" Thermospin effects in magnetic multilayers"

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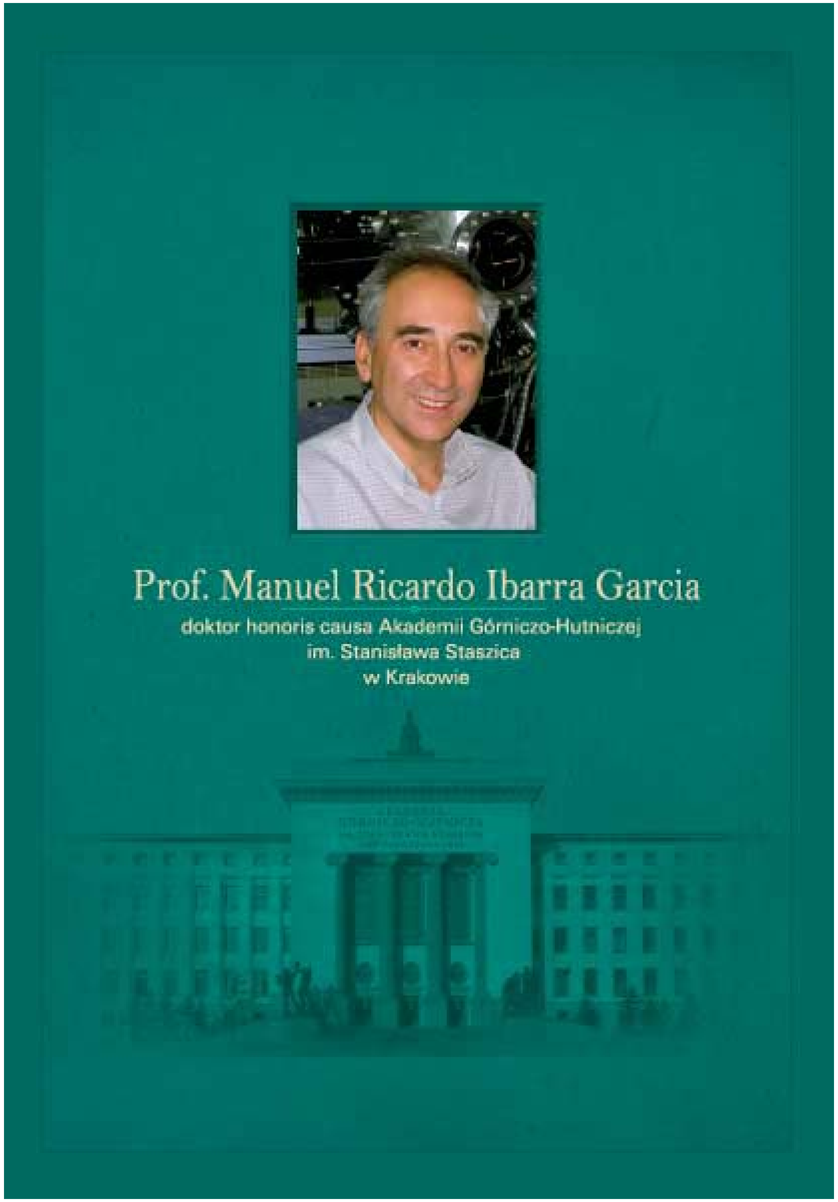
AGH

LMA
LABORATORIO DE MICROSCOPIAS AVANZADAS


Prof. Manuel Ricardo Ibarra Garcia
doktor honoris causa Akademii Górniczo-Hutniczej
im. Stanisława Staszica
w Krakowie

Outline

- The concept of spin currrents
- The thermoelectric conversion
- Introduction to Thermospin effects
- SSE effects in $[Fe_3O_4/Pt]_n$ multilayers
- Spin Peltier effect in $[Fe_3O_4/Pt]_n$ multilayers
- Thermoelectric power: thermopiles
- Conclusions

The concept of spin current

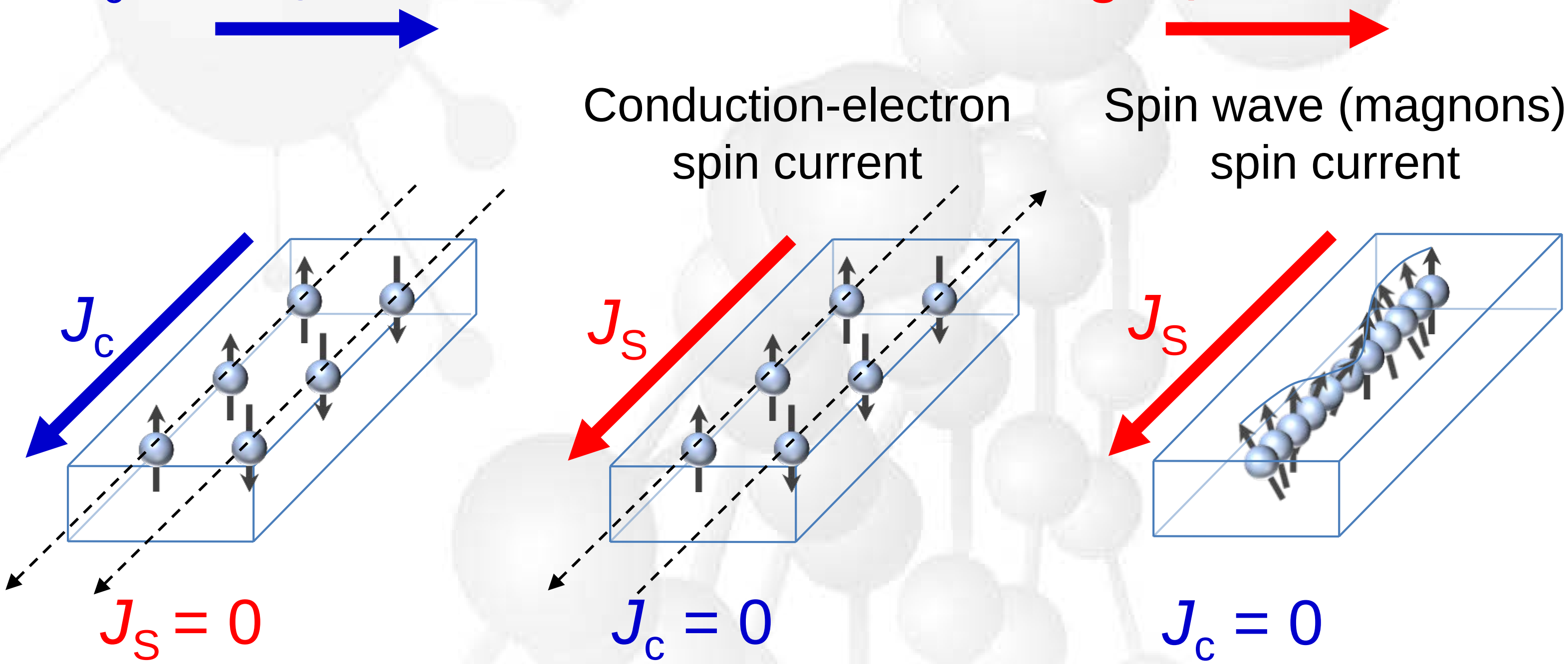
Charge and spin currents

J_c: charge current

J_S: spin current

Conduction-electron spin current

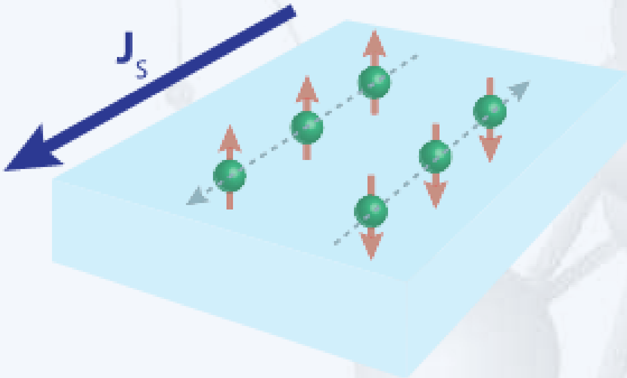
Spin wave (magnons) spin current



	Charge current	Spin current
Unpolarized current		0
Spin-polarized current		
Fully spin-polarized current		
Pure spincurrent	0	

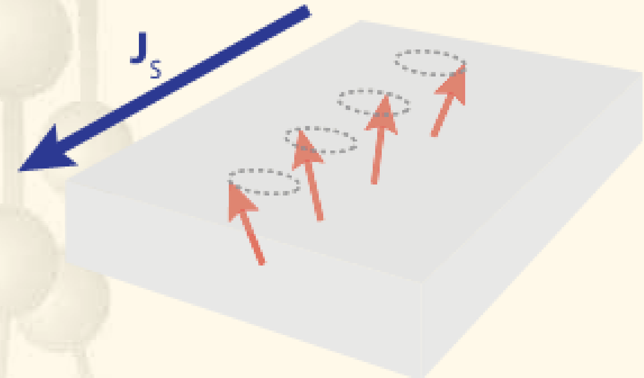
Pure Spin Currents

Non-magnetic Metal



Net electron spin flow

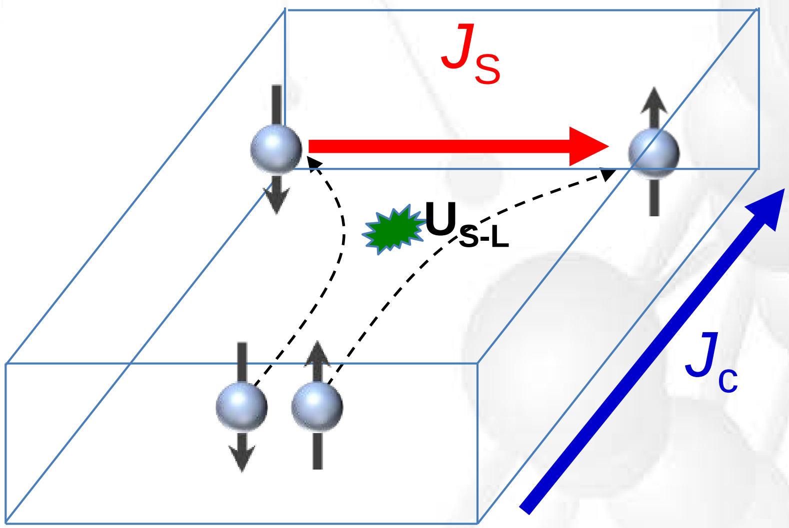
Magnetic Insulator

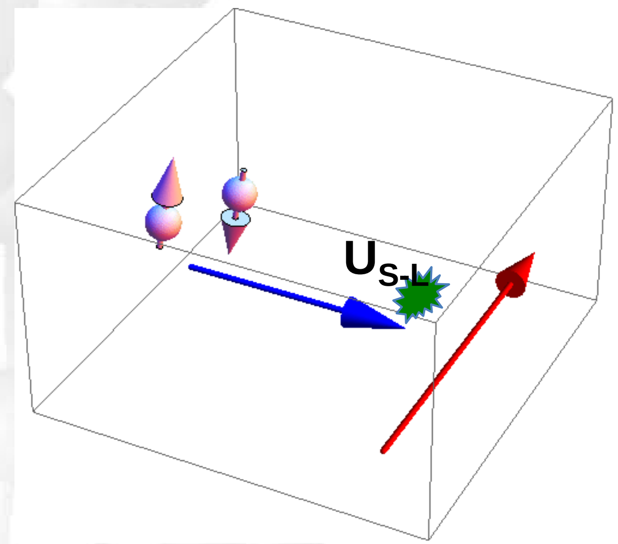


Magnon flow

Spin Hall effect (SHE)

Interconversion of charge – spin currents in materials with high spin orbit coupling (high Z)
(Dyakanov & Parel 1971,Hirch 1999)



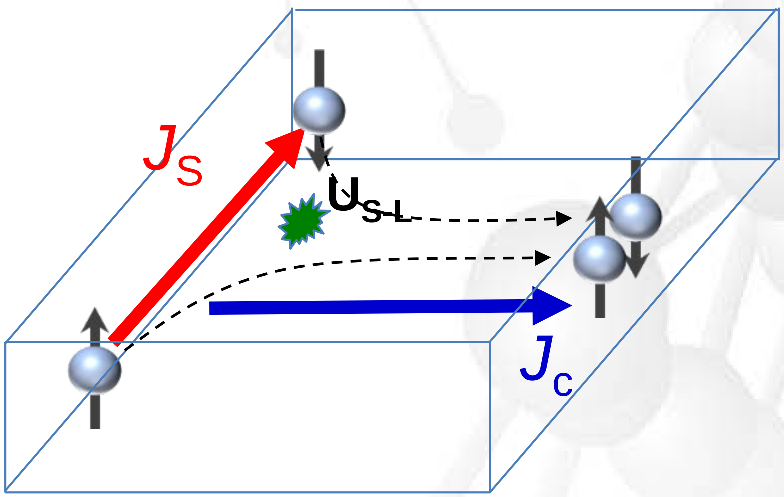


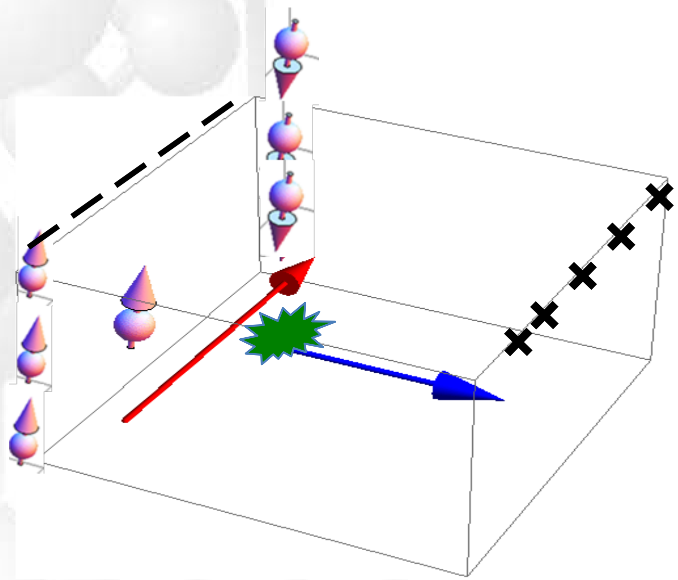
(J_c) Charge → (J_s) Spin

Inverse Spin Hall effect (ISHE)

Interconversion of spin currents – charge currents in non-magnetic metals with high spin orbit coupling (high Z)

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.

