Spin Torque and Magnetic Tunnel Junctions

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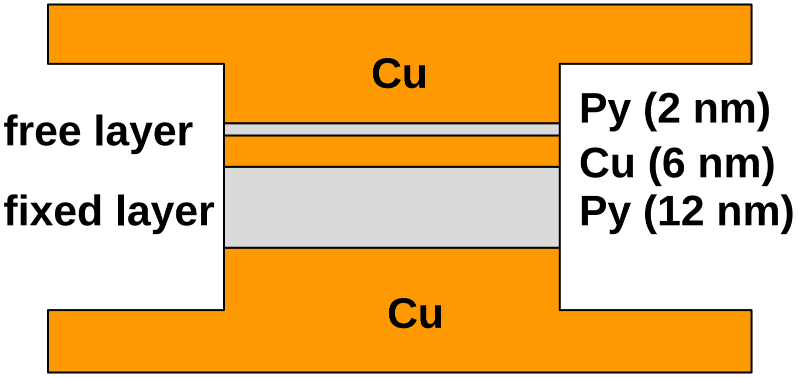
Outline

- Spin torque switching in spin valves
  - Switching speeds
  - Asymmetry of switching currents (spin torque and spin accumulation)
  - Reducing switching current levels

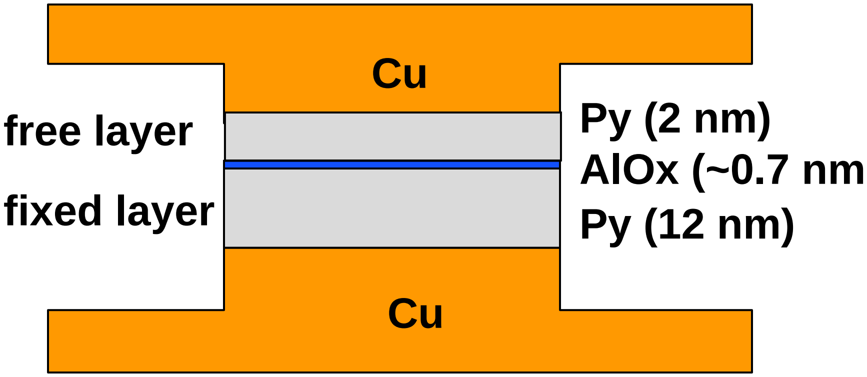
- Non-uniform spin torque systems
  - Switching by concentrated spin current injection
  - Vortex spin torque oscillator

- Spin torque in magnetic tunnel junction
  - Probing spin torque as function of tunnel junction bias

Realizing Spin Transfer Effects



Nanopillar GMR
SPIN VALVE



Nanopillar
MAGNETIC TUNNEL JUNCTION

Low impedance ~ 0.01 Ω-μm^2
GMR (ΔR/R) ~ **10**-20%

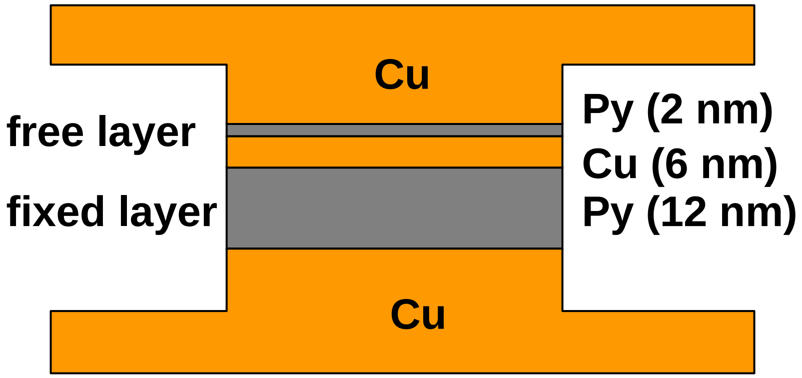
High impedance ~ 1 - 100 Ω-μm^2
GMR (ΔR/R) ~ < 50-90+%
(varies with barrier thickness)

Critical current densities quite similar in good spin valves and MTJs
High polarization of MTJs may give a ~ 2x advantage

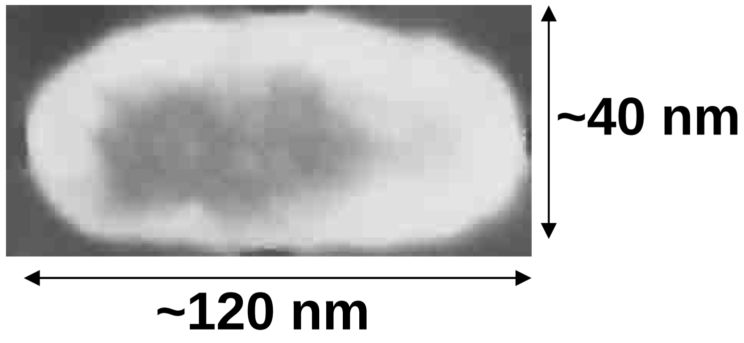
Conventional ferromagnet spin transfer devices require lateral dimensions ≤ 250 nm to avoid significant self-field effects from required current levels

Practical issues for spin-torque switching**: speed, switching currents, impedance**

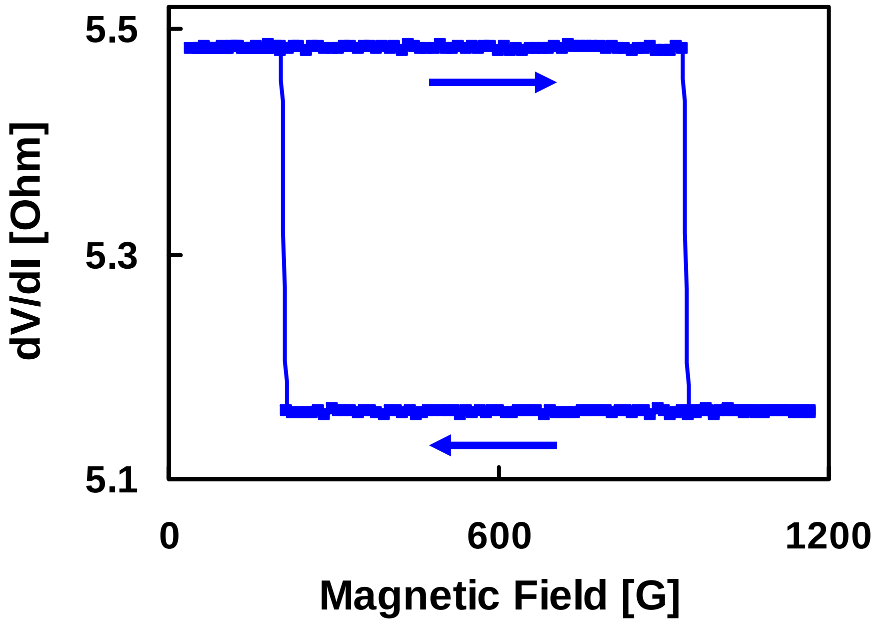
Spin Transfer Driven Magnetic Reversal

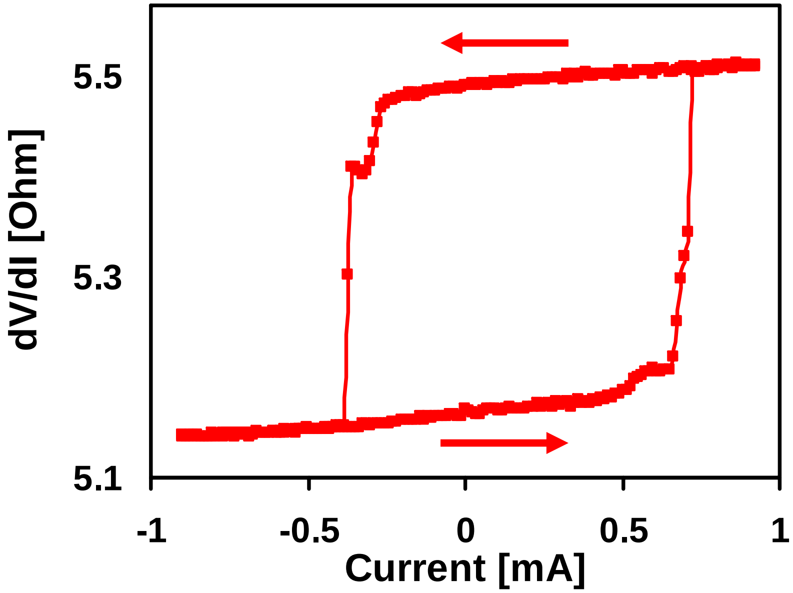


Nanopillar Spin-Valve



T = 4.2 K





Time Resolved Measurements of Nanomagnet Dynamics

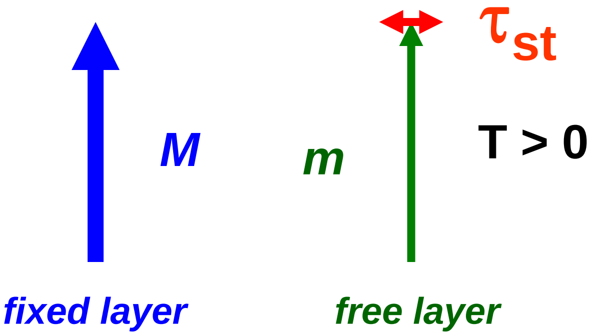
Challenges

In "standard" nanopillar devices, initial direction of spin torque is determined by a random thermal fluctuation from equilibrium. This leads to a random phase of the precessional dynamics.

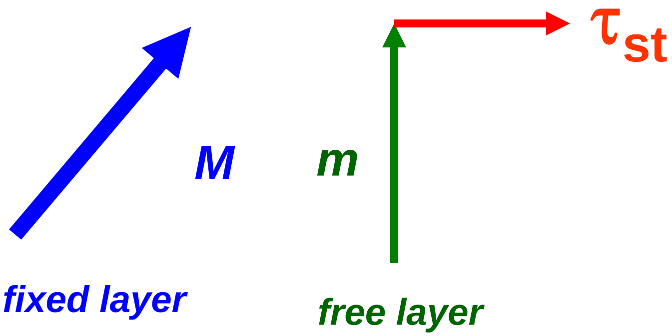
Time-resolved measurements require devices with a non-zero angle between the free and the fixed layers.

V(t) < 1 mV, Δt ~ 10-100 psec

$$\left|\vec{\tau}_{st}\right| \sim \left|\vec{m}\times\vec{I}\times\vec{m}\right| = m^2 I\cdot\sin(\theta)$$

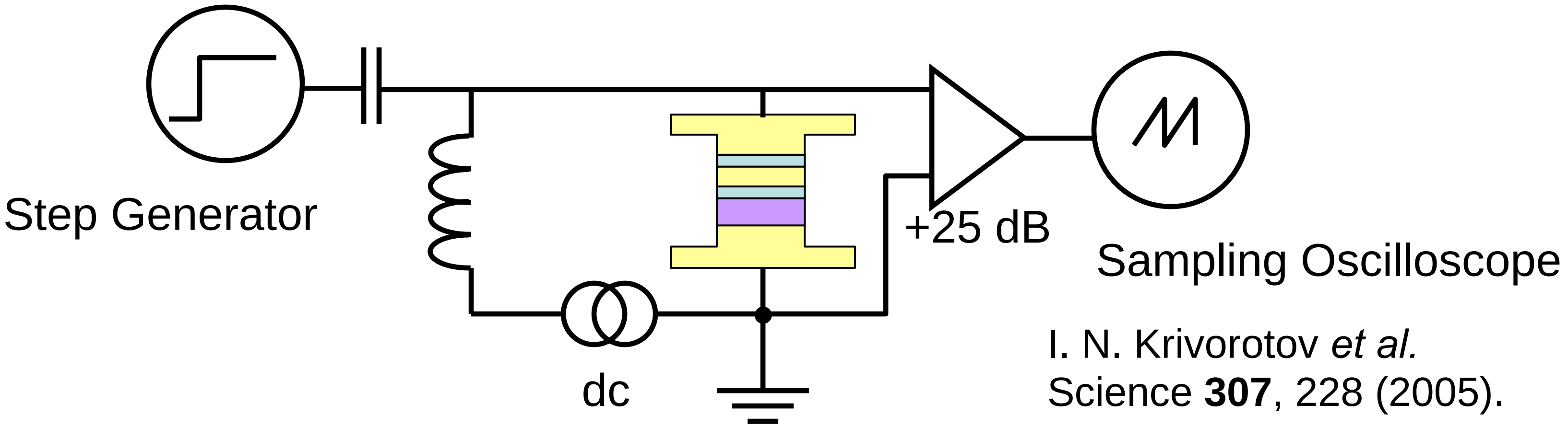


$$\sin(\theta) << 1$$

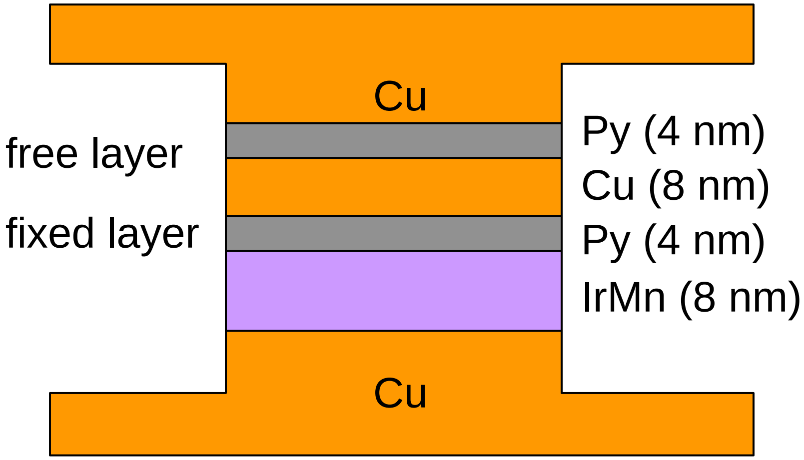


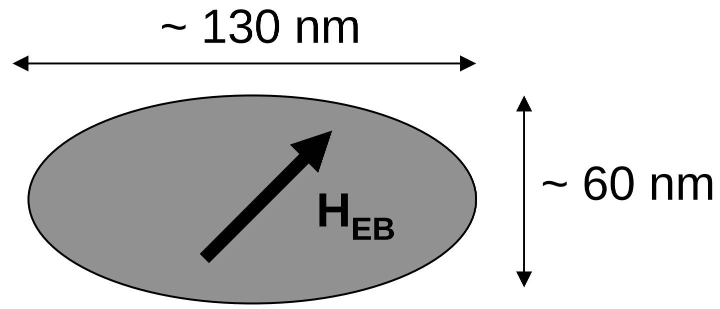
$$\sin(\theta) \approx 1$$

Measurements of Spin-Transfer Dynamics



I. N. Krivorotov *et al.*
Science **307**, 228 (2005).

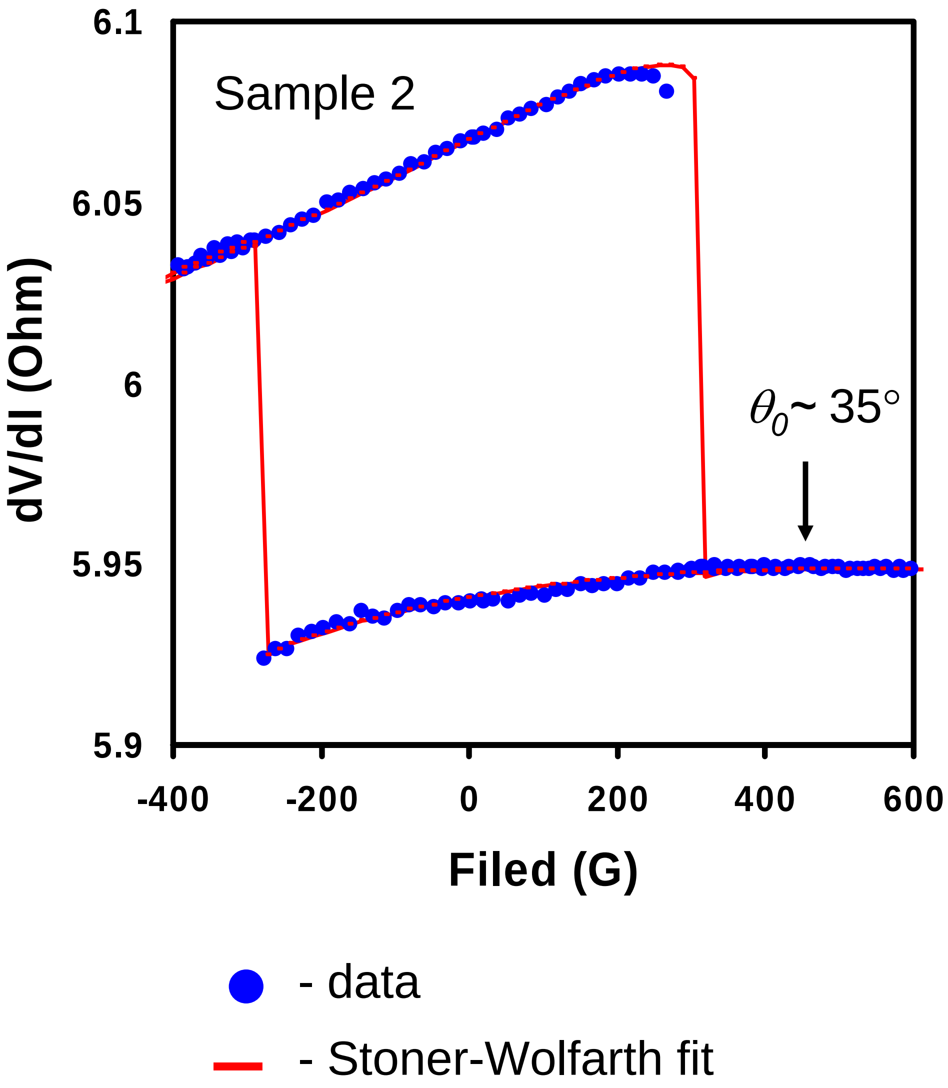




$\mathbf{H}_{\mathbf{EB}}$ = exchange bias field

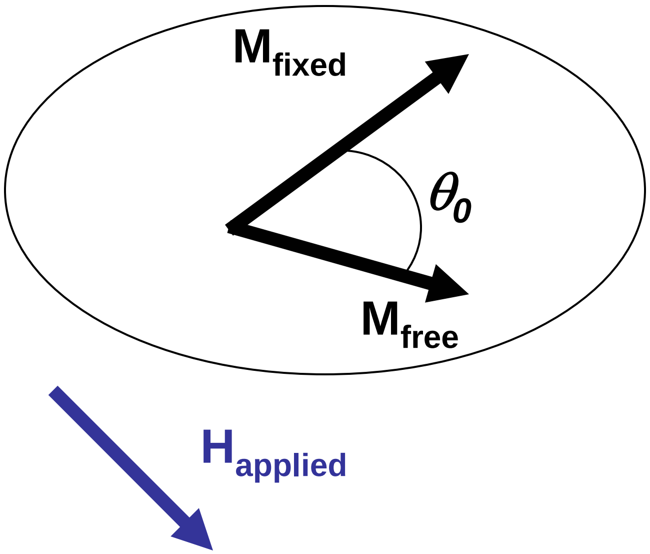
Exchange biasing of the fixed Py layer at 45º to the easy axis results in a non-zero initial angle between magnetic moments of the fixed and free layers. This establishes a well-defined phase for precessional dynamics of the magnet.

