Huge thermospin effect in Fe_3O_4/Pt thin film multilayers

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Spin, charge and energy transport in novel materials
Hvar, Croatia, October 1 - 7, 2017

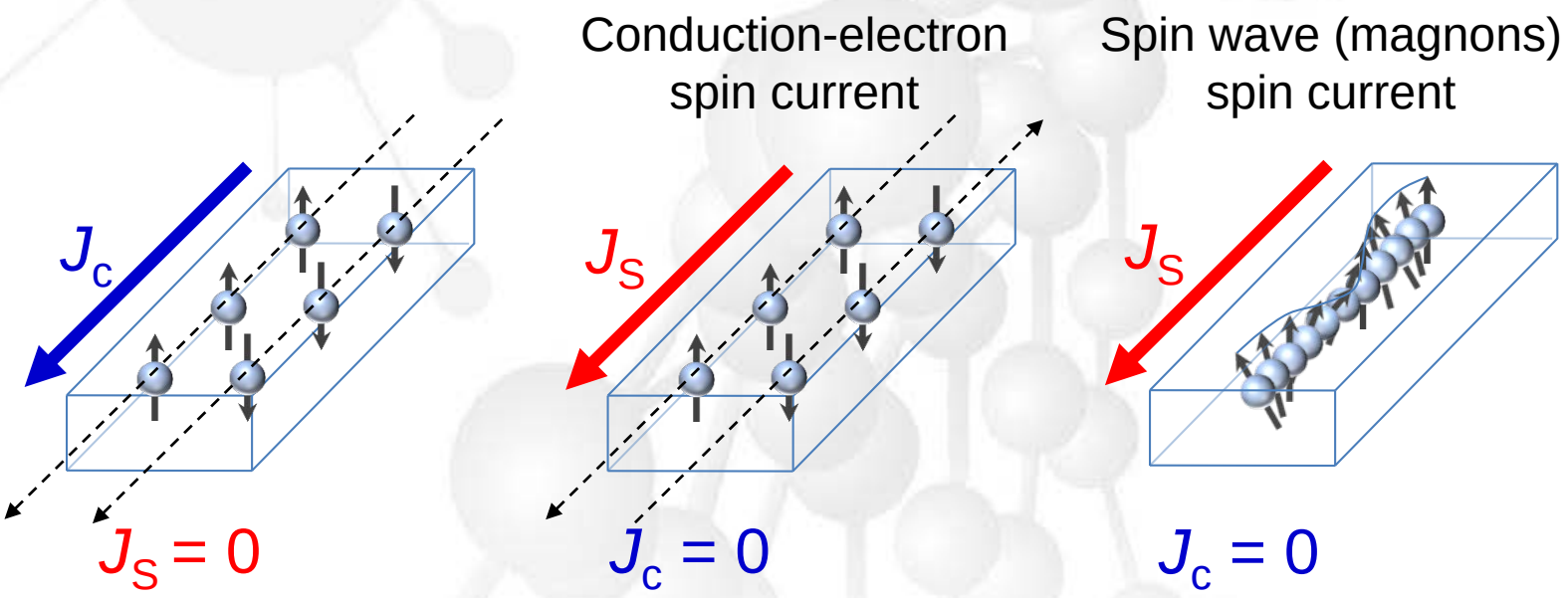
LMA

The concept of spin current

Charge and spin currents

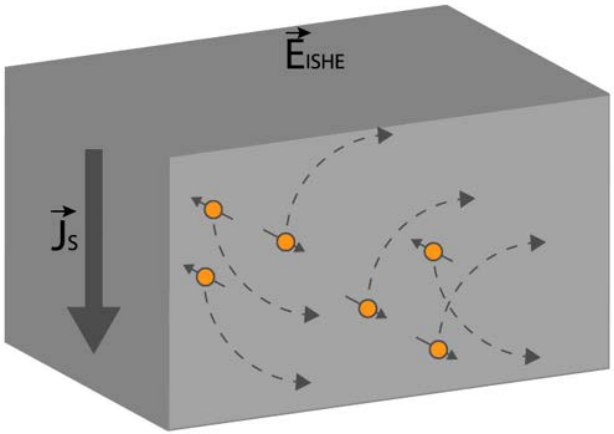
J_c: charge current

J_S: spin current



Spin current: no Joule heating!

Spin current detection: Inverse spin hall effect



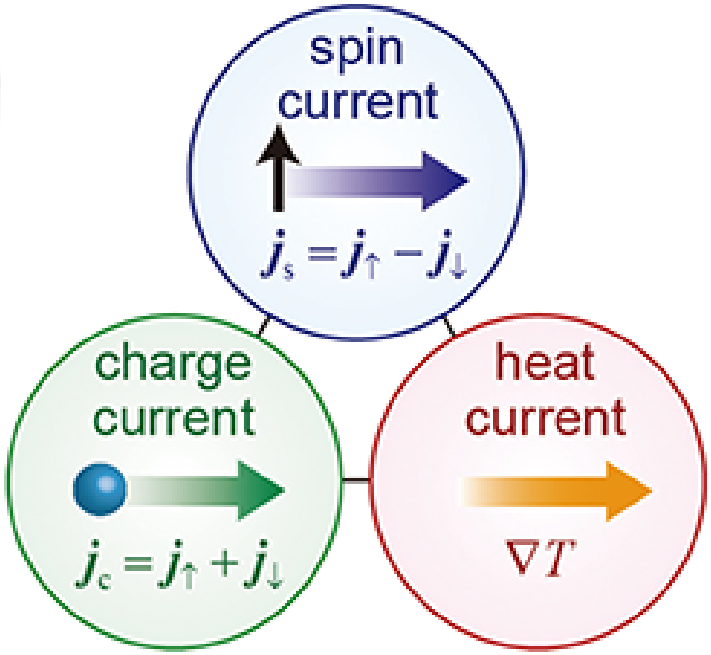
High SOC metal

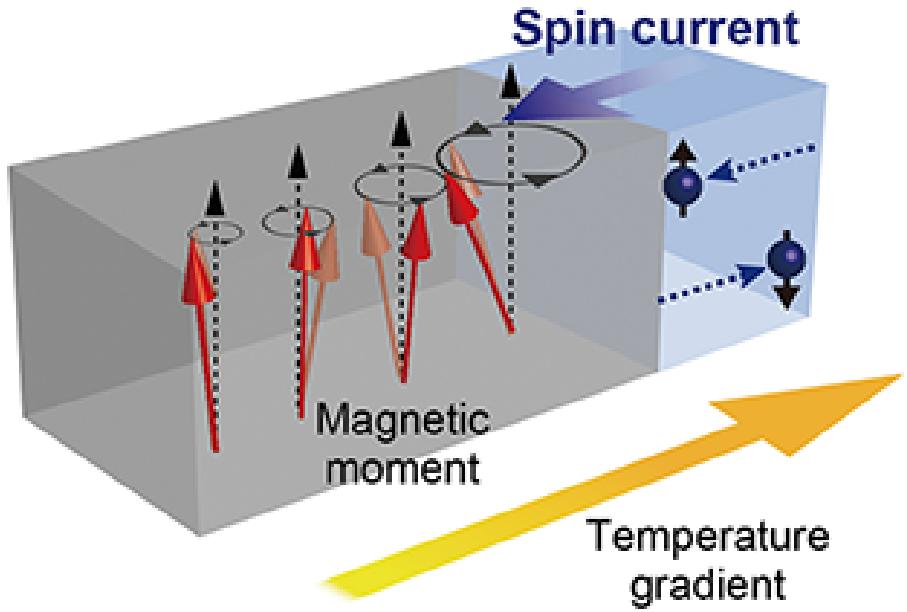
$$\boldsymbol{J_C} = \frac{\theta_{SH}\rho}{A}\left(\frac{2e}{\hbar}\right)\boldsymbol{J_S} \times \boldsymbol{\sigma}$$

Saitoh, E., Ueda, M., Miyajima, H., & Tatara, G. (2006). Conversion of spin current into charge current at room temperature: Inverse spin-Hall effect. *Applied Physics Letters*, *88*(2006), 1–4.

Thermospin concept

Spin Seebeck effect effect: Spin current generation by heat





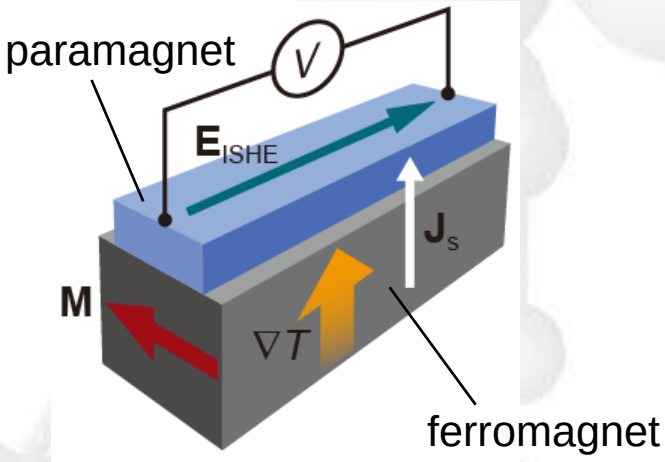
$$I_S = -G_S \frac{k_B}{\hbar}(T_F - T_N)$$

J. Xiao et al. PRB **81,** 214418 (2010)

H. Adachi et al. PRB **83**, 094410 (2011), Rep. Prog. Phys. **76,** 036501 (2013)

Longitudinal spin Seebeck effect (LSSE)

Longitudinal SSE setup

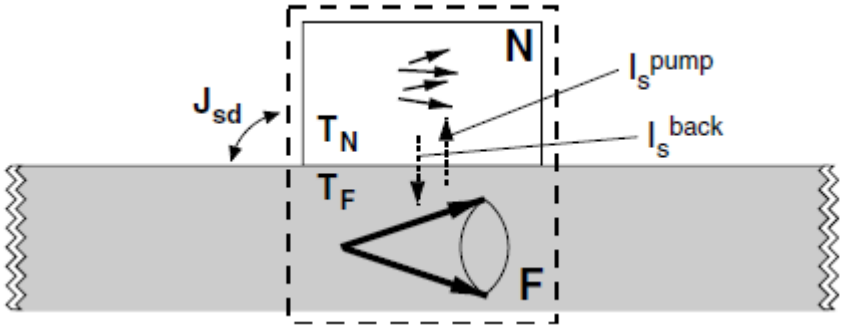


Inverse spin Hall effect:

$$\mathbf{E}_{\mathrm{SHE}} \propto \mathbf{j}_{\mathrm{s}} \times \boldsymbol{\sigma}$$

