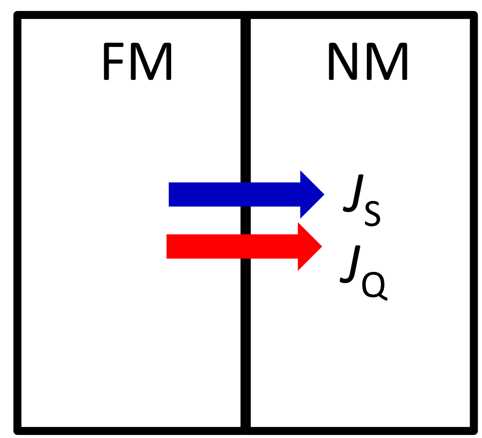
Conclusion



Demagnetization→ $g_S = -\frac{dM}{dt}$

SDSE → $G_S \propto S_S J_Q$

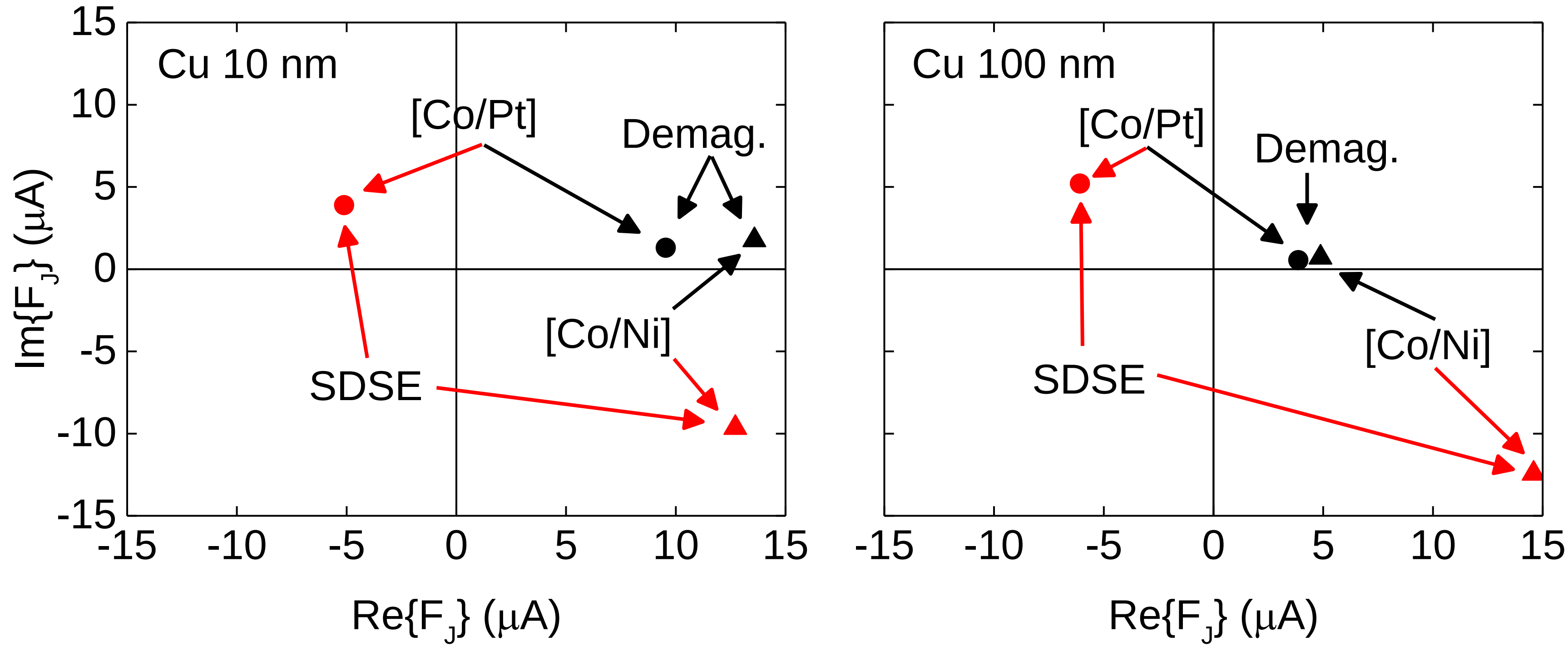




Conclusion

Pt (20)/ FM1 (3)/ Cu (10 or 100)/ FM2 (2) (in nm)

