Experiments on Magnetic Nanostructures

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1. Spin-transfer-driven ferromagnetic resonance in single magnetic nanostructures

comparisons to Tulapurkar et al., Nature 438, 339 (2005).

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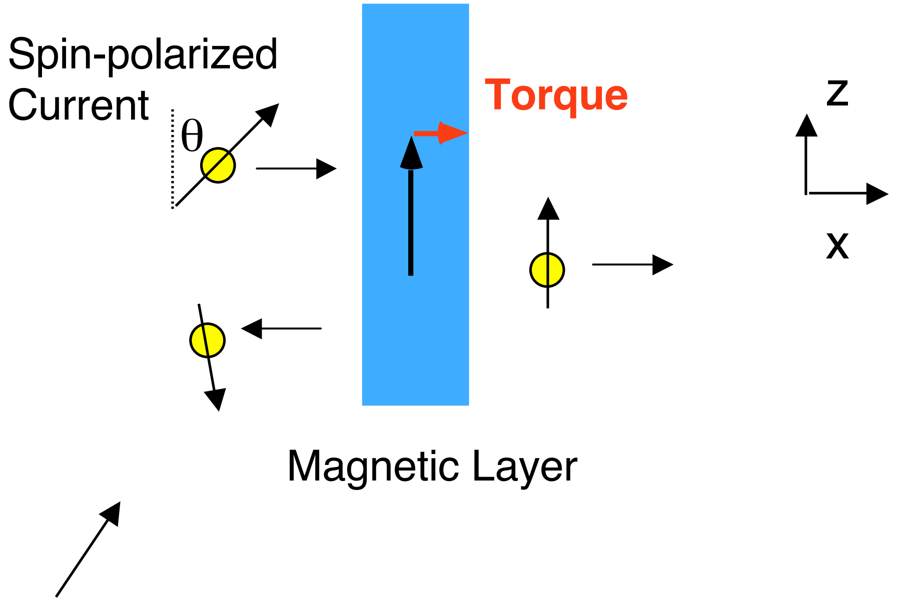
Kirill Bolotin, Ferdinand Kuemmeth, D. C. Ralph

2. "Tunneling Anisotropic MagnetoResistance" in atomic-scale magnetic contacts

comparisons to Viret et al., cond-mat/0602298

Slonczewski/Berger Model of Spin-Transfer Torques:

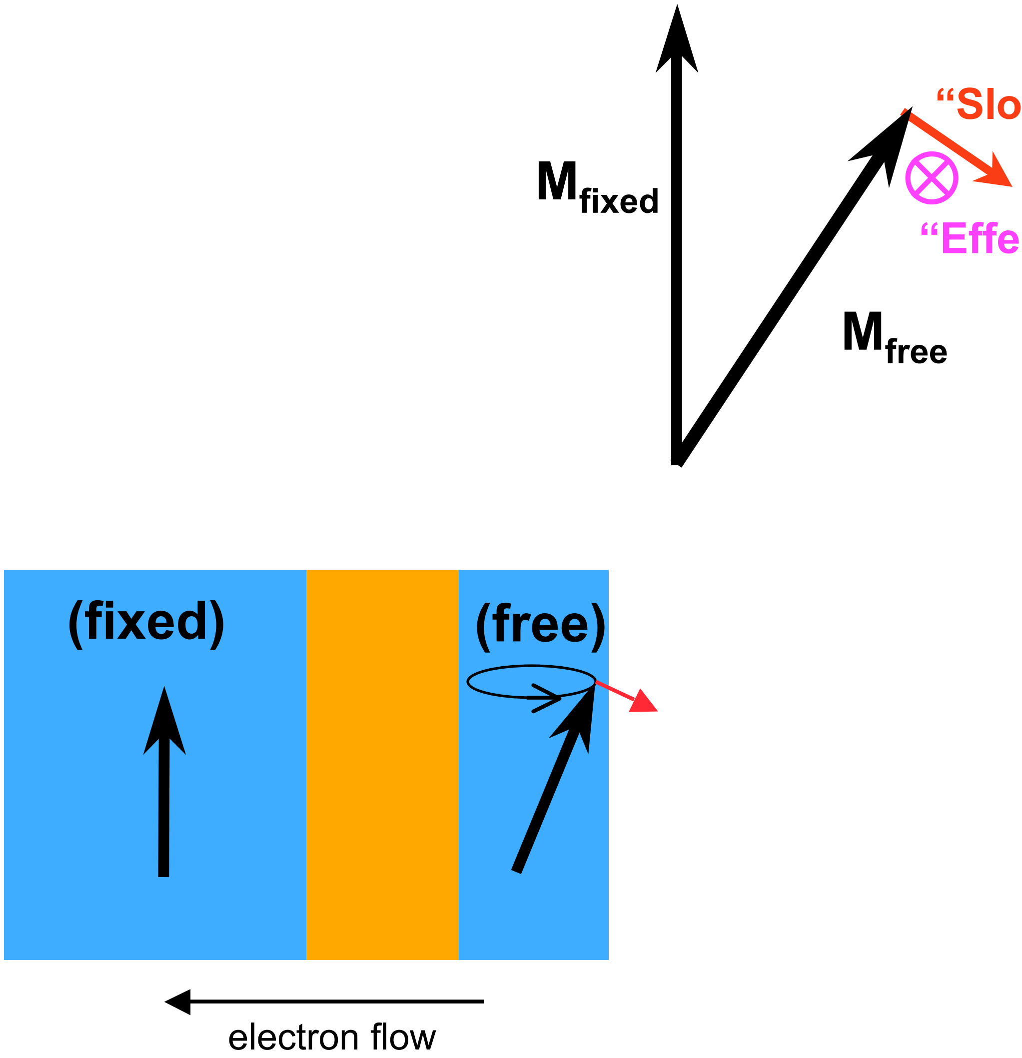
When a spin-polarized current interacts with a magnetic layer, the layer can absorb the transverse component of spin angular momentum and receive a torque.



(Reflected electrons can carry away some
transverse angular momentum.
<~ 10% correction in theory for metal spin valves)

Xia et al., PRB **65**, 22040 (2002); Stiles and Zangwill, PRB **66**, 014407 (2002)

Direction of the Spin Torque in Spin Valves



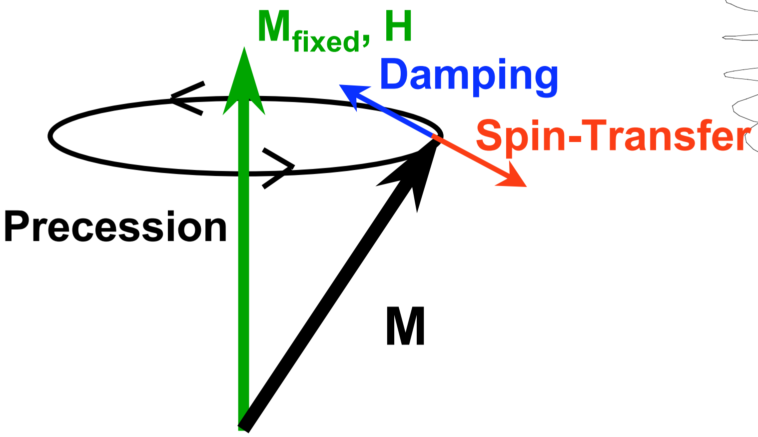
“Slonczewski” Spin-Transfer Torque

(direction depends
on the sign of I)

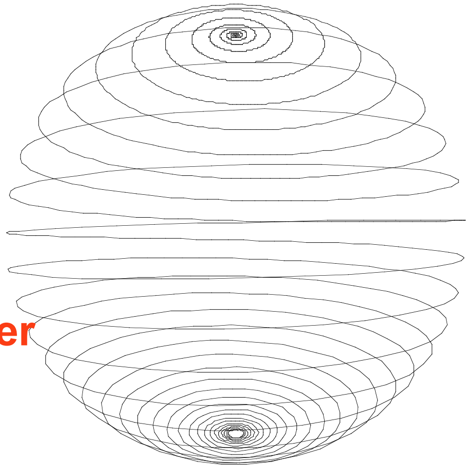
“Effective Field”

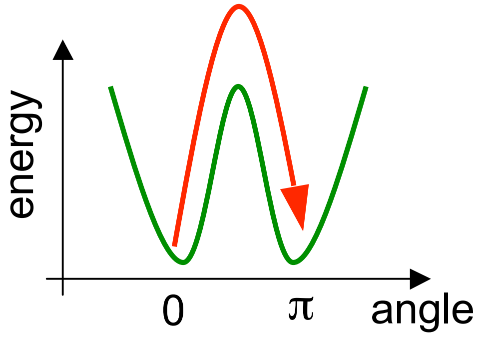
Magnetic Dynamics with Spin Transfer

(assuming a macrospin description)

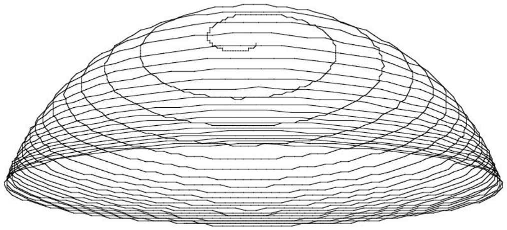


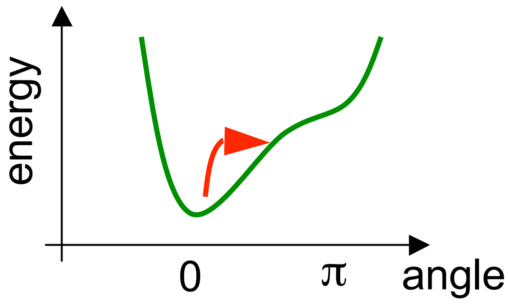
switching





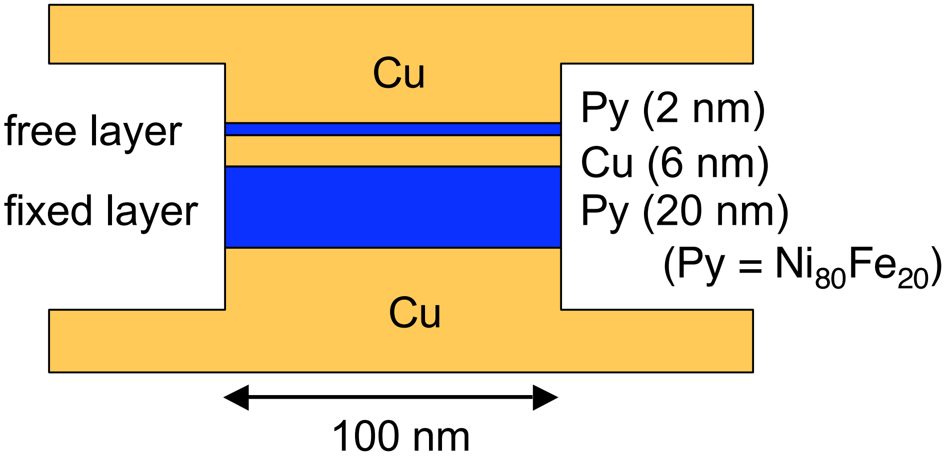
steady-state precession





Spin-Transfer-Driven Magnetic Switching

Metal Multilayer Devices



Cu

free layer

fixed layer

Py (2 nm)

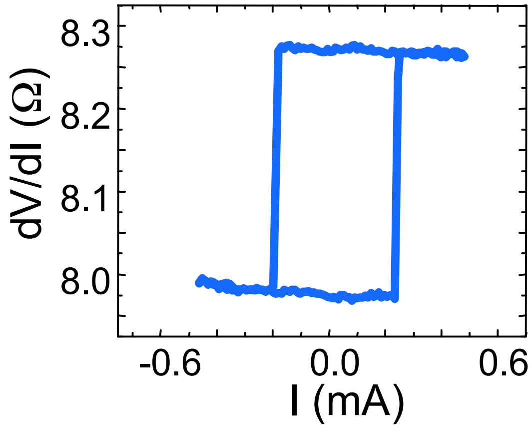
Cu (6 nm)

Py (20 nm)

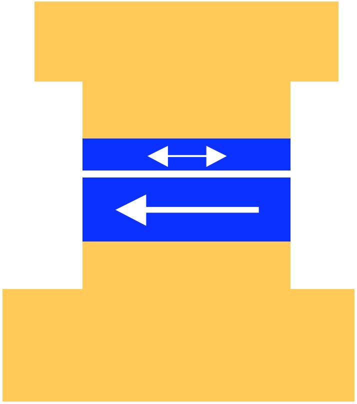
(Py = $Ni_{80}Fe_{20}$)