K. Uchida *et al.*,
Appl. Phys. Lett. **97**, 172505 (2010).

Spin Seebeck basic principles



$$I_S = -G_S \frac{k_B}{\hbar}(T_F - T_N)$$

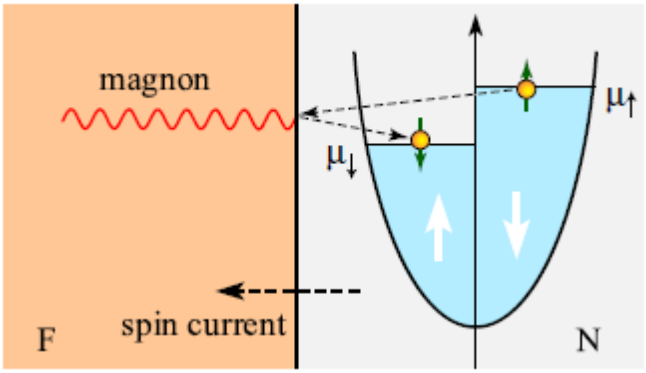
$$\vec{E}_{ISHE} = \frac{\theta_{SH}\rho}{A}\left(\frac{2e}{\hbar}\right)\vec{J}_S \times \vec{\sigma}$$

- Spin current proportional to applied thermal gradient
- Injected spin current converted in electric voltage by the inverse spin Hall effect

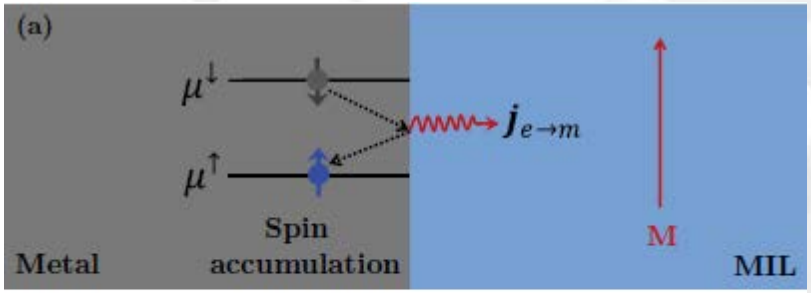
J. Xiao et al. Phys. Rev. B **81,** 214418

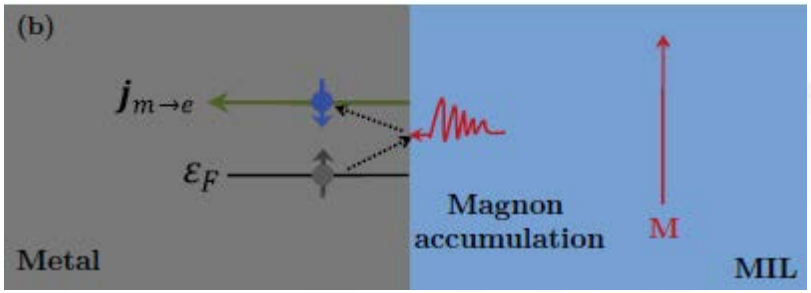
H. Adachi et al. Phys. Rev. B **83**, 094410,& Rep. Prog. Phys. **76,** (2013) 036501

SPIN CURRENT AT THE INTERFACES



Magnon emission associated with spin accumulation at the metal-ferromagnet interface
(Takahasi et al ICM 2009)

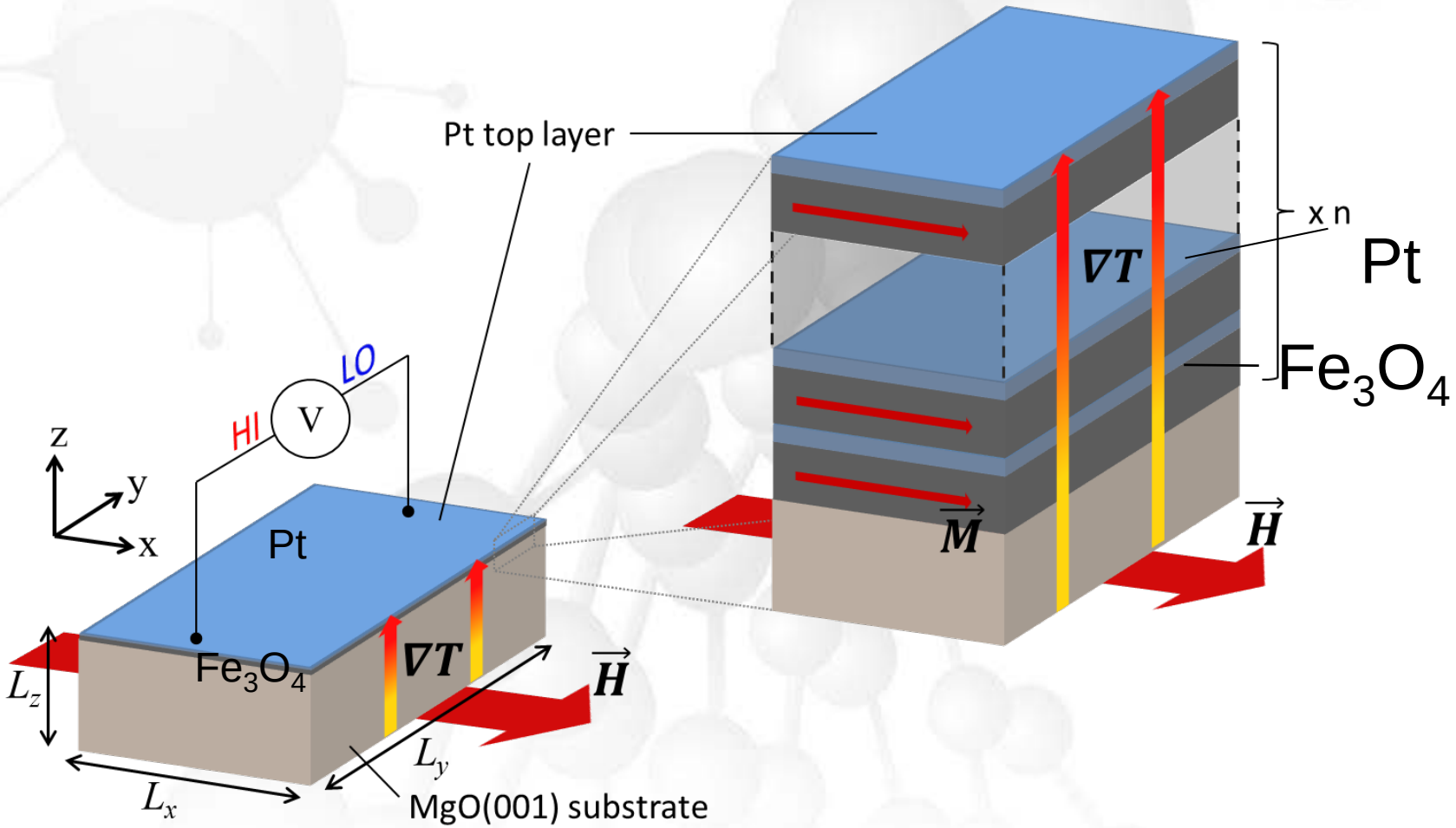




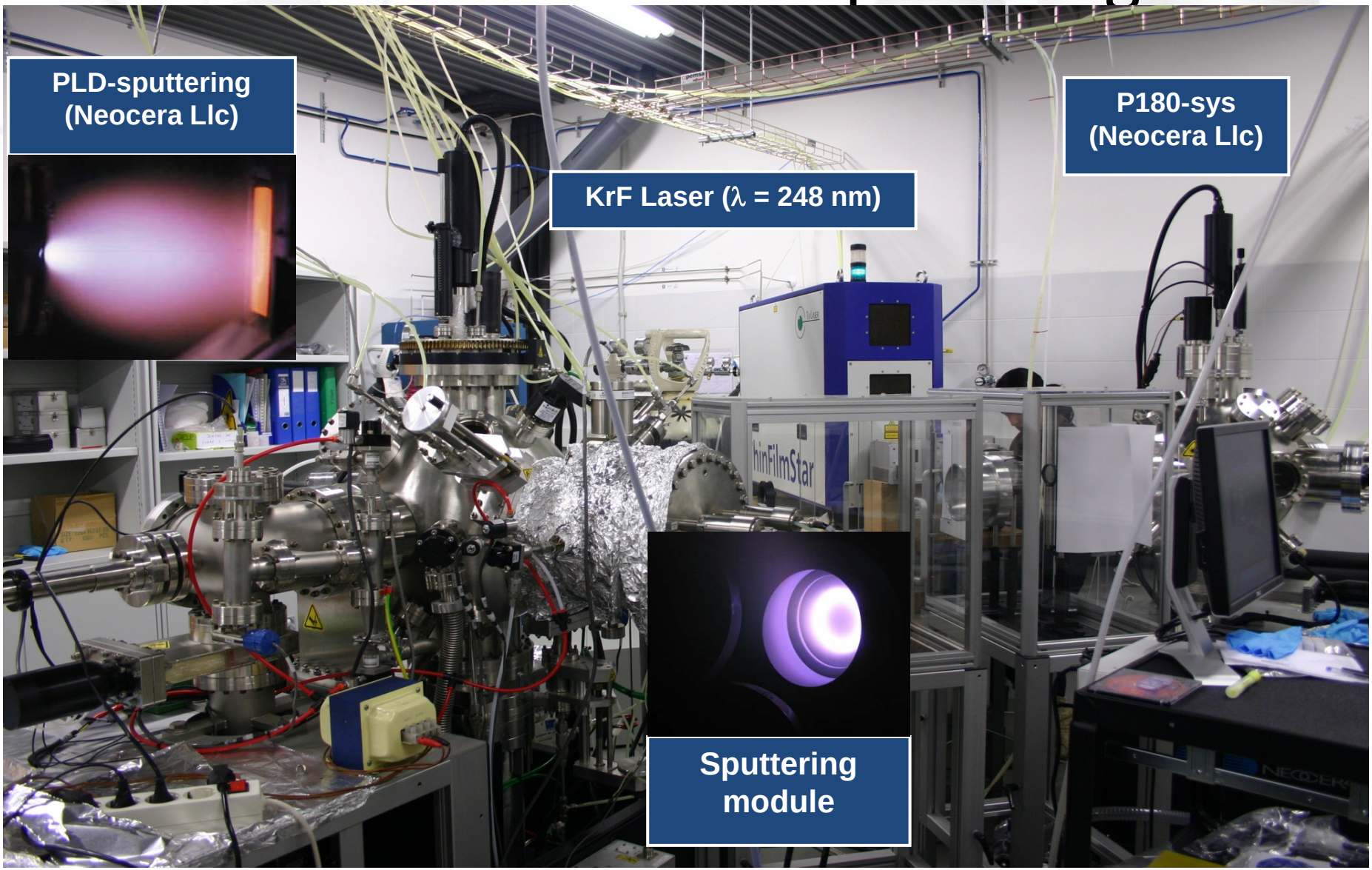
Spin angular momentum transfer at the interface: Magnon and elecron spin current interconversion
(Steven et al. PRB 86 (2012) 214424)

