# *Magnetoresistance and Magnetic Dynamics on the Nanoscale*

Jack Sankey, Ilya Krivorotov, Nathan Emley, Greg Fuchs, Kiran Thadani,
Bob Buhrman, D. C. Ralph

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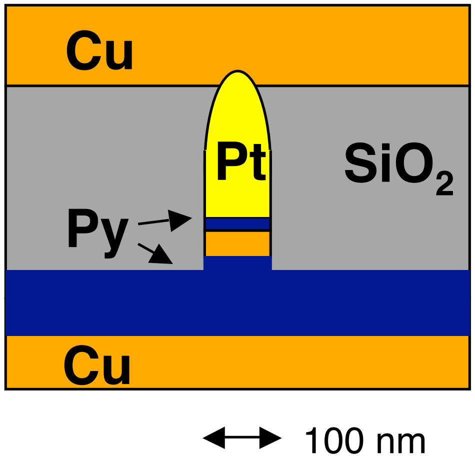
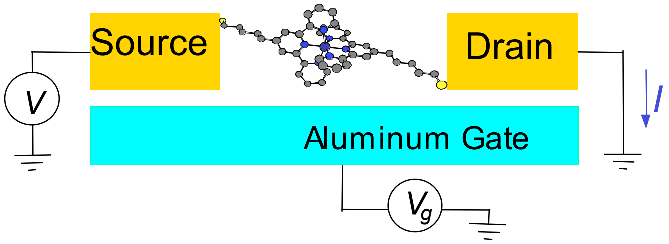
- Using spin-transfer torques to control spin dynamics in 100-nm-scale pillar devices.
  Spin-transfer-driven FMR in Single Nanomagnets

- Can these techniques be extended to the molecular scale?

**Spin-transfer dynamics**



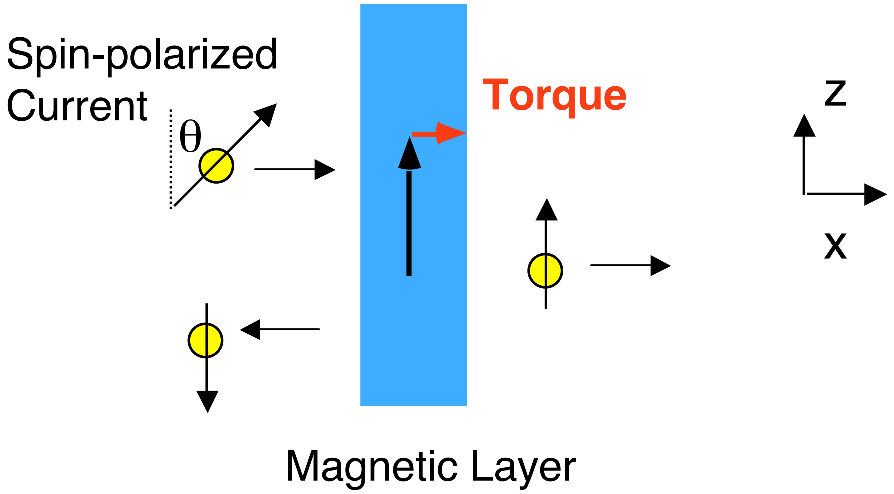
**Single-molecule transistors**



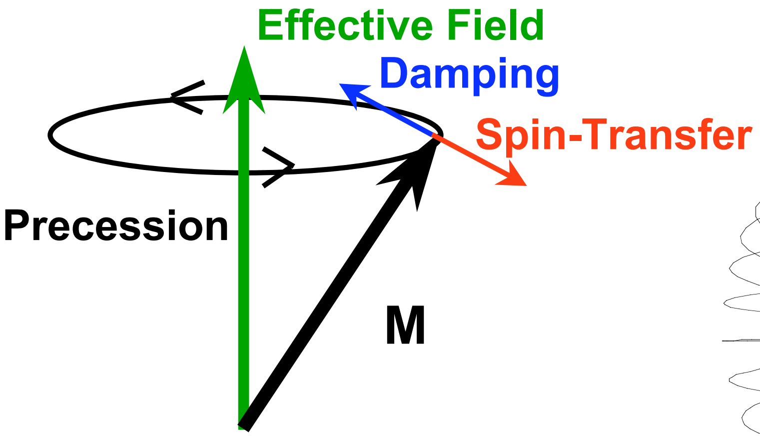
## *Slonczewski/Berger Model of Spin-Transfer Torques:*

