SWISS CONTRIBUTION

NANOSPIN

Magnetization Dynamics in Heat Currents

Jean-Philippe Ansermet
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Group members, Spintronics

Post-docs

- Sylvain Bréchet, — *theory*
- Pedro Saraiva — *ESR*

Present grad students

- E. Papa, — *inductive FMR in SSE geometry*
- Antonio Vetro — *TMR and spin valves*
- F. Comandè — *OMAR and ESR of Organic LED*

Collaborations, recent PhD, intern

- Prof. Stewart Barnes — Uni. of Florida, Miami
- Prof. T. Stobiecki, Prof. J. Dubowik — Poland-CH collaboration
- Arndt von Bieren — *Nernst imaging of magnetization domains*
- Haiming YU — *Spin valves, switching, Pekin Uni.*

Funding

Swiss NSF,
Joint research programs : Poland
SCOPES : Moldova + Romania

Interraction of heat current and magnetization

Outline

- Motivation and challenges
- Quasi-static effects in metallic spin valves
- FMR of metallic spin valves in nanowires
- FMR of YIG crystals

Thermodynamics of irreversible processes (for charges with (+) or (-) *label*)

$$\begin{pmatrix} \mathbf{j}_s \\ \mathbf{j}_+ \\ \mathbf{j}_- \end{pmatrix} = - \begin{pmatrix} L_{ss} & L_{s+} & L_{s-} \\ L_{+s} & L_{++} & L_{+-} \\ L_{-s} & L_{-+} & L_{--} \end{pmatrix} \begin{pmatrix} \nabla T \\ \nabla \mu_+ - q_+ \mathbf{E} \\ \nabla \mu_- - q_- \mathbf{E} \end{pmatrix}$$

L. Gravier et al, PRB 2006

The «three-current model» predicted heat-driven spin currents

... but we did not consider it at the time !

Heat-driven spin torque

$$\begin{pmatrix} j_s \\ j_+ \\ j_- \end{pmatrix} = - \begin{pmatrix} \kappa & \sigma_-\varepsilon_- & \sigma_+\varepsilon_+ \\ \sigma_+\varepsilon_+ & \frac{\sigma_+}{q} & 0 \\ \sigma_-\varepsilon_- & 0 & \frac{\sigma_-}{q} \end{pmatrix} \begin{pmatrix} \nabla T \\ \nabla \mu_+ \\ \nabla \mu_- \end{pmatrix}$$

$$\boldsymbol{j}_p = \boldsymbol{j}_+ - \boldsymbol{j}_-$$

$$\sigma_\pm = \frac{\sigma}{2}(1 \pm \beta) \qquad \varepsilon_\pm = \varepsilon(1 \pm \eta)$$

$$\boldsymbol{j}_p = - \sigma\varepsilon(\eta - \beta)\,\nabla T$$

away from interfaces ($\nabla\mu_+ = \nabla\mu_-$)

S. Brechet, JPA, PPS, 1862-6270 (2011)

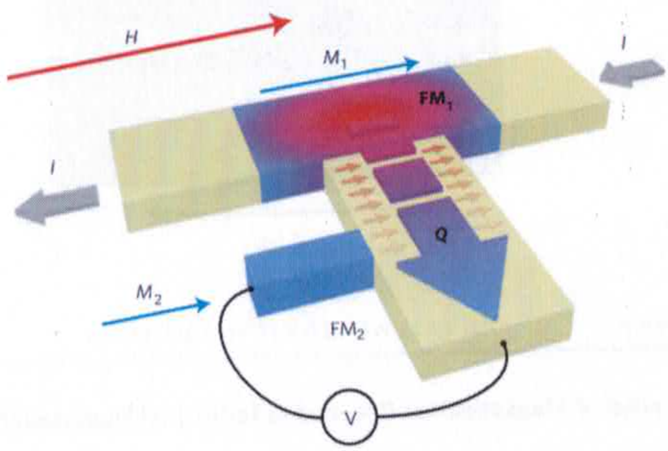
nature physics

LETTERS

PUBLISHED ONLINE: 19 SEPTEMBER 2010 | DOI: 10.1038/NPHYS1767

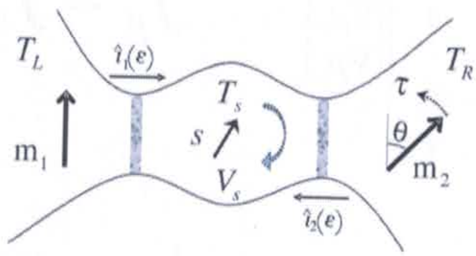
Thermally driven spin injection from a ferromagnet into a non-magnetic metal

A. Slachter*, F. L. Bakker, J-P. Adam and B. J. van Wees



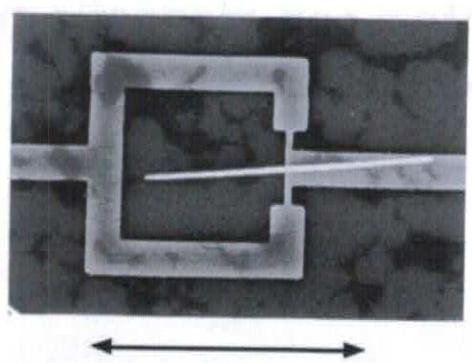
Thermal spin torque predicted in 2007

M. Hatami, G.E.W. Bauer, Q. Zhang, P.J. Kelly, Phys. Rev. Lett. 99, 066603 (2007)



$$\tau \sim P\Delta V + P'S\Delta T$$

Need large heat currents
but...
must avoid large temperature changes !