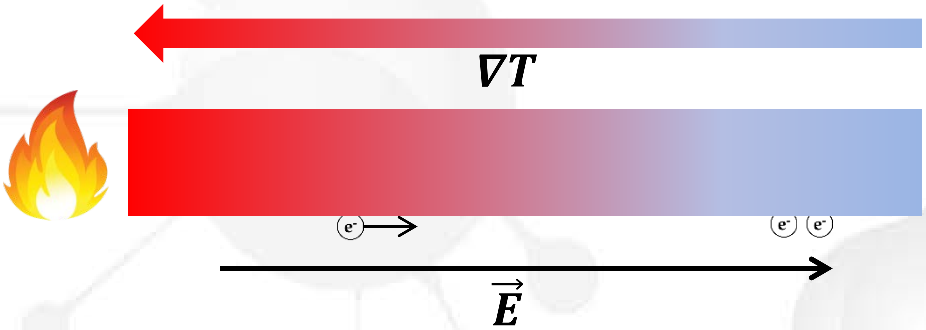


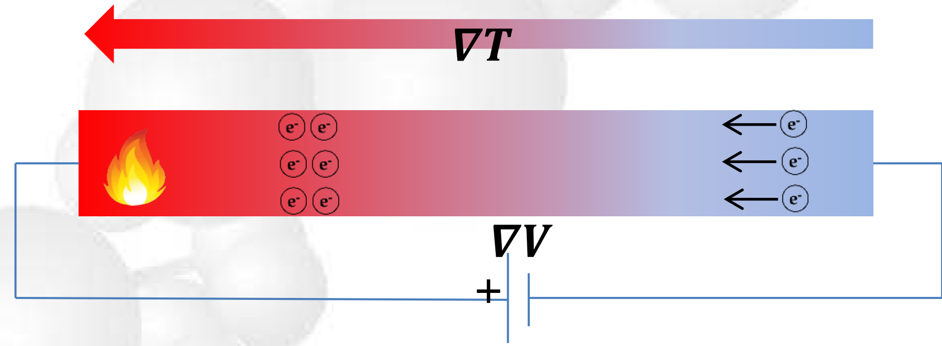


(J_S) Spin → (J_c) Charge

Thermoelectric conversion

Thermoelectric effects





$\vec{J} = \sigma(\vec{E} - S\,\nabla T) = 0$

Seebeck effect: $S = \frac{\vec{E}}{\nabla T}$

Peltier effect: $\Pi = S\,T$

Thermoelectric power generation

Thermoelectric cooling

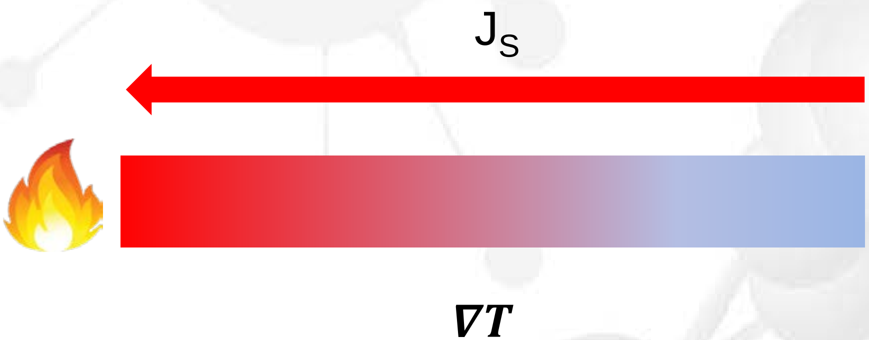
Figure of merit

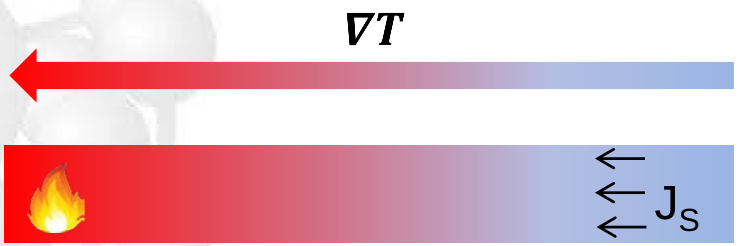
$$ZT = \frac{S^2\sigma}{\kappa}T$$

$$\kappa = \kappa_e + \kappa_l \qquad \kappa_e = L\sigma T$$

$$L = \frac{\pi^2}{3}\left(\frac{k_B}{e}\right)^2 = 2.44 \times 10^{-8}\ {}^{W\Omega}/_{K^2}$$

Would it be posible thermoelectric effect due to spin?





Spin Seebeck Effect (SSE)

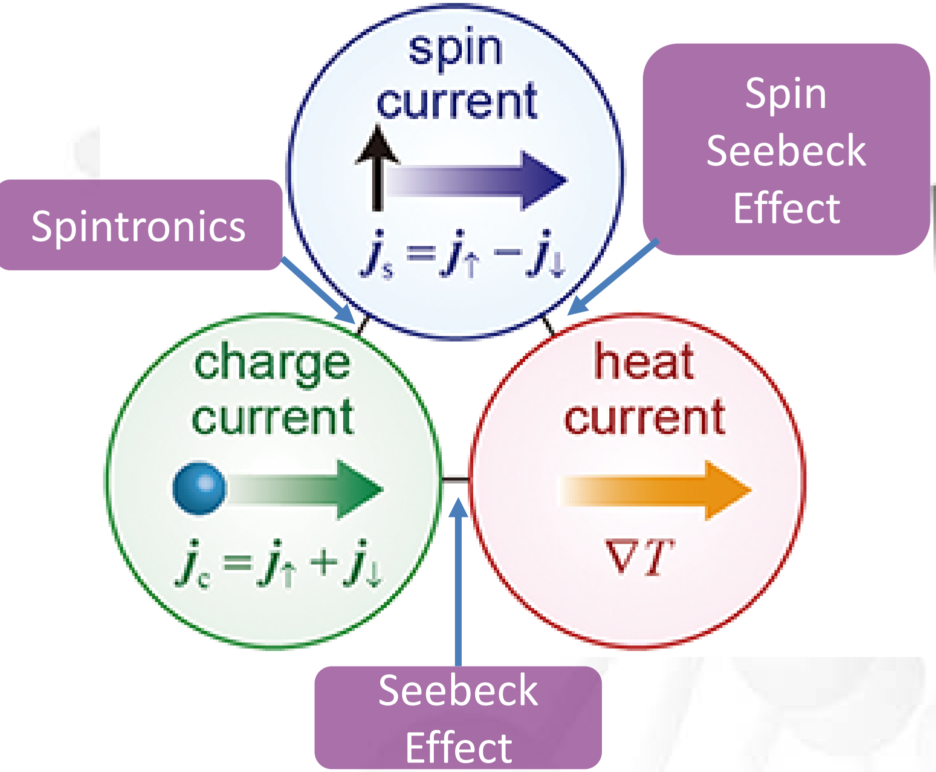
Spin Peltier Effect (SPE)

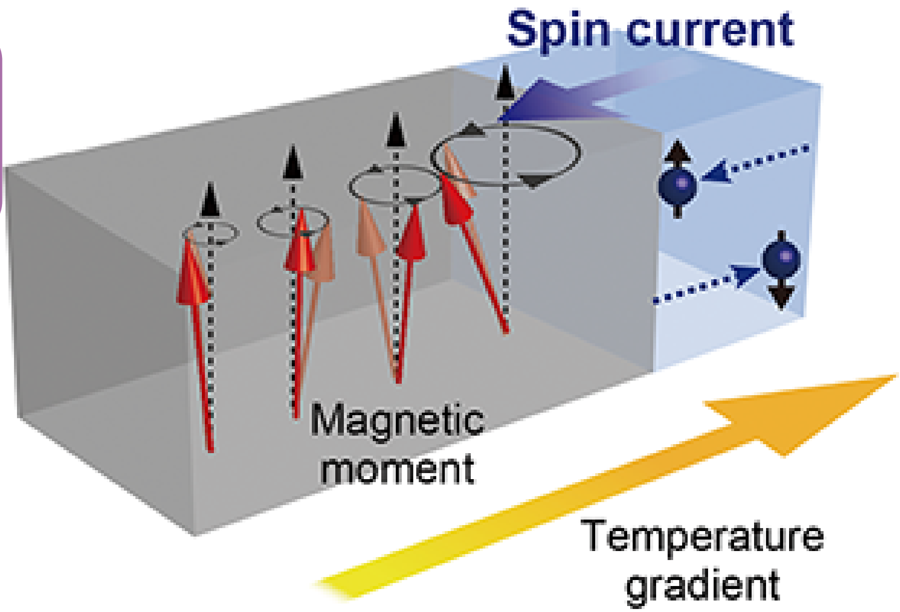
Heat vs. Electricity

	To get Electricity	To get Heat
Charge	**Seebeck effect**	**Peltier effect**
Spin	**Spin Seebeck effect** Uchida 2008	**Spin Peltier effect** Flipse 2014 Daimon 2016

Thermospin concept

Spin Seebeck effect effect: Spin current generation by heat



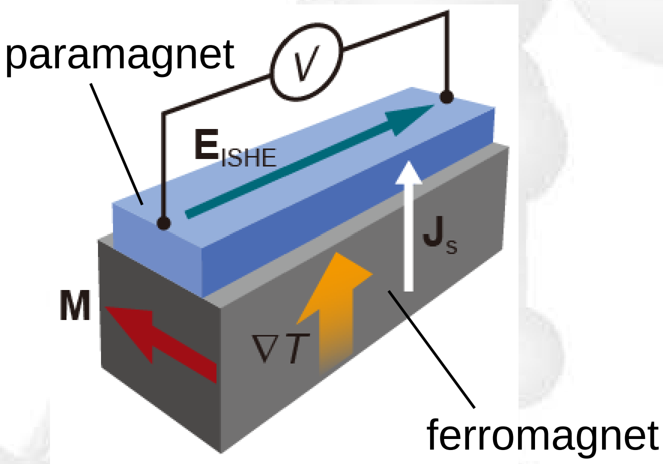


$$I_S = -G_S \frac{k_B}{\hbar}(T_F - T_N)$$

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

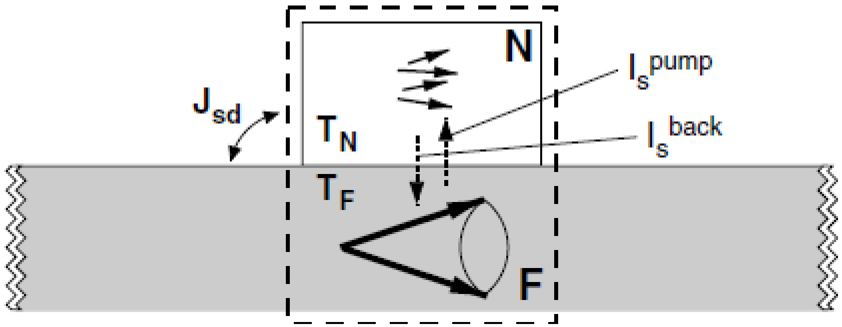


Inverse spin Hall effect:

$$\mathbf{E}_{\mathrm{ISHE}} = \theta_{\mathrm{SH}}\rho(\mathbf{J}_{\mathrm{S}} \times \boldsymbol{\sigma})$$

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

Spin Seebeck basic principles



- Spin current proportional to applied thermal gradient

- Injected spin current converted in electric voltage by the inverse spin Hall effect

