Nanomagnetism

Some concepts in magnetism actually aren't all that sensitive to the length scale:

- Magnetic moments — similar from nuclei to bulk
- Precession in fields, magnetic resonance
- Spin filtering by magnetic layers
  - happens within first nm or so

But there is new physics on the 1-100 nm scale, too

- Single-domain response as opposed to domain structure
- superparamagnetism – at room temperature, on the scale of 10's of nm and below
- changes in the average magnetization and magnetic anisotropy strength for nanoparticles (mostly a surface-to-volume effect)
- Spin-polarized transport
- Spin-transfer torques

This part is my focus today. Relevant when the sample size is smaller than the spin relaxation length, a few 100 nm in many materials.

Torques from Spin-Polarized Currents

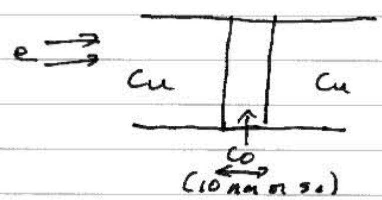
- A new way of manipulating the orientation of the moments in small magnets, using spin-polarized currents instead of magnetic fields
- Idea: by transferring angular momentum from a spin-polarized current to a magnet, you can apply a torque directly

This lecture will deal with a very different experimental regime than my previous talks

- Electrons will no longer be tunneling – instead metallic flow
- Larger devices – generally 100 nm scale rather than < 10 nm, but it will be interesting to think about consequences in smaller devices, too.

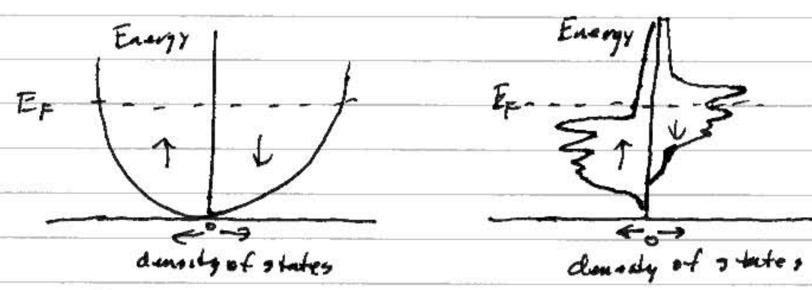
Background: A magnetic layer can act like a filter for spins.

Consider a Cu / Co / Cu device (Cu nonmagnetic, Co magnetic)



Shoot unpolarized electrons from the left. What emerges on the right?

Band structures of Cu and Co:



Cu – reasonably like a free-electron metal near the Fermi surface

Co – combinations of s and d states near E_F. More spin ↓ states than spin up near E_F.

equal numbers of spin-up & spin down

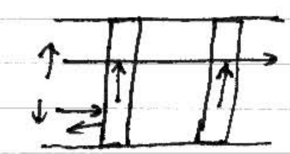
Because of the differences in the band structures of Cu and Co, many of the minority-spin (↓) electrons incident from the Cu will be reflected at the Cu/Co interface. However, the Cu band structure matches reasonably well with the Co majority-band (↑) electron states, so many of these electrons can be transmitted

ref. M.D Stiles, J. Appl. Phys 79, 5805 (1996)
K Xia et al., PRB 65, 220401 (2002)

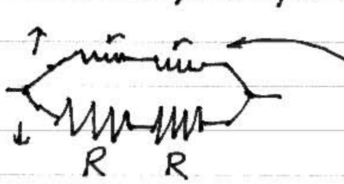
Furthermore, spin-up and spin-down electrons will have different scattering rates within Co. For most scattering events, the electron does not flip its spin. The scattering rate will be approximately proportional to the density of final states into which the electron can scatter. Since the minority spins (↓) have a larger density of states near E_F, they will have a greater scattering rate.

Both effects allow spin-↑ electrons to be transmitted more easily through the Co layer, so it acts as a spin filter, a partial polarizer for the spins. (final $P \approx 35\%$).

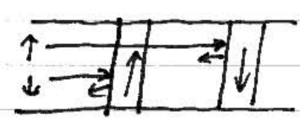
This leads to "<u>giant magnetoresistance</u>" in multilayers



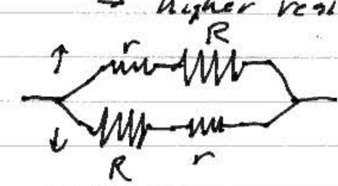
for 2 parallel layers, up spins can be transmitted easily through both layers
⇒ large I per unit V, low resistance



small r in spin ↑ channel

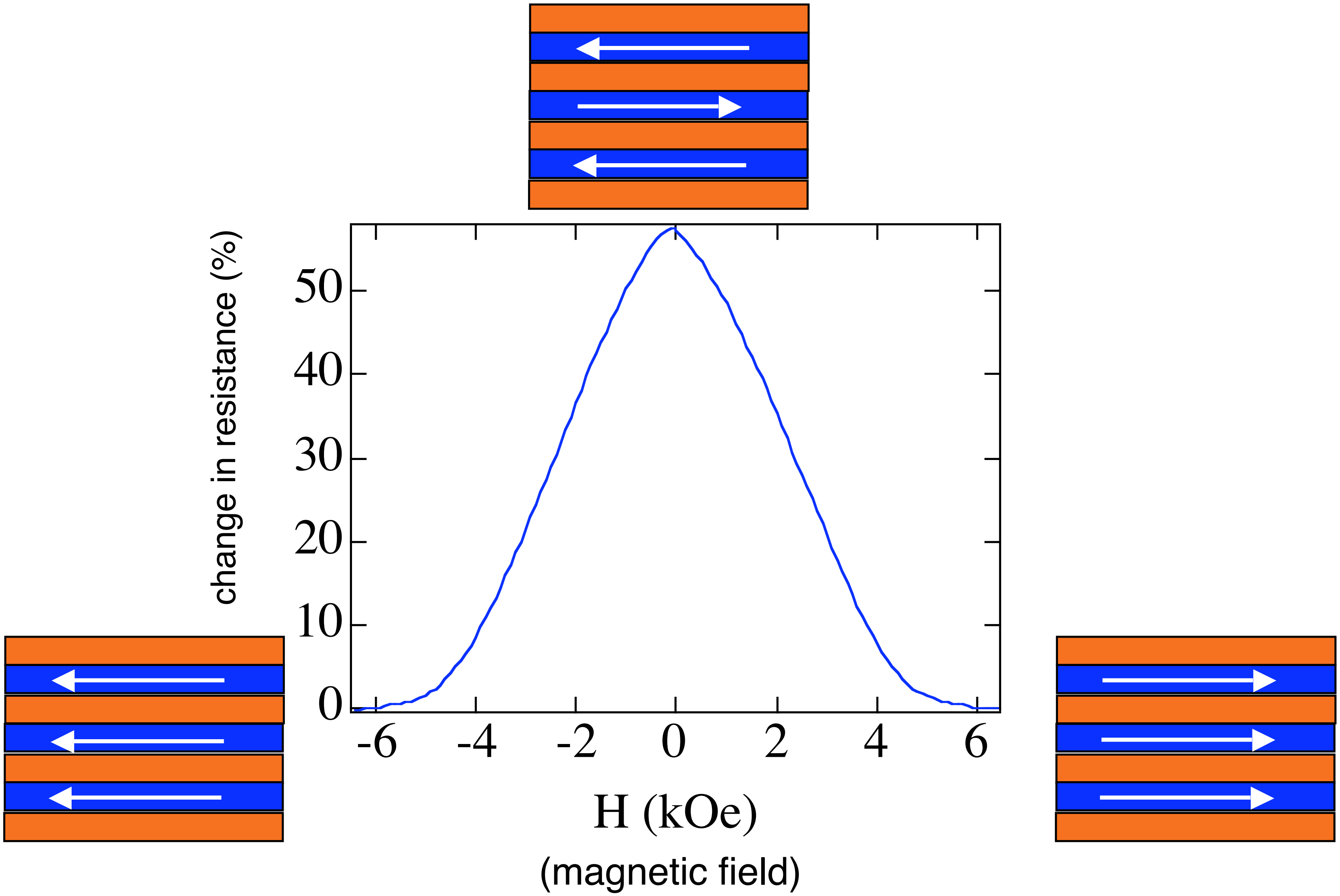


For antiparallel layers, both types of spins are scattered.
⇒ higher resistance



higher overall resistance.

