

Processos de Geração e Manipulação de Correntes **Puras** de Spin em Estruturas Magnéticas Híbridas



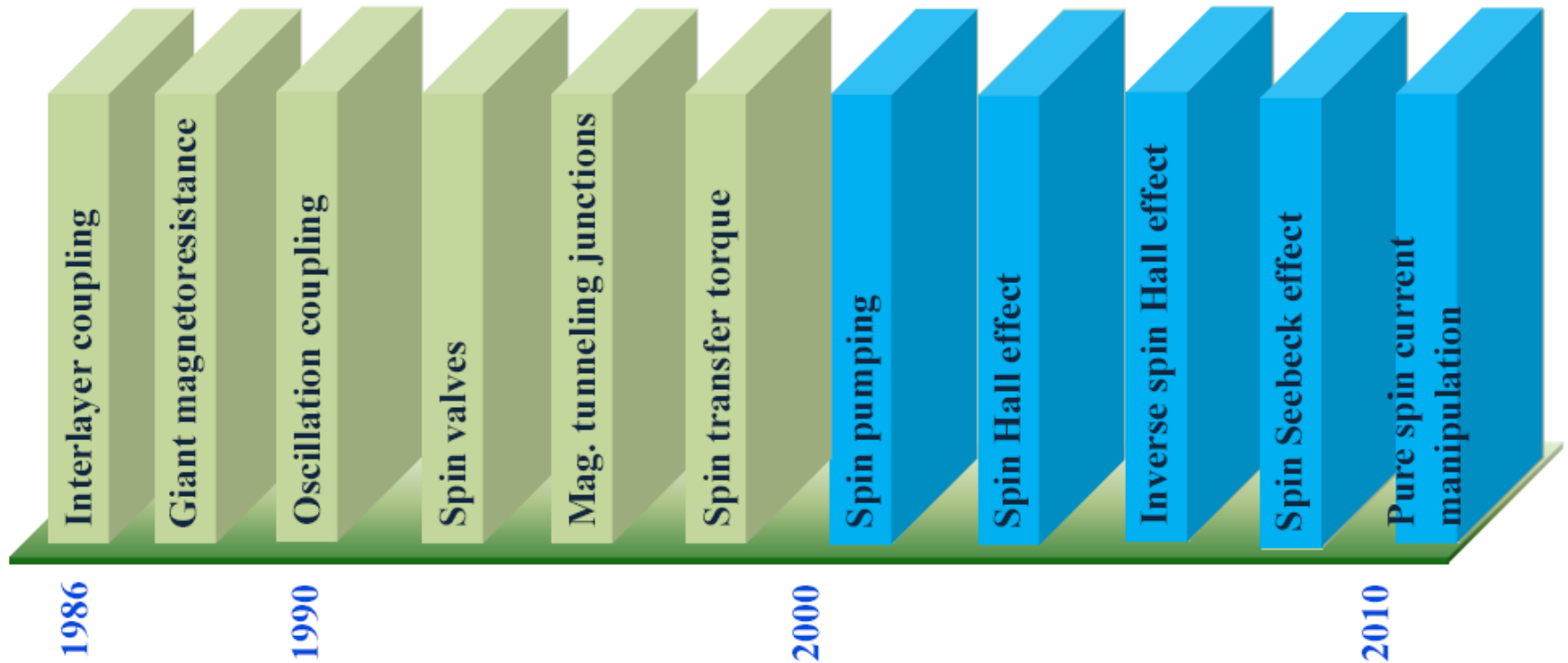
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Recife, PE

Colaboradores: S. Rezende, R. Rodríguez-Suárez, Eduardo Padron, L. H. Vilela-Leão, Rafael Otoniel, G. L. da Silva Vilela, Obed Alves, Gabriel Fonseca, Marcio M. Soares...

Spintrônica em metais: evolução

(escolha pessoal)



O avanço das descobertas continua!

A spintrônica de metais teve um novo ímpeto a partir do ano 2000!



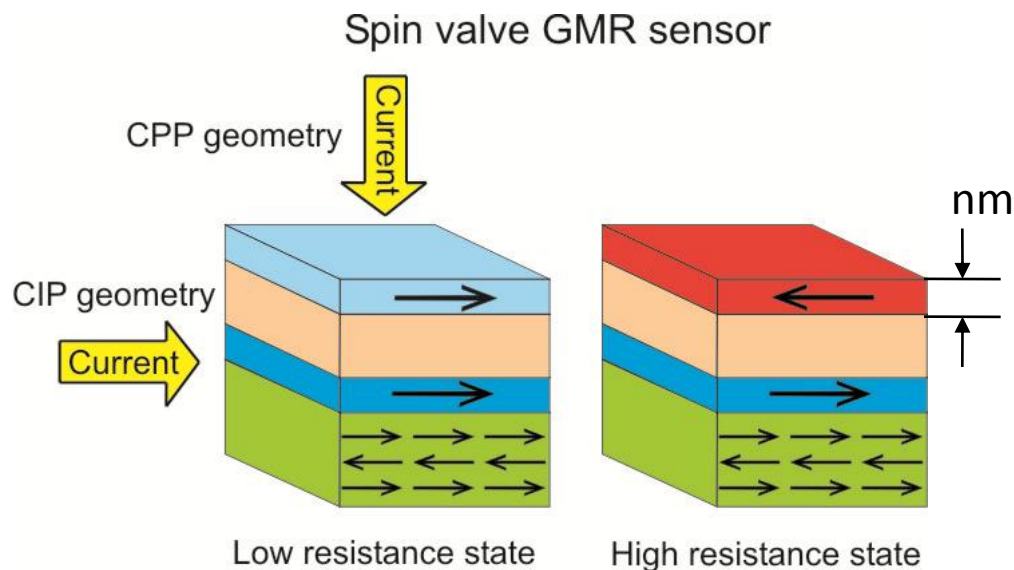
The Nobel Prize in Physics 2007

“for the discovery of giant magnetoresistance”



A. Fert

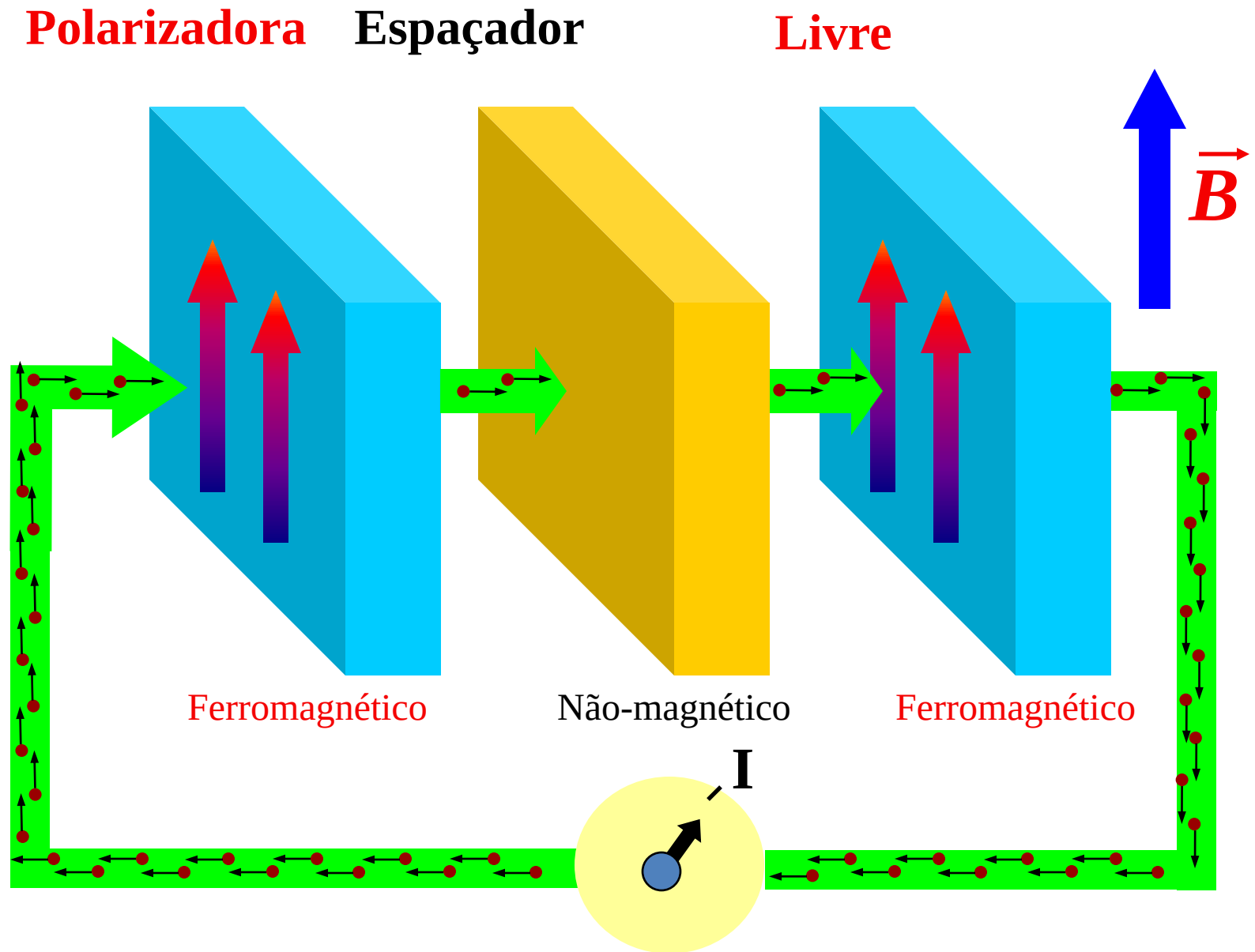
P. Grünberg



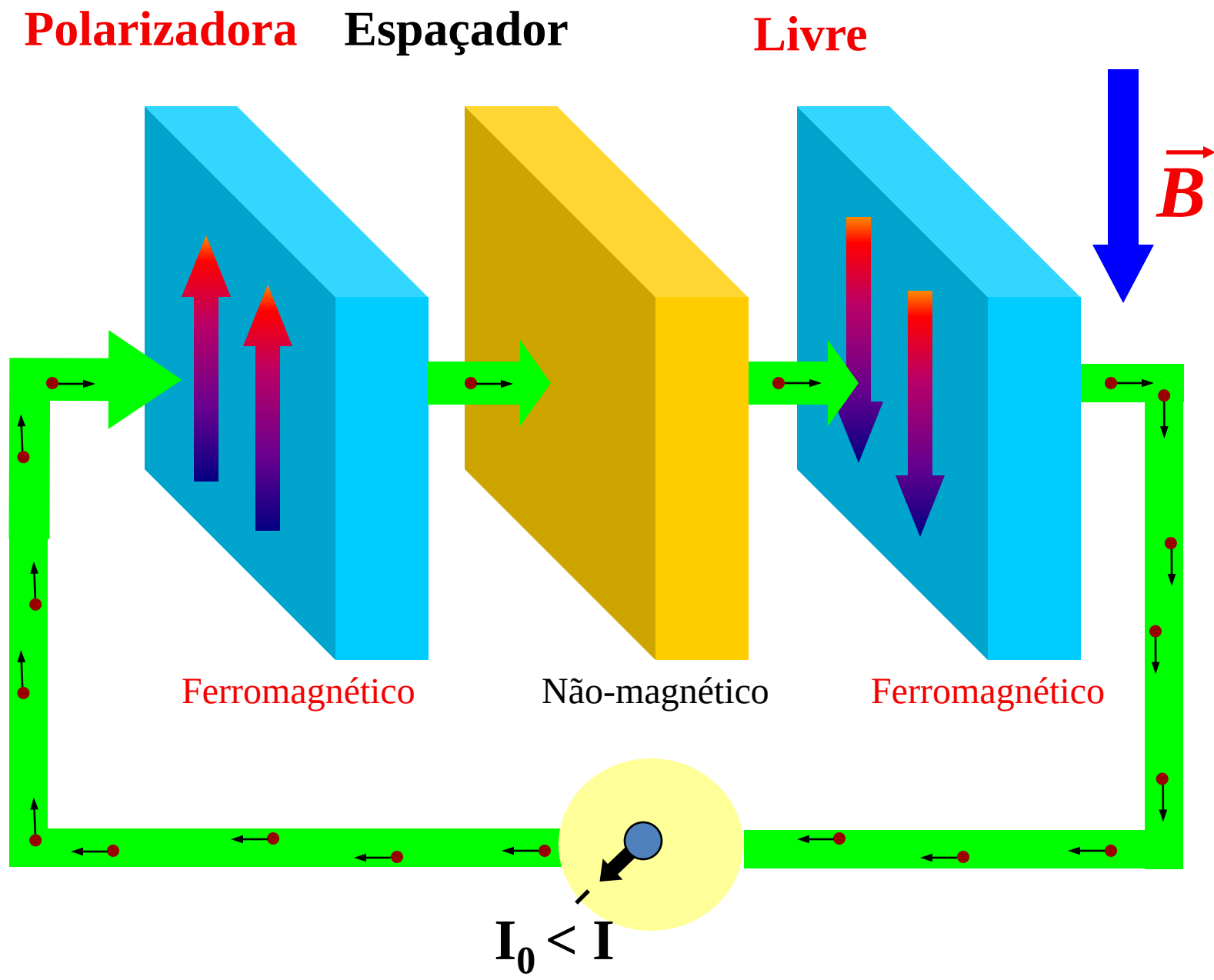
Descoberta combinou dois conceitos:

- Engenharia de fabricação em nanoescala: Sandwiches com magnetizações apontando em direções diferentes
- A corrente torna-se “spin polarizada” e flui em dois canais separados (“up” e “down”) com diferentes resistividades – Modelo de duas correntes de Mott

Válvula de spin

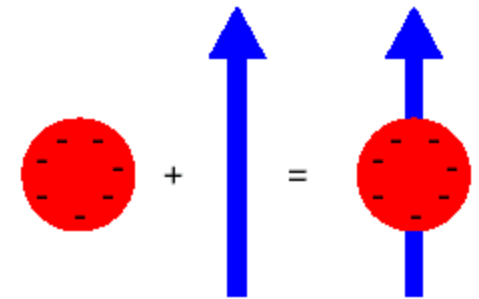


Válvula de spin



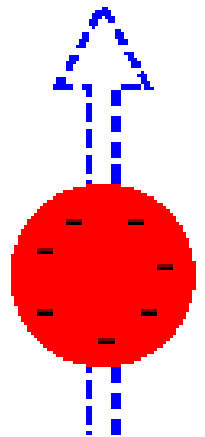
Elétron!

Partícula com **carga elétrica negativa** ($q = -e$)
e **spin** $\frac{1}{2}$ (momento magnético $m = \mu_B$)



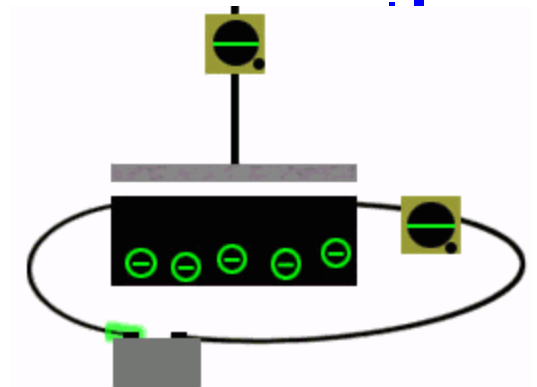
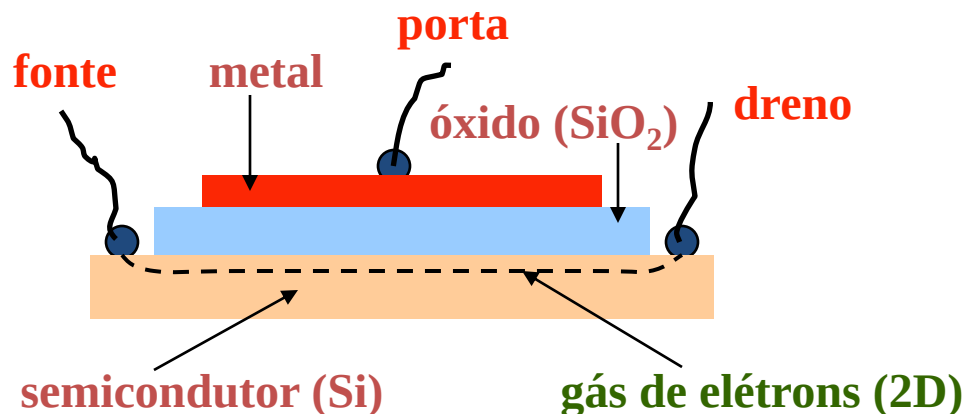
Eletrônica = manipulação de elétrons pelo uso de sua carga para gerar e processar sinais.