2 µm

VOLUME 77, NUMBER 9 PHYSICAL REVIEW LETTERS 26 AUGUST 1996

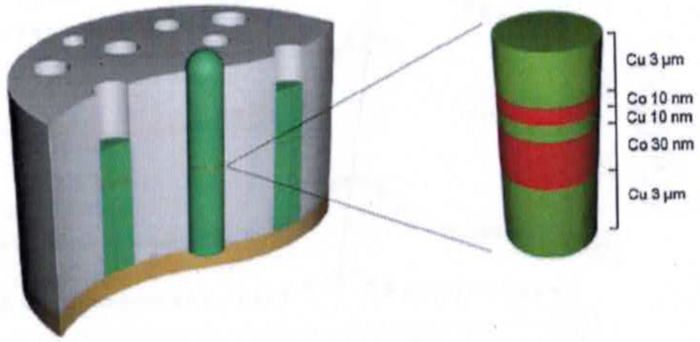
Nucleation of Magnetization Reversal in Individual Nanosized Nickel Wires

W. Wernsdorfer,[1,2] B. Doudin,[3] D. Mailly,[4] K. Hasselbach,[1] A. Benoit,[1] J. Meier,[3] J.-Ph. Ansermet,[3] and B. Barbara[2]

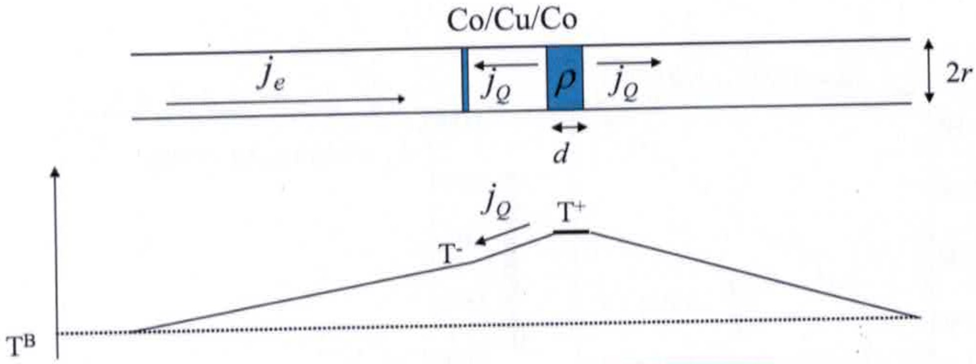
PRL 104, 146601 (2010) PHYSICAL REVIEW LETTERS week ending 9 APRIL 2010

Evidence for Thermal Spin-Transfer Torque

Haiming Yu,[1,2] S. Granville,[1] D. P. Yu,[2] and J.-Ph. Ansermet[1]
[1]*Ecole Polytechnique Fédérale de Lausanne, IPMC, Station 3, CH-1015 Lausanne-EPFL, Switzerland*
[2]*State Key Laboratory for Mesoscopic Physics, School of Physics, Peking University, Beijing 100871, People's Republic of China*



Joule heating spin valves in a nanowire

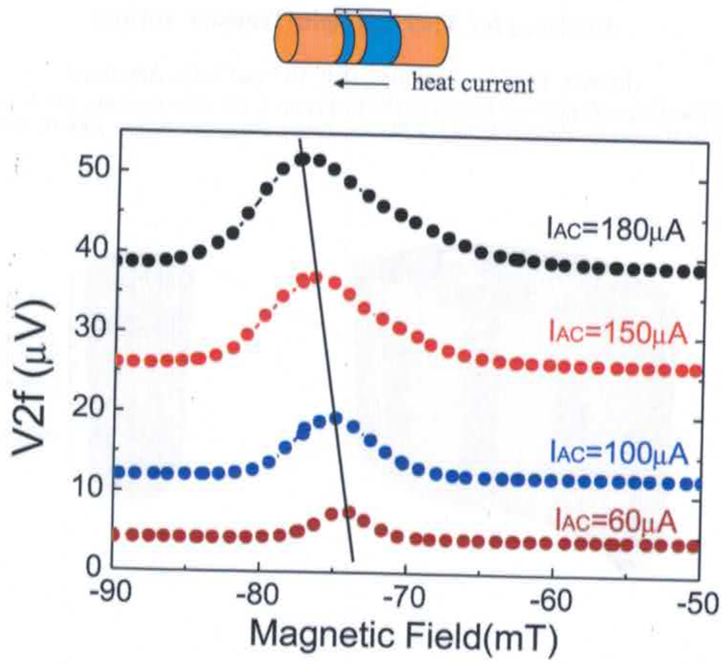


$$\nabla T \approx 10'000 K/cm!!$$

$$\frac{1}{2}\rho\frac{d}{\pi r^2}I^2 = j_Q \pi r^2 \quad \Rightarrow \quad j_Q \propto \frac{1}{r^4}$$