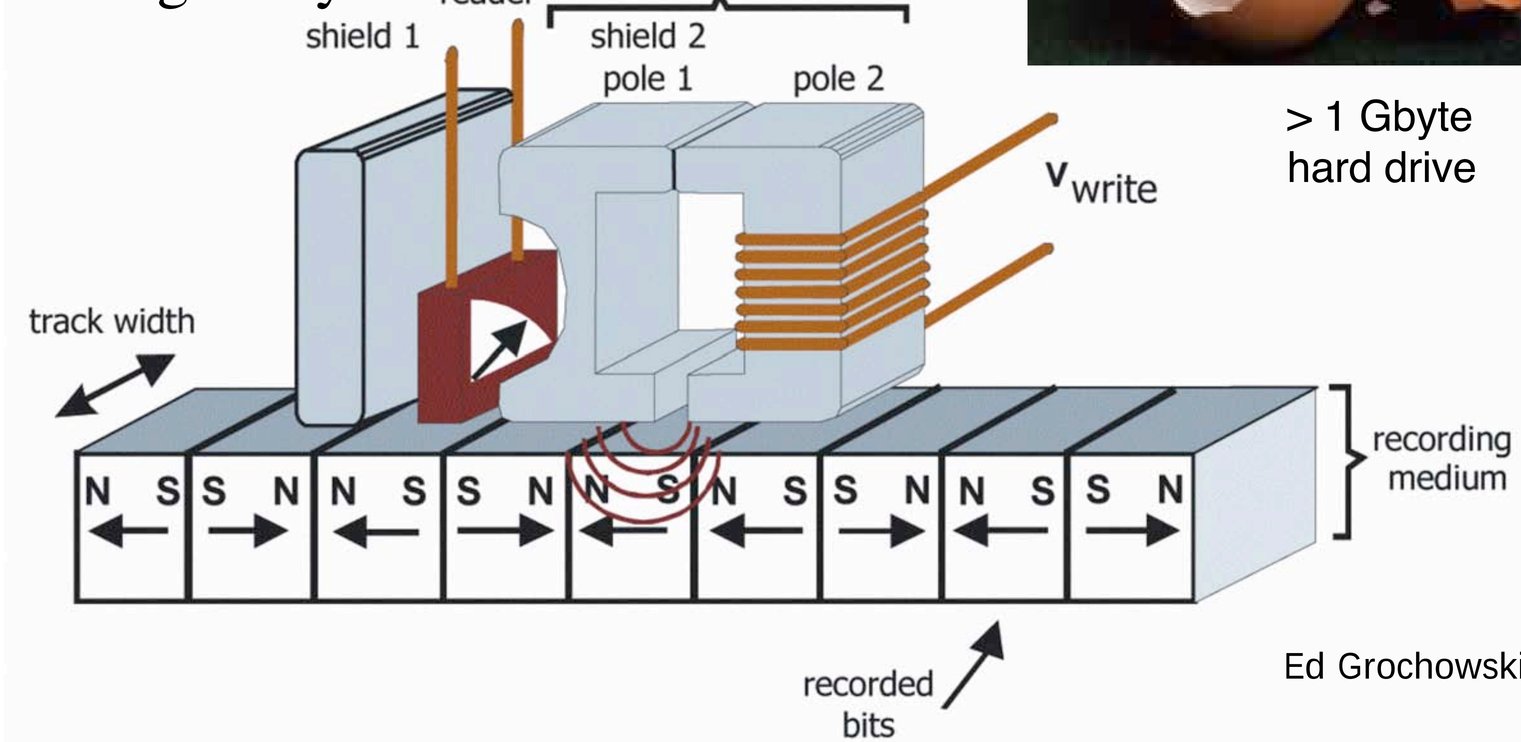
GMR Allows Mangetic-Field Sensing



Magnetic Recording

- Three core magnetic components
  - media
  - writer
  - reader
- All require nanoscale engineering today

> 1 Gbyte
hard drive



Ed Grochowski

So, the orientations of magnets can affect the flow of spin-polarized currents. What about the reverse - can spin-polarized currents affect the orientations of magnets?

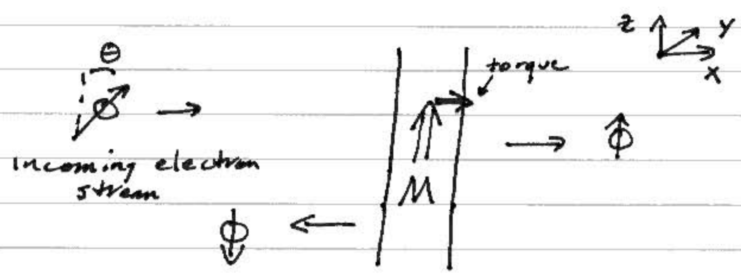
Yes - Because magnets act like spin filters, Newton's 3rd Law will say that magnets feel torques.

(predicted by John Slonczewski, Luc Berger)

These "spin-transfer torques" turn out to be much stronger per unit current in nanoscale devices than the torques due to current-generated magnetic fields. Spin transfer is therefore potentially very useful.

To get started: Cartoon picture of spin transfer

Assume that the magnet is a 100% efficient spin filter



Summing over an ensemble of incoming spins, all polarized at the same angle θ, the consequence of spin filtering is a spin ↑ current transmitted and a spin ↓ current reflected.

From conservation of angular momentum, the x component of the incoming angular momentum is absorbed during the filtering process. Therefore the magnet must feel a torque in that direction.

Now More Realistic Situation: Less than perfect filter.

Some notation: Ψ a spinor

charge density $\rho(r) = e \langle \sum_\alpha \Psi_\alpha^+(r) \Psi_\alpha(r) \rangle$ ← expectation value

current density: $\vec{J}(r) = \frac{-i\hbar e}{2m} \sum_\alpha \langle \Psi_\alpha^+(r) \vec{\nabla} \Psi_\alpha(r) - (\vec{\nabla}\Psi_\alpha^+(r)) \Psi_\alpha(r) \rangle$

$= \frac{\hbar e}{m} \text{Im} \sum_\alpha \langle \Psi_\alpha^+(r) \vec{\nabla} \Psi_\alpha(r) \rangle$

Can write similar expressions for spin density and spin current density

$$\vec{\text{spin density}} = \frac{\hbar}{2} \langle \Psi^+(r) \vec{\sigma} \Psi(r) \rangle$$

← Pauli matrices

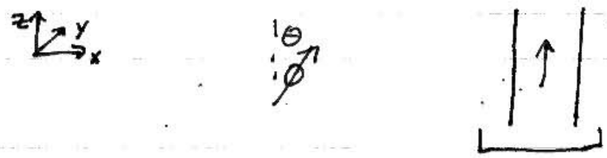
Spin current density (tensor)

$$\overleftrightarrow{J}_s = \frac{-i\hbar^2}{4m} \langle \Psi^+ \vec{\nabla} \vec{\sigma} \Psi - \vec{\nabla} \Psi^+ \vec{\sigma} \Psi \rangle$$
$$+ \frac{\hbar^2}{2m} \text{Im} \langle \Psi^+ \vec{\nabla} \vec{\sigma} \Psi \rangle$$