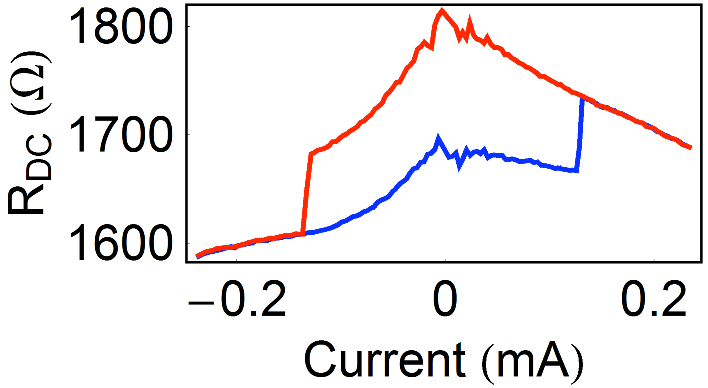
Cu

100 nm

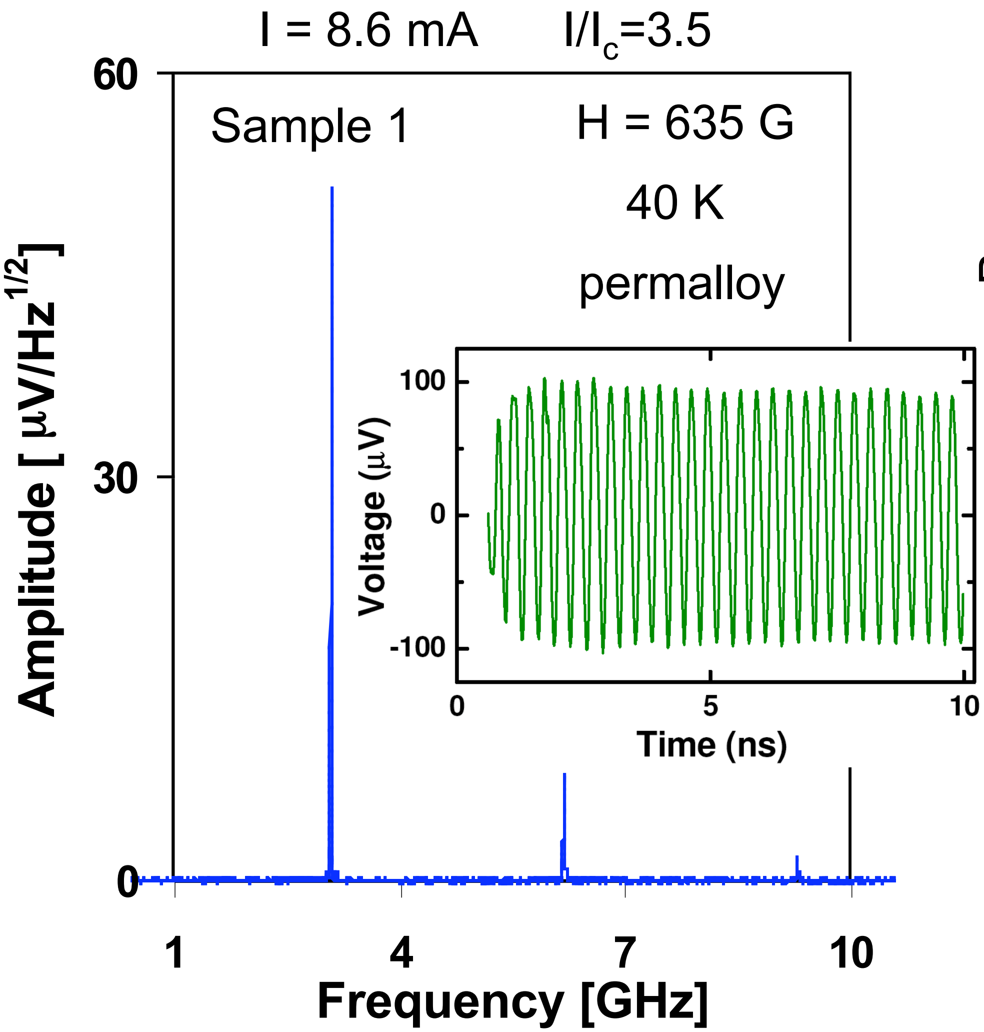


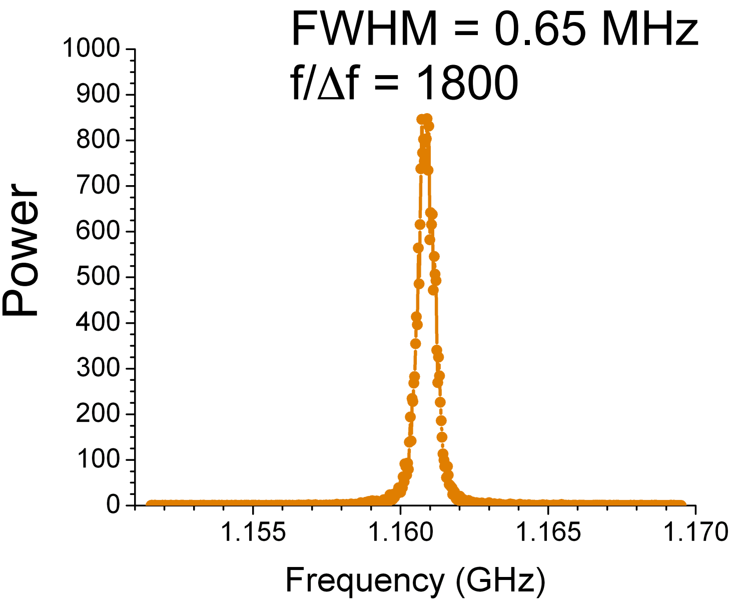
Magnetic Tunnel Junctions

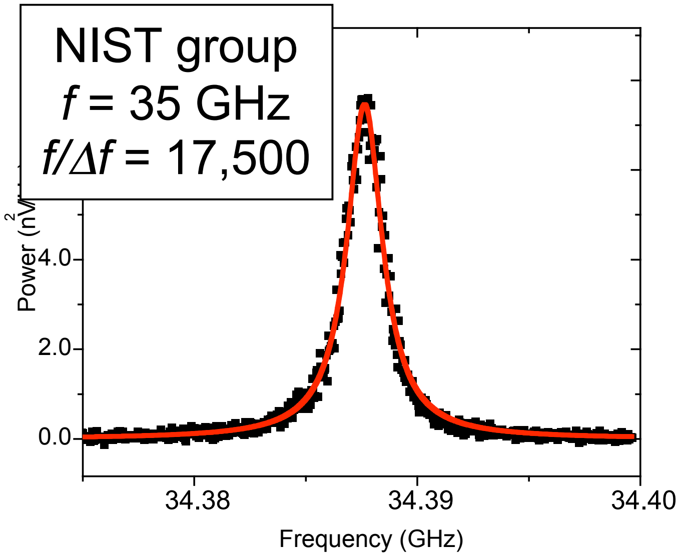




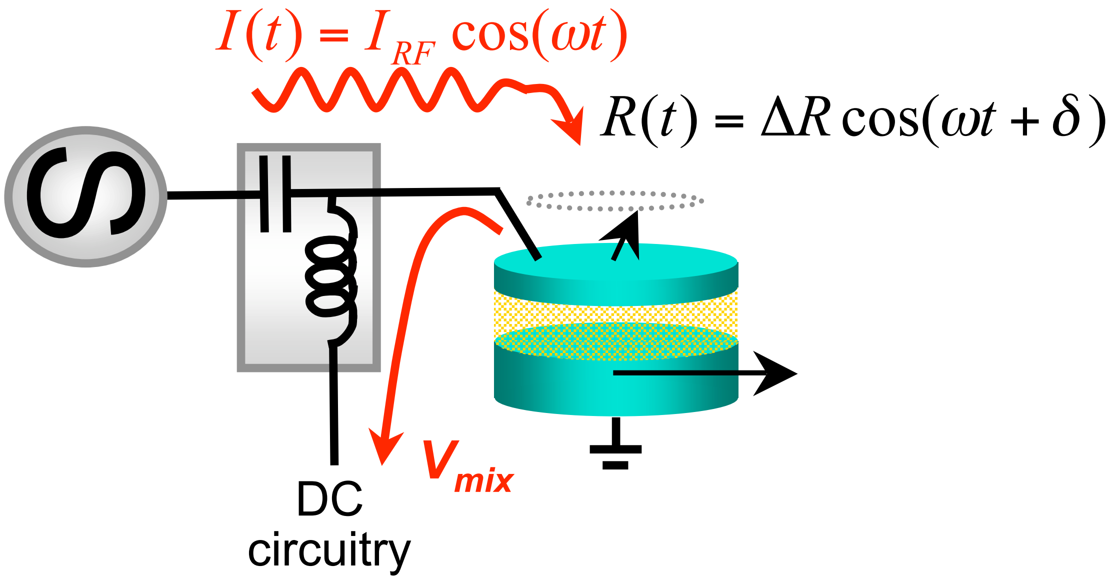
High-frequency Magnetic Dynamics Driven by DC Spin-Polarized Currents







Microwave-Frequency Dynamics:
Resistive Detection of Spin-Transfer-Driven Magnetic Resonance



$$I(t) = I_{RF}\cos(\omega t)$$

$$R(t) = \Delta R\cos(\omega t + \delta)$$

$$V(t) = I(t)R(t) \sim I_{RF}\cos(\omega t)\Delta R\cos(\omega t + \delta)$$

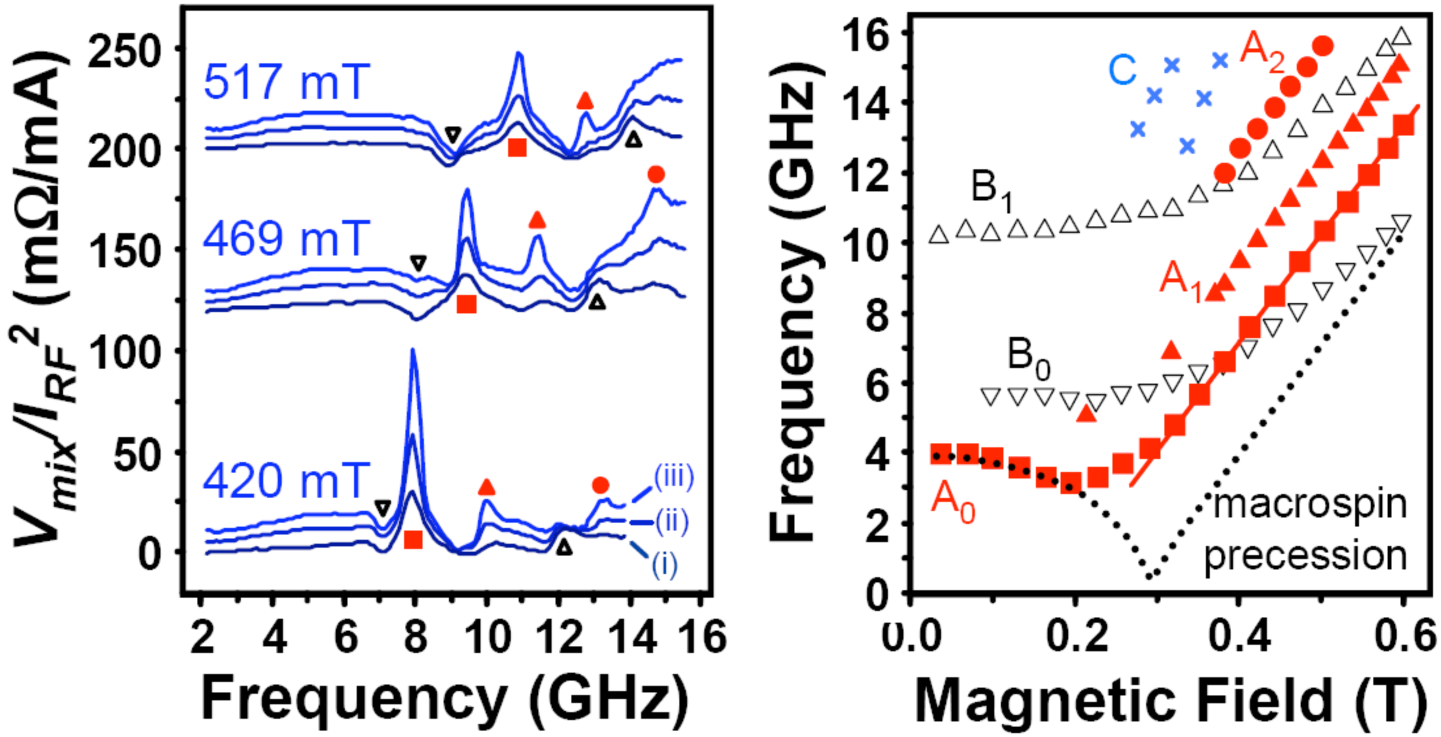
$$= \frac{1}{2} I_{RF}\Delta R\left[\cos(\delta) + \cos(2\omega t + \delta)\right]$$

$$V_{mix} \sim \frac{1}{2} I_{RF}\Delta R\cos(\delta)$$

Resonant resistance oscillations generate a DC voltage component by mixing

(similar technique used for radio-frequency detection by Tulapurkar et al., Nature **438**, 339 (2005))

