Spin-torque devices for Information-Communication Technology applications

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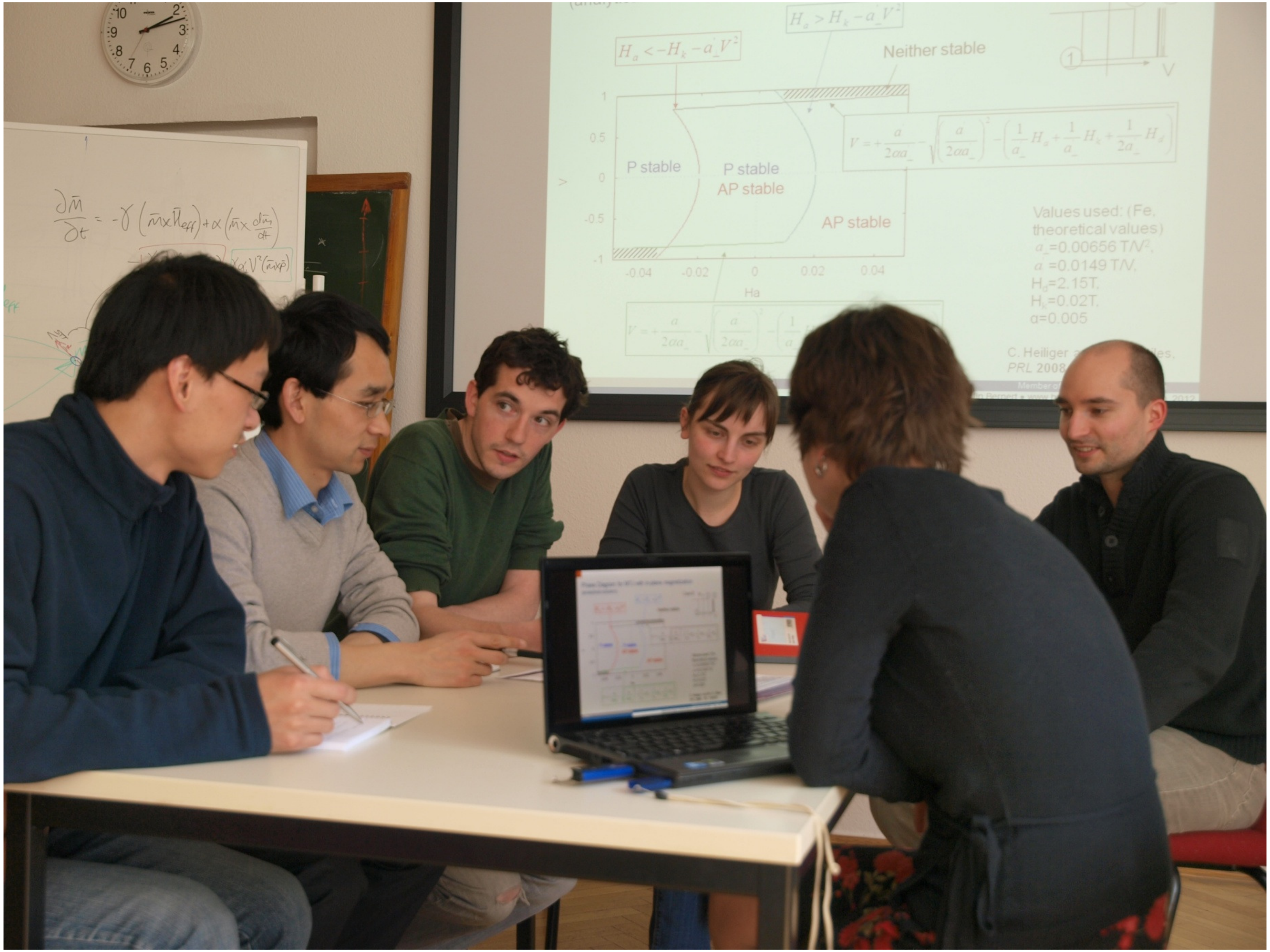
Neither stable
P stable
P stable
AP stable
AP stable
Ha
Values used: (Fe,
theoretical values)
C. Heiliger
PRL 2008

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Outline

1. Magneto-resistance and spin-transfer

2. Spin-transfer induced magnetization switching:

    a. General trends (in-plane magnetized spin-valves)
    b. ST Switching for MRAM
    c. Conclusions

3. Spin-transfer driven precession:

    a. In-plane anisotropy magnetic tunnel junctions
    b. ST precession for RF oscillators
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4. Other applications

5. Final conclusions / Outlook.

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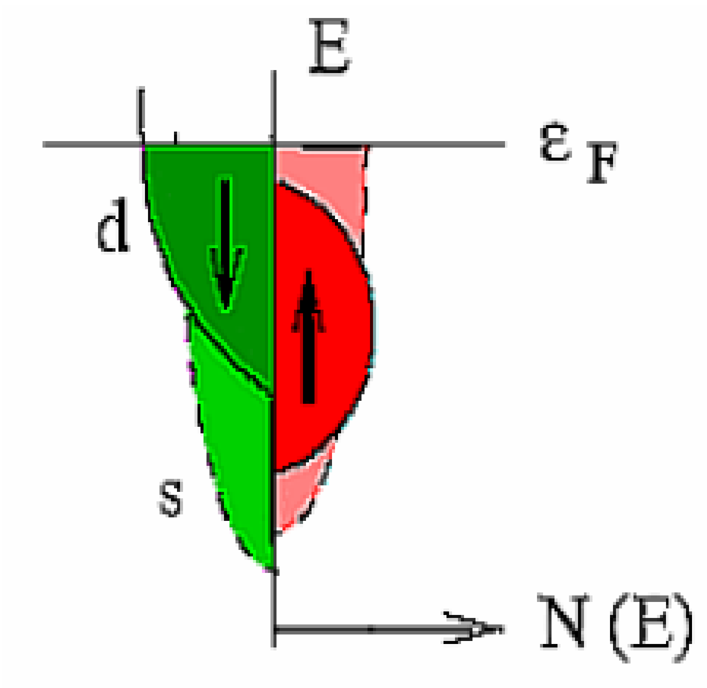
1. Giant Magnetoresistance (GMR)

Electronic structure of Co : exchange splitting



Spin up *d* sub-band completely filled.

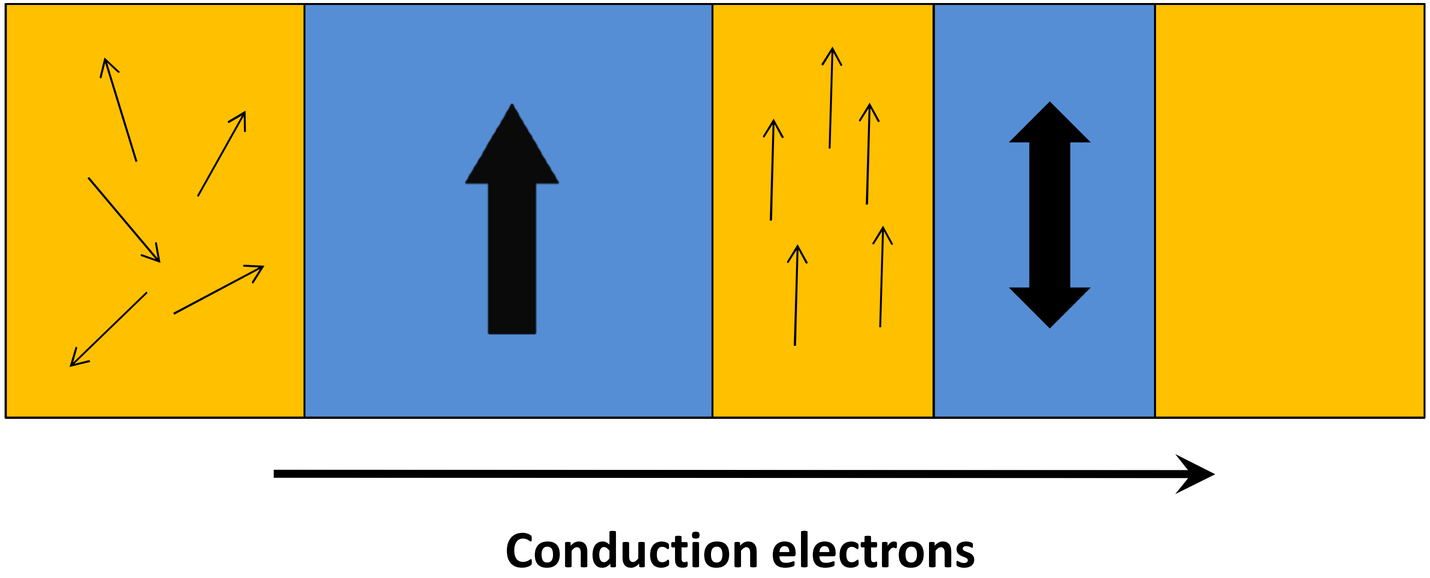
d states at Fermi level contain only spin down electrons

➠ scattering mostly affects spin down electrons; high resistivity

➠ spin up electrons: low resistivity, carry most of electrical current

Electrical current crossing a ferromagnetic metal can gain a spin polarization.

1. Introduction : Giant Magnetoresistance (GMR)



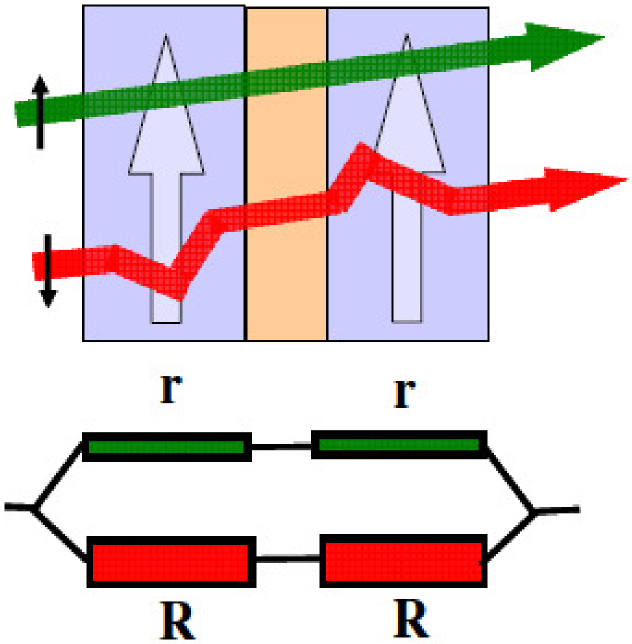
The relative orientation of the 2 magnetic layers determines the resistance of the system ($R = f(\zeta)$)

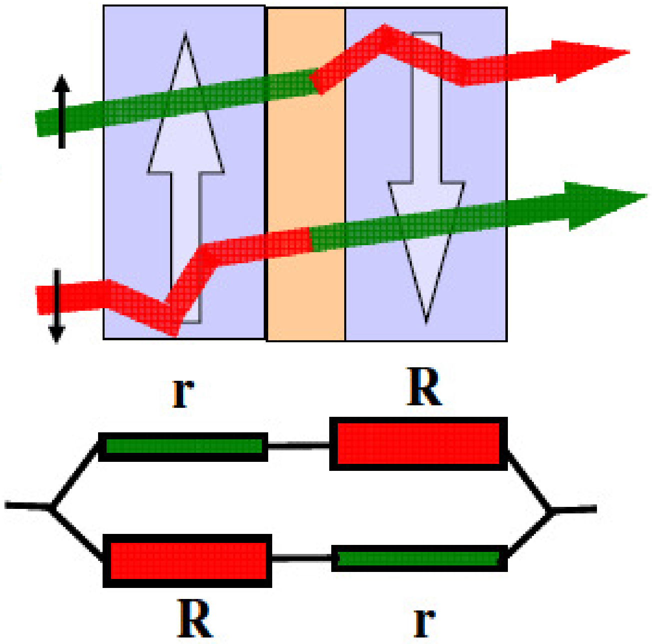
$\Rightarrow$ **Giant Magnetoresistance**

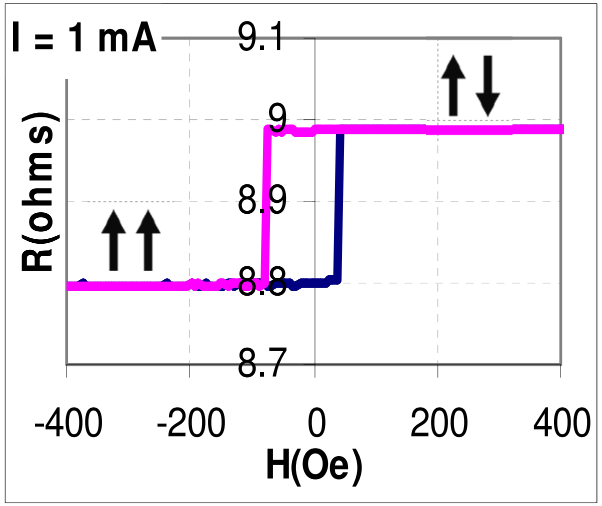
A. Fert & P. Grünberg, Nobel Prize 2007

1. Introduction : Giant Magnetoresistance (GMR)

Two current model: no spin-flip scattering







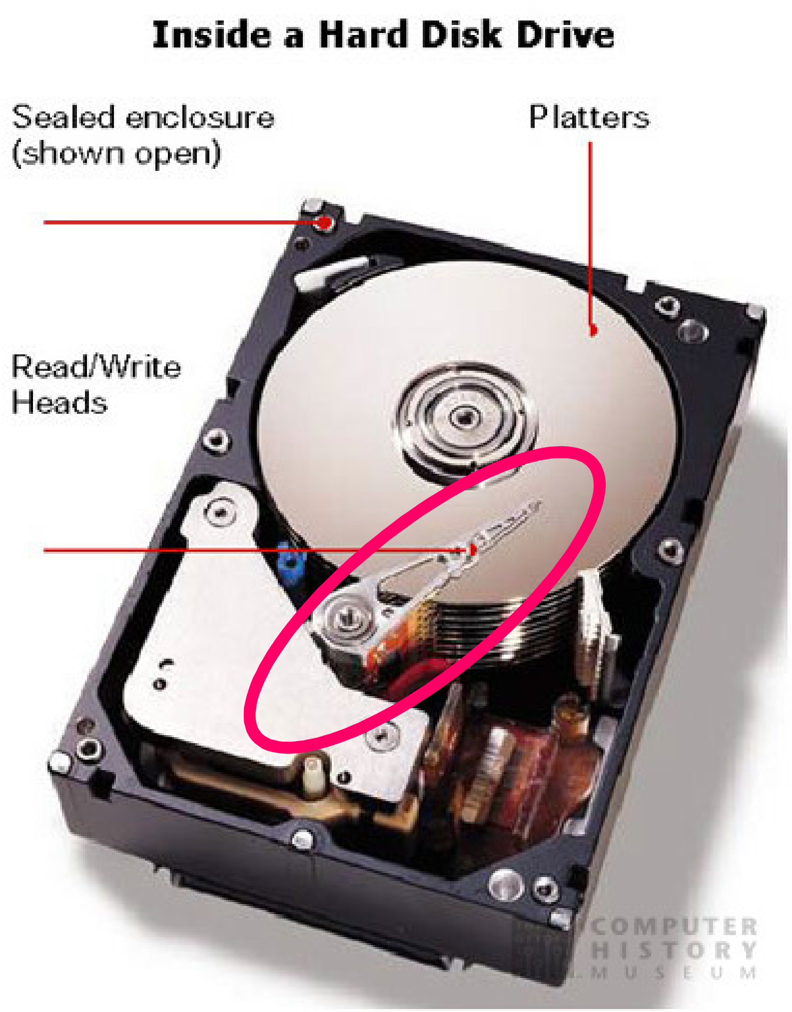
$$R_P = \frac{2rR}{r+R}$$

$$R_{AP} = \frac{r+R}{2}$$

$$GMR = \frac{R_{AP} - R_P}{R_P}$$

Resistance of the multilayer depends on the magnetic configuration : giant magnetoresistance (*Fert and Gruenberg, Nobel Prize 2007*).