Equilibrium Configuration of Magnetization



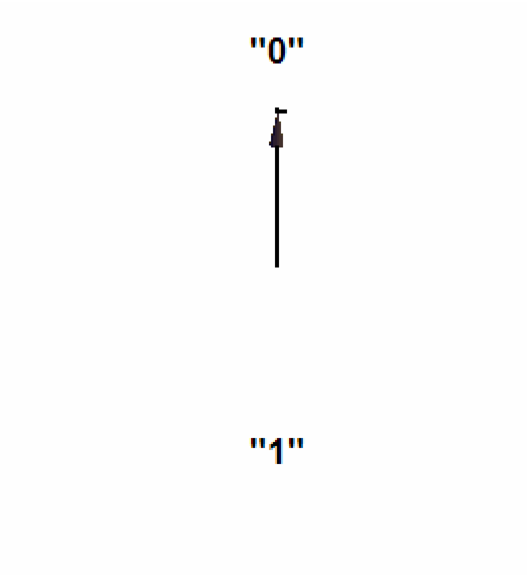
$$R = R_0 + \Delta R \frac{1 - \cos^2(\theta/2)}{1 + \chi \cos^2(\theta/2)}$$

χ = 0.5; H_{eb} = 1.5 kG



High Speed Spin Torque Switching

switching time[1] → $\tau = \dfrac{\ln\left(\pi / 2\theta_0\right)}{\left|I - I_{co}\right|}$



θ_0 ~ initial angle between magnetizations
-set by thermal fluctuations or magnetic pinning

I_{c0} is T= 0 critical current

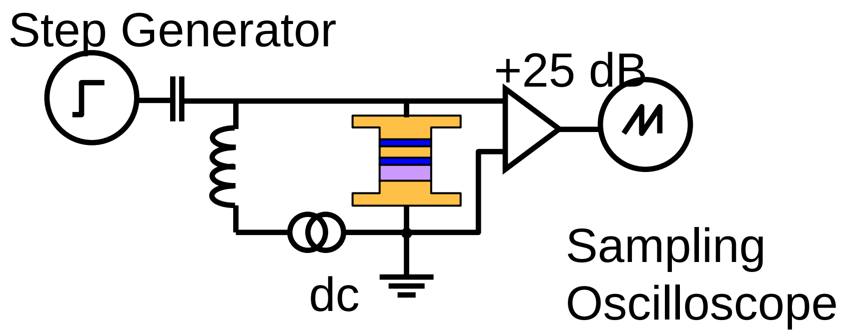
Spin polarized current must deliver sufficient spin angular momentum to nanomagnet to reverse magnetic moment.

Hence **($I - I_{c0}$)x τ = constant**

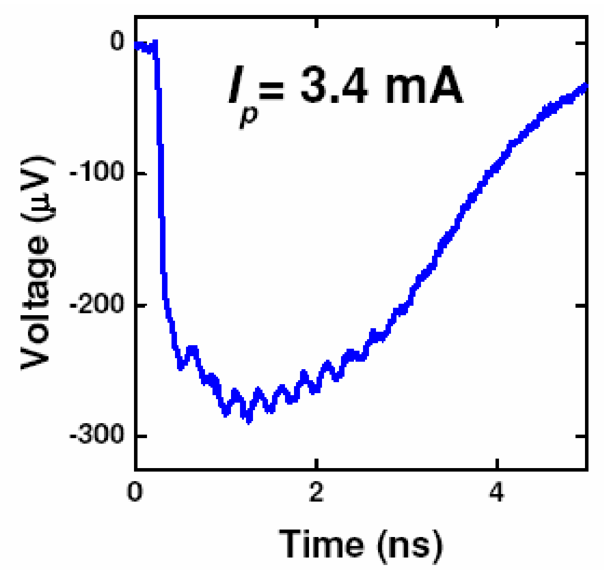
Faster reversal requires larger I_{switch}

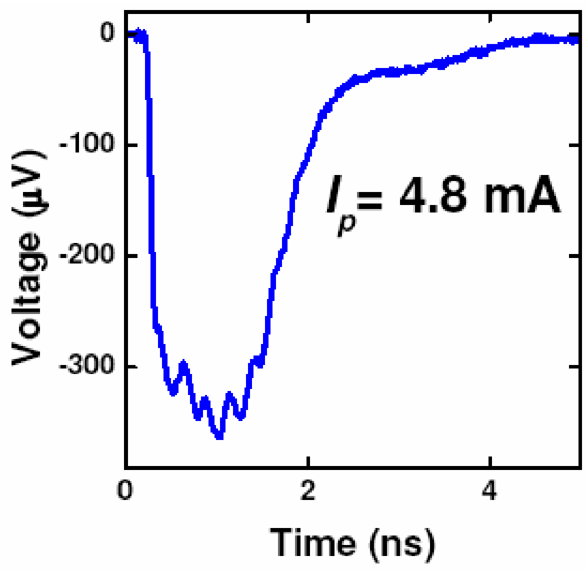
[1] J.Sun, Phys Rev B. **62**, 570 (2000)

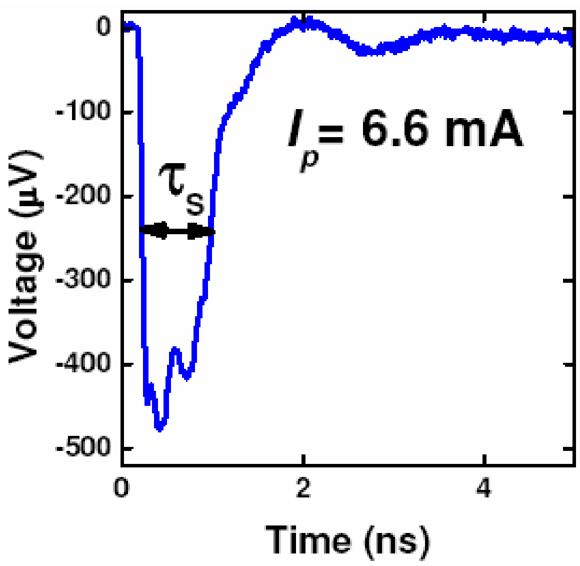
How fast is spin-transfer-driven switching?

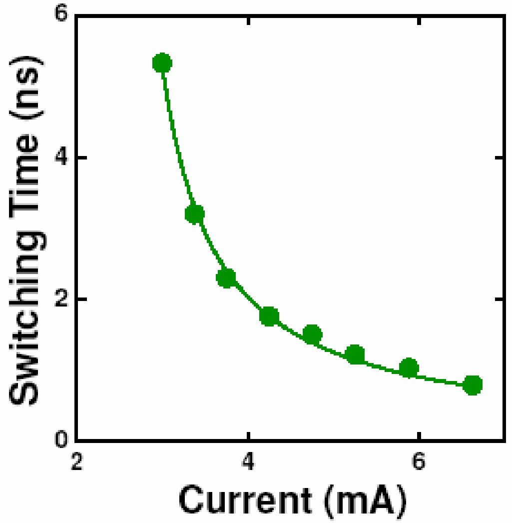


Measure time dependent response of nanopillar resistance to step pulse.









Switching time < 1 ns at high pulse amplitude

I. N. Krivorotov *et al.*
Science **307**, 228 (2005).

Critical Current for Spin Torque Switching

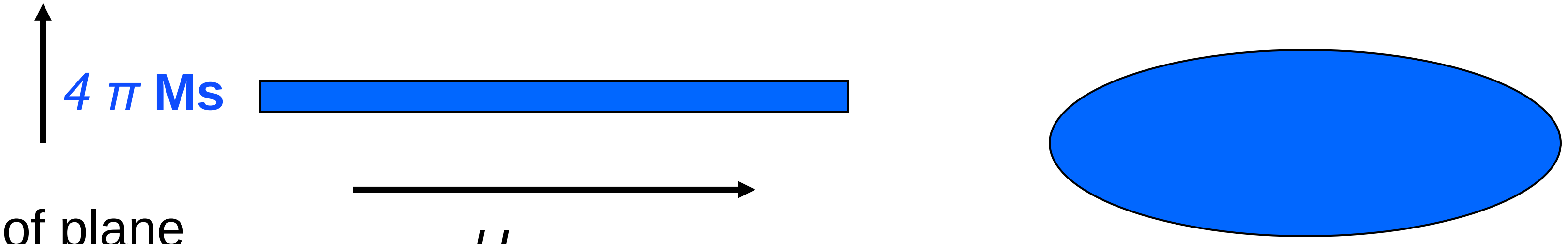
$$I_{co}^{+} = \alpha\, e\, \mathbf{M}_s\, \mathrm{Vol}\, [H + H_{an} + 2\pi \mathbf{M}_s] / hg(0) \approx 2\pi\, \alpha\, e\, \mathbf{M}_s^2\, \mathrm{Vol} / h\, g(0)$$

$$I_{co}^{-} = \alpha\, e\, \mathbf{M}_s\, \mathrm{Vol}\, [H - H_{an} - 2\pi \mathbf{M}_s] / hg(\pi) \approx 2\pi\, \alpha\, e\, \mathbf{M}_s^2\, \mathrm{Vol} / h\, g(\pi)$$

$$J_{co}^{+} \approx 2\pi\, \alpha\, e\, \mathbf{M}_s^2\, t / h\, g(0); \qquad J_{co}^{+} \approx 2\pi\, \alpha\, e\, \mathbf{M}_s^2\, t / h\, g(\pi)$$

t = nanomagnet thickness, α *=Gilbert damping parameter,* $\mathbf{M}_s$ *= magnetization*

H_{an} = shape anisotropy field



out of plane
demagnetization
field

H_{an}

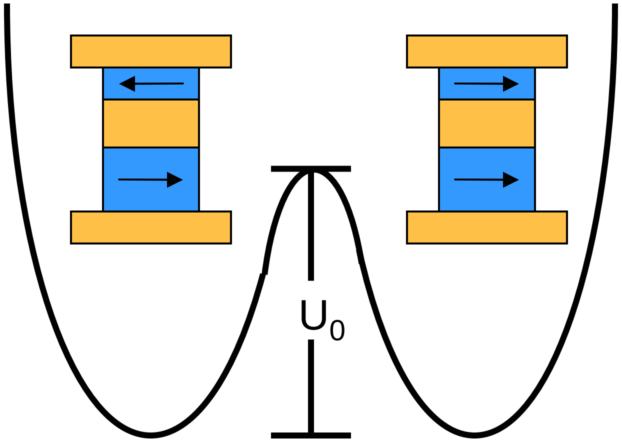
top view

To reduce J_{co} - reduce t, $\mathbf{M}_s$ and/or α but must maintain nanomagnet stability

This requires $U_K = \mathbf{M}_s \boldsymbol{H}_{an}\, \mathrm{Vol}/2 > 50\, k_B T$ *- ten year bit stability*

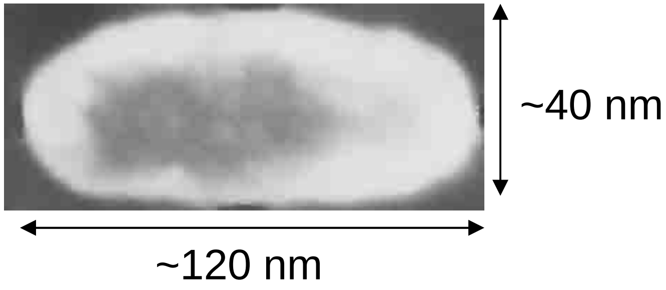
Decreasing Switching Currents

<u>MRAM requirement</u>:
Bit lifetime ~ 10 years → $U_0 = 1$ eV at RT
With heating to 100º C → $U_0 = 1.3$ eV



$$I_c \propto M_s^2\,\alpha\,(\mathrm{Vol})$$
$$U_0 \propto H_{an} M_s (\mathrm{Vol})$$
$$H_{an} \sim M_s (t/t_0)$$

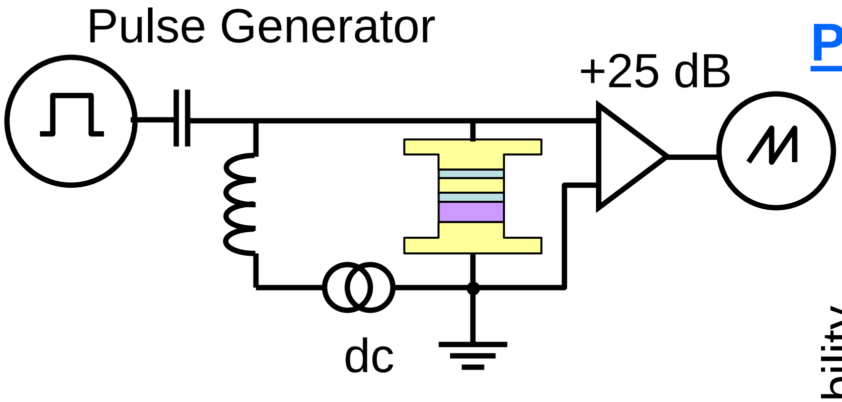
Minimize M_s and sample volume
Use shape anisotropy to maximize H_k
thick and elongated



4.5 nm Py : $U_{0,P\text{-}AP}=0.85\ eV,\ I_{c0}^{+} = .42\ mA$
$U_{0,AP\text{-}P}=0.73\ eV,\ I_{c0}^{-} = .39\ mA$

I_{c0} = zero-temp critical current. **Need $I_{co} < 100\ \mu A$**
Need to decrease damping and improve micromagnetics

Spin torque switching currents of low M_s free layers



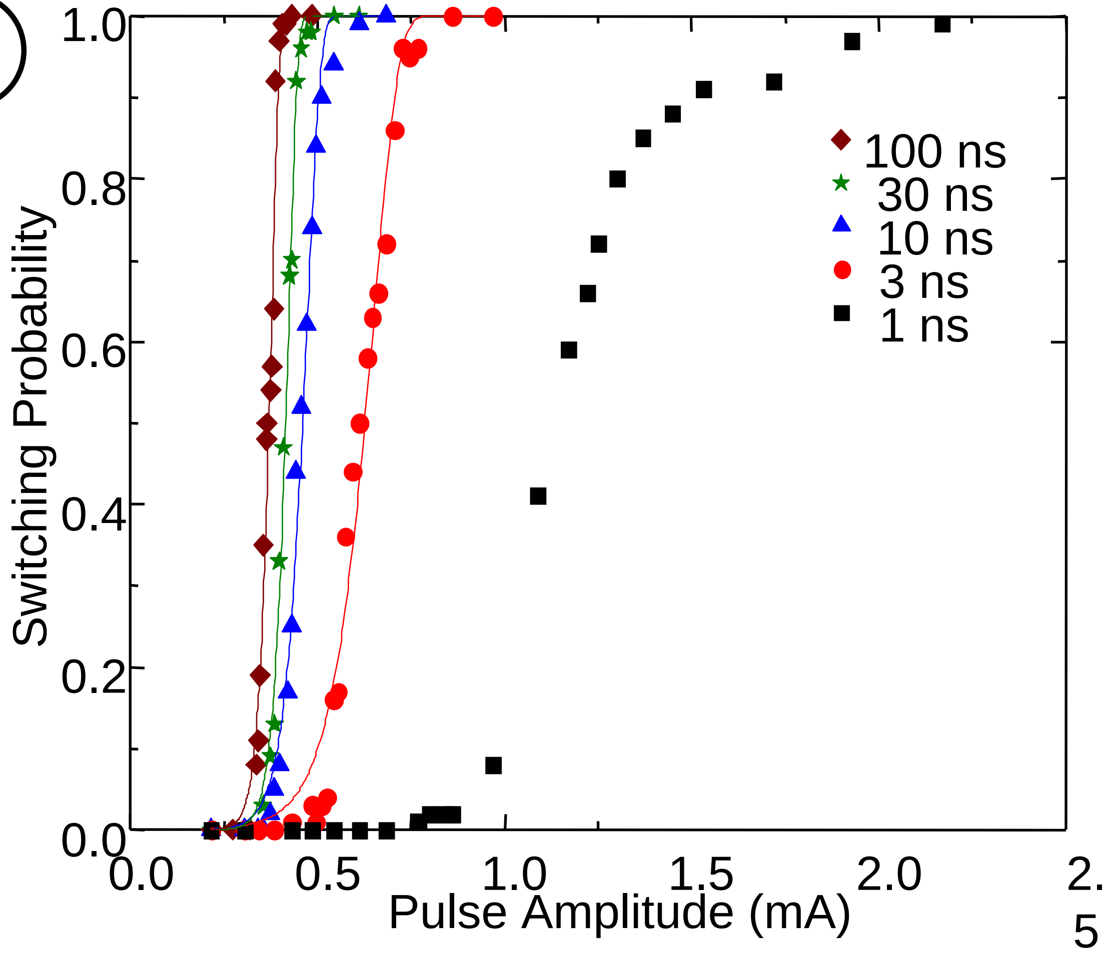
Apply current pulse to device.

