NYU

Spins Dynamics in Nanomagnets

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Lecture 1: Magnetic Interactions and Classical Magnetization Dynamics

Lecture 2: Spin Current Induced Magnetization Dynamics

Lecture 3: Quantum Spin Dynamics in Molecular Nanomagnets

Outline

I. Spin-Transport and Transfer Basics
- _–Giant magnetoresistance (GMR)_
- _–Spin filtering and spin momentum transfer_

II. Spin-Transfer Induced Magnetization Dynamics
- _–Landau-Lifshitz-Gilbert dynamics and spin-torque_
- _–Current threshold for excitations and stability diagrams_

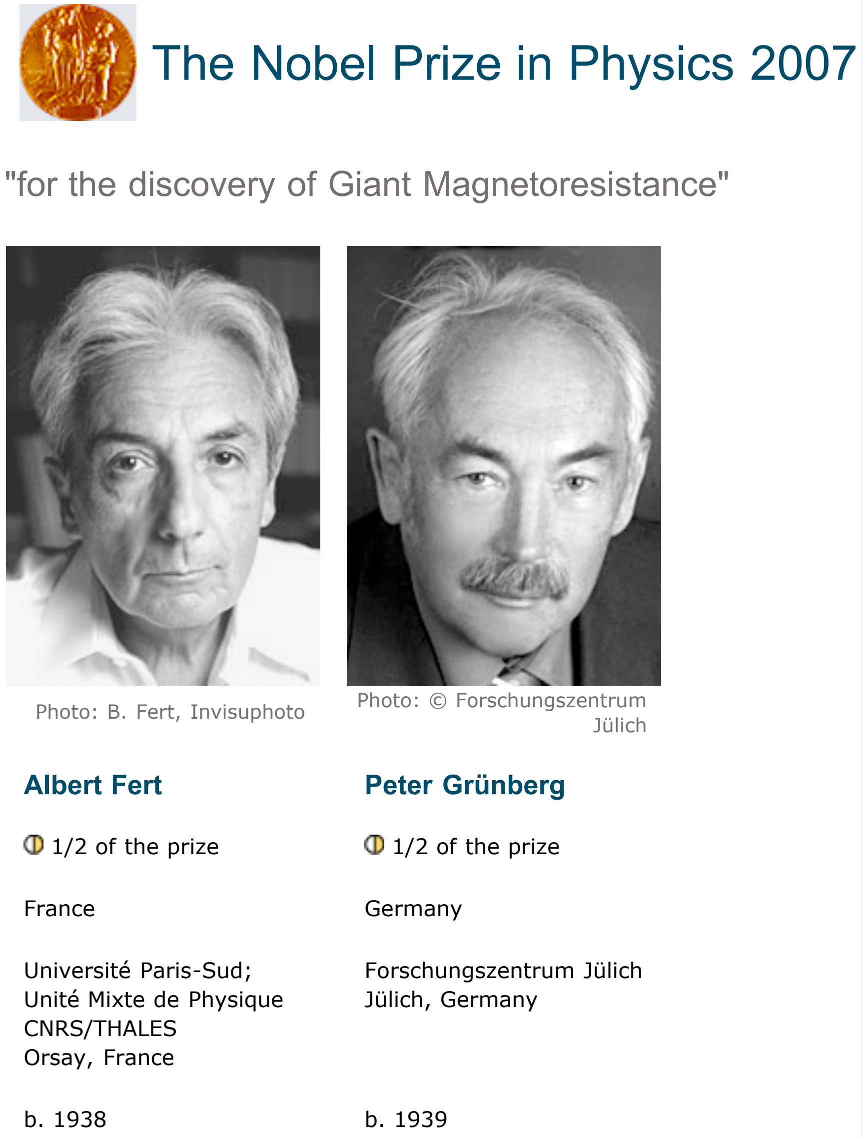
III. Experiments
- _–Point contacts, nanopillars_
- _–dc transport, noise, high frequency characteristics_

IV. Spin-Transfer MRAM
- _–Ultimate miniaturization of MRAM_

V. Summary

References

Giant Magnetoresistance (GMR)



The Nobel Prize in Physics 2007

"for the discovery of Giant Magnetoresistance"

Photo: B. Fert, Invisuphoto

Albert Fert

◑ 1/2 of the prize

France

Université Paris-Sud;
Unité Mixte de Physique
CNRS/THALES
Orsay, France

b. 1938

Photo: © Forschungszentrum Jülich

Peter Grünberg

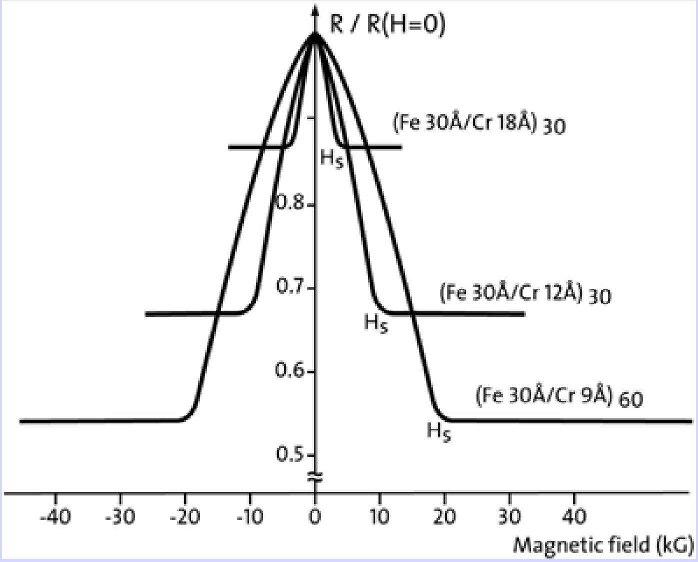
◑ 1/2 of the prize

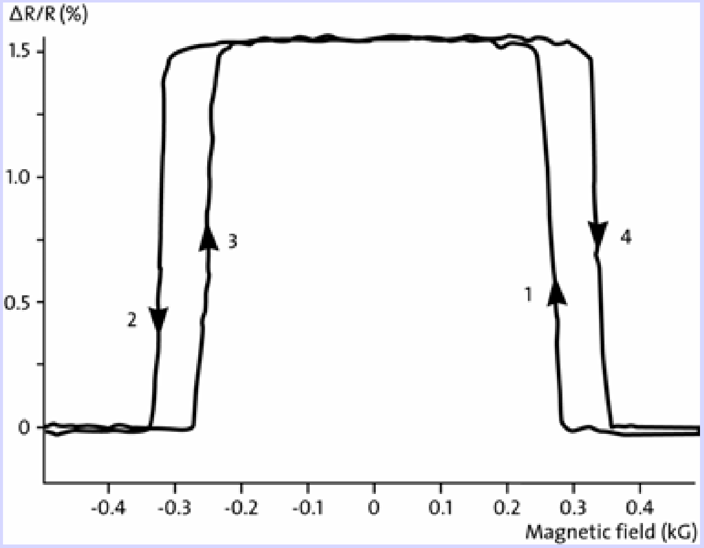
Germany

Forschungszentrum Jülich
Jülich, Germany

b. 1939

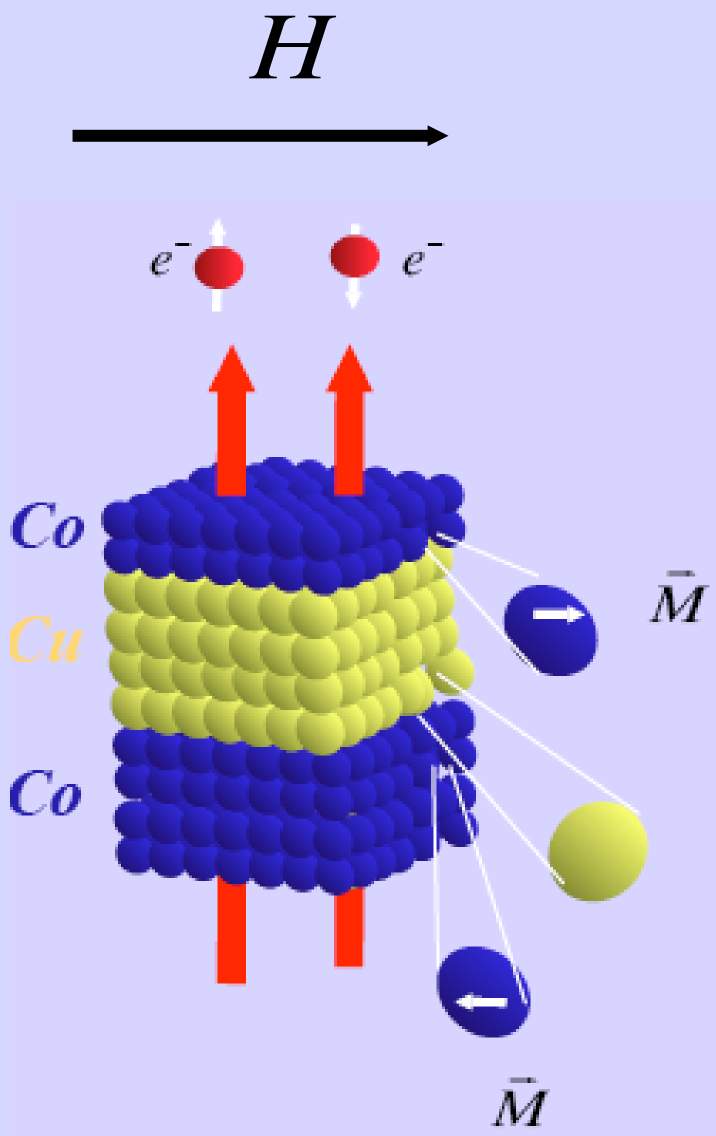
1988



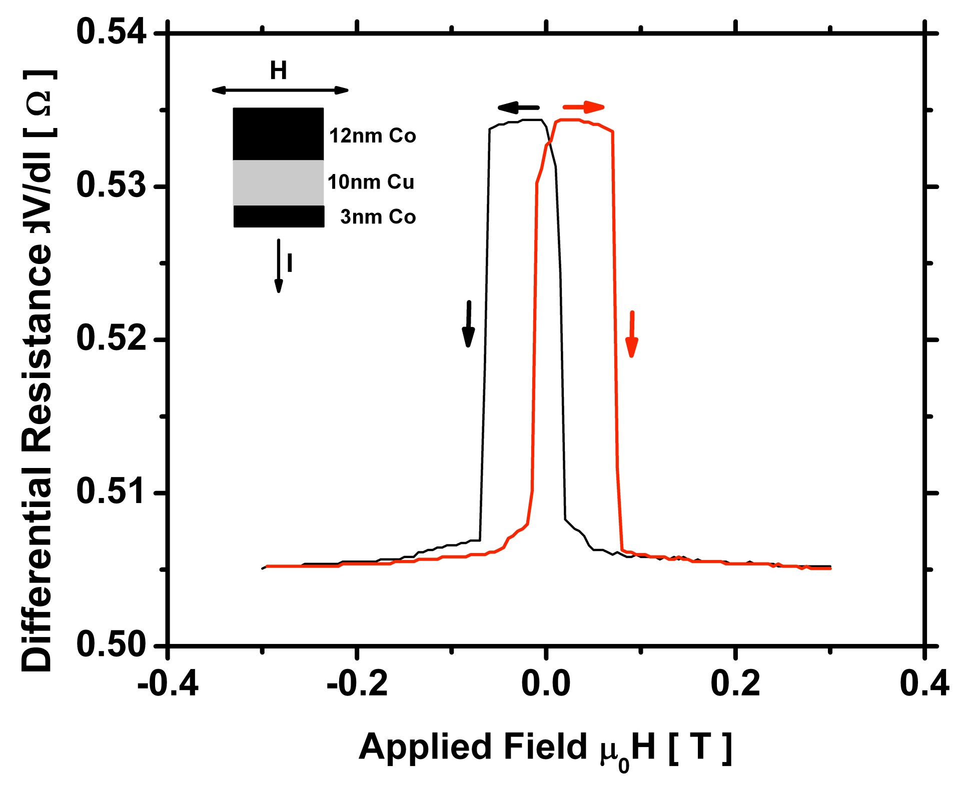


→ ‘Spintronics’= **Spin**+**Tr**ansport+Electr**onics**: control of current using the spin of electrons

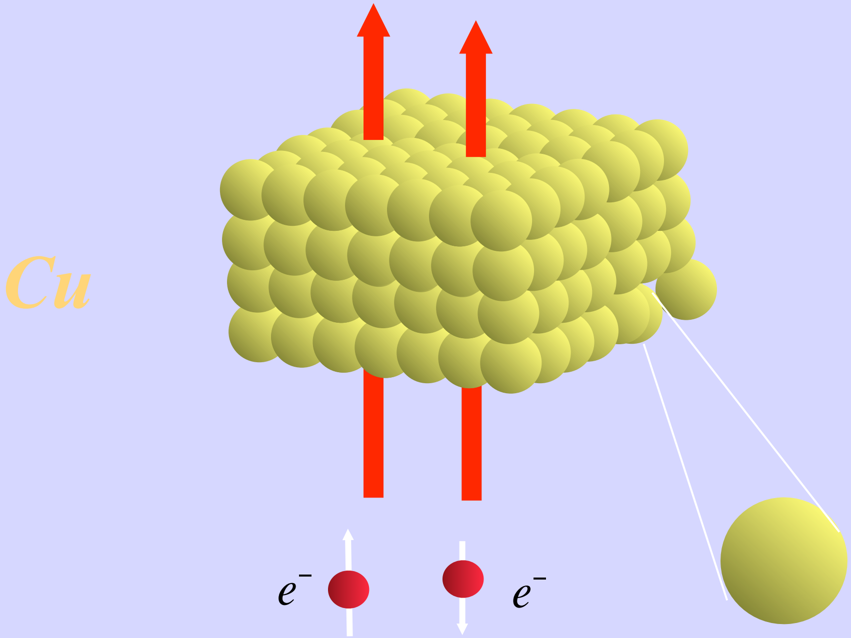
Giant Magnetoresistance (GMR)