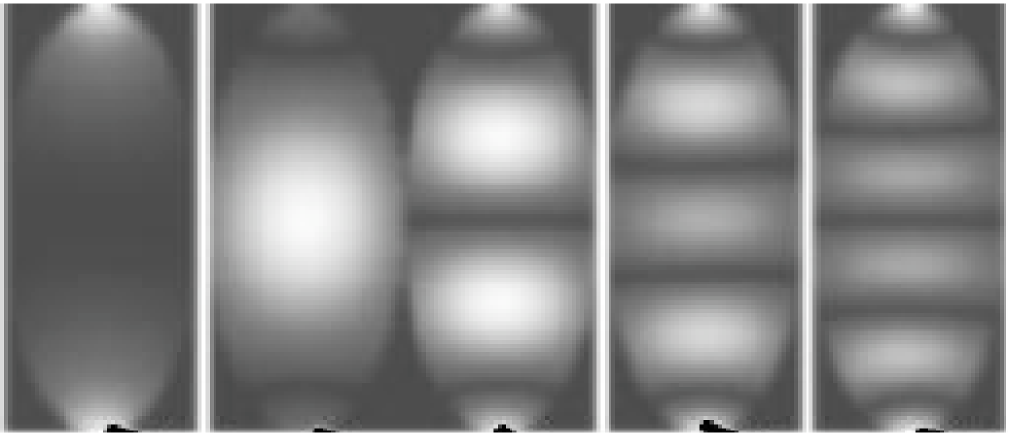
Measuring Normal Modes in a Single Nanomagnet



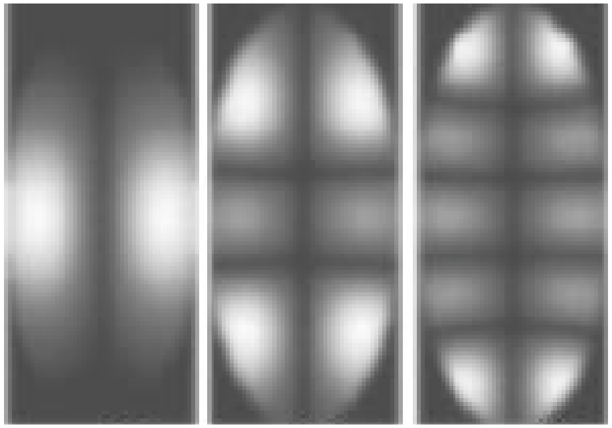
Sequences of modes are observed, for precession of both the free and “fixed” magnetic layers.

Sankey et al., cond-mat/0602105

What are the Expected Normal Modes?



from numerical modeling
with in-plane field

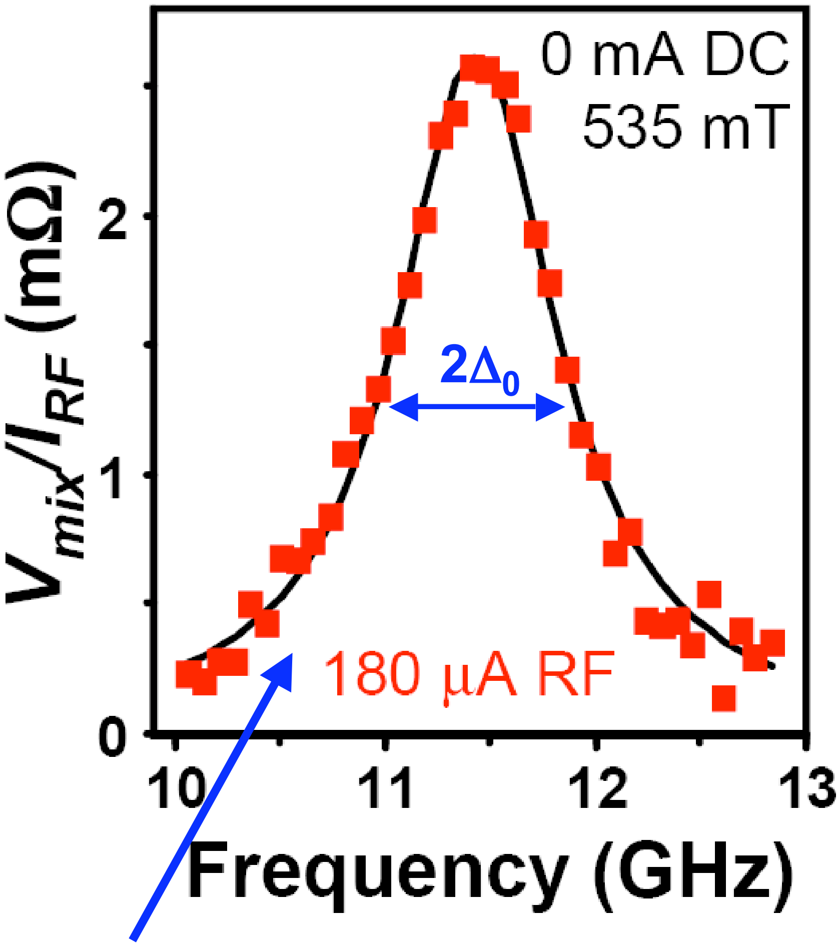


Measured frequencies and frequency spacings are in reasonable qualitative agreement with simulation.

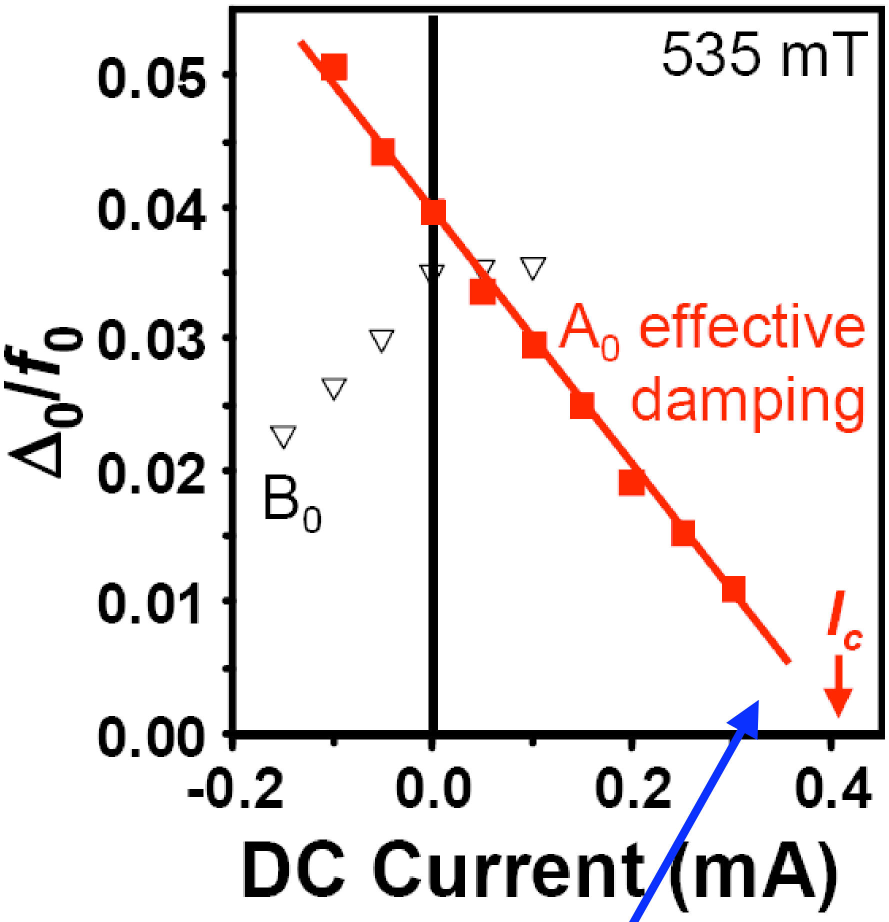
(Detailed modeling of our sample geometry has not been done yet.)

McMichael and Stiles, J. Appl. Phys. **97**, 10J901 (2005)

The width of the resonance curves gives a measure of the damping coefficient for the oscillations



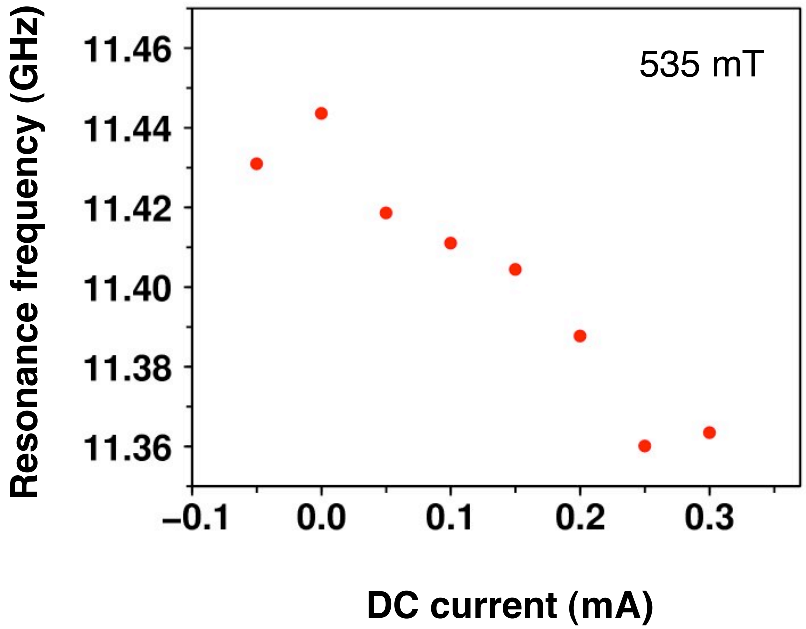
Peak shape is Lorentzian.



Resonance width can be tuned to arbitrarily small values.