O spin é (quase) completamente desprezado!



MOSFET

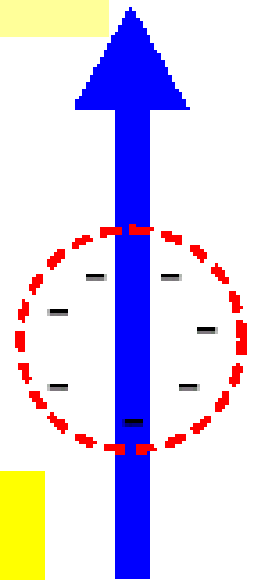
Portas lógicas,
RAM,...



E do ponto de vista do magnetismo? O que é um elétron?

O elétron é visto como um momento de
dipolo magnético.

Magnetismo = desenvolve e utiliza materiais que manipulam o spin eletrônico com o objetivo de obter e entender a interação entre os mesmos!



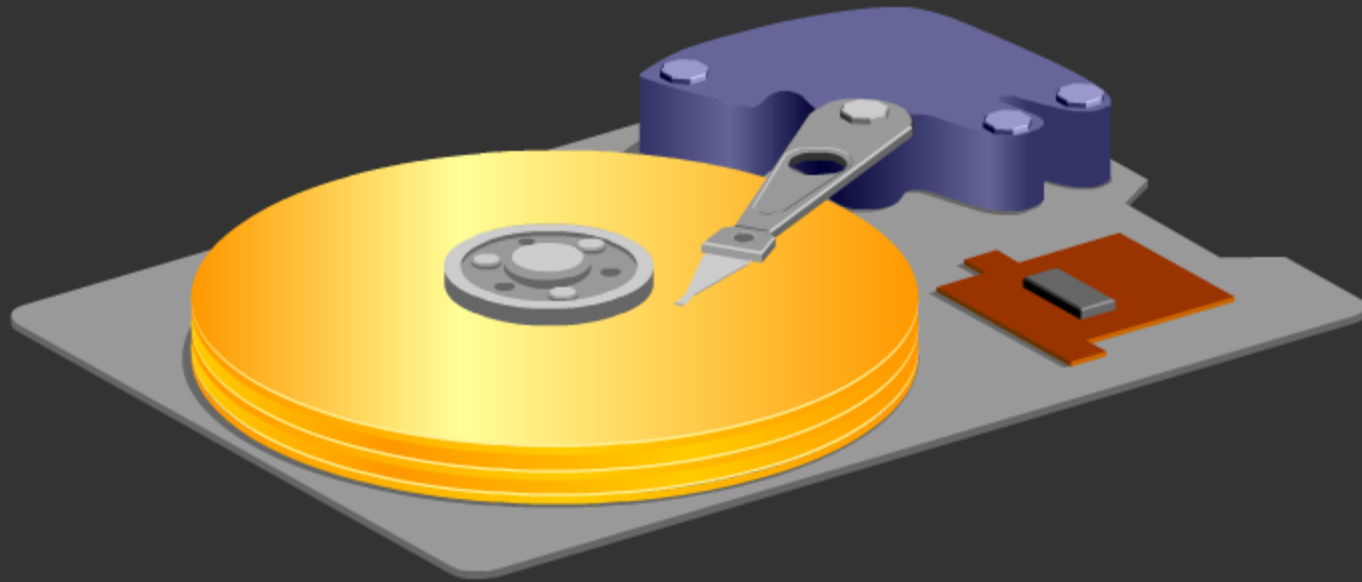
A carga elétrica representa um papel secundário!

Principal aplicação: armazenamento dados em alta escala!

Spintrônica ou Magneto-eletrônica:
combinação de **eletrônica** e **magnetismo**,
onde a **carga** e o **spin** do elétron são
simultaneamente utilizados!

NOVOS FENÔMENOS FÍSICOS!
NOVAS APLICAÇÕES!





THE HARD DISK DRIVE

1 2 3 4 5 6

You are looking at the inside of a hard disk drive. The head is located at the end of the actuator arm, and flies over the disk to read and write data. Click the next button to take a closer look at the read/write element. [NEXT]

Novo ímpeto para a *Spintrônica*

- 1999 - Spin Hall effect (**SHE**) (teoria)
- 2002 - Corrente pura de spin e “spin pumping” (teoria)
- 2006 - Observação experimental de SHE e ISHE
- 2008 - Descoberta do efeito spin Seebeck
- 2010 - Fenômenos com correntes de spin em isolantes magnéticos



Spin Current

Edited by **Sadamichi Maekawa**, **Sergio O. Valenzuela**, **Eiji Saitoh**, and **Takashi Kimura**

Series on Semiconductor Science and Technology 17, 26 July 2012

Handbook of Spin Transport and Magnetism

Edited by **Evgeny Y. Tsybal** and **Igor Žutić**

CRC Press Taylor & Francis Group, 2012

Spin Hall Effects in Metals

Axel Hoffmann

IEEE TRANS. ON MAGNETICS, VOL. 49, NO. 10, OCTOBER 2013

STATE OF THE ART



NATURE MATERIALS | VOL 11 | MAY 2012 |

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Jairo Sinova and Igor Žutić

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PROGRESS ARTICLE

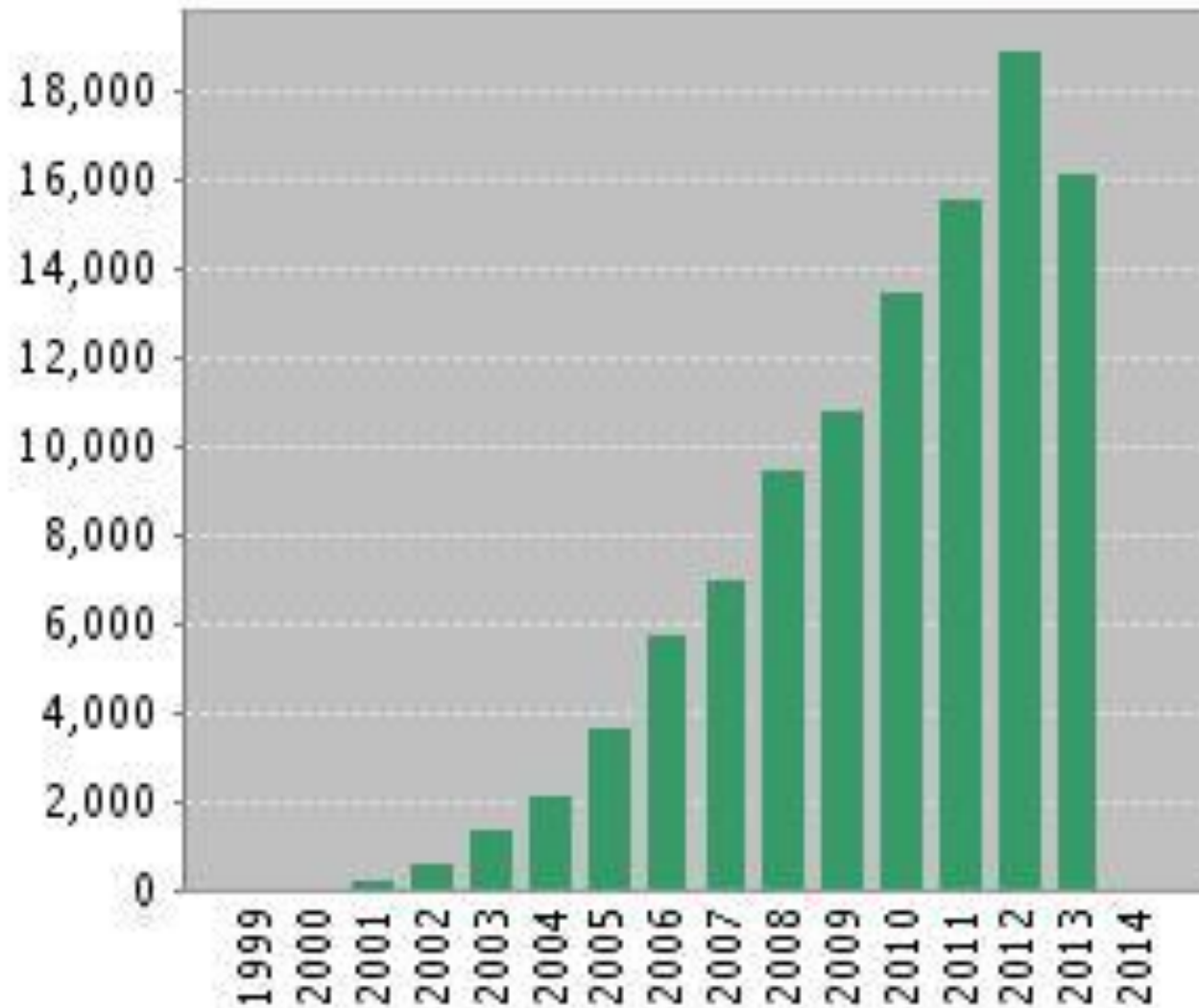
Spintronics and pseudospintronics in graphene and topological insulators

Dmytro Pesin and Allan H. MacDonald

409

Spintronics is the area of condensed-matter physics that studies the properties of the electron spin, with a view to improve the efficiency of electronic devices and to enrich them with new functionalities.

Citações de papers em Spintrônica



Corrente de spin



- O que é uma corrente de spin
- Efeito Hall de Spin
- Efeito Hall inverso de spin
- Spin pumping
- Efeito Seebeck de spin
- Realização experimental

O que é uma corrente de spin?



É um fluxo de momento angular de spin!

Corrente de carga (fluxo de carga)

Carga elétrica (+ ou -)



Importante em eletrônica!

Corrente de spin (fluxo de momento angular)

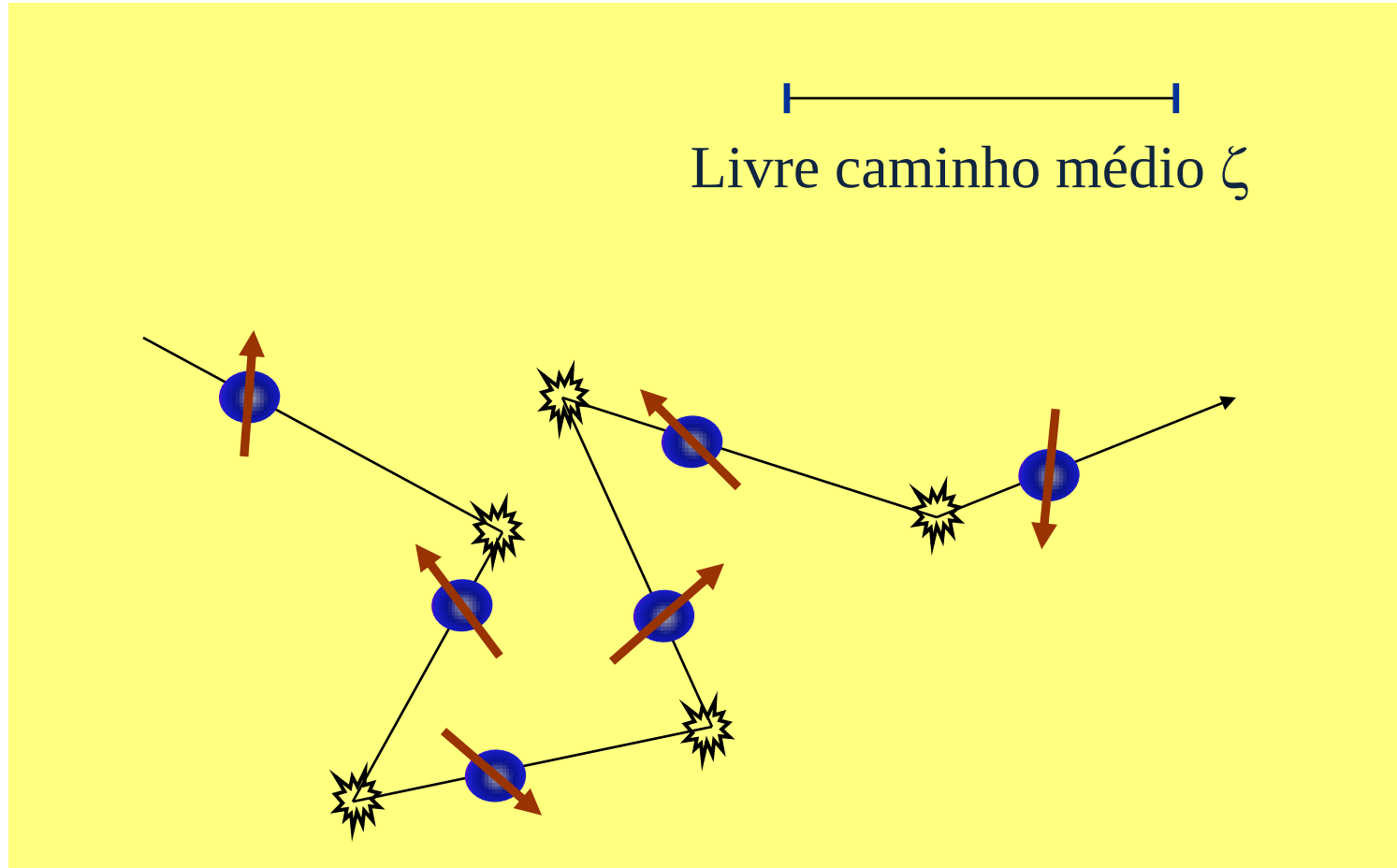
Momento angular de spin



Importante em spintrônica!

Corrente elétrica em amostras macroscópicas

Em amostras massivas os **elétrons** “perdem” a memória de seus spins nas colisões



Na eletrônica convencional o spin dos elétrons é completamente desprezado!

- CORRENTE PURA DE CARGA (por elétrons de condução)**

Corrente de carga finita: $J_C (= J_{\uparrow} + J_{\downarrow}) \neq 0$

Corrente de spin nula: $J_S (= J_{\uparrow} - J_{\downarrow}) = 0$

Corrente pura de carga

Condutor

Seção transversal

Fluxo de carga sem fluxo de spin!

- CORRENTE PURA DE SPIN (por elétrons de condução)**

Corrente de carga nula: $J_C (= J_{\uparrow} + J_{\downarrow}) = 0$

Corrente de spin finita: $J_S (= J_{\uparrow} - J_{\downarrow}) \neq 0$

Corrente pura de spin

Condutor

Seção transversal

Fluxo de spin sem fluxo de carga!

COMO GERAR CORRENTES PURAS DE SPIN?