**An alternative to manipulating magnetic moments with magnetic fields:**

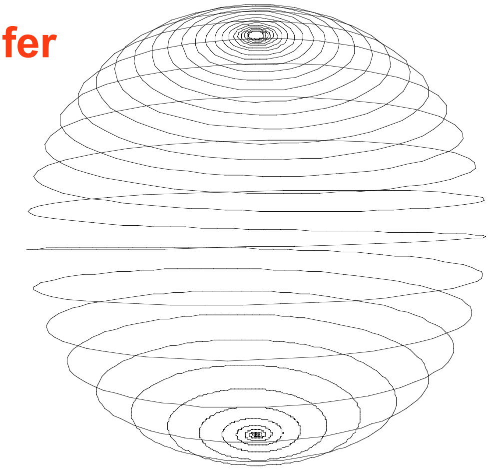
**When a Magnetic Layer Acts as a Spin-Filter, it Can Feel a Torque**



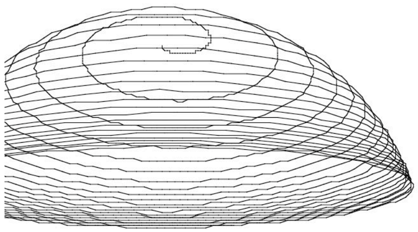
# *Magnetic Dynamics with Spin Transfer*