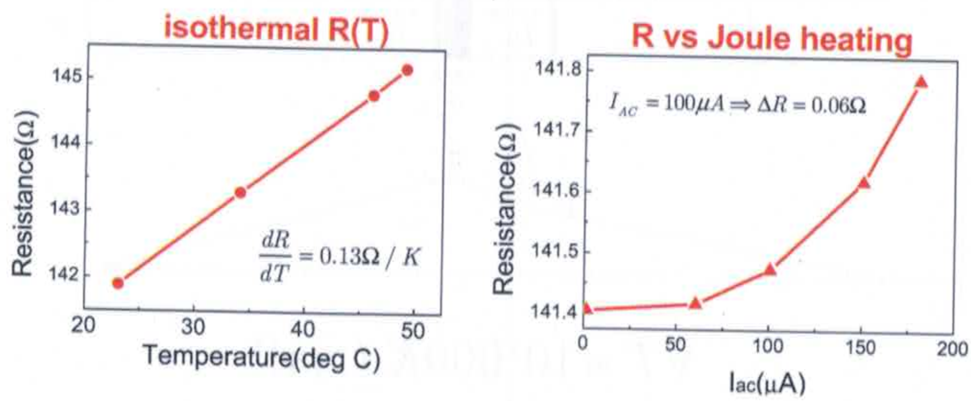
Nanowires **ideal** for large j_Q

Heat current (not temperature) changes the switching field



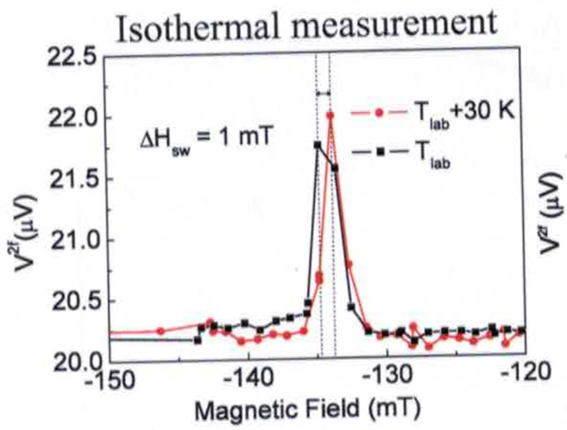
Haiming Yu, et al., Phys. Rev. Lett. **104**, 146601 (2010)

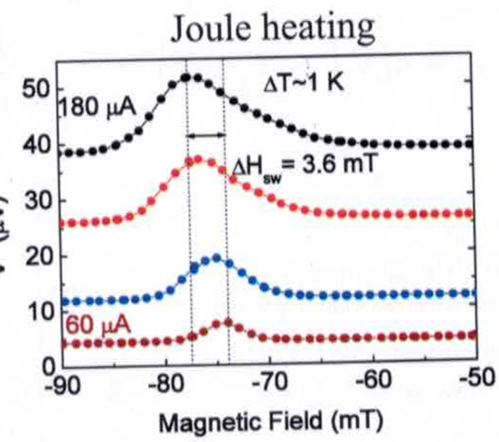
Calibrating the temperature rise



$$I_{AC} = 100\mu A \Rightarrow \boxed{\Delta T \approx 0.5K}$$

change of switching field NOT due to ΔT

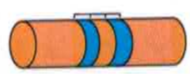




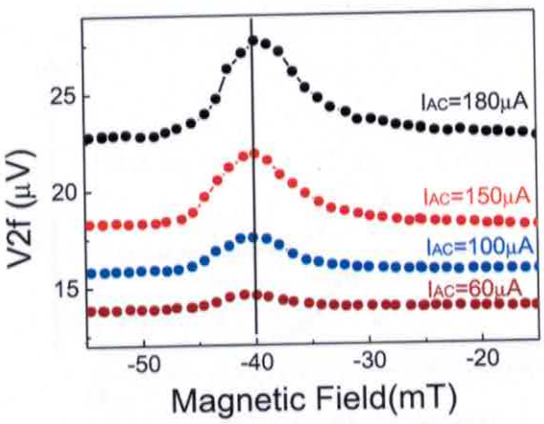
$1\ \text{K} \rightarrow \Delta \text{H}_{SW} = 0.03\ \text{mT}$

$\Delta \text{H}_{SW} = 100 \times \Delta T$ effect

Other check experiment : symmetric spin-valve



Without heat current



Haiming Yu, Phys. Rev. Lett. **104**, 146601 (2010)