Example: If $\Psi = \begin{pmatrix} a \\ b \end{pmatrix} e^{ik\cdot r}$

$$\vec{J}_z = \frac{\hbar^2 k}{2m} (|a|^2 - |b|^2)\, \hat{k}$$
$$\vec{J}_x = \frac{\hbar^2 k}{2m} (ab^* + a^* b) = \frac{\hbar^2 k}{m} \text{Re}[ab^*]$$
$$\vec{J}_y = \frac{\hbar^2 k i}{2m} (ab^* - a^* b) = -\frac{\hbar^2 k}{m} \text{Im}[ab^*]$$

Think about the filtering geometry again, incident electrons in a single state.



$$\Psi_{inc.} = \left[\cos\tfrac{\theta}{2} |\uparrow\rangle + \sin(\tfrac{\theta}{2}) |\downarrow\rangle\right] e^{ikx}$$

consider the scattering properties of the magnetic thin film

Assume no spin-flip scattering, just filtering

Transmission matrix: $\begin{pmatrix} t_\uparrow & 0 \\ 0 & t_\downarrow \end{pmatrix}$ $\quad t_\uparrow \neq t_\downarrow$ for magnetic film (it acts as a filter)

Reflection matrix $\begin{pmatrix} r_\uparrow & 0 \\ 0 & r_\downarrow \end{pmatrix}$ $\quad |t_\uparrow|^2 + |r_\uparrow|^2 = 1$

$\quad |t_\downarrow|^2 + |r_\downarrow|^2 = 1$

Transmitted wavefunction:

$$\Psi_T = [t_\uparrow \cos\tfrac{\theta}{2} |\uparrow\rangle + t_\downarrow \sin\tfrac{\theta}{2} |\downarrow\rangle] e^{ikx}$$

Reflected wavefunction:

$$\Psi_R = [r_\uparrow \cos\tfrac{\theta}{2} |\uparrow\rangle + r_\downarrow \sin\tfrac{\theta}{2} |\downarrow\rangle] e^{-ikx}$$

Compute Torque = [Ang Momentum flow in] − [Ang. Momentum flow out]

$$= [J_{inc} - J_T - J_R] \text{ (area)}$$

Will leave the calculation as an easy exercise. Results:

$$\tau_z = 0$$
$$\tau_x \propto \sin\theta \, [1 - \mathrm{Re}(t_\uparrow t_\downarrow^* + r_\uparrow r_\downarrow^*)]$$
$$\tau_y \propto -\sin\theta \, \mathrm{Im}[t_\uparrow t_\downarrow^* + r_\uparrow r_\downarrow^*]$$

Notes: $\vec{\tau} = 0$ for $\theta = 0$ or π ⇒ No torques for collinear magnets

Check − torque should be zero for nonmagnetic film −

If $t_\uparrow = t_\downarrow$, $r_\uparrow = r_\downarrow$ then $t_\uparrow t_\downarrow^* + r_\uparrow r_\downarrow^* = |t_\uparrow|^2 + |r_\uparrow|^2 = 1$

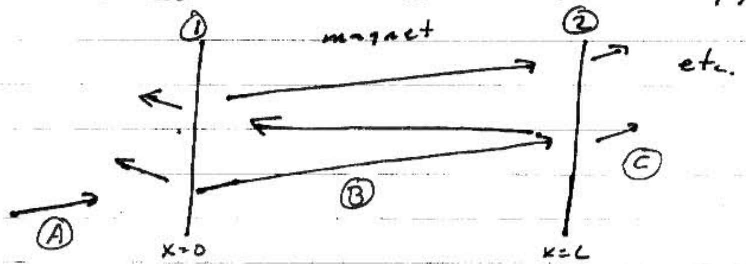
so $\vec{\tau} = 0$. ✓.

τ_x is in the same direction as for the perfect polarizer.

τ_y is new − it is like the torque from an "effective field" pointed in the direction of the spin polarization − causes the moment to precess out of the plane as I have drawn the picture.

Now for a more microscopic view

Think of a thin magnetic film like a Fabry-Perot etalon - can calculate transmission and reflection as a sum of multiply-reflected waves.



Can get some insight even from the first path

Ⓐ $\Psi_{inc} = \left(\cos\frac{\theta}{2}\,|\uparrow\rangle + \sin\frac{\theta}{2}\,|\downarrow\rangle\right) e^{ikx}$.

Ⓑ After transmission through interface ①

$$\Psi_B = t_{1\uparrow}\cos\left(\frac{\theta}{2}\right)|\uparrow\rangle\, e^{ik_\uparrow x} + t_{1\downarrow}\sin\left(\frac{\theta}{2}\right)|\downarrow\rangle\, e^{ik_\downarrow x}$$

important: $k_\uparrow$ and $k_\downarrow$ are different in a ferromagnet. Strong exchange splitting $\gtrsim$ bandwidth, so electrons at the Fermi energy have very different wavelengths for spin $\uparrow$ and spin $\downarrow$ (think different kinetic energies)

Can write $\Psi_B \propto \left[\cos\left(\frac{\theta_F}{2}\right)|\uparrow\rangle + \sin\left(\frac{\theta_F}{2}\right) e^{i\phi_0} e^{i(k_\downarrow - k_\uparrow)x}|\downarrow\rangle\right] e^{ik_\uparrow x}$

phase factor - precession around z-axis as a function of position x : $\phi = (k_\downarrow - k_\uparrow)x$

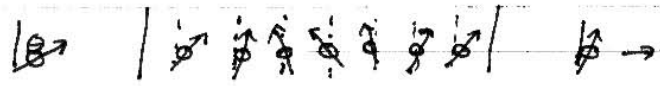
In Co, Fe, Ni $k_\downarrow - k_\uparrow \approx \frac{1}{\text{atomic distance}}$, so a spin will precess many times in going through even a thin film.

Ⓒ $\Psi_C \propto \left[t_{2\uparrow}\cos\left(\frac{\theta_F}{2}\right)|\uparrow\rangle + t_{2\downarrow}\sin\left(\frac{\theta_F}{2}\right) e^{i\phi_0} e^{i(k_\downarrow - k_\uparrow)L}|\downarrow\rangle\right] e^{ik(x-L)}$

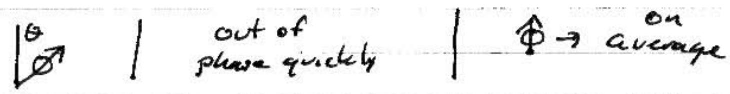
In a real device, electrons are not incident in just one quantum state, but with a variety of different angles, wavelengths. To calculate torque, must sum over all electrons. Even if they all start polarized in the same direction, they will precess incoherently. For transmitted electrons, the average angular momentum in the x and y directions will be zero.

Semiclassical Picture:

one quantum state



sum over many incident wavevectors



From before

$$\tau_x \propto \sin\theta \left[1 - \mathrm{Re}\left(t_\uparrow t_\downarrow^* + r_\uparrow r_\downarrow^*\right)\right] \rightarrow \boxed{\sin\theta \left[1 - \mathrm{Re}\,\langle r_\uparrow r_\downarrow^* \rangle\right]}$$

positive & negative cancel

$$\tau_y \propto -\sin\theta\, \mathrm{Im}\left[t_\uparrow t_\downarrow^* + r_\uparrow r_\downarrow^*\right] \rightarrow \boxed{-\sin\theta\, \mathrm{Im}\,\langle r_\uparrow r_\downarrow^* \rangle}$$

$\tau_z = 0$ obvious - electron just precesses around the exchange field.

At this point, need input from band structure calculations to work out what are the reflection coefficients. These indicate that $\mathrm{Im}(r_\uparrow r_\downarrow^*)$ is only 2-10% of $1 - \mathrm{Re}(r_\uparrow r_\downarrow^*)$

$\Rightarrow$ usually OK to consider only the τ_x term (as in perfect filter case) and ignore the τ_y "effective field" term.