Spin Seebeck effect in magnetic multilayers

SSE in $[F/N]_n$ multilayers



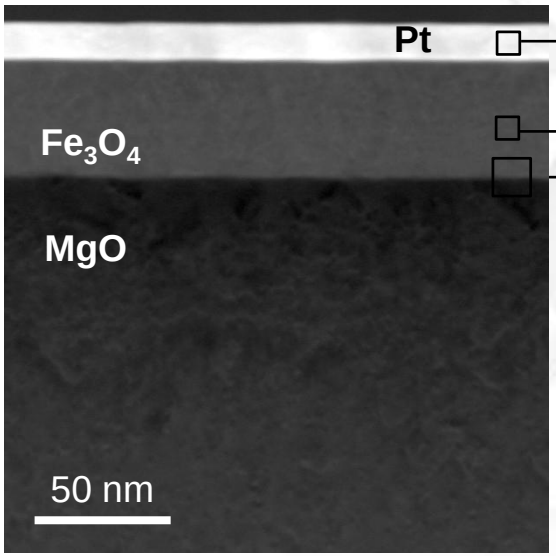
Combined PLD & Sputtering



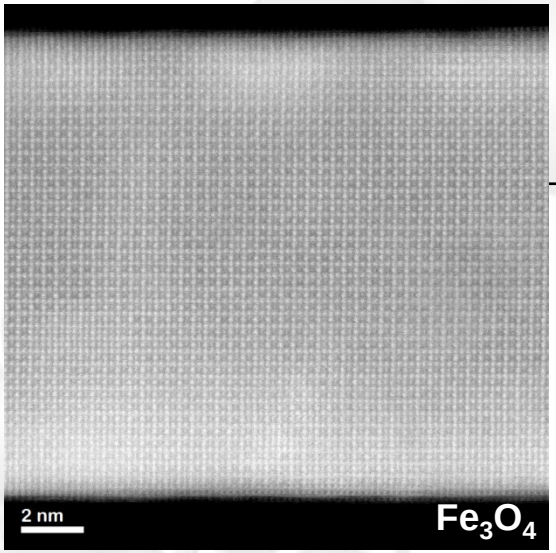
Atomic resolution morphological characterization

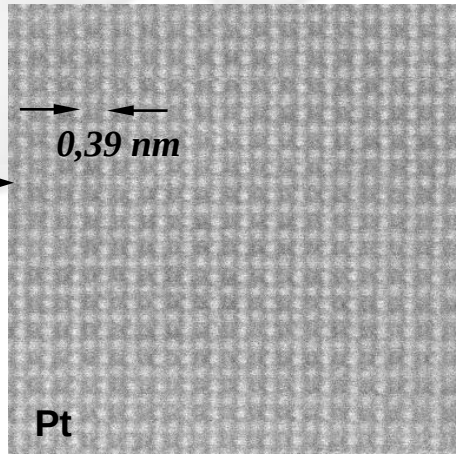
MgO/(Fe_3O_4/Pt)

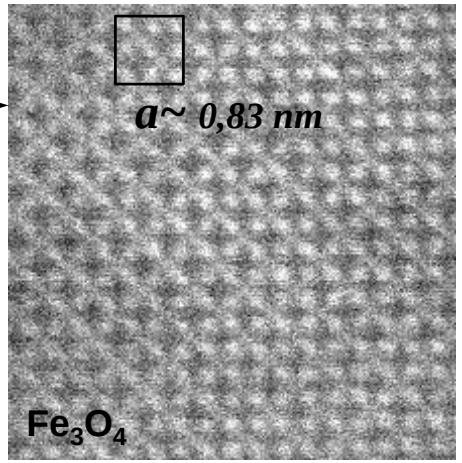
STEM-HAADF image



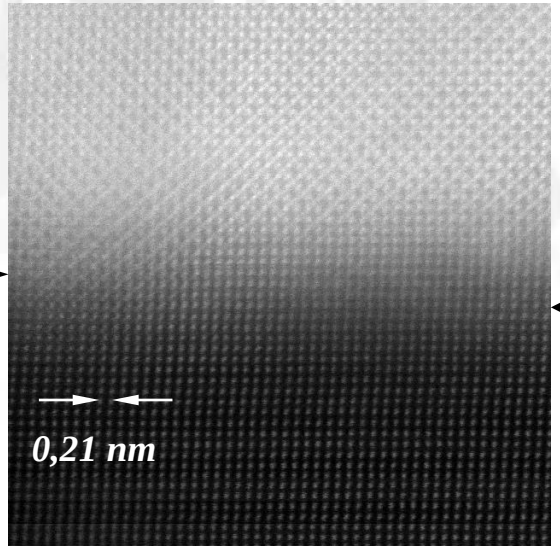
Pt







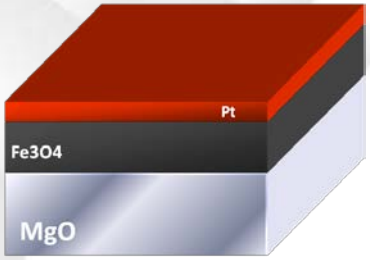
Fe_3O_4

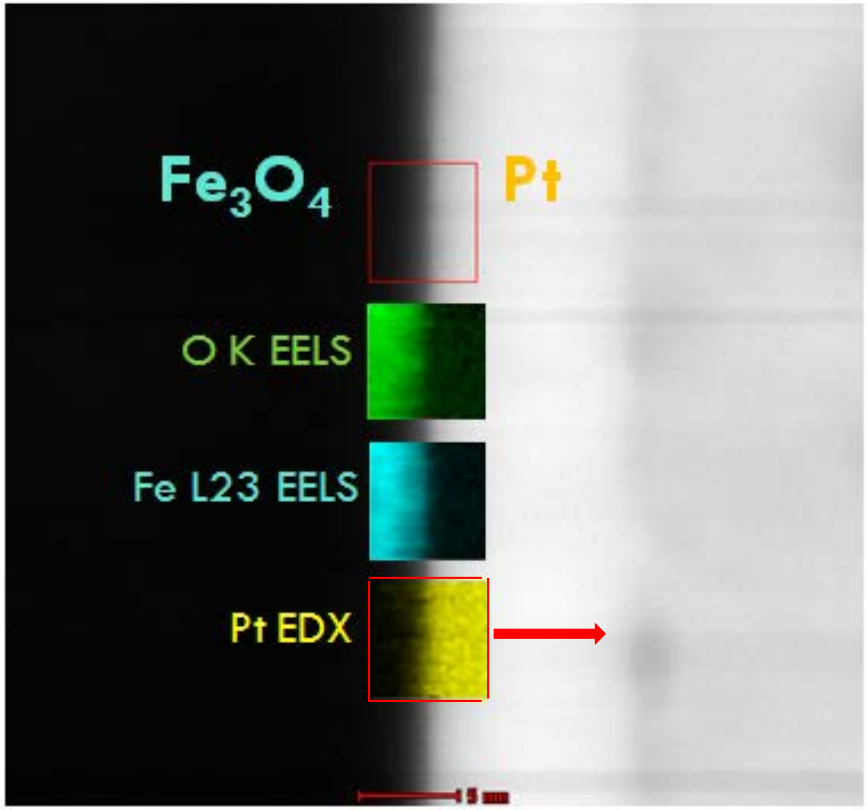


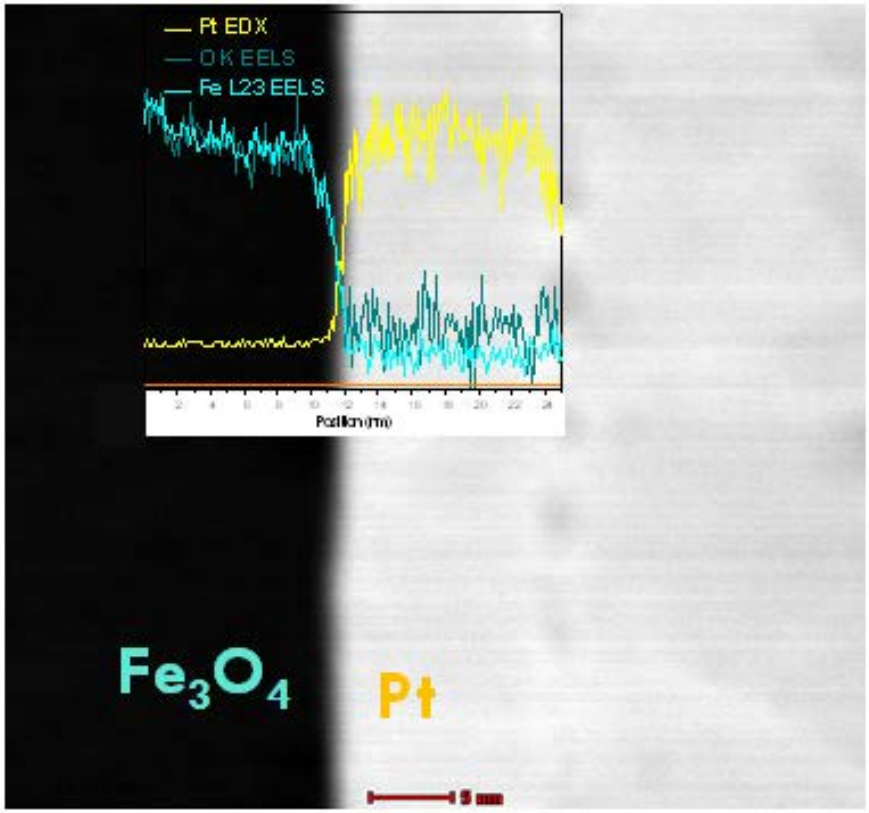
MgO

Interface Fe_3O_4/MgO

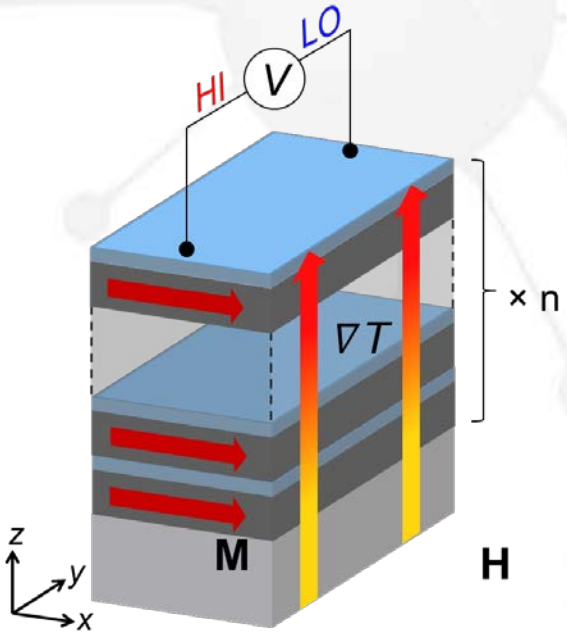
Atomic resolution chemical mapping of the interfaces