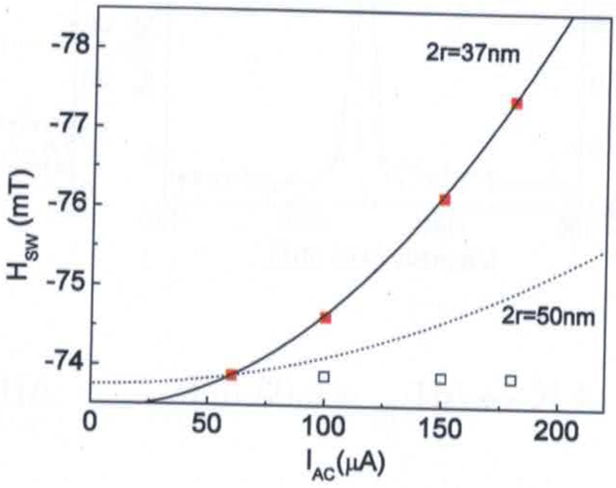
Heat-current and charge-current driven spin torques compared :

$$j_m = c\left(\nabla V - S_{eff}\nabla T\right)$$

$$\frac{\Delta H_{sw}^{TST}}{\Delta H_{sw}^{STT}} = \frac{\tau_{TST}}{\tau_{STT}} = \frac{j_{m,TST}}{j_{m,STT}} = \frac{S_{eff}\nabla T}{\nabla V}$$

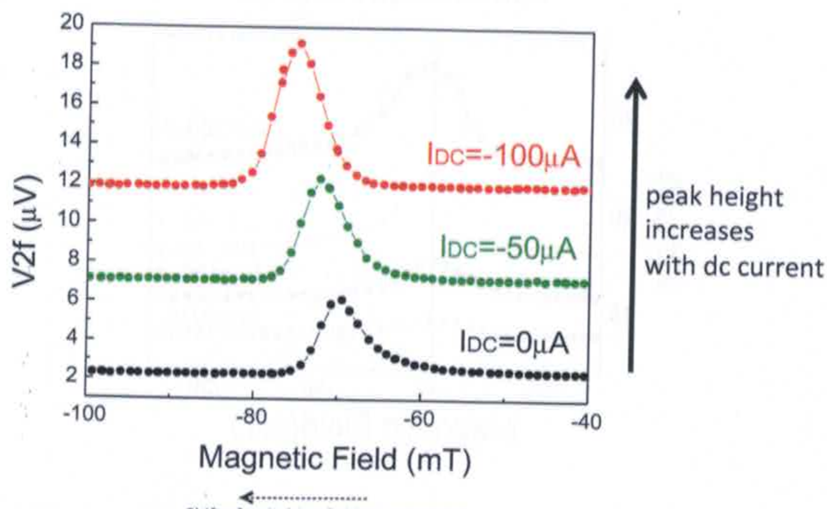
From 3-current model, values measured independently

J. Dubois and J.-Ph. Ansermet, Phys. Rev. B 78, 184430 (2008).



V2f peak height vs dc current

$$V = R(\tau, T)I \qquad V^{2f} = \frac{\partial R}{\partial \tau}\left(\tau^{f}_{STT} I_{AC} + \tau^{2f}_{TST} I_{DC}\right) + \frac{\partial R}{\partial T}\Delta T_{2f} I_{DC}$$



peak height increases with dc current

Shift of switching field is normal STT

V2f peak height

(just a 2nd order development, sorry)

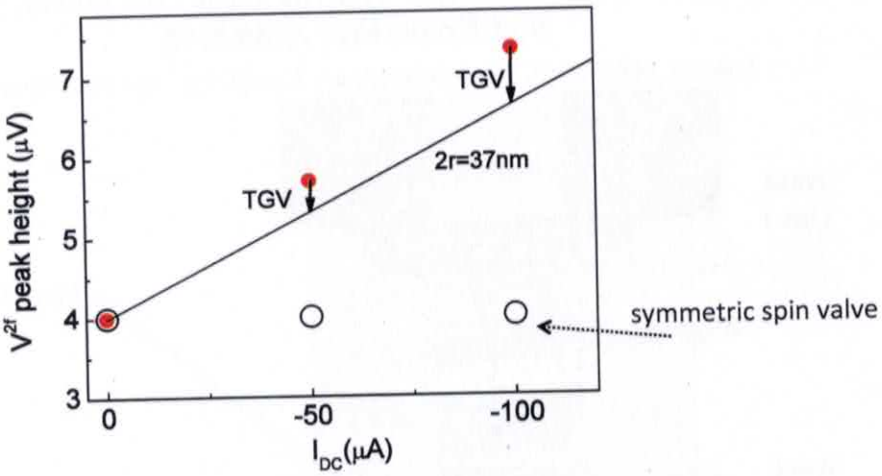
$$V = R(\tau,T)I \qquad \Delta V = I\left[\left(\frac{\partial R}{\partial \tau}\frac{\partial \tau}{\partial j_m} j_m\right) + \frac{\partial R}{\partial T}\Delta T^{2f}\right]$$

$$j_m = 2c\left(\nabla V - S_{eff}\nabla T\right) \qquad \nabla T = A_1 I^2 \qquad I = I_{AC} + I_{DC}$$