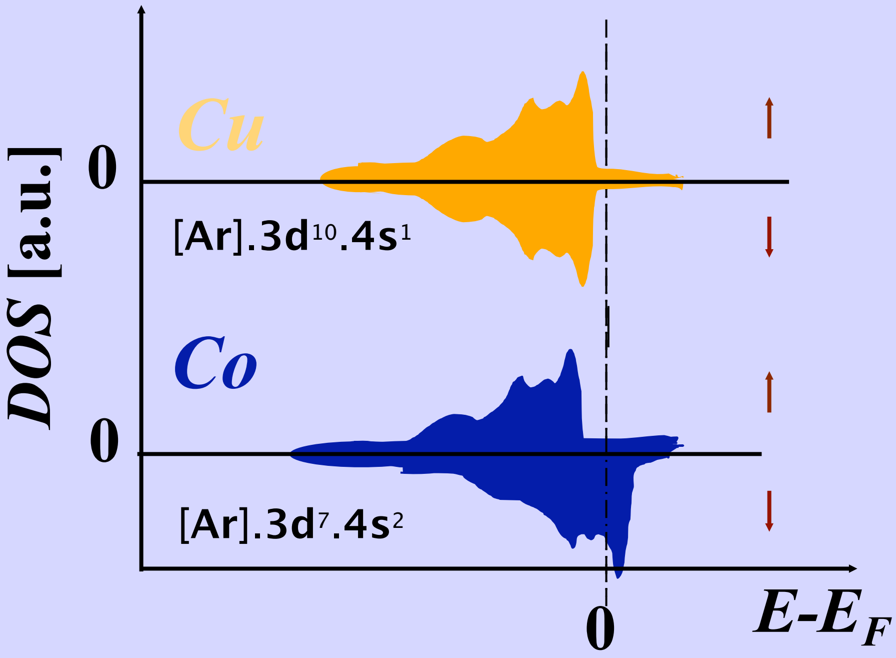


GMR=5.4 % at 4.2 K



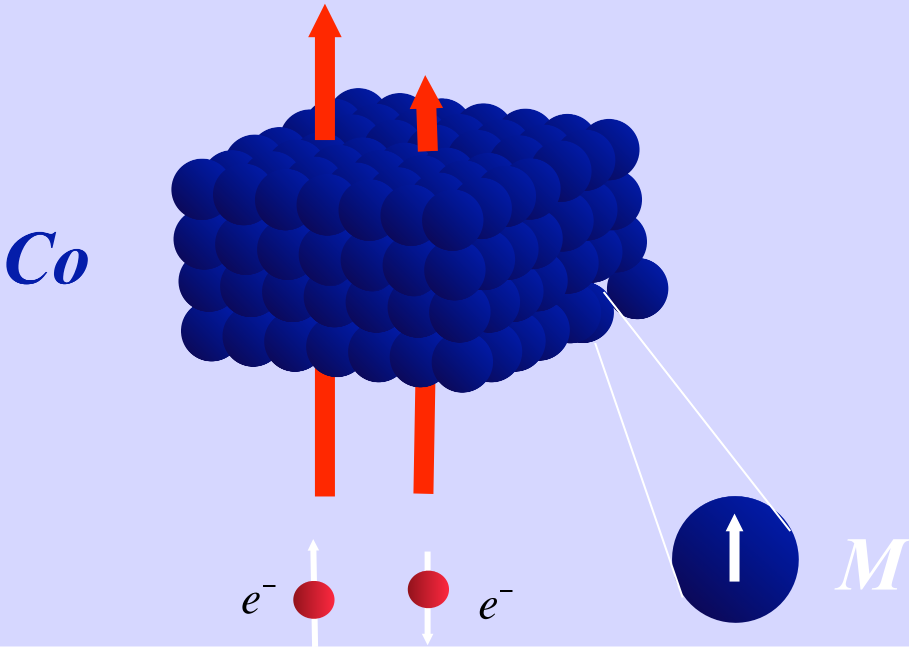
Magnetoresistance (MR) ΔR/R





$$R_{spin\text{-}down} = R_{spin\text{-}up}$$

$MR \cong 0$

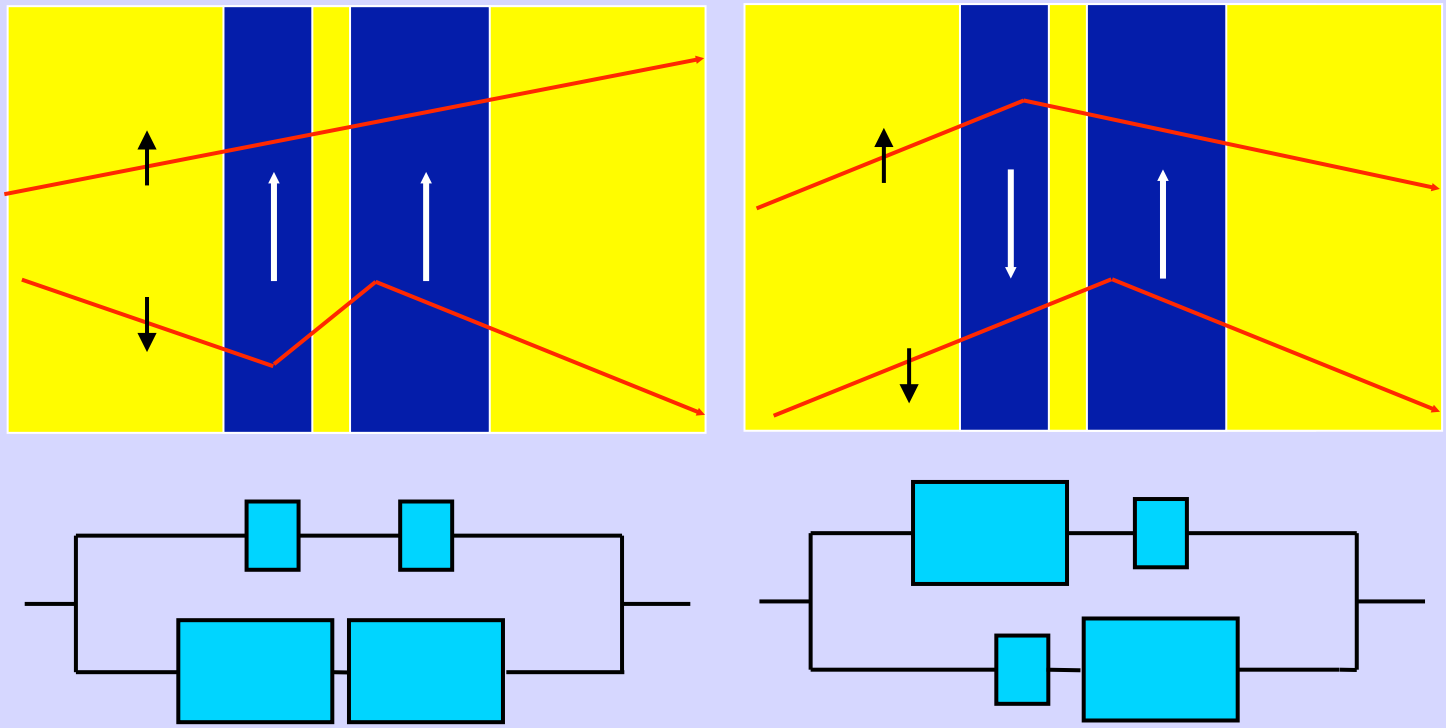


$$R_{spin\text{-}down} > R_{spin\text{-}up}$$

$MR \sim 1\ \%$

The Two Channel Model of GMR

Spin-dependent scattering of conduction electrons & change of scattering rate with an external field.



Resistance $R_{parallel} \ll R_{anti\text{-}parallel}$

$\Delta R/R \sim 1\text{-}10\ \%$

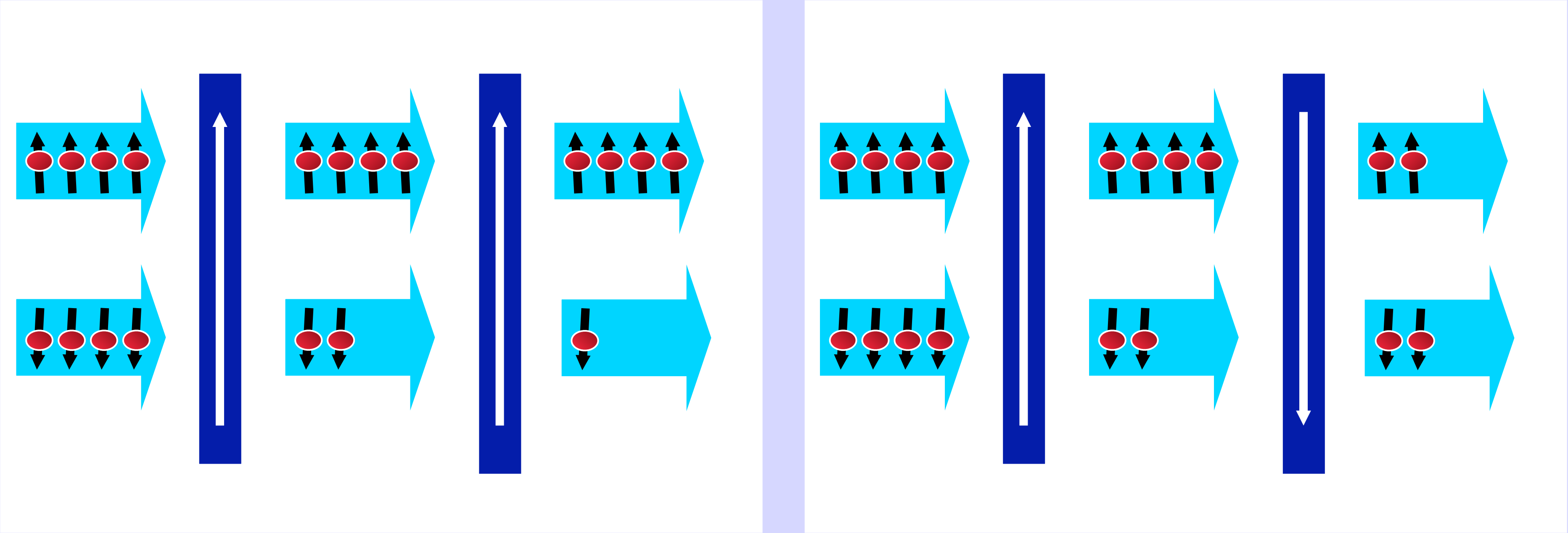
Spin Filtering by Ferromagnetic Layers

Parallel

low resistance state

Antiparallel

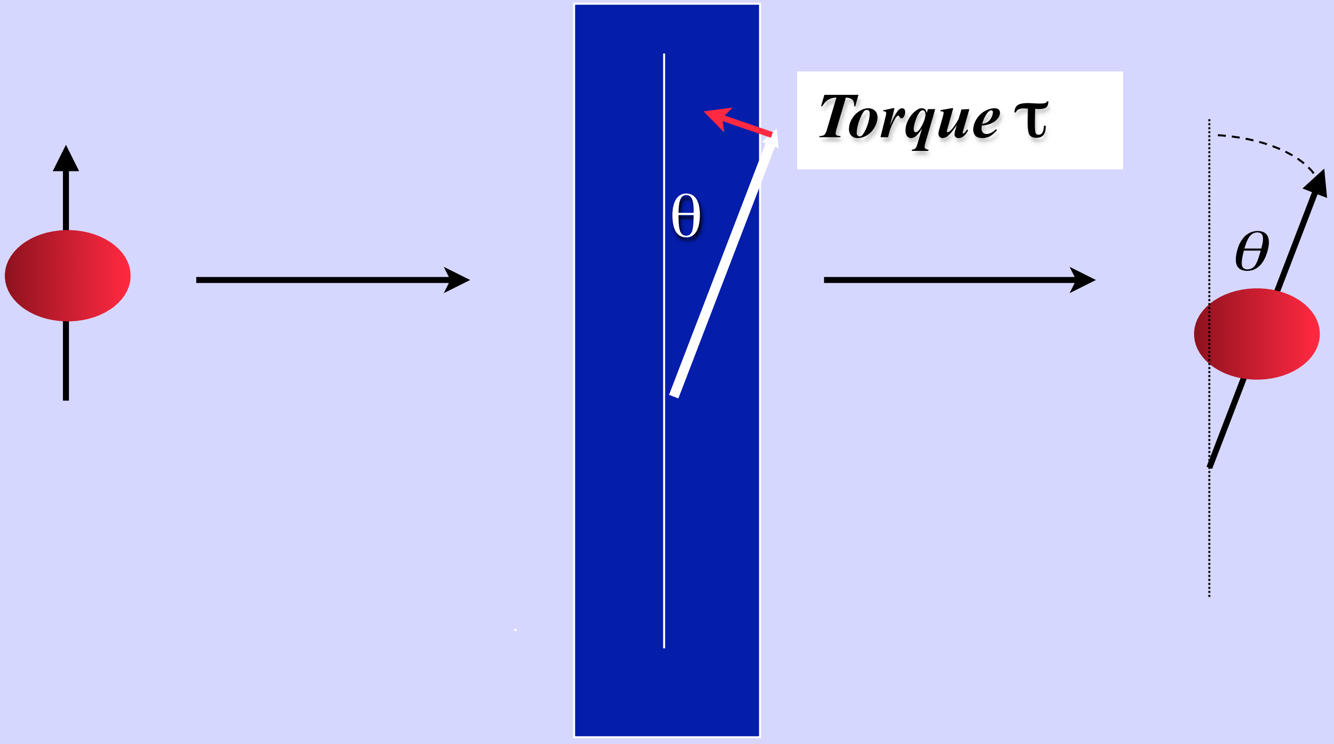
high resistance state



Ferromagnetic layers act spin polarizers and analyzers for an electric current!