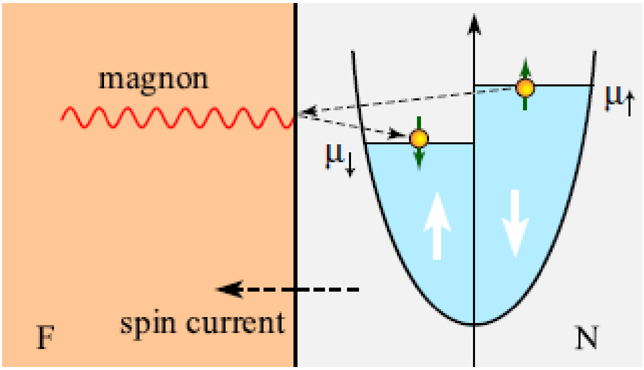
$$I_S = -G_S \frac{k_B}{\hbar}(T_F - T_N)$$

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

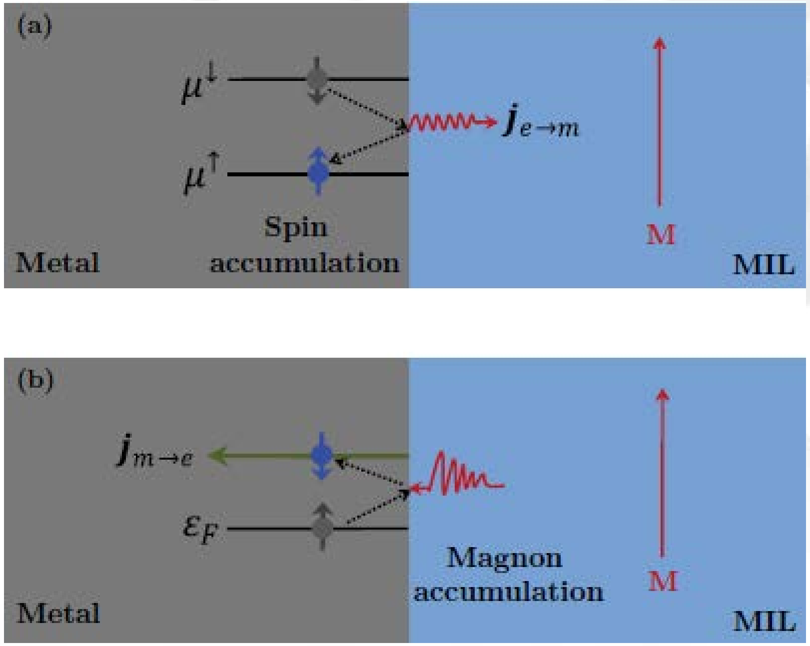
J. Xiao et al. Phys. Rev. B **81,** 214418

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

SPIN CURRENT AT THE INTERFACES



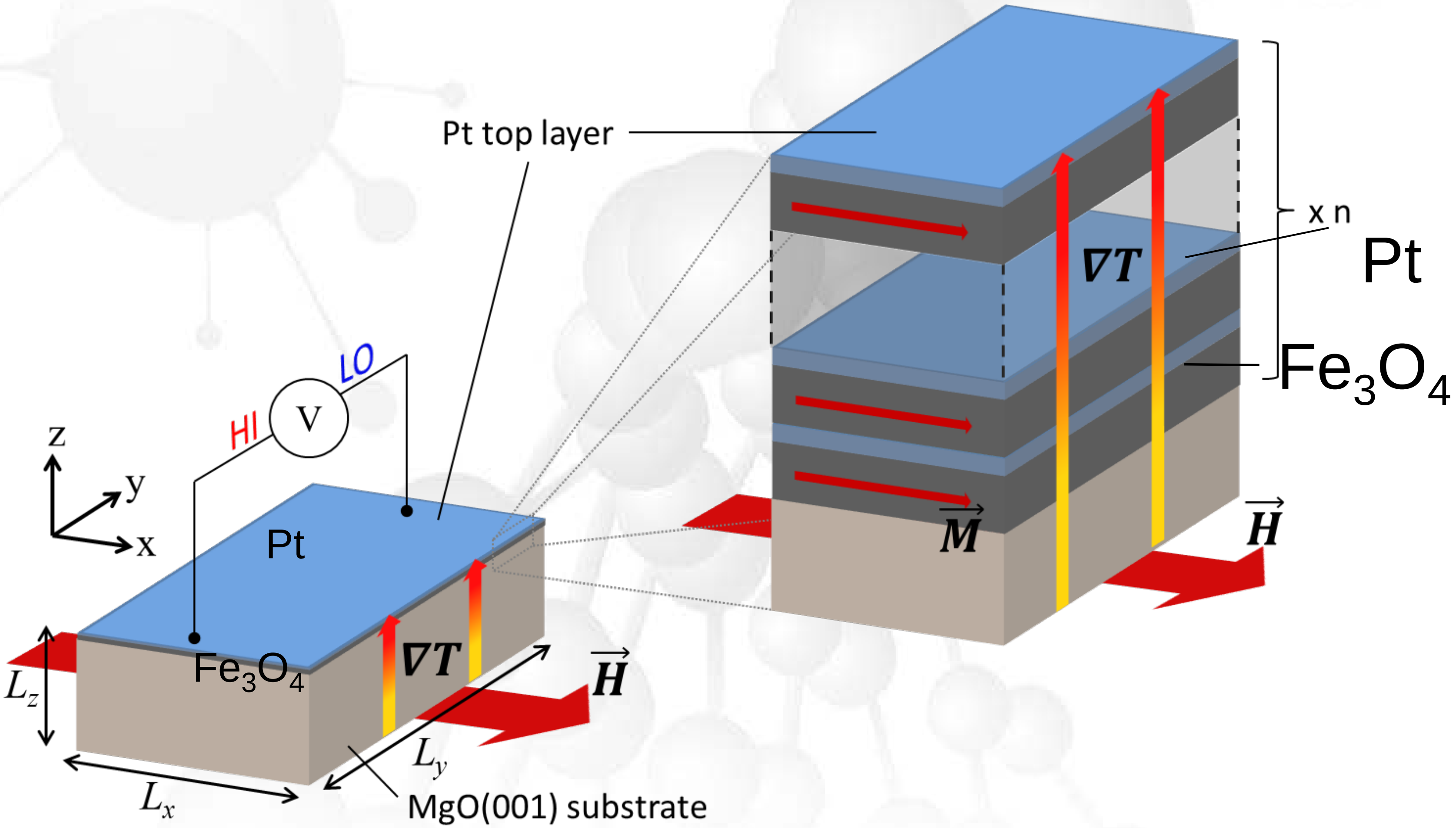
Magnon emission associated with spin accumulation at the metal-ferromagnet interface
(Takahasi et al ICM 2009)



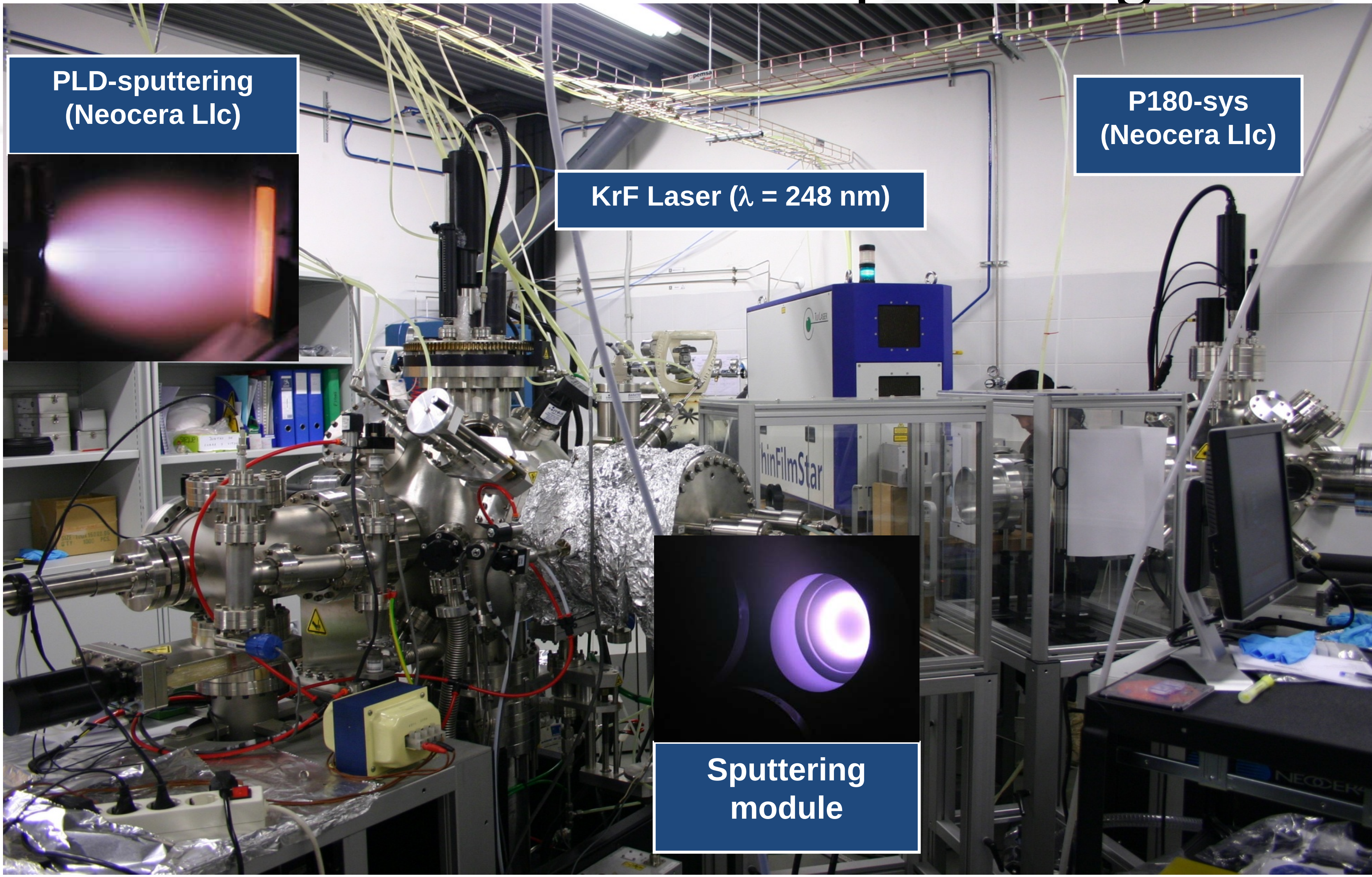
Spin angular momentum transfer at the interface: Magnon and elecron spin current interconversion
(Steven et al. PRB 86 (2012) 214424)