$$\Delta V = \left(I_{AC} + I_{DC}\right)\left[-\frac{\partial R}{\partial \tau}\frac{\partial \tau}{\partial j_m}2c\left(\rho\frac{\left(I_{AC}+I_{DC}\right)}{\pi r^2} + S_{eff}A_1\left(I_{AC}+I_{DC}\right)^2\right) + \frac{\partial R}{\partial T}\Delta T^{2f}\right]$$

$$V^{2f}{}_{peak} = \left(-\frac{\partial R}{\partial \tau}\frac{\partial \tau}{\partial j_m}2c\left(\rho\frac{I_{AC}{}^2}{\pi r^2} + 3S_{eff}A_1 I_{DC} I^2_{AC}\right)\right) + \frac{\partial R}{\partial T}\Delta T^{2f} I_{DC}$$

V_{2f} peak height vs. I_{dc}



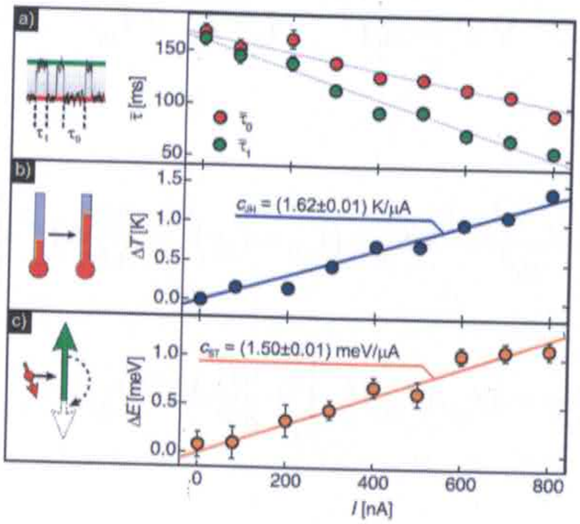
$$V^{2f}{}_{peak} = \left(\frac{\partial R}{\partial \tau}\frac{\partial \tau}{\partial j_m}2c\left(\rho\frac{I_{AC}{}^2}{\pi r^2} + 3S_{eff}A_1 I_{DC} I^2_{AC}\right)\right) + \frac{\partial R}{\partial T}\Delta T^{2f} I_{DC}$$

Other studies

PRL **107,** 186601 (2011) PHYSICAL REVIEW LETTERS week ending 28 OCTOBER 2011

Joule Heating and Spin-Transfer Torque Investigated on the Atomic Scale Using a Spin-Polarized Scanning Tunneling Microscope

S. Krause,* G. Herzog, A. Schlenhoff, A. Sonntag, and R. Wiesendanger



$$\bar{\tau}_{0,1}(I) = \frac{1}{f_0}\exp\left(\frac{E_b \pm \Delta E(I)}{k_B[T + \Delta T(I)]}\right)$$

2 data series

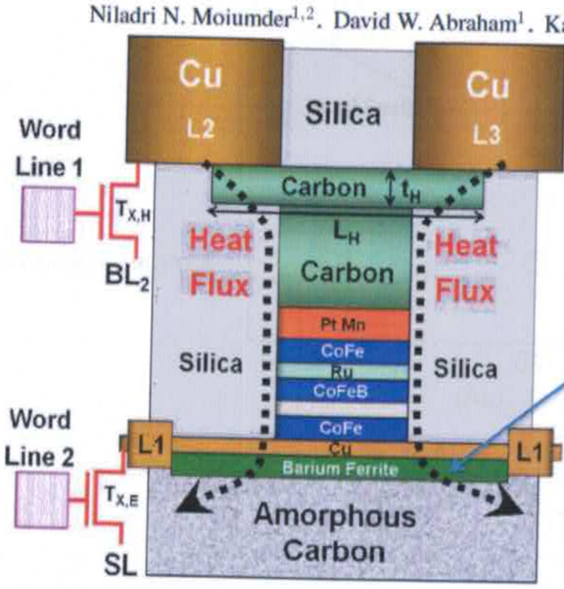
Other studies

2016

IEEE TRANSACTIONS ON MAGNETICS, VOL. 48, NO. 6, JUNE 2012

Magnonic Spin-Transfer Torque MRAM With Low Power, High Speed, and Error-Free Switching

Niladri N. Mojumder[1,2], David W. Abraham[1], Kaushik Roy[2], and D. C. Worledge[1]



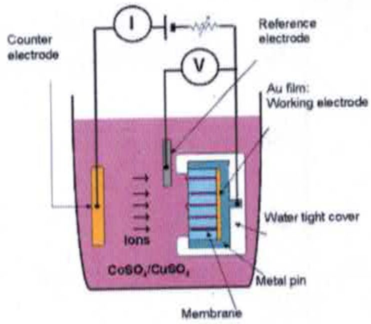
Insulating ferrite

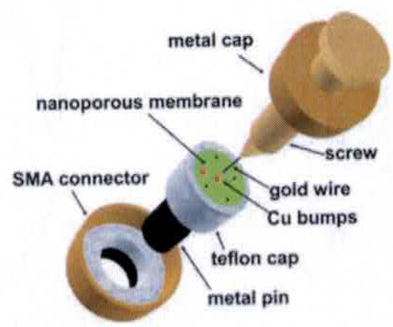
See :
J.C. Slonczewski
PRB 82, 054403 (2010)

Effect of heat current on Magnetization Resonance

FMR of spin valves in nanowires

GHz electronics on (short-lived) nanowires ?