Key Idea!!!

If a magnetic layer acts as a spin-filter, then it must also experience a torque.

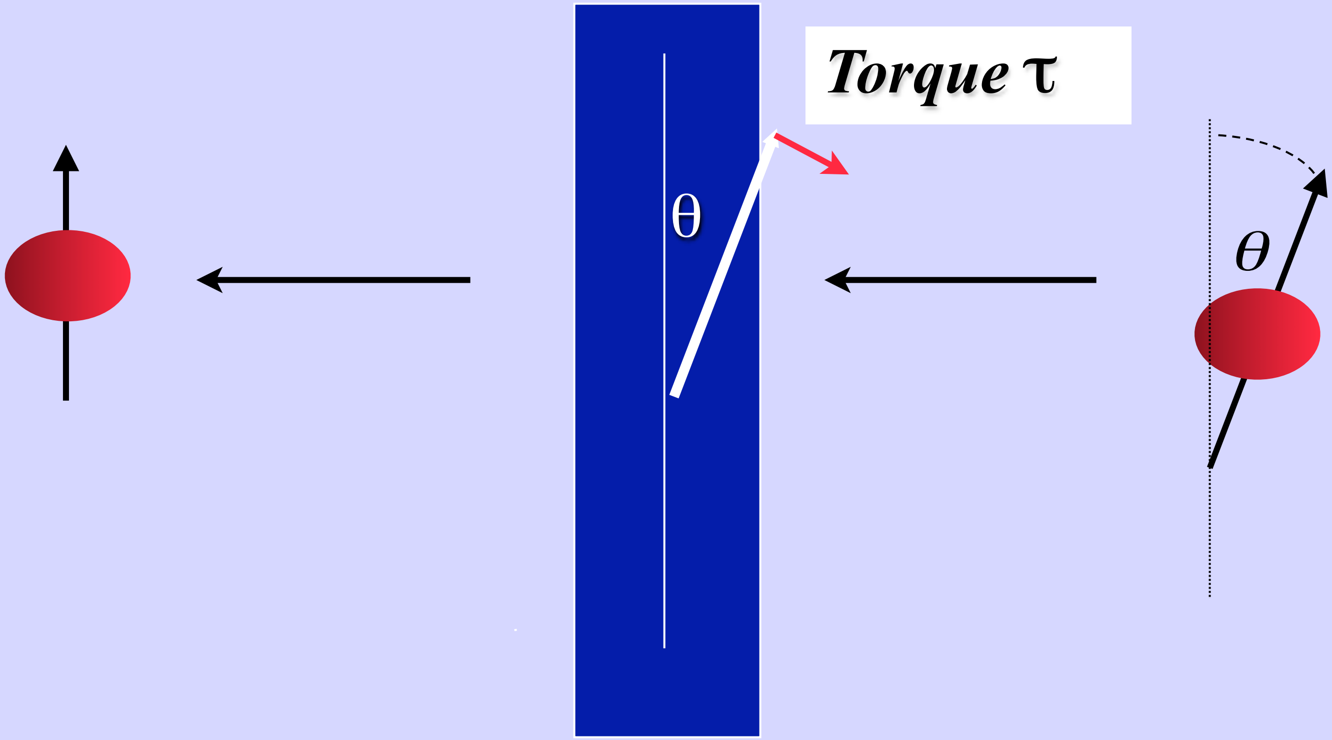


$\tau \propto I \sin\theta$

Slonczewski 1996 and Berger 1996

Seeds of the idea in Slonczewski 1988

Reversing the direction of the current changes the sign of the torque

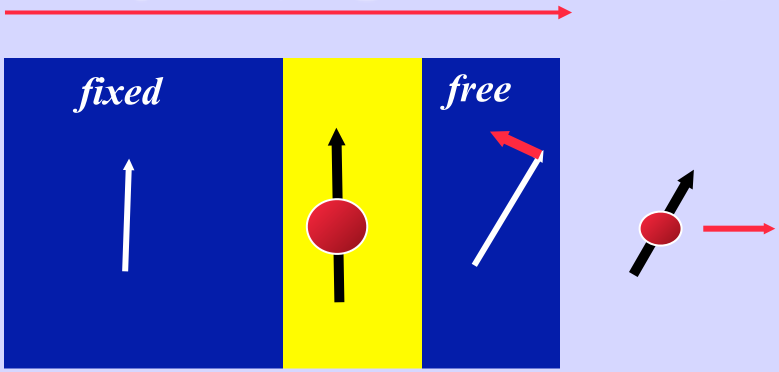


Torque τ

τ ∝ ***I sin***θ

Torques with Two Magnetic Layers

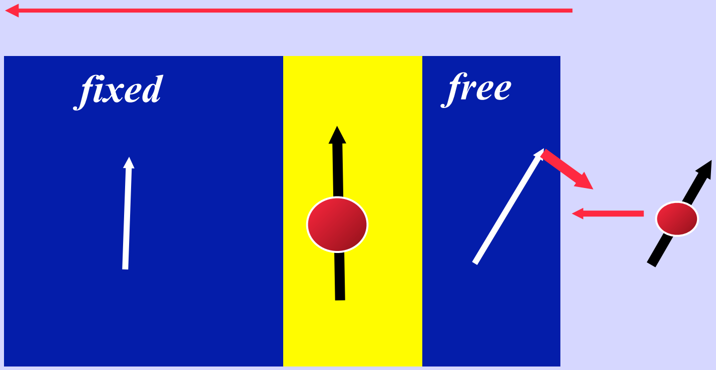
Electron flow (negative current)



Spin currents moving to the right exert a torque favoring parallel alignment

(and a low resistance state)

Electron flow (positive current)



Spin currents moving to the left exert a torque favoring antiparallel alignment

(and a high resistance state)

Spin-transfer is an interface effect:

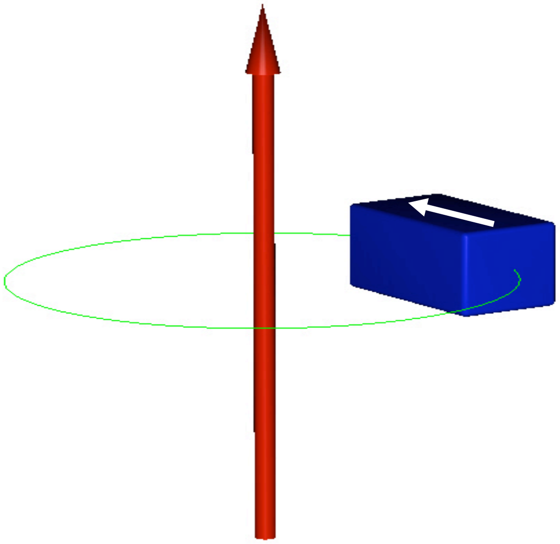
Transverse spin coherence length: $$\lambda_c = \frac{2\pi}{k_{f\uparrow} - k_{f\downarrow}}$$

Stiles and Zangwill, PRB 2002

Spin Transfer – A new method to manipulate nanomagnets

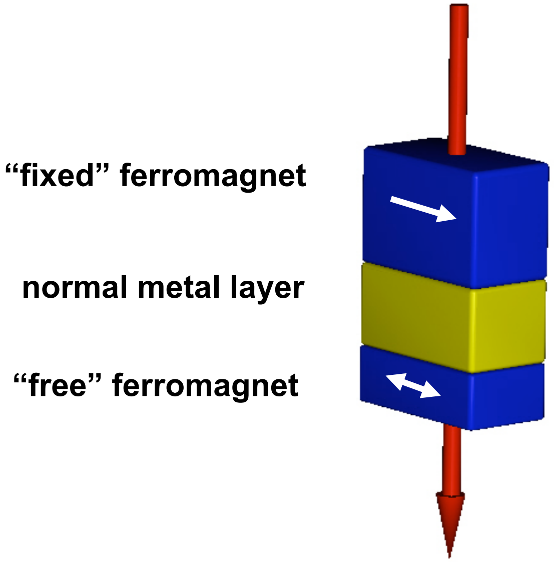
- Spin current induced switching, Coherent dynamic precession.

Charge current



C. Oersted, 1819

Spin current



J.C. Slonczewski, 1996

New Physics:

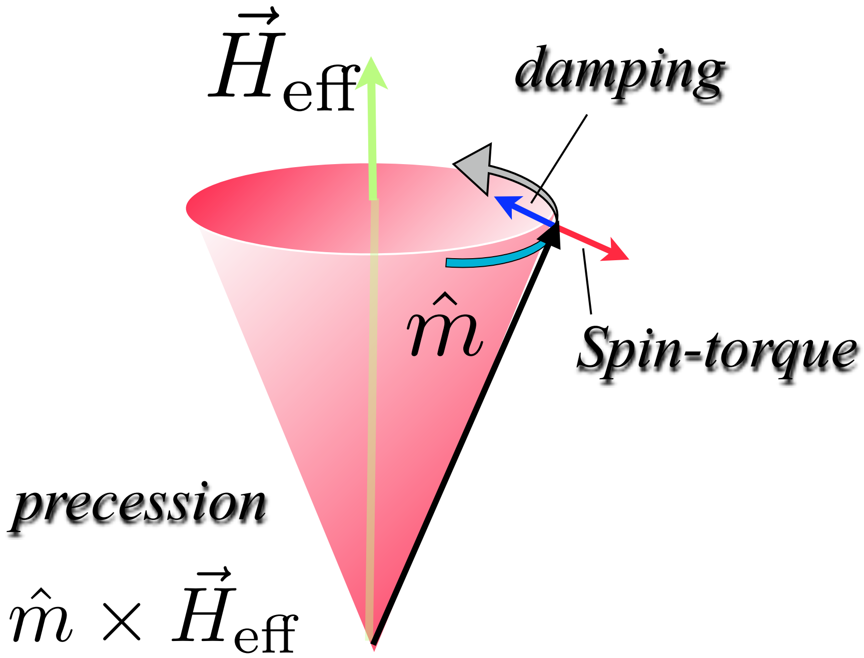
- Insight into spin transport: injection, diffusion and coherence
- Fundamentally new types of magnetic excitations
- Most of the theories are still untested

Dynamics: LLG+spin-torque (LLGS)

$$\frac{d\hat{m}}{dt} = -\gamma \hat{m} \times \vec{H}_{\text{eff}} + \alpha \hat{m} \times \frac{d\hat{m}}{dt} + \gamma a_J \hat{m} \times (\hat{m} \times \hat{m}_P)$$

$$\|$$

$$-[\hat{m}_{\mathsf{p}} - (\hat{m} \cdot \hat{m}_{\mathsf{p}})\hat{m}]$$



$$\boxed{\gamma/2\pi = 28\ \mathsf{GHz/T}}$$

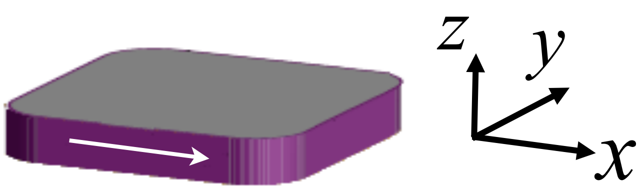
$$a_J = \frac{\hbar P J}{2eM_{\mathsf{s}}t}$$

When the spin-torque exceeds the damping, instabilities can occur!