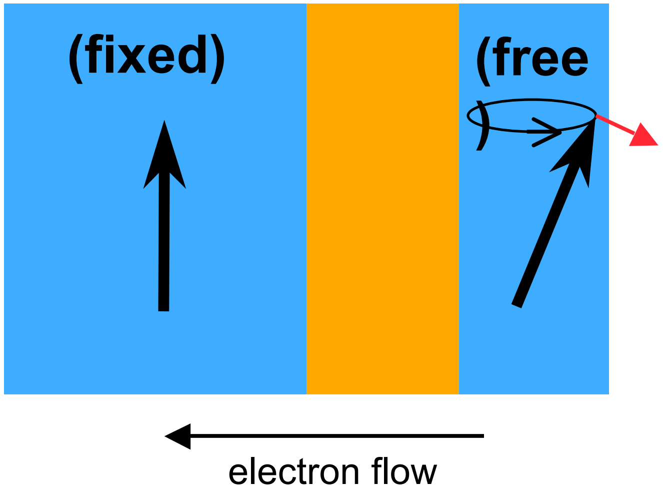


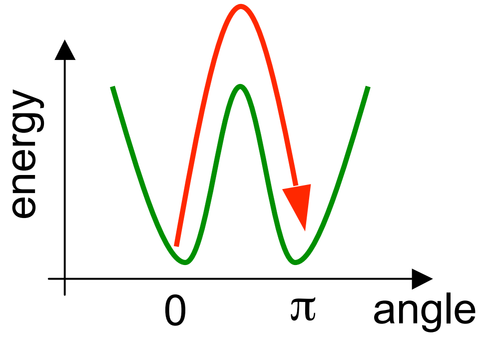
switching

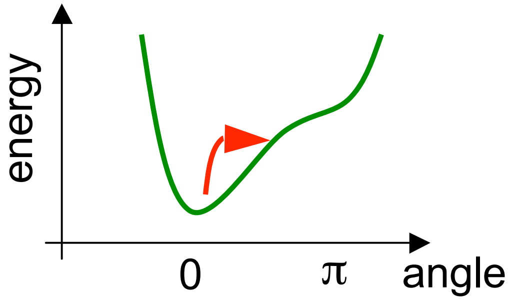


steady-state
precession



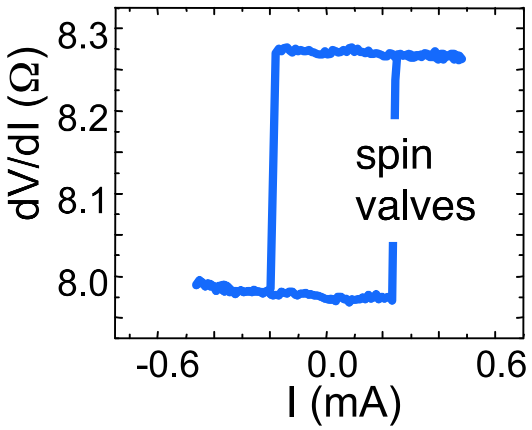


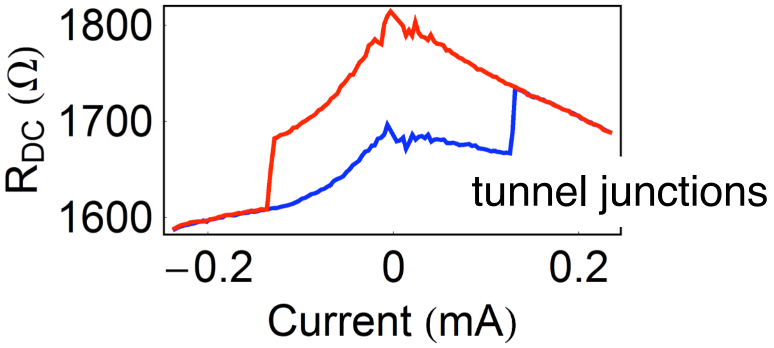




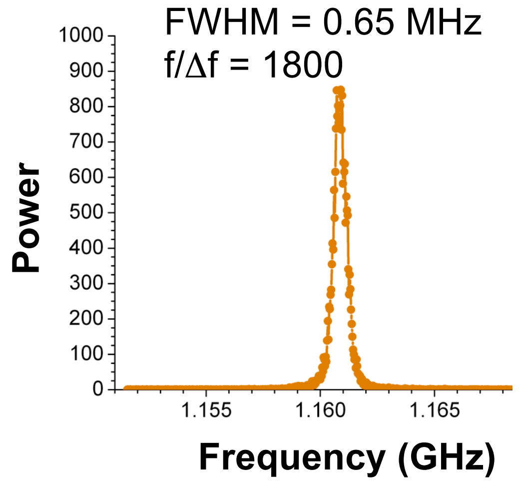
# *Controlling Dynamics in 100-nm-Scale Magnetic Devices Using Spin Transfer Torques*