Determine if pulse has switched device.

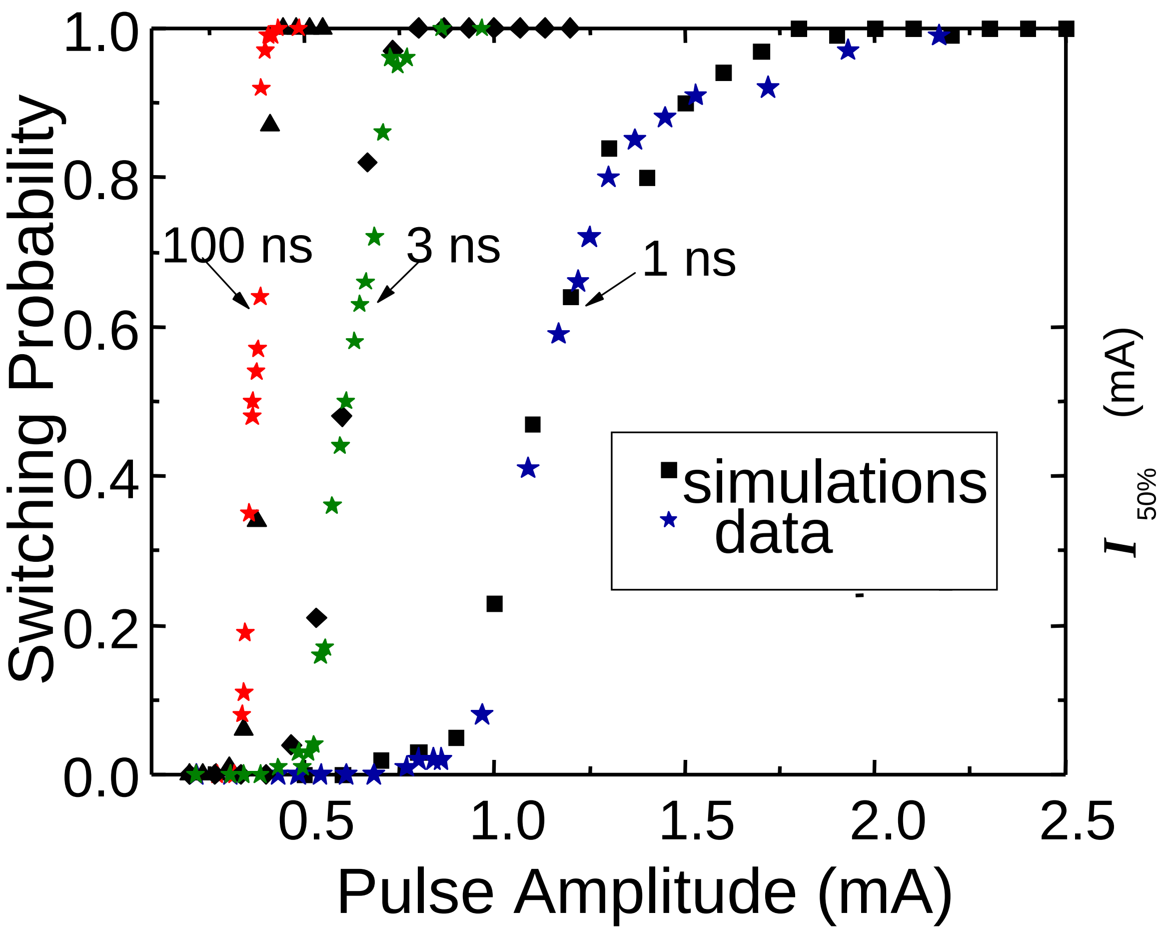
Increase pulse duration until probability of switching goes to unity.

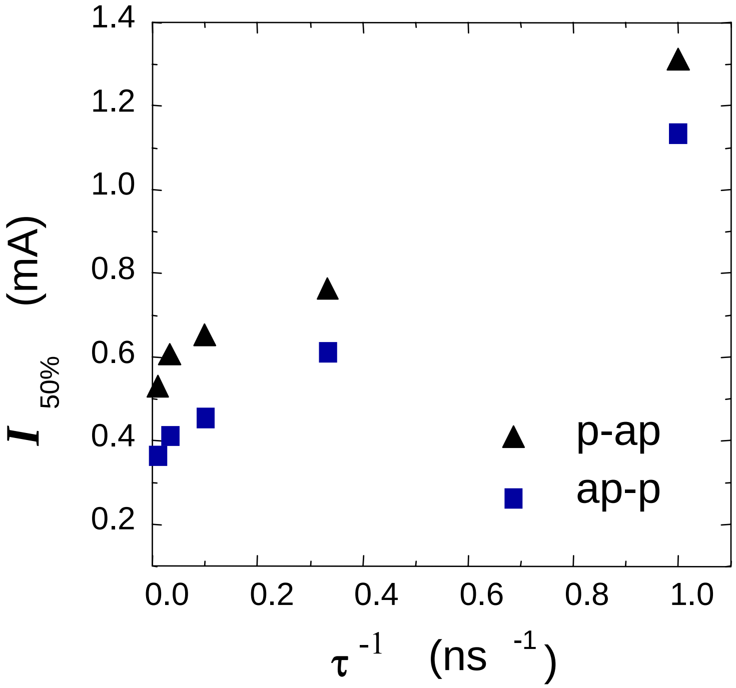
Increase current pulse amplitude and repeat.

Pulse-response measurements



Comparison with Single Domain LLG Simulations





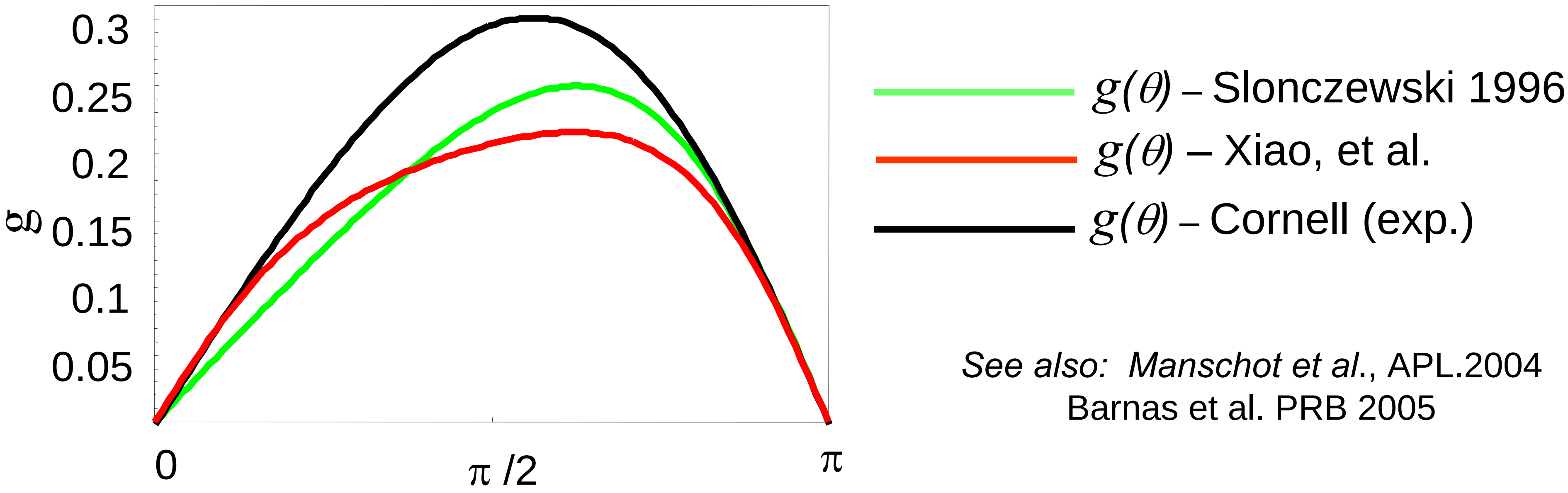
Fitting to LLG simulation yields empirical spin-torque function and damping

N.B. Similar AP-P and P-AP switching currents in these devices

Braganca et al. APL ‘05

Spin Transfer Torque Function

$$\frac{d\mathbf{m}}{dt} = \gamma\left(\mathbf{m}\times\mathbf{H}_{\mathbf{eff}}\right) - \alpha\left(\mathbf{m}\times\frac{d\mathbf{m}}{dt}\right) + \frac{\mu_B}{e}\,\frac{g(\theta)}{m^2\sin(\theta)}\left(\mathbf{m}\times\mathbf{I}\times\mathbf{m}\right)$$



See also: Manschot et al., APL.2004
Barnas et al. PRB 2005

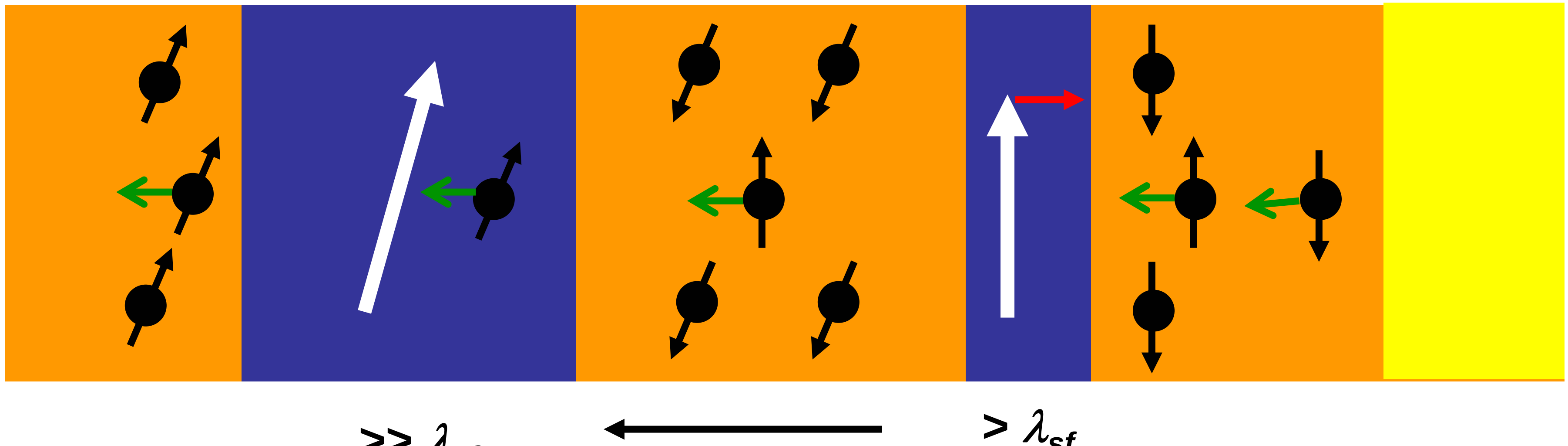
$I_{c,\,P\text{-}AP} \sim g'(0)$; $I_{c,\,AP\text{-}A} \sim g'(\pi)$

$$\boxed{g(\theta) = \frac{A\sin(\theta)}{1+B\cos(\theta)}}$$

– effect of device geometry on g(θ)

–spin accumulation affects?

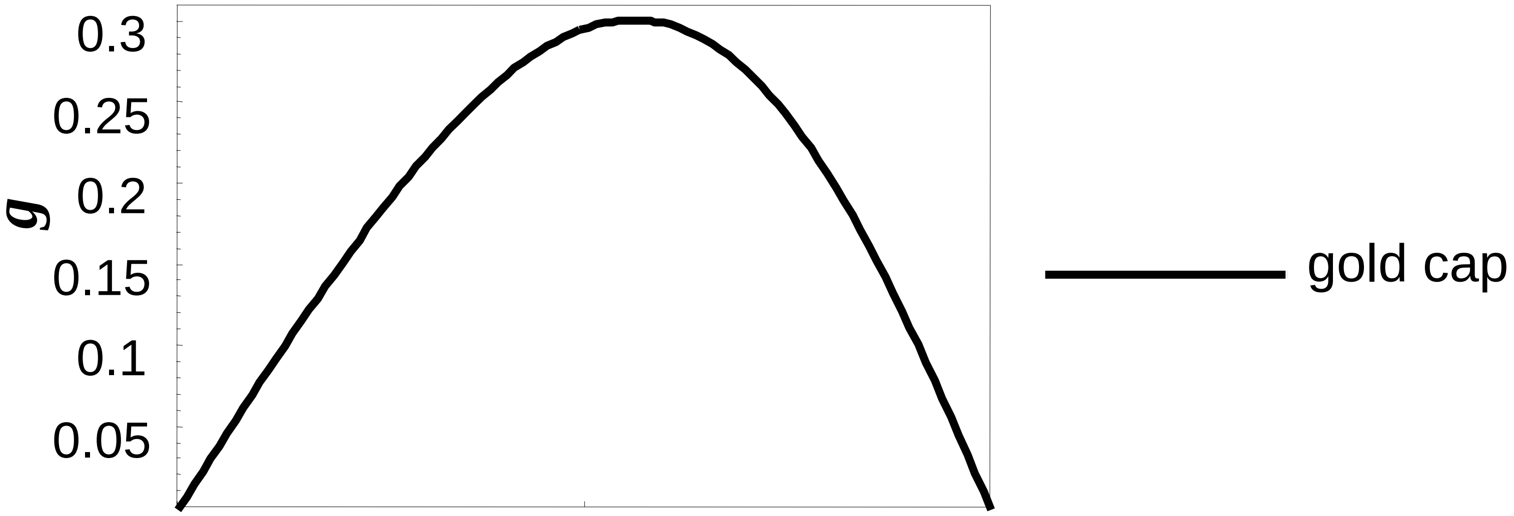
Effect of Electrode Structure on Spin Torque