<u>Bottom Line</u>: To a good approximation, the transverse component of angular momentum is effectively absorbed (just as in the perfect filter case) in the first few monolayers of a magnet. (effectively a torque applied to the magnet's surface)

total $\tau_x \sim \sin\theta \times$ a good fraction of $\hbar$ per electron.

This can be a big torque.

For real calculations, there is a convenient "circuit theory" to determine torques

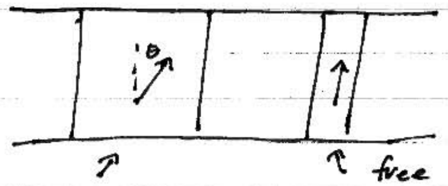
A Brataas et al., PRL <u>84</u>, 2481 (2000).

Y. Tserkovnyak et al., PRB <u>66</u>, 224403 (2002)

A. Kovalev et al., PRB <u>66</u>, 224424 (2002)

Dynamical Consequences of Spin Transfer

For the simplest real device, need 2 magnetic layers, a polarizer and a "free layer"



↑ polarizer ↑ free layer $\frac{d\vec{M}}{dt} = \vec{\tau}$, can respond to torque.

polarizer: thick enough not to respond to any torques

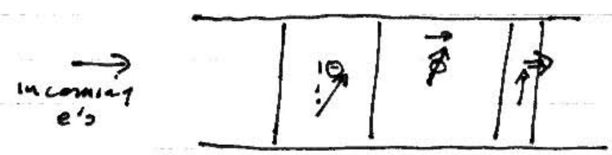
Consider a linear stability analysis - imagine a small fluctuation Θ angle between the two moment directions. Pass a current. Will the torque from the current amplify or suppress the deviation?

Lesson: Will depend on current direction

Could do a full calculation as for the single layers (Waintal et al., PRB 62, 12317 (2000))

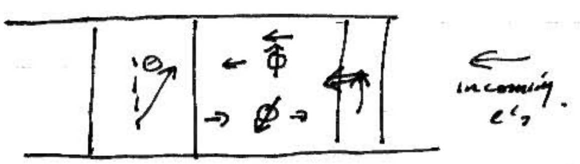
but the cartoons are good enough for our purpose.

One direction of current:



as before. This direction of current stabilizes the parallel orientation

Other direction of current

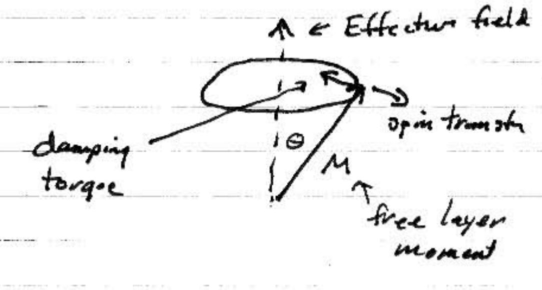


Here spin transfer twists the free layer away from the polarizer direction

Next: Can possibly destabilize parallel configuration with one sign of current.

To understand fully the resulting dynamics, one must consider all the torques acting on the free layer
→ Magnetic field and damping too

Picture first - can discuss Landau-Lifshitz-Gilbert equation later
Assume effective field and the polarizer point in the same direction



Torque due to effective field causes precession of free layer

Damping - gives torque toward the field direction to lower energy

Spin transfer: If current is in the correct direction, gives a torque that points opposite to the damping

Can give effectively a negative damping - spiral away from the applied field direction.

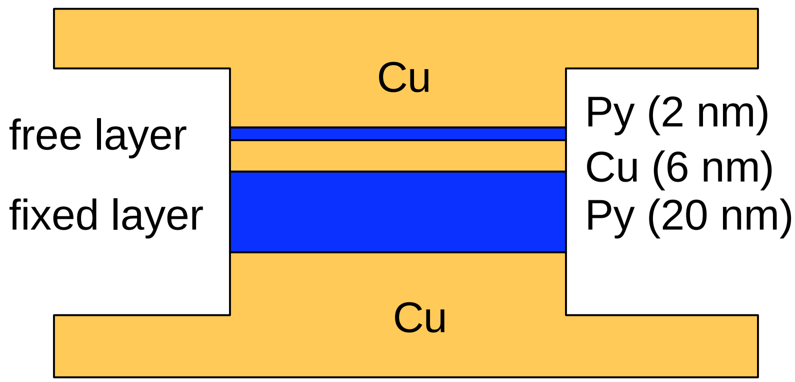
<u>3 possible types of regimes</u>

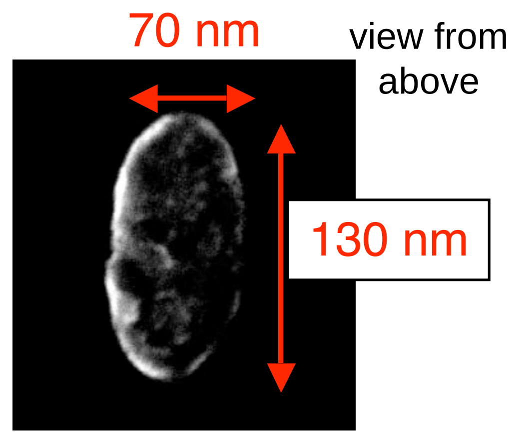
1. switching - free layer flips 180°, antiparallel to polarizer (reversed current can flip it back)
2. dynamical equilibrium - at some angle damping balances spin transfer torque. DC current drives steady-state precession
3. Single-domain approximation fails - spatiotemporal chaos?

experimental evidence for all 3 regimes

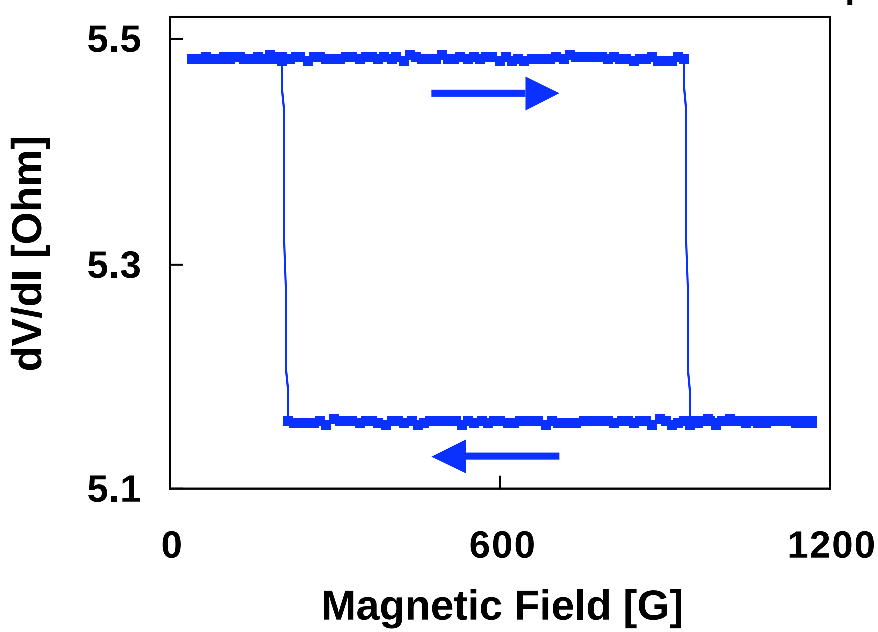
switching - low applied magnetic fields
steady-state precession - larger fields, current not too high
not single domain - probably for large fields, large currents.