Very Weak Dependence of Precession Frequency on DC Current

Less than 1% shift in *f* for I up to the critical current

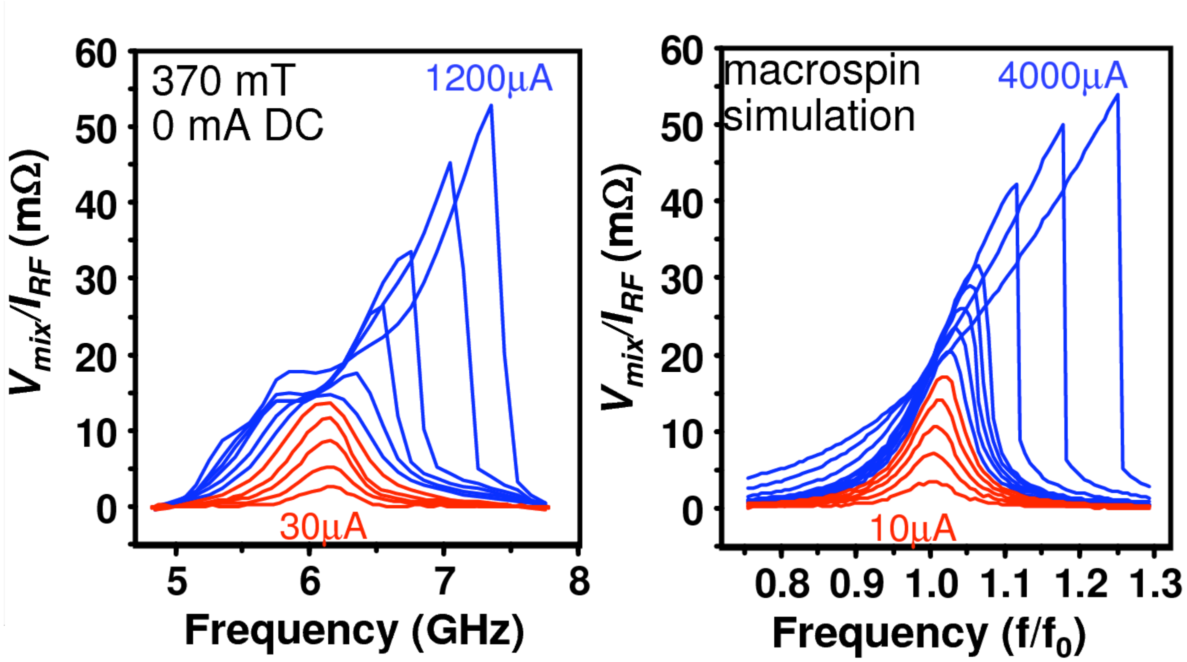


Limits on the Effective-Field Contribution of Spin Transfer
< 15% of the “Slonczewski Torque”

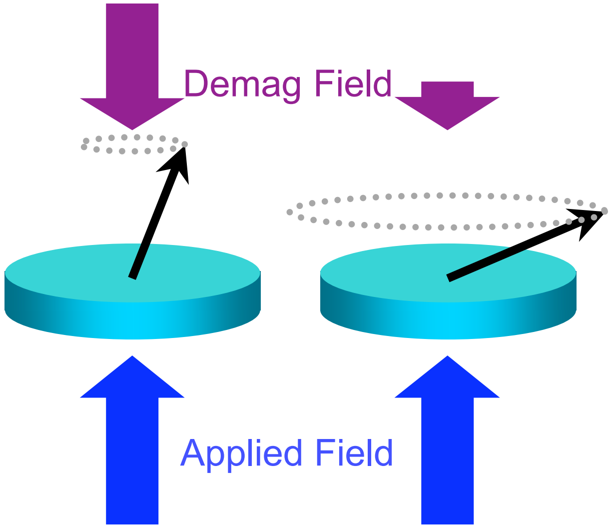
(The measured shift is probably dominated by a changing dipole interaction between the magnetic layers, as their relative angle changes slightly, or by the Oersted field, not by an effective field from spin transfer.)

This result agrees with conclusions of the Kent group (NYU), based on an analysis of the current-field phase diagram (PRB **70**, 184438 (2004)).

Nonlinearities at Large Precession Angle

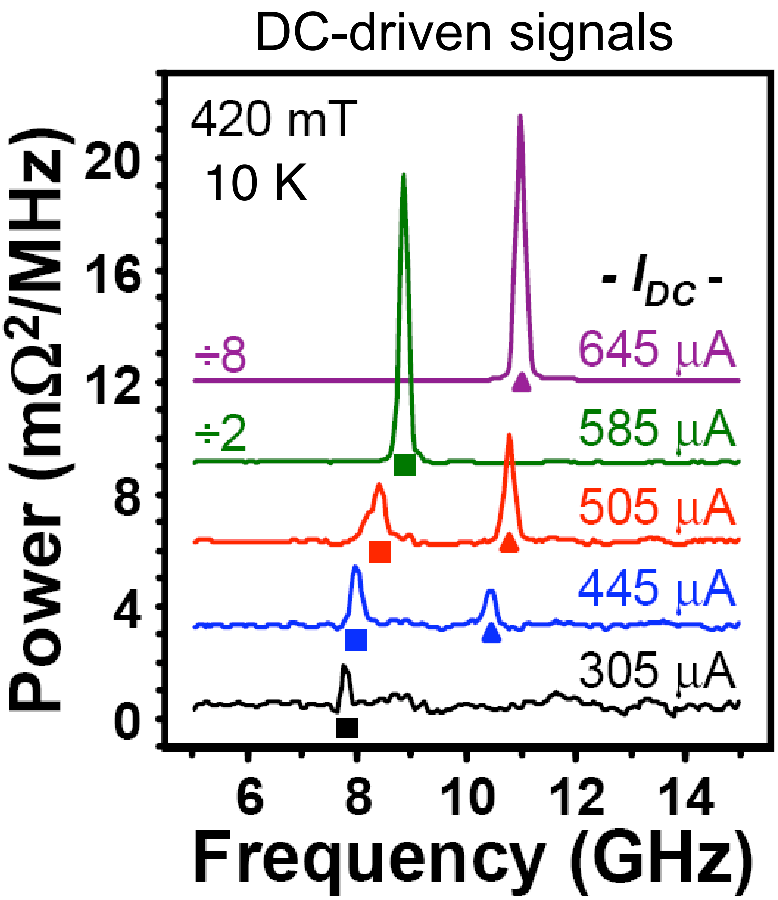


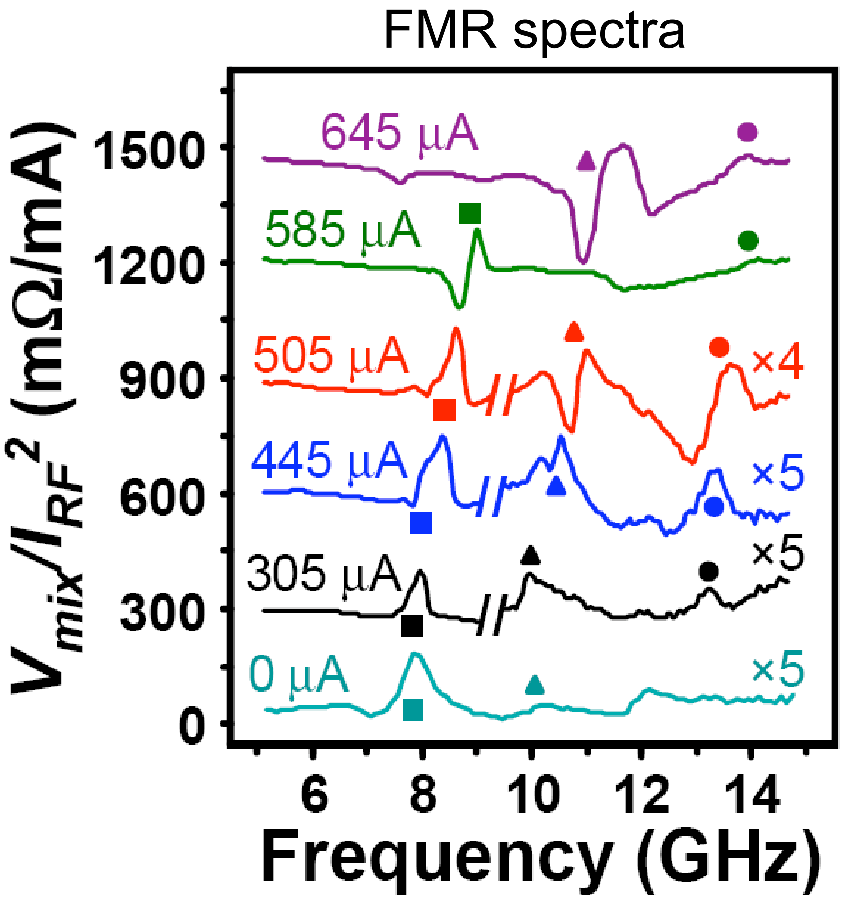
Largest precession angle observed experimentally ~ 40°



Nonlinearities can be explained by the dependence of the average demag field on the precession angle.

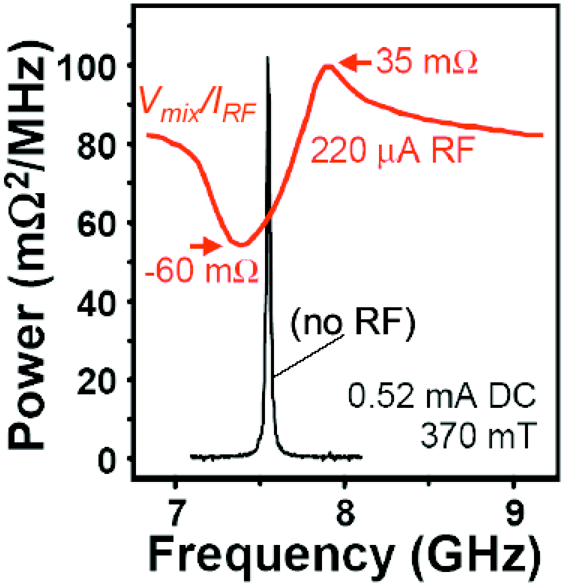
What modes are excited in DC-Driven Precession?


DC-driven signals

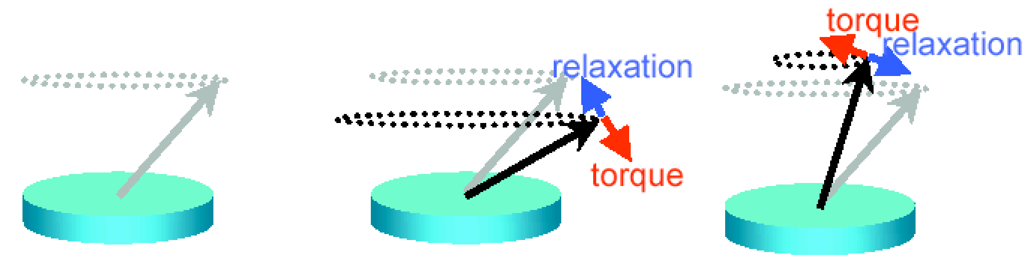

FMR spectra

At the onset for precession, DC spin-transfer excites the lowest frequency, most-spatially-uniform magnetic normal mode.

Peak Shape in the Phase-Locking Regime



- Peak shape for the phase-locking regime has a negative response on low-frequency side.
- Dip below the natural frequency:
  The RF drive forces smaller amplitude precession, phase locking ~180° out of phase with precession
- Macrospin simulation confirms this picture

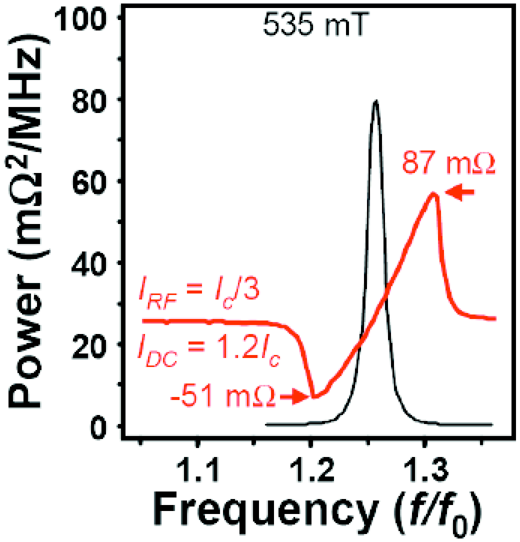


natural DC-driven resonance (no AC drive)

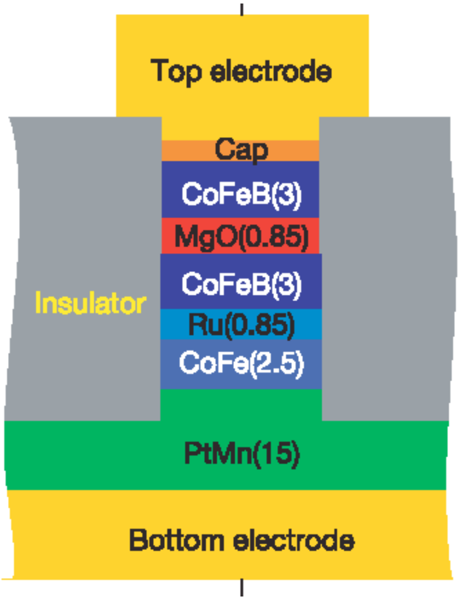
higher-frequency AC drive (in phase)