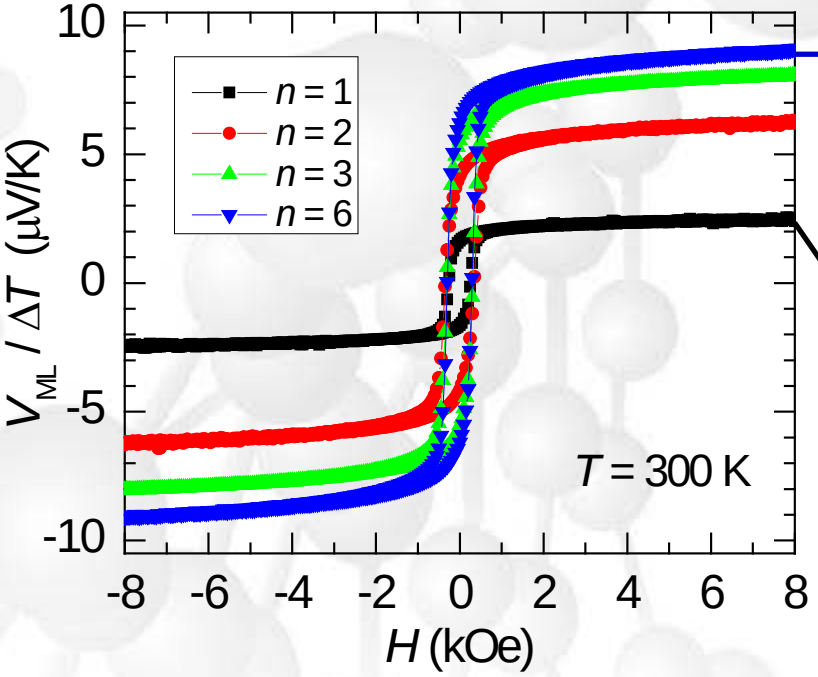


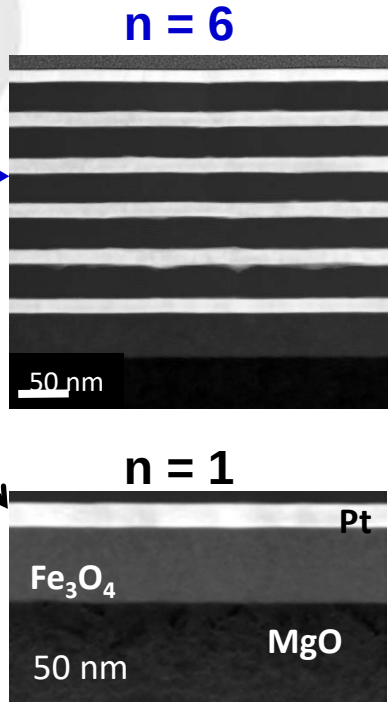




SSE vs number of Fe_3O_4/Pt bilayers



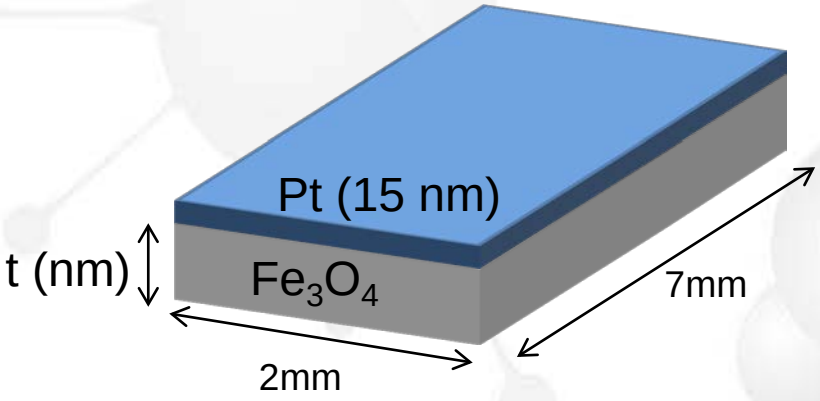


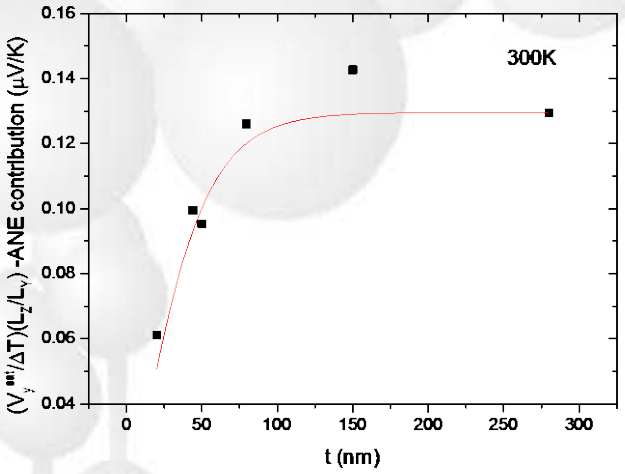


SSE voltage enhancement with incresing number of Fe_3O_4/Pt bilayers

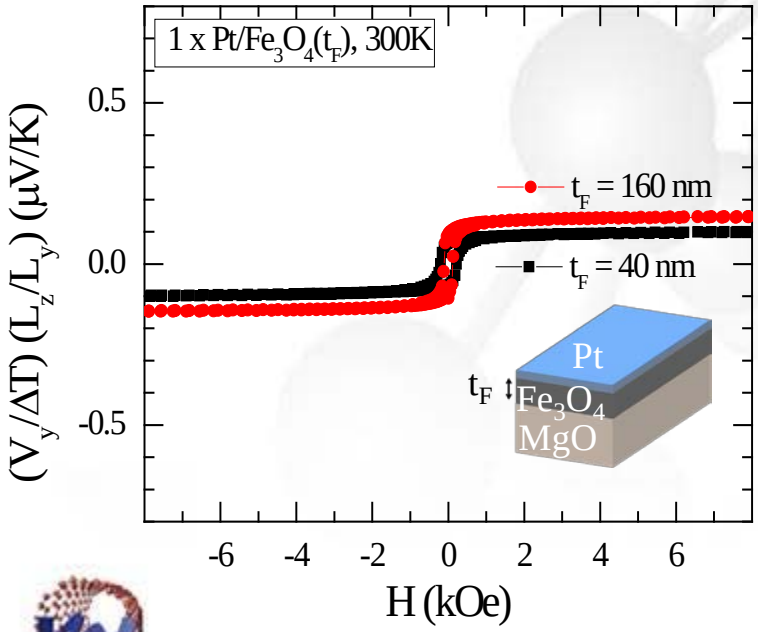
Ramos et al. Phys. Rev. B **92**, 220407(Rap. Comm.) (2015)