1. Introduction : Giant Magnetoresistance (GMR)

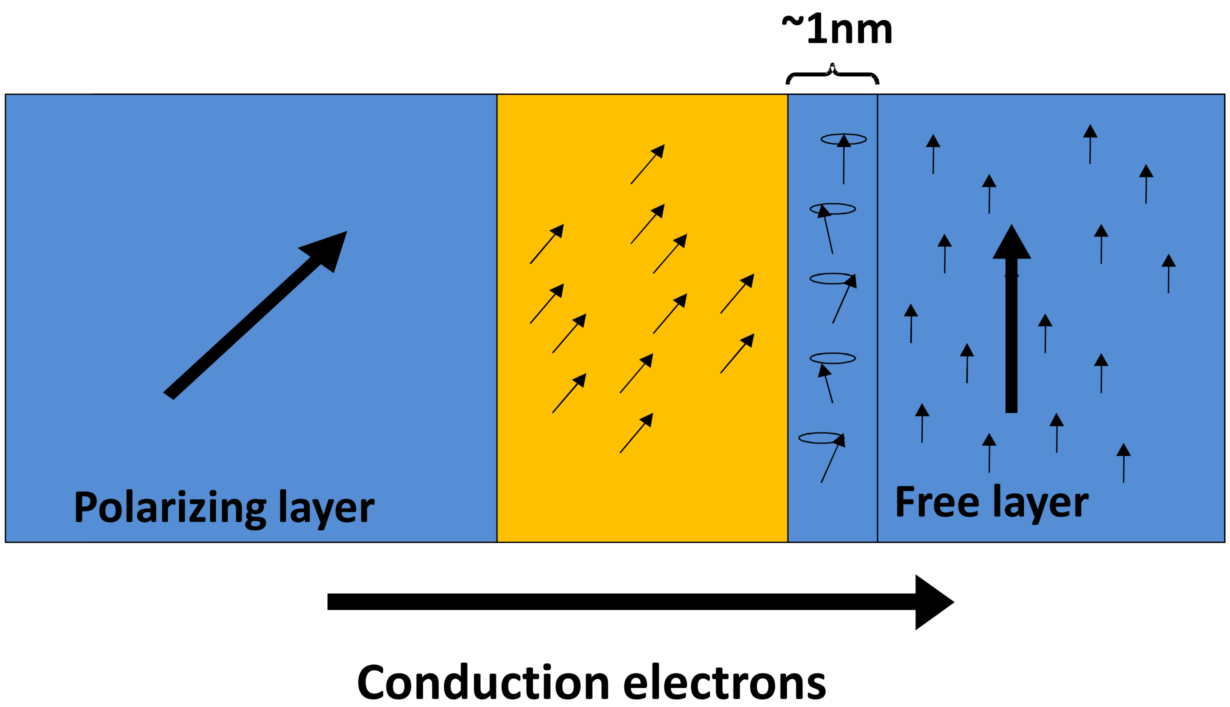


www.computerhistory.org

IBM RAMAC 305: 5 MB (1956)

Samsung S1 mini: 250 GB, 88 g (2010)

1. Introduction : Spin-transfer



Angular momentum transfer from the spin current to the magnetization of the free layer F

$\Rightarrow$ **Torque on the F magnetization**

Magnetic moments can be manipulated by current.

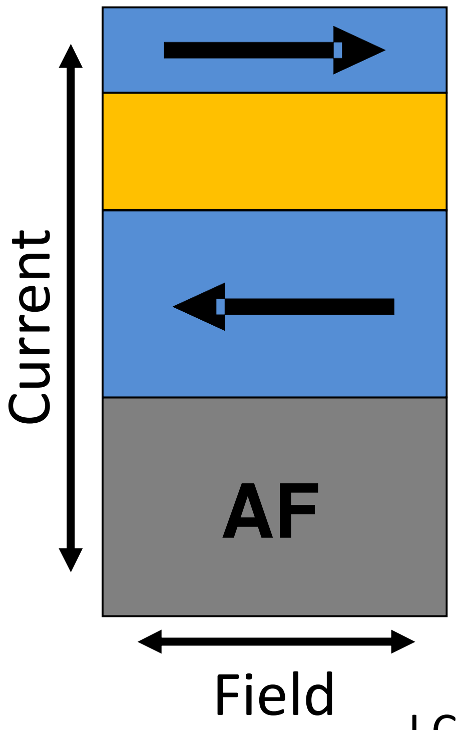
M.D. Stiles and A.Zangwill, Phys. Rev. B. 2002

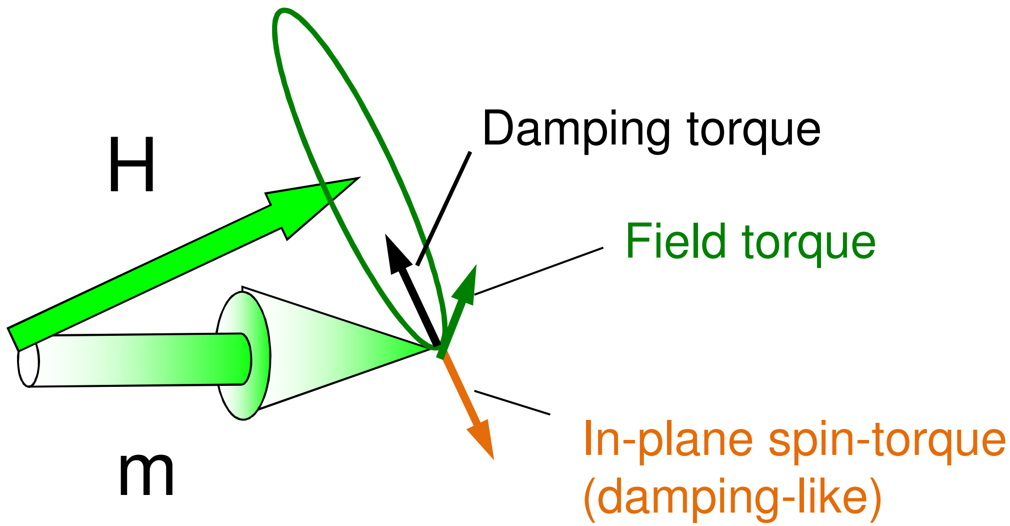
1. Introduction : Notable spin-transfer effects

Magnetization dynamics with a spin-transfer torque:

precession — damping — spin-transfer torque

$$\frac{d\vec{m}}{dt} = \underbrace{-\gamma \; \vec{m}\times\vec{H}}_{\text{precession}} + \underbrace{\alpha \; \vec{m}\times\frac{d\vec{m}}{dt}}_{\text{damping}} + \underbrace{\gamma \; a(\zeta) \; I \; \vec{m}\times(\vec{m}\times\hat{p})}_{\text{spin-transfer torque}}$$





J.C. Slonczewski, J. Magn. Magn. Mater. 1996, 2002

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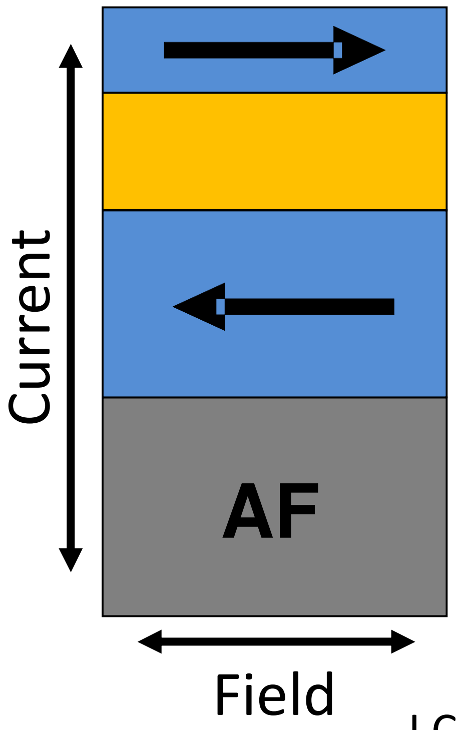

Spin-torque acting as antidamping

1. Spin torque > Damping torque
   → **Switching**

   F.J. Albert et al., Appl. Phys. Lett. 2000

2. Spin torque ~ Damping torque
   → **Steady state precession**

   S.I. Kiselev et al., Nature 2003

J.C. Slonczewski, J. Magn. Magn. Mater. 1996, 2002

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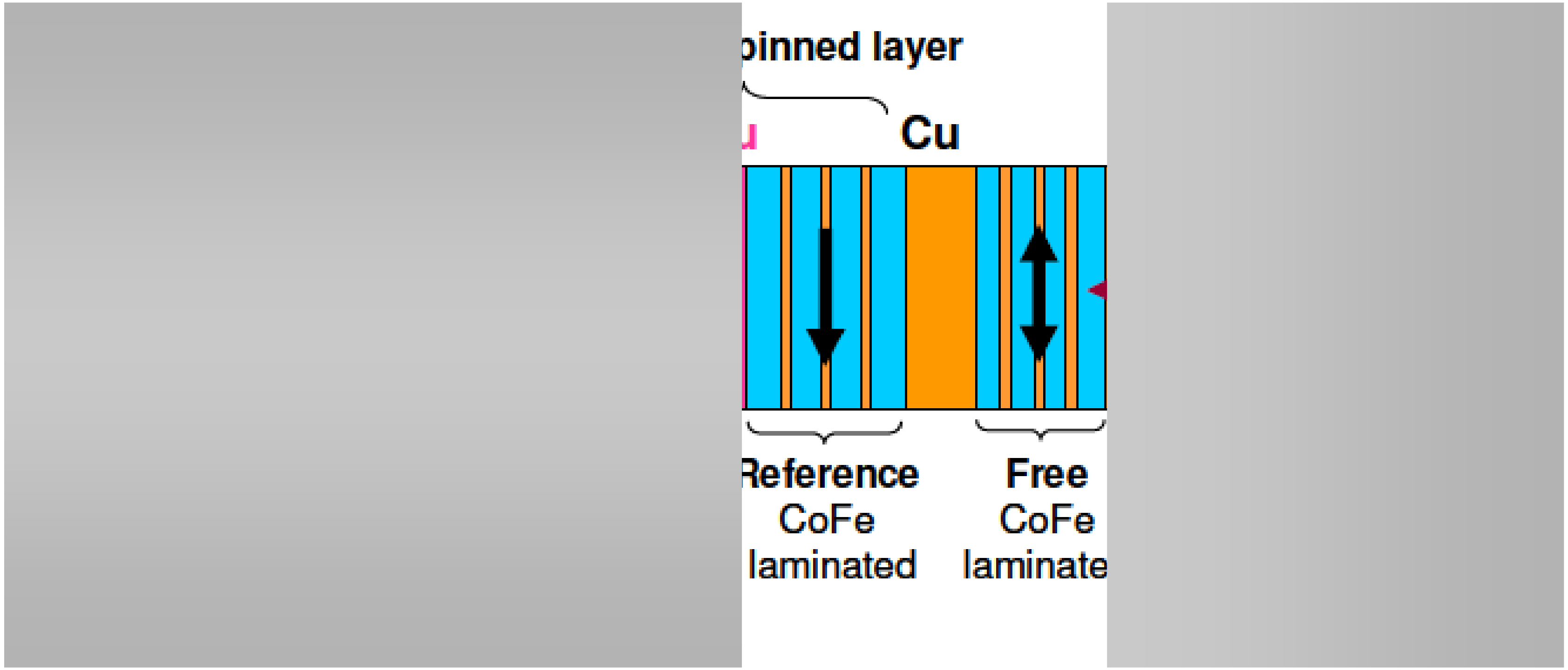
2a. Spin-transfer switching: In-plane spin-valves

Samples:

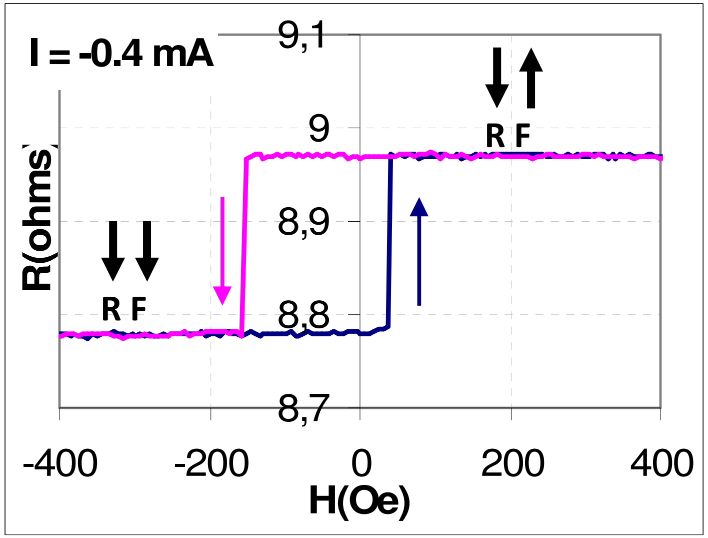


Metallic spin-valves with synthetic pinned layers and laminated free and pinned layers, fabricated by Headway Technologies Inc. Developed for CPP-GMR heads.