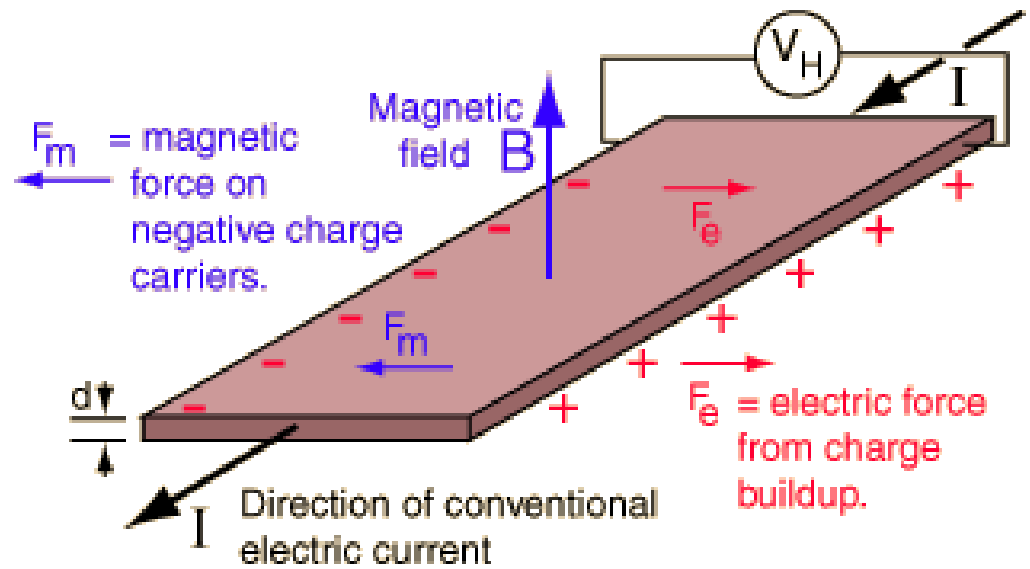
Efeito Hall de spin (redescoberto em 1999)

Efeito de spin pumping (proposta teórica 2002)

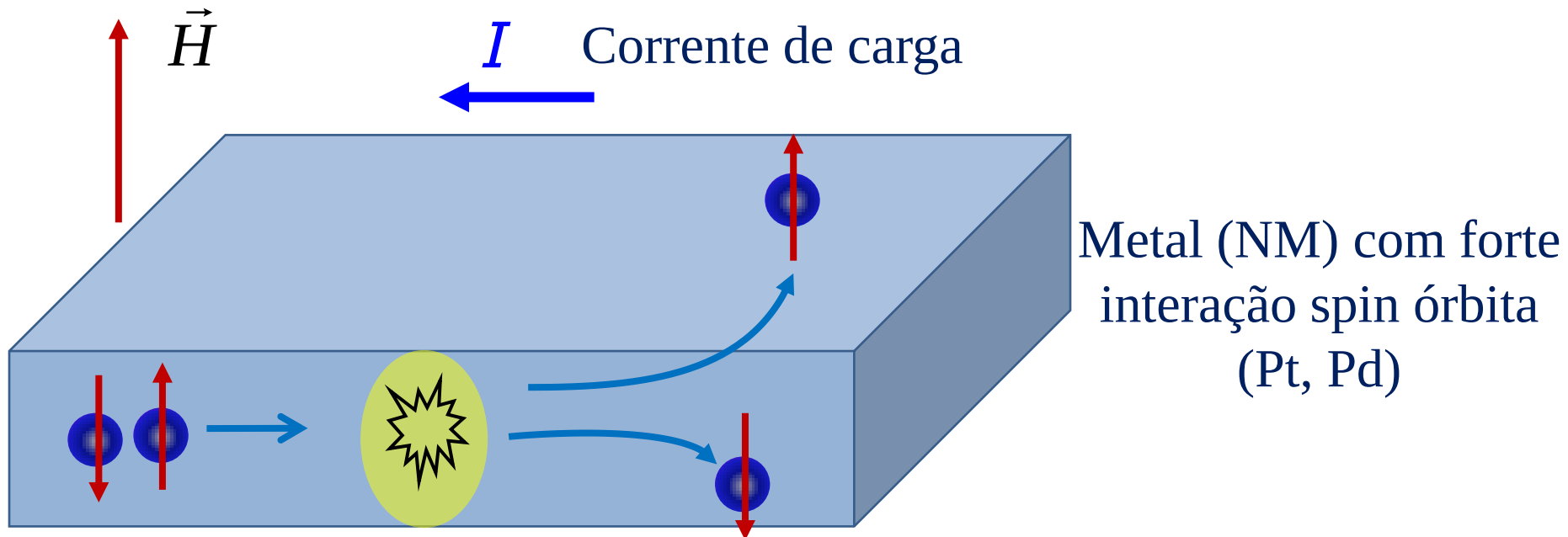
Efeito Seebeck de spin (descoberto em 2008)

Efeito Hall Clássico

E. H. Hall (1879)



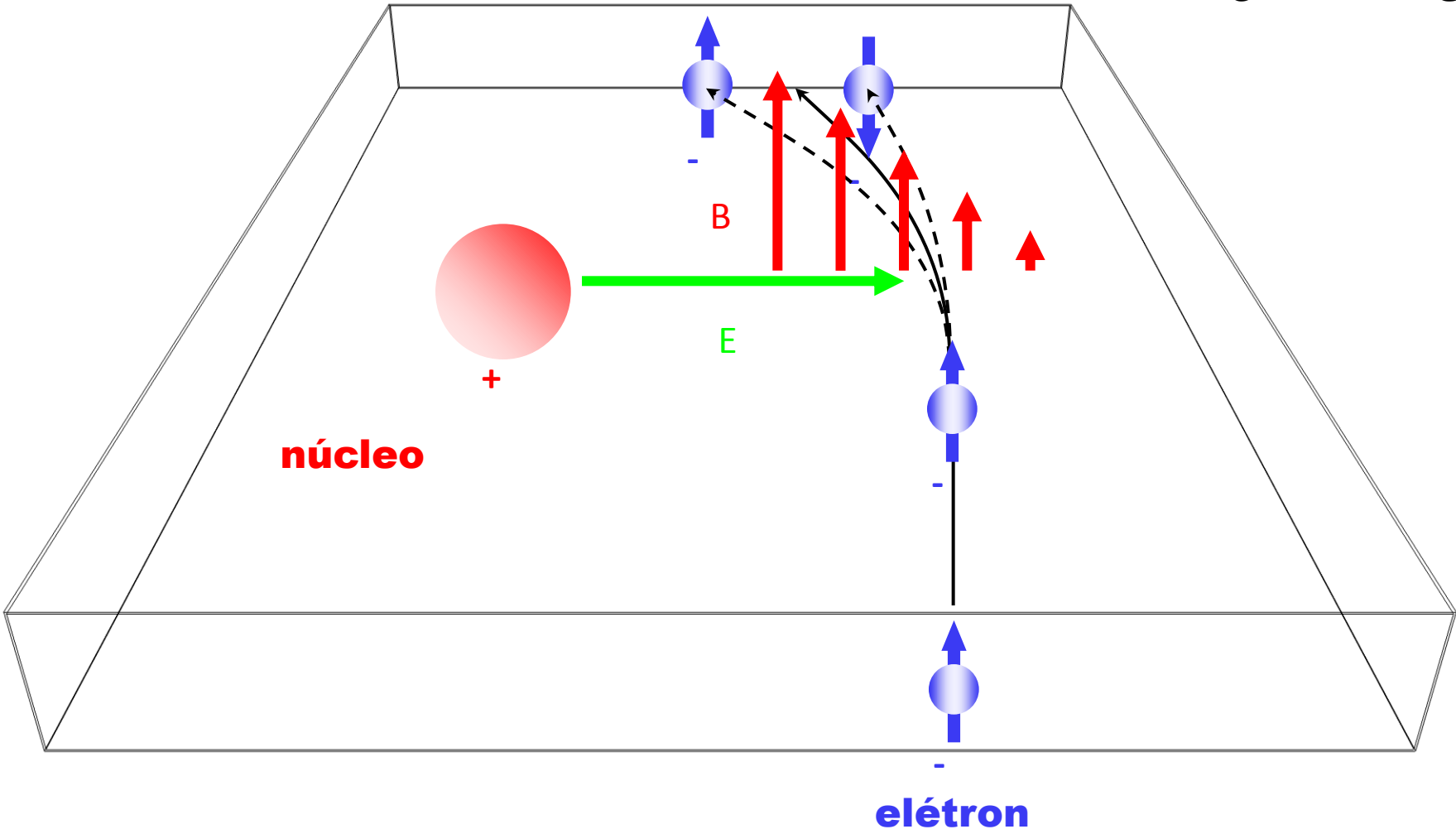
Efeito Hall de Spin (Dyakonov & Perel 1971; Hirsch 1999)



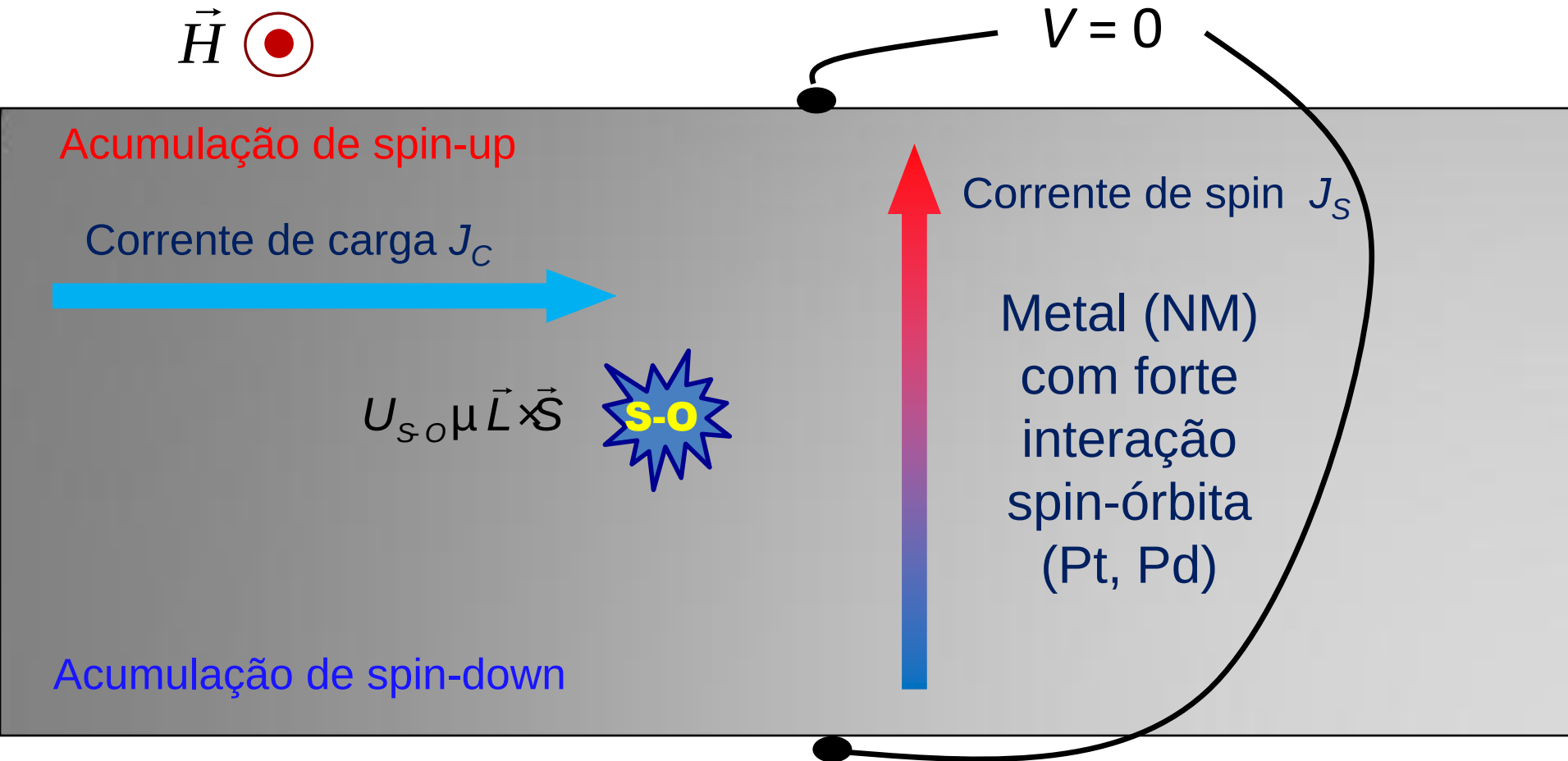
Spin-Skew Scattering

$$\vec{B} \propto -\vec{v} \times \vec{E}$$

$$V = V_C(r) + V_{SO}(r)$$



- EFEITO HALL DE SPIN (SHE) [Dyakonov & Perel 1971; Hirsch 1999]



Elétrons com spins opostos em J_C são defletidos para lados opostos do filme criando **corrente de spin**.

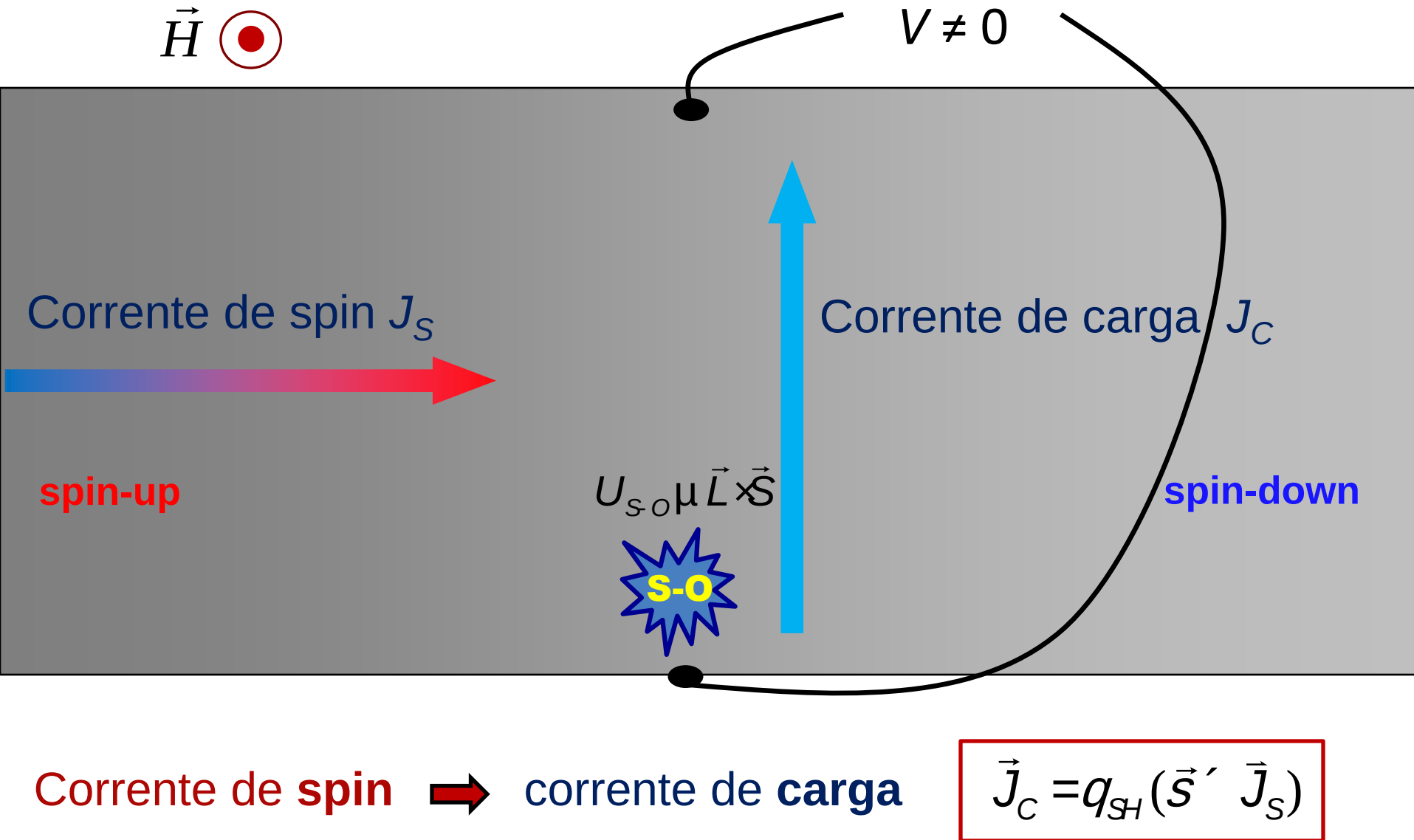
Corrente de **carga** $\Rightarrow$ corrente de **spin**

$$\vec{J}_S = \theta_{SH} (\vec{\sigma} \times \vec{J}_C)$$

Se existe o efeito Hall de spin direto,

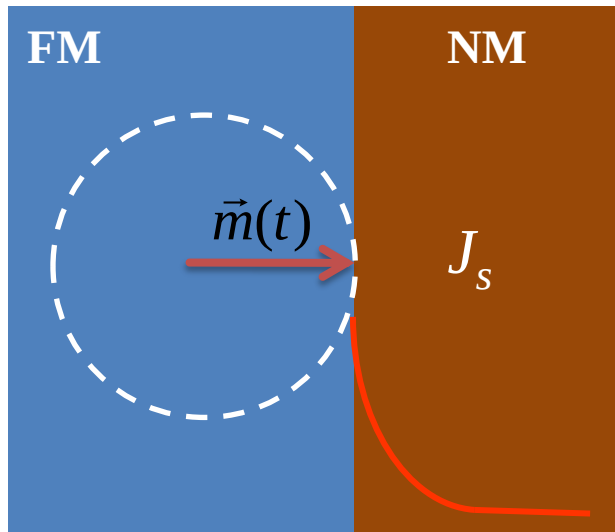
“deve existir o efeito inverso”!