Spin Seebeck effect in magnetic multilayers

SSE in $[F/N]_n$ multilayers



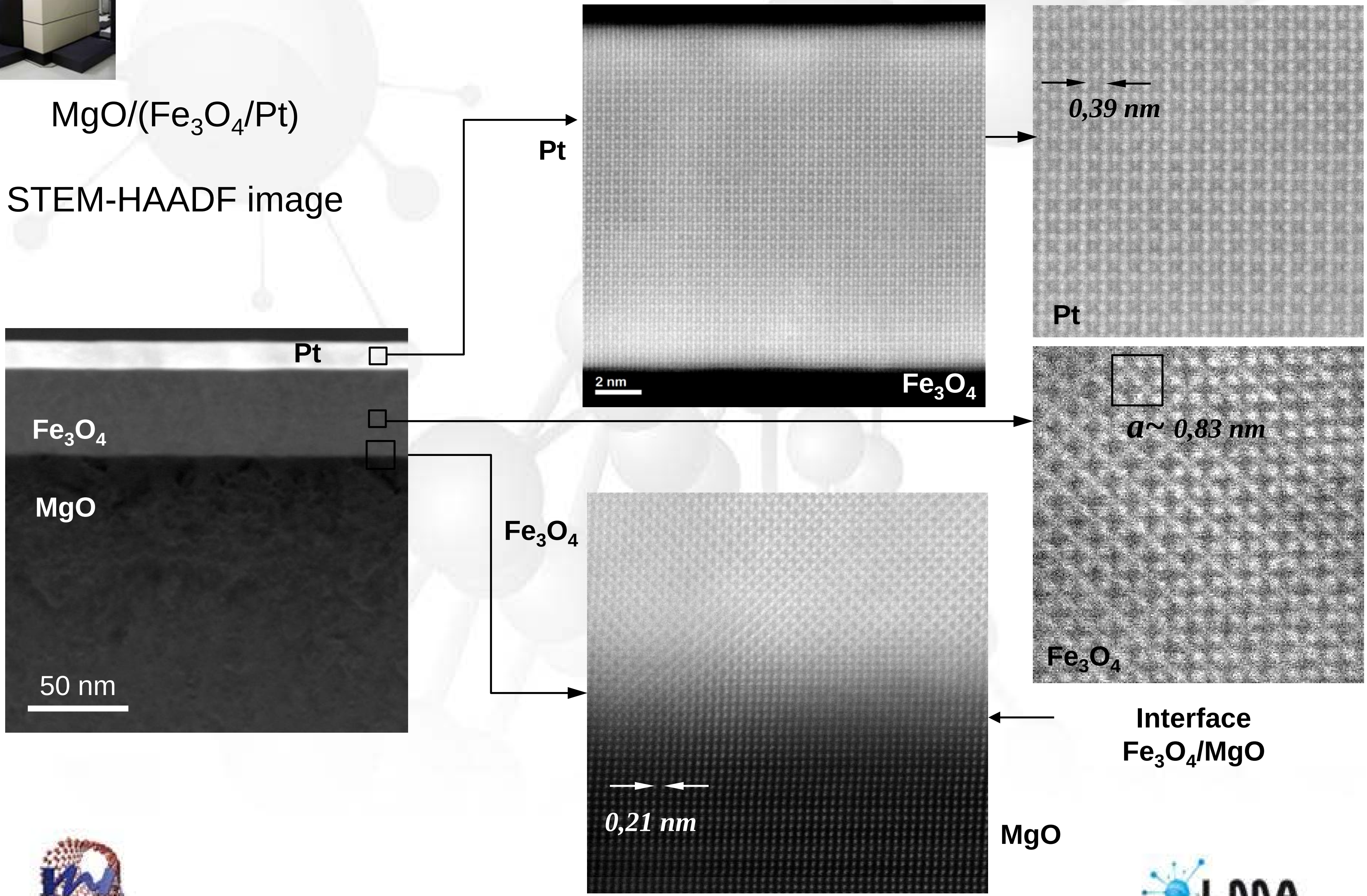
Combined PLD & Sputtering



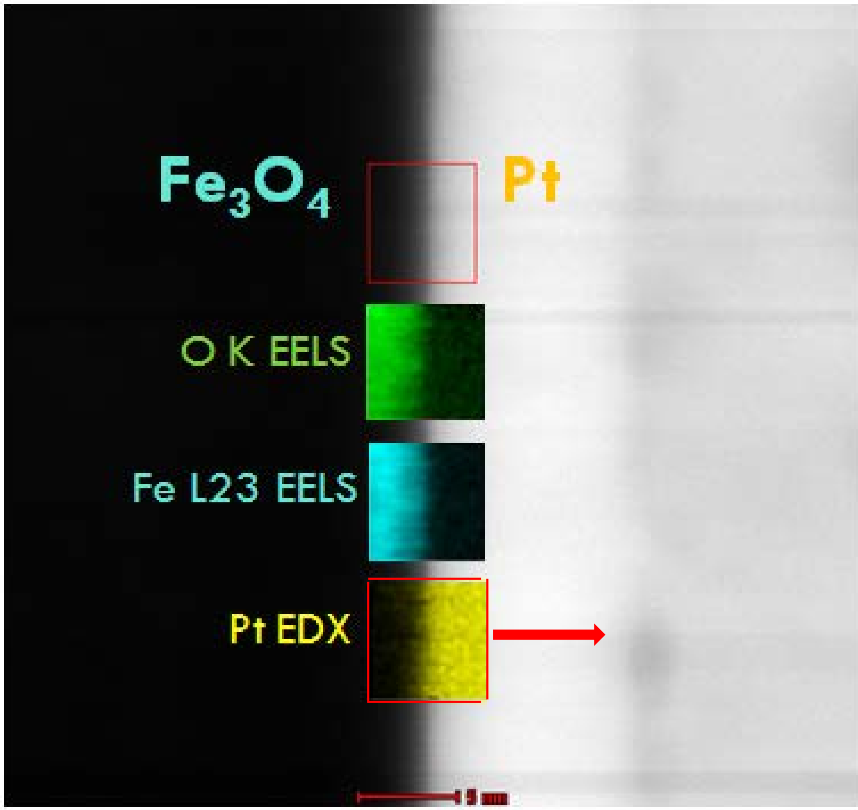
Atomic resolution morphological characterization

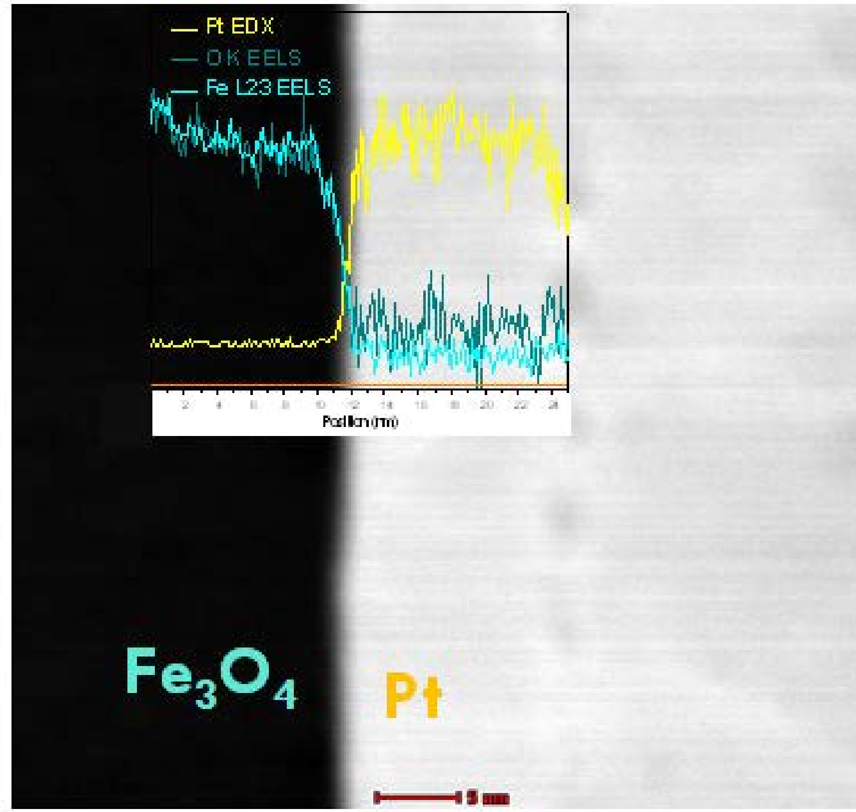
$MgO/(Fe_3O_4/Pt)$

STEM-HAADF image

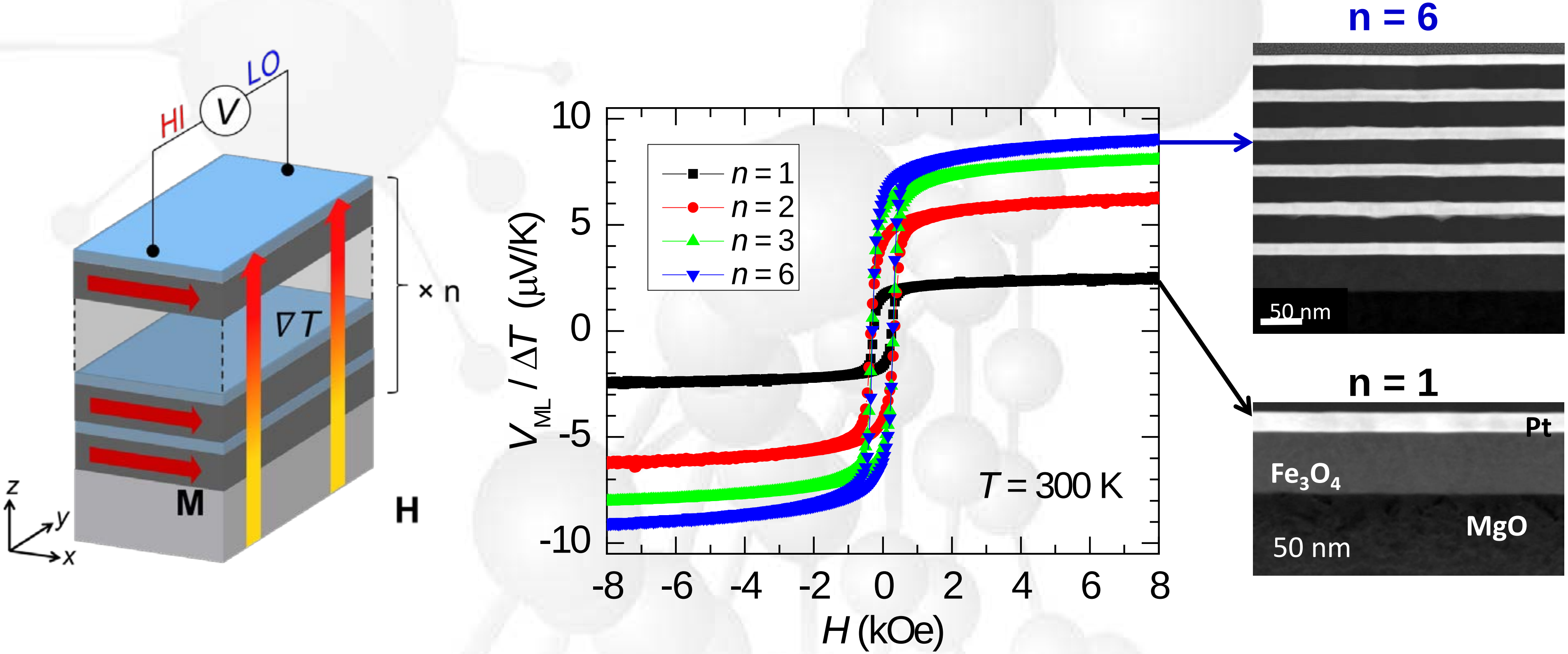


Atomic resolution chemical mapping of the interfaces





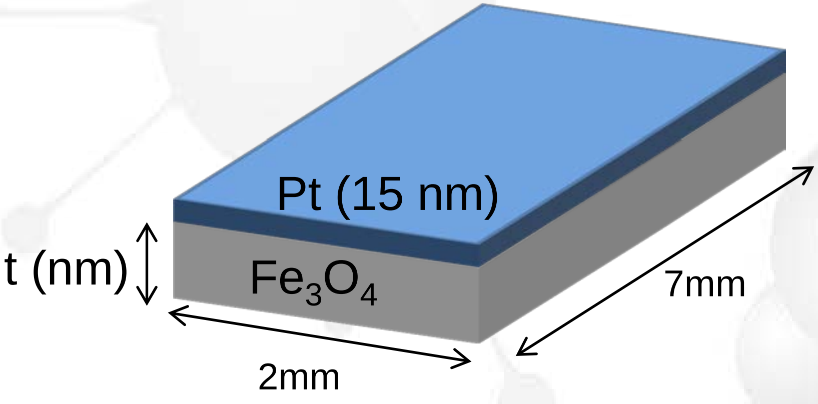
SSE vs number of Fe_3O_4/Pt bilayers

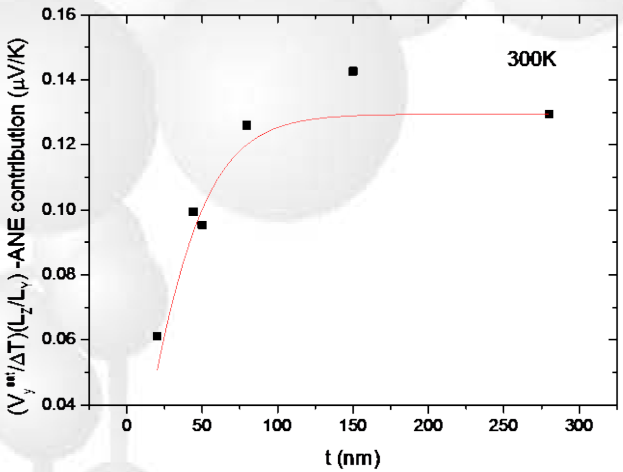


SSE voltage enhancement with incresing number of Fe_3O_4/Pt bilayers

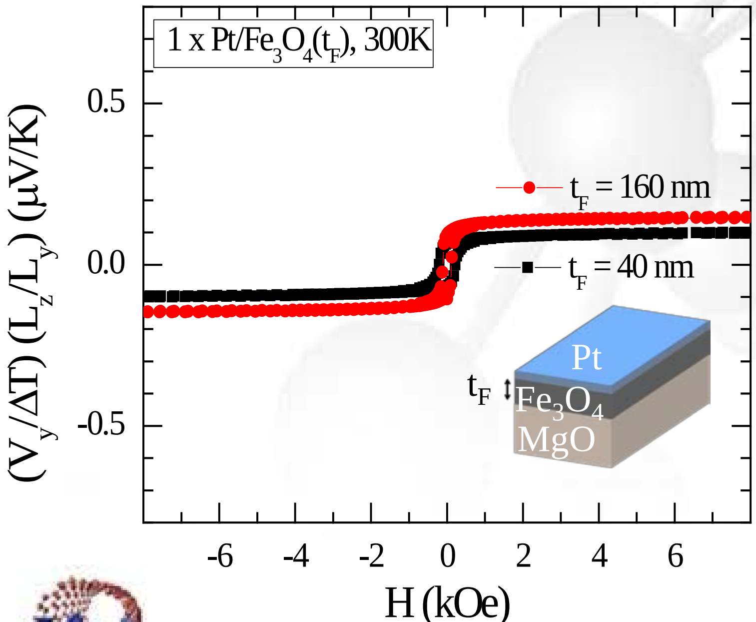
Ramos et al. Phys. Rev. B **92**, 220407(Rap. Comm.) (2015)