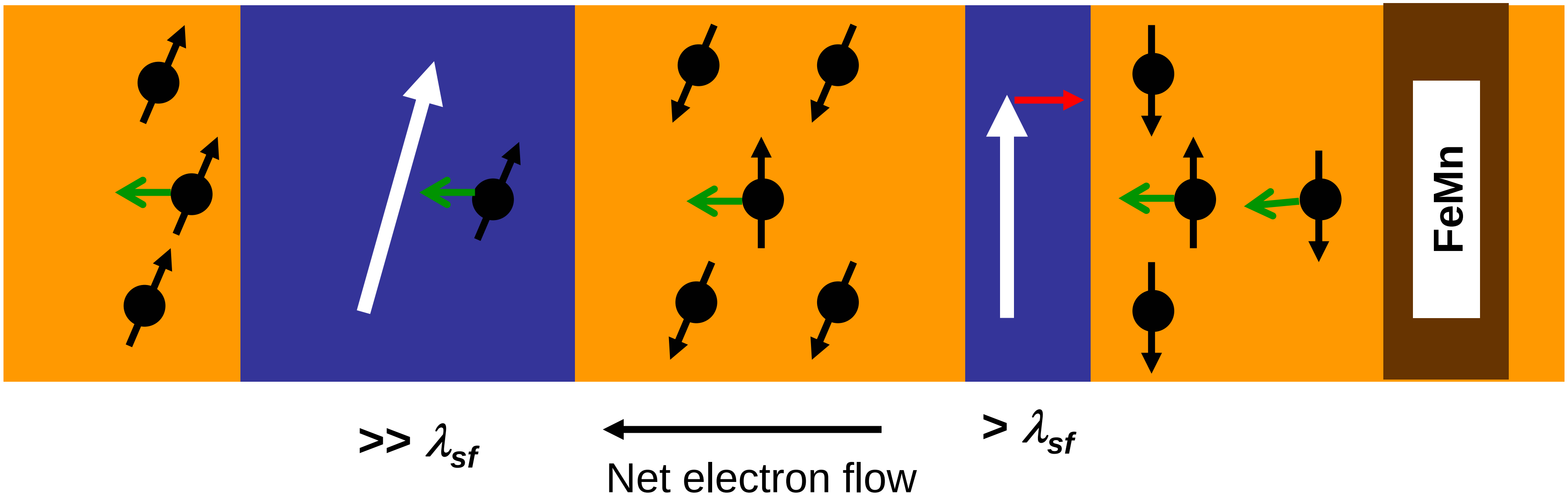
$>> \lambda_{sf}$

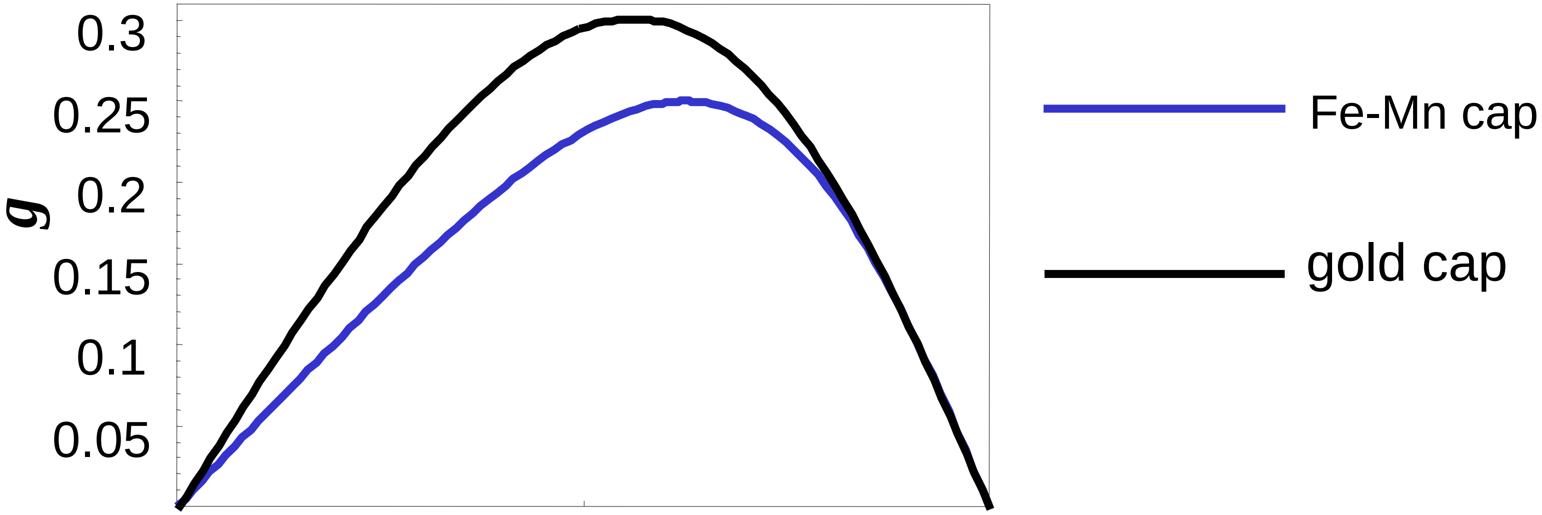
Net electron flow

$> \lambda_{sf}$



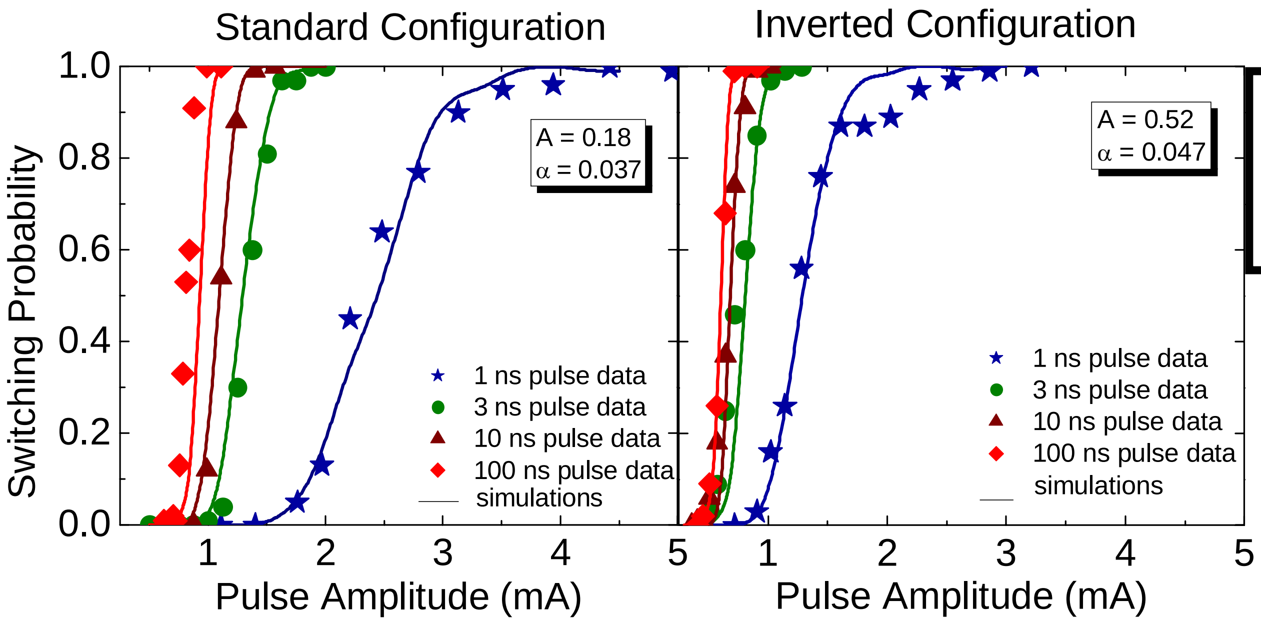
Effect of Electrode Structure on Spin Torque

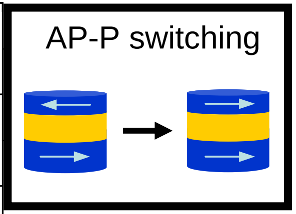


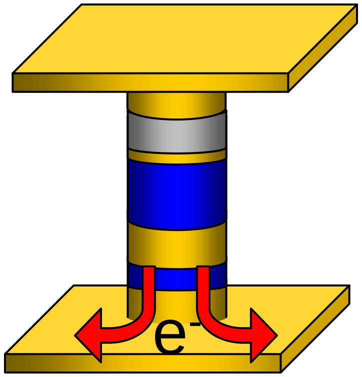


Pulsed Current Experiments

Pt Capped Devices







LLG simulations

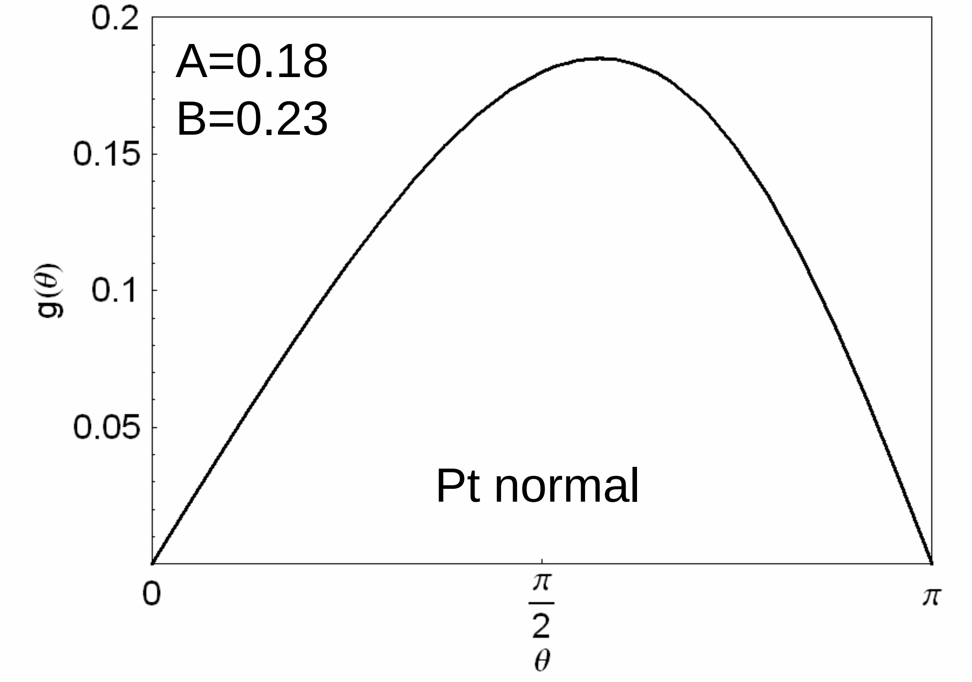
Torque angular dependence ⟶ $$g(\theta) = \frac{A\sin(\theta)}{1+B\cos(\theta)}$$

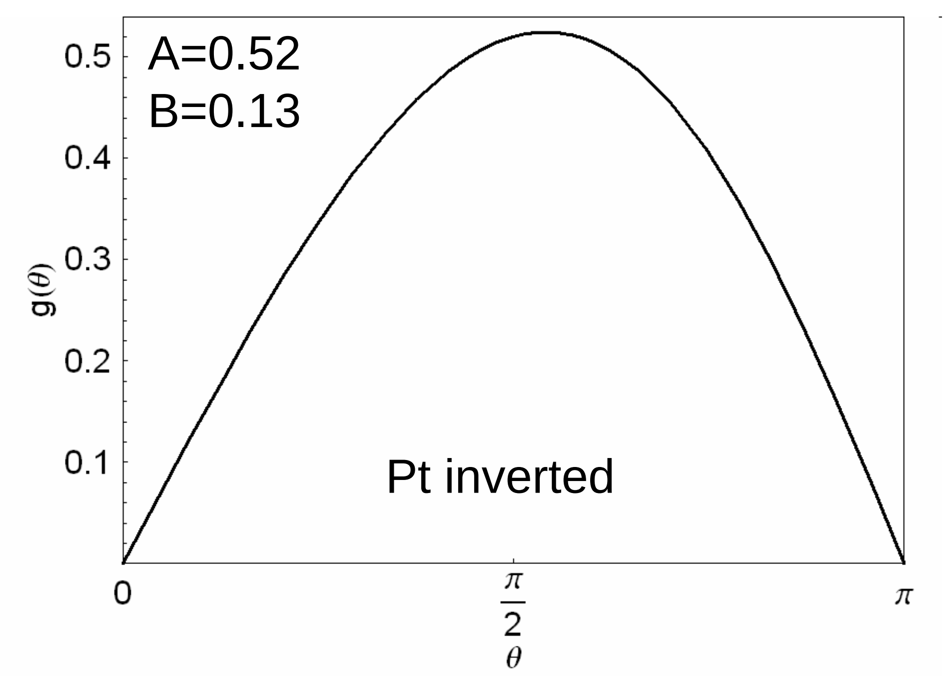
A – Torque amplitude – from spin current and spin accumulation

$$B = \frac{1-\gamma}{1+\gamma} \qquad \gamma = \frac{I_{switch,AP\rightarrow P}}{I_{switch,P\rightarrow AP}}$$

- **Spin pumping enhancement** in inverted samples → Better spin sinking in extended Cu lead
- LLG fit deviation from data at large currents – microwave oscillations

	Au cap	Fe-Mn cap	Pt cap	Pt inv.
A	0.25-0.30	0.12-0.16	0.18-0.21	0.45-0.52
B	0.02-0.19	0.32-0.33	0.11-0.23	0.08-0.13
α	0.025-0.030	0.033-0.037	0.033-0.037	0.047



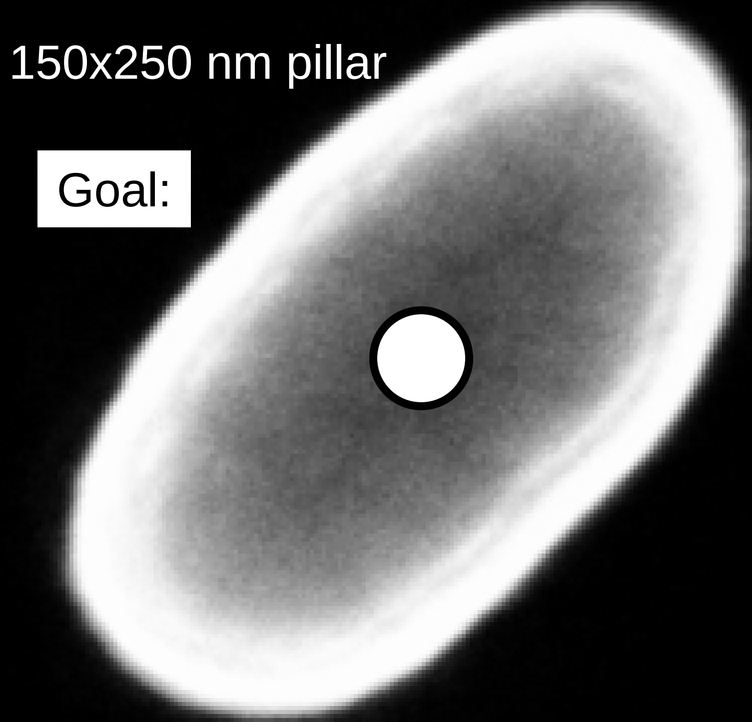


Spin-Transfer-Switching by Spatially Non-Uniform Currents

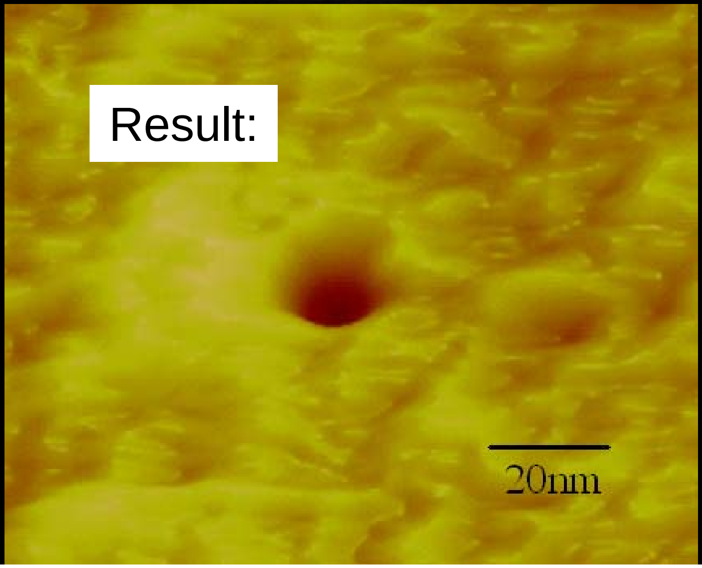
A 3nm Al_2O_3 insulating barrier with a nano-orifice is inserted into a Cu/Py spin-valve nanopillar

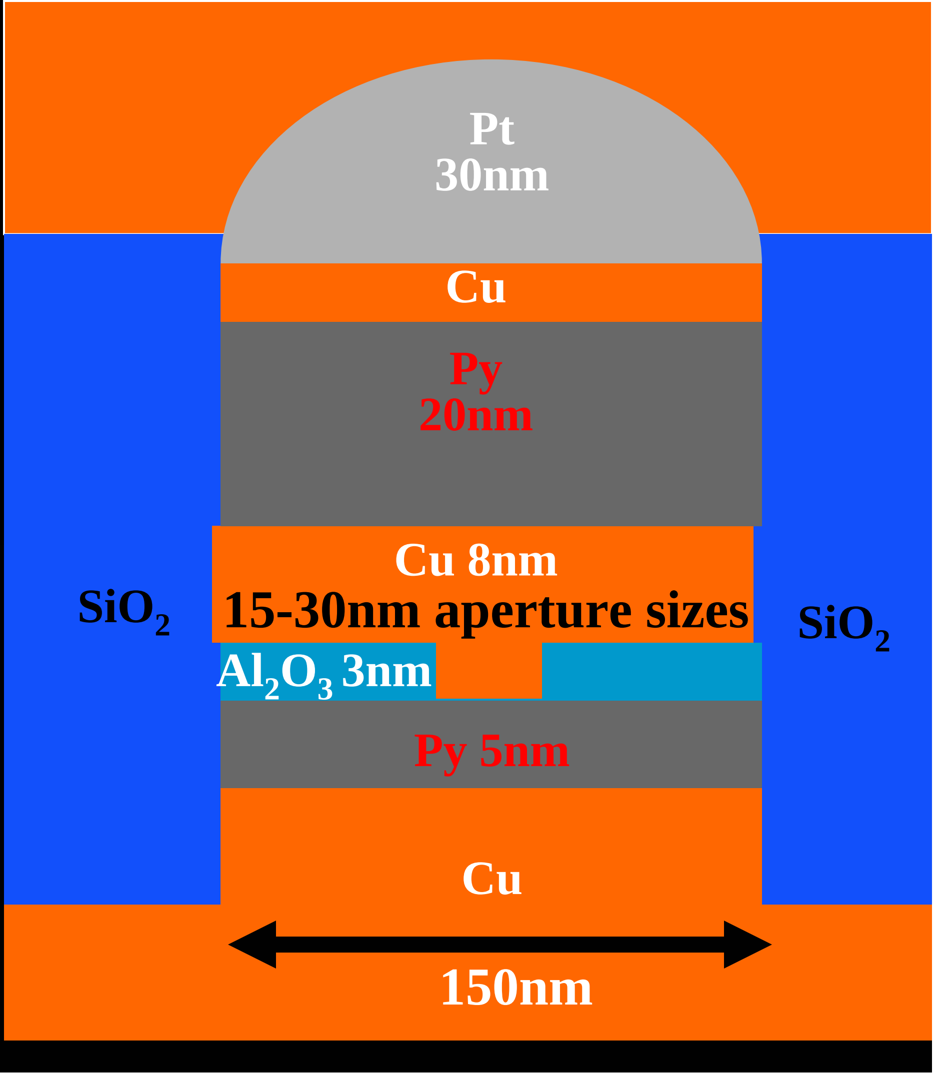
150x250 nm pillar

Goal:



Result:





Pt
30nm

Cu

Py
20nm

Cu 8nm
15-30nm aperture sizes

Al_2O_3 3nm

Py 5nm

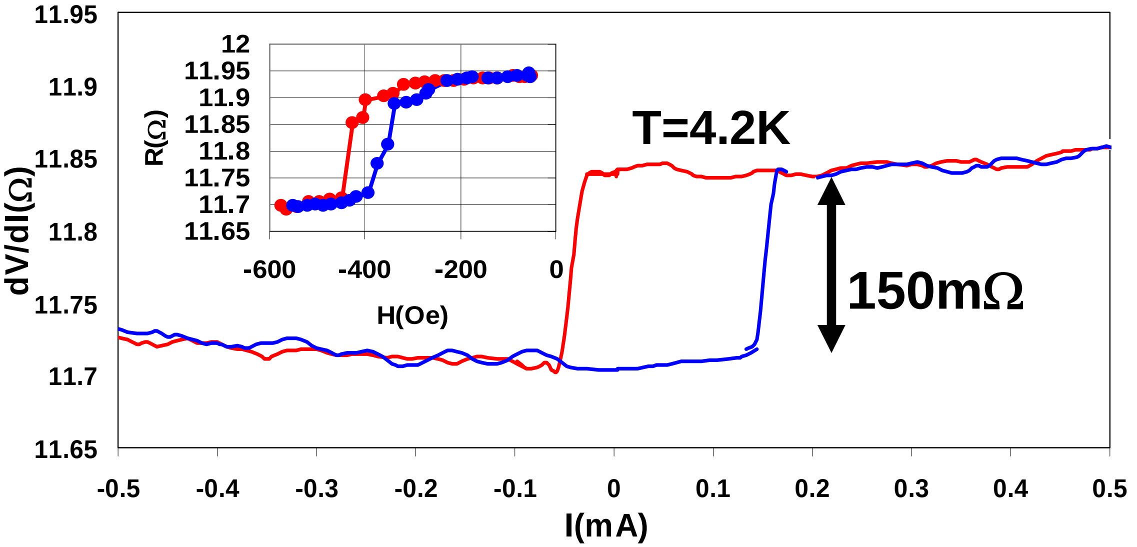
Cu

SiO_2

SiO_2

150nm

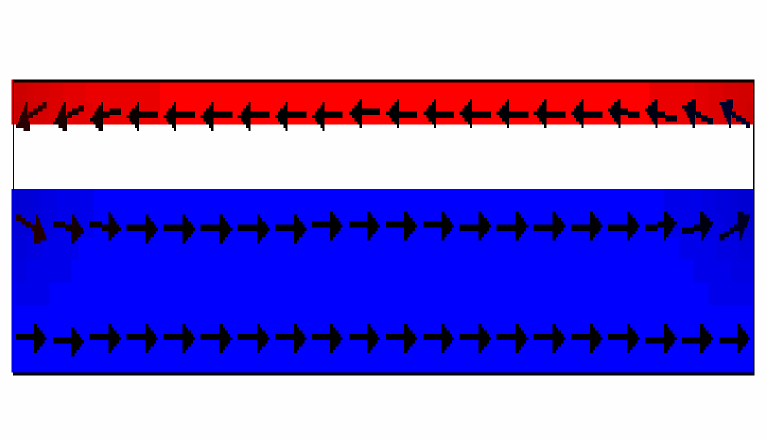
Spin-Transfer-Switching by Spatially Non-Uniform Currents

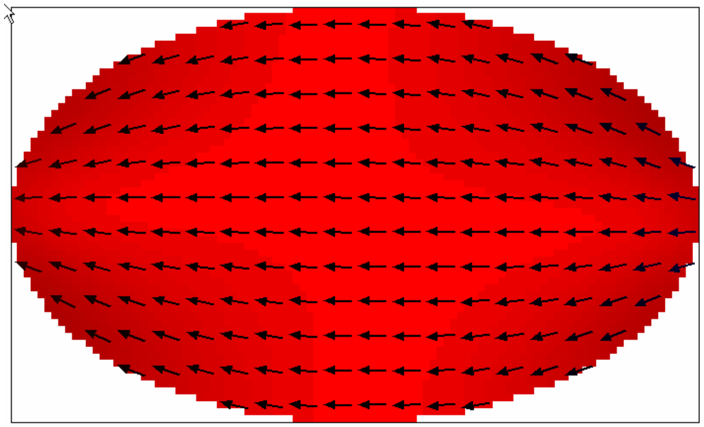


- **The nano-aperture device requires much less current to induce switching than a nanopillar with uniform current flow.**
- **Current-induced switching may not result in full reversal of the nanomagnet**

150 x 250 nm^2 with 30 nm aperture	P-AP I_{c+} = 180 μA	AP-P I_{c-} = 50 μA	J_{pillar} ~ 4x10^5 A/cm^2 J_{hole}~1.6x10^7 A/cm^2	R = 12 Ω
100 x 200 nm^2 uniform current	P-AP I_{c+} = 7.8 mA	AP-P I_{c-} = 4 mA	J ~ 1.2x10^7 A/cm^2	R = 3 Ω

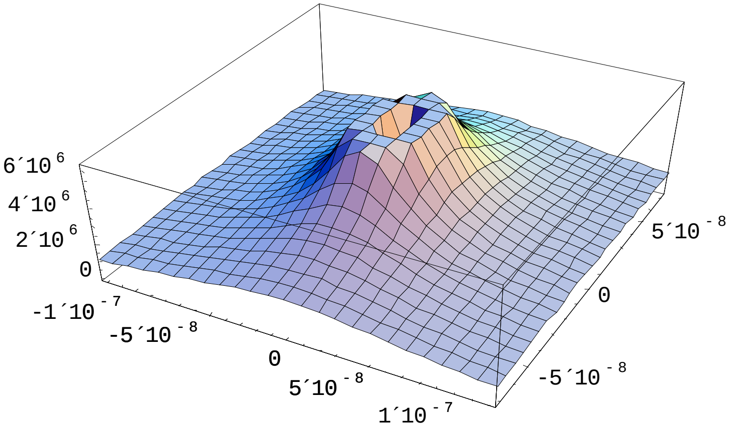
3D OOMMF Simulations

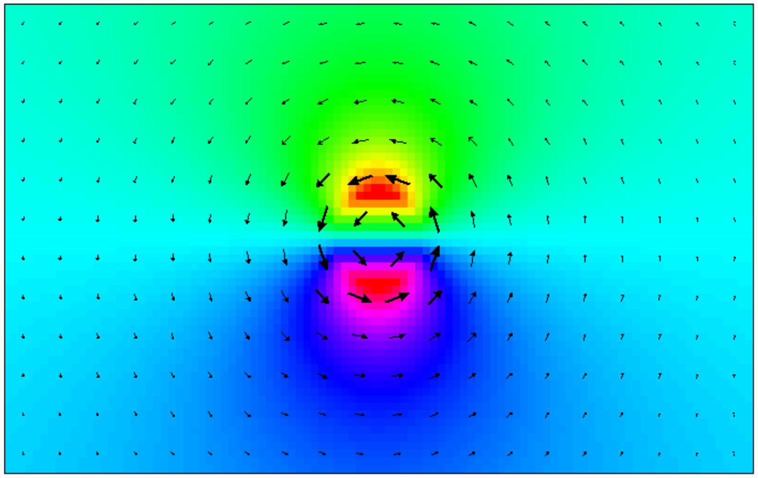


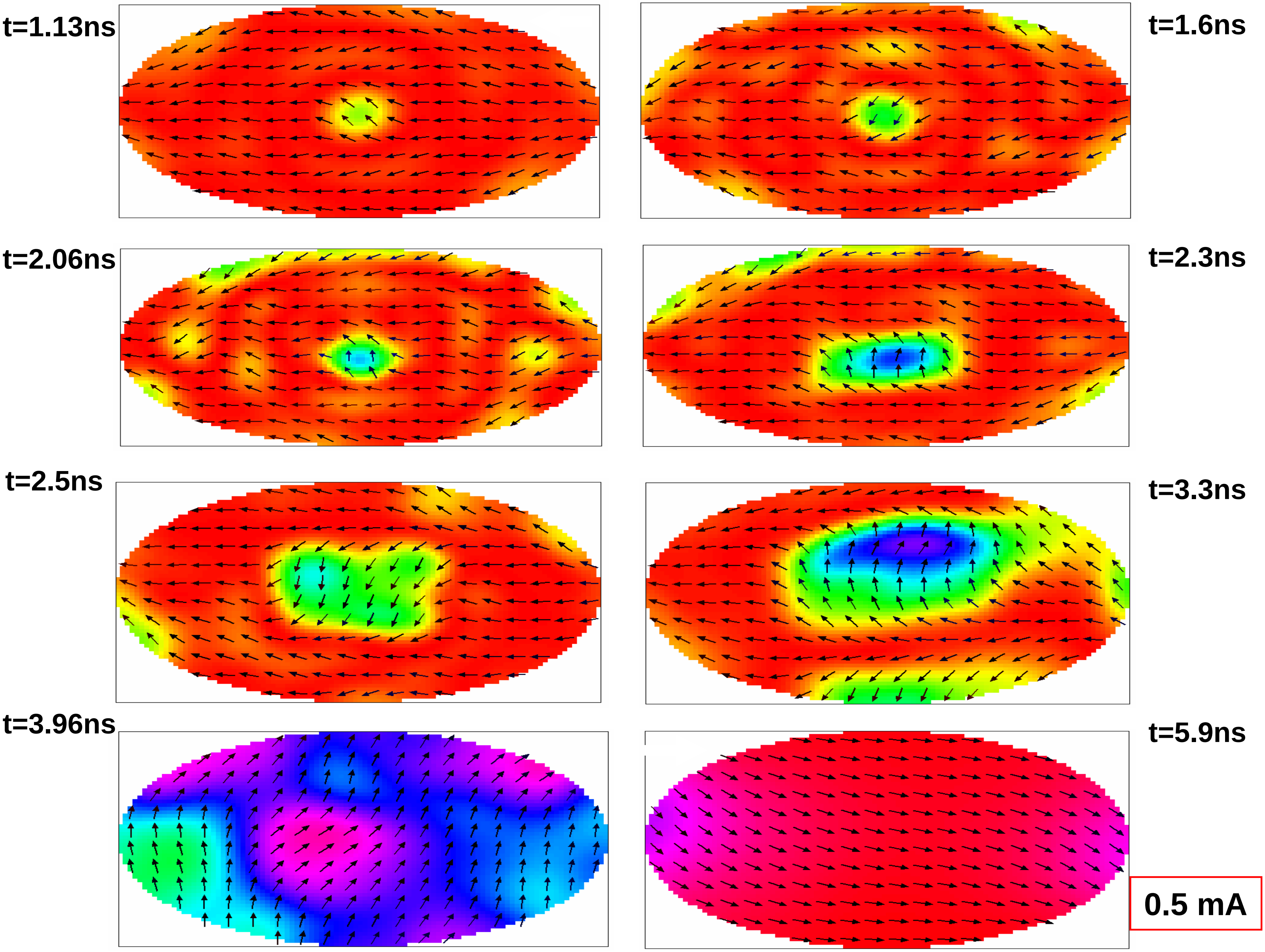


OOMMF is a public software developed by M.J.Donahue and D.G. Porter from NIST

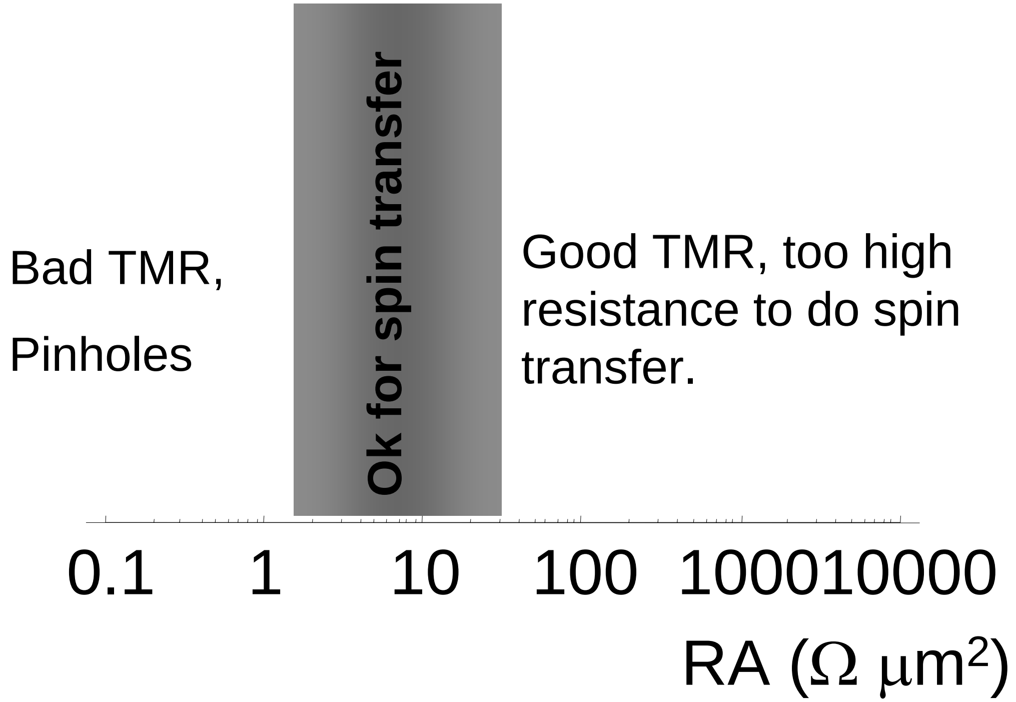
➢**The effect of spin torque was modeled using LLG equation with the Slonczweski term for each cell. The simulations were performed taking into account the Oersted field created by electron flow through a wire.**






t=1.13ns
t=1.6ns
t=2.06ns
t=2.3ns
t=2.5ns
t=3.3ns
t=3.96ns
t=5.9ns
0.5 mA

Spin Transfer with Magnetic Tunnel Junctions

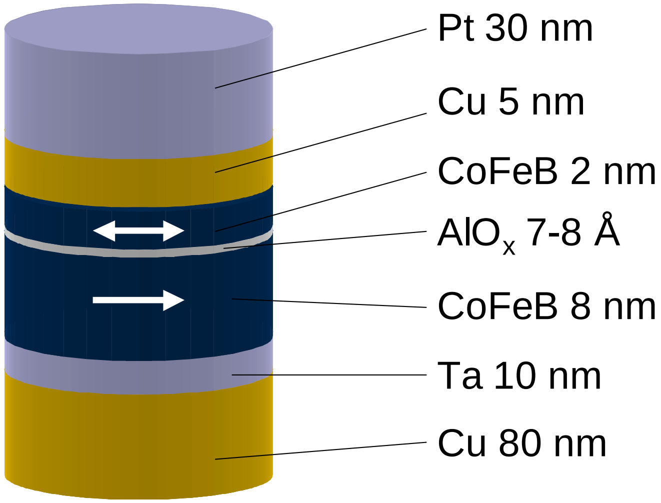


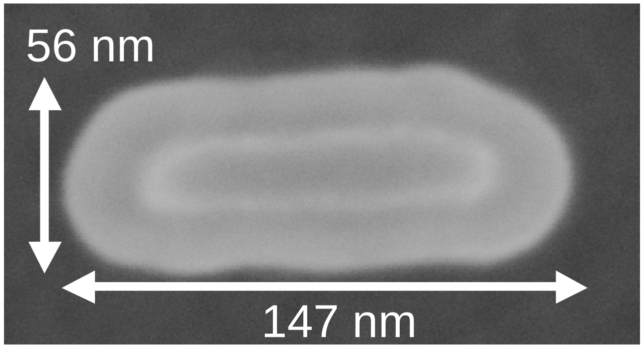
Bad TMR,

Pinholes

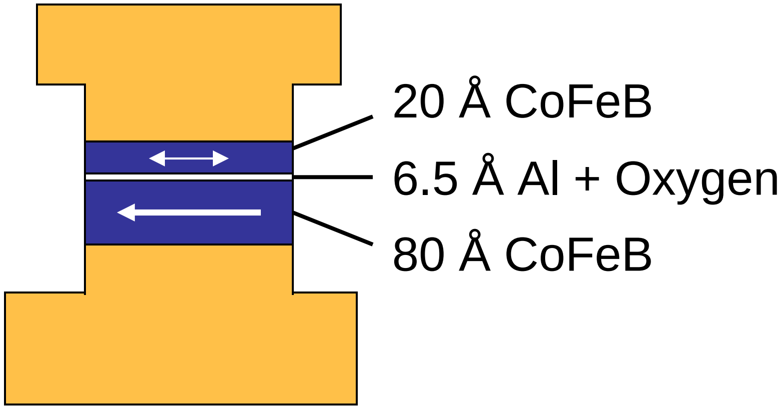
Good TMR, too high resistance to do spin transfer.