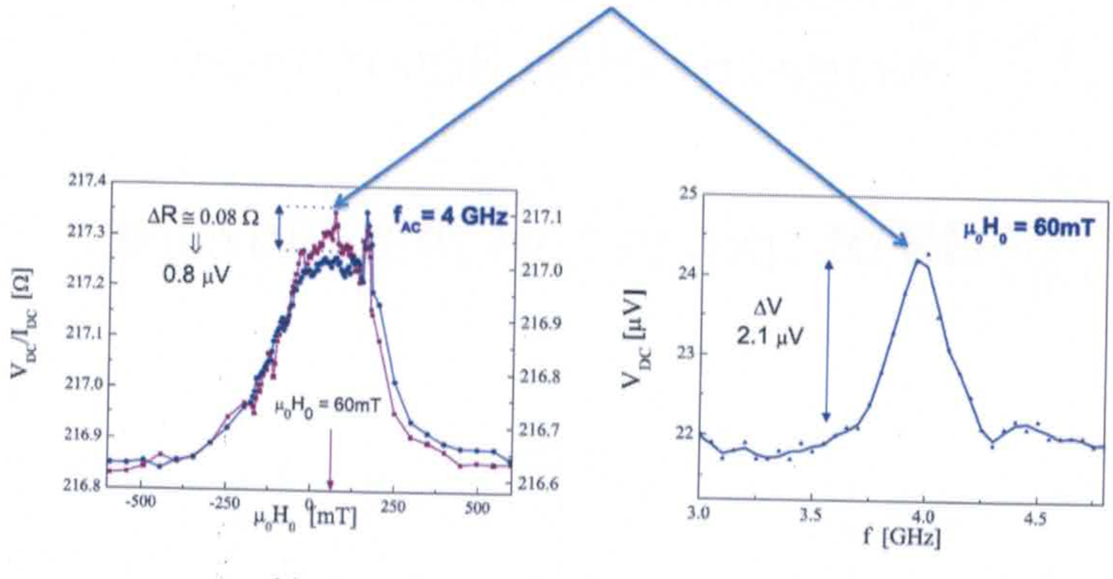


- One sample, many spin vavles !
- Driving microwave currents into a nanowire !

Lithography-free study of spin torque

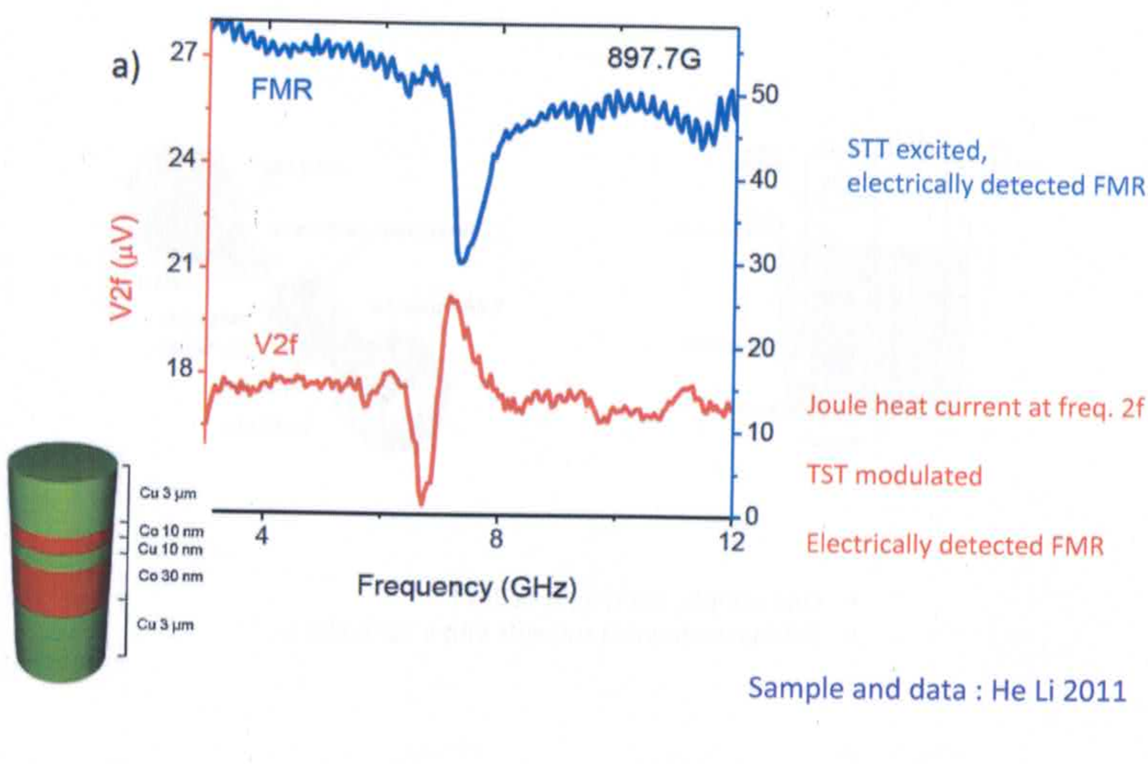
E. Murè *, N. Bizière, J.-Ph. Ansermet

Journal of Magnetism and Magnetic Materials 322 (2010) 1443



(a) (b)