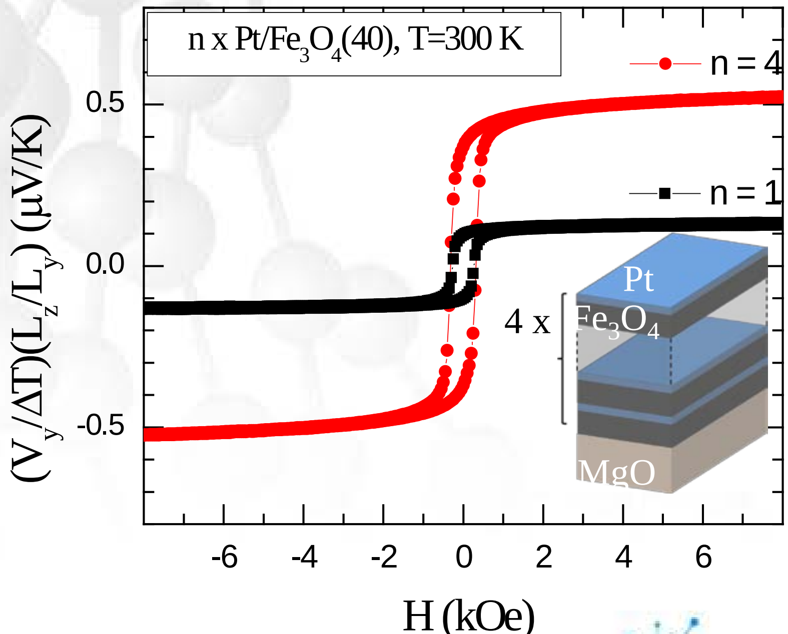
SSE dependence on Fe_3O_4 thickness



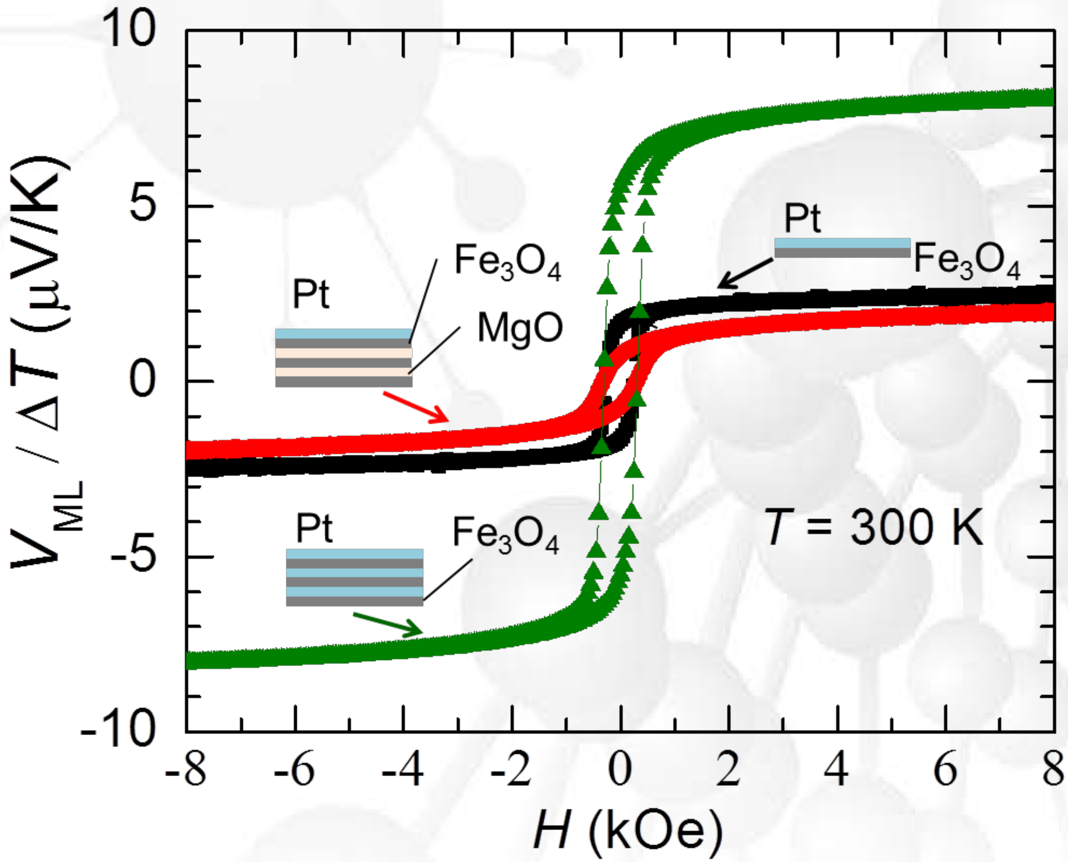


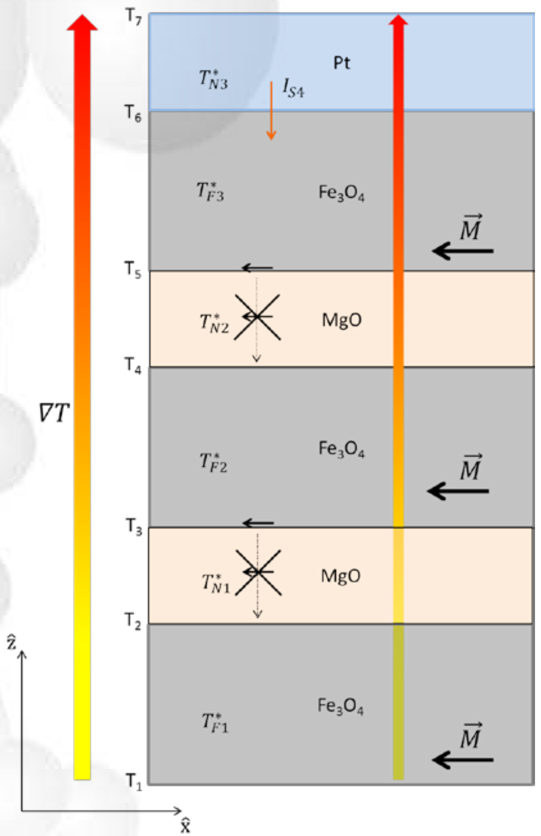
A. Anadón et al. 2016) APL (2016)





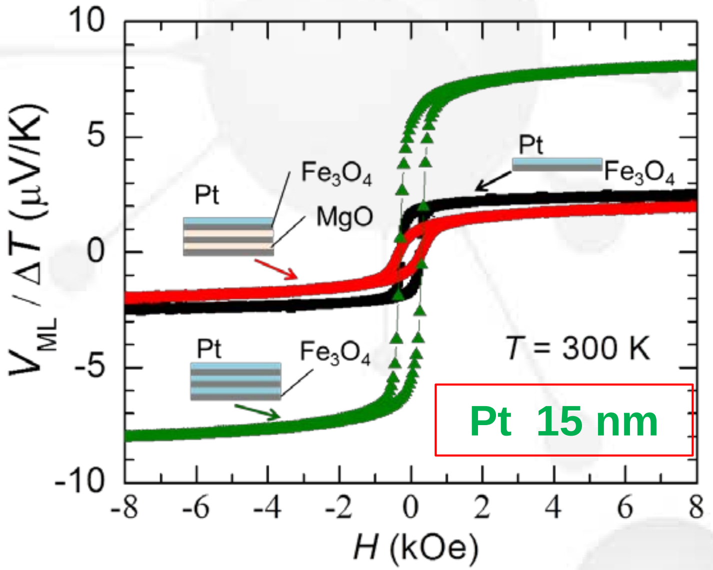
Dependence of SSE versus metal/insulator interlayer

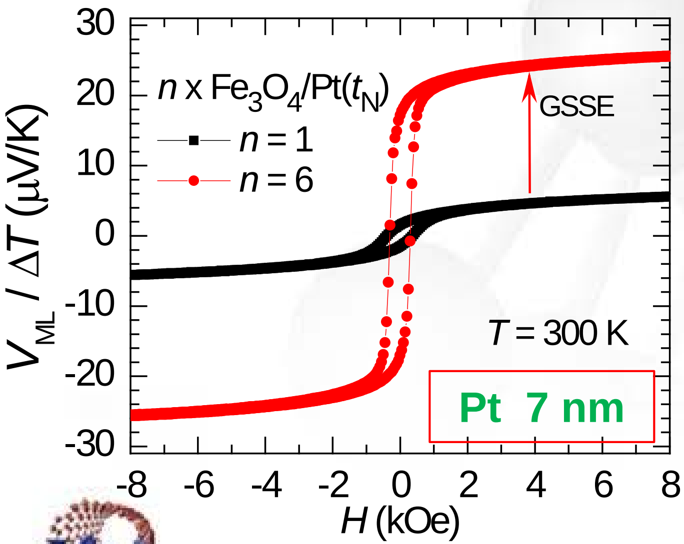


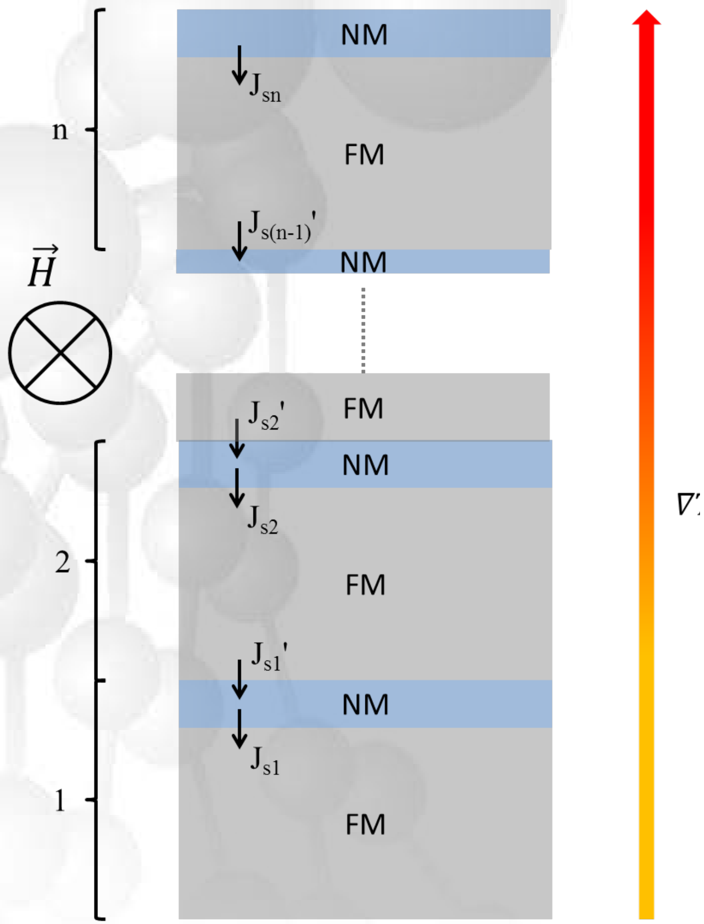


Spin current across the multilayer must be considered

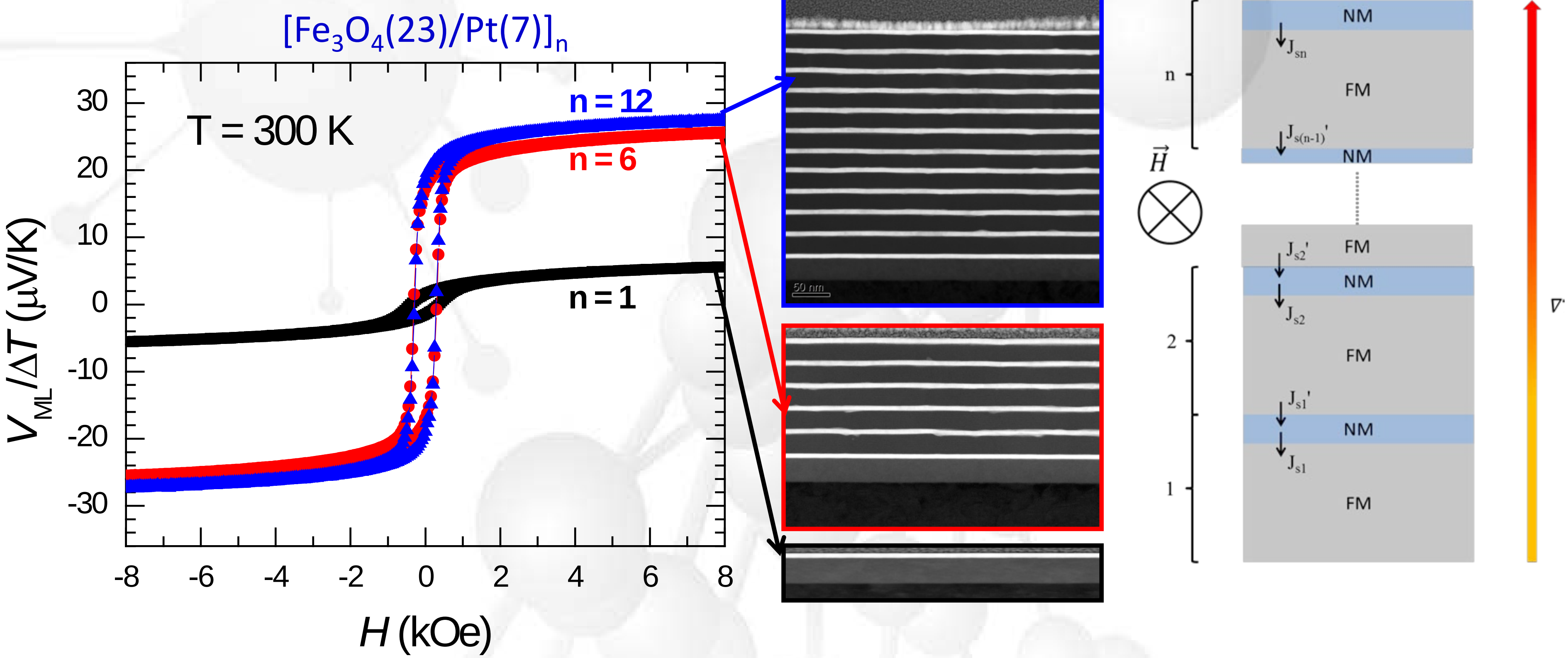
Relevance of the Pt interlayer thickness