A. Deac et al., Phys. Rev. B 2006

2a. Spin-transfer switching: In-plane spin-valves

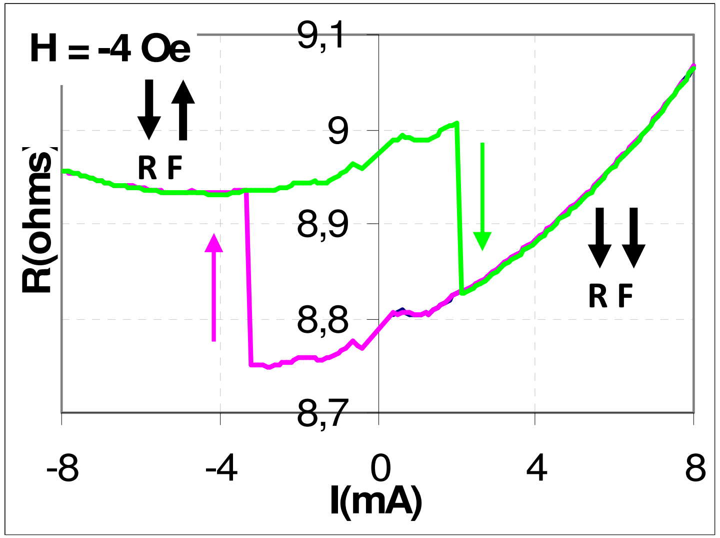
Field scan



H_c = 91 Oe, H_{ms} = 48 Oe

MR = 2.16%

Current scan



$I_c^{AP\text{-}P}$= 2 mA ($j_c^{AP\text{-}P}$ = 2.52*10^7A/cm²)

$I_c^{P\text{-}AP}$ = -3.3 mA ($j_c^{P\text{-}AP}$ = -4.16*10^7A/cm²)

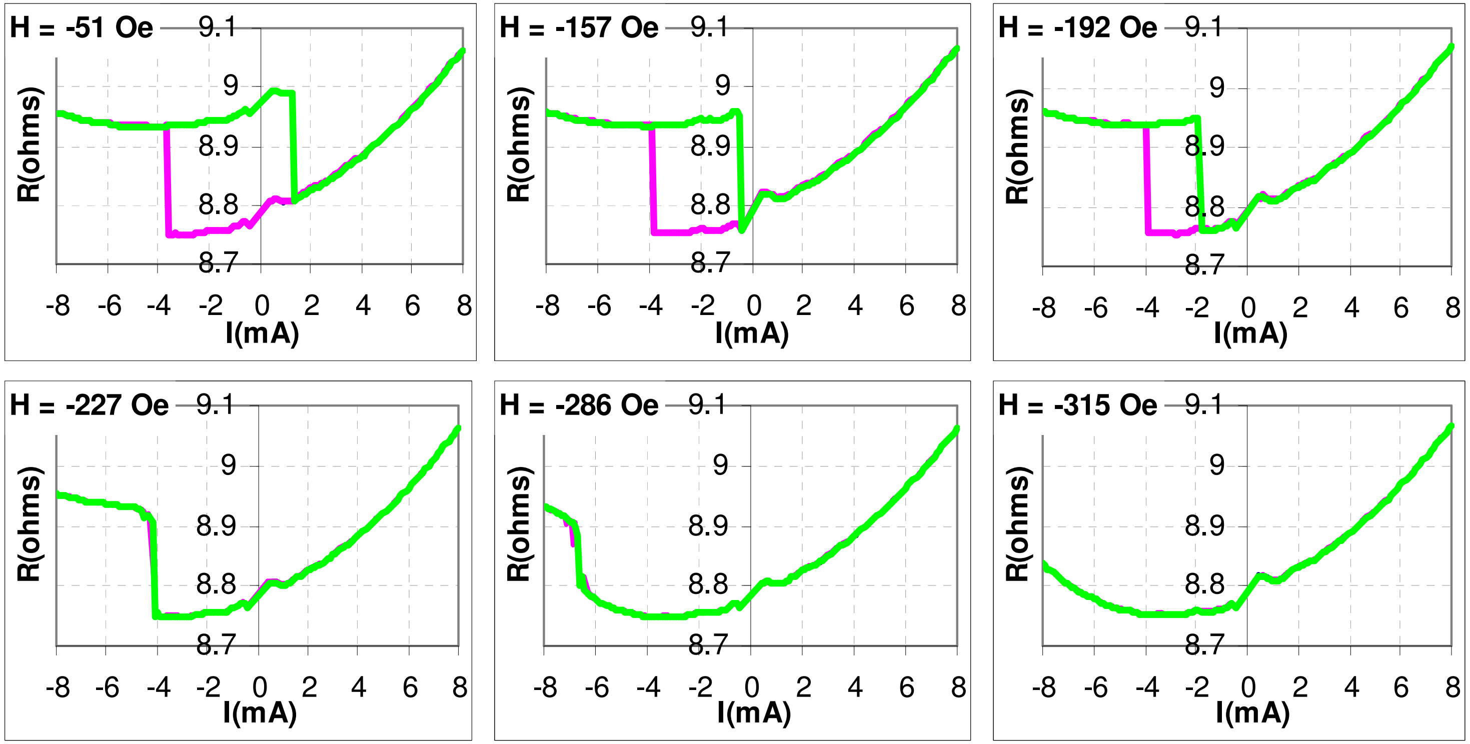
Angle dependence of the STT (larger close to AP) ➠ $I_c^{AP\text{-}P} < I_c^{AP\text{-}P}$

Switching current densities ~ 10^7 A/cm²

A. Deac et al., Phys. Rev. B 2006

2a. Spin-transfer switching: In-plane spin-valves

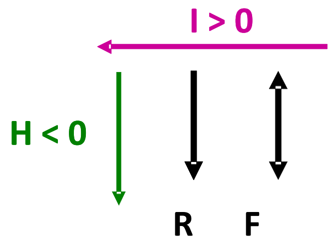
Resistance versus current at different constant fields:



Transitions shift with field at different speeds

➠ Reversible switching at large fields

If field too large, no switching.

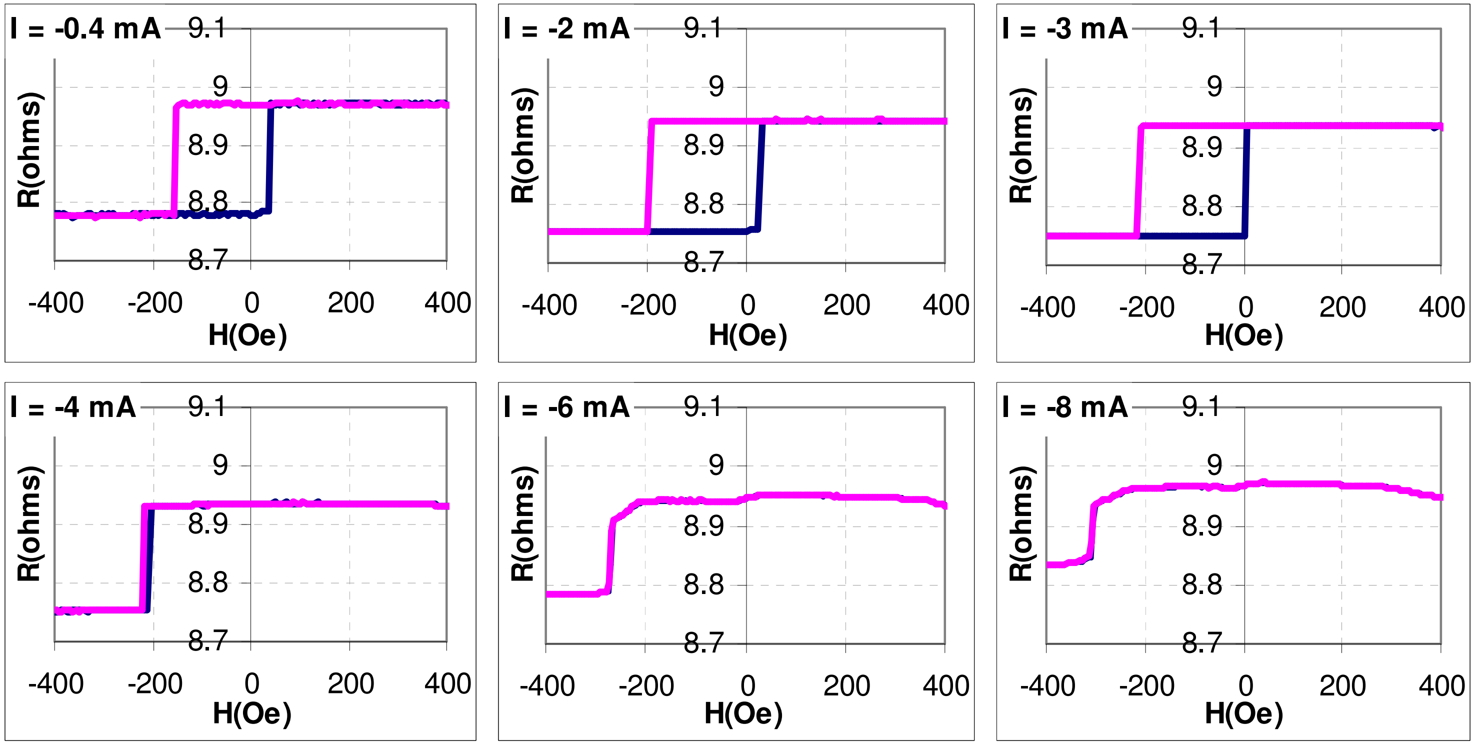


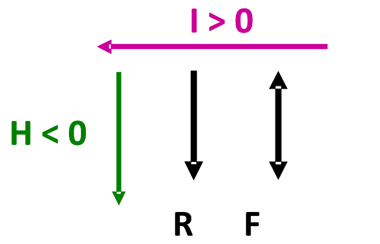
H < 0 favors P config .
I > 0 favors P config .

A. Deac et al., Phys. Rev. B 2006

2a. Spin-transfer switching: In-plane spin-valves

Resistance versus field at different constant currents:





H < 0 favors P config .
I > 0 favors P config .

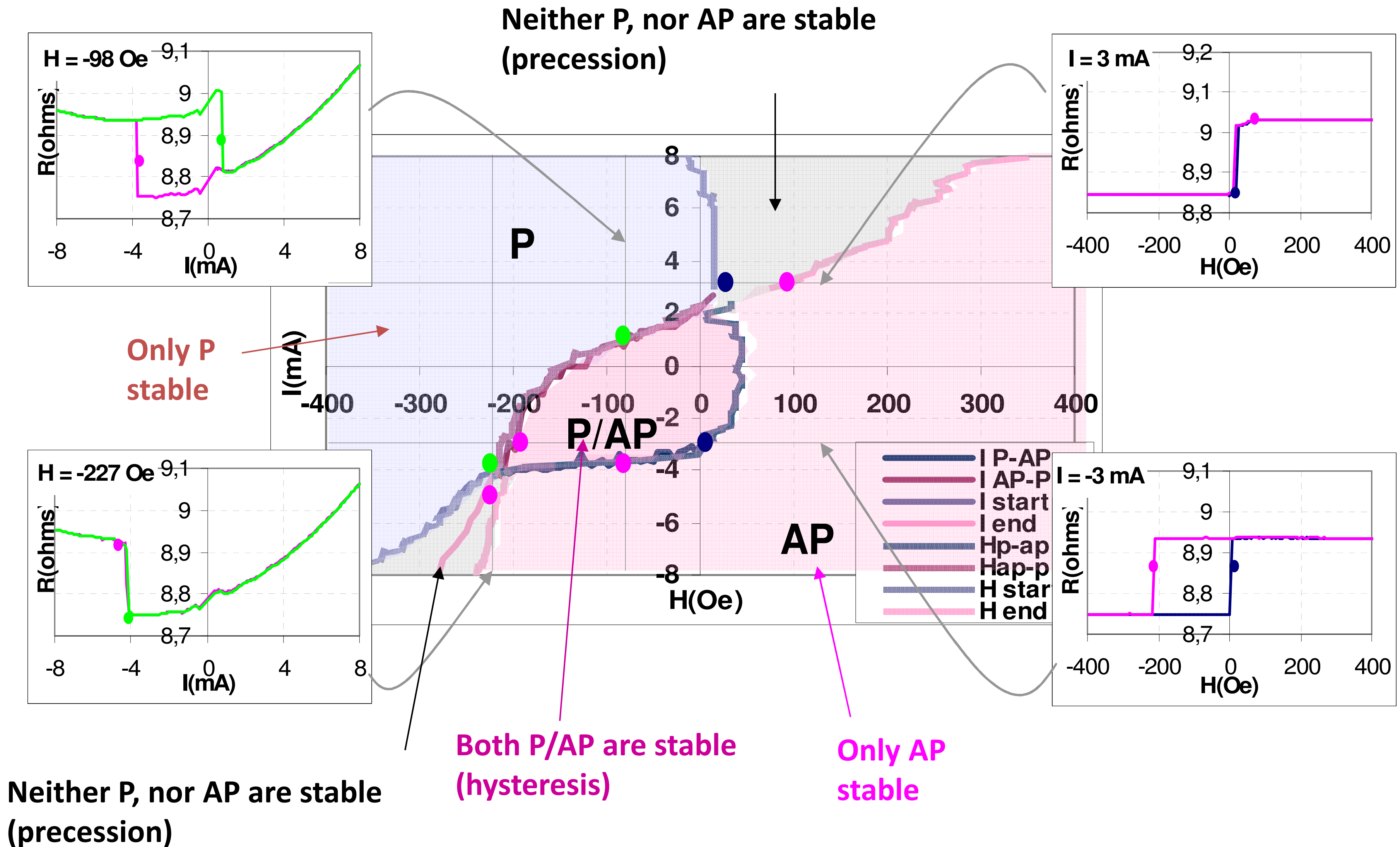
Negative currents favor the AP alignment ➠ Shift (especially for the P to AP transition, assisted by the current).