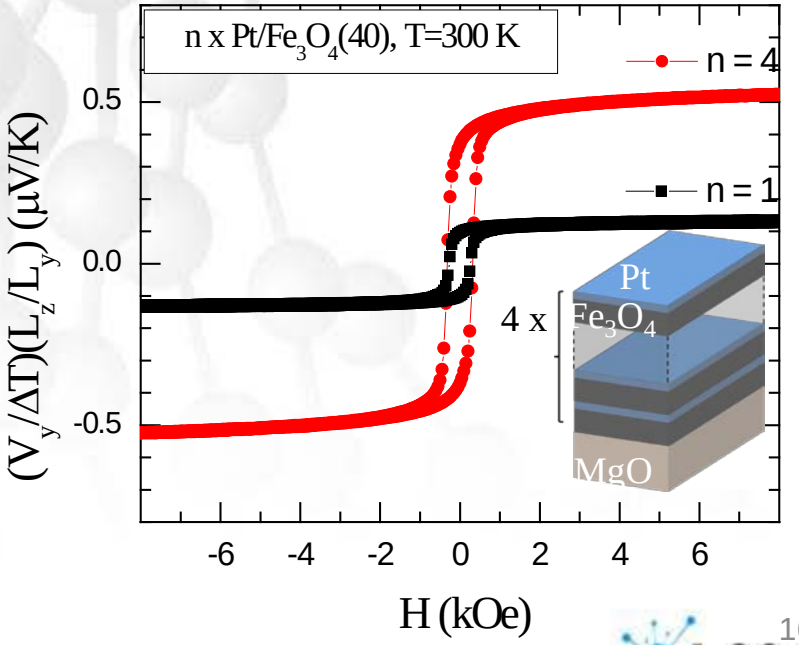
SSE dependence on Fe_3O_4 thickness



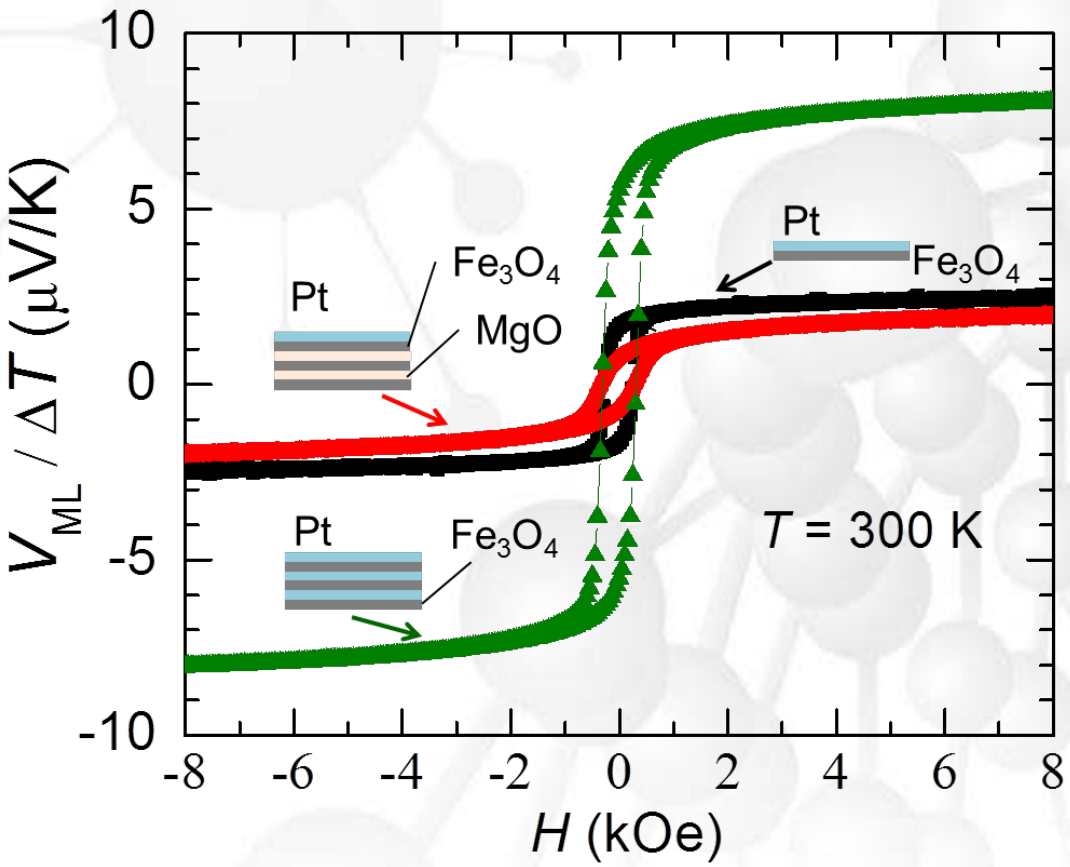


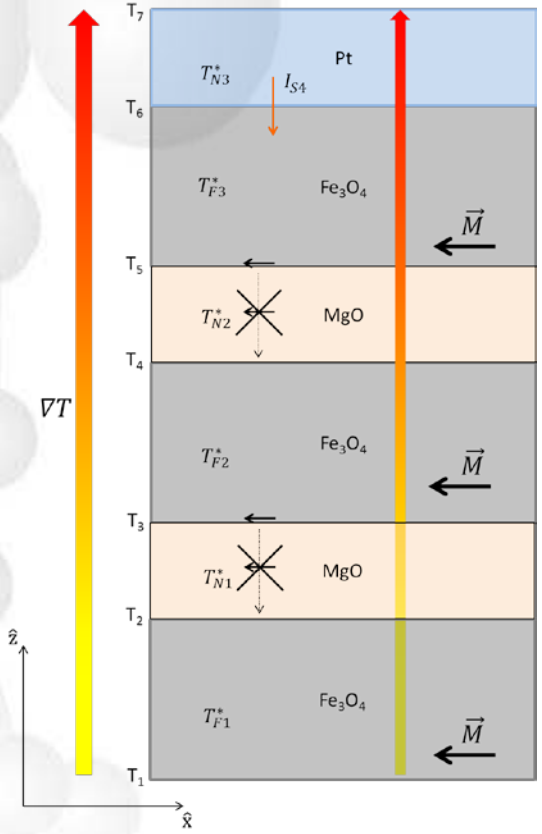
A. Anadón et al. 2016) APL (2016)





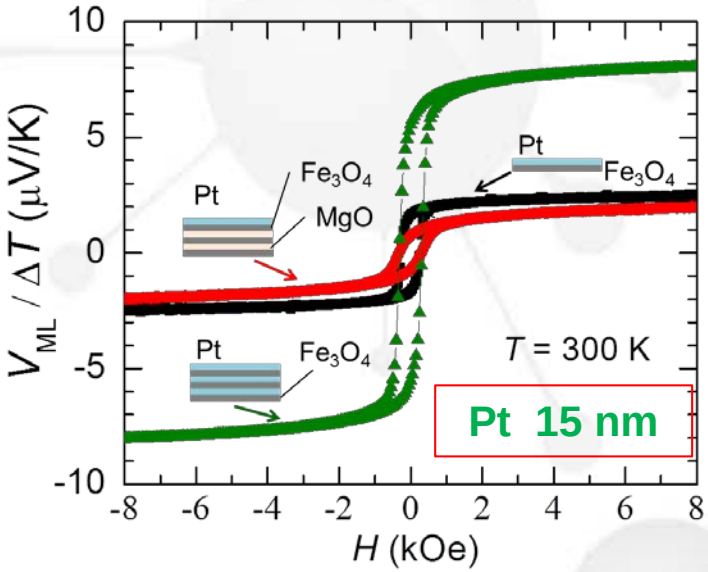
Dependence of SSE versus metal/insulator interlayer