- EFEITO HALL DE SPIN INVERSO (ISHE) [Hirsch 1999, Saitoh 2006]



Efeito spin pumping!

Spin-pumping: técnica simples para injetar corrente pura de spin em um meio NM



Pure spin current

2002- A. Brataas, Y. Tserkovnyak,
G.E Bauer, B. I. Halperin

Spins em precessão na camada FM

“bombeiam” **corrente de spin** (momentum angular) na camada NM que produz amortecimento (spin pumping damping)

Precessão de spins

SPE



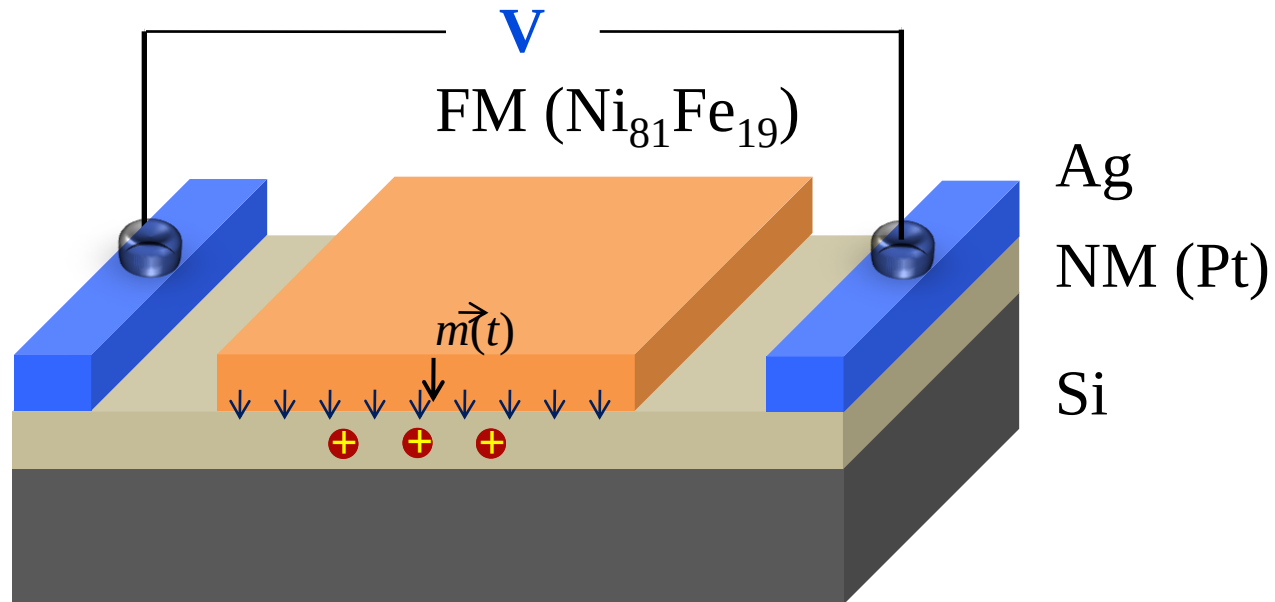
Corrente de spin

Spin mixing
conductance

$$\vec{J}_s = \frac{\hbar g_r^{\uparrow\downarrow}}{4\pi M^2} \left(\vec{M} \times \frac{\partial \vec{M}}{\partial t} \right)$$

Usando a geração de corrente pura de spin poderemos testar o efeito Hall inverso de spin medindo-se uma **tensão elétrica!**

Ilustração do conceito!

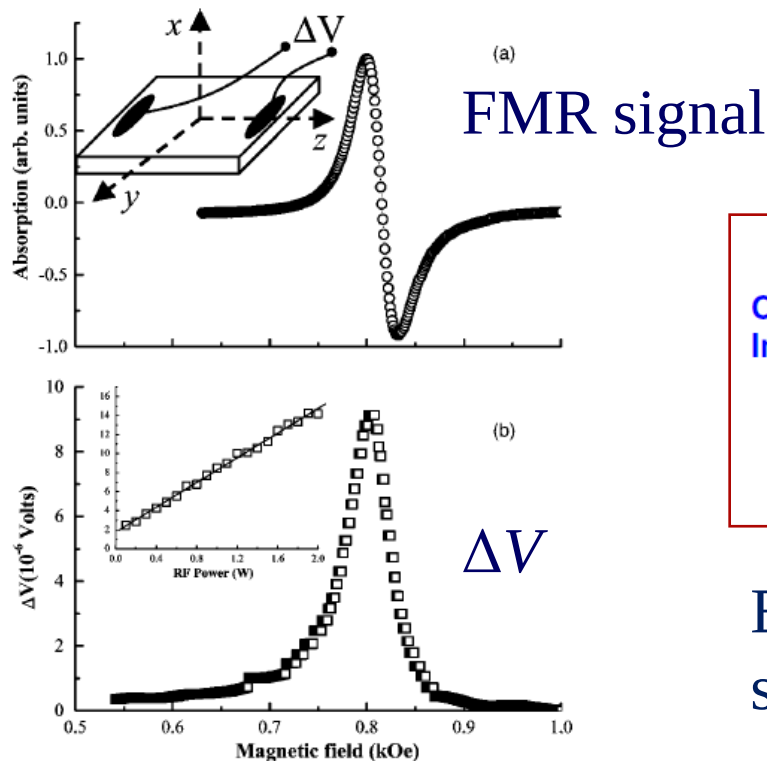


Observação de spin pumping

JOURNAL OF APPLIED PHYSICS 97, 10C715 (2005)

dc effect in ferromagnetic resonance: Evidence of the spin-pumping effect?

A. Azevedo,^{a)} L. H. Vilela Leão, R. L. Rodriguez-Suarez, A. B. Oliveira, and S. M. Rezende
Departamento de Física, Universidade Federal de Pernambuco, Recife, Pernambuco 50670-901, Brazil



APPLIED PHYSICS LETTERS 88, 182509 (2006)

Conversion of spin current into charge current at room temperature: Inverse spin-Hall effect

E. Saitoh,^{a)} M. Ueda, and H. Miyajima
Department of Physics, Keio University, Yokohama 223-8522, Japan
G. Tatara
PRESTO, Japan Science and Technology Agency (JST), Department of Physics, Tokyo Metropolitan University, Tokyo 192-0397, Japan

Explica a geração de V_{DC} em termos de spin-pumping e ISHE

**É possível interagir corrente de spin
com ondas de spin?**

Spin waves: semi-classical treatment

Landau-Lifshitz equation with exchange (without losses)

$$\frac{\partial \vec{M}}{\partial t} = \gamma \vec{M} \times \vec{H}_i - \gamma \frac{D}{M} \vec{M} \times \nabla^2 \vec{M}$$

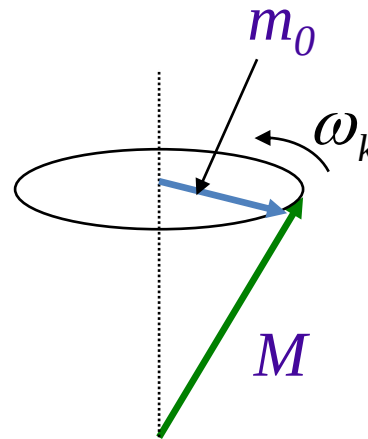
$$\vec{M} = \hat{z} M_z + \hat{x} m_x + \hat{y} m_y$$

$$m_{x,y} = g\mu_B (N/V) S_{x,y}$$

$$m^{\pm} = m_x \pm im_y$$

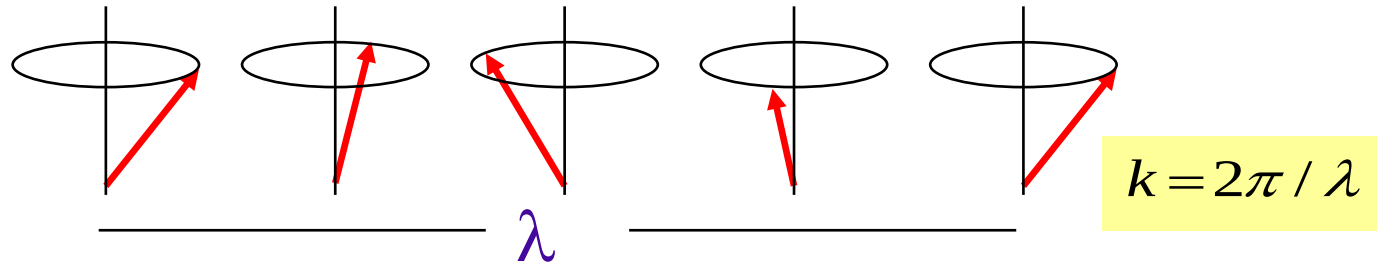


$$m^+(\vec{r}, t) = m_0 e^{i\vec{k} \cdot \vec{r} - i\omega_k t}$$



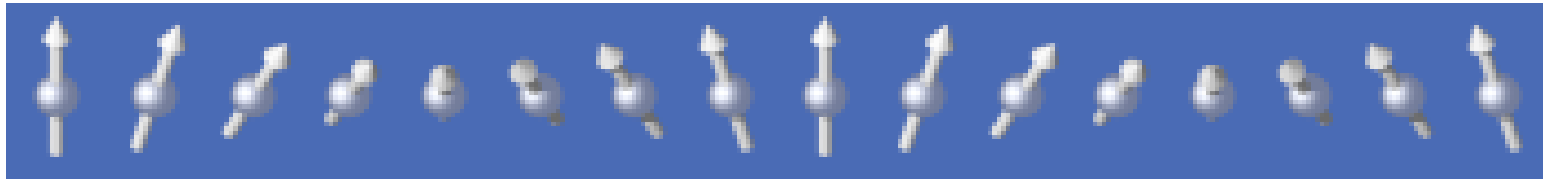
Spin waves are quantized: $|m_0|^2 \propto$ number of magnons

Spin waves: semi-classical interpretation

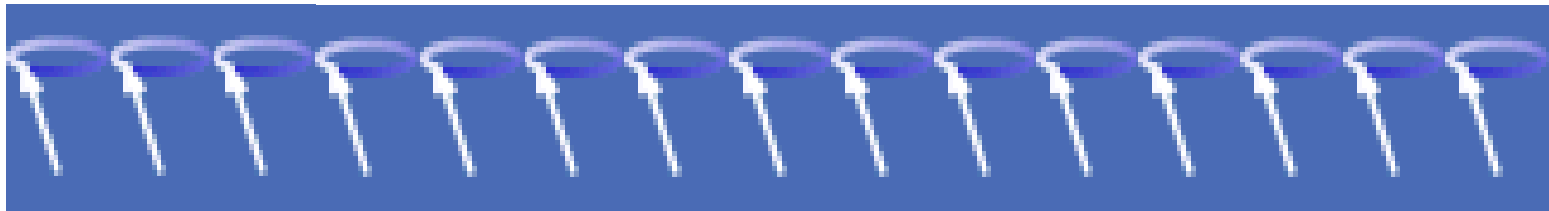


Travelling spin wave

$$m^+(\vec{r}, t) = m_0 e^{i \vec{k} \cdot \vec{r} - i \omega_k t}$$

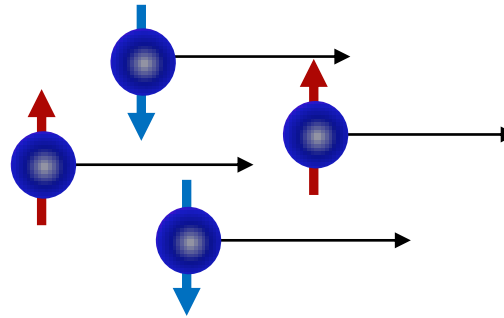


Standing spin wave



Portadores de informação

Eletrônica:

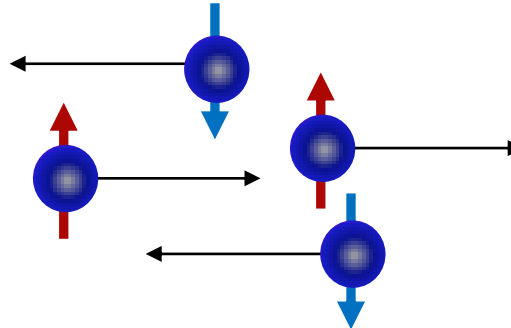


Corrente de carga

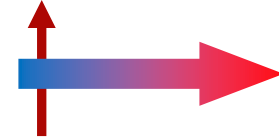


$$I_C (= I_{\uparrow} + I_{\downarrow}) \neq 0$$

Spintrônica:



Corrente de spin



$$I_S (= I_{\uparrow} - I_{\downarrow}) \neq 0$$

Magnon
spintrônica:

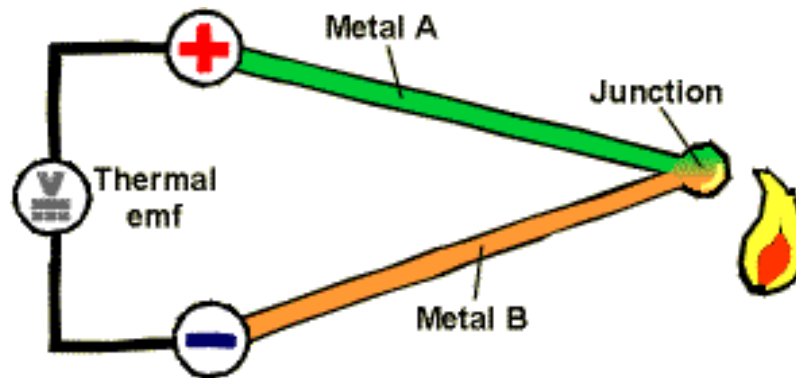
Spin Caloritronics
A new guy on the block!