Also possible: $b_J \hat{m} \times \hat{m}_P$

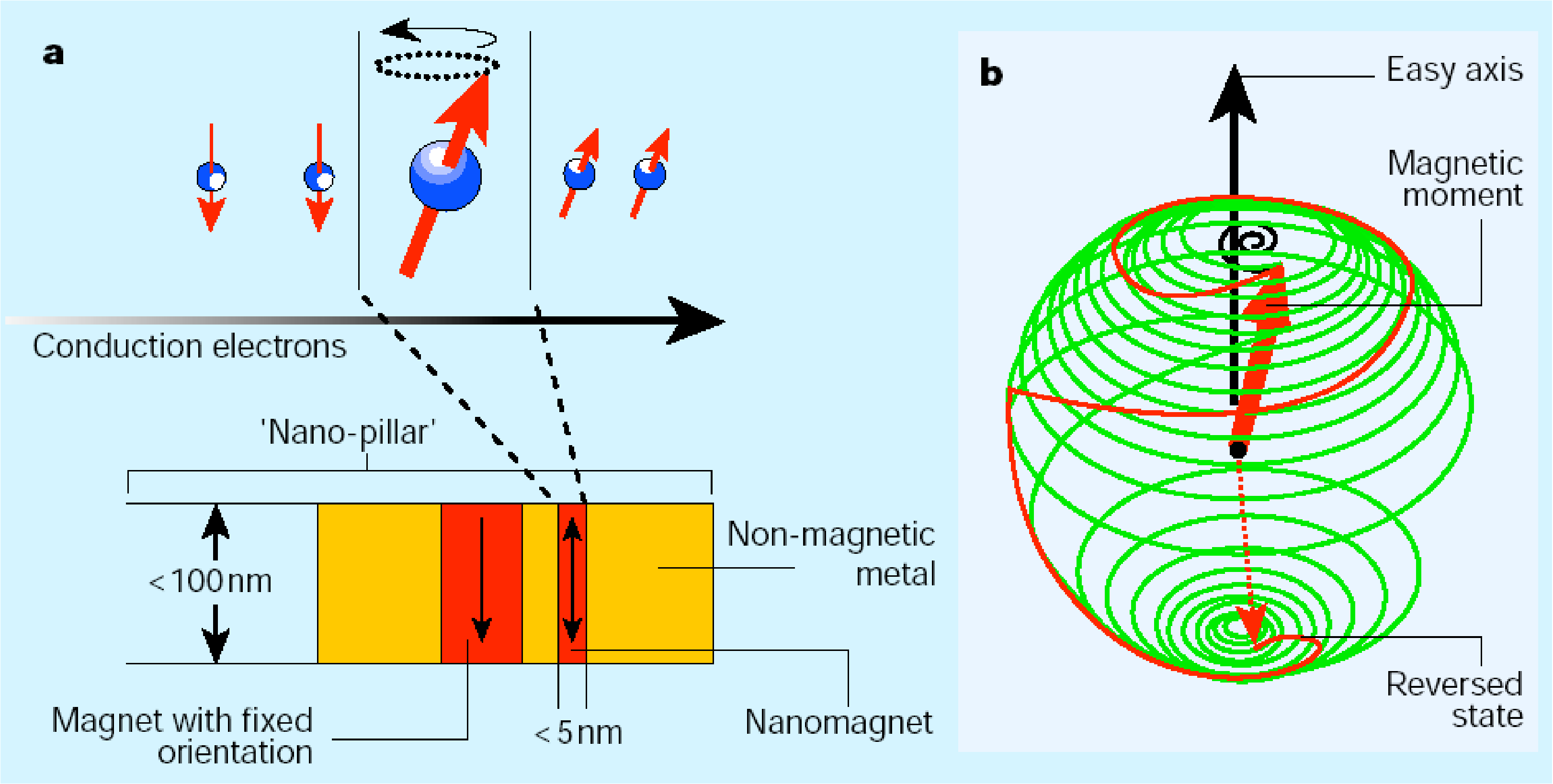
‘Current-Induced Effective field’

Thin film elements



$$\vec{H}_{\text{eff}} = \vec{H} - 4\pi M_{\text{eff}}(\hat{m} \cdot \hat{z})\hat{z} + H_{\mathsf{K}}(\hat{m} \cdot \hat{x})\hat{x}$$

Magnetic Excitations



Spin-current amplifies the motion for currents greater than a critical value:

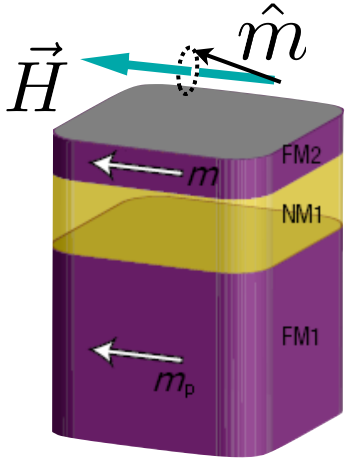
$$J_c = \frac{2e}{\hbar}\frac{\alpha}{P} M_{\mathrm{s}} t (H + H_{\mathrm{K}} + 2\pi M_{\mathrm{eff}})$$

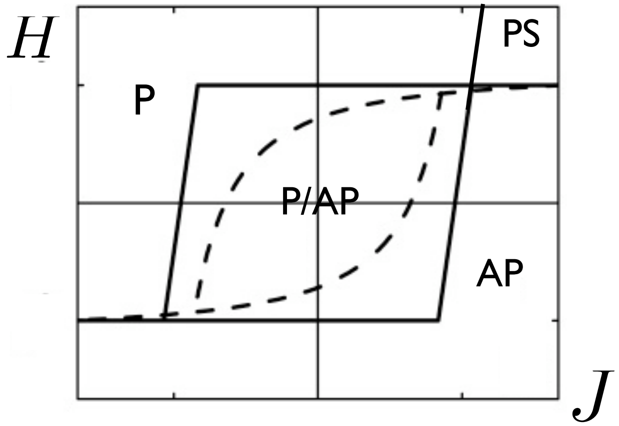
J. Z. Sun, PRB 2000

Stability Diagrams

- In-plane magnetization and field:

$$J_c = \frac{2e}{\hbar}\frac{\alpha}{P} M_{\mathrm{s}} t(H + H_{\mathrm{K}} + 2\pi M_{\mathrm{eff}})$$

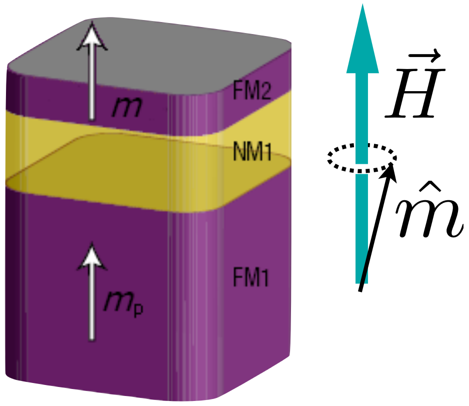


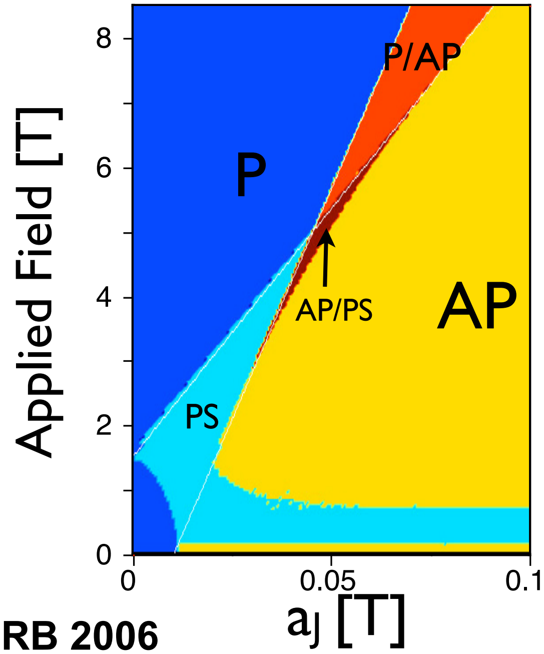


- Perpendicular magnetization and field:

$$J_c = \frac{2e}{\hbar}\frac{\alpha}{P} M_s t(H - 4\pi M_{\mathrm{eff}})$$

$H > 4\pi M_{\mathrm{eff}}$ $H_K \ll 4\pi M_{\mathrm{eff}}$

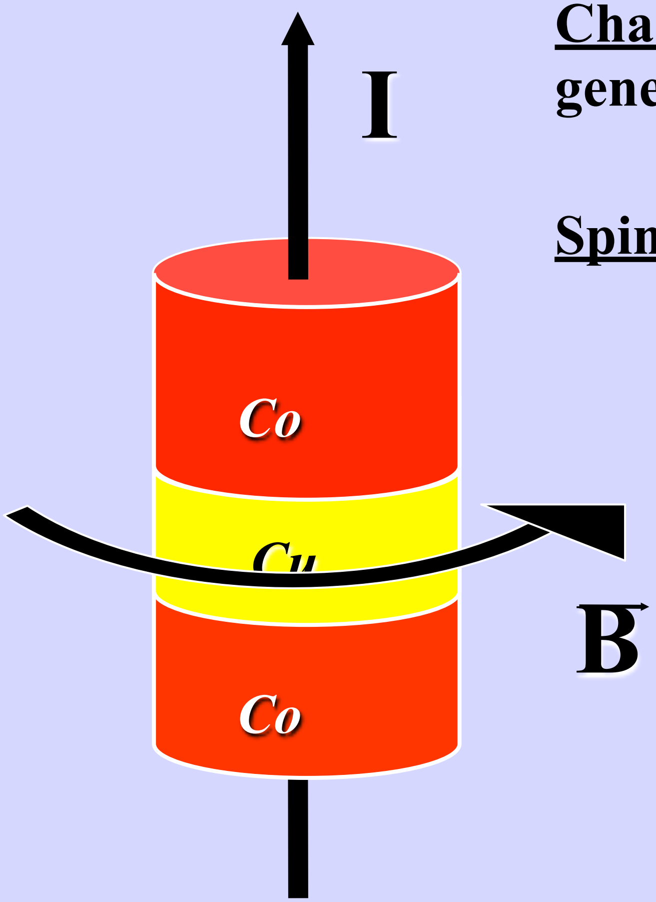




J. Z. Sun, PRB 2000; Bertotti et al., PRL 2005, Chen et al PRB 2006

Charge versus Spin Currents

In both cases there will be a current threshold at which the magnet will respond

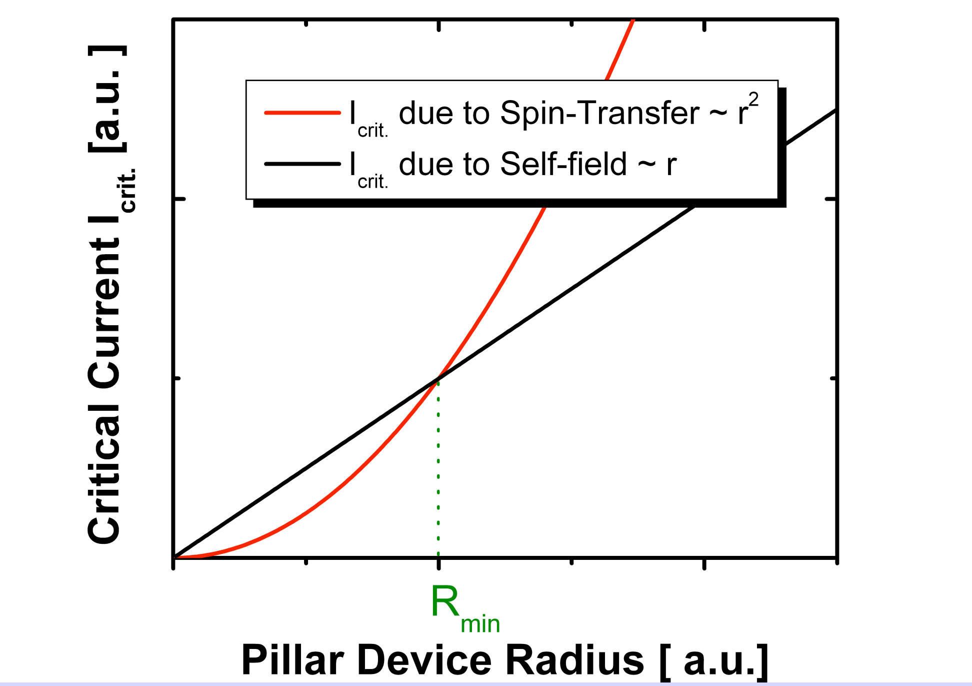


Charge current: magnet responds to the magnetic field generated:

$$B_c = \frac{\mu_o I_c}{2\pi r} \longrightarrow I_c \sim r$$

Spin Current: there is a critical current density

$$J_c = \frac{I_c}{\pi r^2} \longrightarrow I_c \sim r^2$$

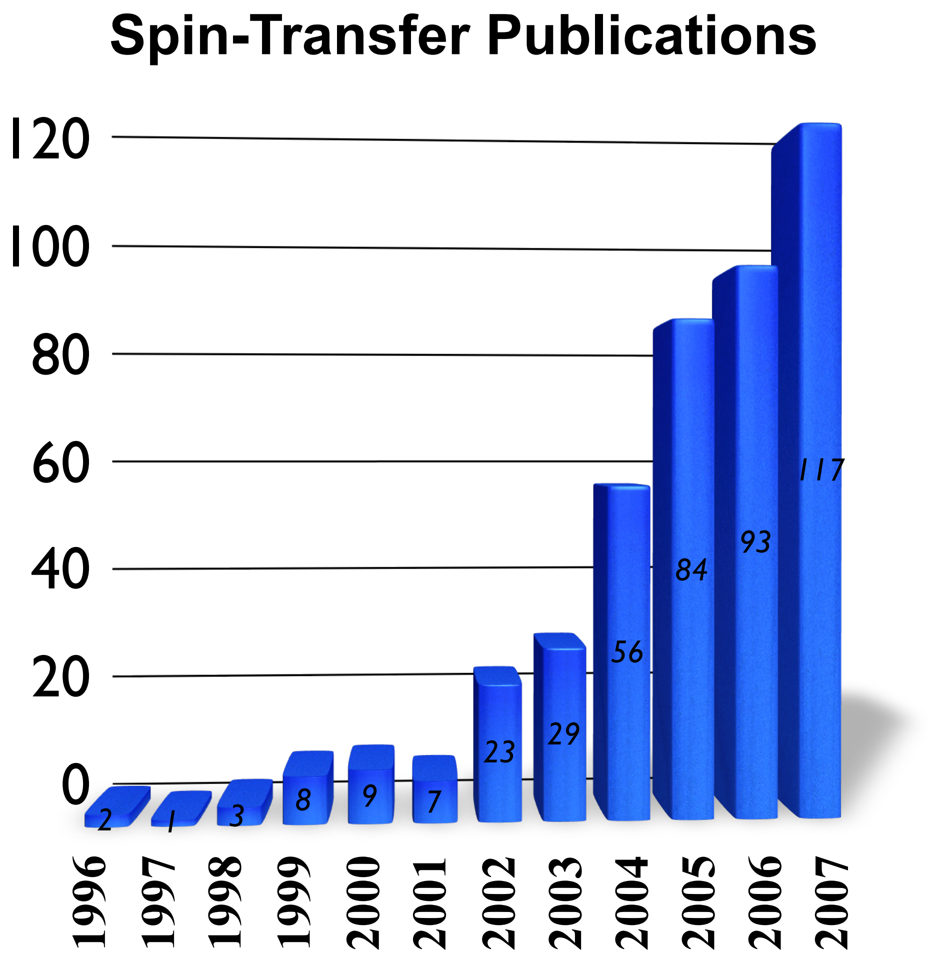


In devices with radii less than R_{min}:

The critical current due to the spin-current will be less than that due to the charge current

$R_{min} \approx 250$ nm for Co

Experiments on Spin-Transfer



Geometries

- *Point contacts*
- *Nanopillars*
- *Nanowires*
- *Nanorings*

Structures

- *Spin-values*
- *Multilayers*
- *Tunnel junctions*
- *Single magnetic layers*

Materials

- *Metallic ferromagnets*
- *Magnetic semiconductors*
- *Metallic antiferromagnets*
- *Oxide ferromagnets*

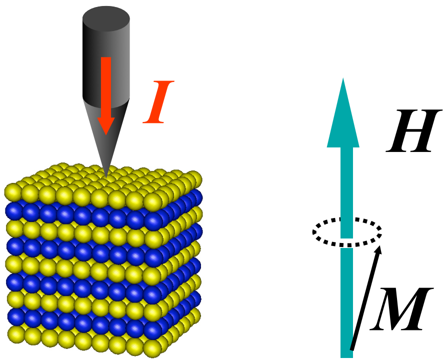
Phenomena

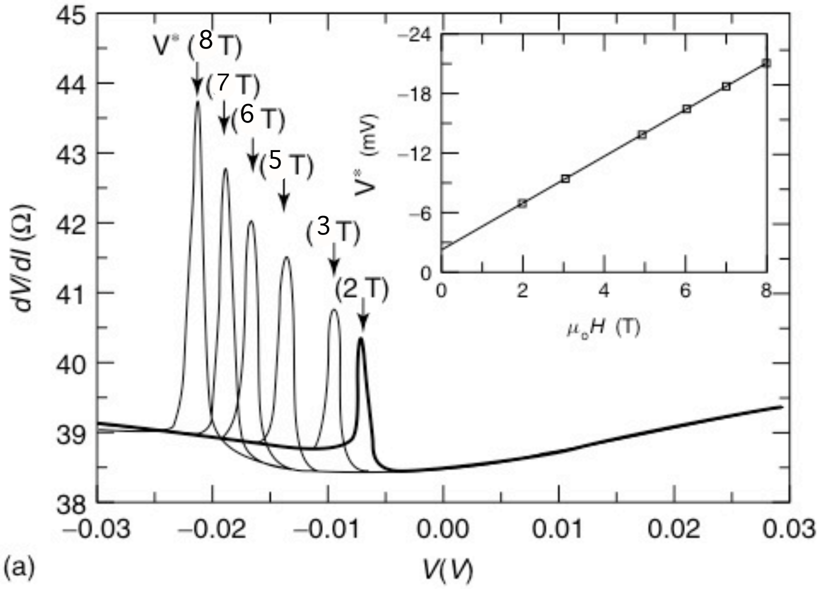
- *Current induced switching & precession*
- *Current induced domain wall motion*

Experiments on Spin-Transfer

Point-contacts

➔ Uniform precession of M



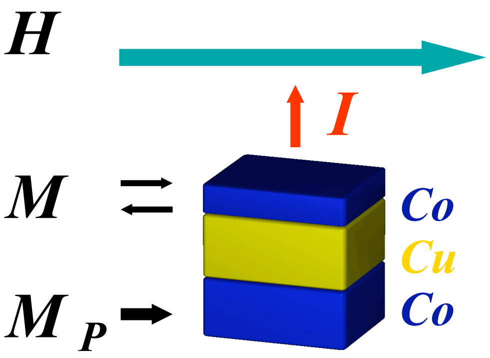


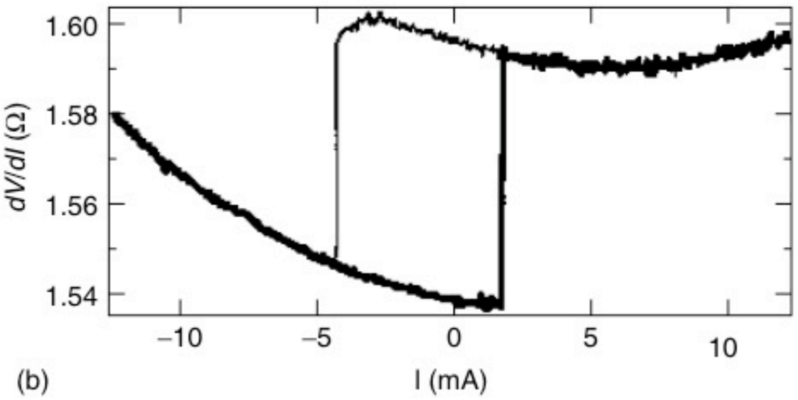
M. Tsoi et al. ; E.B.Myers et al.; Y. Ji et al., …

1998

Pillars junctions

➔ Hysteretic Switching of M





J. A. Katine et al. ; J. Grollier et al.;…

2000

VOLUME 91, NUMBER 6 PHYSICAL REVIEW LETTERS week ending 8 AUGUST 2003

Current-Induced Magnetization Reversal in High Magnetic Fields in Co/Cu/Co Nanopillars

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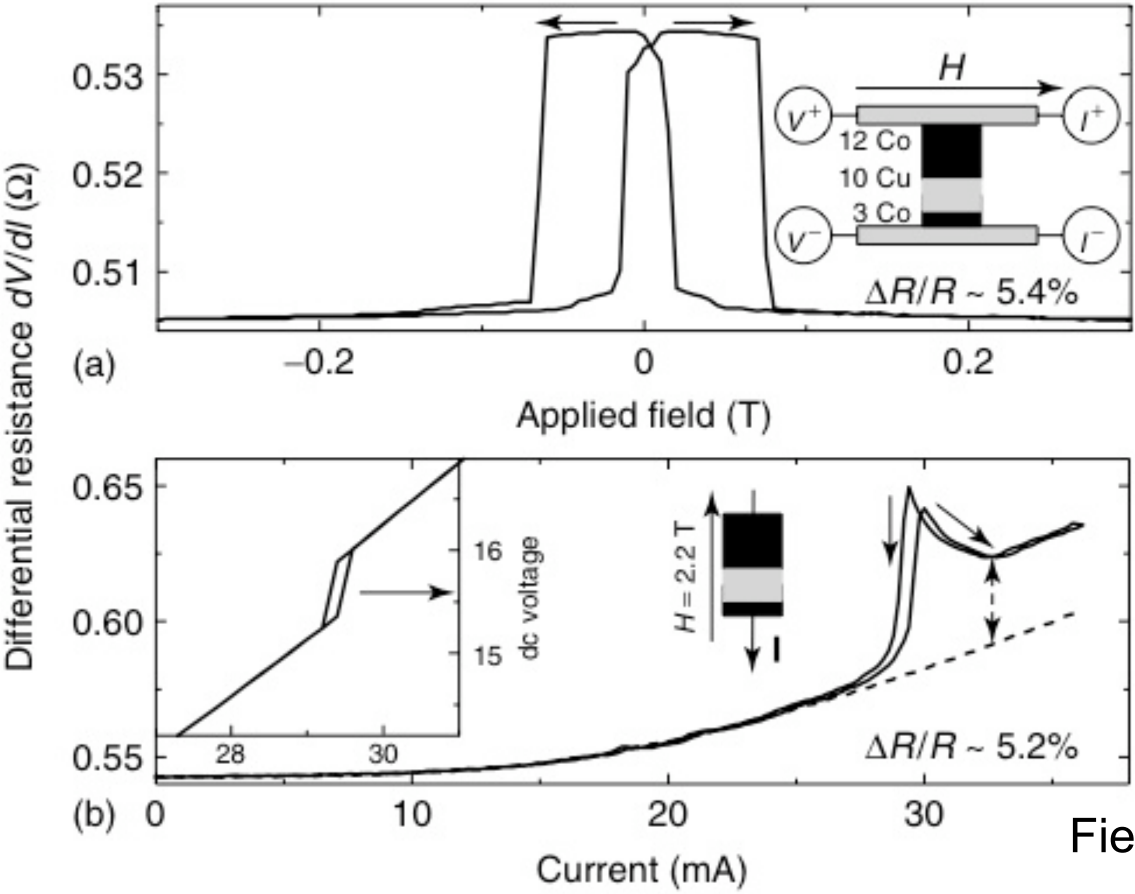
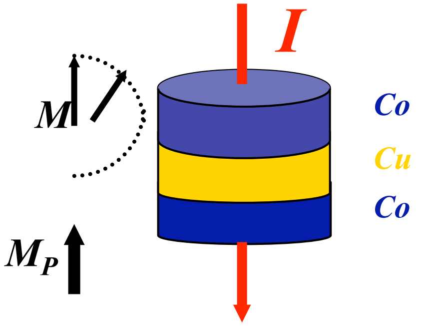
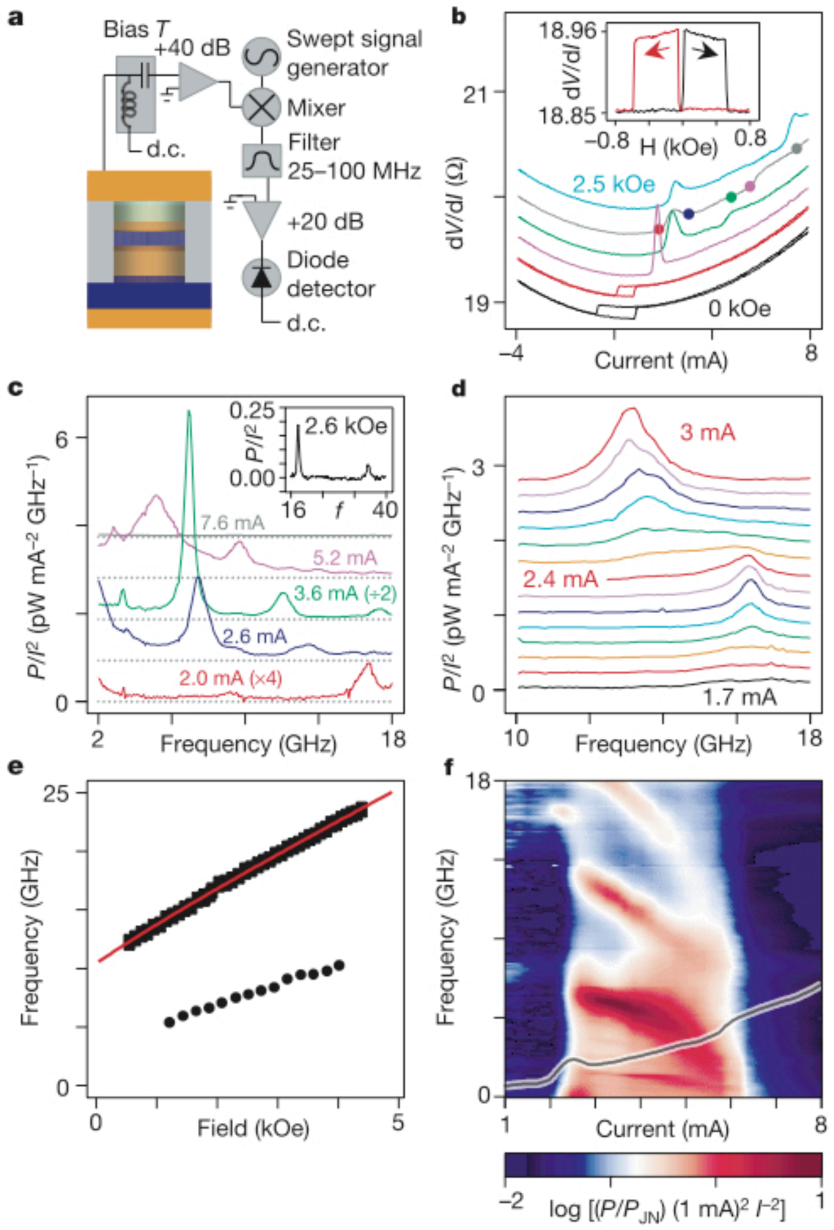
(Received 17 December 2002; published 8 August 2003)





Field applied perpendicular to the plane of the film

Microwave Oscillations of a Nanomagnet Driven by a Spin-Polarized Current



Kiselev et al., Nature 2003

Microwave Oscillations in Point Contact Geometries

Rippard et al. PRL 2004

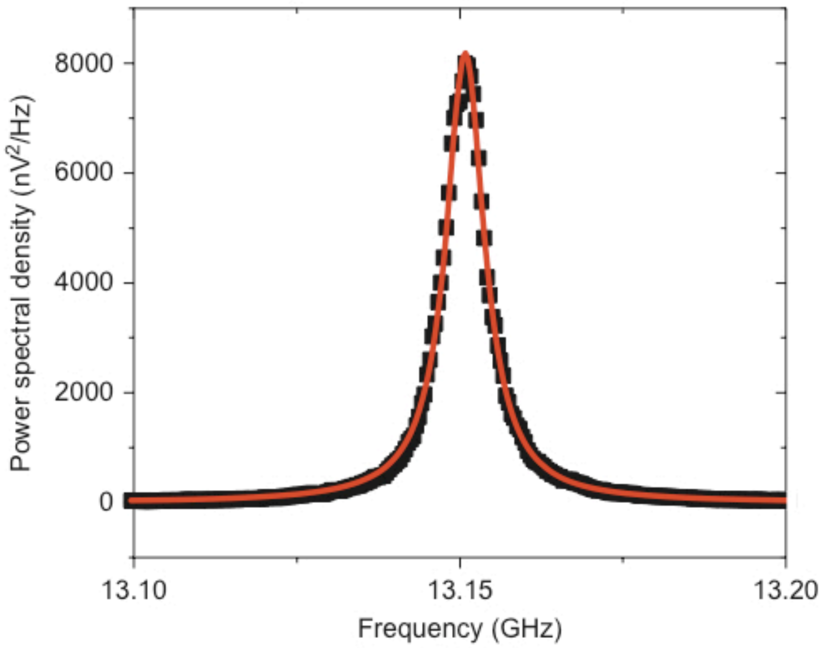


Fig. 1. Spectrum of the emitted microwave signal for a spin torque nano-oscillator using a point contact structure.