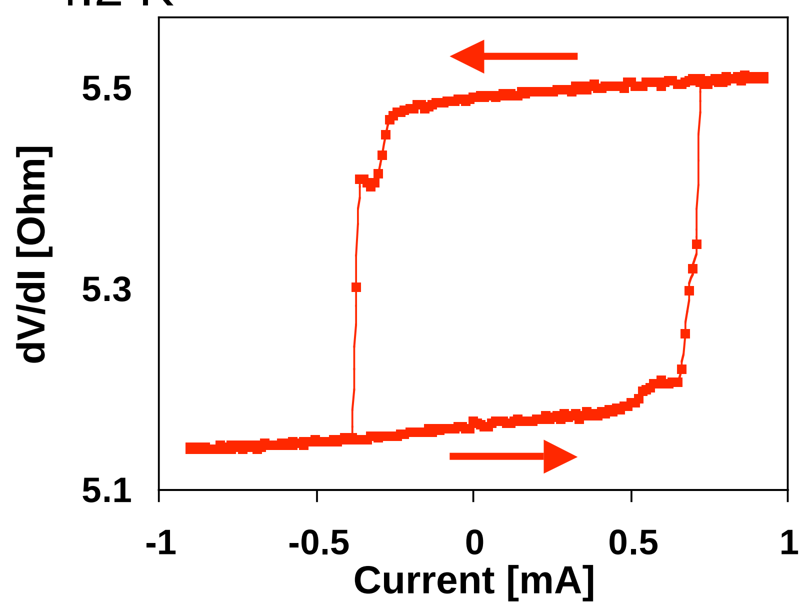
Spin-Transfer-Driven Magnetic Reversal



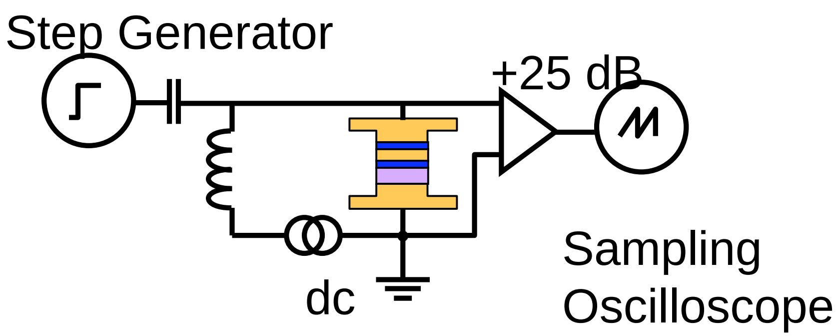


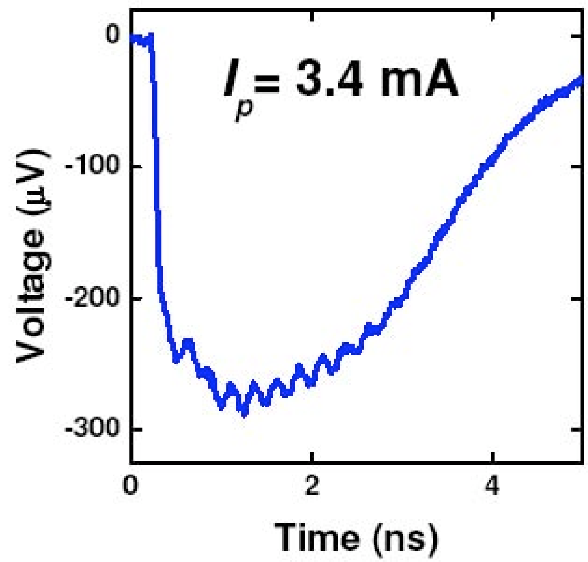
T = 4.2 K



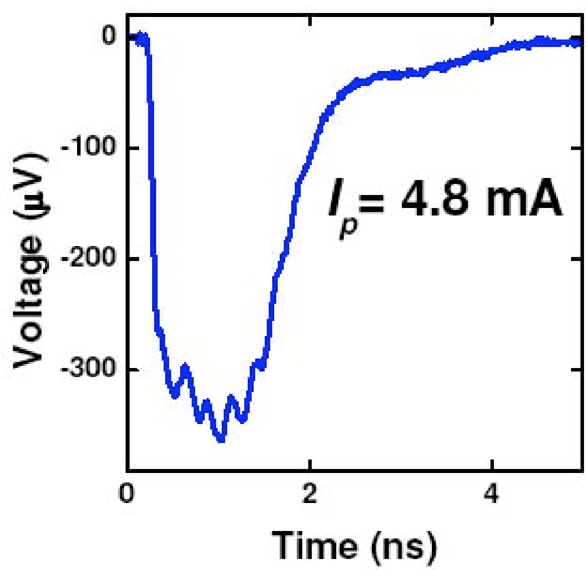


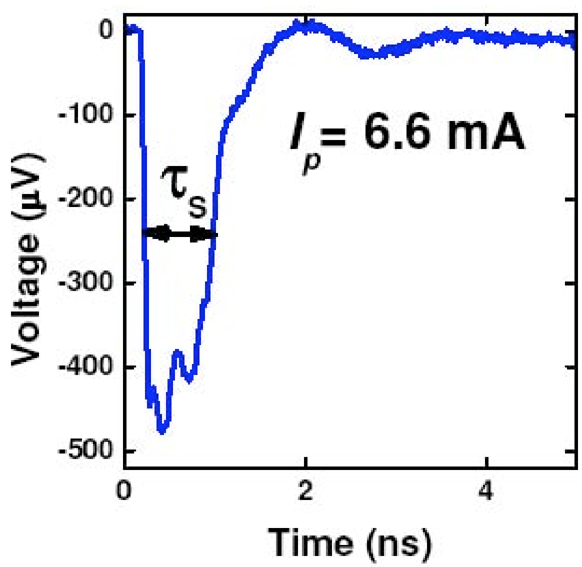
How fast is spin-transfer-driven switching?

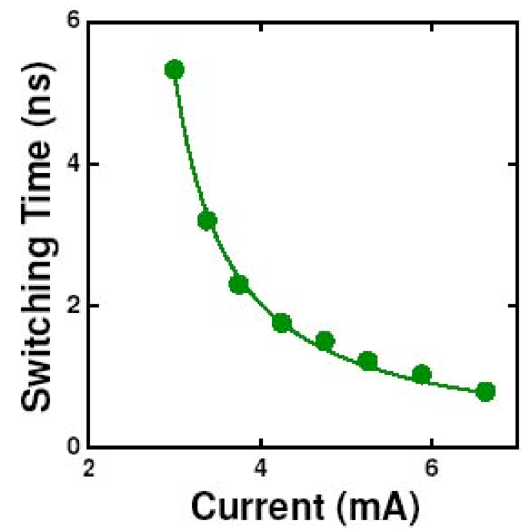




Measure time dependent response of nanopillar resistance to step pulse.







Switching time < 1 ns at high pulse amplitude

Krivorotov *et al*.