Large current ➠ Reversible switching.

A. Deac et al., Phys. Rev. B 2006

2a. Spin-transfer switching: In-plane spin-valves

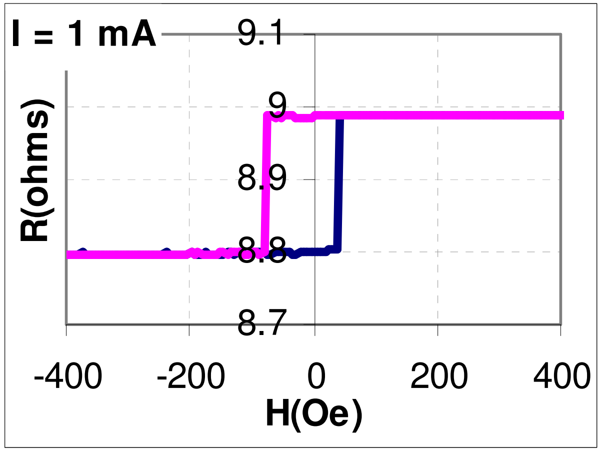
Phase diagram:



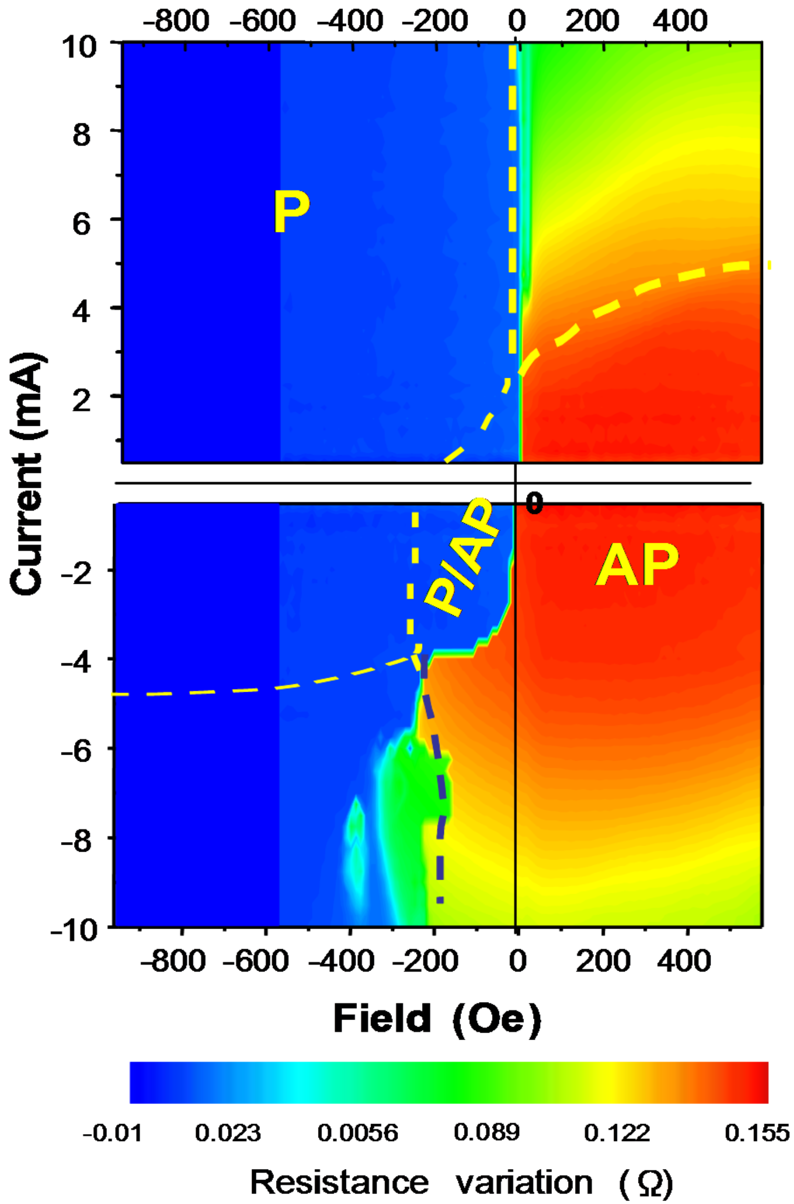
A. Deac et al., Phys. Rev. B 2006

2a. Spin-transfer switching: In-plane spin-valves

Phase diagram:



R (I;H) - R_{min}



A. Deac et al., Phys. Rev. B 2006

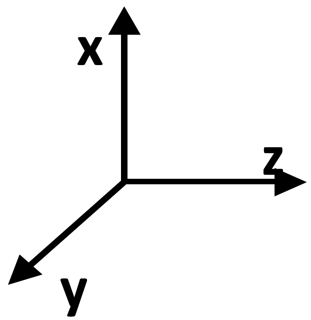
2a. Spin-transfer switching: In-plane spin-valves

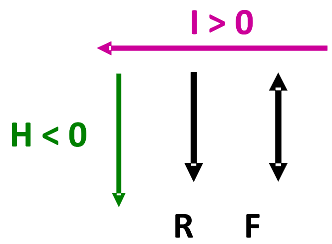
Modelling: Calculating the stability lines:

$$\frac{\partial \vec{m}}{\partial t} = -\gamma\, \vec{m} \times \vec{H}_{eff} + \alpha \cdot \vec{m} \times \frac{\partial \vec{m}}{\partial t} + \frac{\hbar}{2e} \cdot \frac{\gamma}{M_s V} \cdot g(\theta) \cdot I \cdot \vec{m} \times \left[\vec{m} \times \vec{u}_x \right]$$

$$\vec{H}_{eff} = H \cdot \vec{u}_x - H_k m_x \cdot \vec{u}_x - H_d m_z \cdot \vec{u}_z$$

Static states: $$\frac{\partial \vec{m}}{\partial t} = 0$$





+ stability check for the static solutions (perturbation theory)

H < 0 favors P config .
I > 0 favors P config .

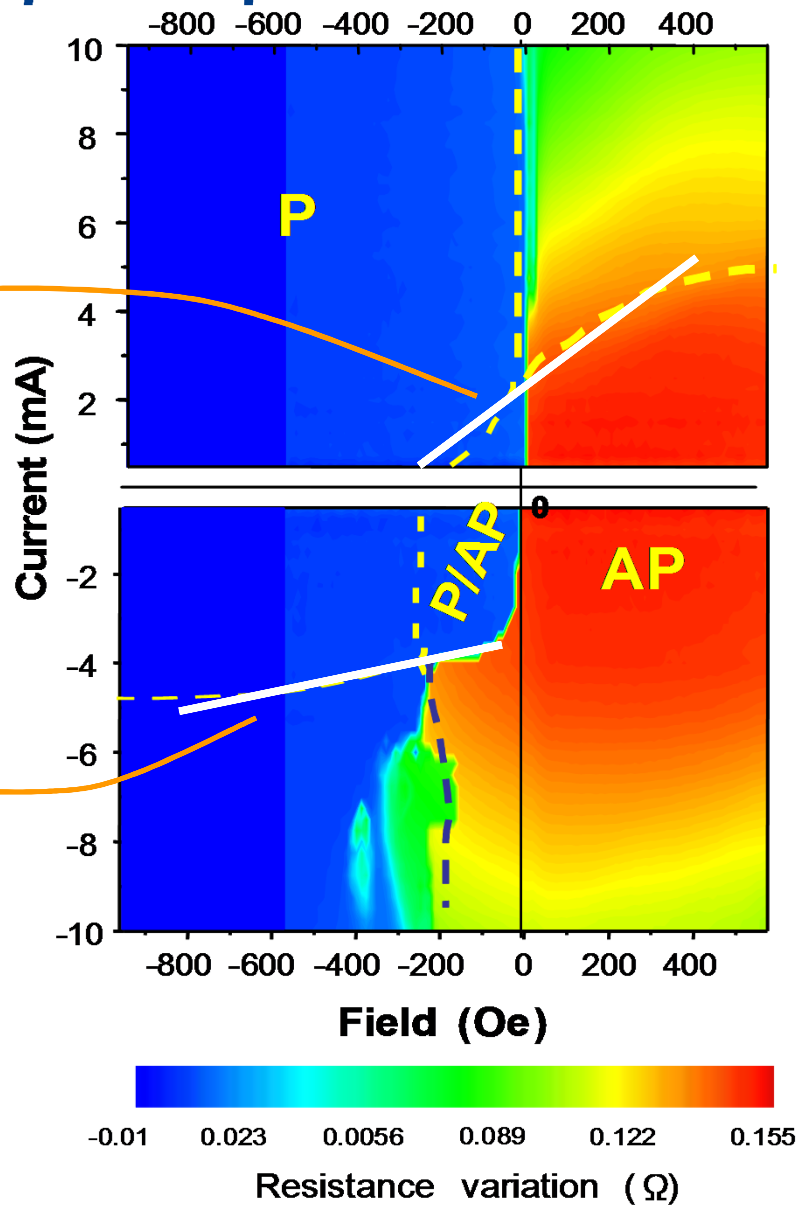
A. Deac et al., Phys. Rev. B 2006

2a. Spin-transfer switching: In-plane spin-valves

Phase diagram:

$$I_c^{AP-P} = \frac{2e}{\hbar} \frac{\alpha M_s V}{g(\pi)} \left(2\pi M_s + H_k + H \right)$$

$$I_c^{P-AP} = \frac{2e}{\hbar} \frac{\alpha M_s V}{g(0)} \left(-2\pi M_s - H_k + H \right)$$

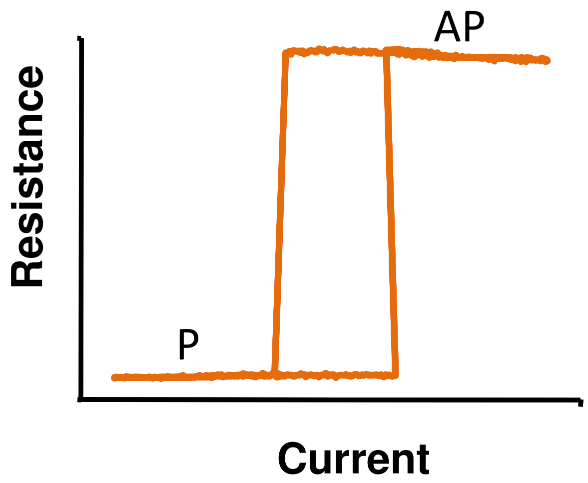


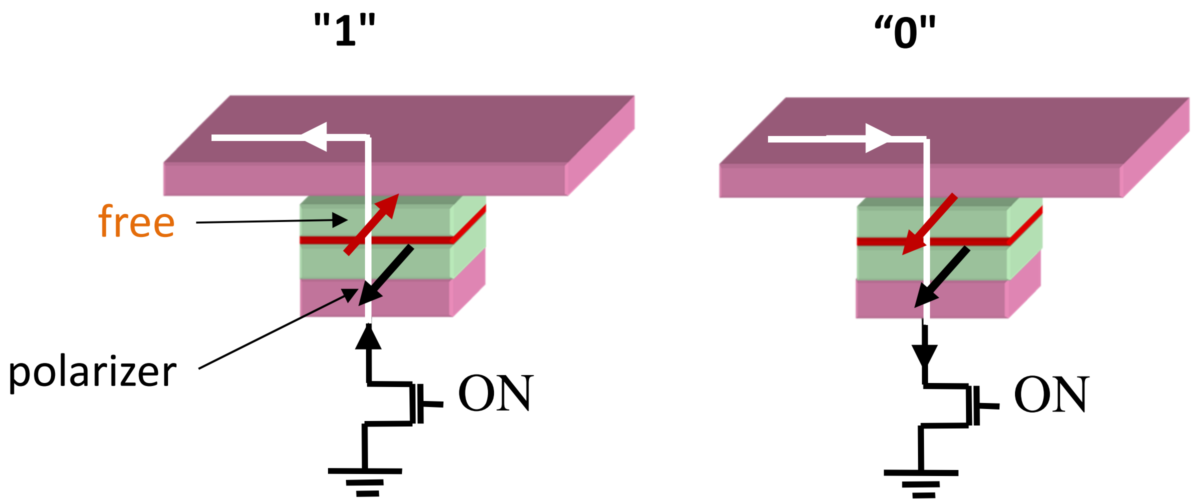
Different slopes reflecting the ST angular dependence.

Order of magnitude set by demagnetizing field.

A. Deac et al., Phys. Rev. B 2006

2b. Spin-transfer switching for MRAM





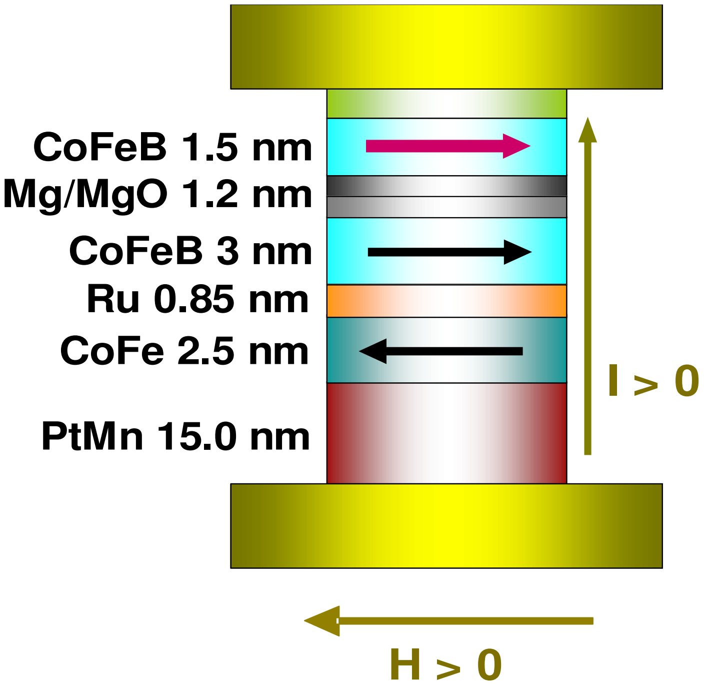
Very fast, non-volatile, CMOS compatible, perfect write selectivity.