Optimized configuration



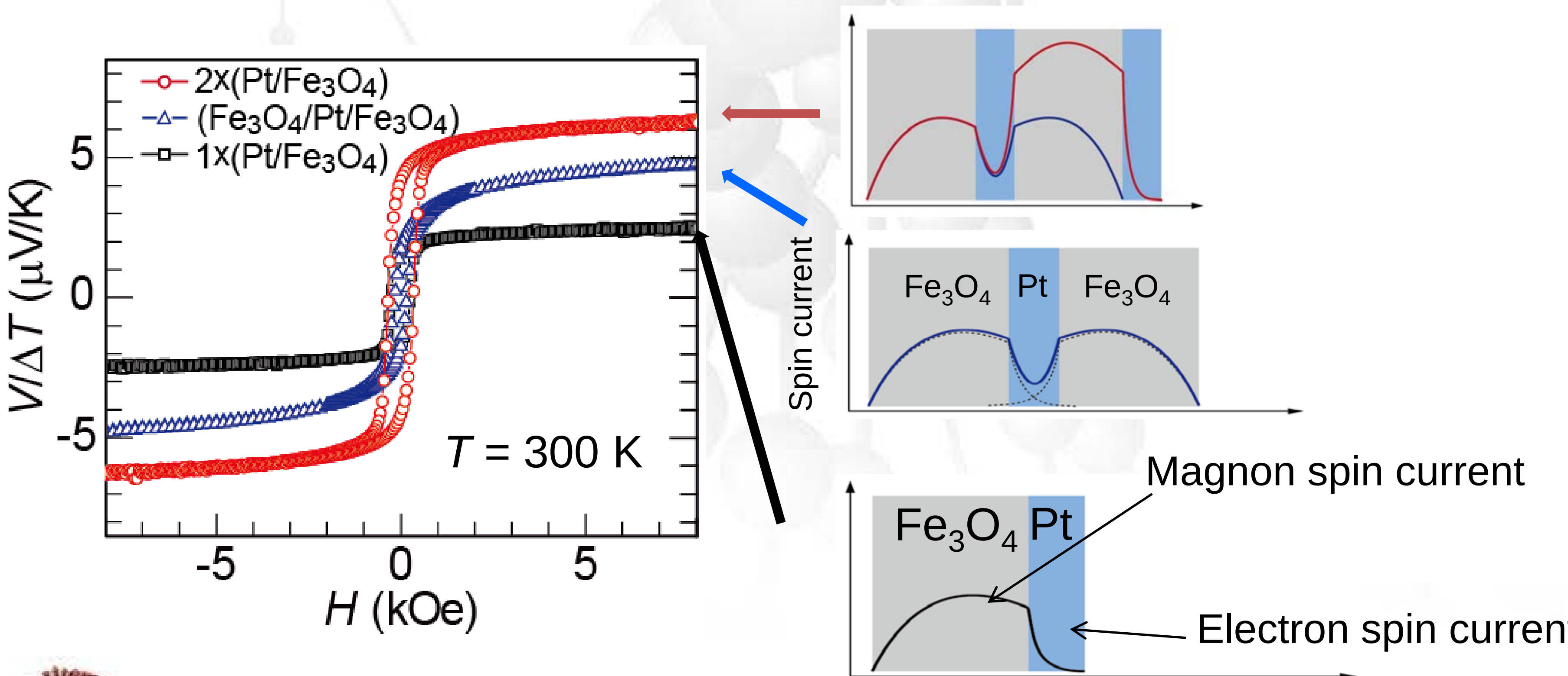
Largest SSE voltage measured in a thin film based structure!!

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

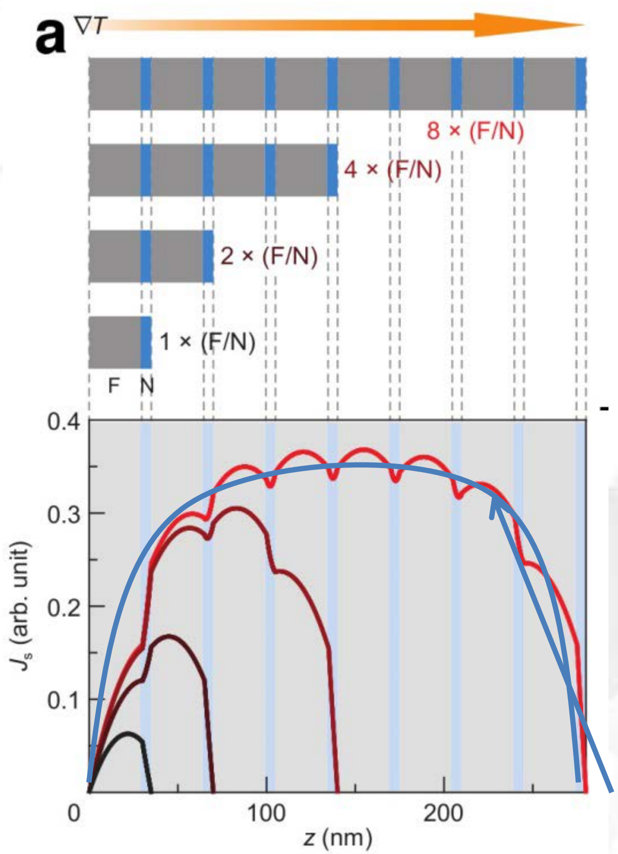
Mechanism of LSSE enhancement in multilayer systems

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

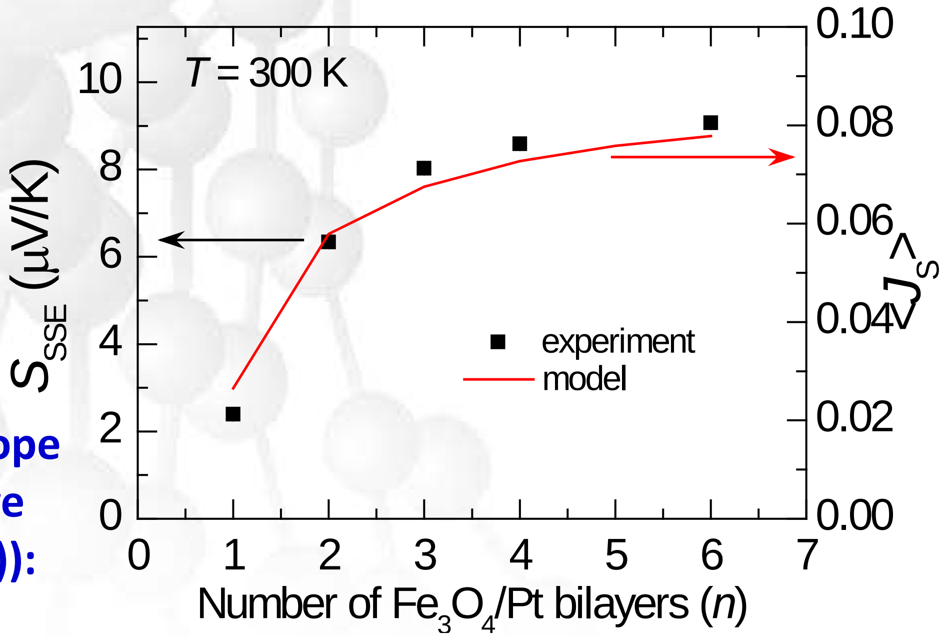


Maximum spin current at central interlayers

Envelope curve ($J_S(z)$):

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

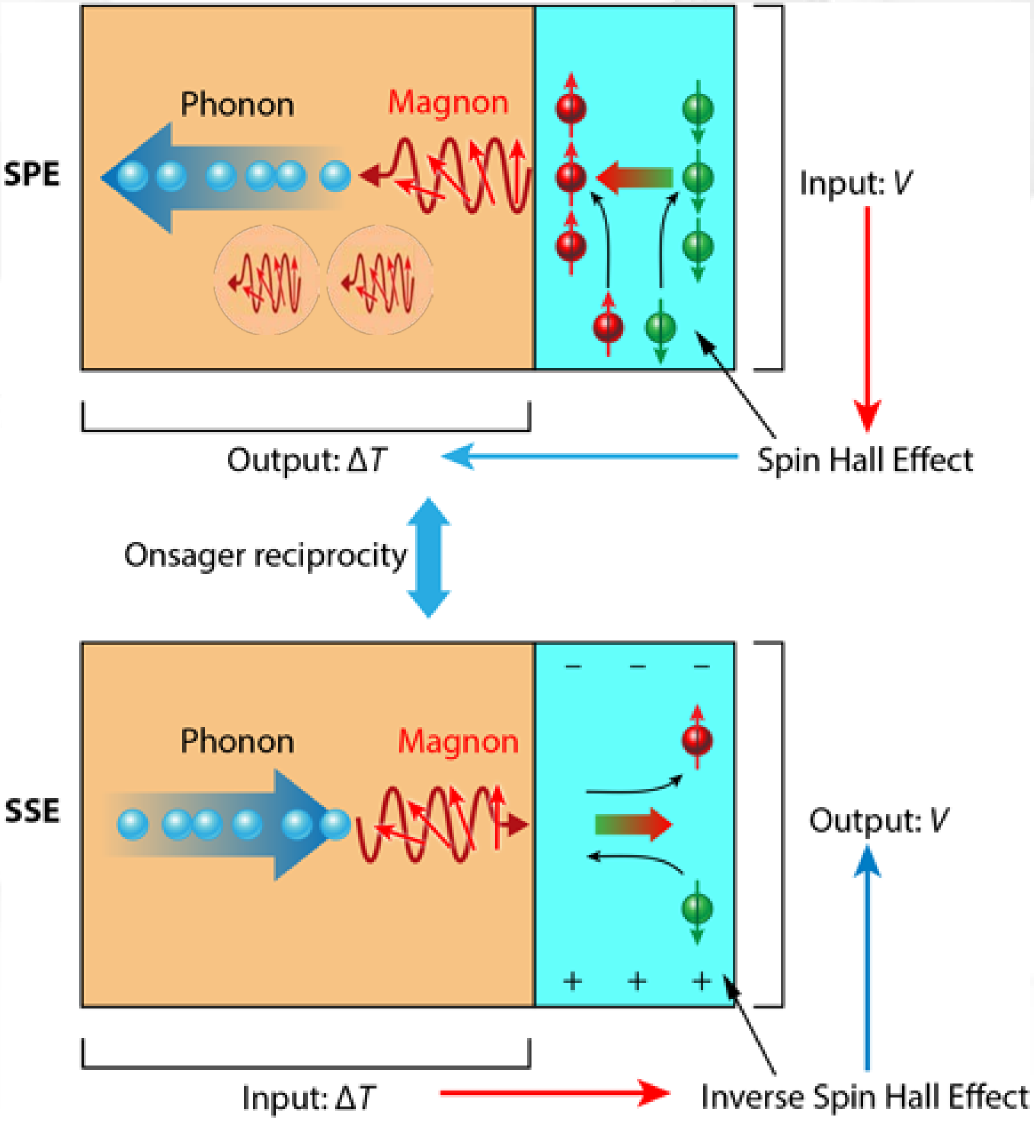
Average SSE voltage measured:



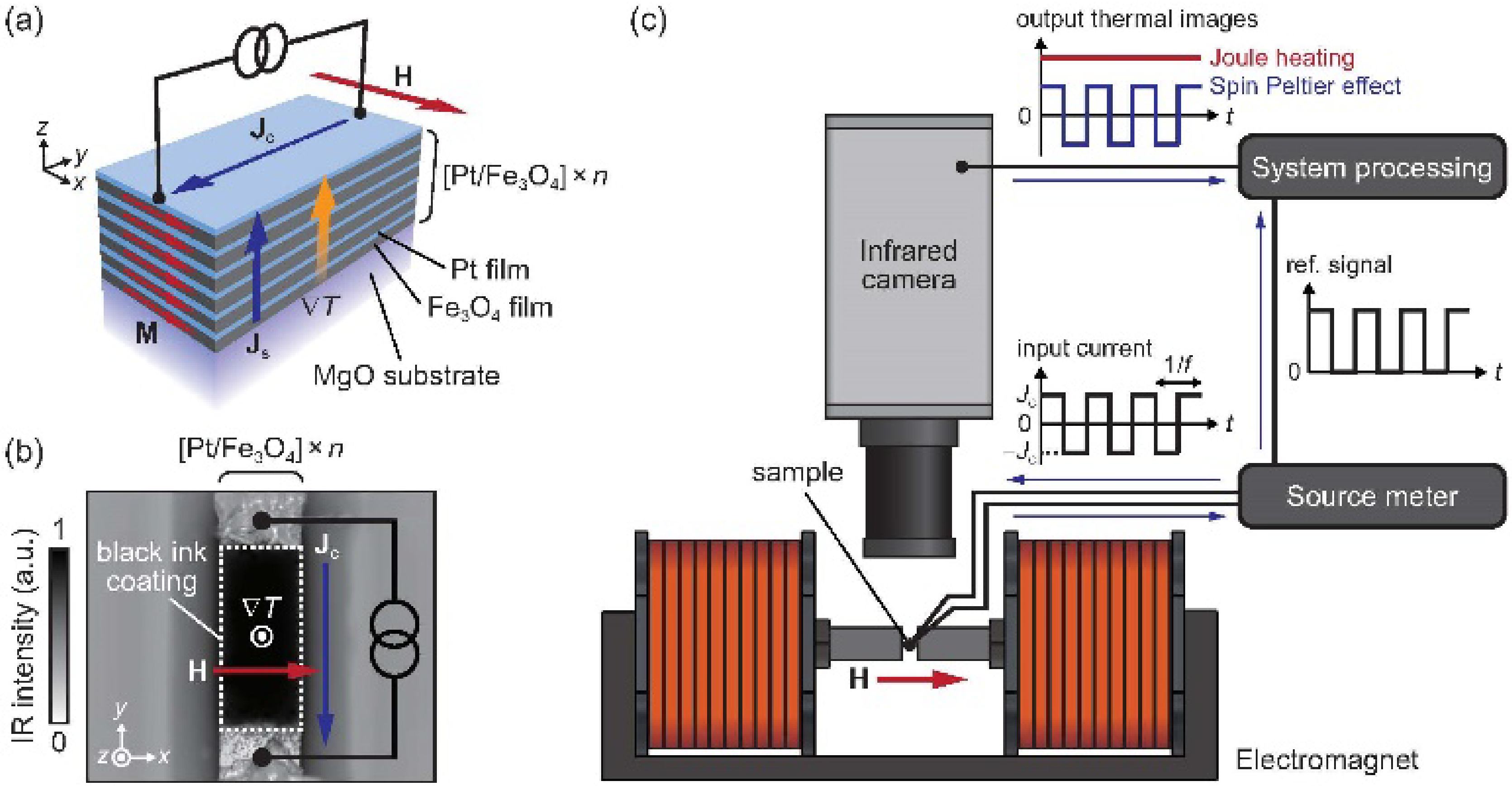
Ramos et al. Phys. Rev. B **92**, 220407(Rap. Comm.) (2015)

Spin Peltier effect in magnetic multilayers

Thermo-spin effects

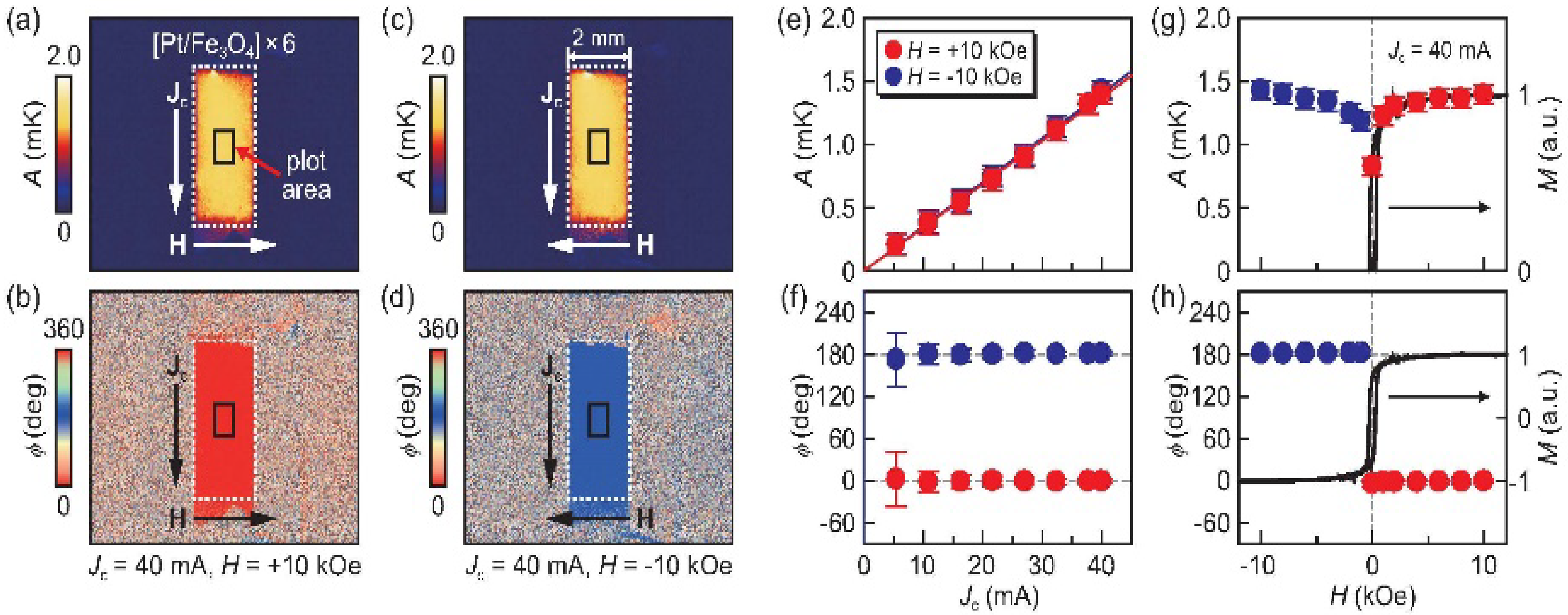


(Ilustration from Graham Jones)



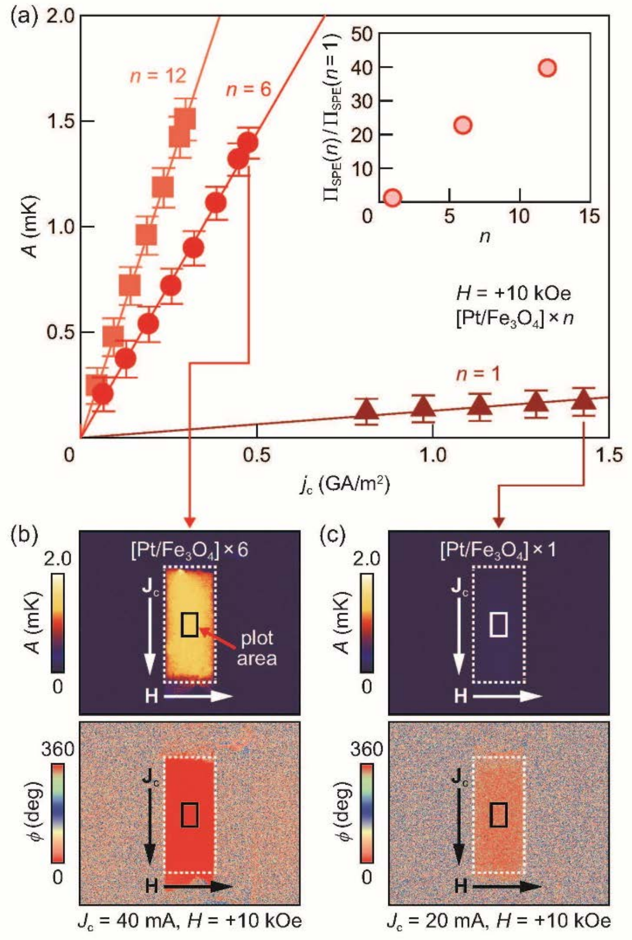
K. Uchida et al. Phys. Rev.B **95**, 184437 (2017)

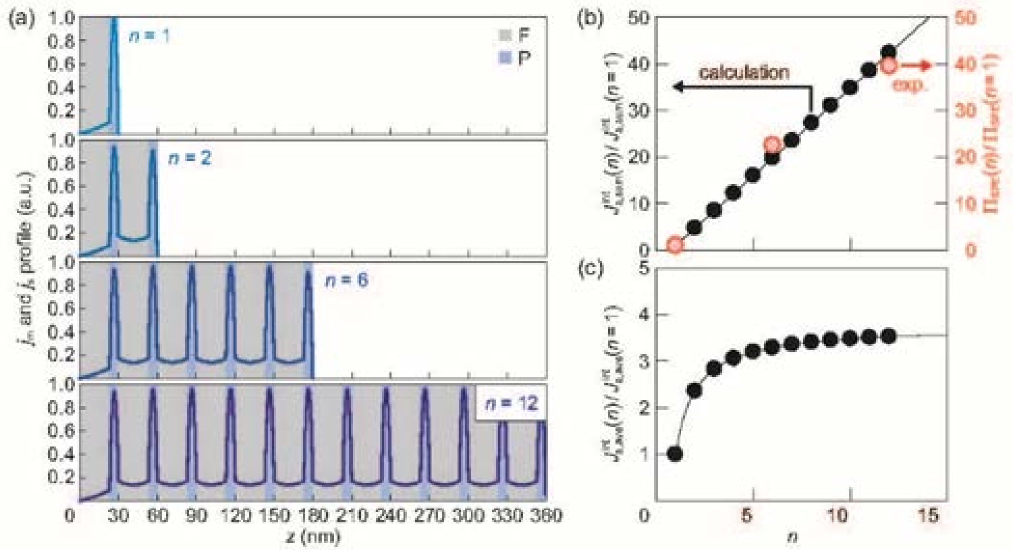
Spin peltier effect



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

Strong enhancement of the spin peltier effect in multiple bilayers

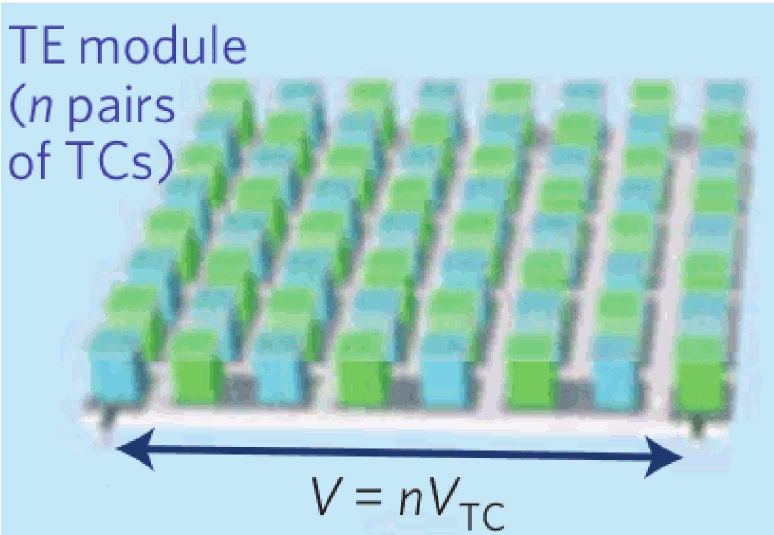


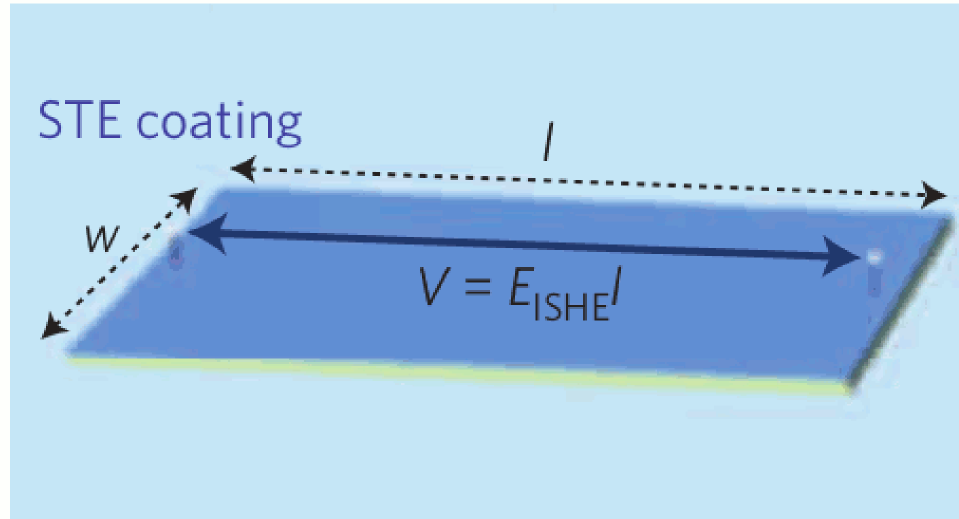


Spin Seebeck devices: thermopiles

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

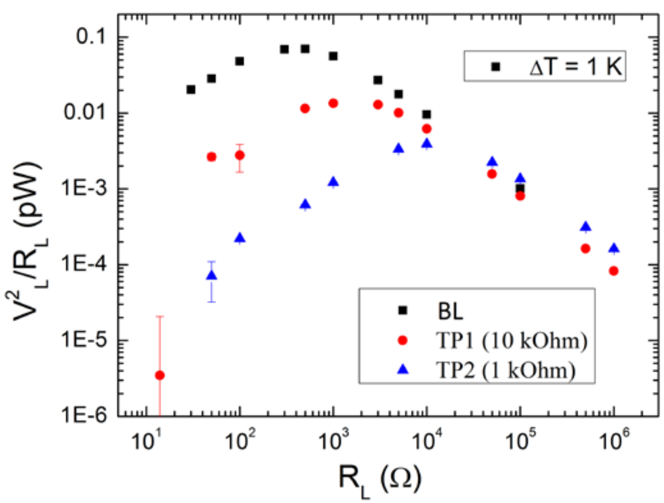
Many thermocouples unnecessary
→**Low cost, ultimate integration**