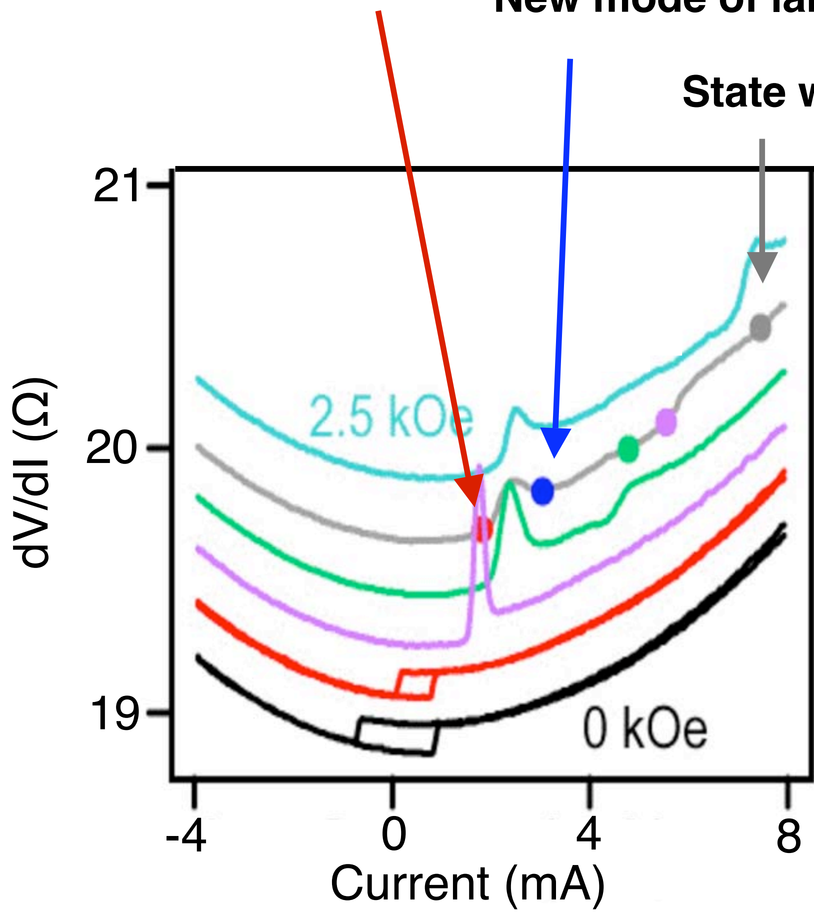
Evolution of Dynamical Modes

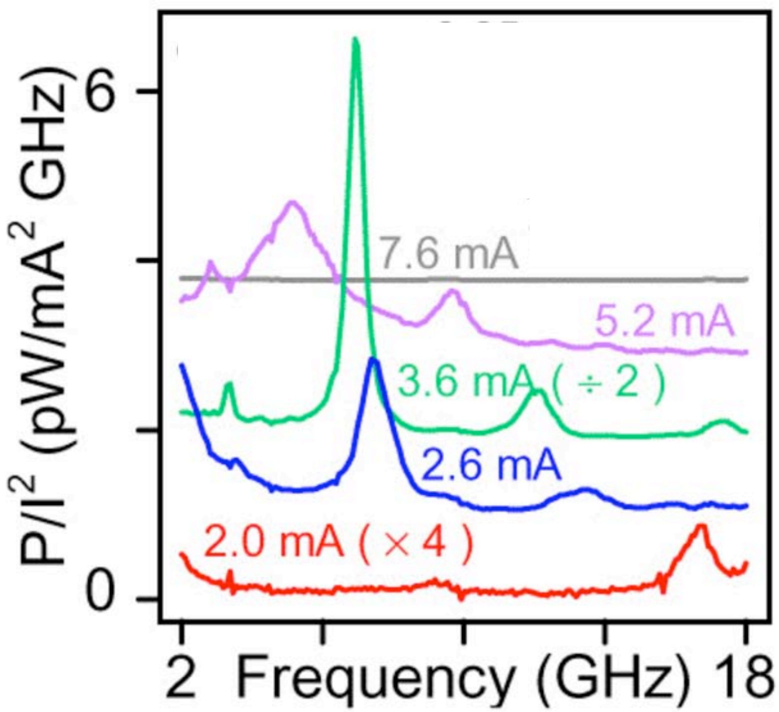
(Co/Cu/Co, room temp.)

Precession begins

New mode of large amplitude motion

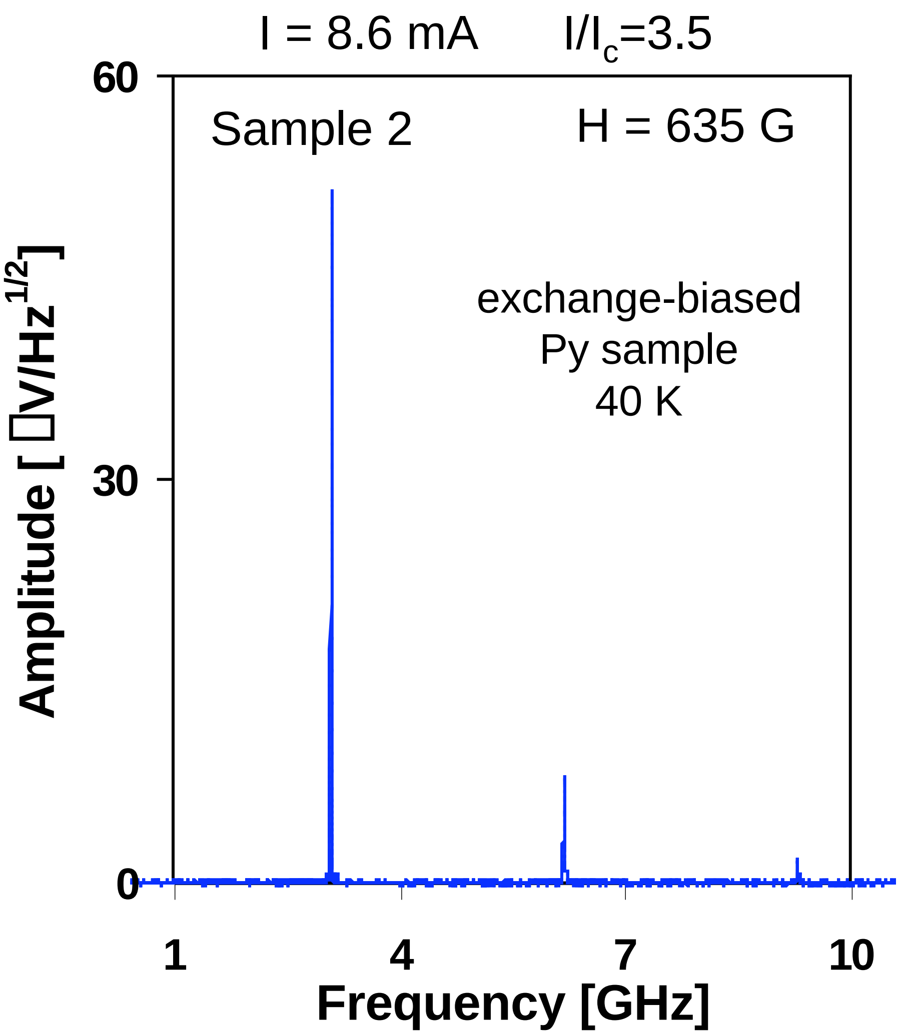
State with small microwave power emission.



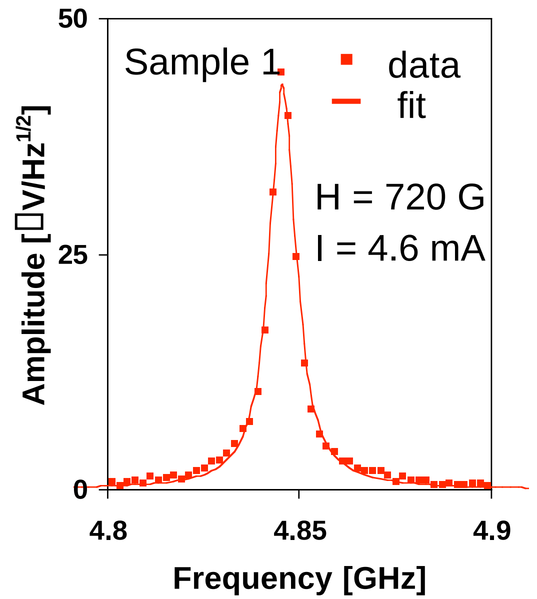


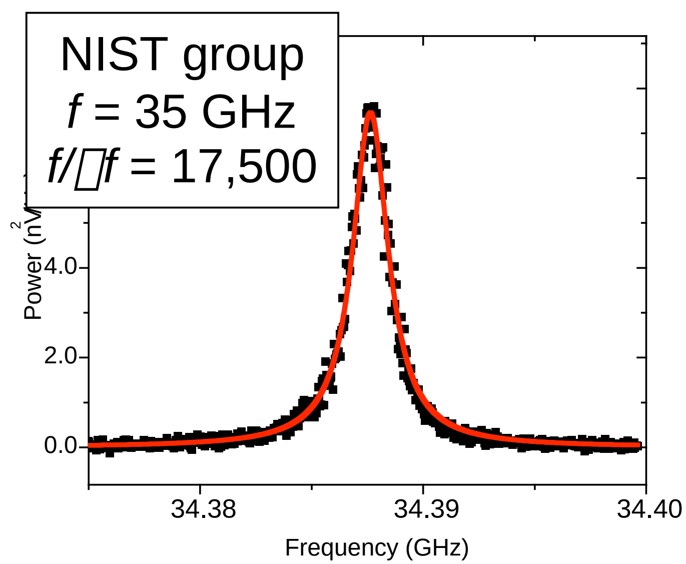
S.I. Kiselev, J.C. Sankey, et al.
Nature **425**, 380 (2003)