Need to:

- **Use tunnel junctions (high MR signal);**
- **Lower the current density required for current induced switching to make it compatible with CMOS (10^6-10^5 A/cm²);**
- **Keep thermal stability reasonable.**

2b. Spin-transfer switching for MRAM

Increase the signal: use MgO-based magnetic tunnel junctions



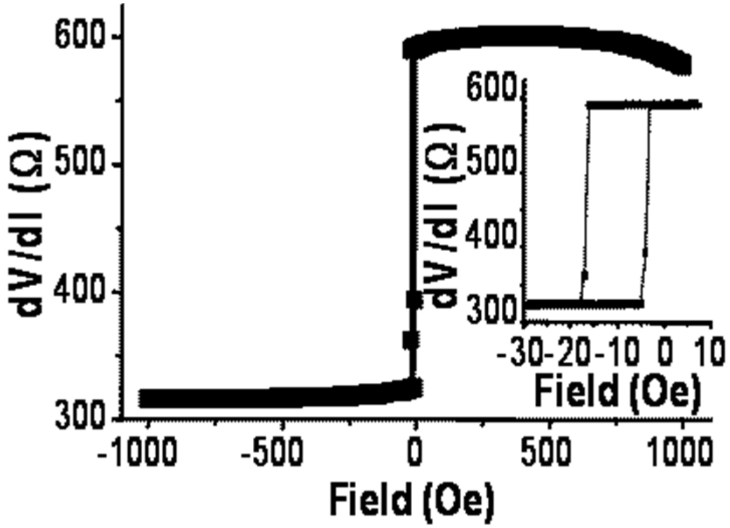
RA (P) ≈ 4 $\Omega \cdot \mu m^2$, MR = 110%

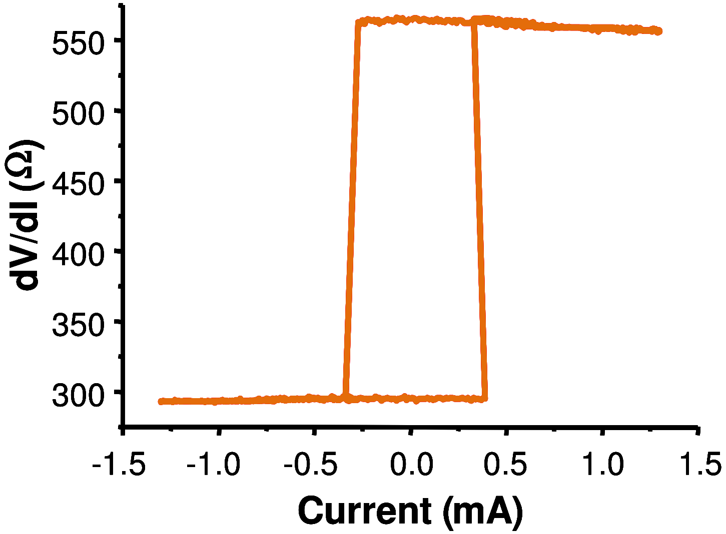
H_c = 6 Oe, H_{ms} = 13 Oe (AP)

$I_c^{P\text{-}AP}$ ≈ 0.3 mA (~ 87 mV)

$I_c^{AP\text{-}P}$ ≈ -0.3 mA (~ -165 mV)

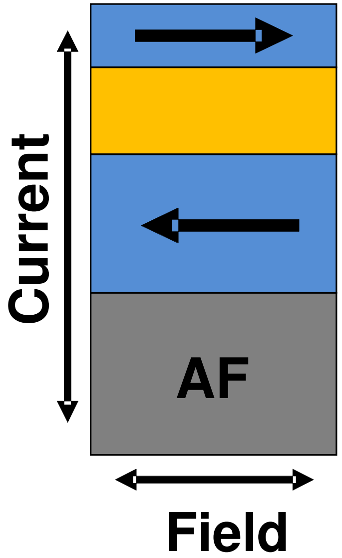
A. Deac et al., Nature Phys. 2008





2b. Spin-transfer switching for MRAM

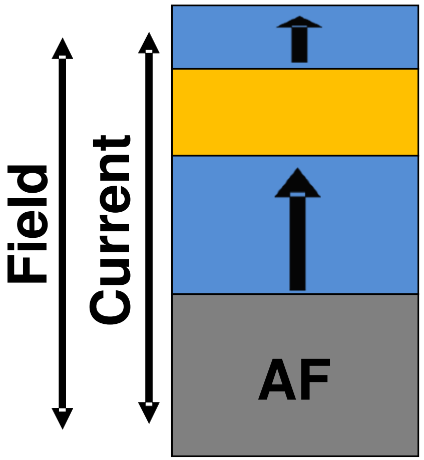
Decrease the switching currents: use perpendicular anisotropy layers



H_k ~ 100 Oe

$2\pi M_s$ ~ 10000 Oe

j_c ~ 10^7 A/cm²



$$H_{k\perp} - 4\pi M_s = H_{keff} > 0$$

H_{keff} ~ 100-1000 Oe

j_c ~ 10^5-10^6 A/cm²

$$j_c = \frac{2e}{\hbar}\frac{\alpha M_s t}{g(\theta)}\left(2\pi M_s + H_k + H\right)$$

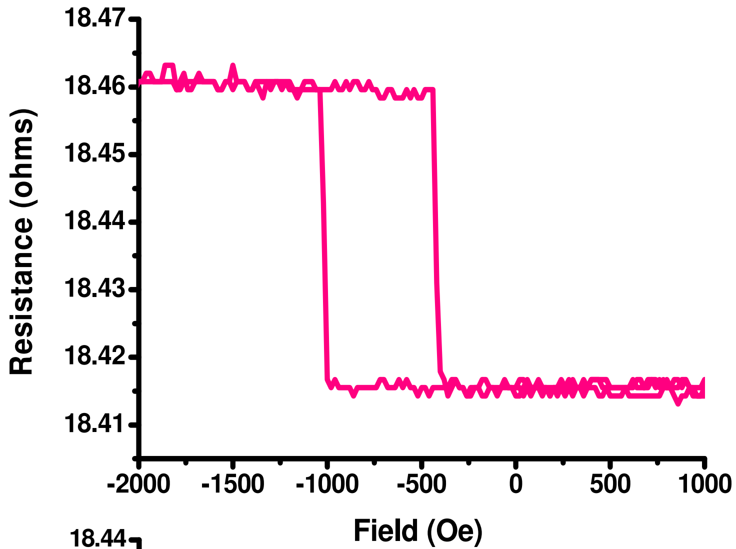
$$j_c = \frac{2e}{\hbar}\frac{\alpha M_s t}{g(\theta)}\left(H_{k\perp} - 4\pi M_s + H\right)$$

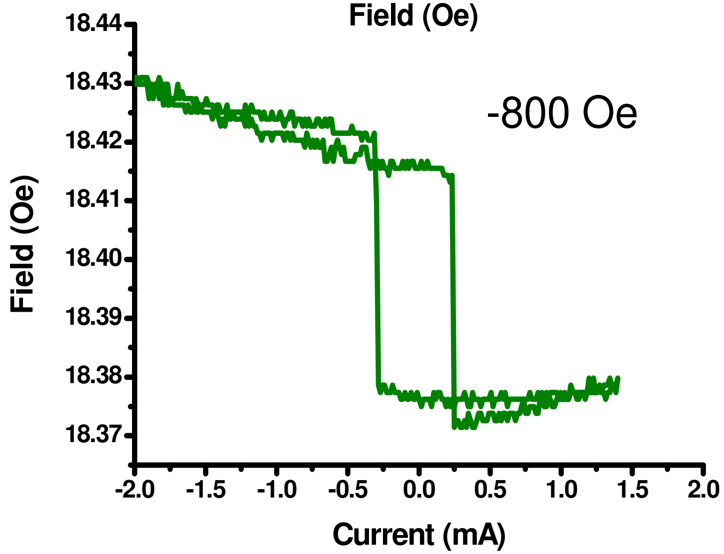
Can reduce switching current density by 1-2 orders of magnitude by reducing the effective anisotropy, without trading on thermal stability.

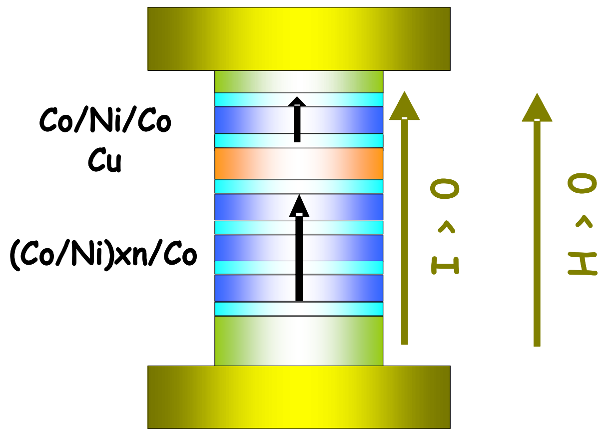
S. Mangin et al., Nature Mater. 2006

2b. Spin-transfer switching for MRAM

Decrease the switching currents: use perpendicular anisotropy layers







75 x 75 nm^2
(circular)
cross-section

H_{keff} = 330 Oe
H_{ms} = 720 Oe

$j_c^{AP-P} = 3.4*10^6$ A/cm^2
$j_c^{P-AP} = -9.3*10^6$ A/cm^2

J_c one order of magnitude lower by reducing coercivity.

A. Deac et al., unpublished

2b. Spin-transfer switching for MRAM

ST – MRAM challange:

Combine high TMR, low switching current and decent thermal stability.

Dr. Alina Deac | Spinelectronics FWIN | www.hzdr.de/FWIN

2c. Spin-transfer switching: Conclusions

Magnetic moments can be switched by a spin-polarized current, provided its amplitude is above a critical value.

Current-field phase diagrams summarize the allowed states under given conditions.

Bistability (P, AP) for currents below the switching values and field less than the anysotropy (hysteresis).

For in-plane spin-valves, the critical current is set by the out-of-plane demagnetizing field; current density ~ 10^7 A/cm^2.

For perpendicular anisotropy spin-valves, the critical current is set by the effective anisotropy; current density ~ 10^6 A/cm^2; better thermal stability.

MgO- tunnel junctions provide signal levels compatible with MRAM.

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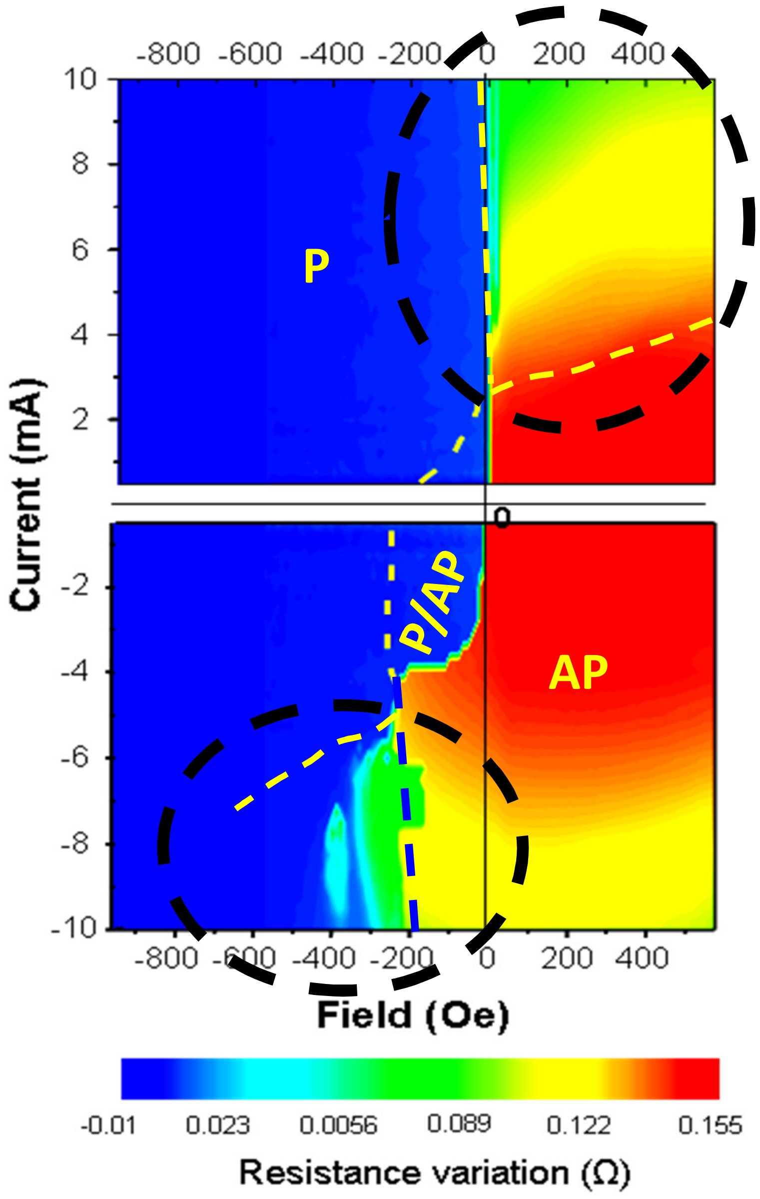
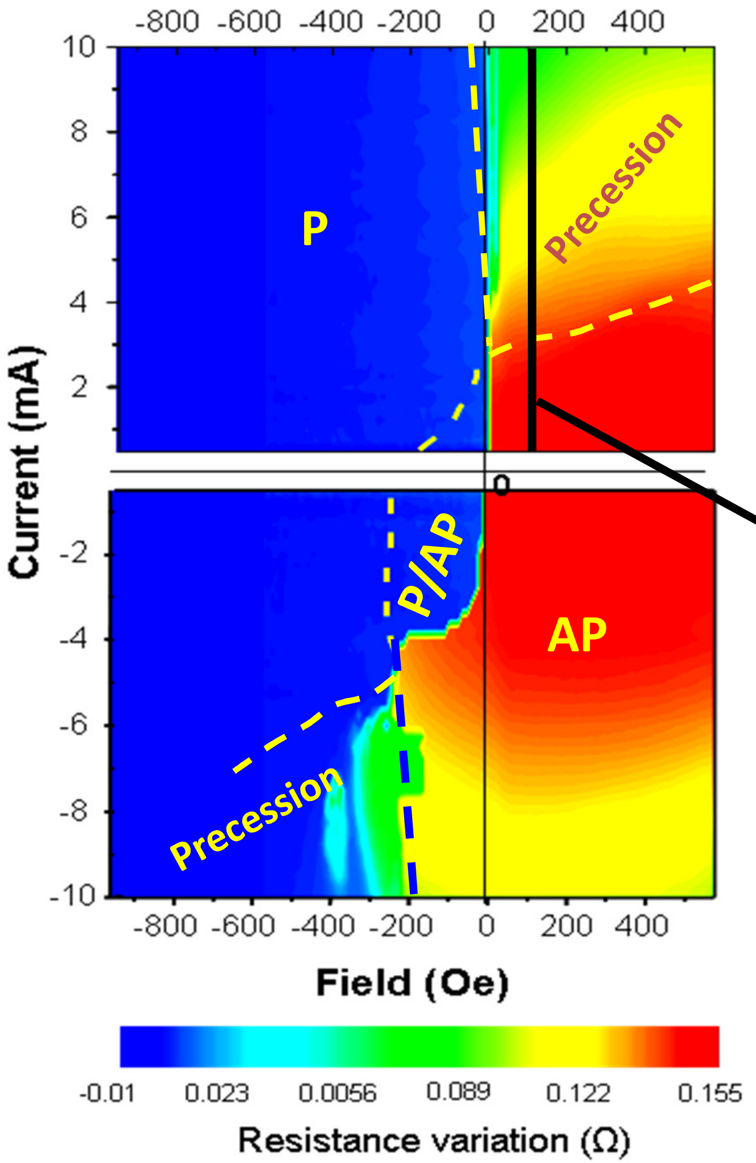
3a. Spin-transfer driven precession



- No static states allowed.
- Experiment: gradual / reversible resistance variation vs current and / or field.
- Precession?