Efeitos termo-elétricos: Efeito Seebeck

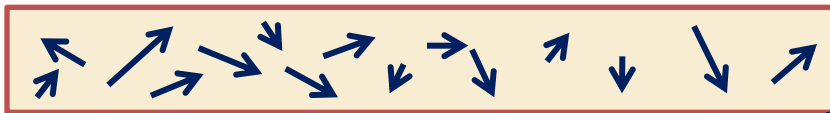


Thomas Seebeck (1770-1831)

Descobriu o efeito Seebeck em 1821



Diferença de temperatura entre dois metais distintos com uma junção gera uma diferença de potencial



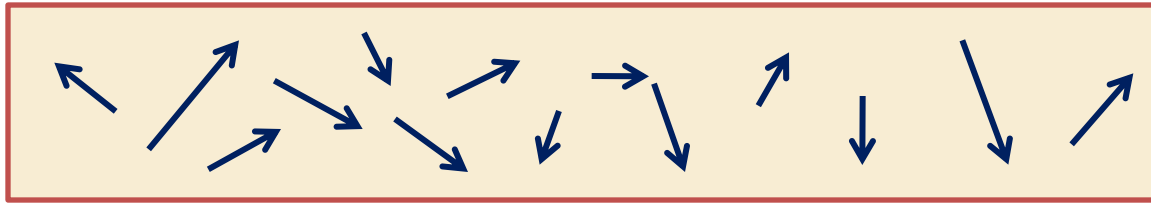
$$\Delta V = -S \Delta T$$

↑
Coeficiente Seebeck
ou termopotência



$$J_C = -\sigma S \nabla T$$

Termo-eletricidade em metais e semicondutores



$\Delta V, \Delta T$

$$\begin{pmatrix} J_C \\ J_Q \end{pmatrix} = - \begin{pmatrix} \sigma & -\sigma S \\ -\sigma \Pi & K \end{pmatrix} \begin{pmatrix} \nabla V \\ \nabla T \end{pmatrix}$$

Efeitos termoeletricos dependentes de **spin**?

Lorentz center

Spin Caloritronics

Workshop February 9 – 13 2009, Leiden, The Netherlands

Scientific Organizers

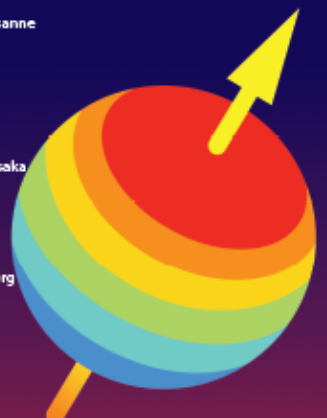
- Gerrit Bauer, Delft
- Sadamichi Maekawa, Sendai

Invited Speakers

- Jean-Philippe Ansermet, Lausanne
- Arne Brataas, Trondheim
- Ekkehard Brück, Delft
- Rembert Duine, Utrecht
- Vladimir Fal'ko, Lancaster
- Akio Fukushima, AIST
- Tero Heikkilä, Helsinki
- Jun Ieda, Tohoku
- Ronnie Jansen, Twente
- Hiroshi Katsuyama-Yoshida, Osaka
- Paul Kelly, Twente
- Andrei Kirilyuk, Nijmegen
- Mathias Kläui, Konstanz
- Hiroshi Kohno, Osaka
- Bert Koopmans, Eindhoven
- Allan MacDonald, Texas
- Laurens Molenkamp, Würzburg
- Shuichi Murakami, Tokyo IT
- Kornelius Nielsch, Hamburg
- Qian Niu, Texas
- Hideo Ohno, Tohoku
- Teruo Ono, Kyoto
- Yoshinori Onose, U. Tokyo
- Yoshichika Otani, ESSP
- Stuart Parkin, Almaden
- Eiji Saitoh, Keio
- Jing Shi, Riverside
- Yoshishige Suzuki, Osaka
- Hidenori Takagi, U. Tokyo
- Saburo Takahashi, Tohoku
- Koki Takanashi, Tohoku
- Gen Tatara, Tokyo Met.
- Yaroslav Tserkovnyak, Los Angeles
- Bart van Wees, Groningen
- Xincheng Xie, Oklahoma and Beijing
- Shinji Yusa, AIST

Topics

- Spin, charge and entropy/energy transport in conducting nanoscale structures and devices.
- Spin and: Seebeck effect, Peltier effect, thermal conductance
- Heat and: Spin transfer torque, spin Hall effects, anomalous Hall effects



The Lorentz Center is an international center in the sciences. Its aim is to organize workshops for scientists in an atmosphere which fosters collaborative work, discussions and interactions. For registration see: www.lorentzcenter.nl

Design: SuperNova Studio, Den Haag

SIM!

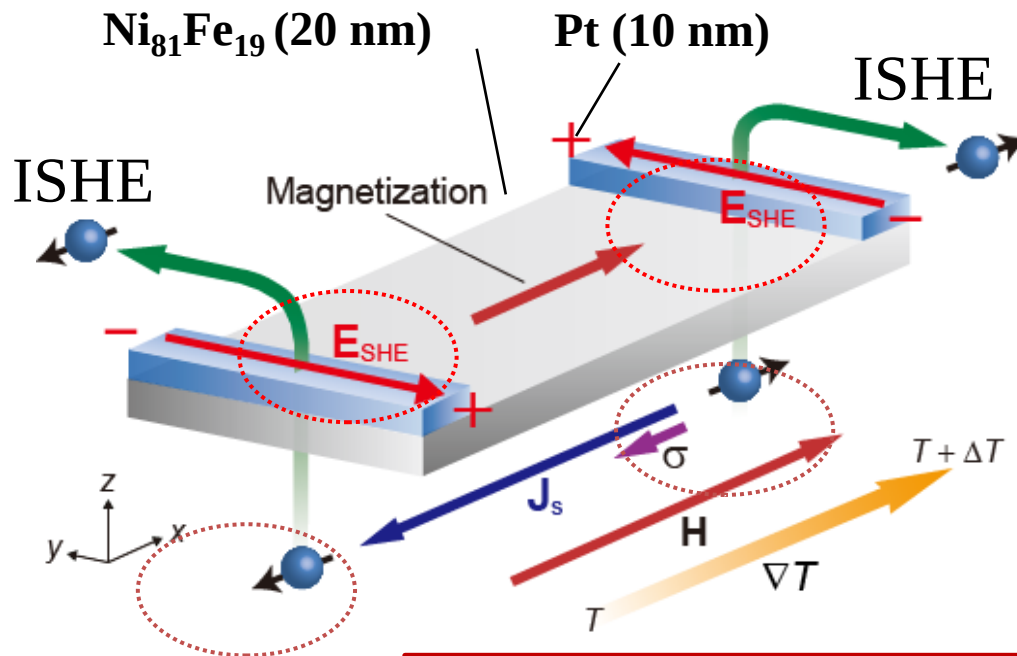
Gradiente de temperatura gera corrente de spin

nature

Vol 455 | 9 October 2008 | doi:10.1038/nature07321

Observation of the spin Seebeck effect

K. Uchida¹, S. Takahashi^{2,3}, K. Harii¹, J. Ieda^{2,3}, W. Koshibae⁴, K. Ando¹, S. Maekawa^{2,3} & E. Saitoh^{1,5}



In FM metálicos a corrente de spin é transportada pelos spin dos elétrons de condução

$$J_s = J_{\uparrow} - J_{\downarrow} = -(\sigma_{\uparrow} S_{\uparrow} - \sigma_{\downarrow} S_{\downarrow}) \nabla T$$

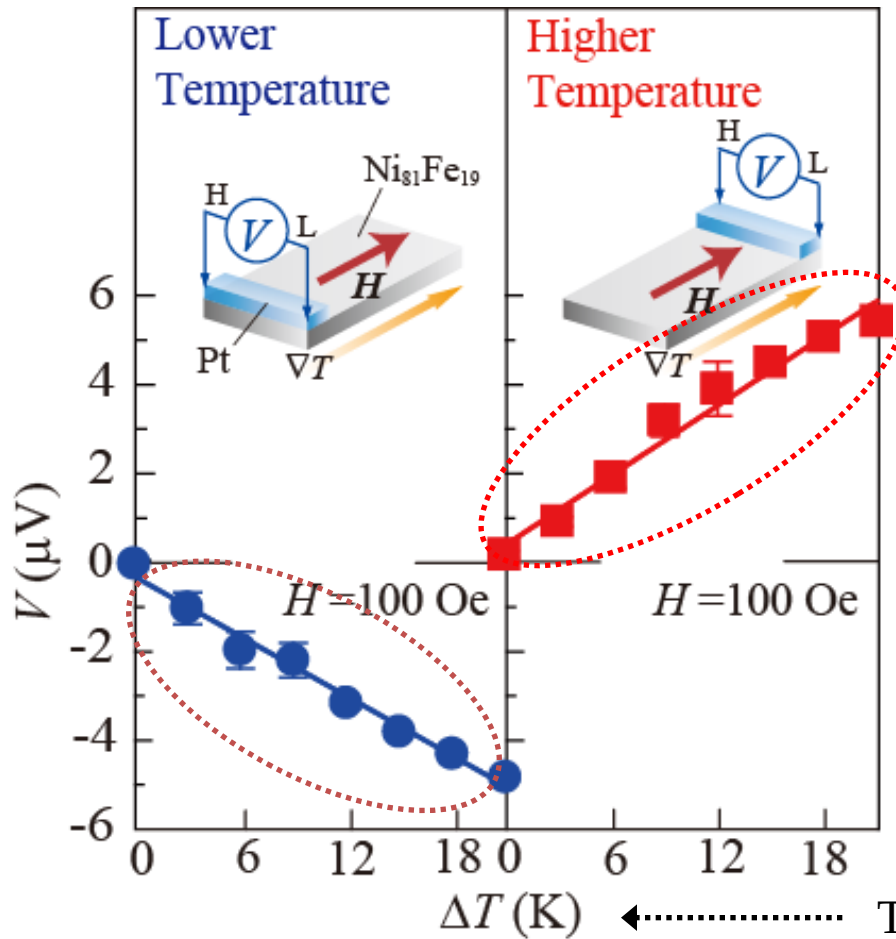
Corrente de calor



Corrente de spin

Efeito spin Seebeck - SSE

ΔT dependence of V



The magnitude of V is proportional to ∇T .

The sign of V is reversed between the lower and the higher temperature ends.



ISHE voltage induced by the spin-Seebeck effect

Efeito spin Seebeck também em FM isolantes

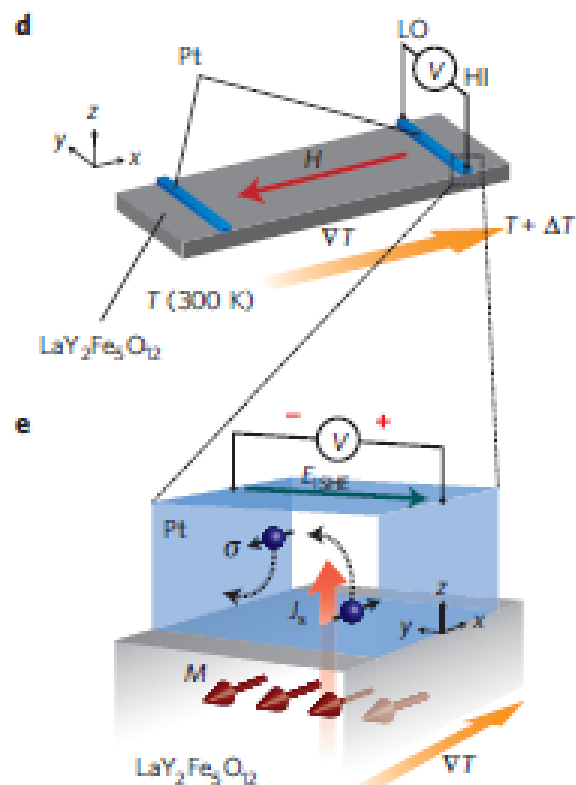
LETTERS

PUBLISHED ONLINE: 26 SEPTEMBER 2010 | DOI: 10.1038/NMAT2856

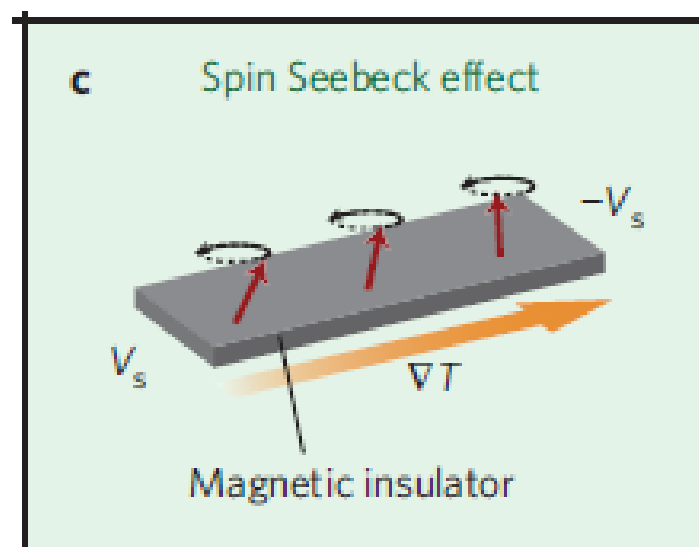
nature
materials

Spin Seebeck insulator

K. Uchida¹, J. Xiao^{2,3}, H. Adachi^{4,5}, J. Ohe^{4,5}, S. Takahashi^{1,5}, J. Ieda^{4,5}, T. Ota¹, Y. Kajiwara¹,
H. Umezawa⁶, H. Kawai⁶, G. E. W. Bauer³, S. Maekawa^{4,5} and E. Saitoh^{1,4,7}★



Em FM isolantes a corrente de spin é transportada por ondas de spin (magnons)