Narrow Linewidths In Nanopillars



Power linewidth = 4 MHz

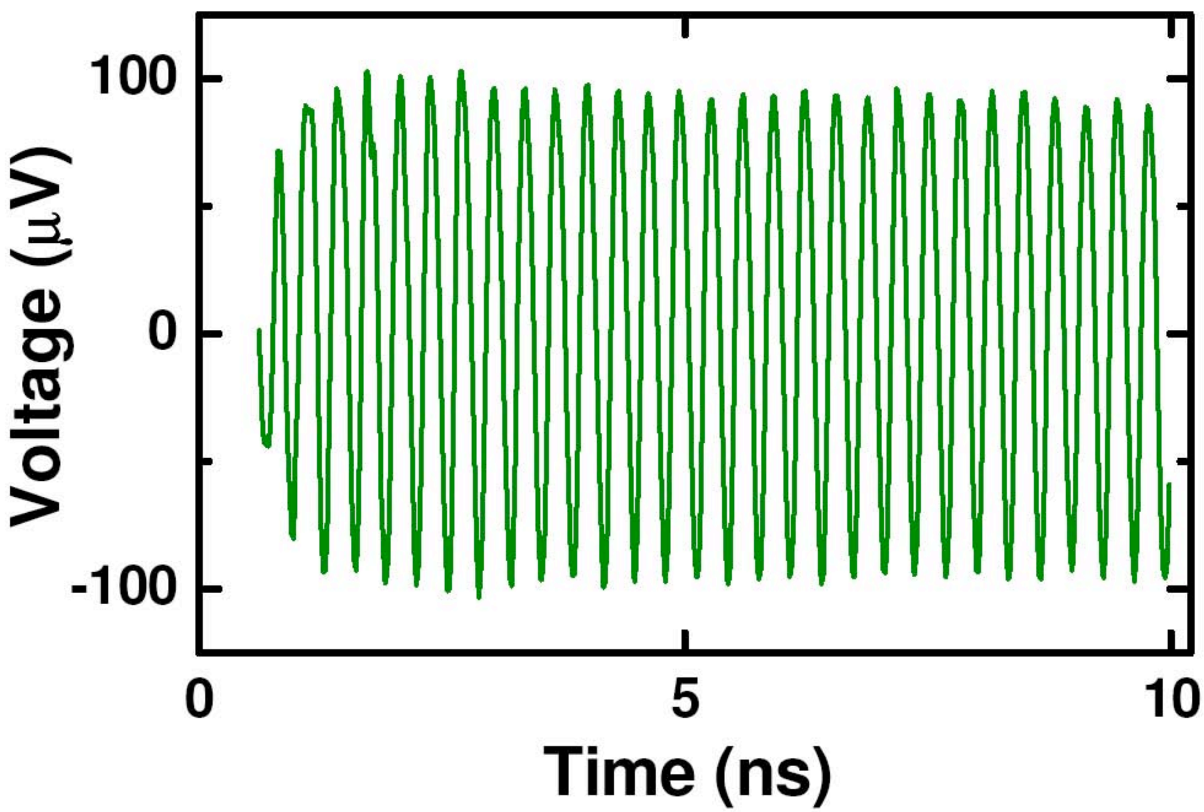


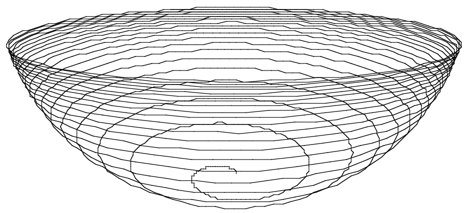


J. C. Sankey et al., submitted to Phys. Rev. Lett.

Precession in Time-Domain Measurements

H = 625 Oe V_{pulse} = 240 mV



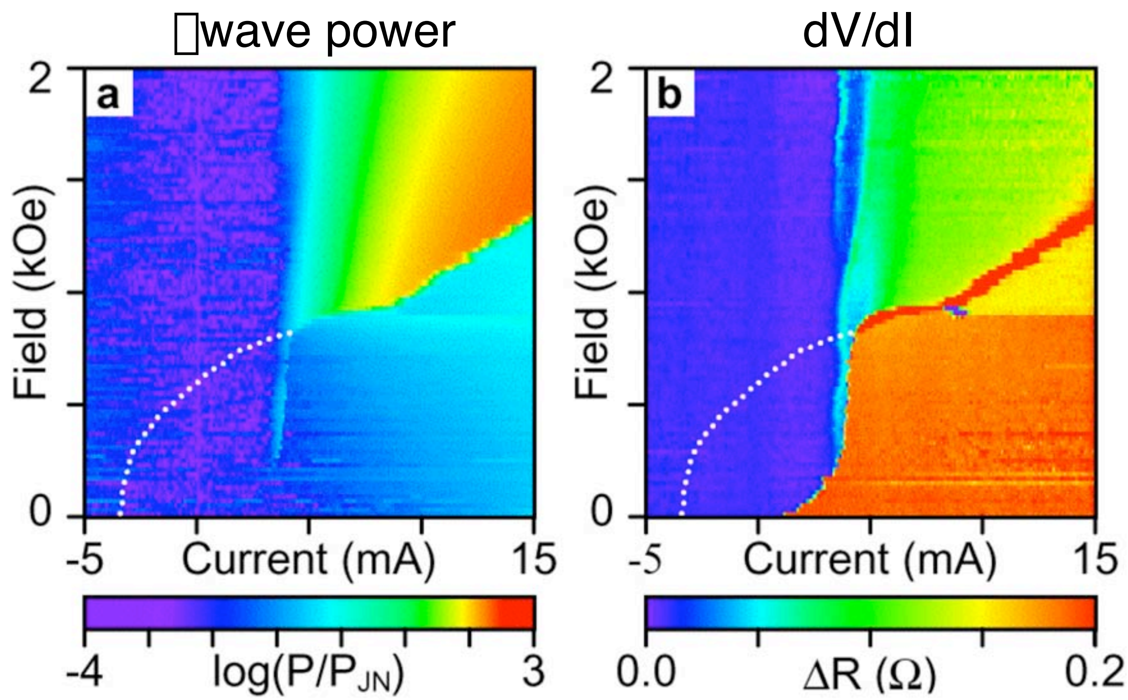


Dephasing time ≥ 50 nsec, hundreds of oscillations can be observed

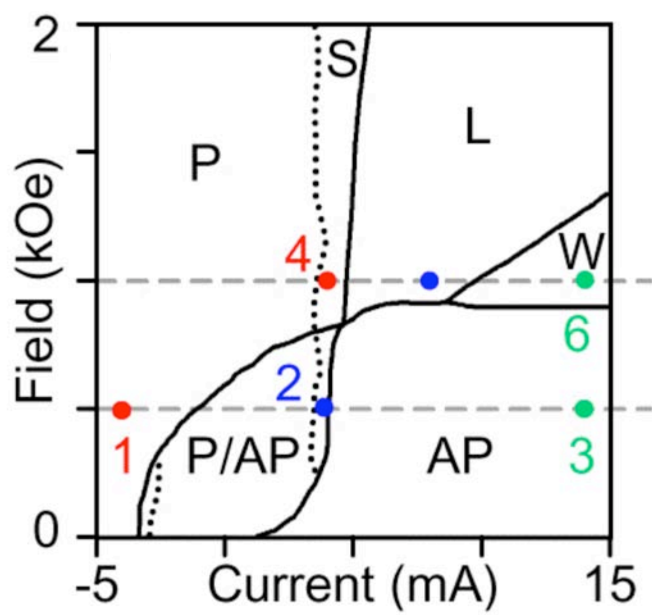
~1 nsec required to establish a steady precession state (~ 4 oscillation periods)