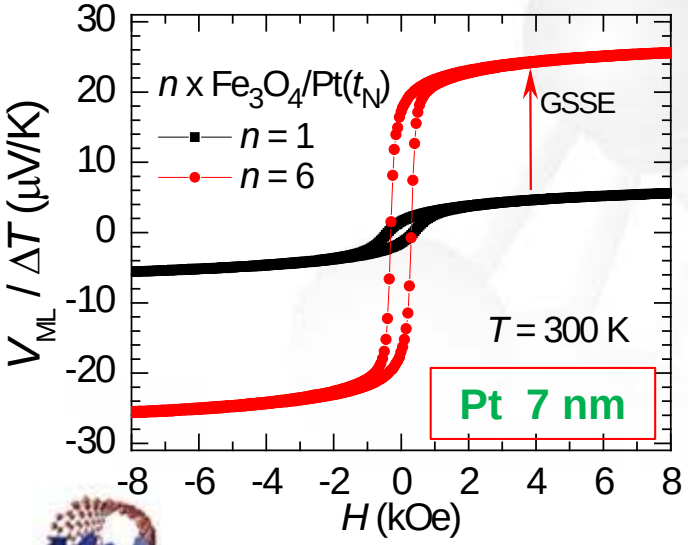


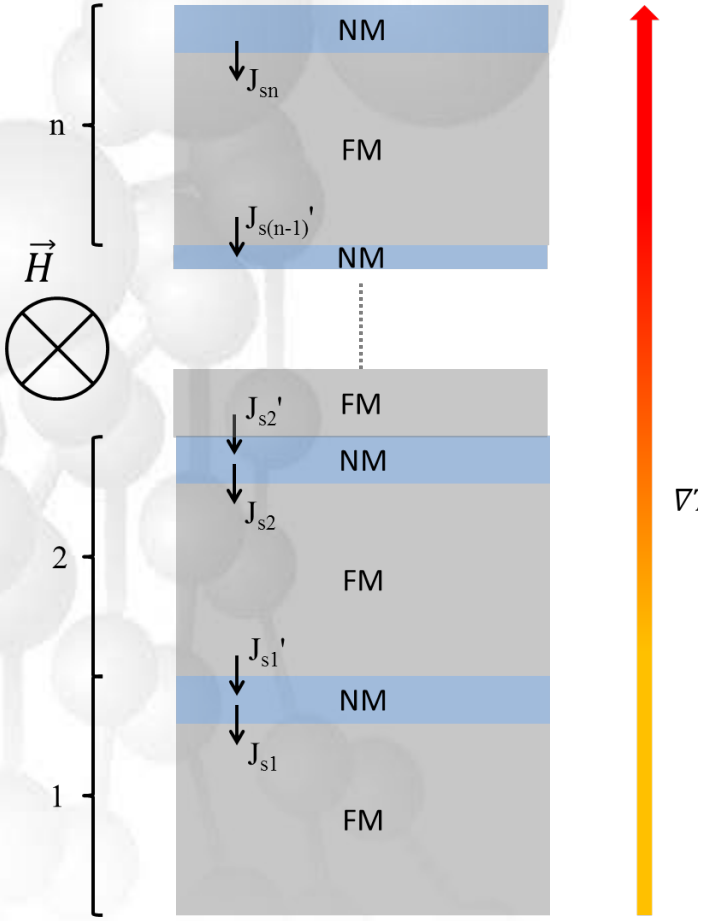


Spin current across the multilayer must be considered

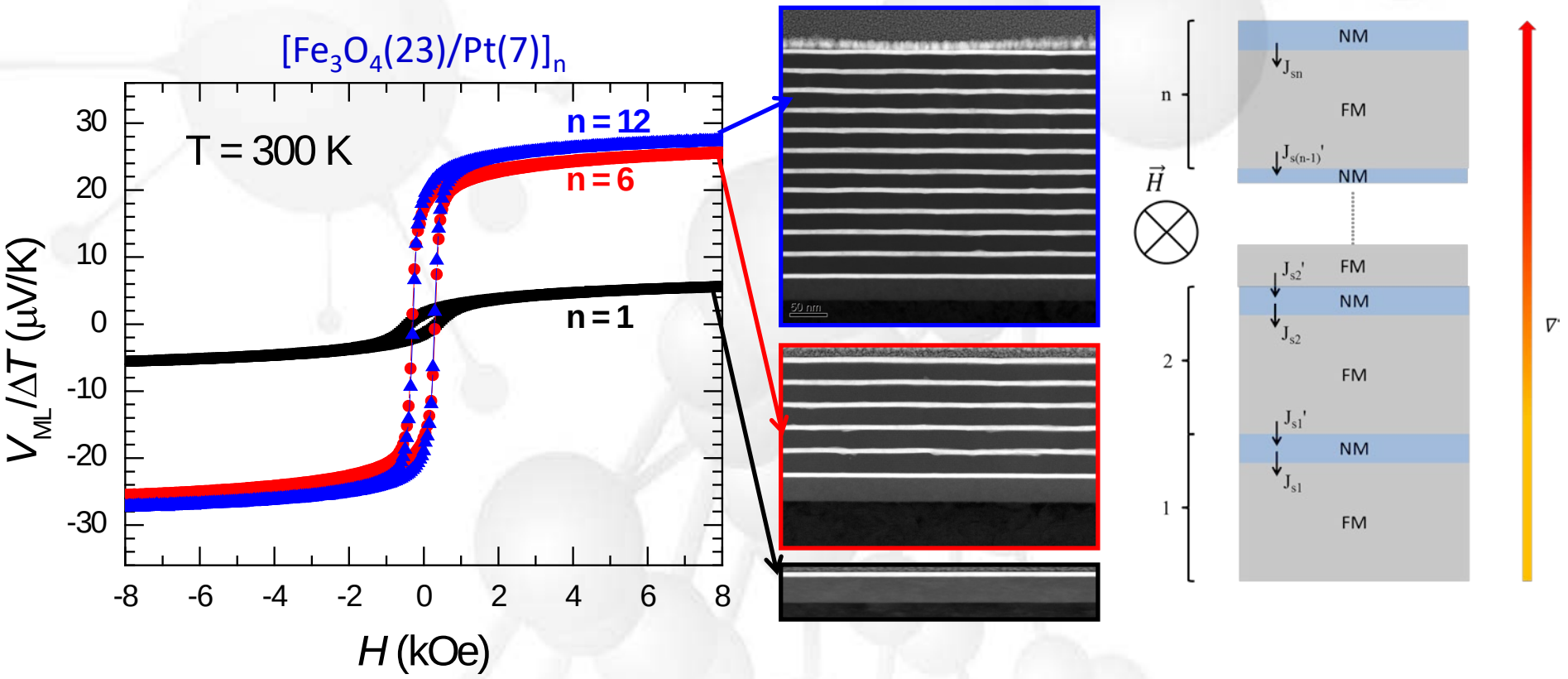
Relevance of the Pt interlayer thickness







Optimized configuration



Largest SSE voltage measured in a thin film based structure!!

$V_{ML} \approx 28\ \mu V/K$!!

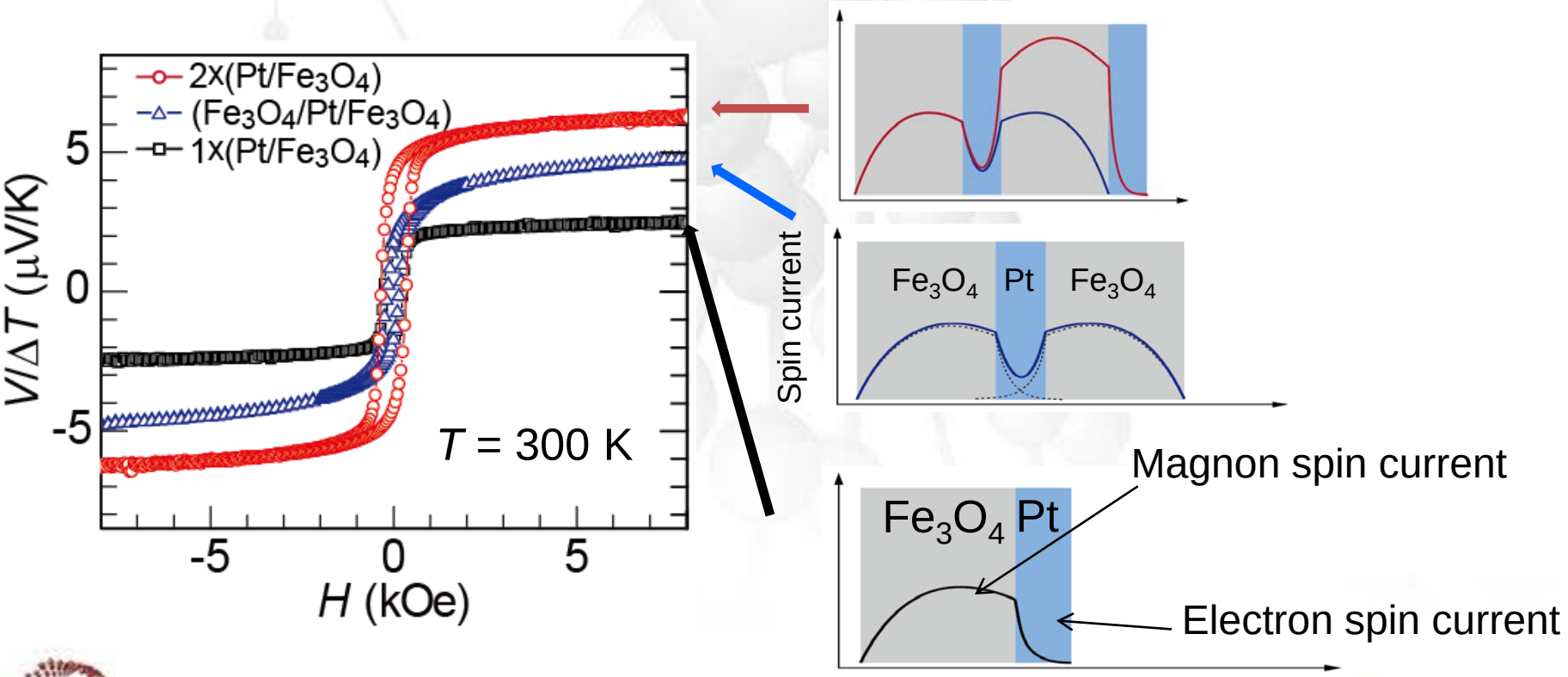
Mechanism of LSSE enhancement in multilayer systems

Essence of LSSE enhancement:

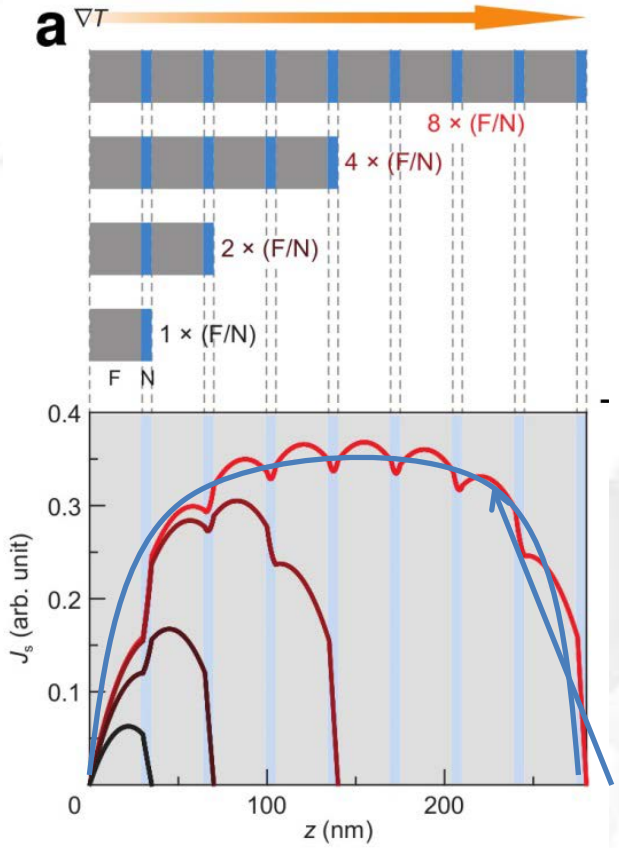
Boundary conditions for spin currents flowing normal to P/F interfaces

(i) spin currents must disappear at the top and bottom surfaces

(ii) spin currents are continuous at the interfaces



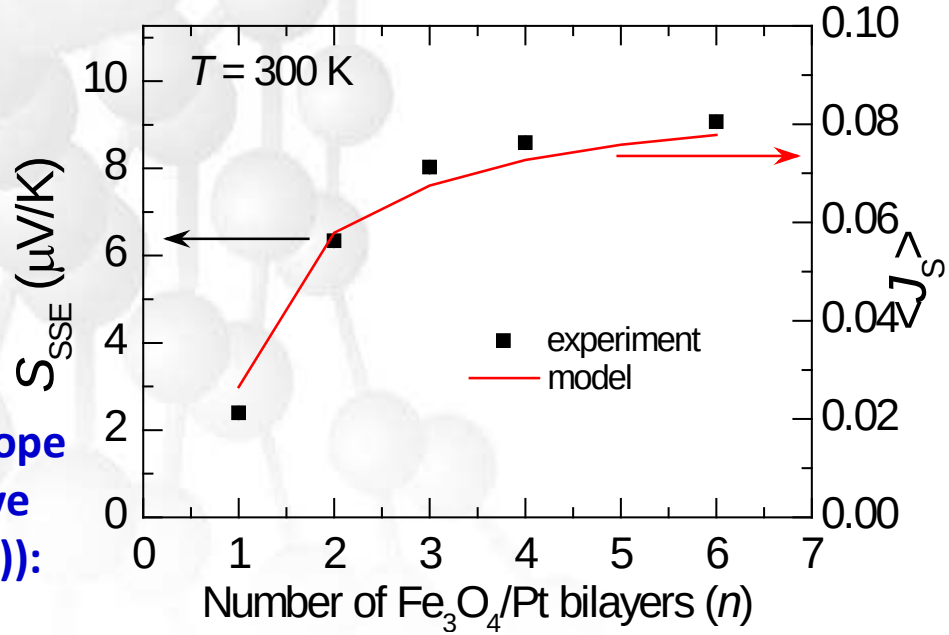
Qualitative agreement with experimental results



Maximum spin current at central interlayers

$$\langle J_S \rangle = \frac{1}{t_N n} \sum_{i=1}^{n} \int_{z_i=0}^{t_N} dz\, J_s^{(i)}(z)$$