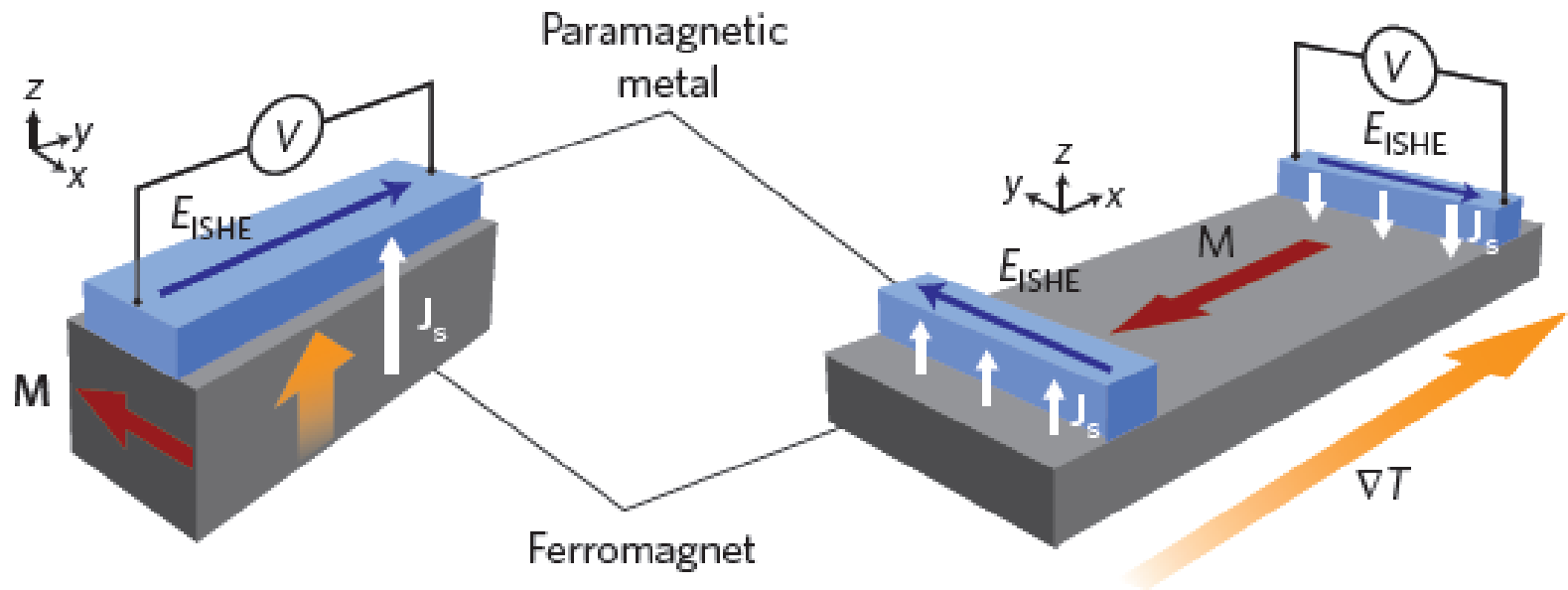


Spin caloritronics

Gerrit E. W. Bauer^{1,2*}, Eiji Saitoh^{1,3} and Bart J. van Wees⁴

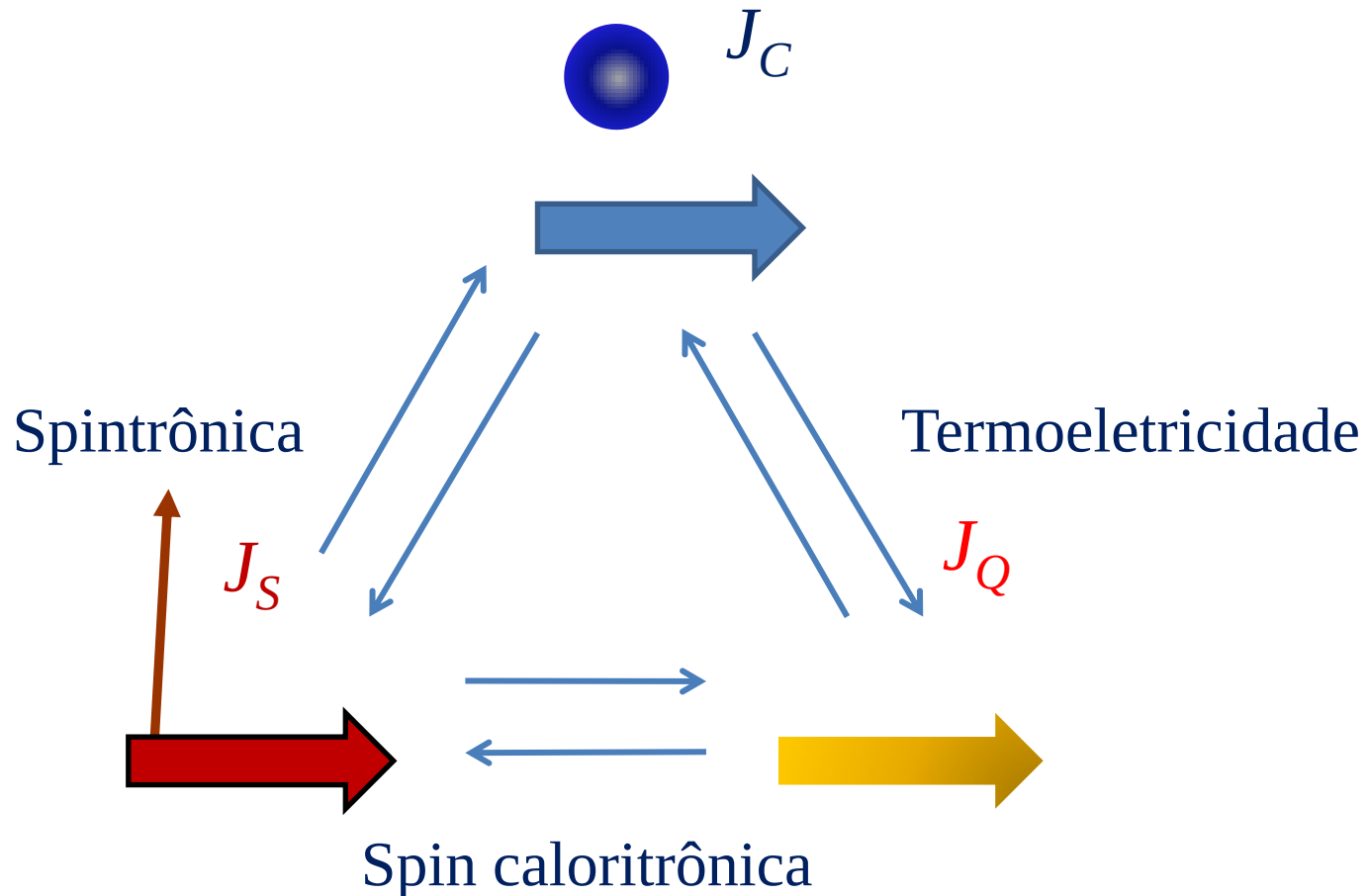
d Longitudinal configuration

e Transverse configuration



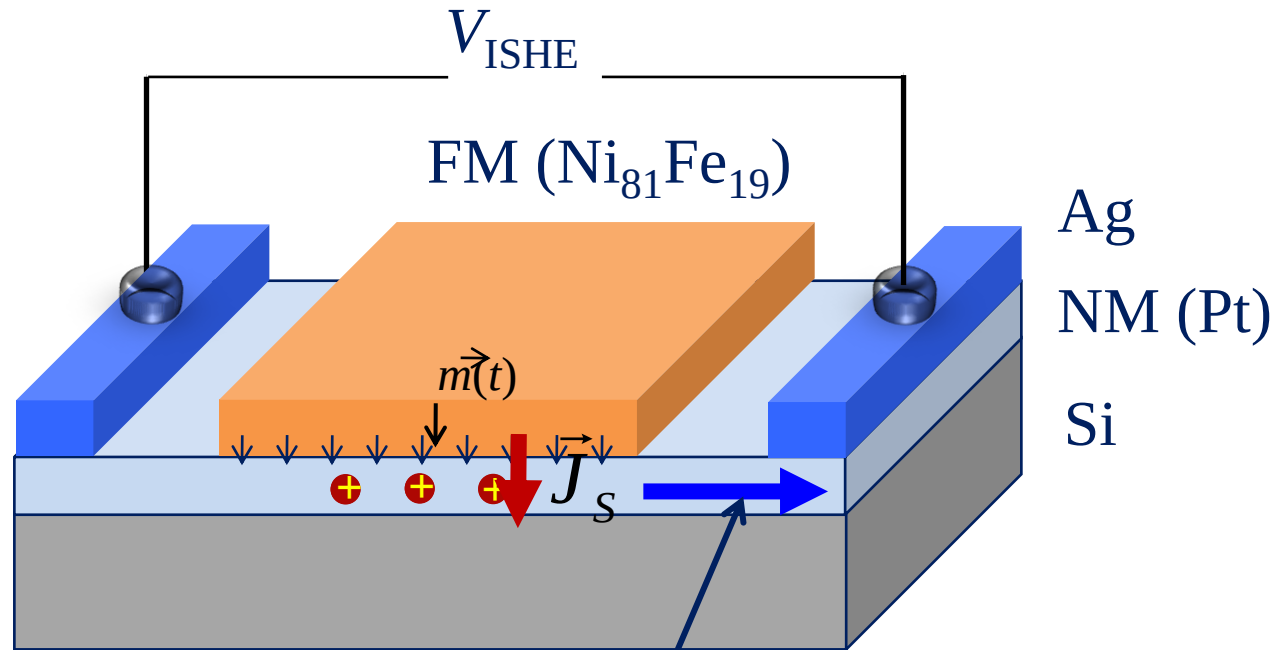
Conversão entre correntes

Inter-conversão entre correntes de carga, spin e calor, amplia muito as possibilidades para processamento de sinais por spintrônica



Alguns experimentos realizados no Recife!

Detecção elétrica de FMR (Spin pumping + ISHE)



$$\vec{J}_C = \theta_{SH} \vec{J}_S \times \vec{\sigma}$$

Corrente de carga criada por corrente de spin pelo ISHE

PHYSICAL REVIEW B 83, 144402 (2011)

Spin pumping and anisotropic magnetoresistance voltages in magnetic bilayers: Theory and experiment

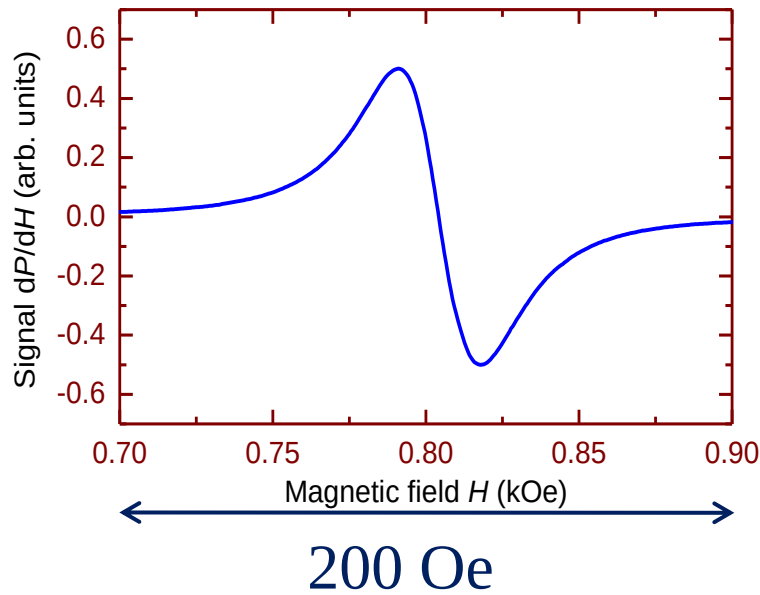
A. Azevedo,^{1,*} L. H. Vilela-Leão,¹ R. L. Rodríguez-Suárez,² A. F. Lacerda Santos,¹ and S. M. Rezende¹

¹Departamento de Física, Universidade Federal de Pernambuco, Recife, Pernambuco 50670-901, Brazil

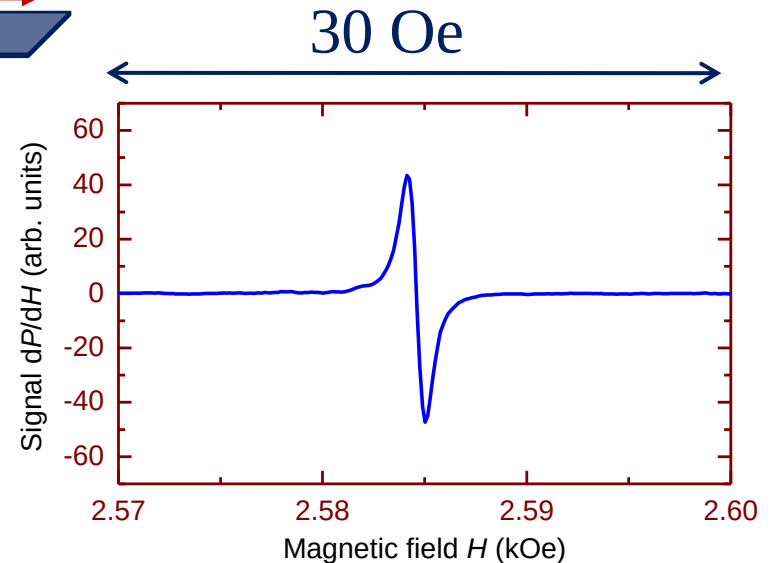
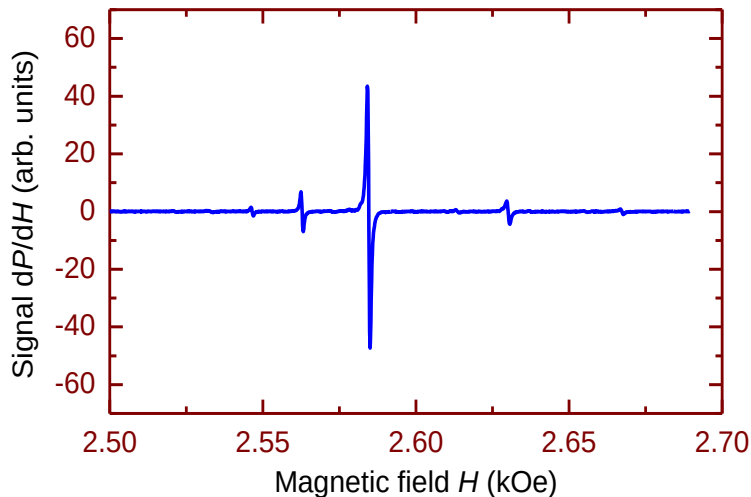
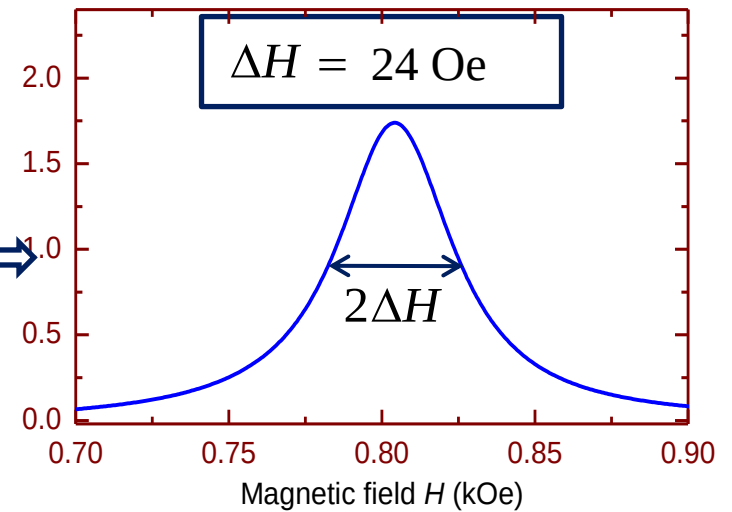
²Facultad de Física, Pontificia Universidad Católica de Chile, Casilla 306, Santiago, Chile

Relaxação em ressonância ferromagnética

Permalloy film (60 nm)



$\int dH$



Yttrium Iron Garnet (28 μm)-YIG ($\text{Y}_3\text{Fe}_5\text{O}_{12}$)

Alargamento das linhas de FMR em YIG/Pt

APPLIED PHYSICS LETTERS **102**, 012402 (2013)



Enhanced spin pumping damping in yttrium iron garnet/Pt bilayers

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PHYSICAL REVIEW B **88**, 014404 (2013)

Magnetic relaxation due to spin pumping in thick ferromagnetic films in contact with normal metals