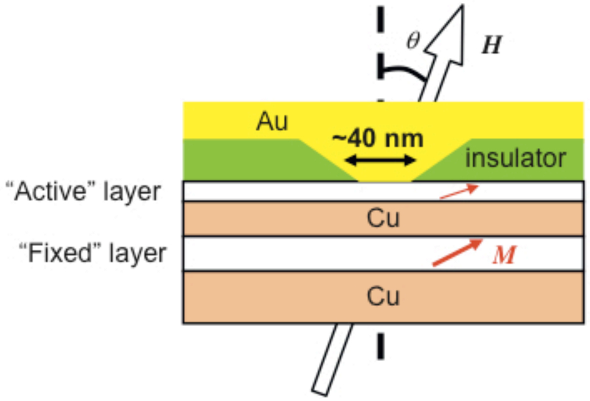
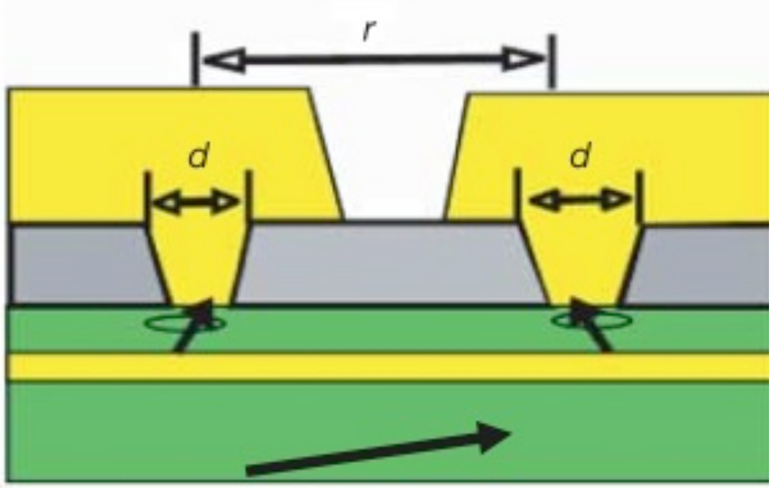
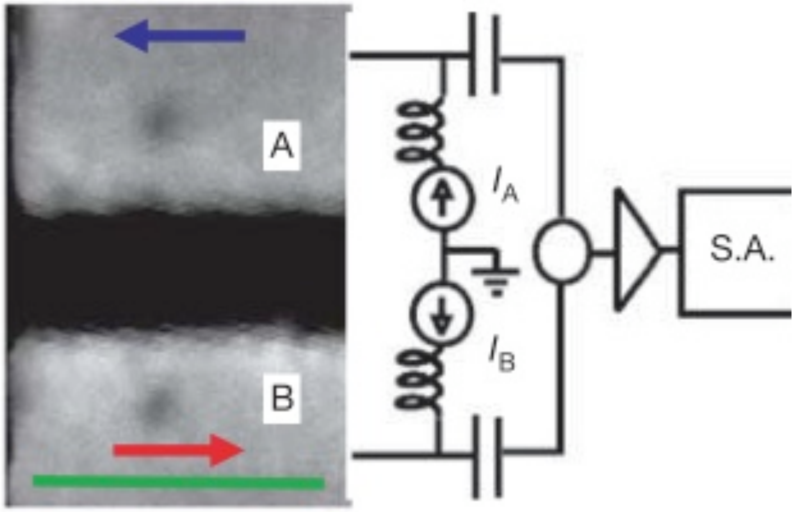


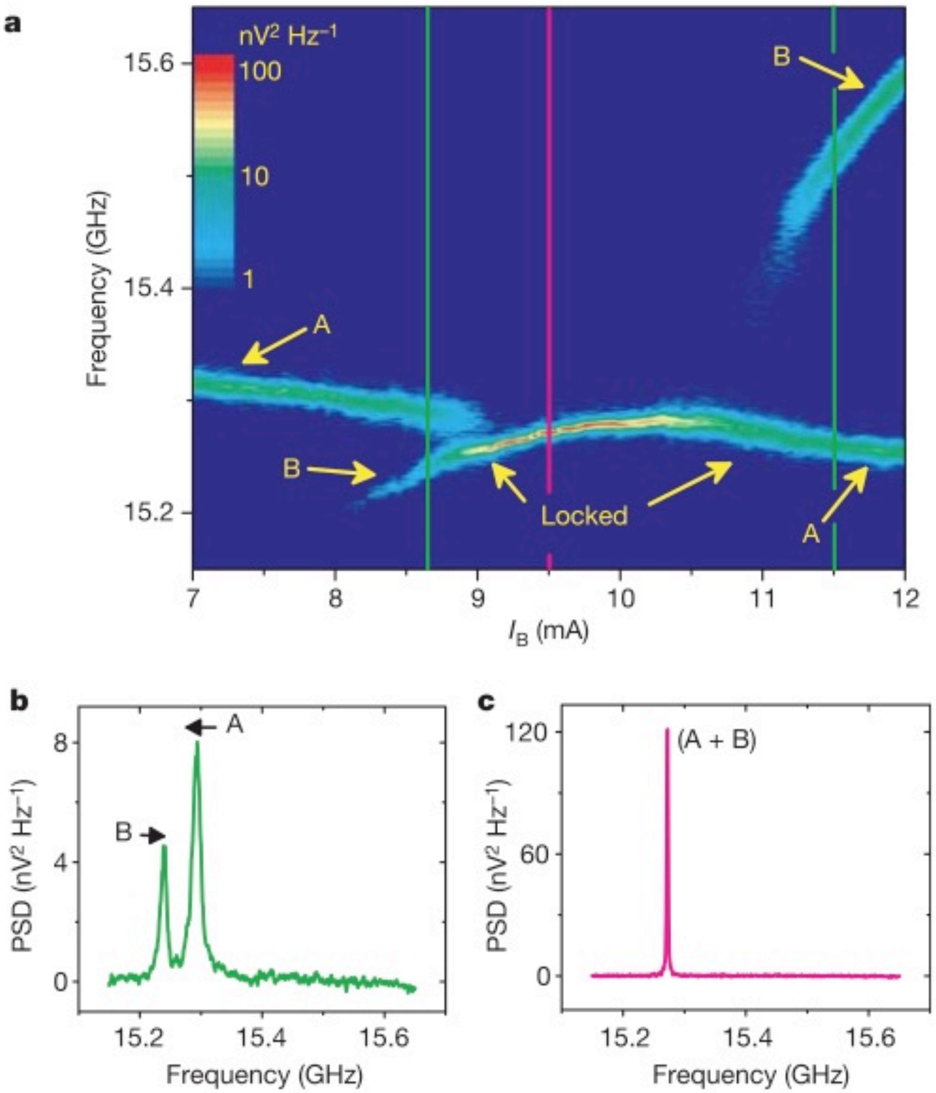
Fig. 2. Cross-sectional sketch of a spin torque nano-oscillator. The two magnetic layers are labeled "active" and "fixed" by virtue of the differing thickness and magnetic moment of the two layers; a thin, low-moment layer has a lower threshold current for excitation of spin-torque-induced dynamics. The trilayer structure below the point contact is of large lateral extent, on the order of tens of micrometers. A magnetic field H is usually applied at some angle θ when studying gigahertz excitations in such devices.

Theory on linewidth: Slavin 2007

Phase Locking of Two Spin-Torque Oscillators



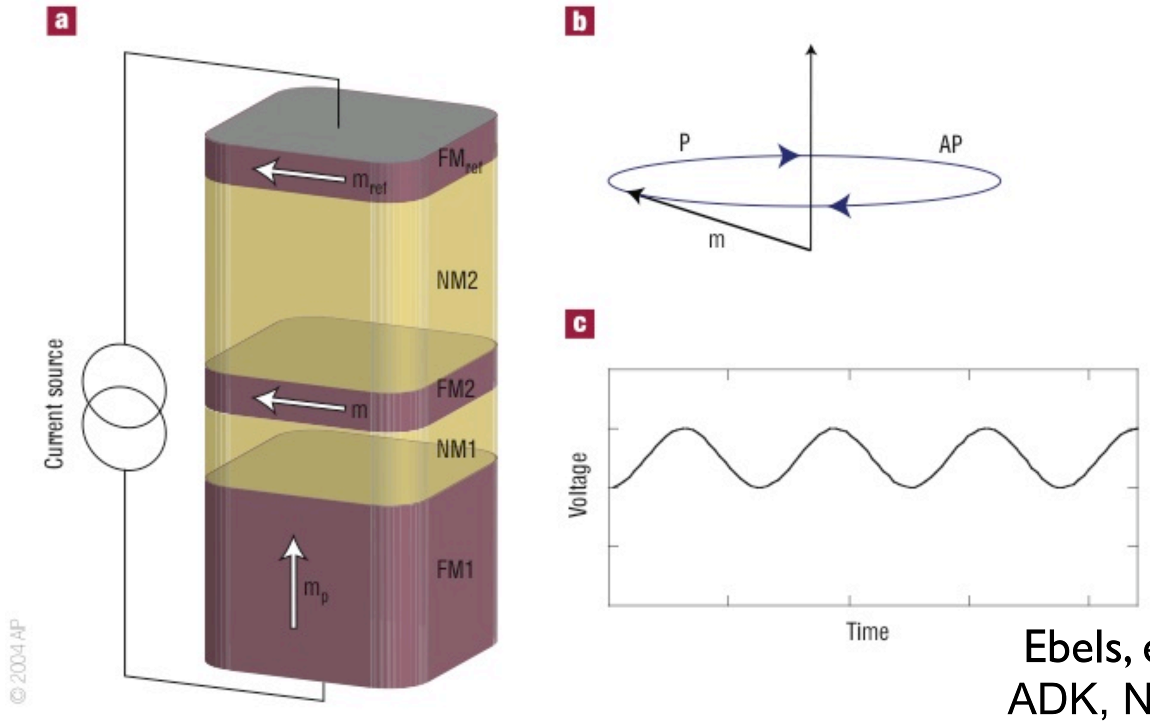




Kaka et al., Nature 2005 and Mancoff et al. Nature 2005

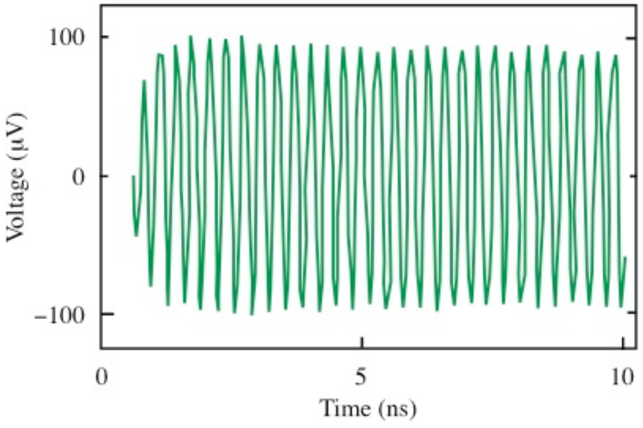
Spin-Transfer Induced Precession

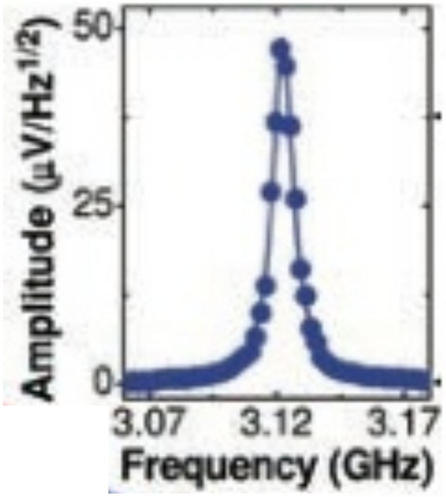
A nanomagnet oscillator



Ebels, et al., Nat. Mat (2007)
ADK, Nature Materials (2007)

Experiments: Kiselev et al., Nature (2003); Krivorotov et al., Science 2005.