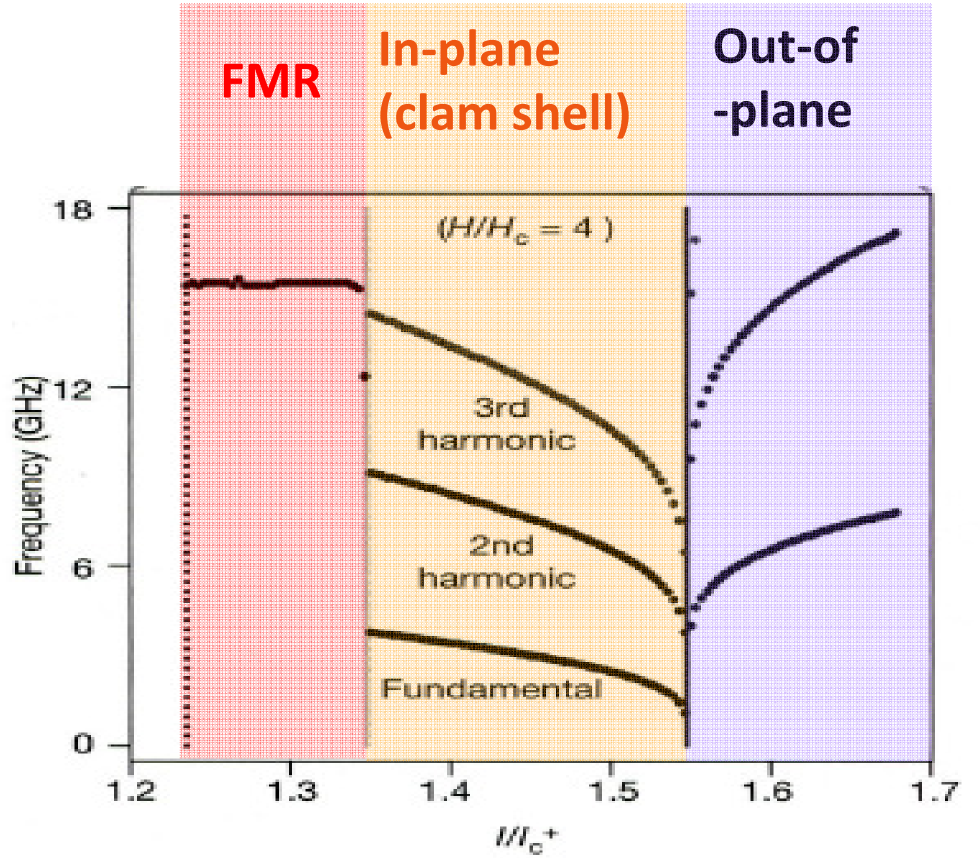
A. Deac et al., J. Phys. Cond. Matter 2008

3a. Spin-transfer driven precession



Macrospin model:

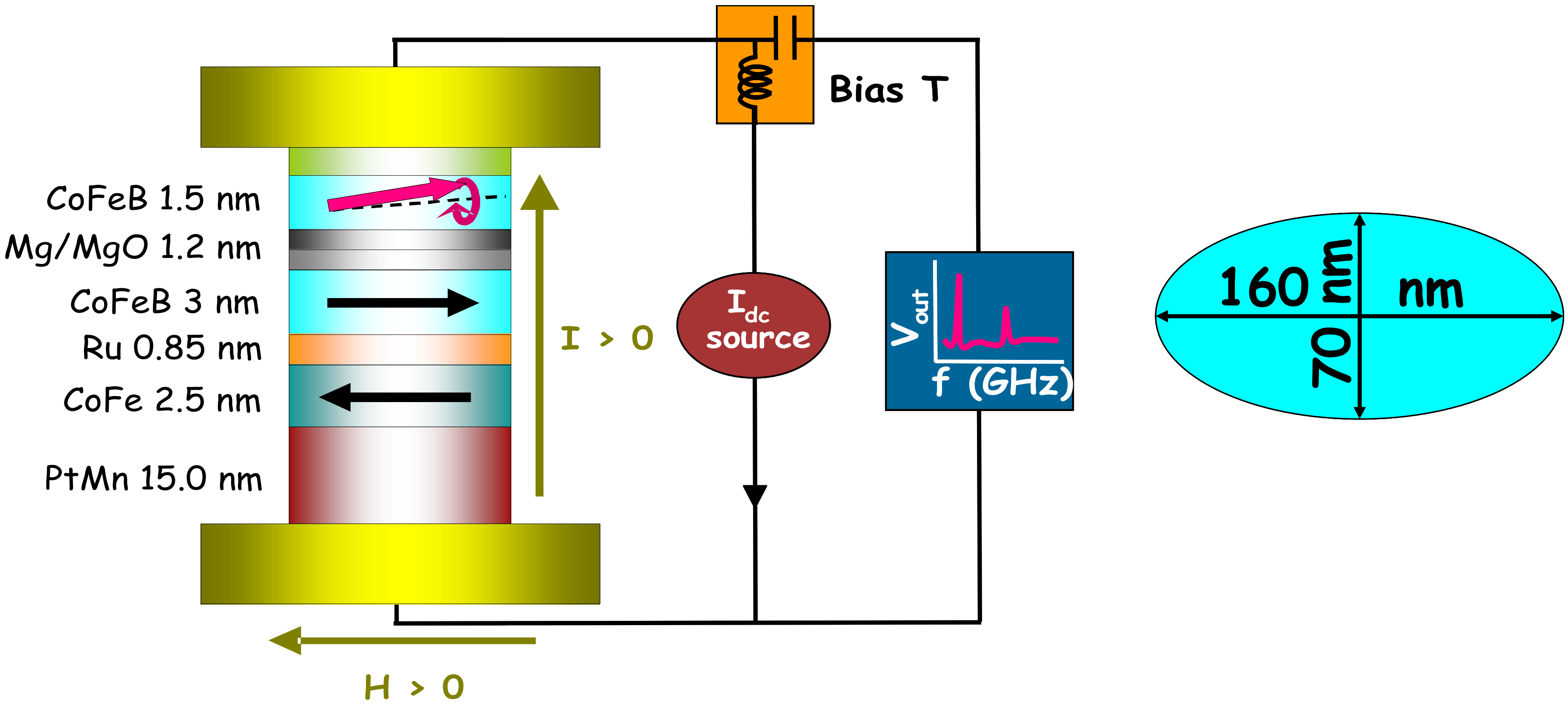
$$\int_0^T \left(damping + ST \right) dt = 0$$



S. Kiselev, Nature 2003

3a. Spin-transfer driven precession

Measurement technique and sample structure:



Precession ⇒ oscillatory voltage (GHz)

A. Deac et al., Nature Phys. 2008

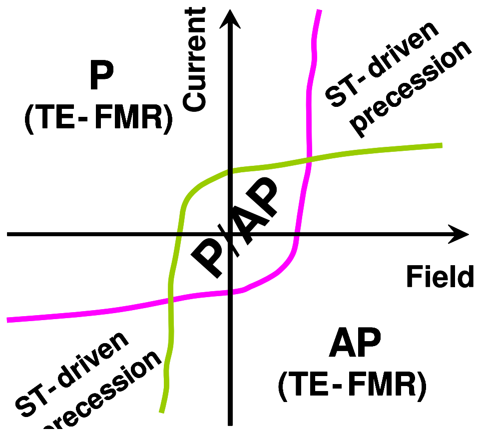
3a. Spin-transfer driven precession

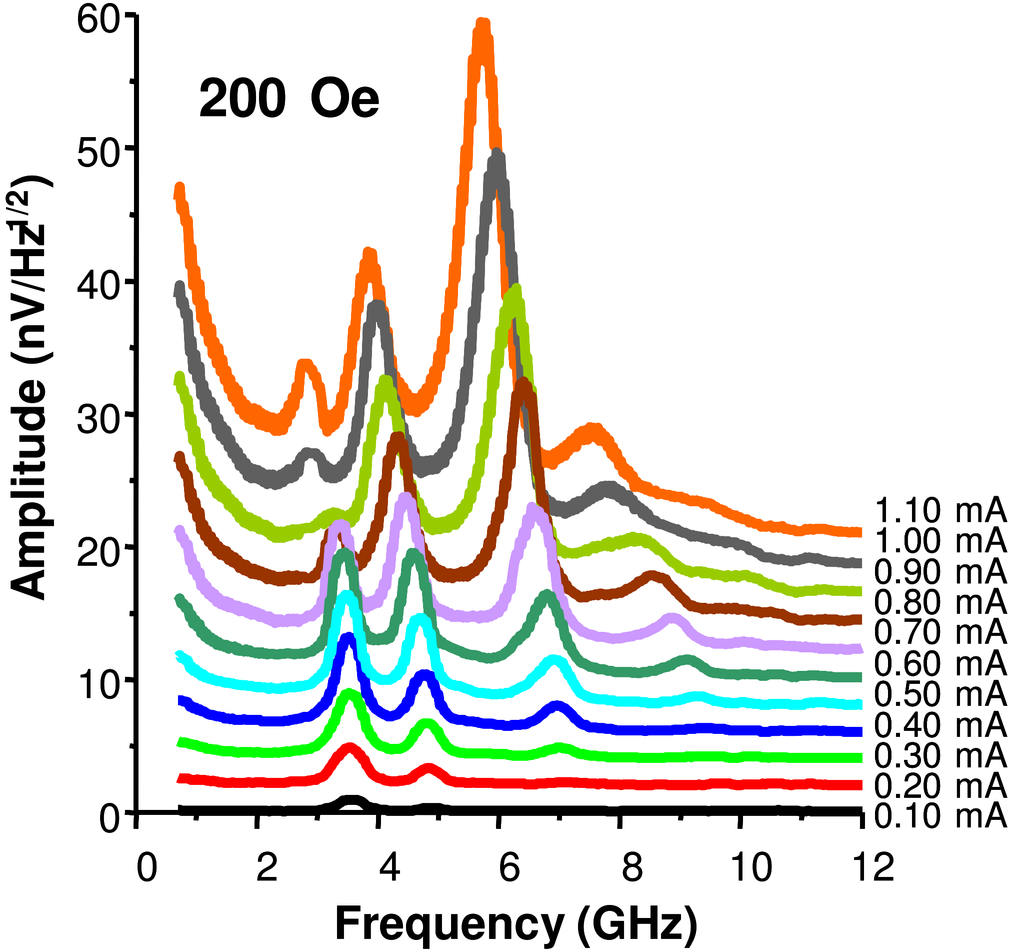
Two signals corresponding to two dynamic modes (center, ends of ellipse).

Peaks shift to lower frequency with increasing current.

Power increases with the current.

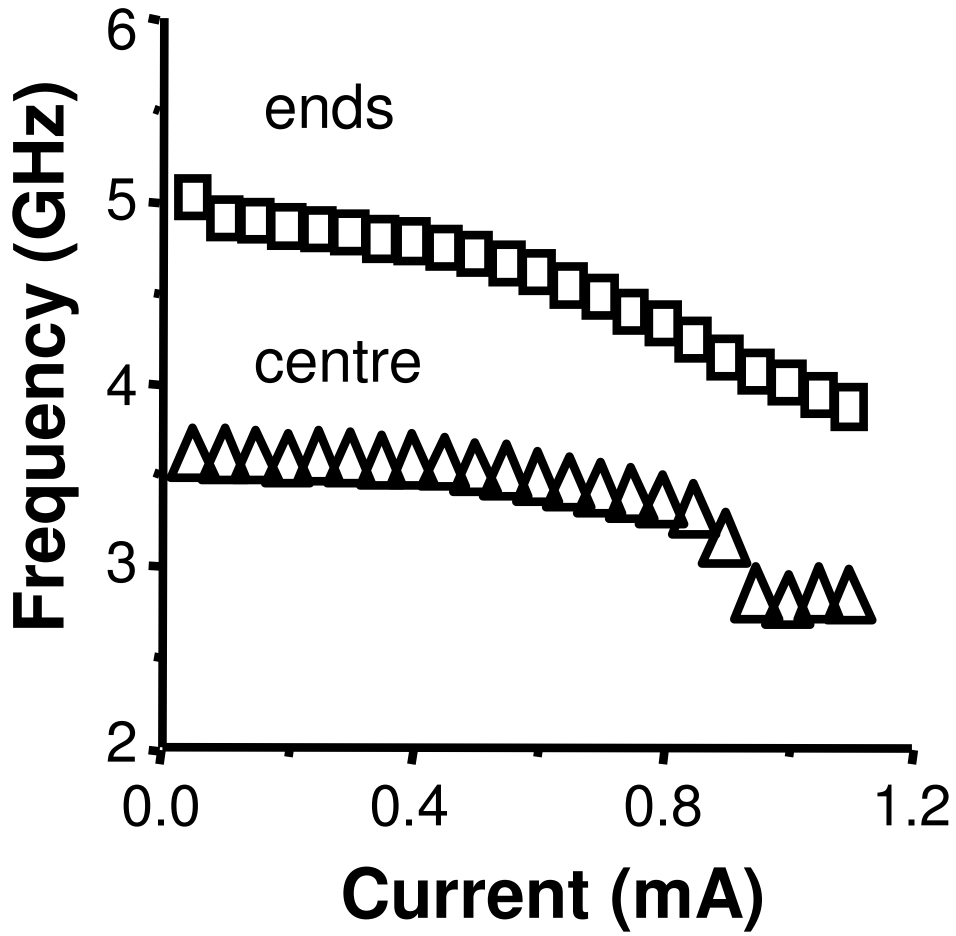
Increasing *1/f* noise and peak width.