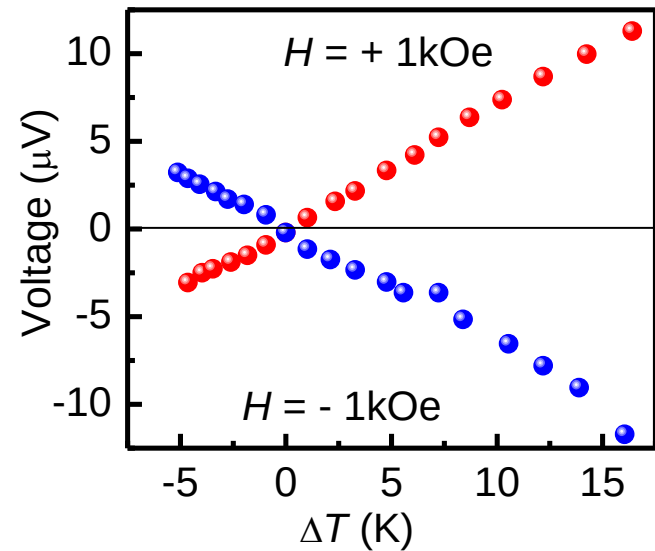
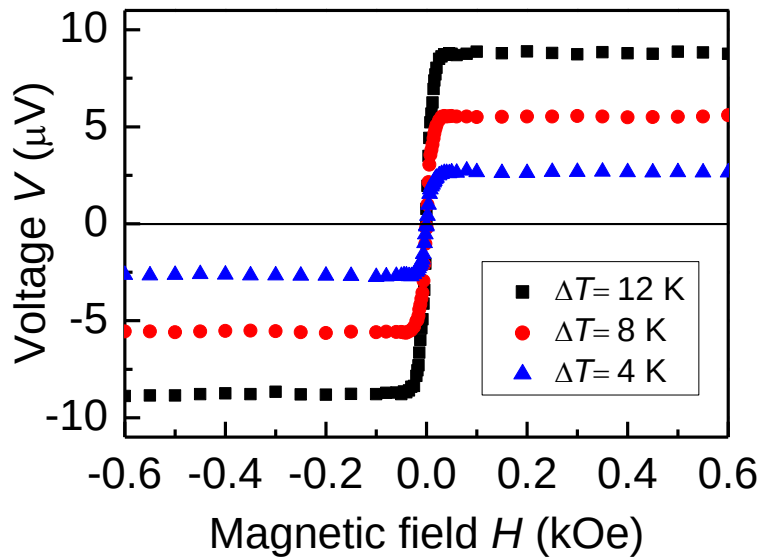
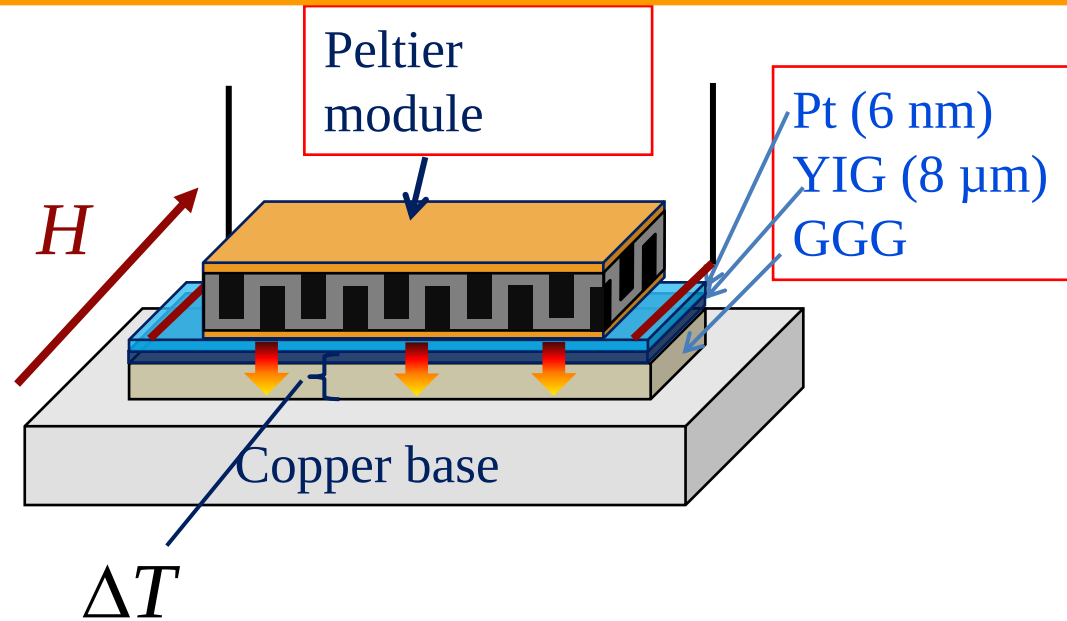
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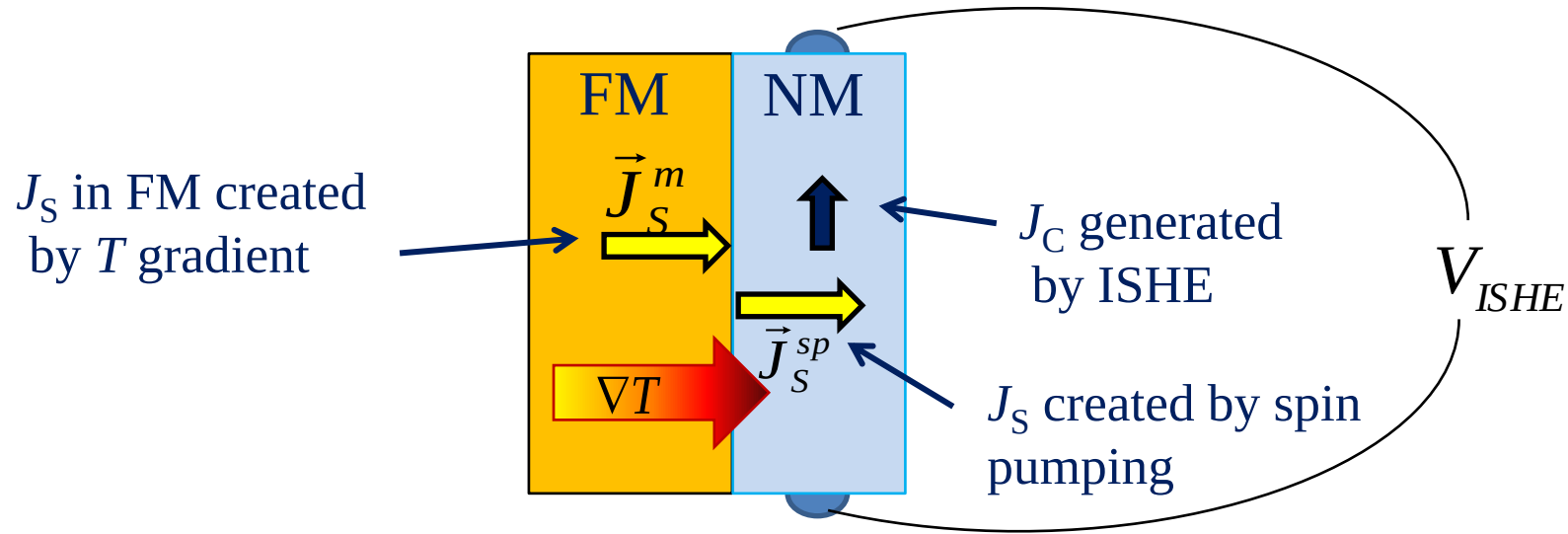
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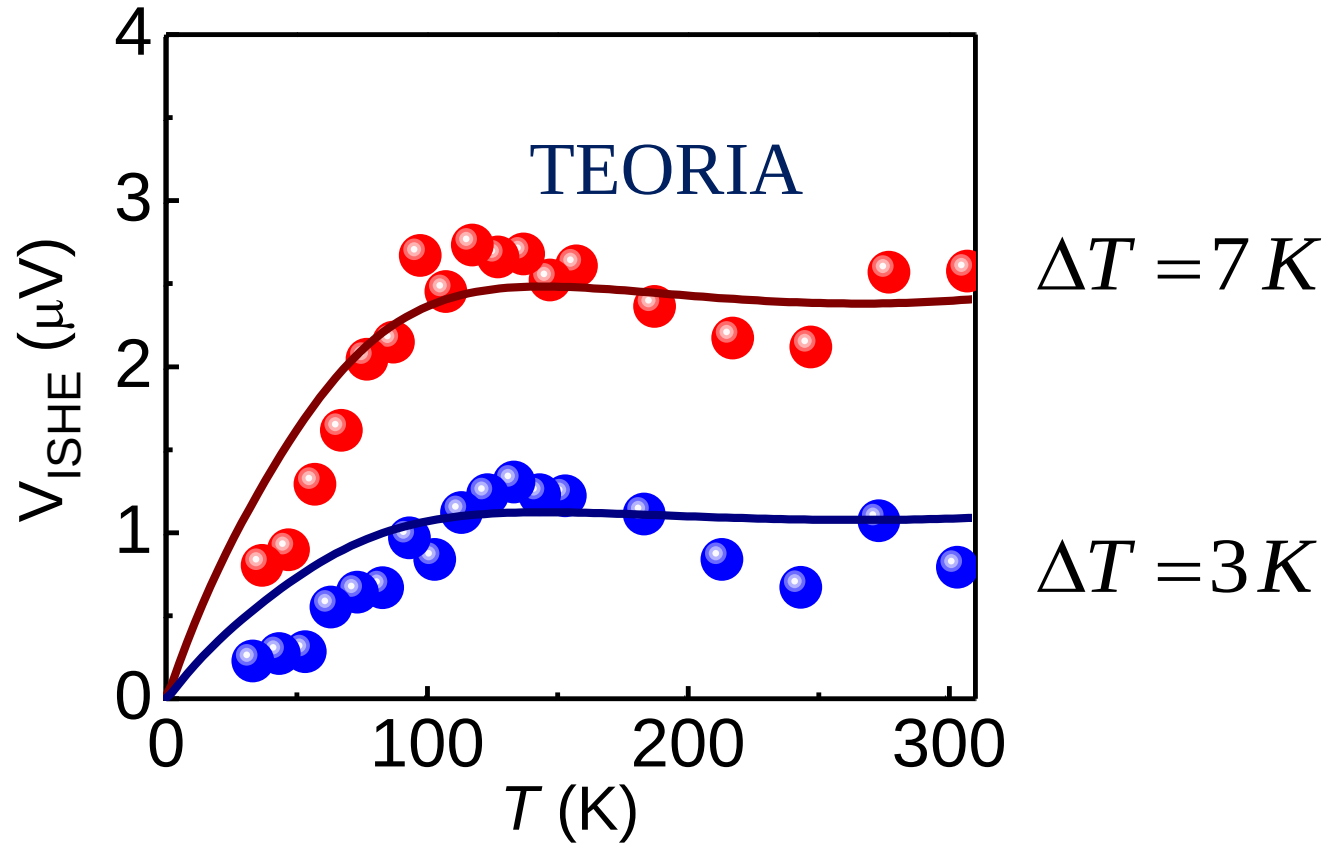
Longitudinal spin Seebeck effect in YIG/Pt



Modelo para o SSE longitudinal



Medidas de LSSE em função de T



Magnon Spin Current as the Source of the Longitudinal Spin Seebeck Effect

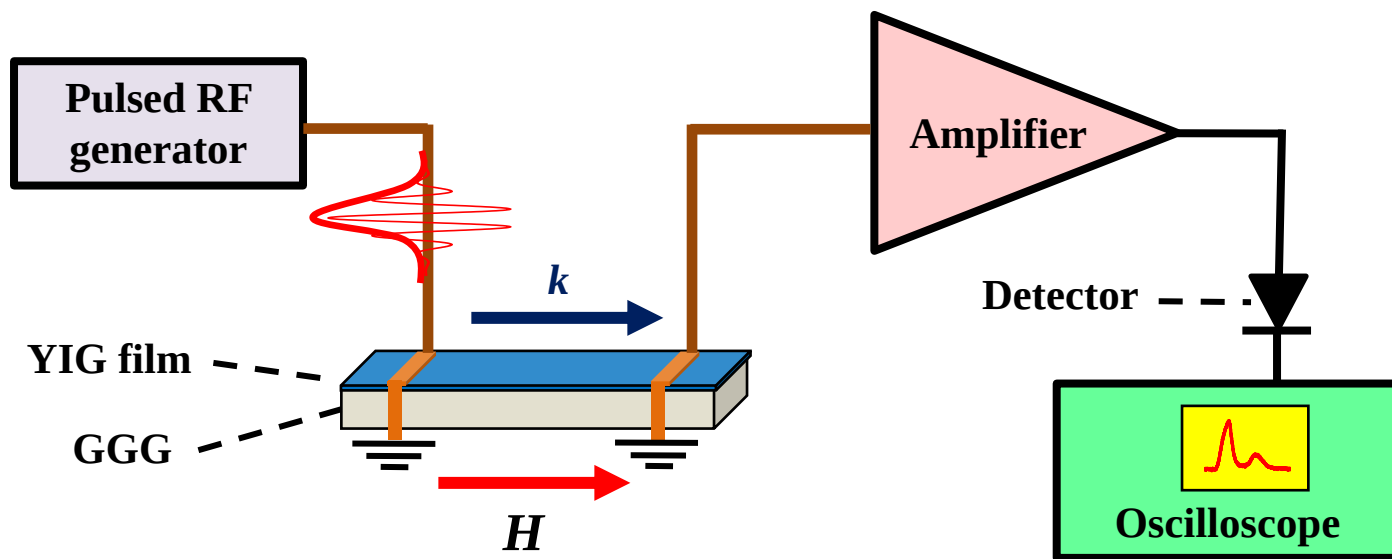
S.M. Rezende¹, R. Rodríguez-Suárez², R.O.Cunha¹, A.R. Rodrigues¹, F.L.A. Machado¹,
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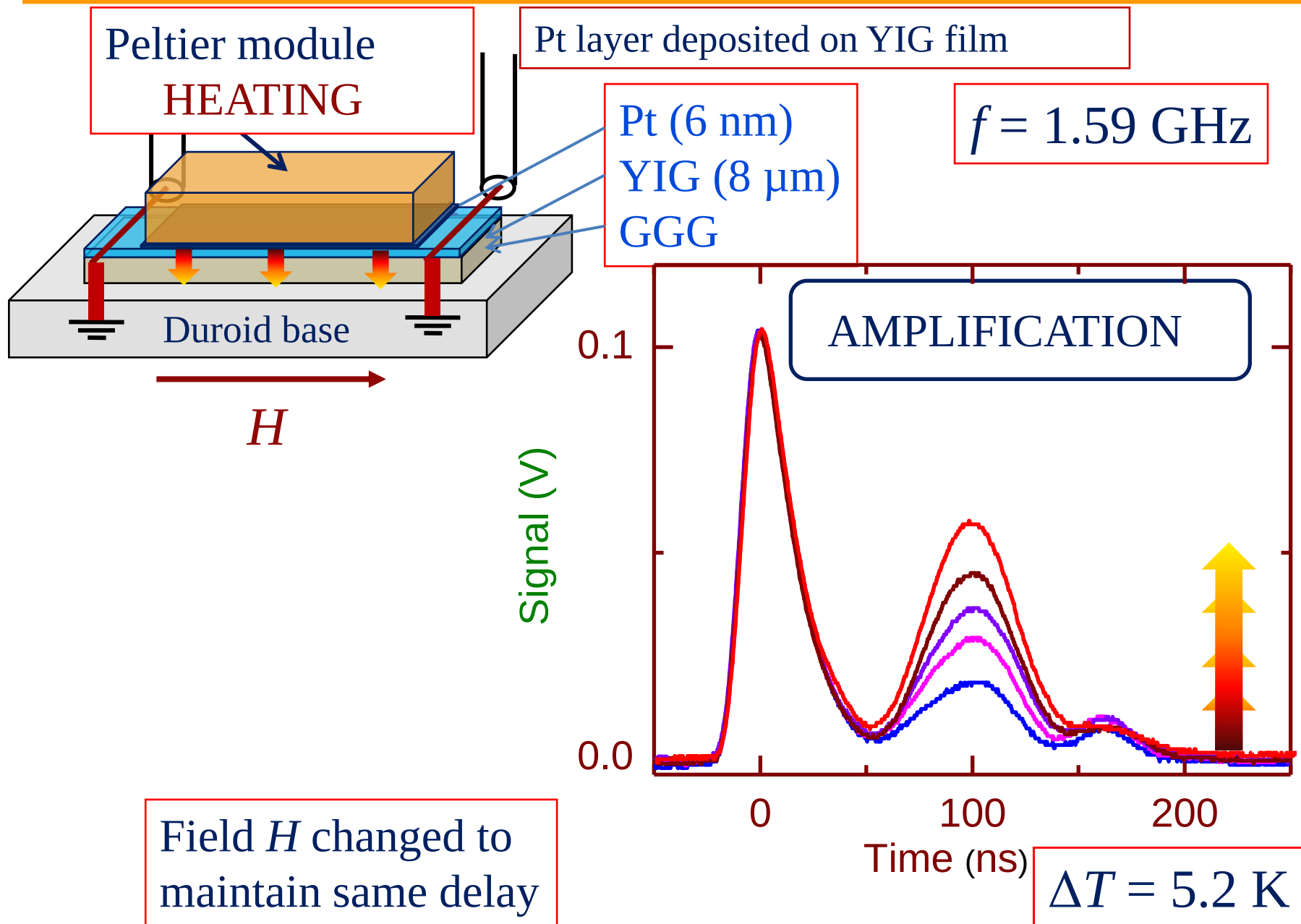
²Facultad de Física, Pontificia Universidad Católica de Chile, Casilla 306, Santiago, Chile.