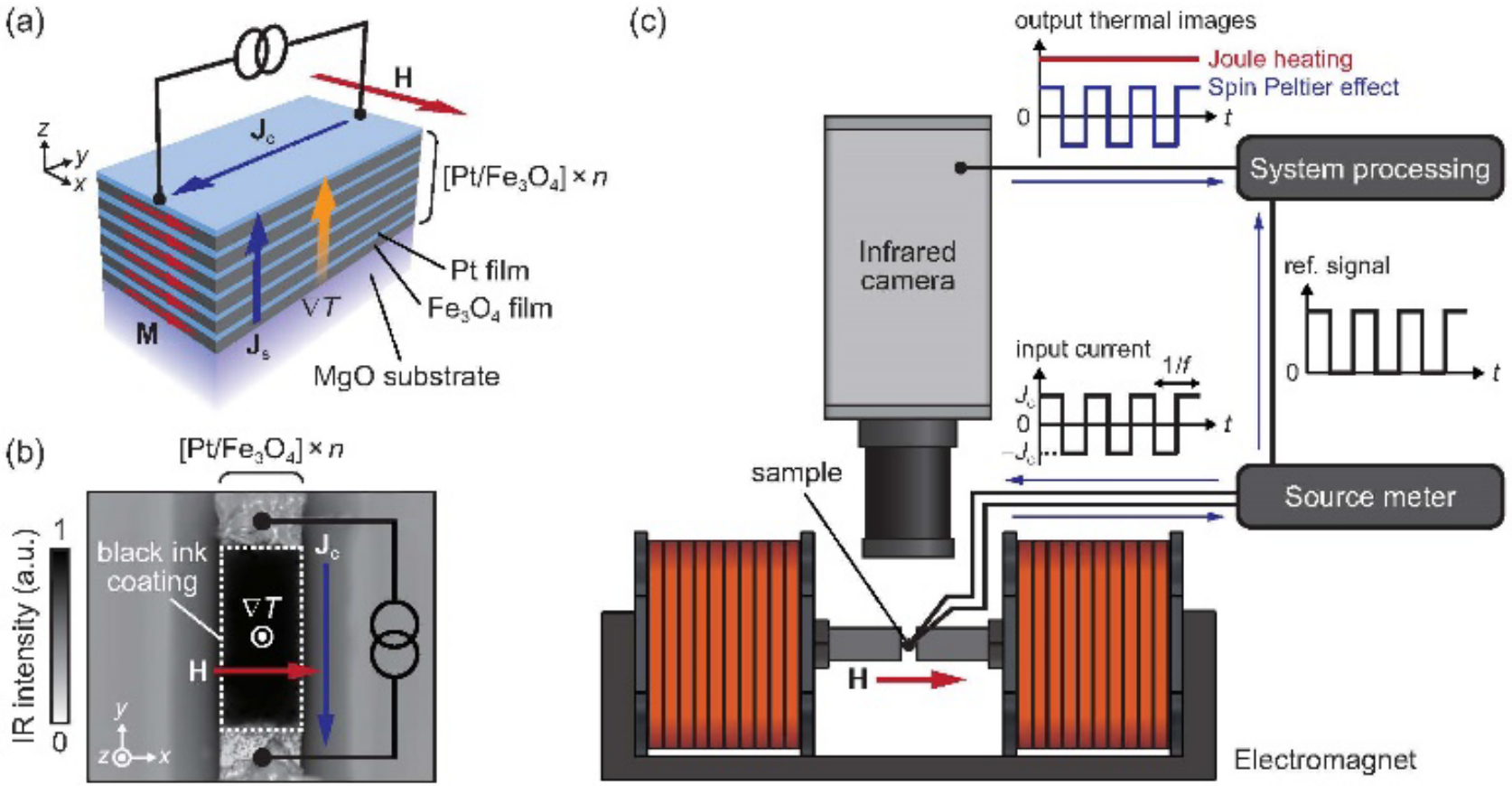
Average SSE voltage measured:



Envelope curve ($J_S(z)$):

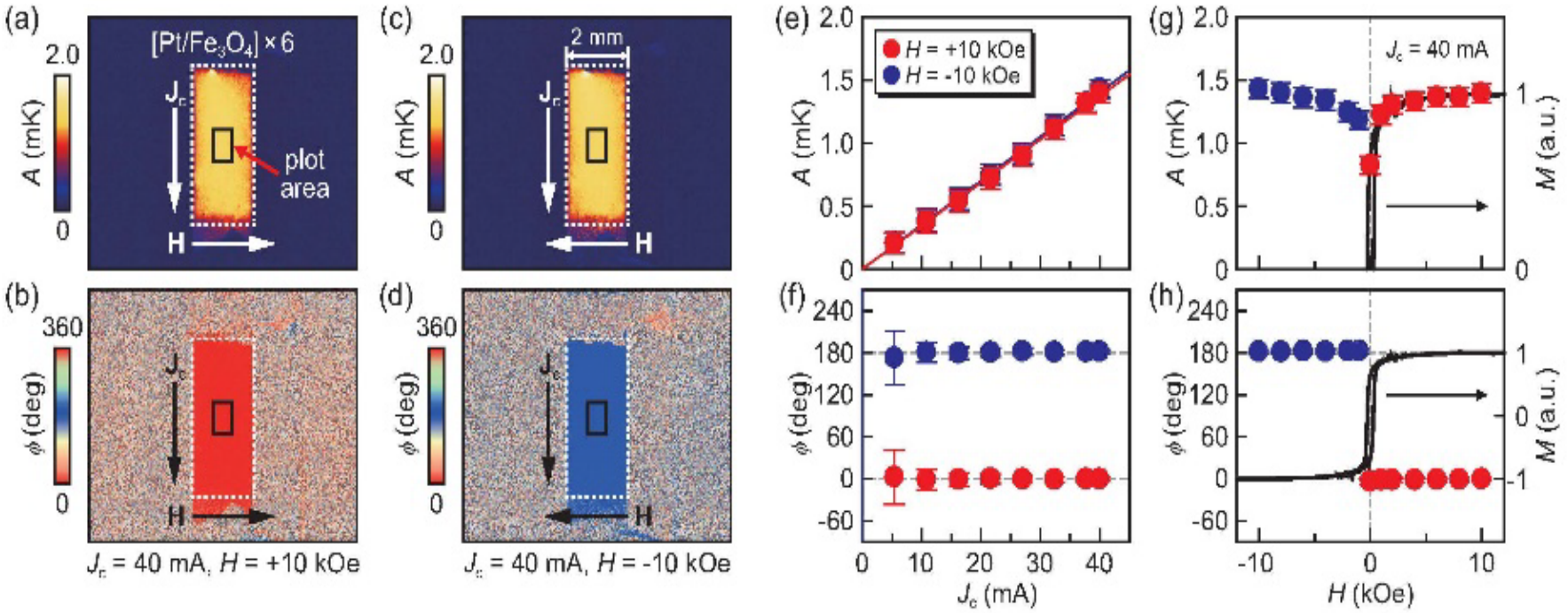
Ramos et al. Phys. Rev. B **92**, 220407(Rap. Comm.) (2015)

Spin Peltier effect in magnetic multilayers



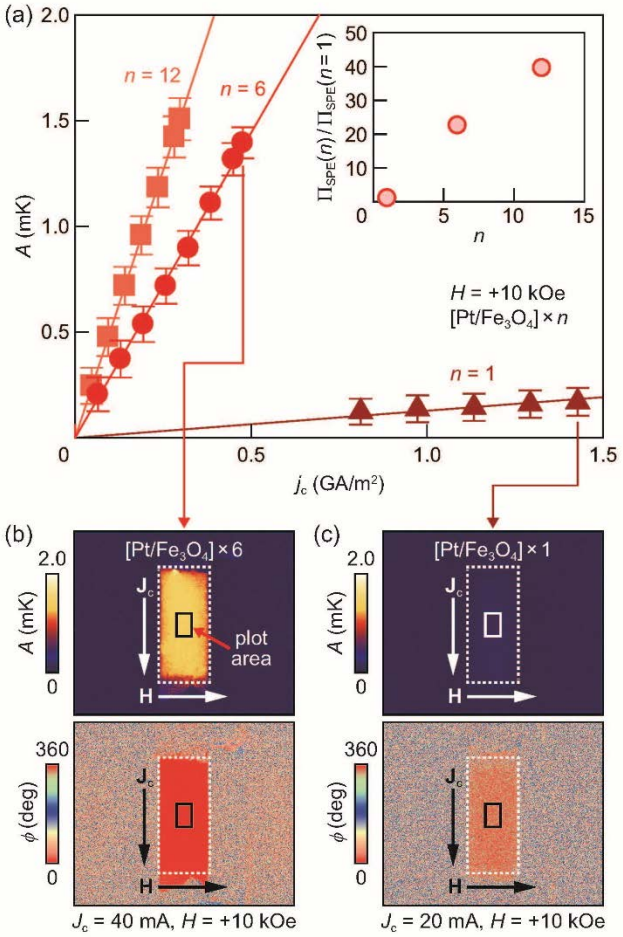
K. Uchida et al. Phys. Rev.B **95**, 184437 (2017)