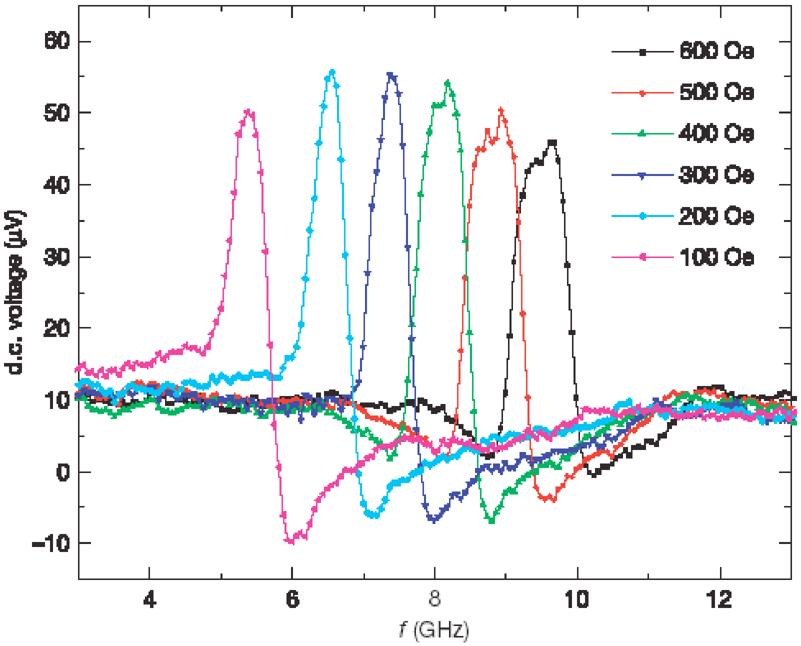
lower-frequency AC drive (opposite phase)

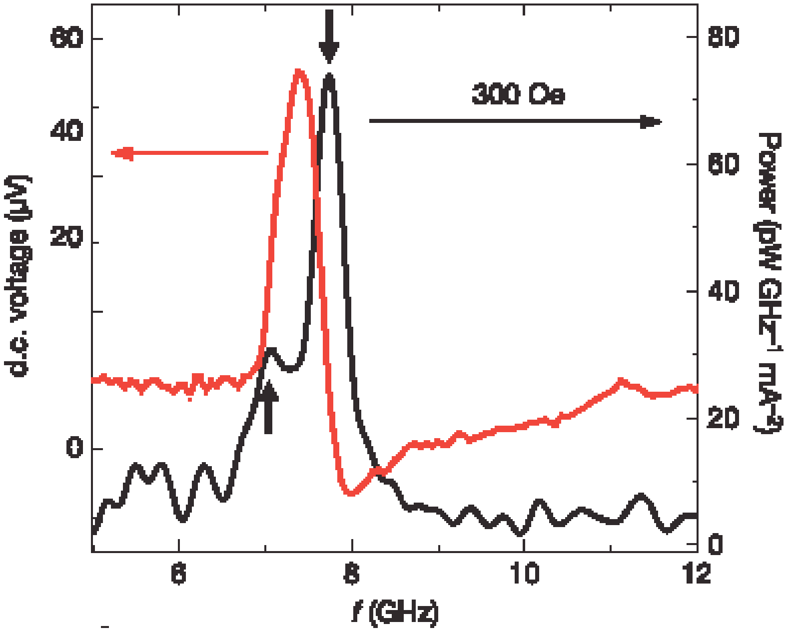
macrospin simulation



Tulapurkar et al., Nature **438**, 339 (2005)







Why the non-Lorentzian peak shape?

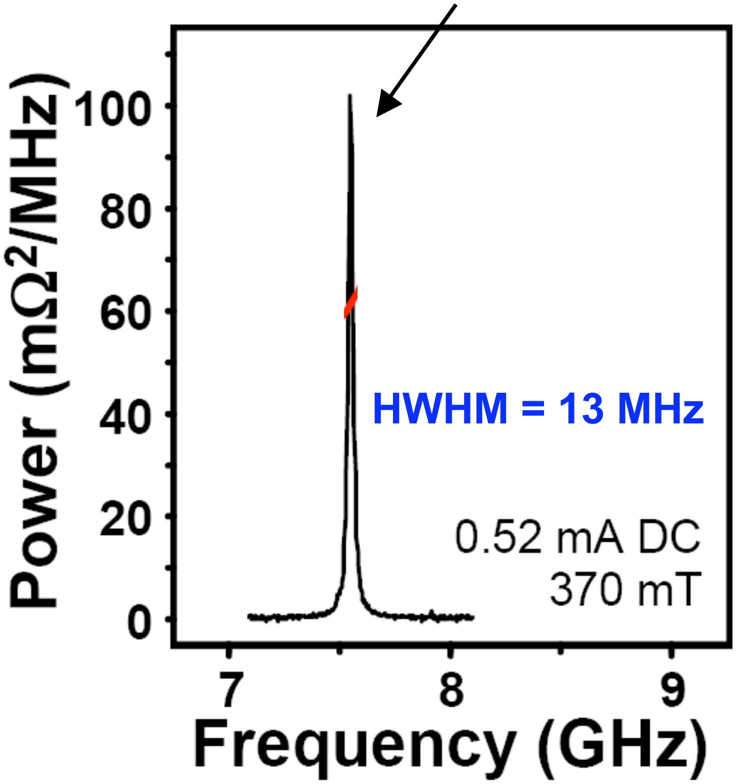
- Larger effective-field torque in tunnel junctions?
- Phase locking to thermally-excited precession?
- Superposition of signals from two different modes?
- Precession axis not along symmetry axis? (suggested by G.E.W. Bauer)

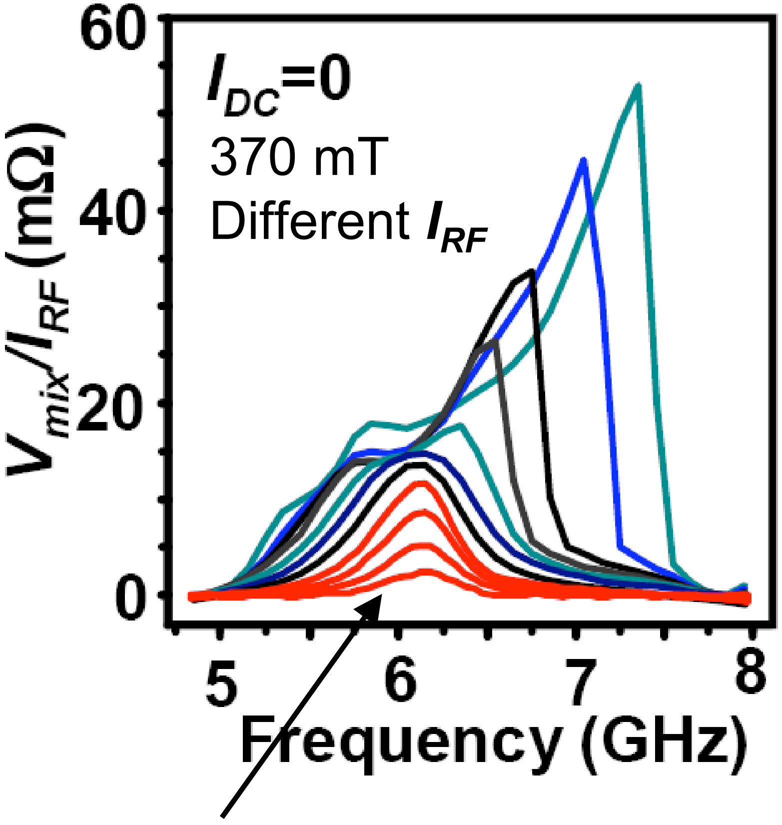
The DC-driven spectral peaks can be much narrower than the FMR resonances

DC-driven

T = 10 K

FMR

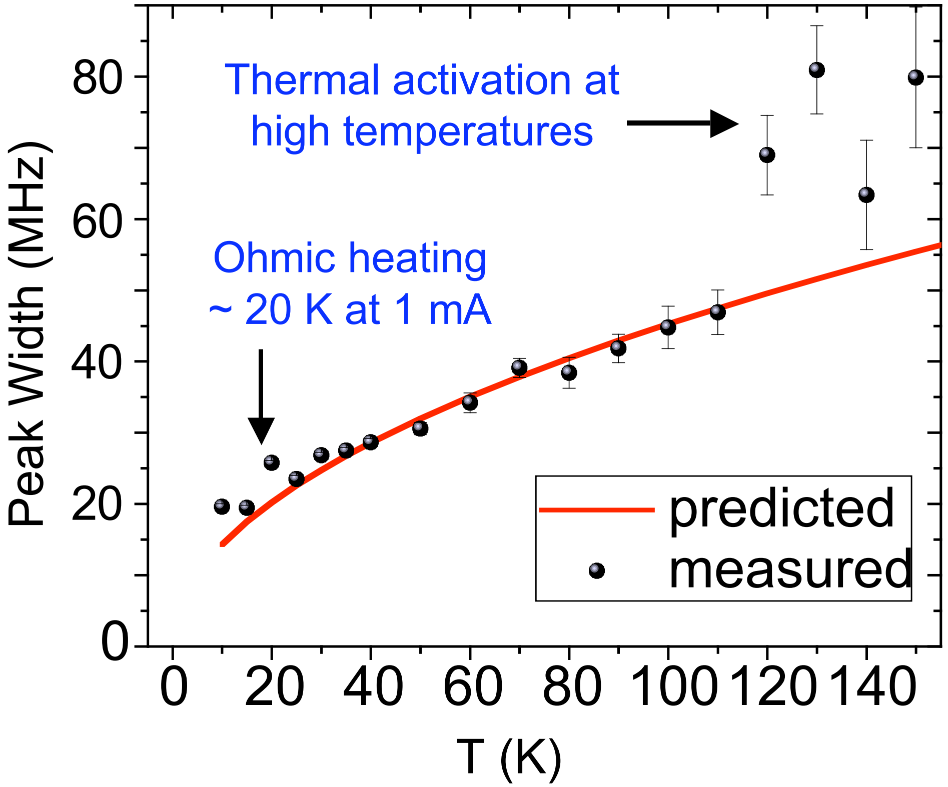




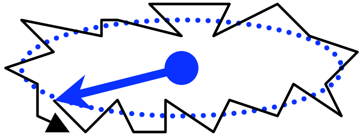
HWHM = 250 MHz

What sets the linewidths of the DC-driven signals?

Affected by thermal fluctuations. Not determined by the damping.



Top view of precession



Thermal fluctuations deflect moment in a random walk around trajectory, inducing a spread in the orbital period

At low T in a macrospin model,

$$\sigma_f \propto \sqrt{\frac{k_B T}{M_s V}}$$

But -- the measured low-T widths can be 8 times narrower than predicted by macrospin simulations.

Sankey et al., PRB **72**, 224427 (2005)

Why are the DC-driven linewidths so narrow?

- Narrower than expected within simple macrospin models.

- Micromagnetic calculations to date tend to predict larger linewidths than the macrospin model, not narrower.

Is something missing in the assumptions of the micromagnetic codes?

e.g., Current-mediated effective interactions between different parts of the precessing layer?

Magnetoresistance of Magnetic Point Contacts

Caution:

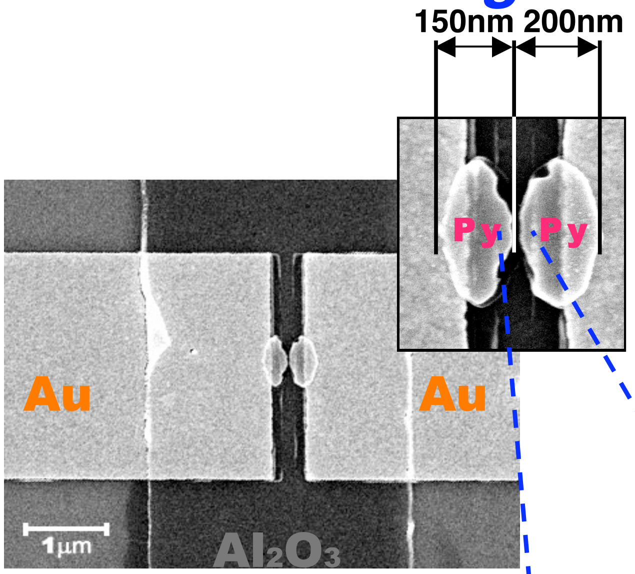
Mechanical stability needs to be a big concern.

Previous measurements of huge "Ballistic Magnetoresistance" at room temperature in magnetic point contacts (Garcia et al., PRL **82**, 2923 (99); Hua and Chopra, PRB **67**, 060401 (2003)) have been challenged due to artifacts from magnetostriction and magnetostatic forces (Gabureac et al., PRB **69**, 100401; Yang et al., APL **84**, 2865 (2004); Egelhoff et al., J. Magn. Magn. Mater. **287**, 496 (2005)).