Controle da relaxação de ondas de spin por SSE

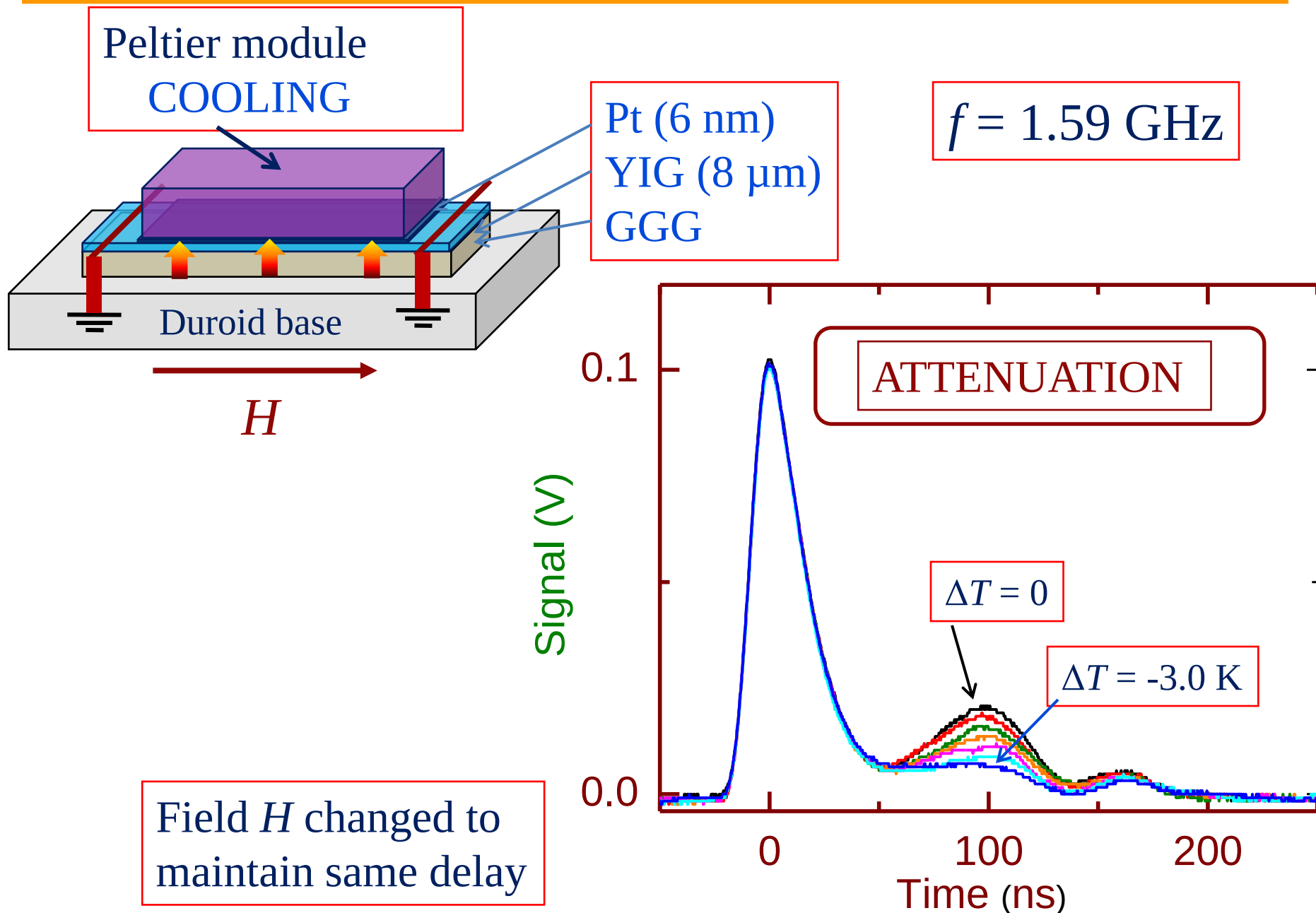
Se a corrente de spin J_s gerada por spin pumping produz amortecimento, é possível controlar a relaxação pela J_s criada por efeito spin Seebeck?



Controle da relaxação de ondas de spin por SSE



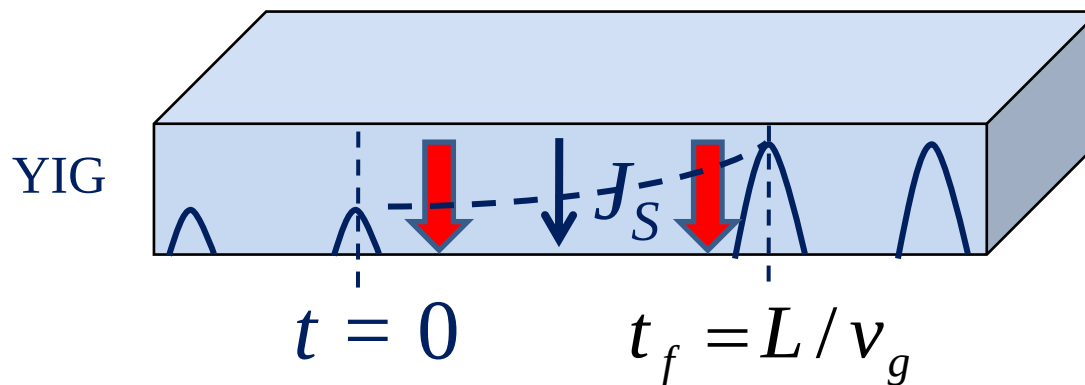
Controle da relaxação de ondas de spin por SSE



Model for SW amplification by thermal gradient

T difference creates spin current J_s

Spin current changes the
spin pumping damping



Spin-wave variable

relaxation rate

Damping due to T gradient

$$c_k(t) = c_k(0) e^{-i\omega t} e^{-(\eta_k - \beta' \nabla T) t_f}$$

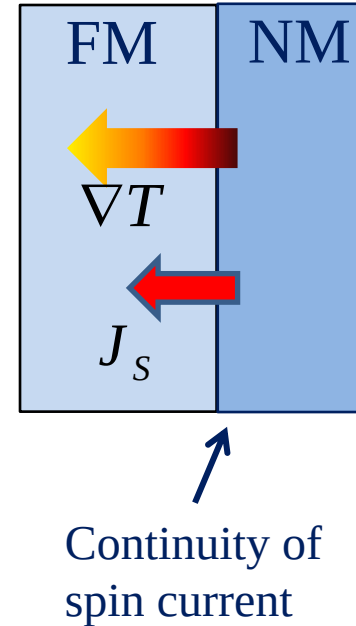
Model for relaxation due to thermal gradient

Magnon spin current due to magnon flow
in thermal gradient

$$\vec{J}_s = \frac{1}{V} \sum_k [f(\vec{r}, \vec{k}) - f_0(\vec{r})] \vec{v}_k$$

Magnon accumulation

$$\delta n_m = \frac{1}{V} \sum_k [f(\vec{r}, \vec{k}) - f_0(\vec{r})]$$



Model for relaxation due to thermal gradient

Total relaxation rate in YIG/Pt

$$\eta_t = \eta_0 + \eta_{sp} + \eta_{tg}$$

$$\eta_{sp} = \frac{\gamma \hbar \omega g_{eff}^{\uparrow\downarrow}}{4\pi M t_{FM}}$$

Spin pumping
Always positive

Control of relaxation by thermal gradients

PRL **107**, 197203 (2011)

PHYSICAL REVIEW LETTERS

week ending
4 NOVEMBER 2011

Amplification of Spin Waves by Thermal Spin-Transfer Torque

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PHYSICAL REVIEW B **87**, 184401 (2013)

Controlling the relaxation of propagating spin waves in yttrium iron garnet/Pt bilayers with thermal gradients

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Spin pumping and T gradients in YIG/Pt structures

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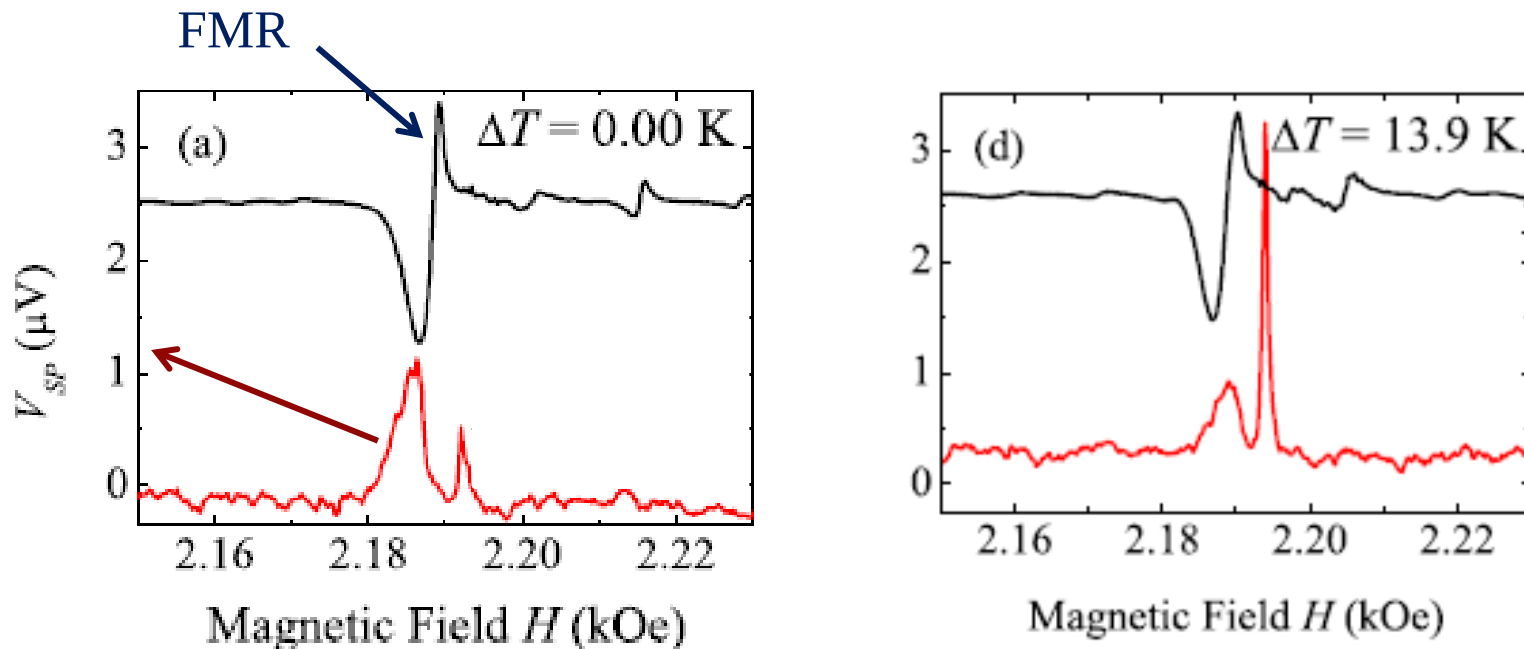


Enhancement of spin wave excitation by spin currents due to thermal gradient and spin pumping in yttrium iron garnet/Pt

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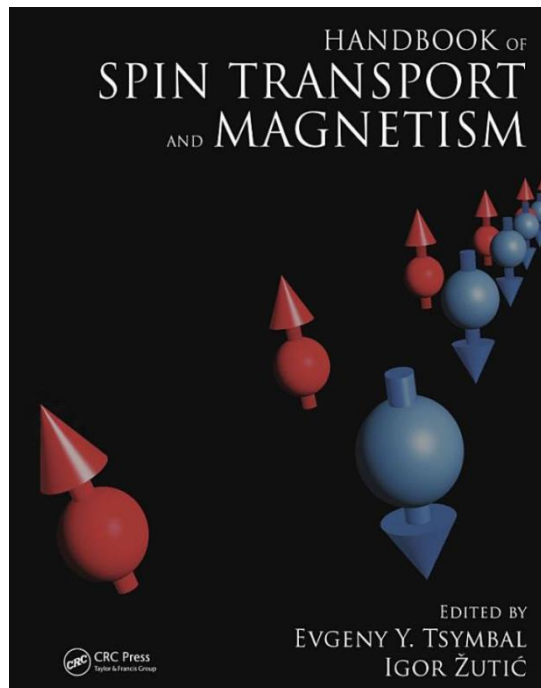
Selective amplification of modes by thermal gradients

Trabalhos publicados no DF-UFPE em: spin pumping, spin Hall, spin Seebeck

- 1) dc effect in ferromagnetic resonance: **Evidence of the spin-pumping effect?**. *Journal of Applied Physics*, American Institute of Physics, v. 97, n. 10, p. 10C715, (2005).
- 2) Amplification of spin waves in yttrium iron garnet films through the **spin Hall effect**. *Applied Physics Letters*, v. 99, p. 192511, (2011).
- 3) Amplification of spin waves **by thermal spin-transfer torque**. *Physical Review Letters*, v. 107, p. 197203, (2011).
- 4) Unidirectional anisotropy in the **spin pumping voltage in yttrium iron garnet/platinum bilayers**. *Applied Physics Letters*, v. 99, p. 102505, (2011).
- 5) **Spin pumping and anisotropic magnetoresistance** voltages in magnetic bilayers: Theory and experiment. *Physical Review. B*, **83**, 144402, (2011).
- 6) **Direct current voltage** generated in metallic layers by **spin pumping**. *Journal of Applied Physics*, v. 109, p. 1/07C910-3, (2011).
- 7) **Amplification of spin waves by the spin Seebeck effect**. *Journal of Applied Physics*, v. 111, p. 07D504, (2012).
- 8) **Spin current injection by spin Seebeck and spin pumping effects in yttrium iron garnet/Pt structures**. *Journal of Applied Physics*, v. 111, p. 07C513, (2012).
- 9) Enhancement of spin wave excitation by **spin currents due to thermal gradient and spin pumping** in yttrium iron garnet/Pt. *Appl. Phys. Lett.* 102, 012401 (2013).
- 10) **Enhanced spin pumping** damping in yttrium iron garnet/Pt bilayers. *Appl. Phys. Lett.* 102, 012402 (2013).
- 11) Magnetic relaxation due to **spin pumping** in thick ferromagnetic films in contact with normal metals, *Phys. Rev. B*, 88, 014404 (2013).
- 12) Controlling the relaxation of propagating spin waves in yttrium iron garnet/Pt bilayers with **thermal gradients**, *Phys. Rev. B*, **87**, 184401 (2013).

Sumário

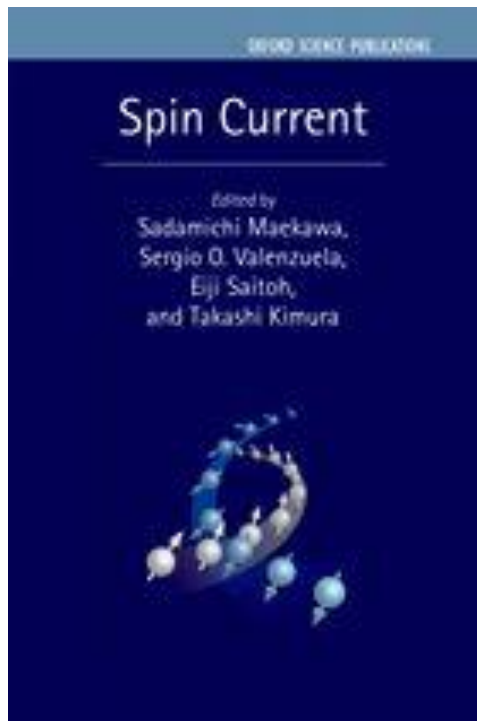
A área de SPINTRÔNICA está em rápida evolução oferecendo ótimas oportunidades de pesquisa básica e aplicada com uma variedade de fenômenos novos.



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- 5: K. Takanashi: Spin-polarization in magnets
- 6: A. Hirohata: Optically Induced and Detected Spin Current
- 7: S. E. Barnes: Theory of spin-motive-forces in ferromagnetic structures
- 8: A. Brataas: Spin Pumping and Spin Transfer
- 9: G. E. W. Bauer: Spin Caloritronics
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