Overall Phase Diagram

(sample 2)

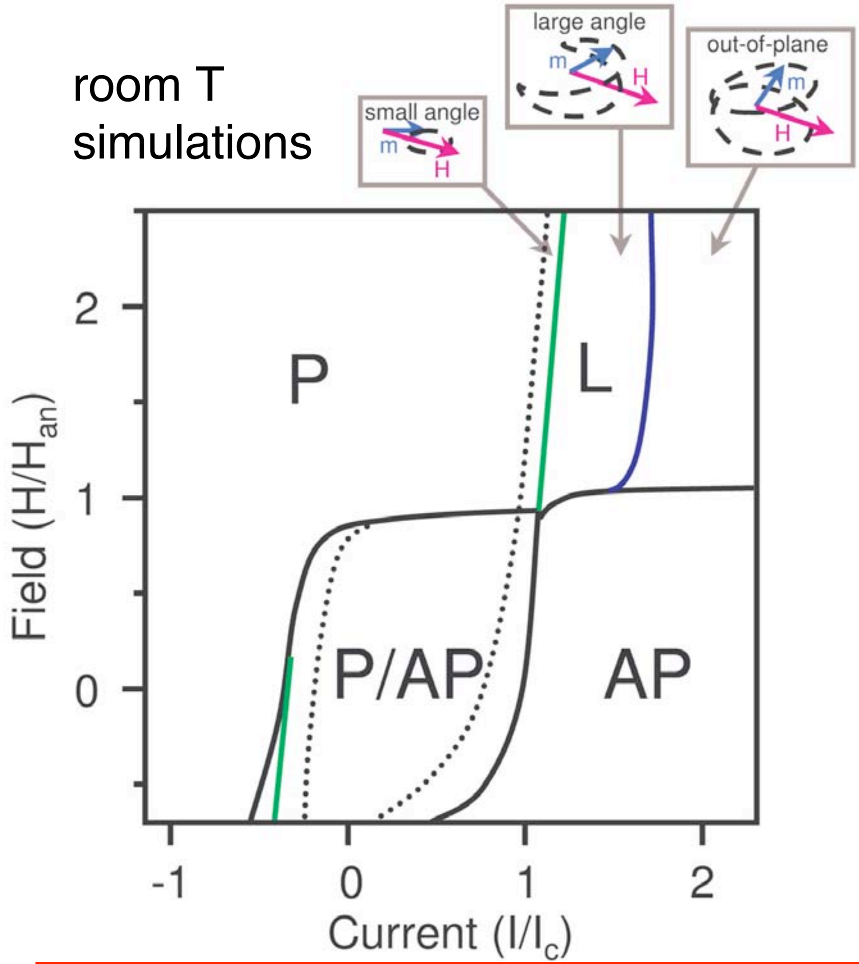


P = parallel
AP = antiparallel
S = small-angle precession
L = large amplitude signal
W = small microwave signal, not P or AP

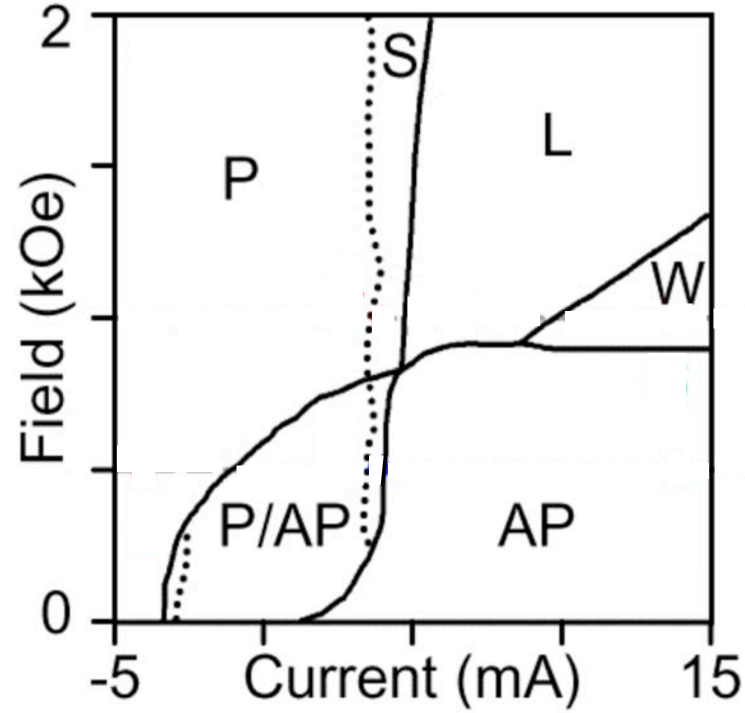


Comparing to Single-Domain LLG Simulations

room T
simulations



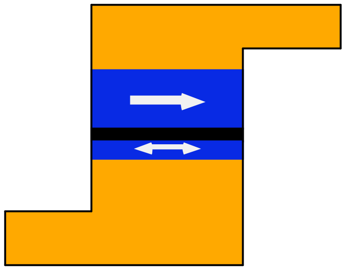
from room T experiment



We see generally good agreement between the measured stability diagram and predictions from single-domain simulations, with some differences at large currents.

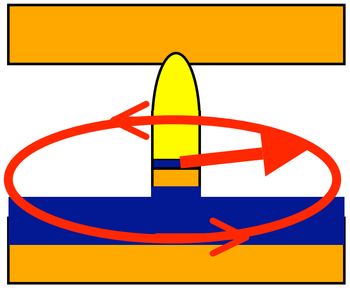
Spatially non-uniform states?

Potential Applications



Magnetic Random Access Memory

- Spin transfer gives stronger torques per unit current than for magnetic fields,in devices smaller than about 250 nm.
- Spin transfer gives short-range forces. No “half-current” problem.
- Excellent scaling to small sizes
- Spin-transfer may allow simpler device geometries.
- Manufacturing tolerances are less critical



Signal Processing with Precessing Nanomagnets

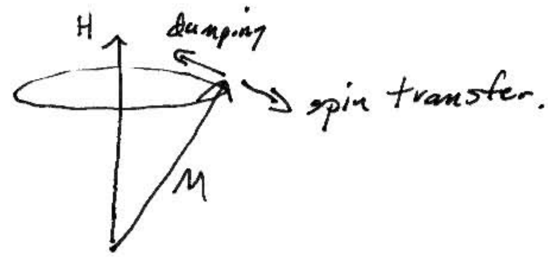
- nm-scale microwave sources, tunable with H and/or I
- Frequency-tunable oscillators, mixers, amplifiers, filters

Summary

Spin-polarized currents apply a torque to a magnetic thin film when that film acts as a spin filter.

At low applied magnetic fields, this torque can be used to switch 2 magnetic layers reversibly between parallel and antiparallel orientations.

At larger applied magnetic fields, a DC spin-polarized current can drive steady-state magnetic precession in a nanomagnet.



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