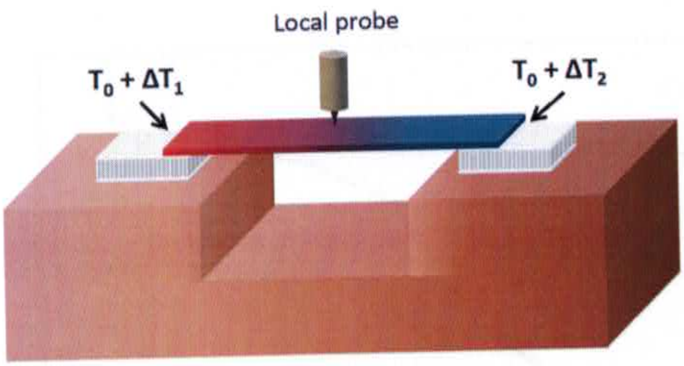
Heat current modulated FMR, spin valves



Sample and data : He Li 2011

Effect of heat current on Magnetization *Dynamics*

FMR in YIG

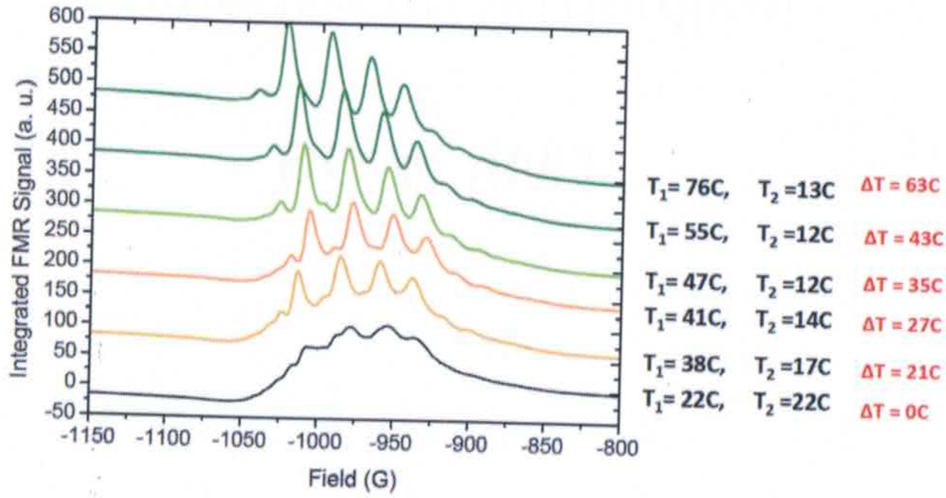


YIG :

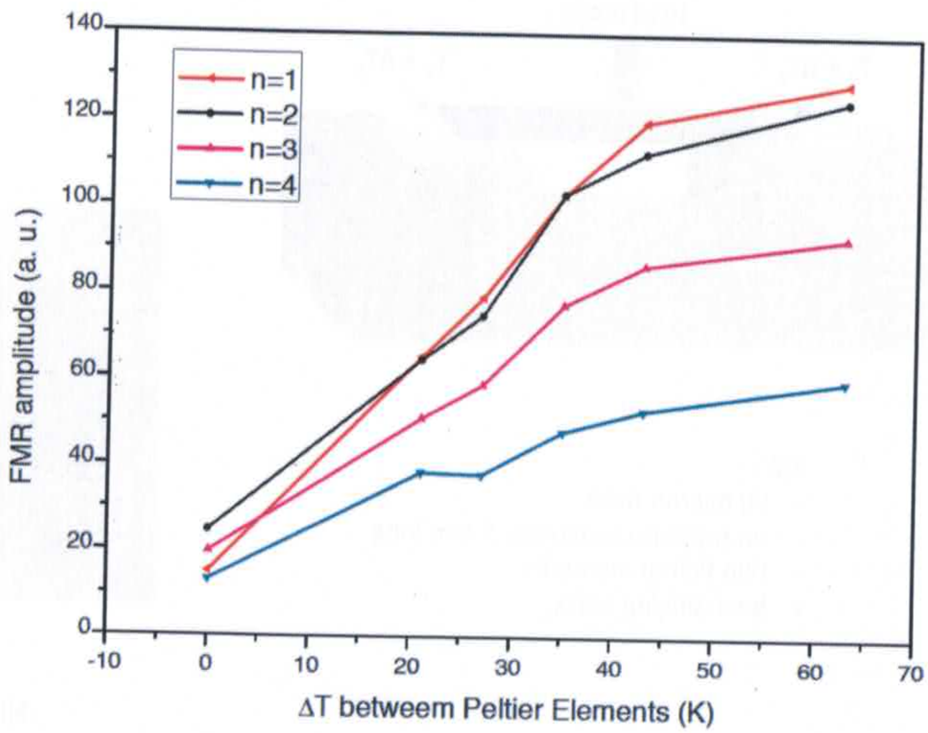
- 50 micron thick
- on sapphire substrate, 7 mm long
- two Peltier elements
- heat-sinking block