Challenge: Tunnel barriers with high TMR that can withstand the currents necessary for switching, particularly for fast switching





Early Demonstrations with AlOx



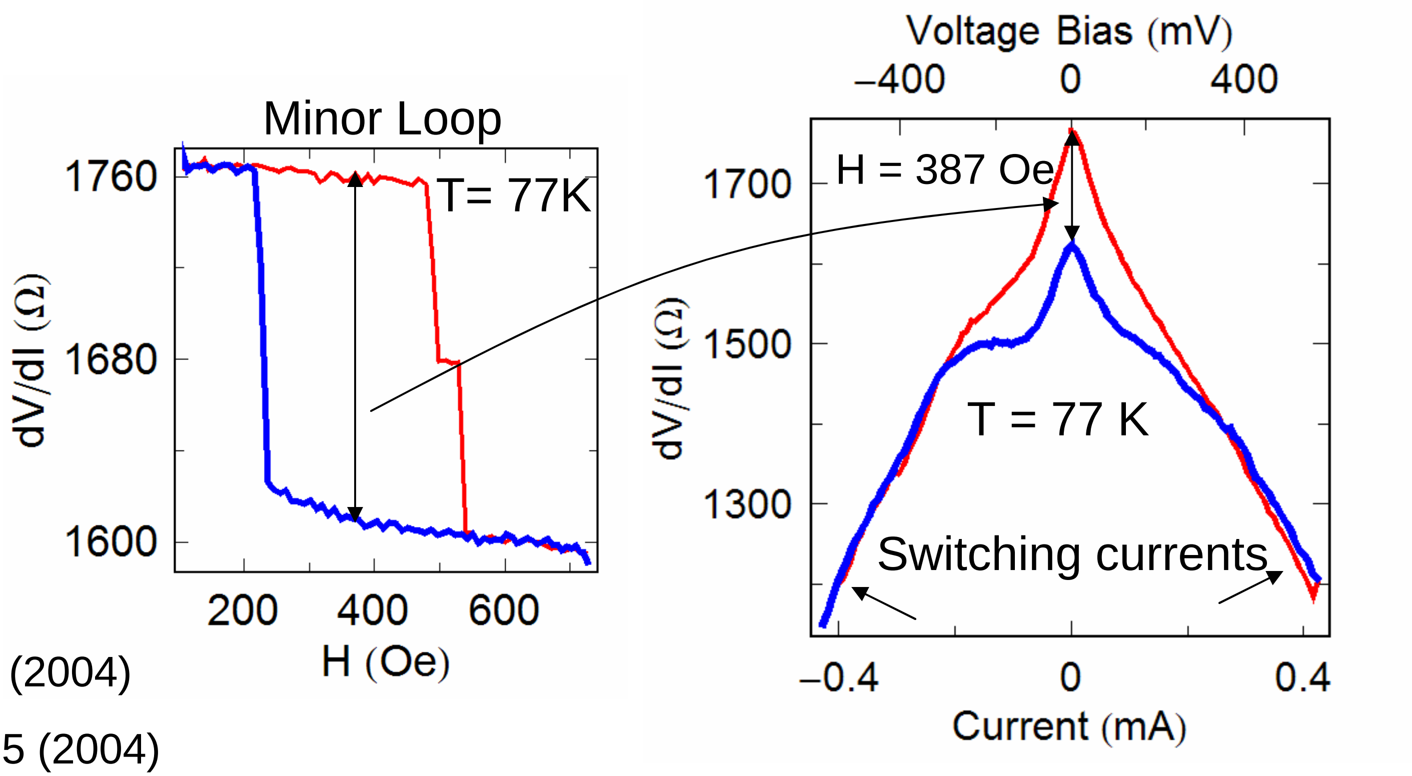
20 Å CoFeB

6.5 Å Al + Oxygen

80 Å CoFeB

$CoFeB=Co_{88.2}Fe_{9.8}B_2$

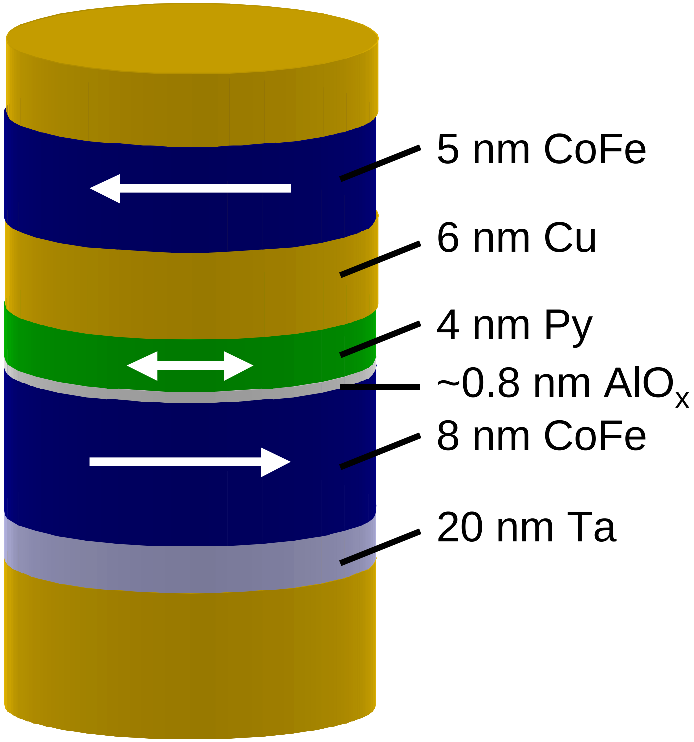
- There is a small TMR measured with DC resistance at switching currents.
- **Wear-out** of barriers a concern due to high critical currents/voltages

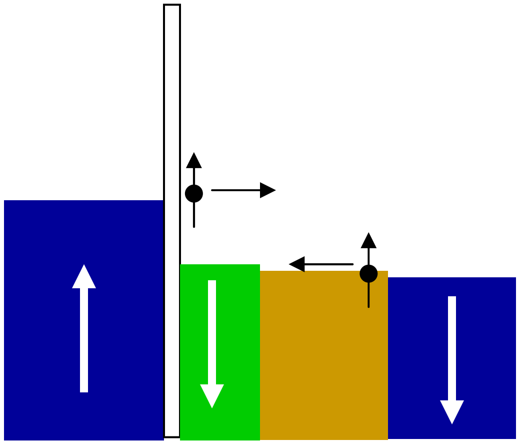


Huai *et. al., APL* **84**, 3118 (2004)

Fuchs *et. al., APL* **85**, 1205 (2004)

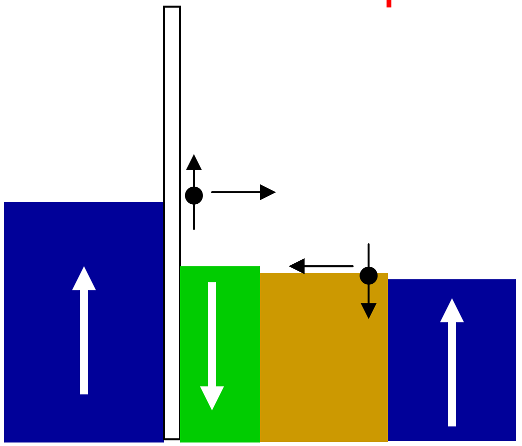
Increasing spin torque in MTJs with three magnetic layers





Anti-aligned fixed layers

Spins from each fixed layer are in the same direction – more spin torque

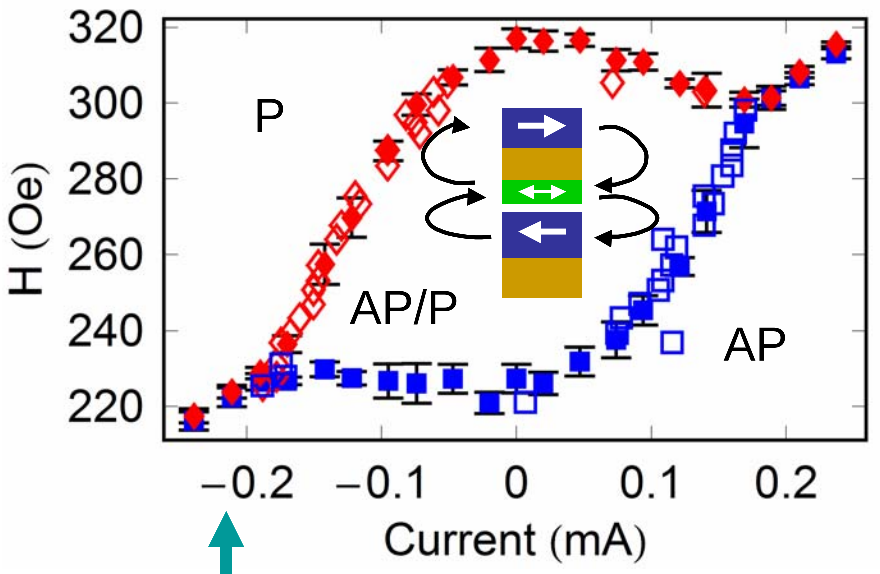


Aligned fixed layers

Spins from each fixed layer are in opposite directions – almost no spin torque

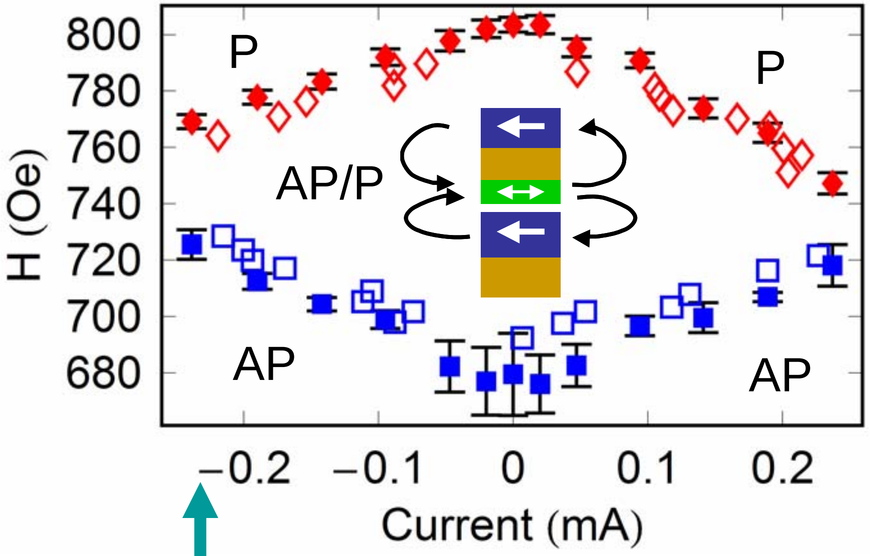
Spin Transfer Switching in 3-layer MTJs

Anti-aligned fixed layers



T=77K

Aligned fixed layers



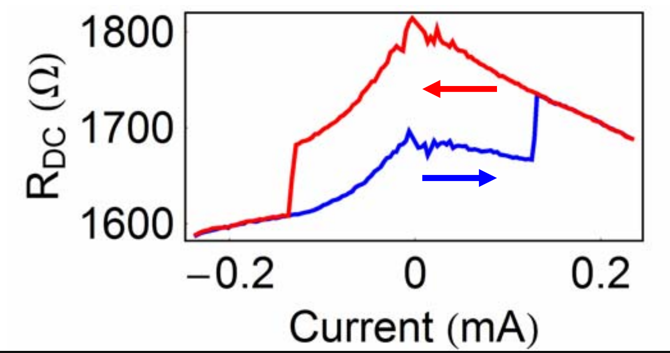
Strong spin torque

Ohmic heating *reduces $H_{c,}$ minimal spin torque*

$I_{c,o+}$ = 0.29±0.01 mA (shape and size

$I_{c,o-}$ = -0.28±0.01 mA not optimized)

$J_{c,o}/t$ = (2.9 ± 0.4) x10^6 A/(cm^2-nm), reduced by 40% compared to a Py free layer with one fixed layer: 5x10^6 A/(cm^2-nm)

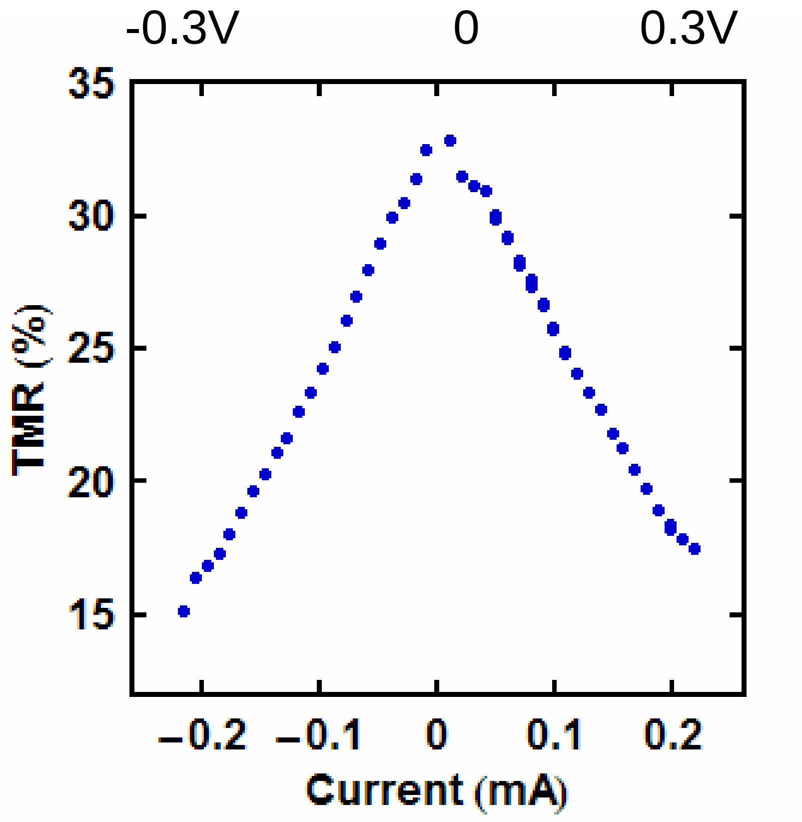


Note the similarity of I_c's

G. D. Fuchs et al., Appl. Phys. Lett. **86**, 152509 (2005).

Questions regarding spin torque in MTJs

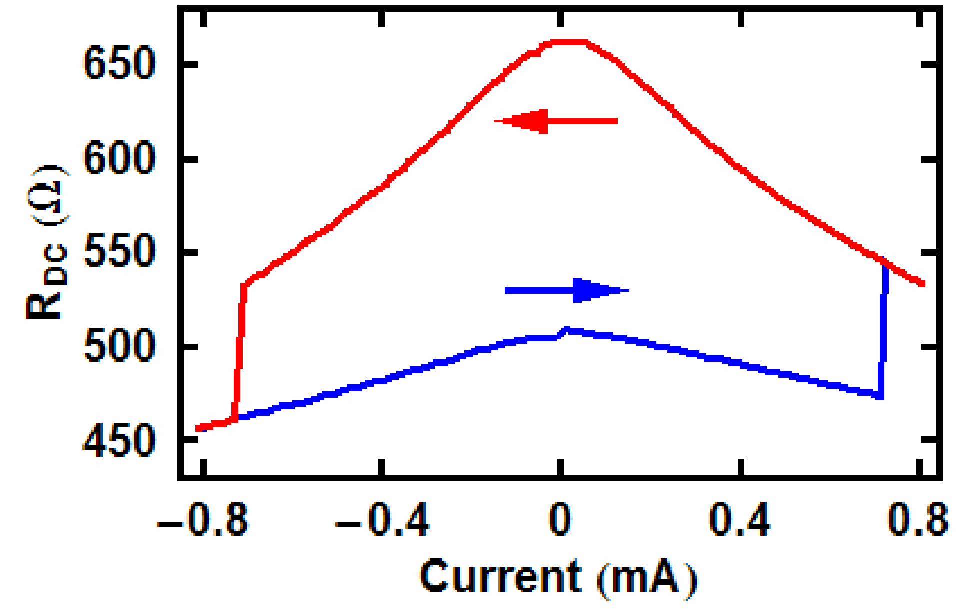
- **Why does TMR decrease with increasing bias?**
- **How does bias affect spin-transfer torque?**
- **What is the nature of spin polarized transport in MgO based MTJs at finite bias?**