VOLUME 92, NUMBER 8 PHYSICAL REVIEW LETTERS week ending 27 FEBRUARY 2004

Time-Resolved Reversal of Spin-Transfer Switching in a Nanomagnet

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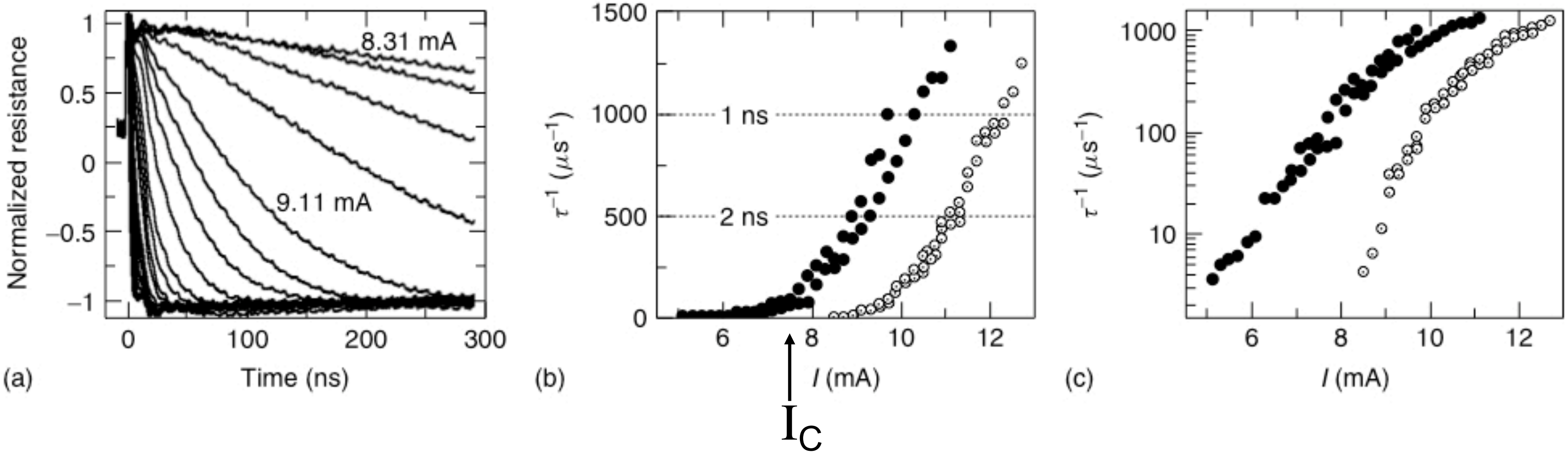


Thermal fluctuations and ST:
- Sun, 2003
- Li and Zhang, 2004
- Visscher and Apalkov 2005

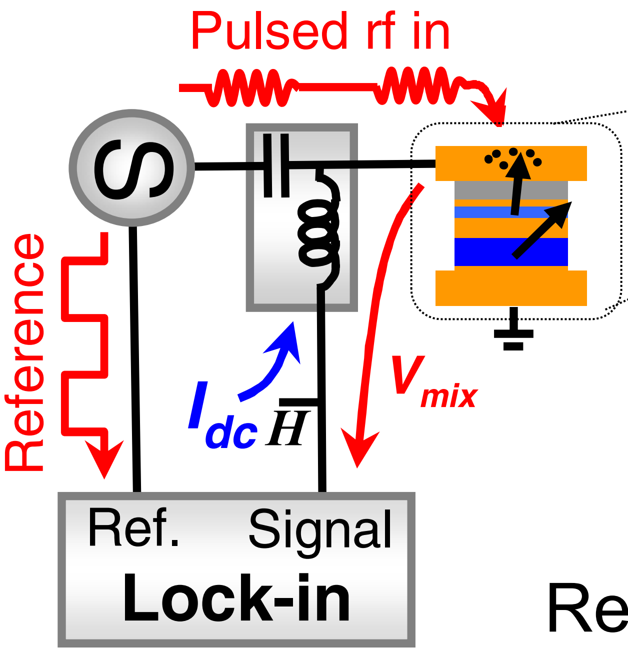
$$\langle\tau\rangle^{-1} \approx \begin{cases} \tau_0^{-1}\exp\left[-\frac{\Delta U}{k_{\mathrm{B}} T}(1-h)^2\left(1-\frac{I}{I_{\mathrm{c}}}\right)\right], \\ \qquad \text{when} \quad (I \ll I_{\mathrm{c}}) \\ \left(\frac{\eta\mu_{\mathrm{B}}}{me}\right)\left[\frac{\ln(4\pi^2 h_{\mathrm{p}})}{\pi\ln(\Delta U/k_{\mathrm{B}} T)}\sqrt{\frac{1+h}{h_{\mathrm{p}}}}\right](I-I_{\mathrm{c}}) \\ \qquad \text{when} \quad (I \gg I_{\mathrm{c}}) \end{cases}$$

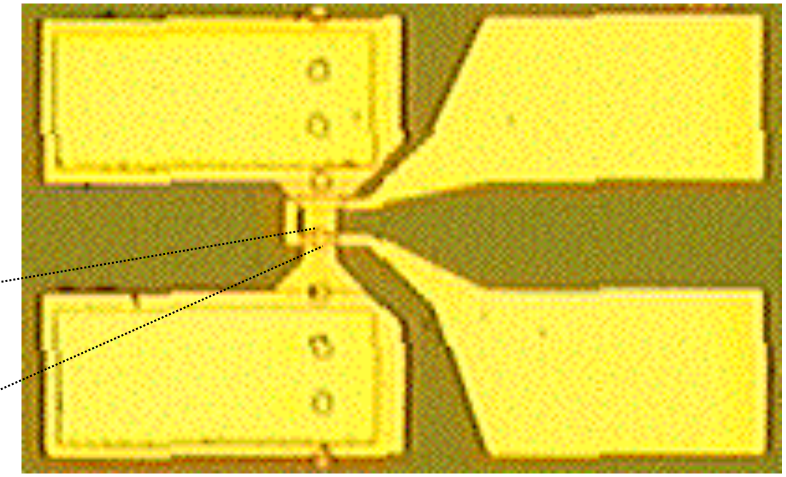
More recent experiments: Krivorotov et al., Science 2005

Spin-Transfer Driven FMR

Measurement Principle

- **Tulapurkar et al., Nature 2005**
- **Sankey et al., PRL 2006**





$$I(t) = I_o sin(\omega t)$$

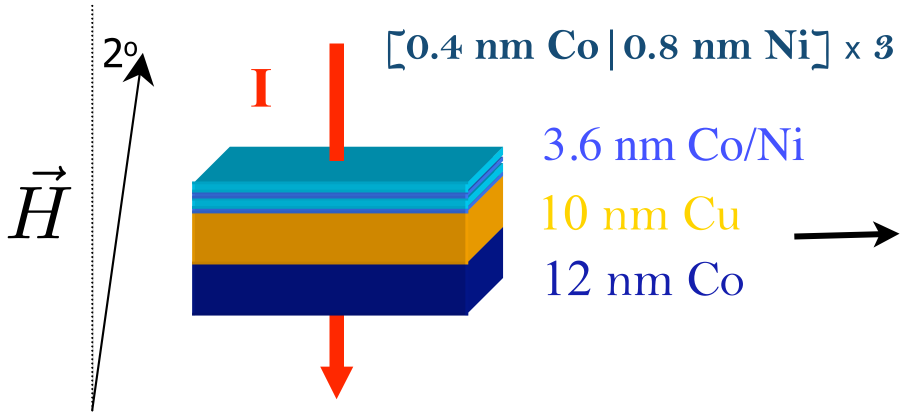
$$R(t) = \frac{\Delta R_o}{2}(1 - \hat{m}(t) \cdot \hat{m}_{\mathrm{p}})$$

Resonance:

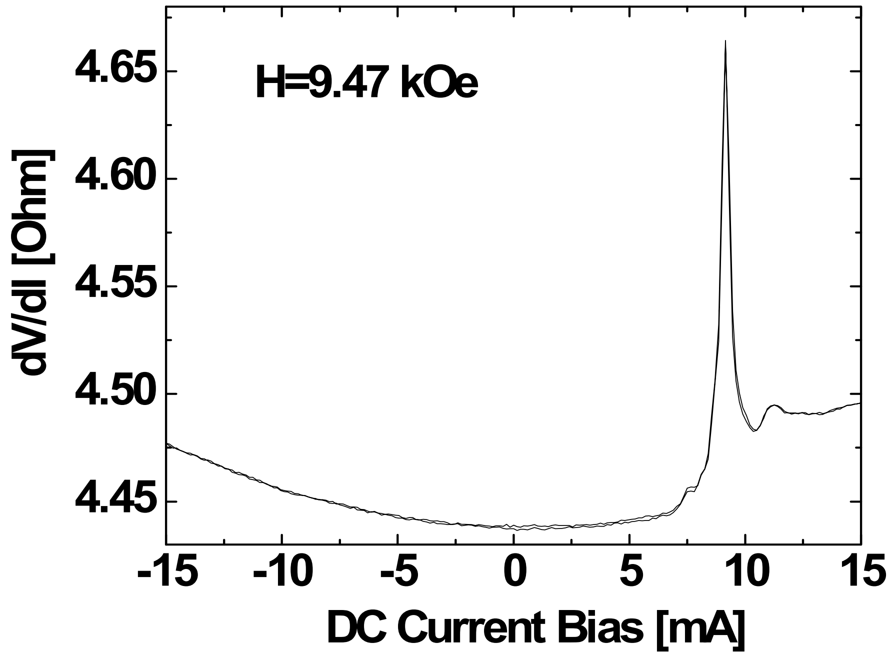
$$\boxed{\begin{gathered} V_{\mathrm{mix}}(f) \propto \frac{I_{\mathrm{rf}}^2/\Delta_0}{1 + [(f - f_0)/\Delta_0]^2} \\ \Delta_0 = \alpha f_0 \end{gathered}}$$

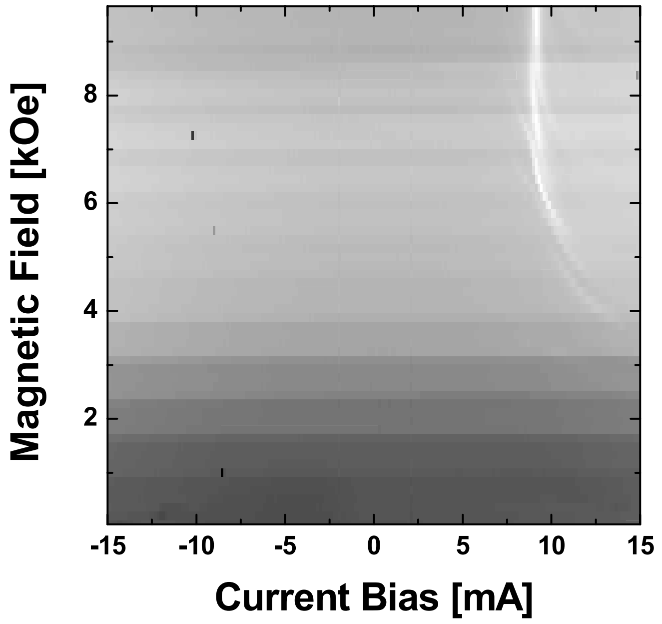
- Determine anisotropies and damping of nanometer scale magnetic elements
- Characterize the spin-transfer interaction near equilibrium
- Excite highly non-linear magnetization dynamics