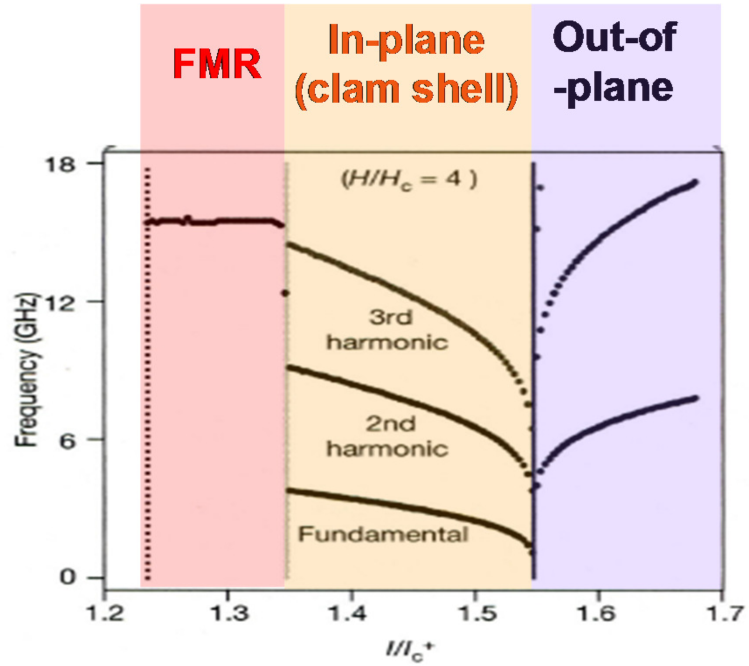
A. Deac et al., Nature Phys. 2008

Frequency versus current:



Red shift (to lower frequency).
➠ In-plane precession.

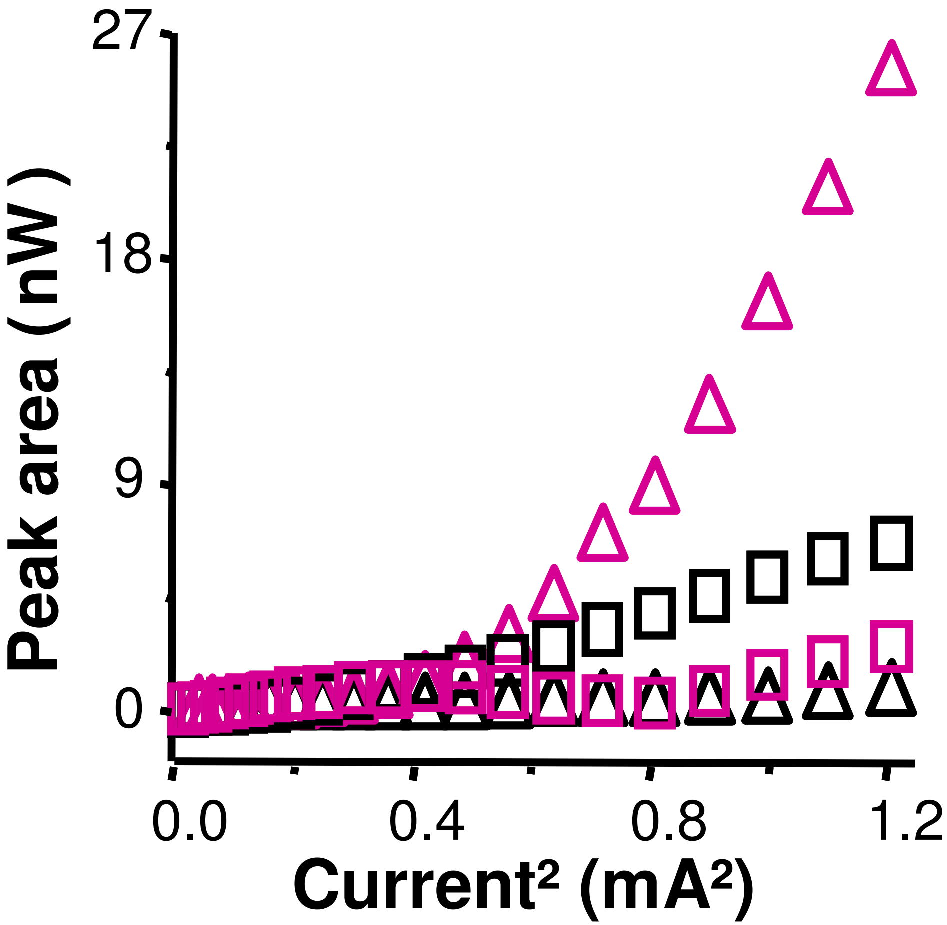
Out-of-plane mode not observed.



A. Deac et al., Nature Phys. 2008

3a. Spin-transfer driven precession

Power versus current:



Output power increases more rapidly than I^2 (i.e the input power)

➠ ST oscillator is an active element.

Precession angle can be calculated from the relative powers of the fundamental and second harmonic signal (up to 70 degrees).

A. Deac et al., Nature Phys. 2008

3a. Spin-transfer driven precession

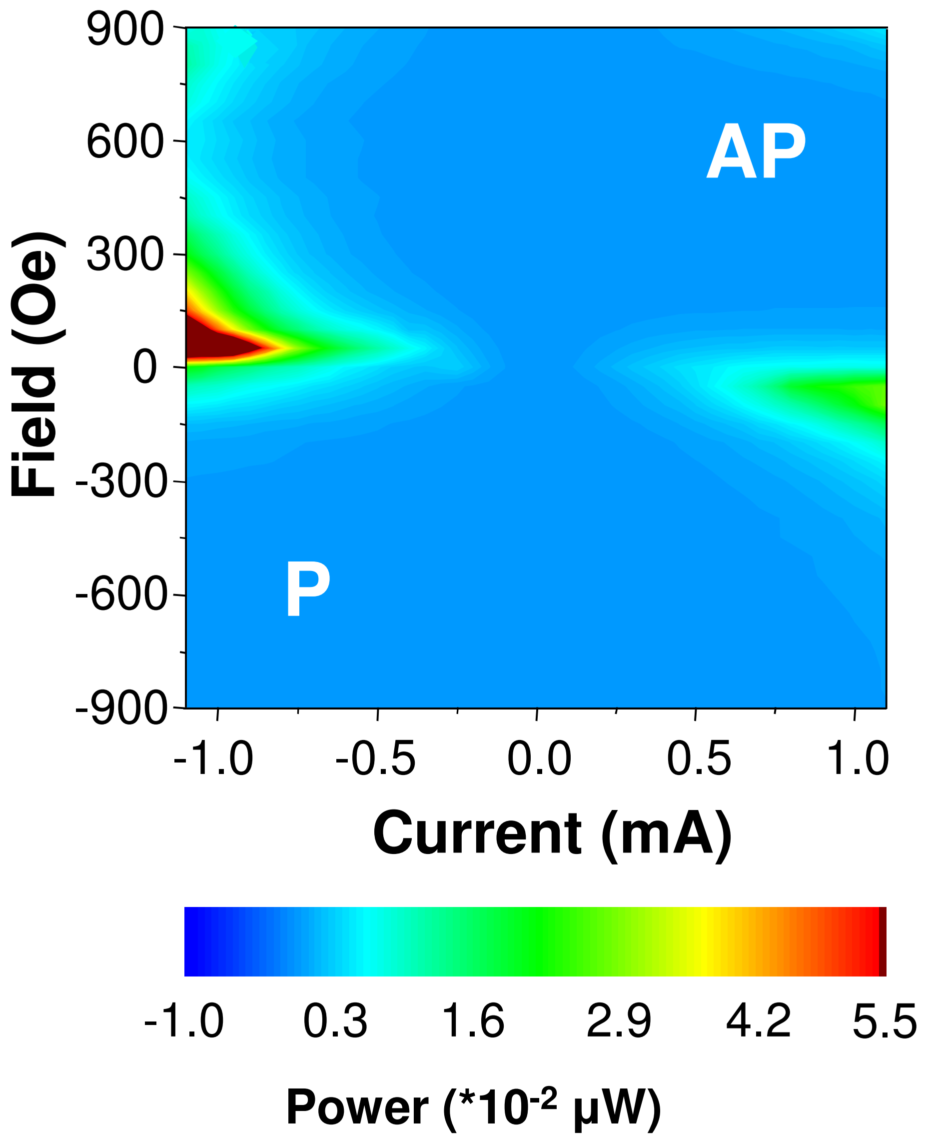
Dynamic phase diagram:

Plot intergrated power vs current and field.

Output power ≠ 0 in the (*I*, *H*) regimes where neither P, nor AP are stable.

Power increases with current; decreases with field.

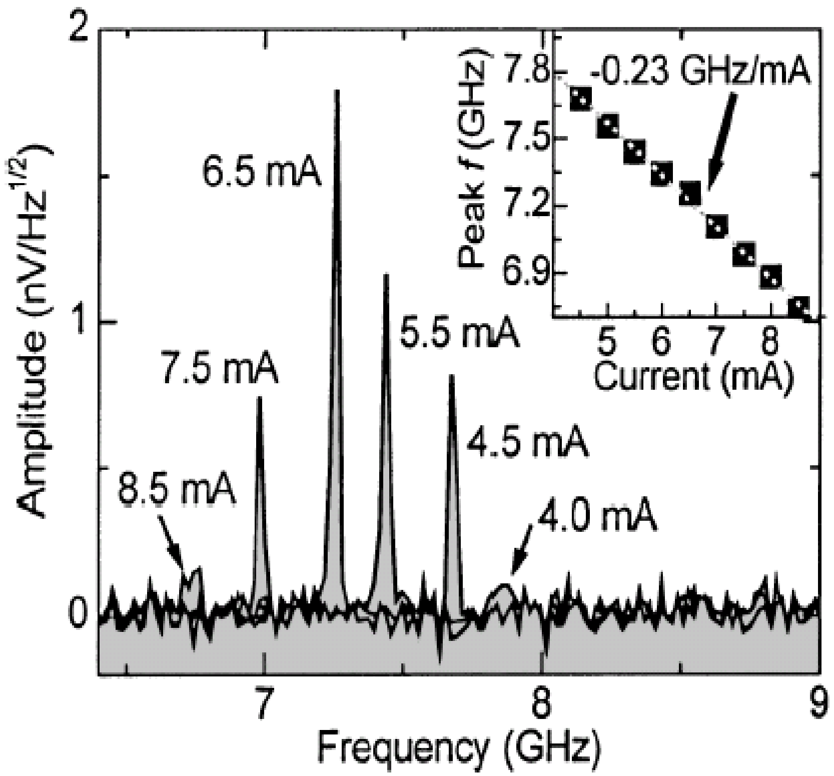
Max. measured power: 0.14 μW (~10% of emitted power) (rest lost due to capacitance effects in the circuit).



A. Deac et al., Nature Phys. 2008

3b. Spin-transfer driven precession for RF oscillators

- Frequency-tunable
- Output power compatible with applications (when using MgO-MTJ)
- High quality factors (Q > 10000) (in point-contacts, high fields)
- Low consumption ($I \approx$ mA)
- Small area ($d \approx$ 100 nm)



W.H. Rippard, Phys. Rev. Lett. 2004

3b. Spin-transfer driven precession for RF oscillators

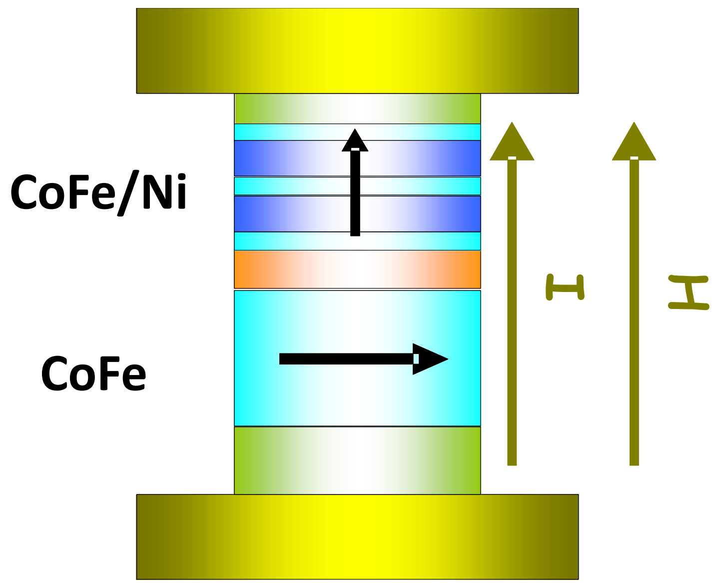
The ST oscillator trilemma:

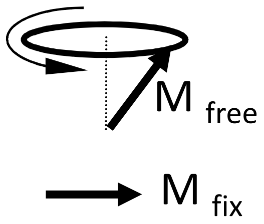
Combine high output power, narrow linewidth and low external fields.

Dr. Alina Deac | Spinelectronics FWIN | www.hzdr.de/FWIN

3b. Spin-transfer driven precession for RF oscillators

In-plane polarizer / perpendicular free layer systems:





Good read-out geometry + no need for large field/current.