Our Strategy:

- No suspended magnetic parts
- Measure only at low temperature

Magnetic Electrode Fabrication



- We fabricate permalloy contacts connected by a narrow constriction using e-beam lithography

- The constriction is than narrowed down using controlled electromigration* at 4K
Strachan et al.APL* ***86**, 043109 (2005)*

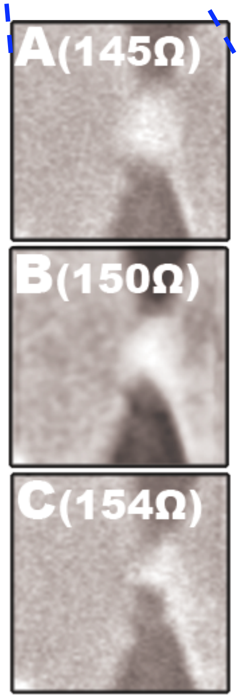
- By monitoring the resistance of the junction we can estimate the size of the constriction.

Narrowing the contact using electromigration

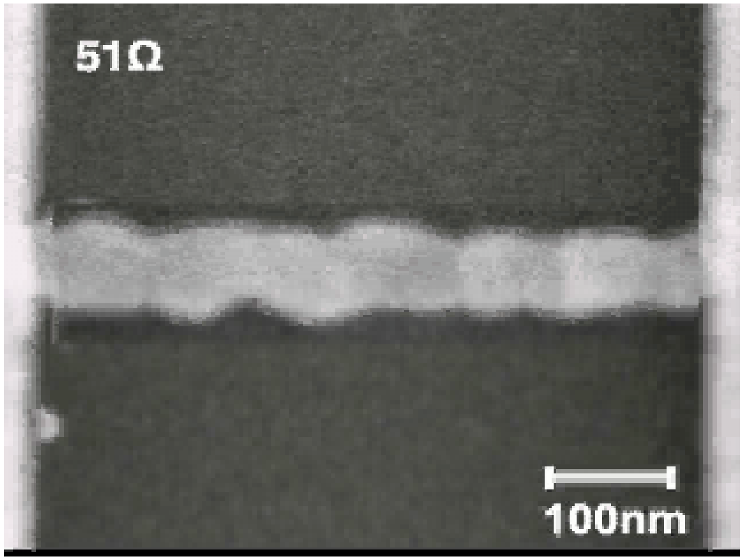
145 Ω

150 Ω

154 Ω



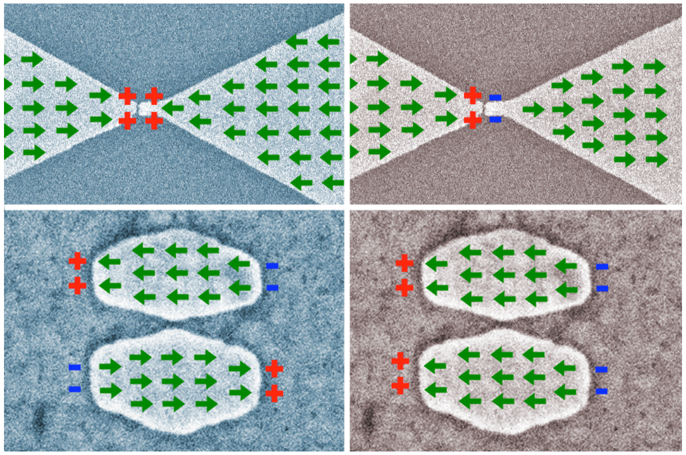
Electromigration in a test gold device live



The Design of the Magnetic Electrodes

- We design the shape of the electrodes to enable controlled studies with both parallel and antiparallel moment configurations, with clean switching.

- Use of Permalloy -- low magnetostriction, high polarization, small crystalline anisotropy

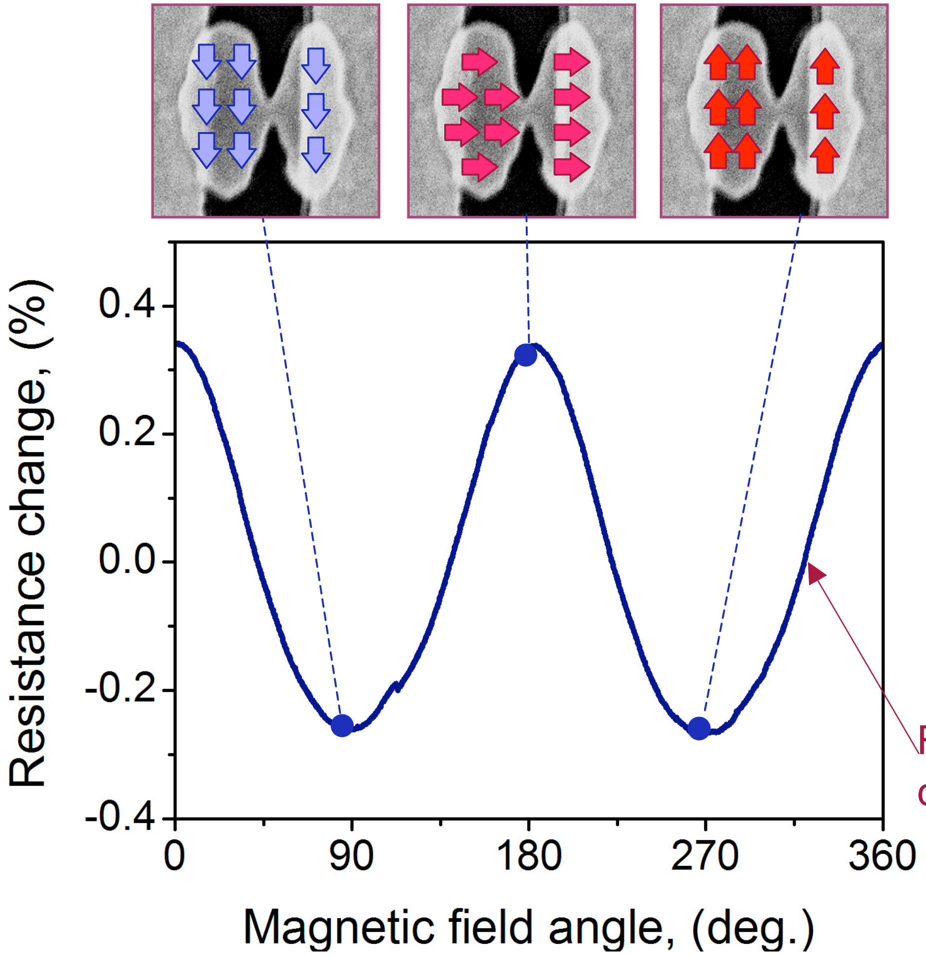


With conventional “bowtie” electrodes, dipole fields act to destabilize the antiparallel configuration.

With this shape for electrodes, accurate antiparallel and parallel orientations are both accessible.

“Bulk” magnetoresistance measurement

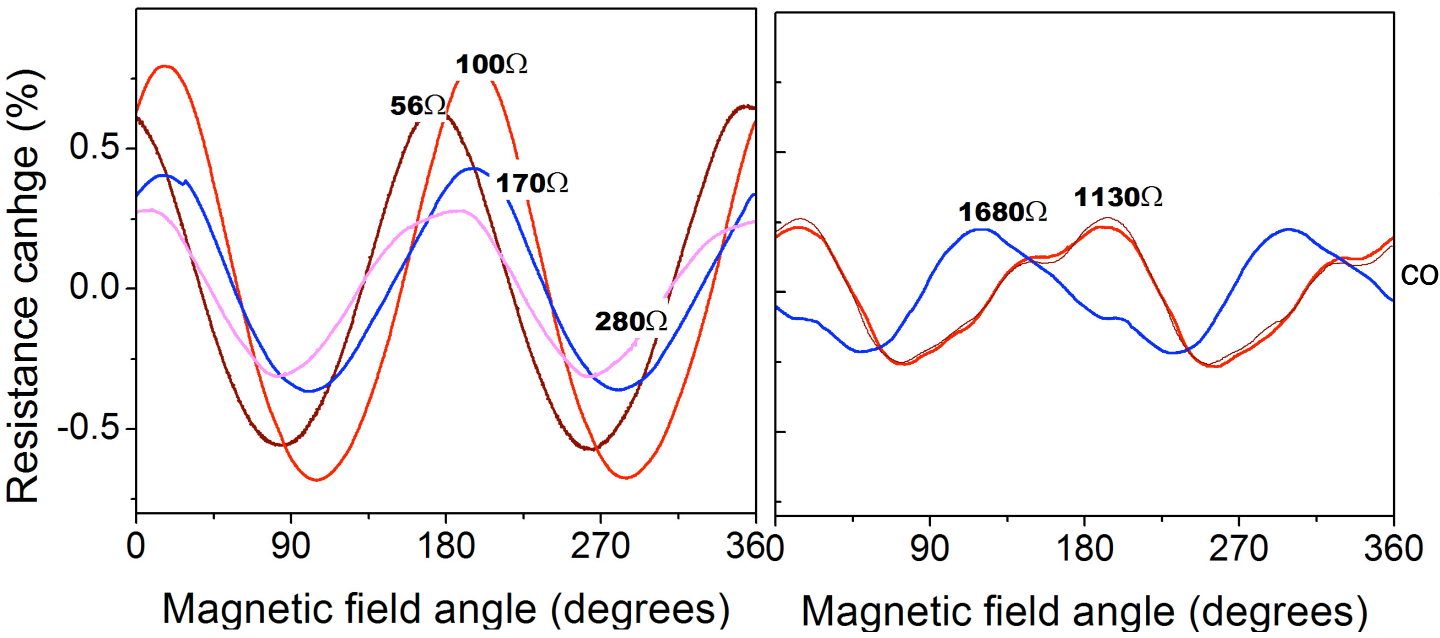
*sweeping magnetic field **angle** at 800mT*



R follows cos$^2(\theta)$,
consistent with AMR

- We measure our samples at 4.2 K, inside a 3D magnet.
- We apply magnetic field 800mT, large enough to saturate magnetization, and rotate its direction in the plane of the sample
- The resistance change is due to anisotropic magnetoresistance (AMR) **~ 1%**

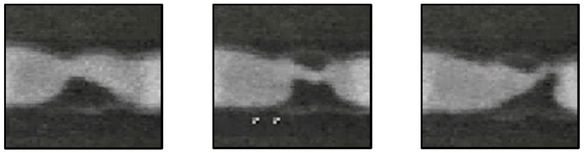
Evolution of AMR with contact size: low-resistance contacts



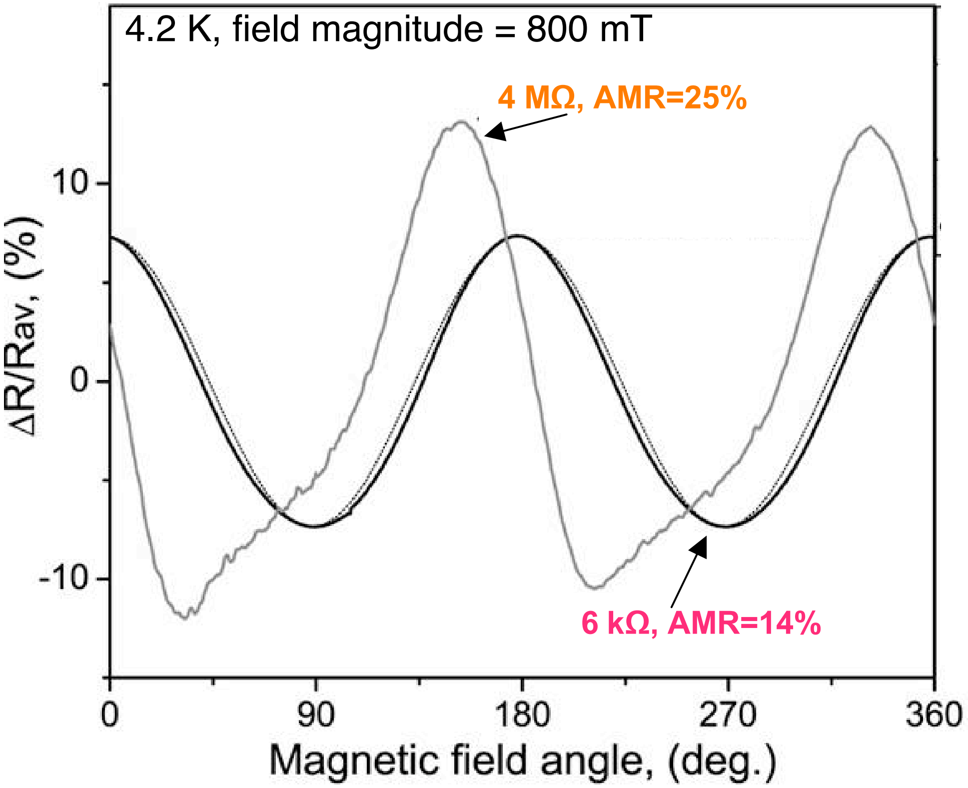
$\Delta g = e^2/h$
would
correspond to
$\Delta R \sim 5\%$