Fourier analysis of J_S to FM2



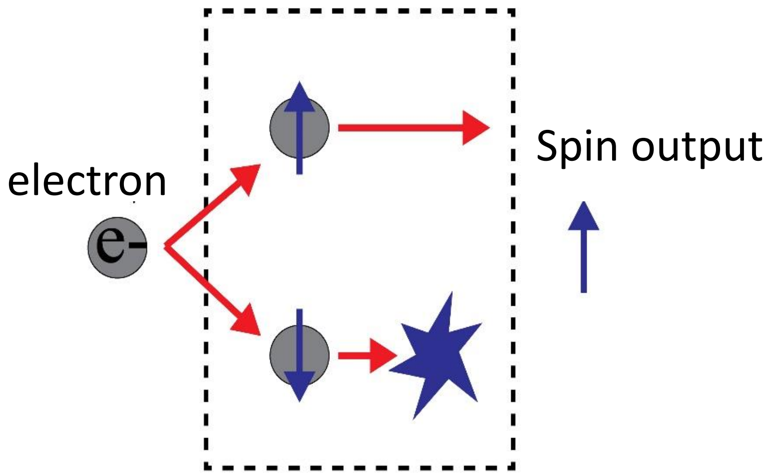
[Co/Pt] with Cu 10 nm: **Demagnetization** > SDSE

[Co/Ni] with Cu 100 nm: **SDSE** > Demagnetization

Choi *et al.* Nature Phys. 11, 576 (2015)

Future plan: Quantum yield

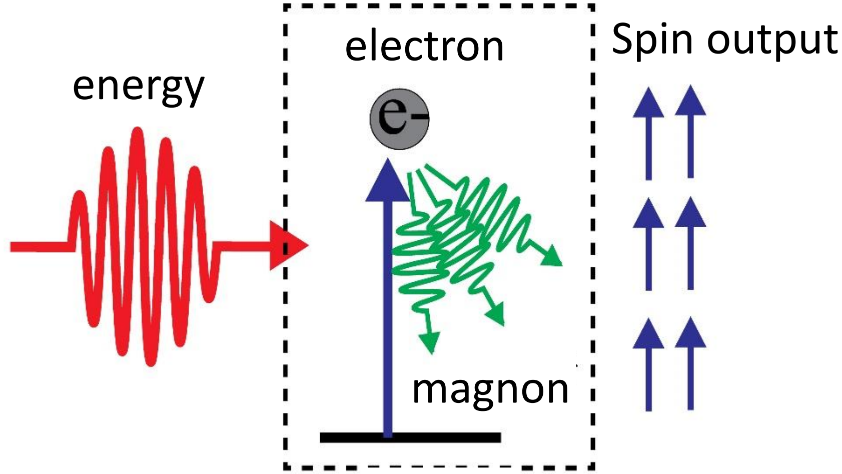
Electrical spin generation



Ferromagnet

$$\varepsilon < \frac{1}{2}$$

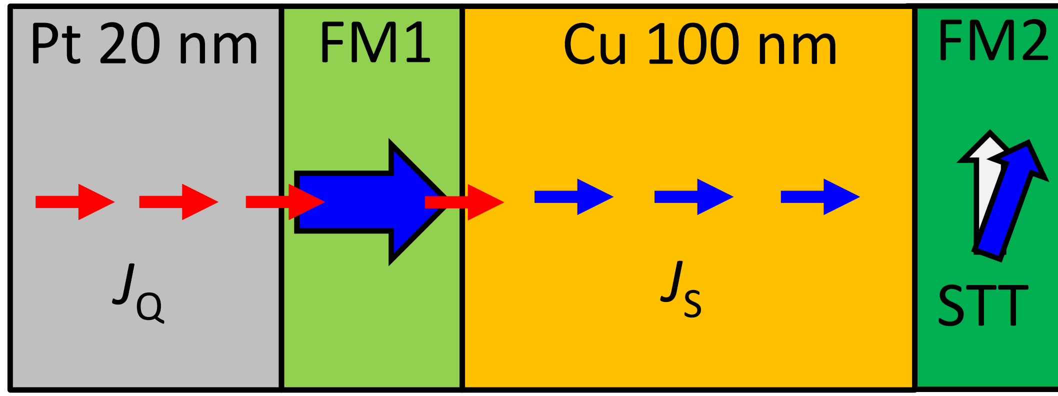
Thermal spin generation



Ferromagnet

$$\varepsilon \approx 1$$

Future plan: Spin loss



<Spin absorption>

		Pt	FM1	Cu	FM2
Demag.	[Co/Pt] (τ_S=0.02 ps)	7 %	88 %	1 %	4 %
	[Co/Ni] (τ_S=0.1 ps)	20 %	66 %	1 %	13 %

		Pt	FM1	Cu	FM2
SDSE	[Co/Pt] (τ_S=0.02 ps)		89 %	1 %	10 %
	[Co/Ni] (τ_S=0.1 ps)		87 %	1 %	12 %

Acknowledgement

Collaborators

KIST: Chul-Hyun Moon, Dr. Byoung-Chul Min

Korea University: Prof. Kyung-Jin Lee

University of Illinois: Prof. David G. Cahill