Nanopillar Characteristics: DC



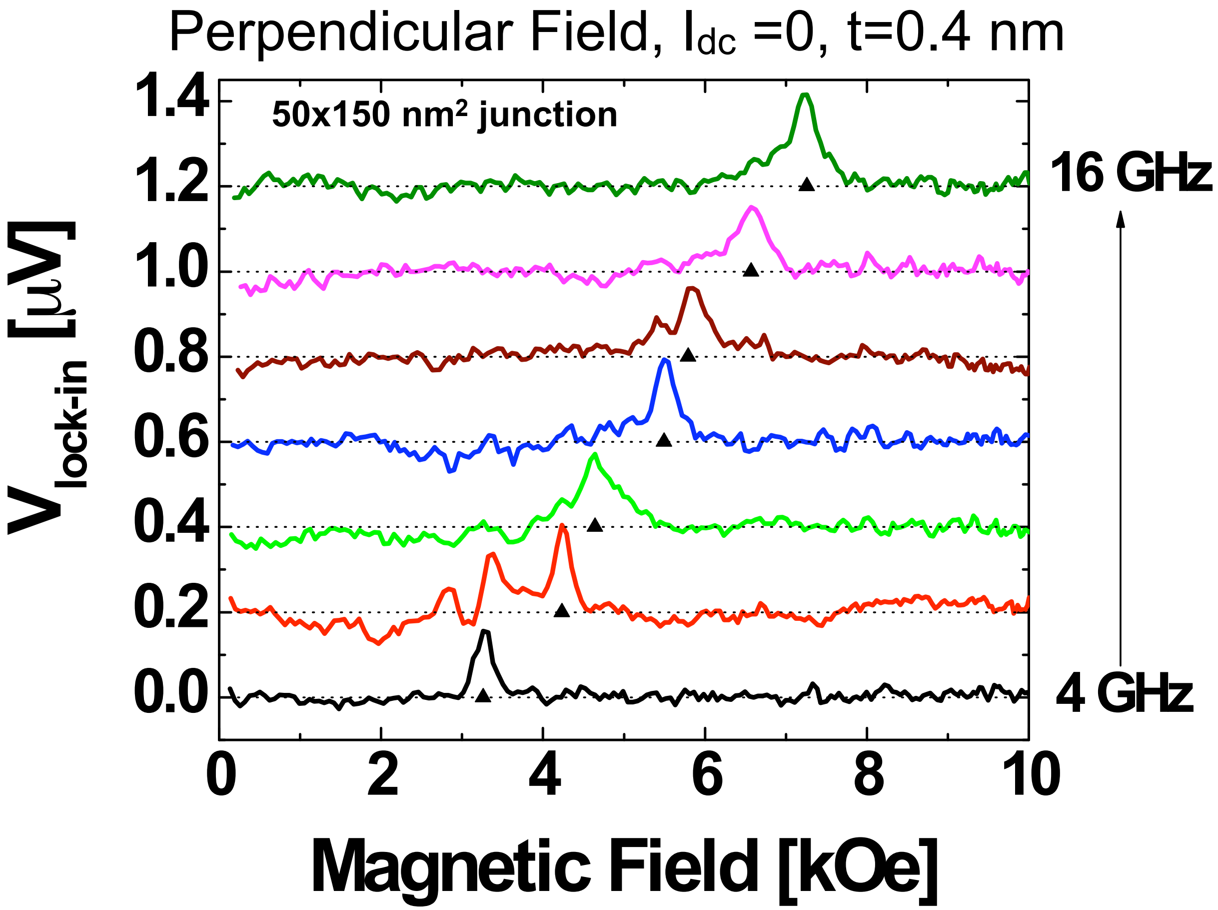
Perpendicular applied field





- **High field dV/dI shows current induced excitations of free layer at ~8 mA**

Spin-Transfer Driven FMR

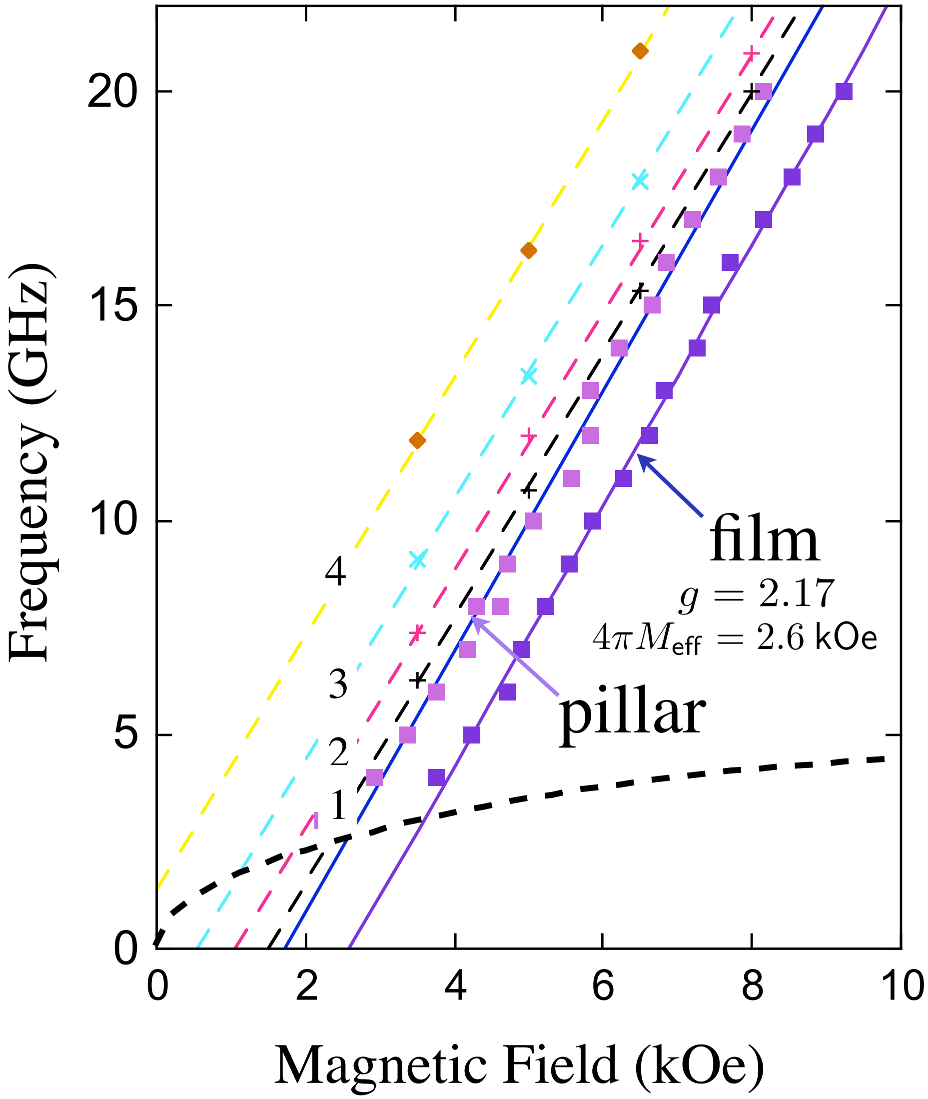


- 20 nV/Hz$^{1/2}$ noise level
- ~2° precession
- rf from 4 to 16 GHz with 2 GHz steps
- Adjacent curves offset by 0.2 μV each

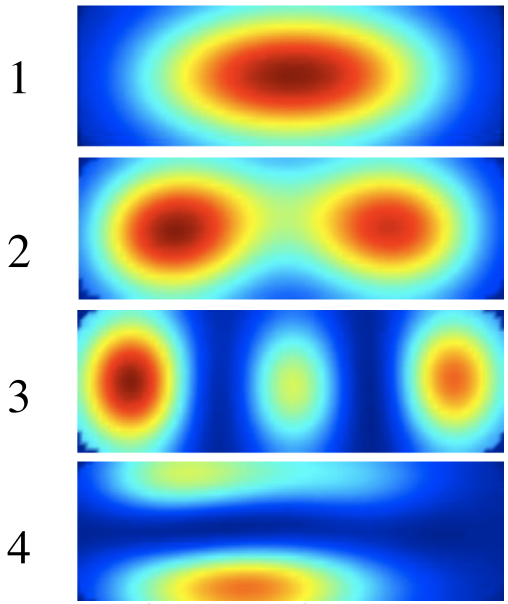
Mode that disperses to higher field with increasing frequency:

- Mirrors the FMR mode on a film of the same composition
- Enables determination of the easy-plane anisotropy and g-factor of an individual nanomagnet

Mode Dispersion: Comparison of Films and Nanopillars



Normal modes



Dipole-exchange spin-wave modes

(Kalinilos and Slavin 1986)

+

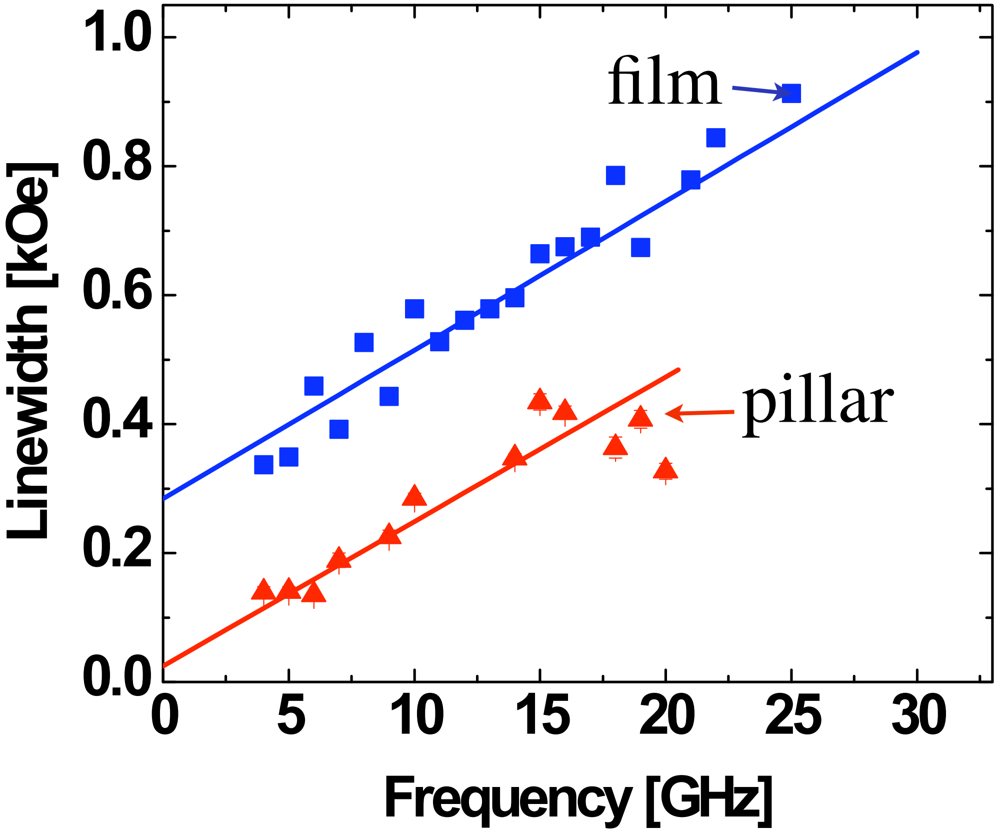
Dipole fields

Co thick layer ~500 Oe

- The resonance frequency is consistent with excitation of the lowest lying mode of the element--shifted from the uniform FMR mode due to finite size effects and dipole fields from other magnetic layers

W. Chen et al., J. Appl. Phys. **103**, 07A502 (2008)

Linewidth & Damping

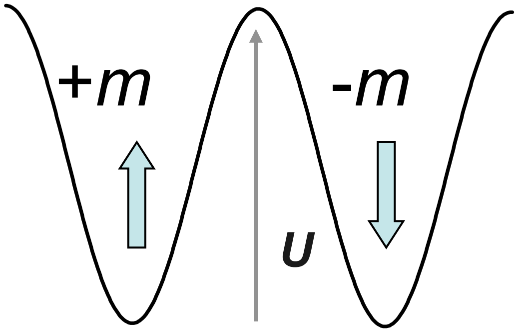


- **Slope:** α = 0.036 ± 0.003 for the film; 0.033 ± 0.003 for the nanopillars
- **Intercept:** ΔH_0 = 284 ± 30 Oe for the film; 24 ± 15 Oe for the nanopillars

W. Chen *et al*. Appl. Phys. Lett. **92**, 012507 (2008)

Spin Transfer MRAM

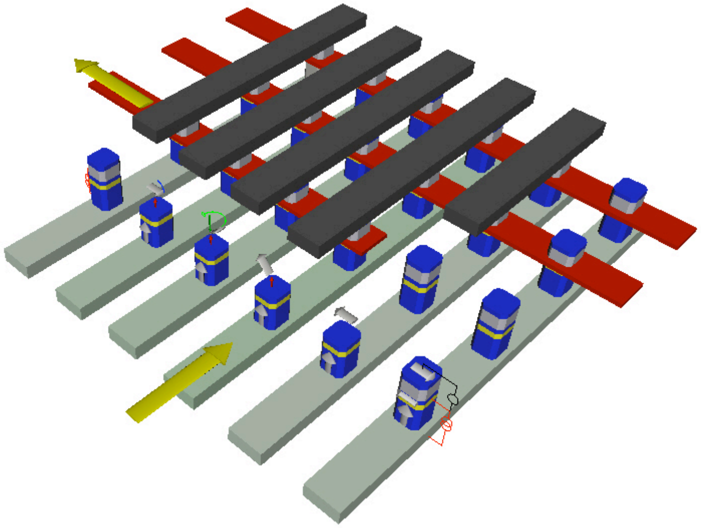
- Spin-transfer interaction may enable the ultimate miniaturization of MRAM to limits set by thermal stability.
- Why? Means of switching very high anisotropy nanomagnets



$$U = \frac{1}{2} H_k M_s V \geq 40 k_B T$$

$$I_c \simeq \frac{2e}{\hbar}\frac{\alpha}{P} M_s V H_k = \frac{4e}{\hbar}\frac{\alpha}{P} U$$

$$I_c \sim 50\ \mu A$$



→ **Potentially compatible CMOS technology!**

Summary

- *Spin transfer is a new mechanism to manipulate nanoscale magnets:*
  - *Reversal*
  - *Precession*
  - *Spin-waves*
- *Many basic and open questions about the interactions and magnetic excitations*
  - *Transport models*
  - *Micromagnetics (beyond LLGS)*
  - *Noise*
- *Great variety of phenomena, materials and structures*
- *New types of devices are possible that operate at the nanoscale and can be realized with present day technology*

References

- **Review Articles:**
  - Journal of Magnetism and Magnetic Materials 320 (2008): Jan. 2008 Current Perspectives
  - Handbook of Magnetism and Advanced Materials, Vol. 5, Spintronics and Magnetoelectronics, Edited by Parkin and Kronmüller 2007
  - IBM J. Res. and Development 50(1) (2006)