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

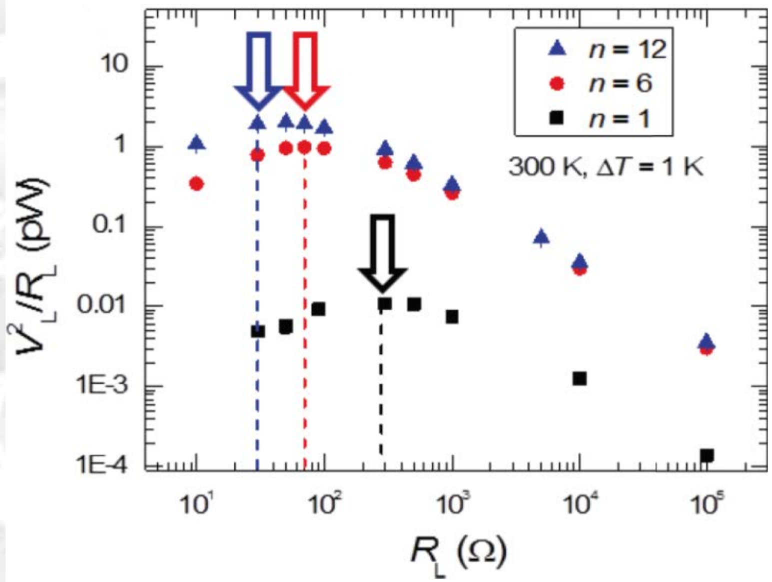
Wide area, low cost thermoelectric devices

SSE thermopiles

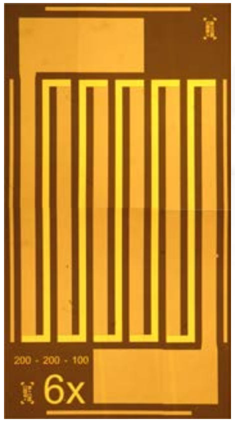
Bilayer



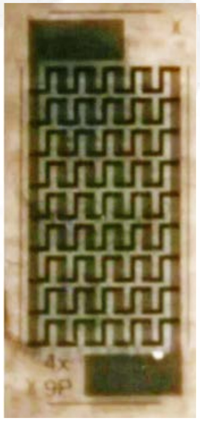
Multilayer



TP1

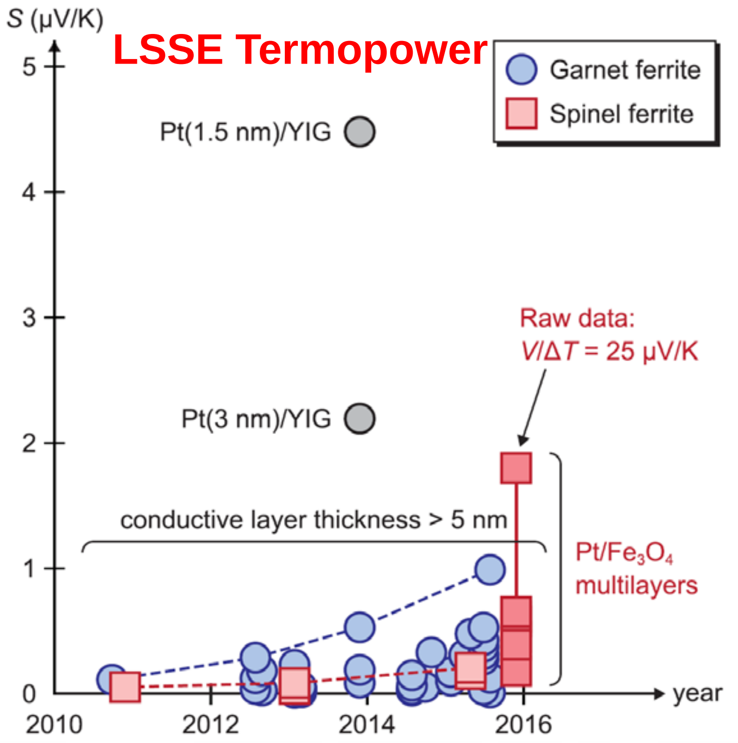


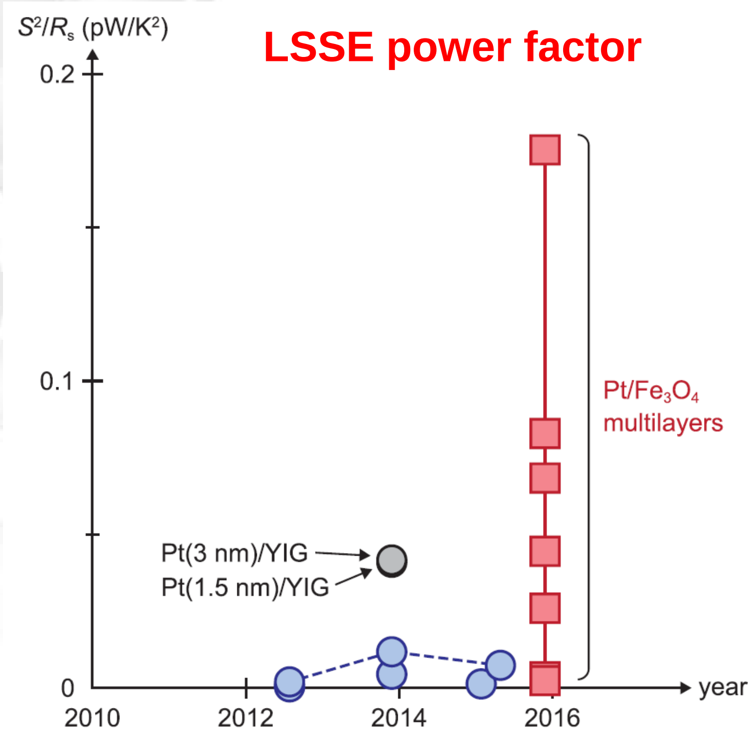
TP2



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





K. Uchida et al. review Proceedings of the IEEE 104, 1499 (2016)

Monographic issue in Journal Phys D: Applied Physics on CALORITRONICS to appear soon

Enhanced thermo-spin effects in iron-oxide/metal multilayers

R Ramos[1], I. Lucas[2,3,4], P. A. Algarabel[4,5], L. Morellón[2,3,4], K. Uchida[6,7,8], E. Saitoh[1,8,9,10] and M. R. Ibarra[2,3,4,11]

Strategic Japanese-Spanish Cooperative Research Program
Nanotechnologies and new materials for environmental challenges

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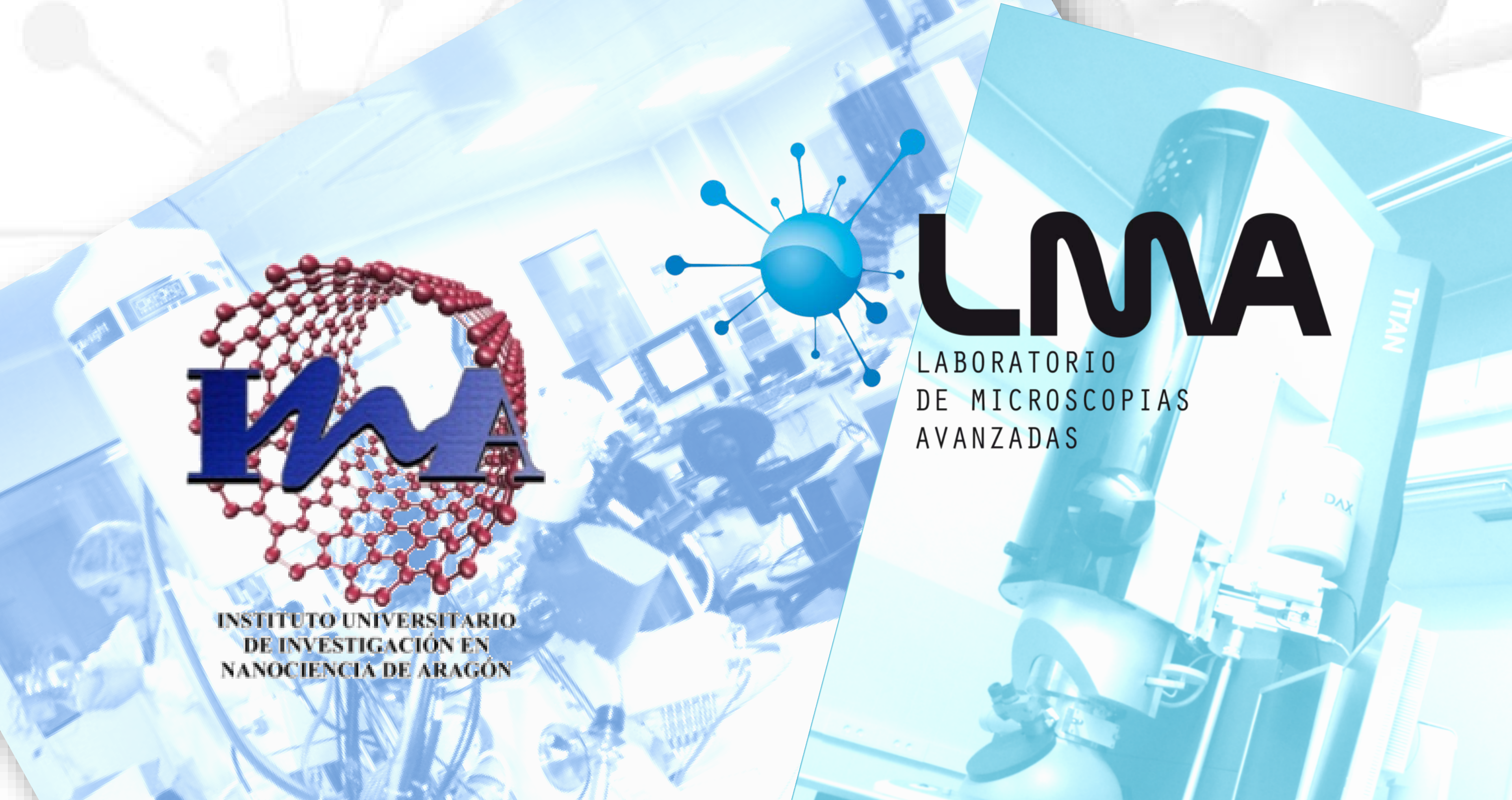
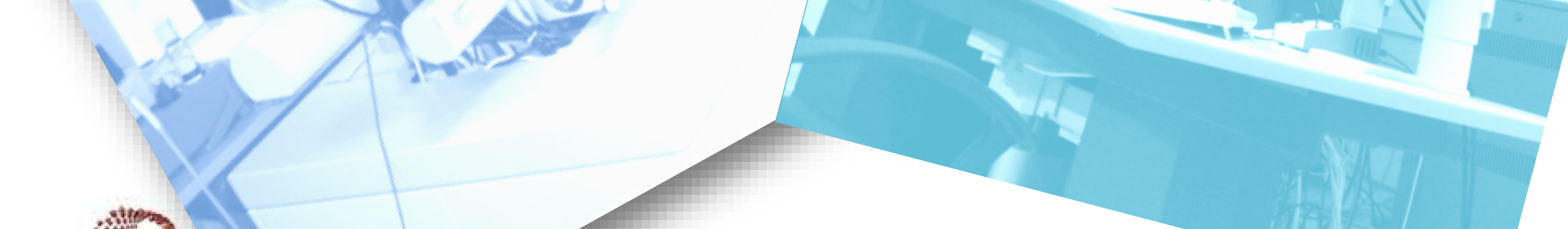
Research Institute for Materials Research, Tohoku University

Development of thin-film thermoelectric SSE based devices



THANK YOU FOR YOUR ATENTION



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