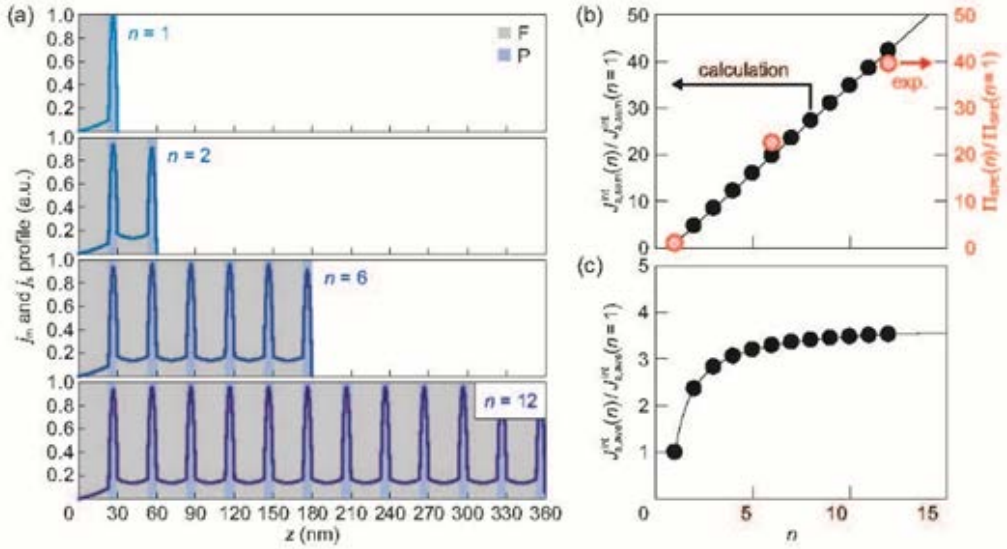
Spin peltier effect



K. Uchida et al. Phys. Rev.B **95**, 184437 (2017)

Strong enhancement of the spin peltier effect in multiple bilayers

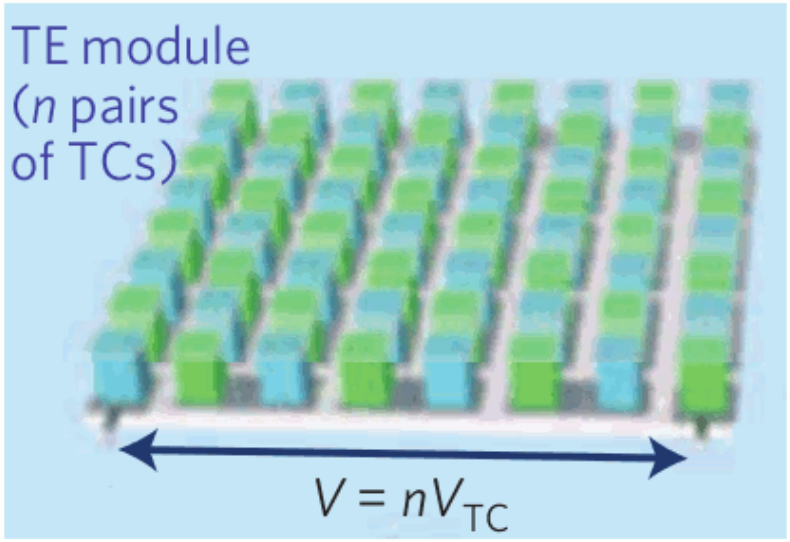


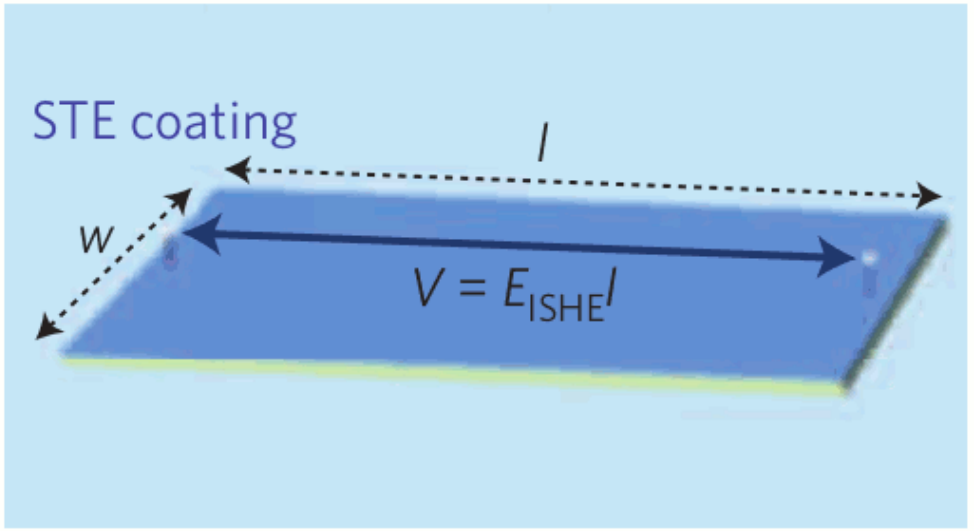


Spin Seebeck devices: thermopiles

Spin Seebeck device

(IMR, Tohoku Univ. / NEC / ASRC, JAEA/Zaragoza)





Conventional charge thermoelectric device:

Many thermocouples necessary
→High cost, difficulty in integration

T-gradient over centimeter scale needed
→Thin film device difficult

Spin-Seebeck thermoelectric device

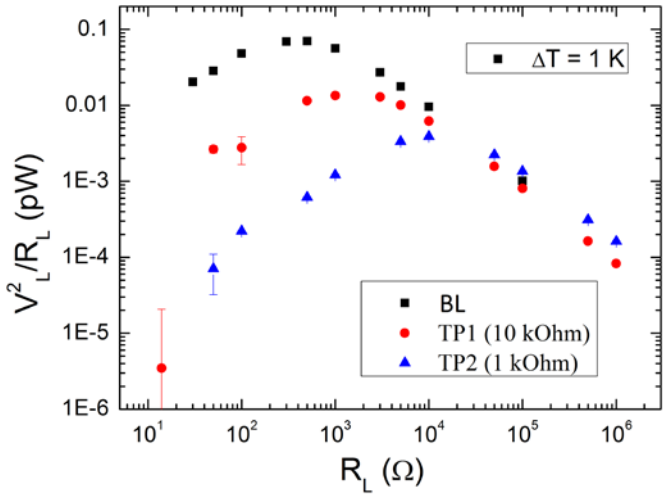
Many thermocouples unnecessary
→**Low cost, ultimate integration**

T-gradient over nanometer scale is sufficient
→**Thin film device possible**

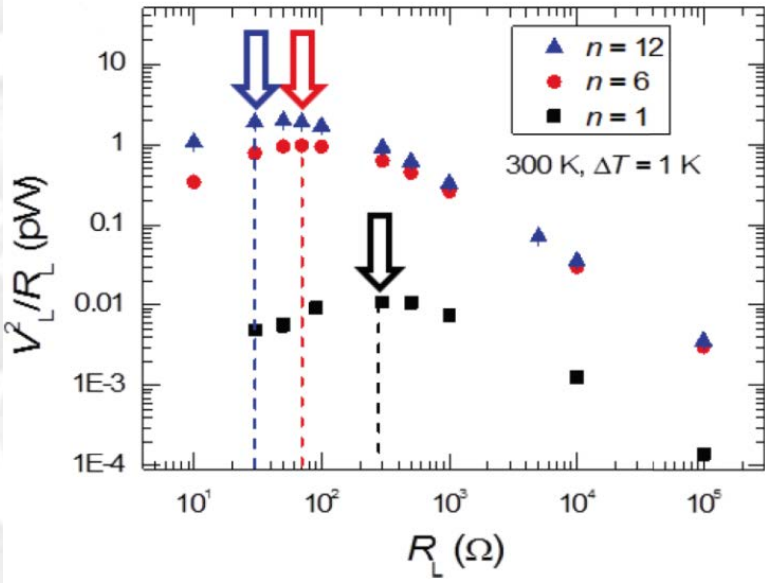
Wide area, low cost thermoelectric devices

SSE thermopiles

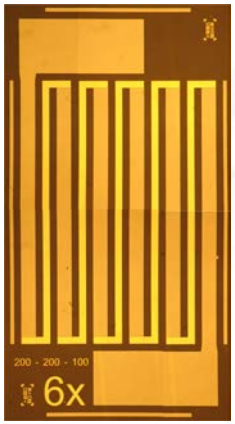
Bilayer



Multilayer



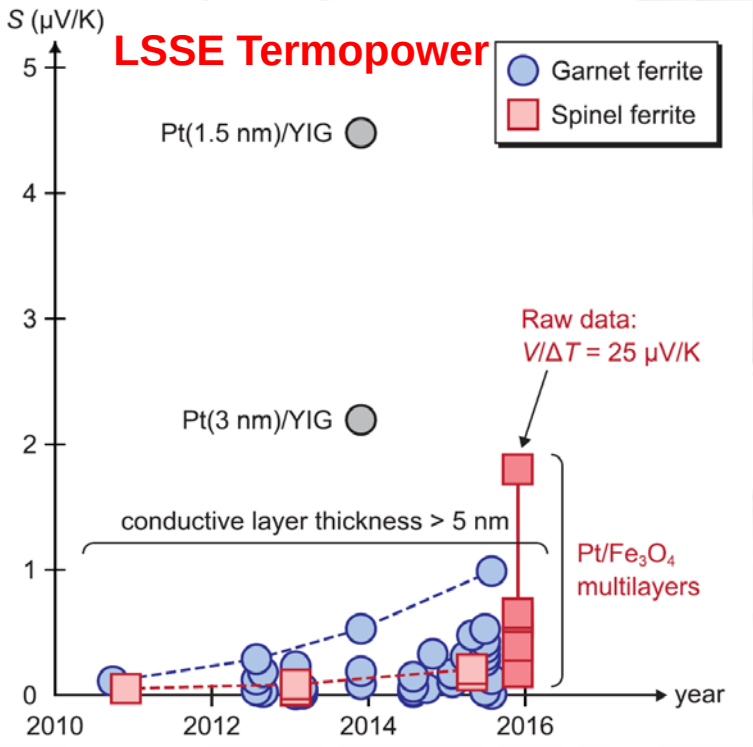
TP1

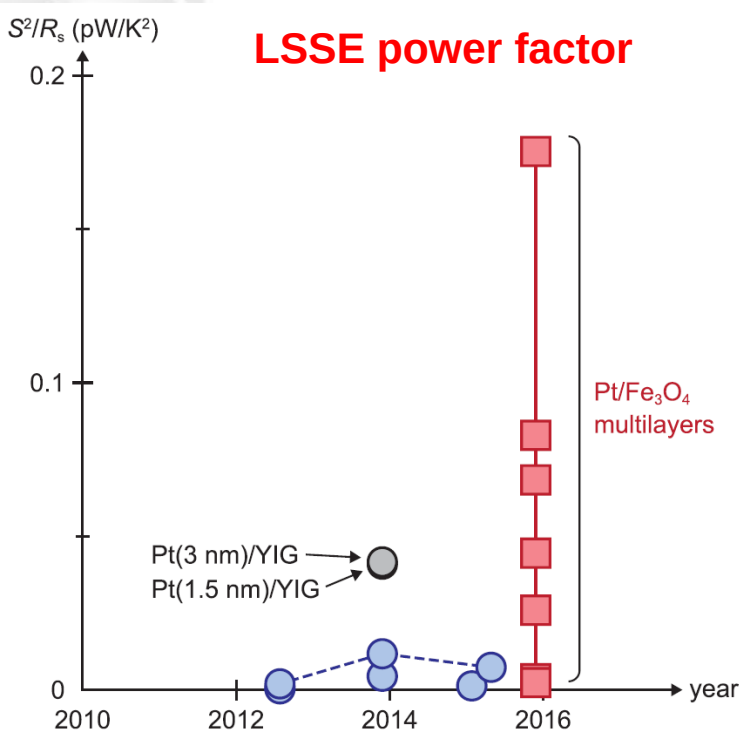


TP2

Conclusions

Spin current conversión at the interfaces F/N gives rise to an strong enhancement of the thermospin effects in multiple bilayers and constitutes an excellent play ground for the study of new physical phenomena and promising for devices application





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Development of thin-film thermoelectric SSE based devices

http://ina.unizar.es ibarra@unizar.es