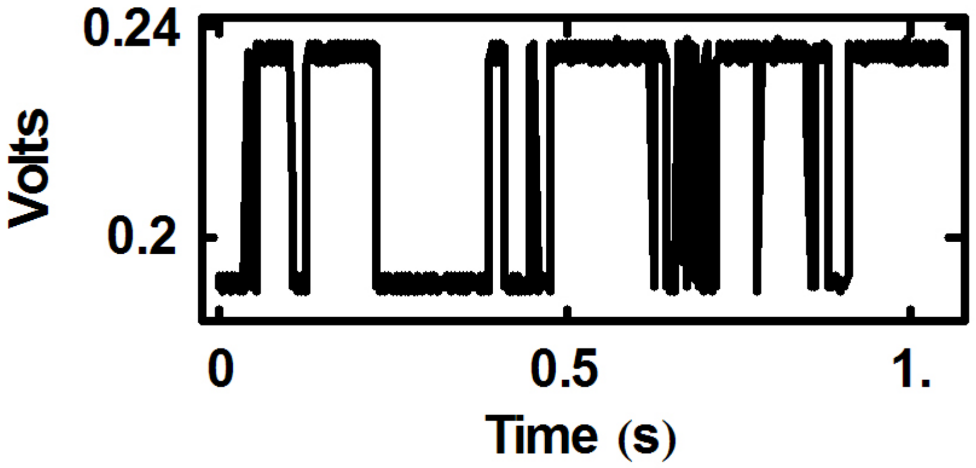
Models that describe TMR(*V*) must also be consistent with spin torque, $N_{st}/I(I)$ and $I(V)$

How to measure torque vs. current

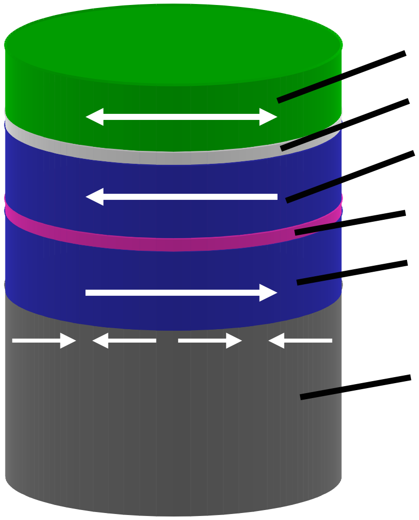
A thermally stable free layer can only provide a measure of the spin-torque at the switching bias



A thermally unstable free layer can provide a measure of spin-torque continuously as a function of bias by applying ***H*** and ***I*** so as to have opposing effects



Sample structure



CoFe 1 nm/Py 1.8 nm

MgO 0.8 nm

CoFe 1.9 nm

Ru 0.7 nm

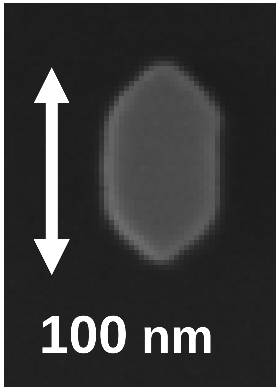
CoFe 2.2 nm

PtMn 15.4 nm

- Bottom pinned SAF nearly cancels the dipole field and has a very large exchange field (~2 kOe)
- Devices are patterned with a 2:1 aspect ratio
- Have a range of thermal activation barriers

CoFe = $Co_{86}Fe_{14}$

Py = $Ni_{91.5}Fe_{8.5}$



Katine and Mauri - HGST

Lacour *et al, APL* **85**, 4681, (2004)

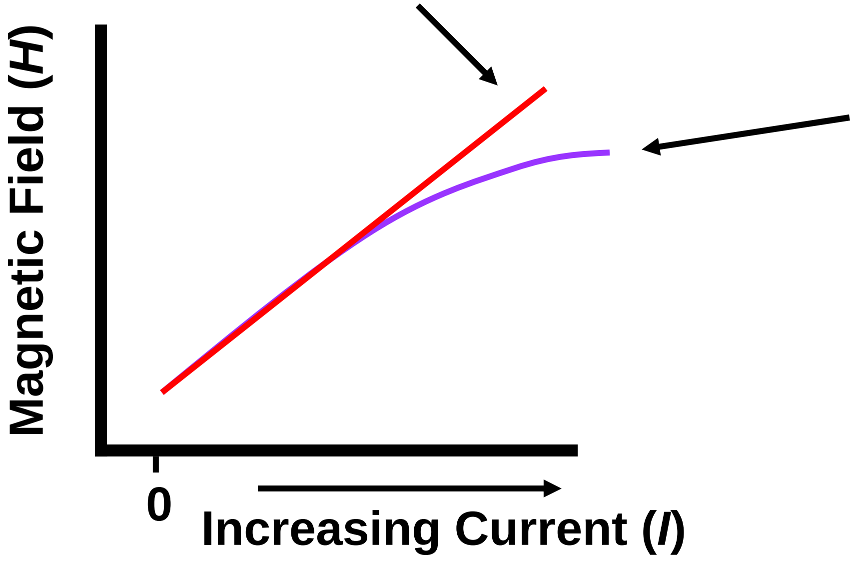
Experimental approach

Lifetime in thermal activation regime

$$\tau_{P/AP} = \tau_o Exp\left[\frac{E_a}{k_B T}\left(1 \pm \frac{H - H_{dip}}{H_{c,o}}\right)^2\left(1 \mp \frac{I\gamma(I)}{I_{c,o}}\right)\right]$$

$\gamma(I)$=Scaling factor to parameterize N_{st}/I variation with *I* - **“Spin Transfer Efficiency”**

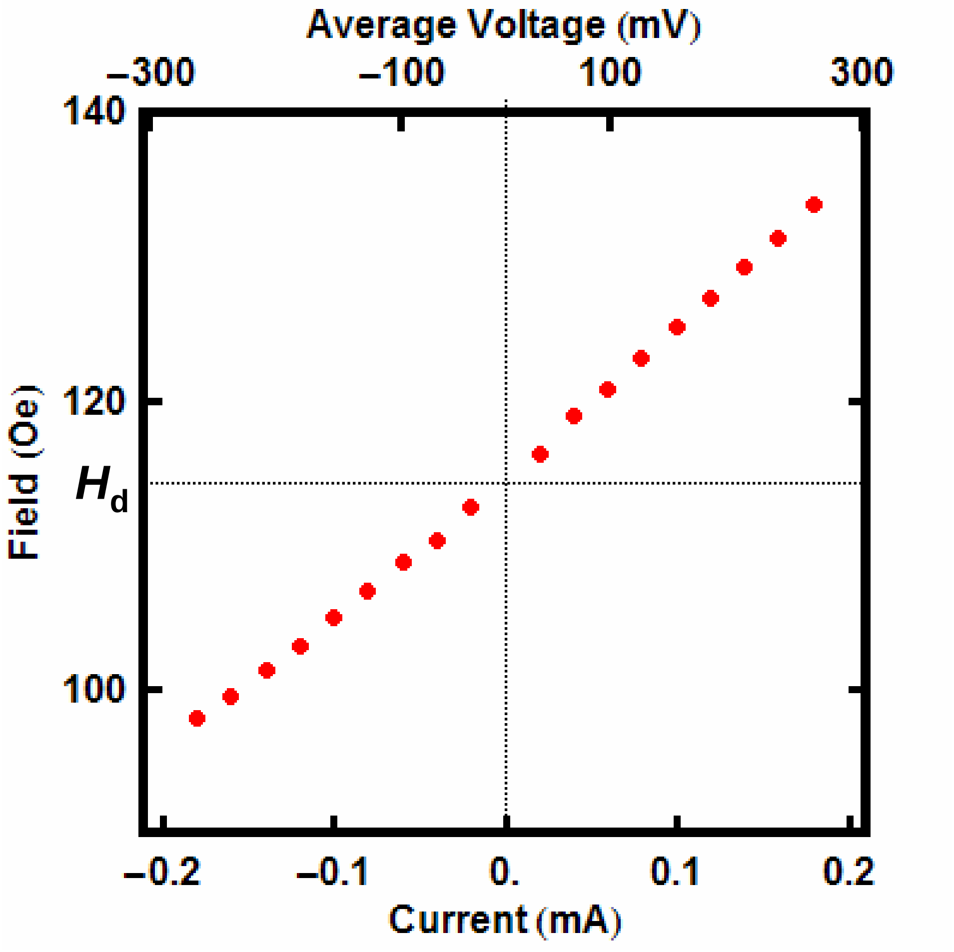
Positions of equal mean lifetimes if the efficiency is constant with bias



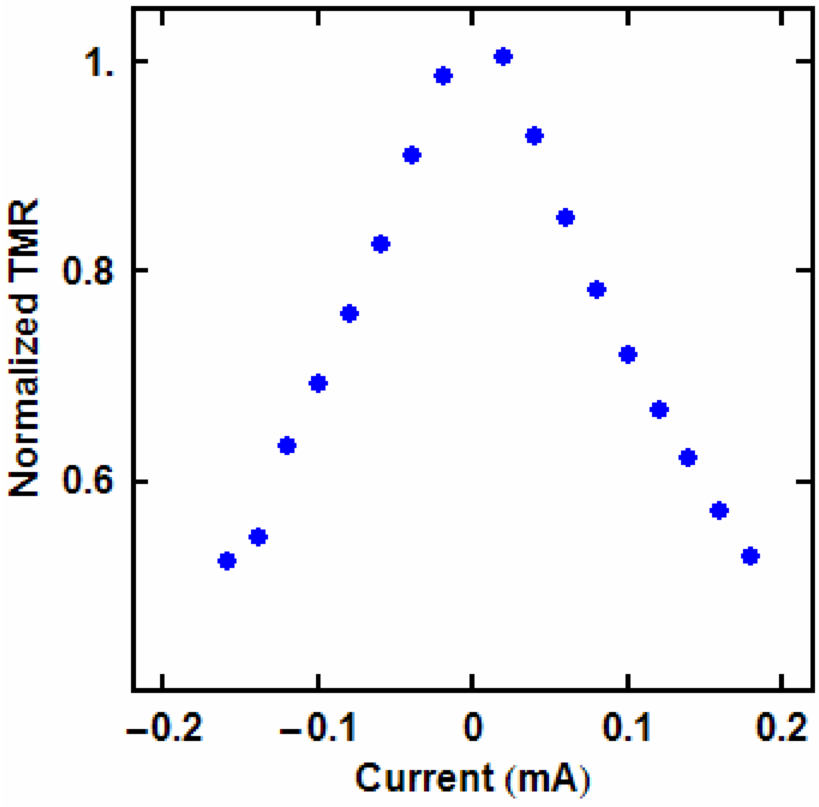
Positions of equal mean lifetimes if efficiency decreases with increasing bias

E. B. Myers, *et al*, *PRL* **89**, 196801 (2002).
Z. Li and S. Zhang, *PRB* **68**, 024404 (2003).
I. N. Krivorotov, *et al*, *PRL* **93** 166603 (2004).