- The magnitude and phase of AMR can change with resistance
- For some samples we can observe deviations from ~*cos*$^2(\theta)$ dependence

gold test device



Large Anisotropic Magnetoresistance in Nanometer-Scale Junctions

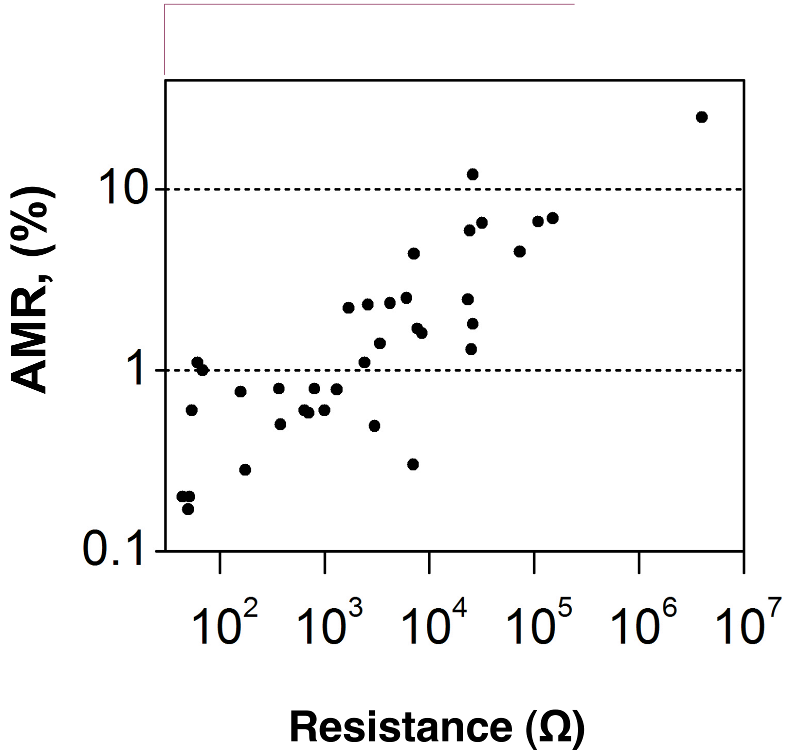


- Large AMR is observed both for metallic samples and in the tunneling regime
- The resistance changes smoothly and reproducibly. Indicates that the large AMR is not a result of mechanical artifacts
- The angular dependence can be non-sinusoidal

Qualitatively similar to effects in GaMnAs junctions, (Gould et al., PRL **86**, 043109 (2005)), but the mechanism is probably different.

K. I. Bolotin et al., cond-mat/0602251

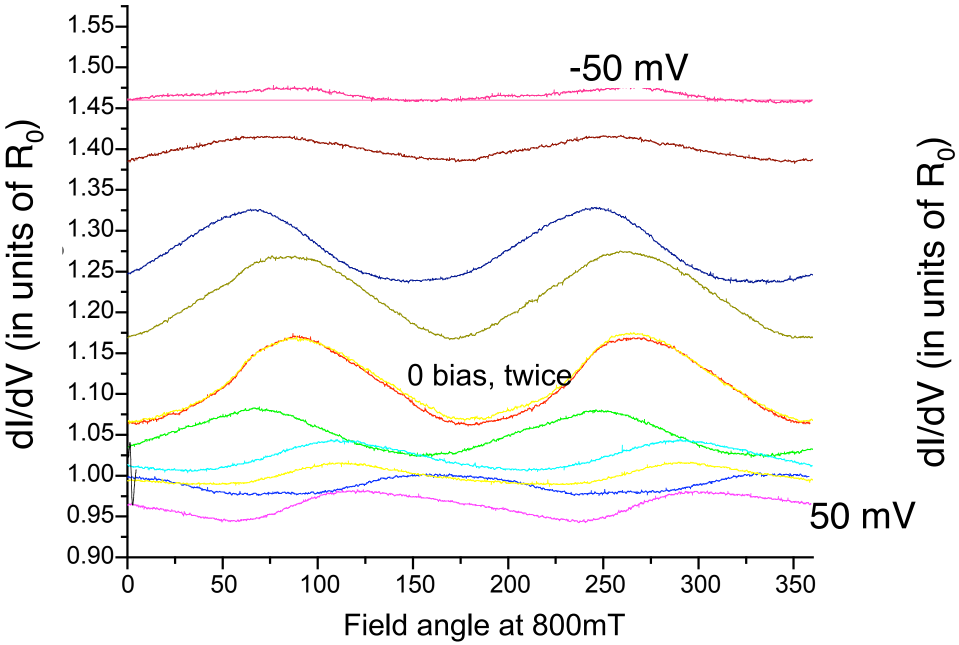
Dependence of the AMR/TAMR on Resistance

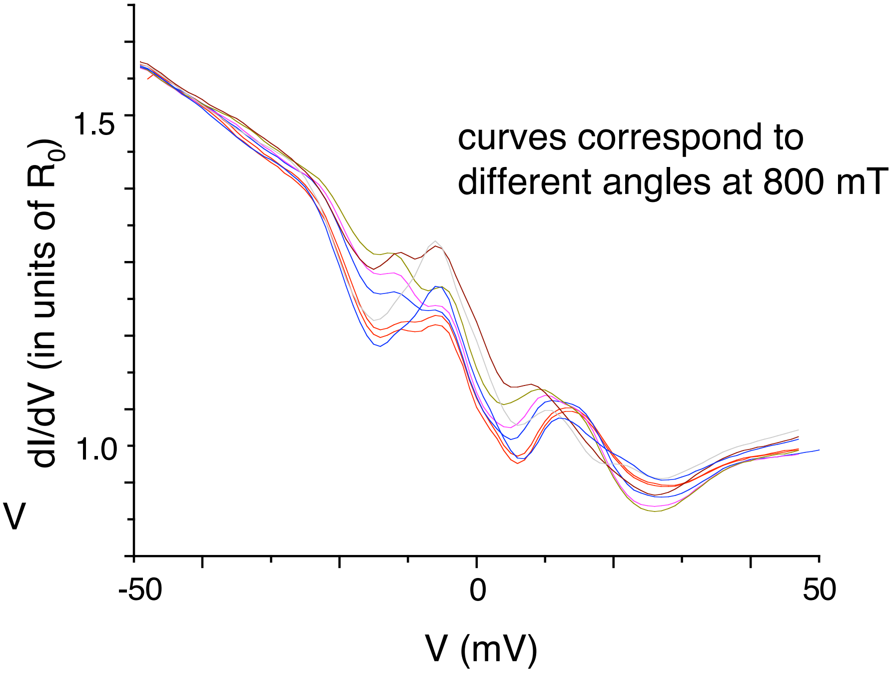


(V=0, 4.2 K)

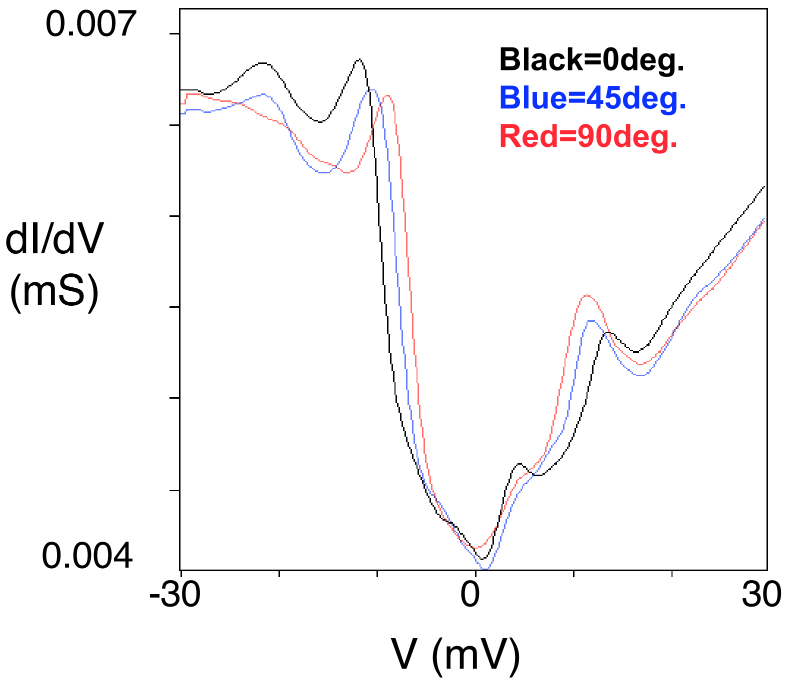
The phase and magnitude of the TAMR depend on bias

470 kΩ sample, ~10% AMR at V=0



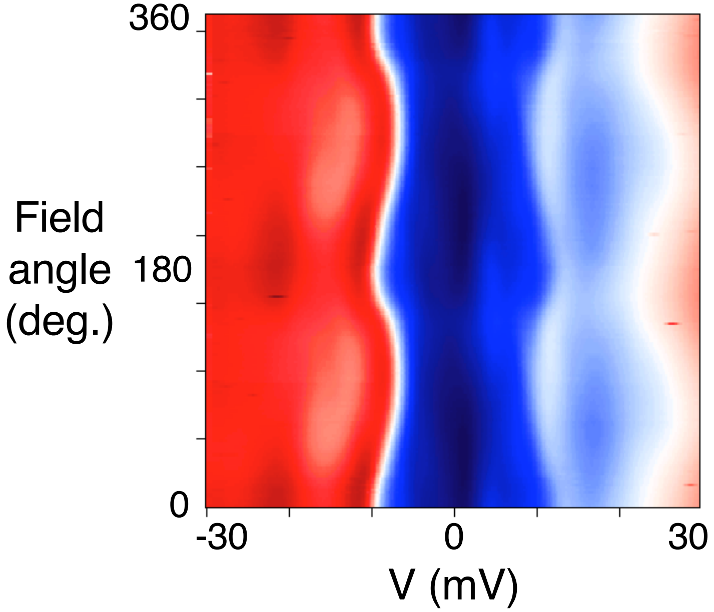


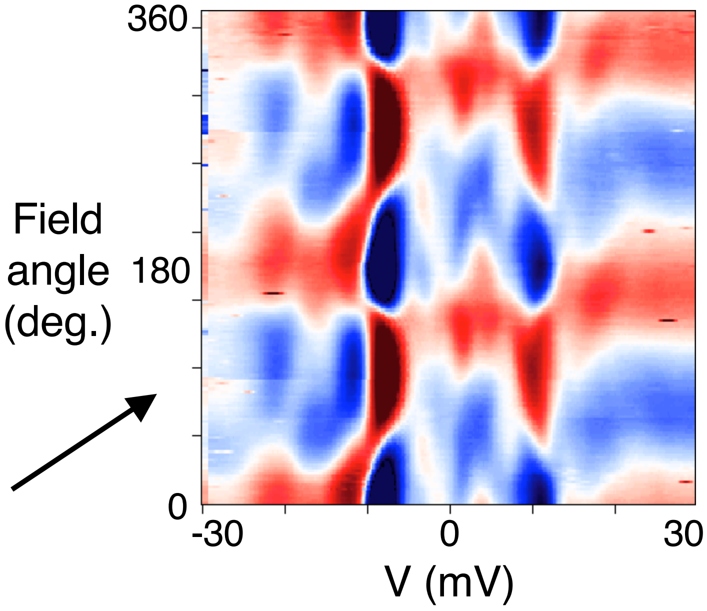
260 kΩ sample, ~10% AMR at V=0



1 e^2/h = 0.04 mS

color = dI/dV





color = dI/dV - (average at fixed V)

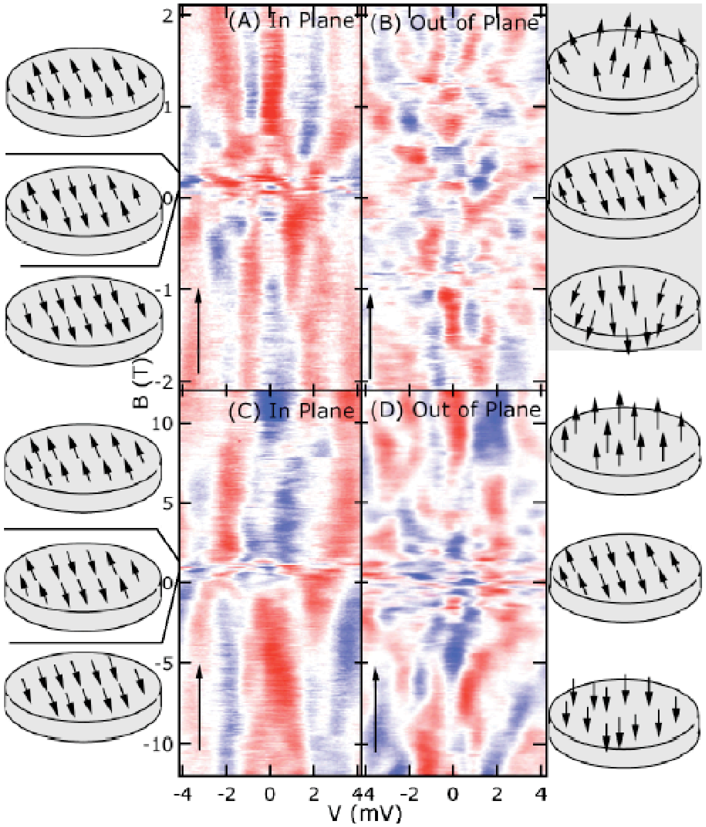
Mechanism?