Elisa Papa

Integrated FMR spectra for various uniform temperatures:

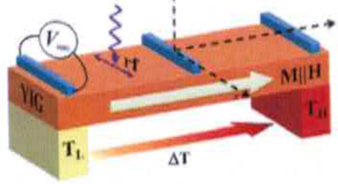


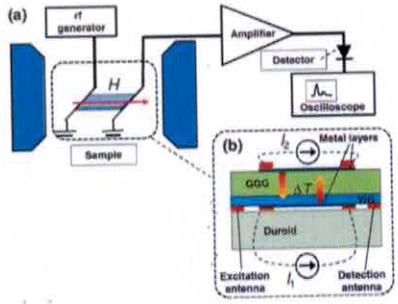
FMR amplitude Versus ΔT

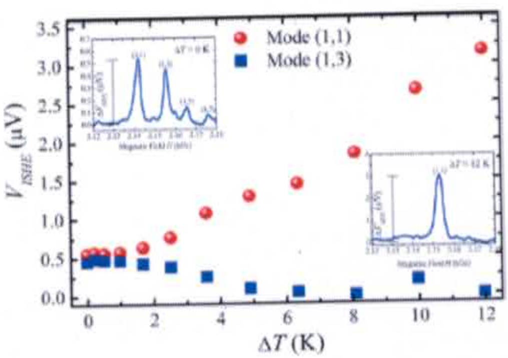


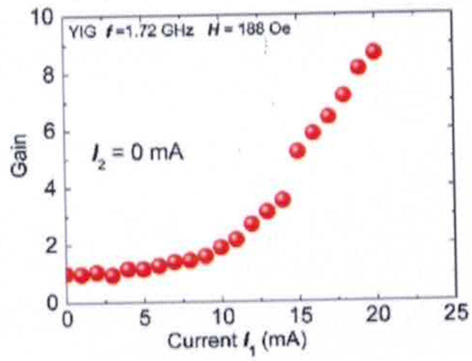
YIG

group of Azevedo, Rezende, JAP 2012 and PRL 2011









Interraction of heat current and magnetization

- Thermodynamics 3-current model :
  heat-driven spin currents in metals
- Thermal spin torque in spin valve (quasi-static)
  The 3-current model account for two independent observations
- FMR in metals
  modulation by heat in spin valves
- FMR in YIG
  Narrowing of the FMR at the cold end

Electromagnetic pumping of spin waves

LETTERS
nature materials

Controlled enhancement of spin-current emission by three-magnon splitting

Hidekazu Kurebayashi[1]*, Oleksandr Dzyapko[2], Vladislav E. Demidov[2], Dong Fang[1], A. J. Ferguson[1] and Sergej O. Demokritov[2]

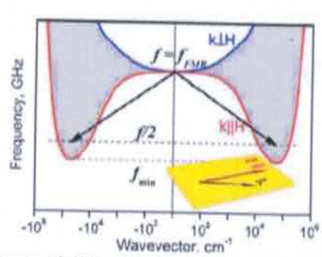
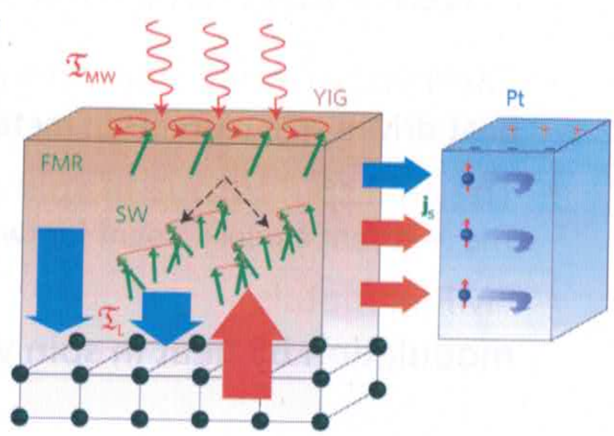


Figure S1: Spin-wave spectrum in YIG and the three magnon splitting. There are available spin-wave states depending on the relative orientation of the applied magnetic field *H* and momentum of spin-wave *k*. The FMR mode is excited by applying the microwave magnetic field with a frequency f ($=f_{FMR}$). The arrows represent the three magnon splitting process that generates two spin-waves with $f/2$ from the FMR mode. This process starts when $f/2$ is greater than the minimum frequency of the spectrum f_{min}.



See also :
- Suhl JAP 1957, J. Phys. Chem Sol 1957