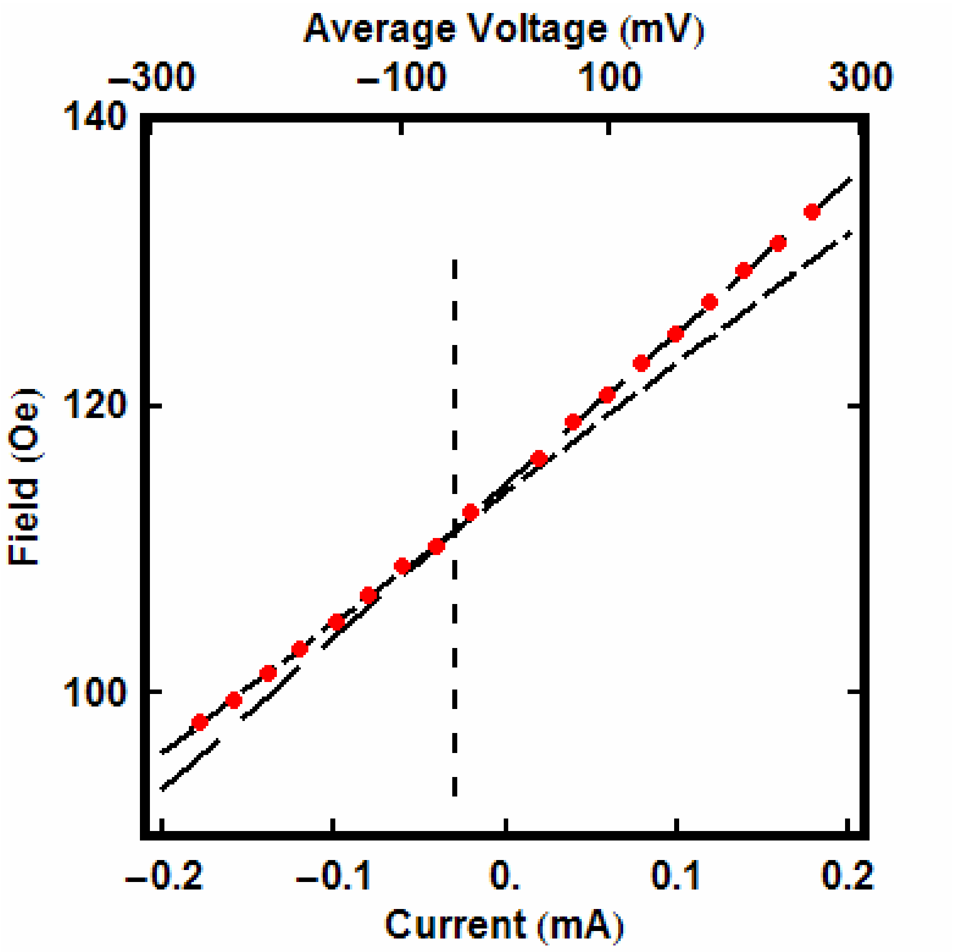
H(I) data - Linear Response



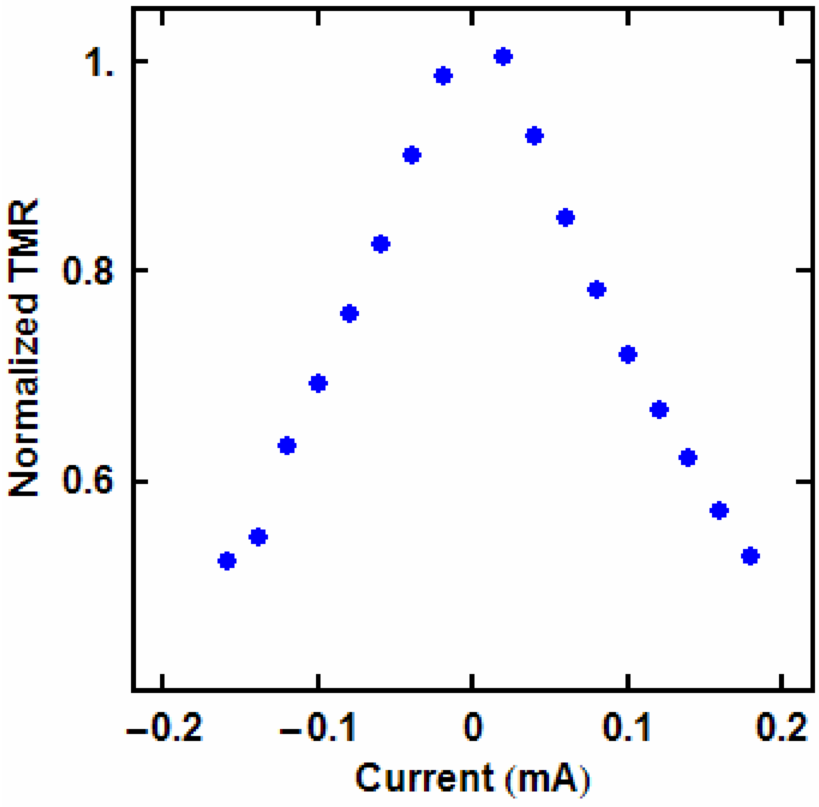
TMR decreases by over 40%



H(I) data - Linear Response



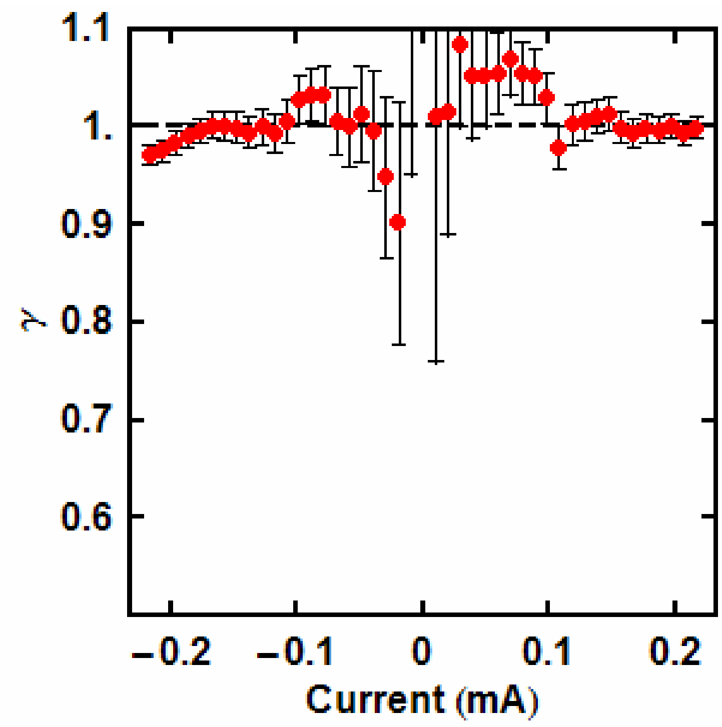
TMR decreases by over 40%

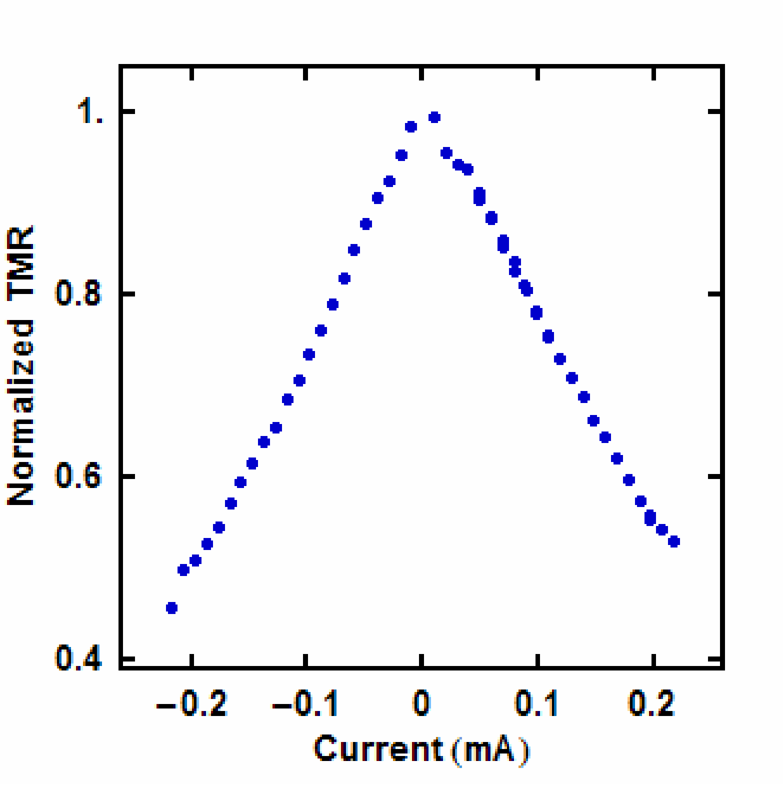


Break in data – crystalline anisotropy effect

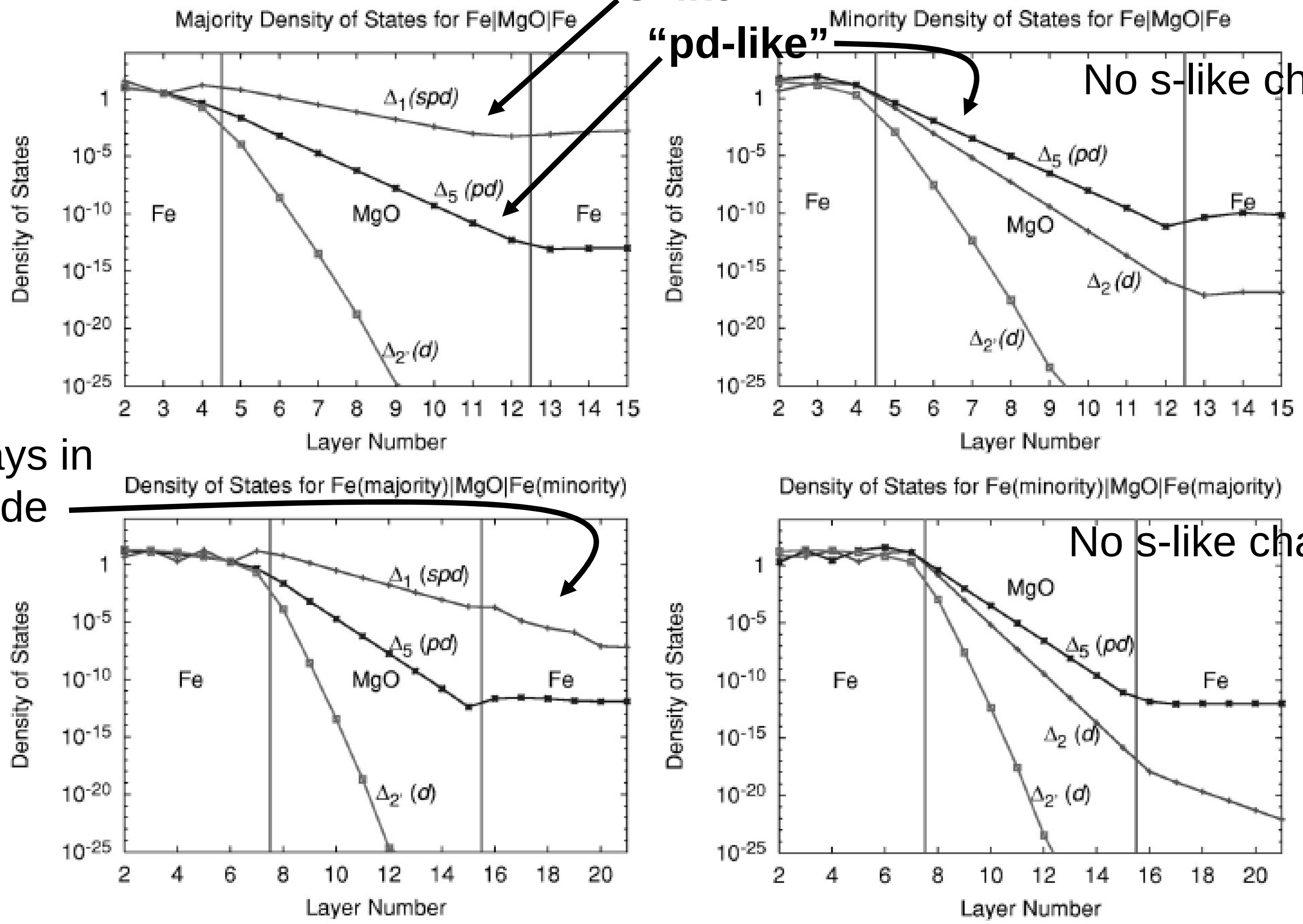
Spin Transfer Efficiency

- Data are consistent with less than a 10% decrease in spin torque efficiency out to the switching bias point (~ 0.3 V)





Tunnel Conductance Through MgO



“s-like”

“pd-like”

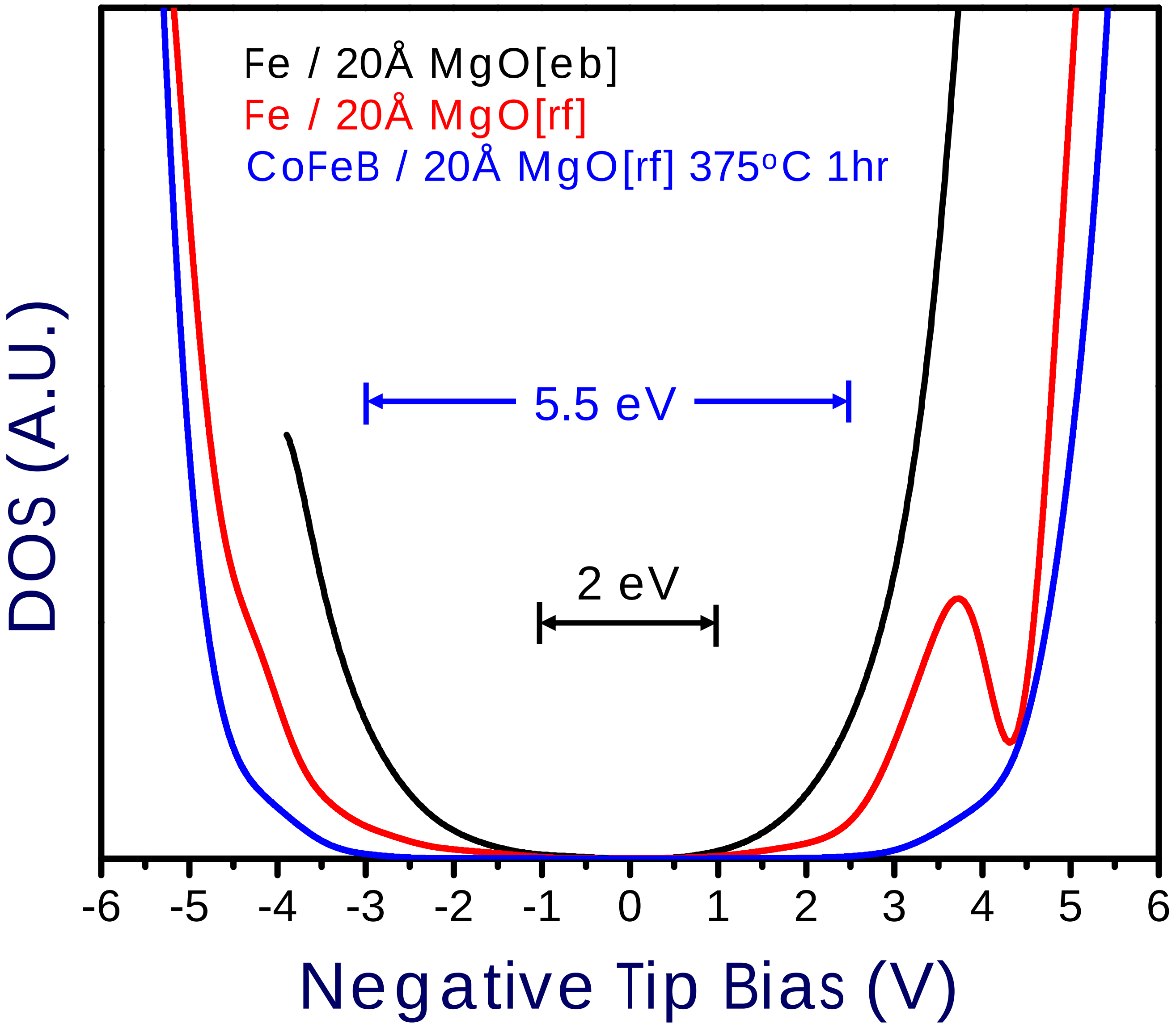
No s-like channels!

s-like decays in the electrode

No s-like channels!

W. H. Butler, X. –G. Zhang, T. C. Schulthess, *PRB* **63**, 054416 (2001).
J. Mathon and A. Umerski, *PRB* **63**, 220403 (2001).

MgO DOS Data



STM tunneling spectroscopy evidence for O vacancy defects in MgO barrier layers

Tunnel Conductance through MgO

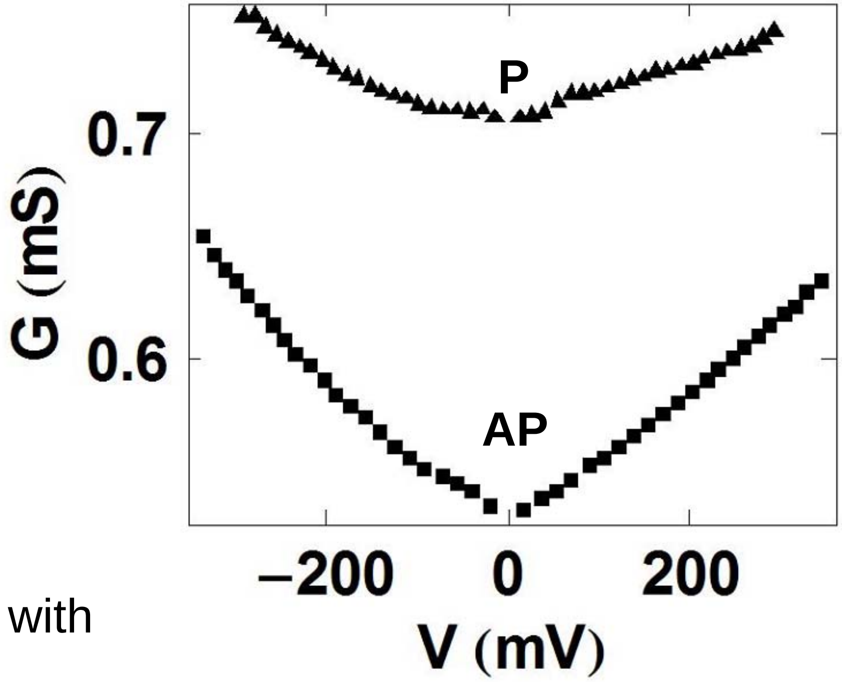
Magnetic state dependent effective mass (decay length):

W. H. Butler, X. –G. Zhang, T. C. Schulthess, *PRB* **63**, 054416 (2001).
J. Mathon and A. Umerski, *PRB* **63**, 220403 (2001).

Simmon's model fit:

$$m^*_{ap} = 1.35 \pm 0.05$$

$$m^*_{p} = 0.82 \pm 0.02$$



Elastic scattering by barrier defects reduces the TMR

***γ(I)*~const implies that:**

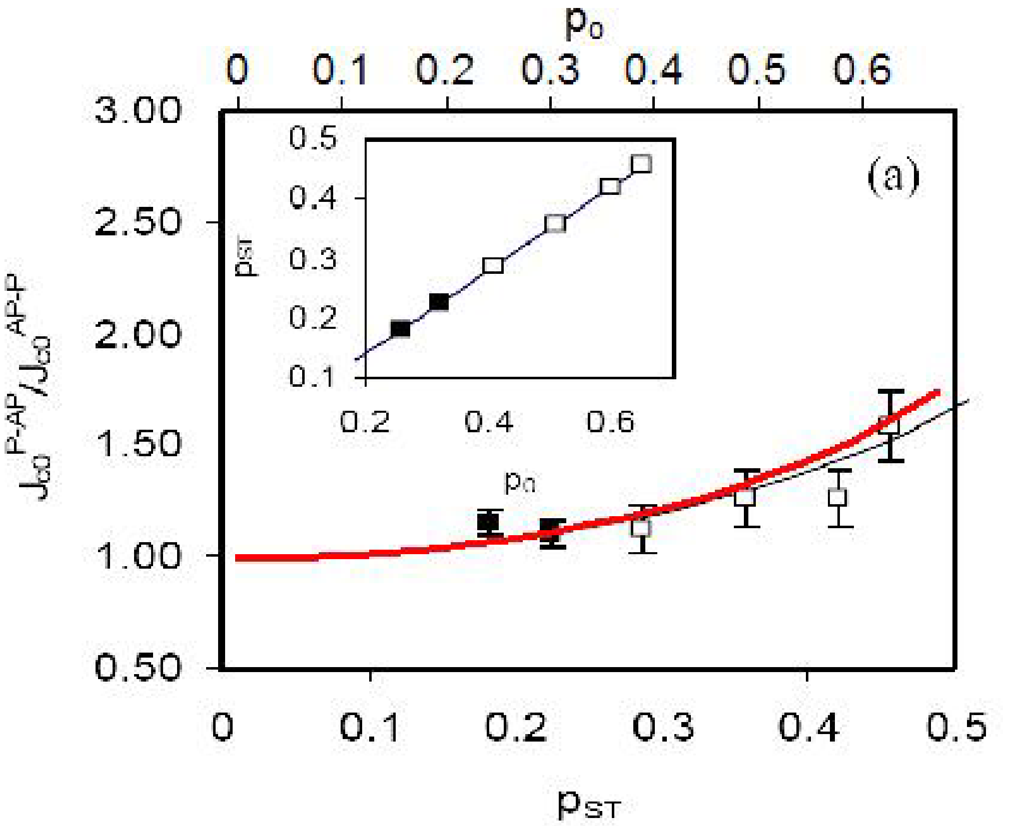
- conductance for each spin channel varies with bias at a rate proportional to the zero bias DOS.
- electron scattering rate from defects is not strongly spin dependent!

Symmetry of Critical Currents

Polarization term

$$g(\theta) = \frac{P(V)}{2[1 + P(V)^2 Cos\theta]}$$

Asymmetry term is present to convert Slonczewski's critical ***voltage*** (V_c) into a critical ***current*** (J_c).



Diao *et al.*, APL 87, 232502, (2005)

A better approximation:

$$g(\theta) = \frac{P(V=0)}{2\left[1 + \left(\frac{TMR(V)}{2 + TMR(V)}\right) Cos\theta\right]}$$

P^2 calculated from *TMR(V)*

Polarization term is a constant function of *V*, ***consistent with our study***

Conclusions – ST in MTJs

- **Spin-transfer torque per unit current is independent of bias** within 10% up to 0.35 V (good news for spin-torque driven MRAM)
- Measurement brings **new information** to help understand the relationship between bias and spin-polarized tunneling
- Results are inconsistent with:

  Free-electron, split-band tunneling models

  Magnon emission models that reduce polarization factors
- Results are consistent with calculations due to Butler *et al* and Mathon *et al* for transport through ultra-thin MgO tunnel barriers allowing for defects in non-ideal tunnel barriers.

Fuchs *et al.*, cond-mat/0510786