The dependence of the amplitude and phase of the fluctuations on V and the disappearance of fluctuations at large V suggest a mesoscopic interference effect.

Simple picture: The local density of states fluctuates as a function of position and energy. (Friedel oscillations) Due to spin-orbit coupling, the pattern of fluctuations changes when the magnetic moment rotates, giving an AMR-like effect.

> Similar to mesoscopic conductance fluctuations measured in non-magnetic point contacts (Holweg et al. PRL **67,** 2549 (1991)) and in non-magnetic tunnel junctions (van Oudenaarden et al., PRL **78**, 3539 (1997)).

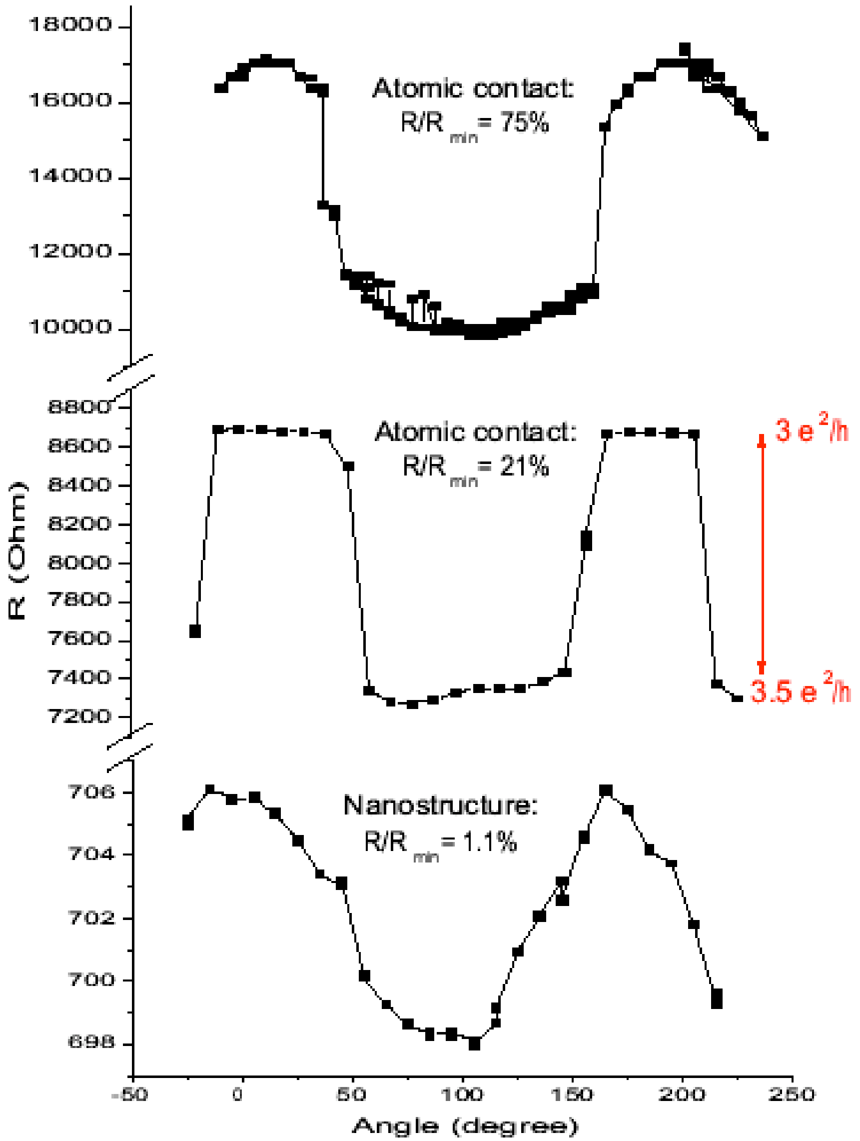
Also likely related to conductance fluctuations observed recently in 200-nm Co samples (~400 Ω) as a function of a swept unidirectional field.
Wei, Davidovic, et al., PRL **96**, 146803 (2006)

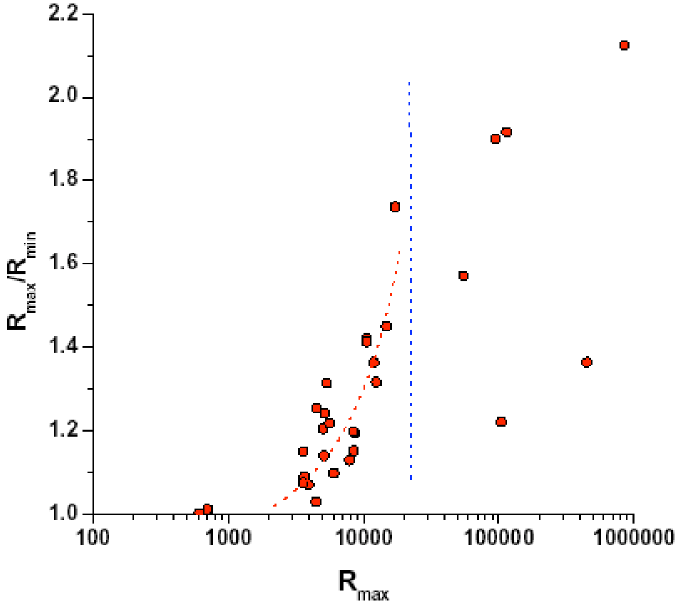


<u>New feature</u>: conductance fluctuations are modulated by changing the the exchange field (coupled to electron motion by spin-orbit coupling), not a direct effect of the magnetic flux.

Correllation angle for Wei experiment estimated by Adam, Brouwer et al., cond-mat/0512287

Viret et al., cond-mat/0602298

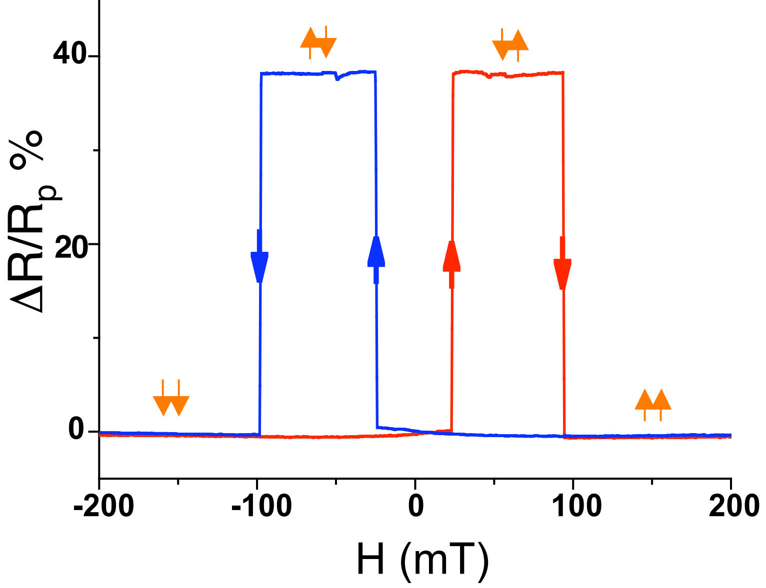




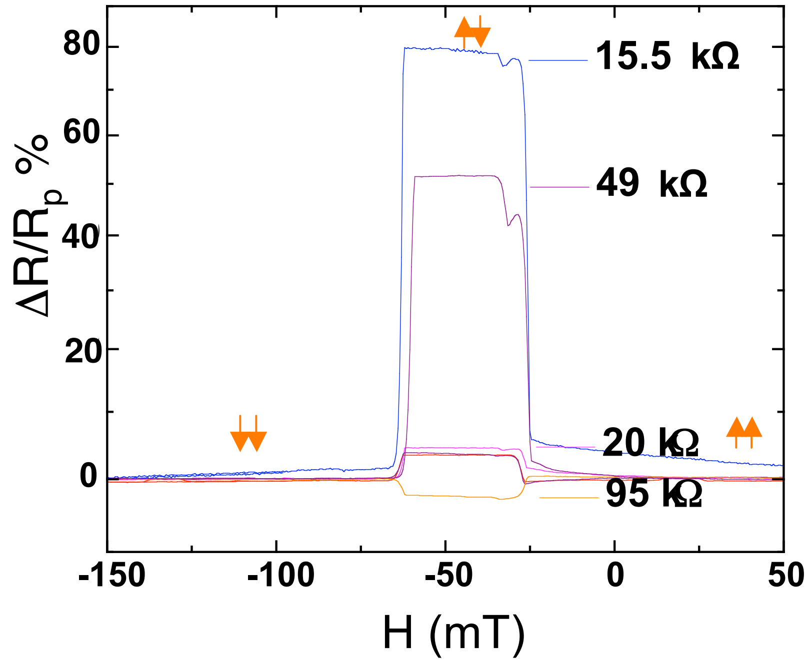
Pure Fe break junctions, on kapton substrate at 4.2 K, 2.5 Tesla.

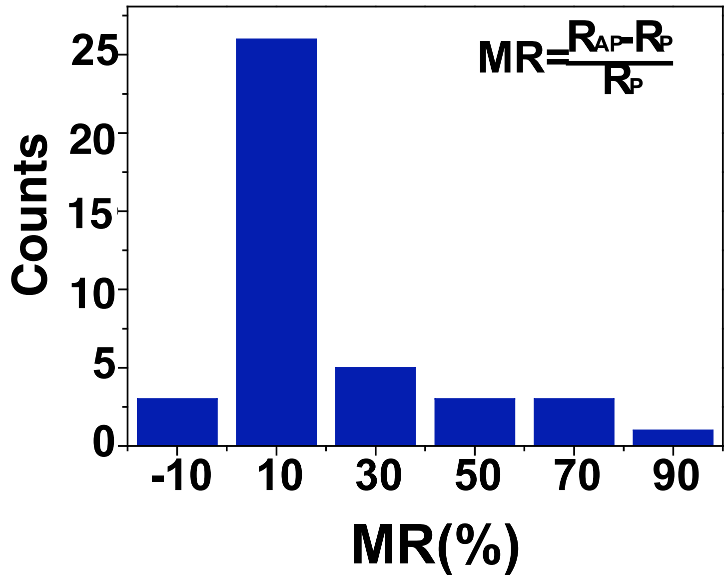
Discontinuities ascribed to pinching off conduction channels.
(Velev et al., PRL **94**, 127203 (2005))

The fluctuations also affect the tunneling magnetoresistance



- Wires can be “rebroken” to change the tunneling gap
- The magnetoresistance can vary with the gap
- The switching fields in general remain the same





Bolotin et al., Nano Lett. **6**, 123 (2006)
see also Keane, Lu, Natelson, APL **88**, 062514 (2006)

Summary

Spin-transfer allows FMR measurements of normal modes in individual nm-scale magnetic samples

Allows efficient measurements of:

- The spectra of normal modes
- The damping coefficient
- The relative strength of the Slonczewski and effective-field torques
- The effects of DC currents on mode dynamics
- Nonlinear magnetic dynamics

Nanoscale magnetic contacts exhibit unexpectedly large AMR-type effects at low temperature.

Proposed mechanism: the dependence of mesoscopic fluctuations on the orientation of the magnetic moment.