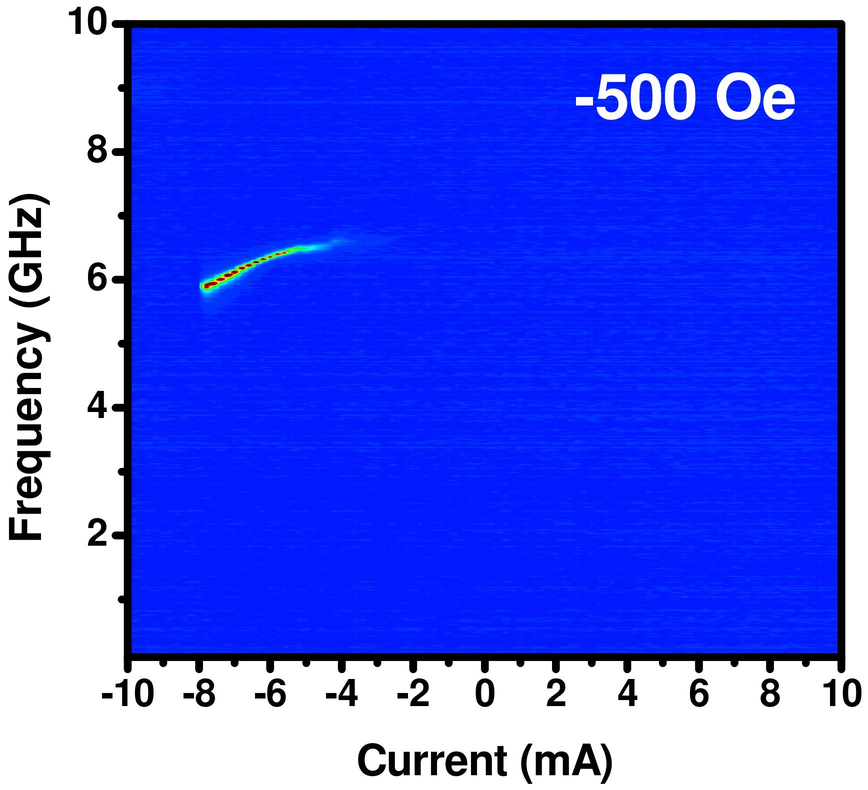
Maximizes GMR signal for given precessional angle (high power).

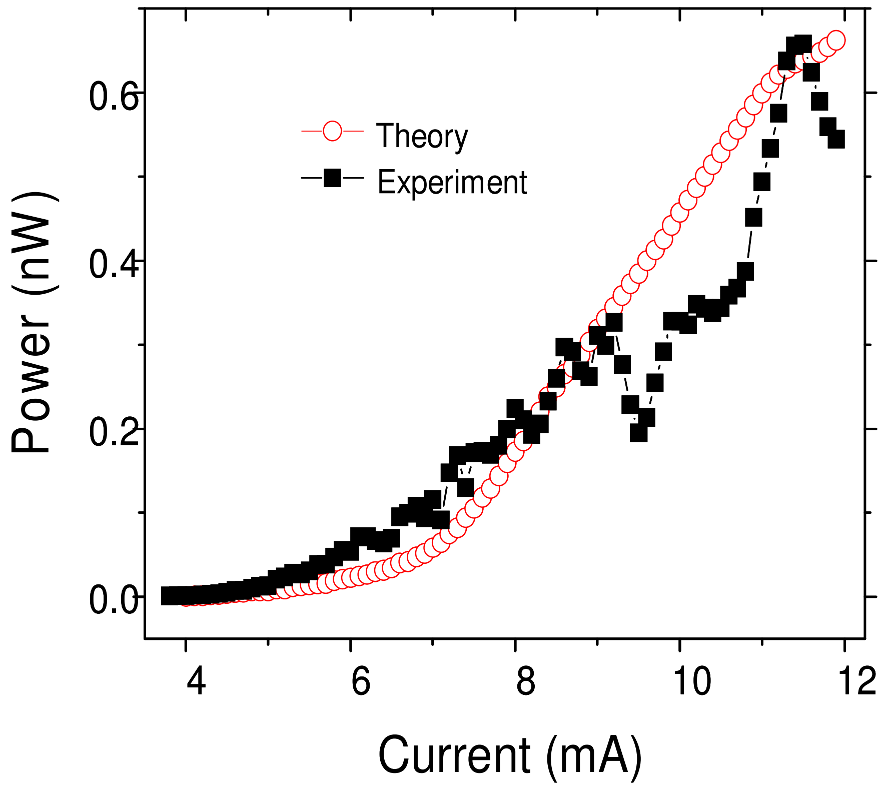
Less affected by inhomogeneous field distributions (edges) than in-plane layers. (Less 1/f noise?)

W.H. Rippard, A. Deac et al., Phys. Rev. B 2010
A. Deac et al., to be published

3b. Spin-transfer driven precession for RF oscillators

In-plane polarizer / perpendicular free layer systems:





Little 1/f noise, even at low field.

W.H. Rippard, A. Deac et al., Phys. Rev. B 2010
A. Deac et al., to be published

3c. Spin-transfer driven precession: Conclusions

Spin-transfer torque can excite steady state precession.

In-plane anisotropy: Clam-shell precession; precession angle up to 70 degrees. Predicted out-of-plane precession mode not observed (except with perpendicular fields > 7000 Oe).

Precession angle increases with the current ➠ frequency decrease. Opposite for field.

MgO- tunnel junctions provide output power in the μW range (ok for RF oscillators). However, most power is in the 1/f noise; peak width too wide for applications.

Perpendicular anisotropy layers have a more homogeneous magnetization configuration, thus less noise.

Outline

1. Magneto-resistance and spin-transfer

2. Spin-transfer induced magnetization switching:

    a. General trends (in-plane magnetized spin-valves)
    b. ST Switching for MRAM
    c. Conclusions

3. Spin-transfer driven precession:

    a. In-plane anisotropy magnetic tunnel junctions
    b. ST precession for RF oscillators
    c. Conclusions

4. Other applications

5. Final conclusions / Outlook.

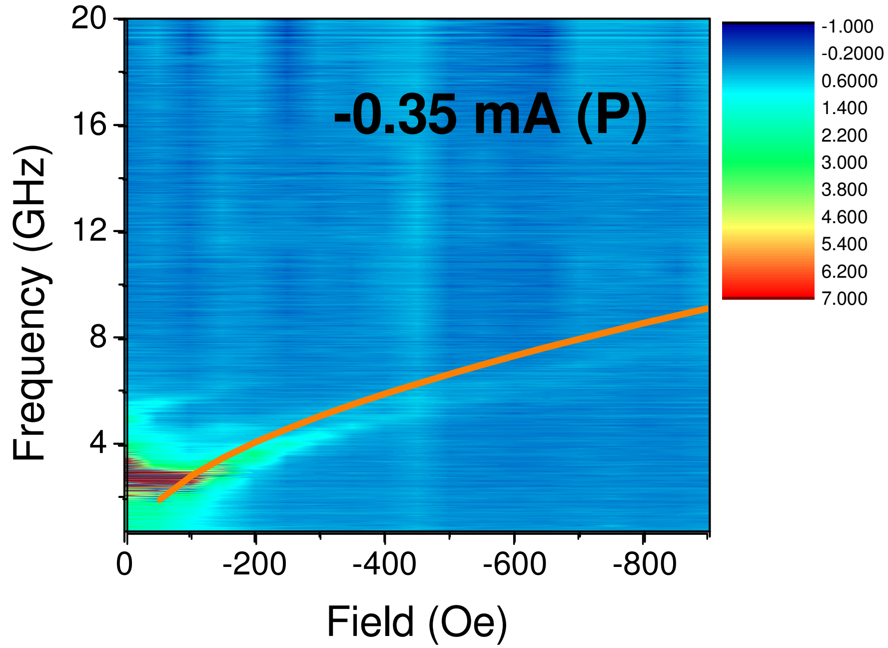
4. Other applications

1) High-frequency read head:

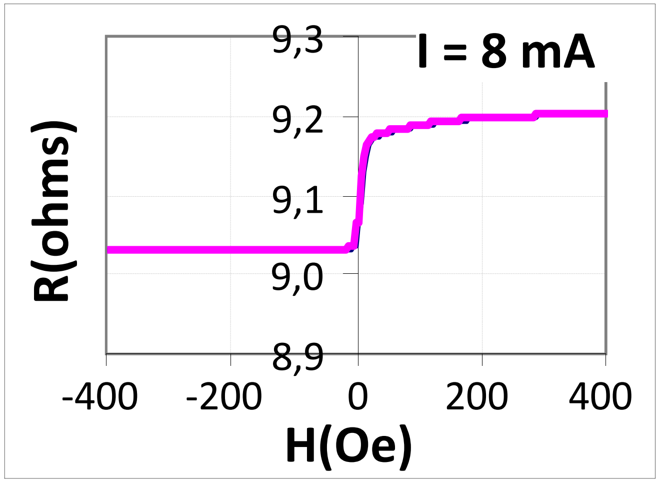
Detect frequency shift with external field.

Same issues as for ST oscillators.

Hitachi GST, MMM/Intermag 2010



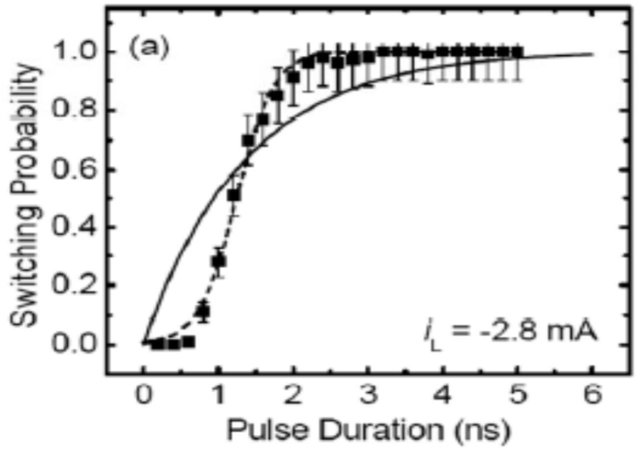
2) Field sensor, negative resistor, voltage amplifier :



Exploit the reversible switching (I, H) area on the phase diagram.

4. Other applications

3) Random Number Generator ("Spin-Dice"):



Switching is (partially) thermally activated, i.e. stochastic.

If P = 0.5, the output will randomly vary between "1" and "0".

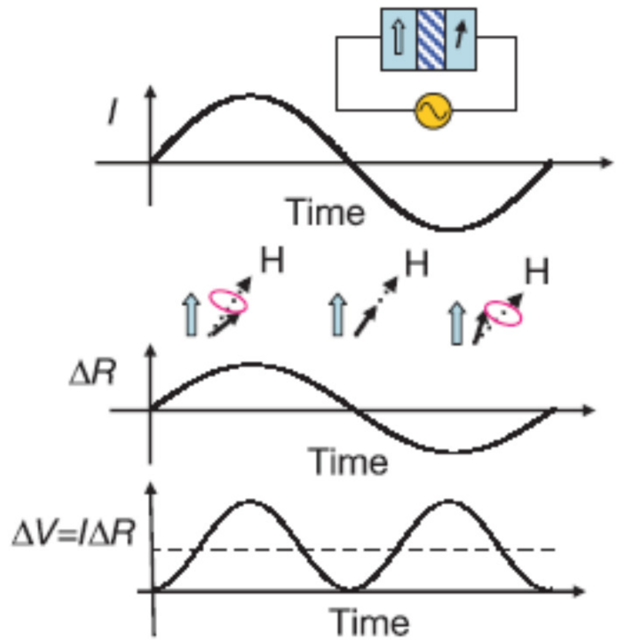
S. Kaka et al., J. Magn. Magn. Mater. 2005

4) Spin-torque diode:

Drive the free layer to resonance using a small ac current (<< I_c).
ac current x *ac* resistance ➠ *dc* voltage.

Can be used to characterise individual nanomagnets (Co/Pd nanodots).

A.A. Tulapurkar et al., Nature 2005



Outline

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5. Final conclusions / Outlook

Switching:

Considerable effort from industry to push ST-MRAM. Concentrate on fabrication of MgO tunnel junctions with perpendicular anisotropy.

Precession:

Still many fundamental questions unanswered:

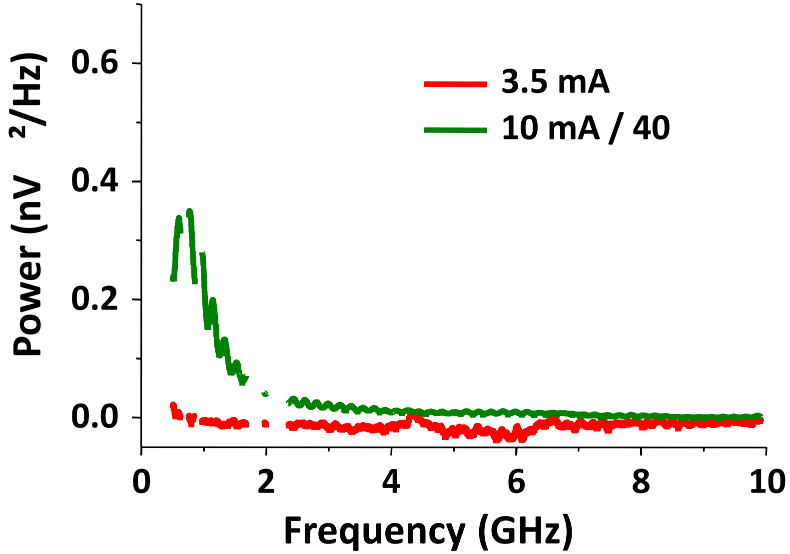
- Origin / modeling of linewidth (other than broadening due to incoherent dynamics)
- Phase / Phase locking between oscillators (series, parallel).

ST-FMR emerging as new tool for characterising individual magnetic nanoobjects.

Other materials: ferrimagnets, antiferromagnets, organic ?

3a. Spin-transfer driven precession: High currents

Experiment



Stochastic jumps between several precessionaltrajectories

Explains the high power excitations at frequency ~1GHz much below usual FMR frequencies.

Strange attractors as in non-linear dynamics.

K.J. Lee, A. Deac et al. , Nature Mater. 2004

Micromagnetic simulations