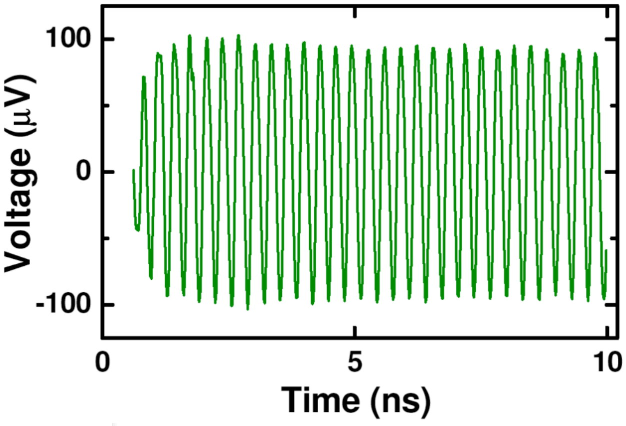
**Magnetic Switching**



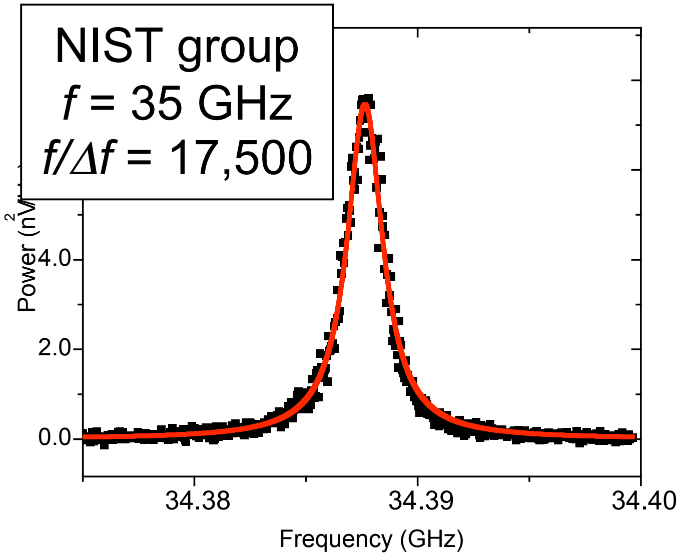


**DC-driven Microwave Oscillations**





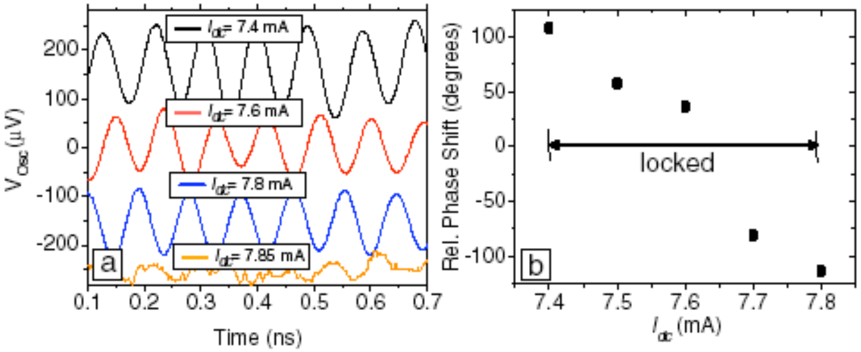
Nanopillar Structures



Point Contact

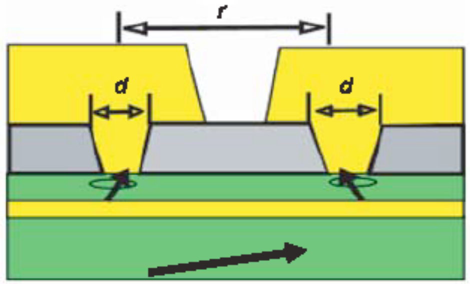
# *Other Recent Experimental Milestones*

## Phase Locking to an External Microwave Drive



Rippard et al., PRL **95**, 067203 (2005)
M. Tsoi et al., Nature 406, 46 (2000)

## Phase Locking of Two Spin-Transfer-Driven Oscillators



Kaka et al., Nature **437**, 389 (2005).
Mancoff et al., Nature **437**, 393 (2005).

## Spin-Transfer Excitations of Single Magnetic Layers

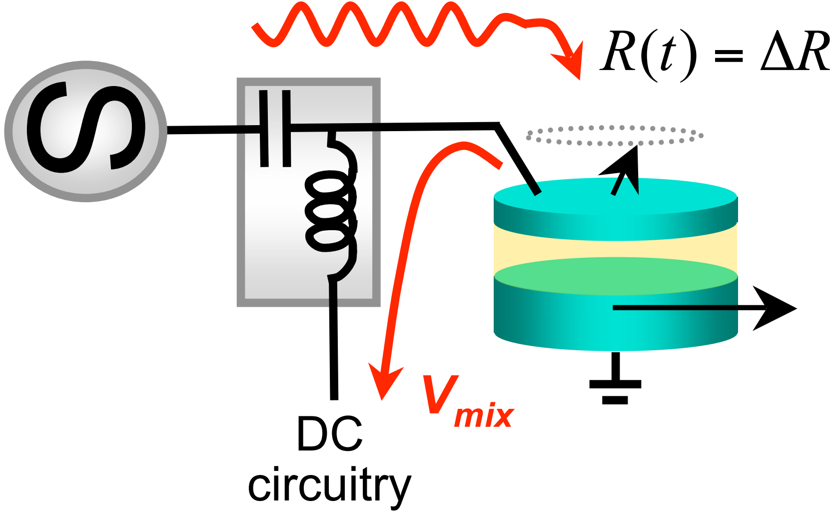
Ozyilmaz et al., PRL **93**, 176604 (2004).

## Spin-Transfer Excitations in Magnetic Semiconductor Devices

(talk by Hideo Ohno, earlier today)

# *Resistive Detection of Spin-Transfer-Driven Magnetic Resonance*

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



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

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

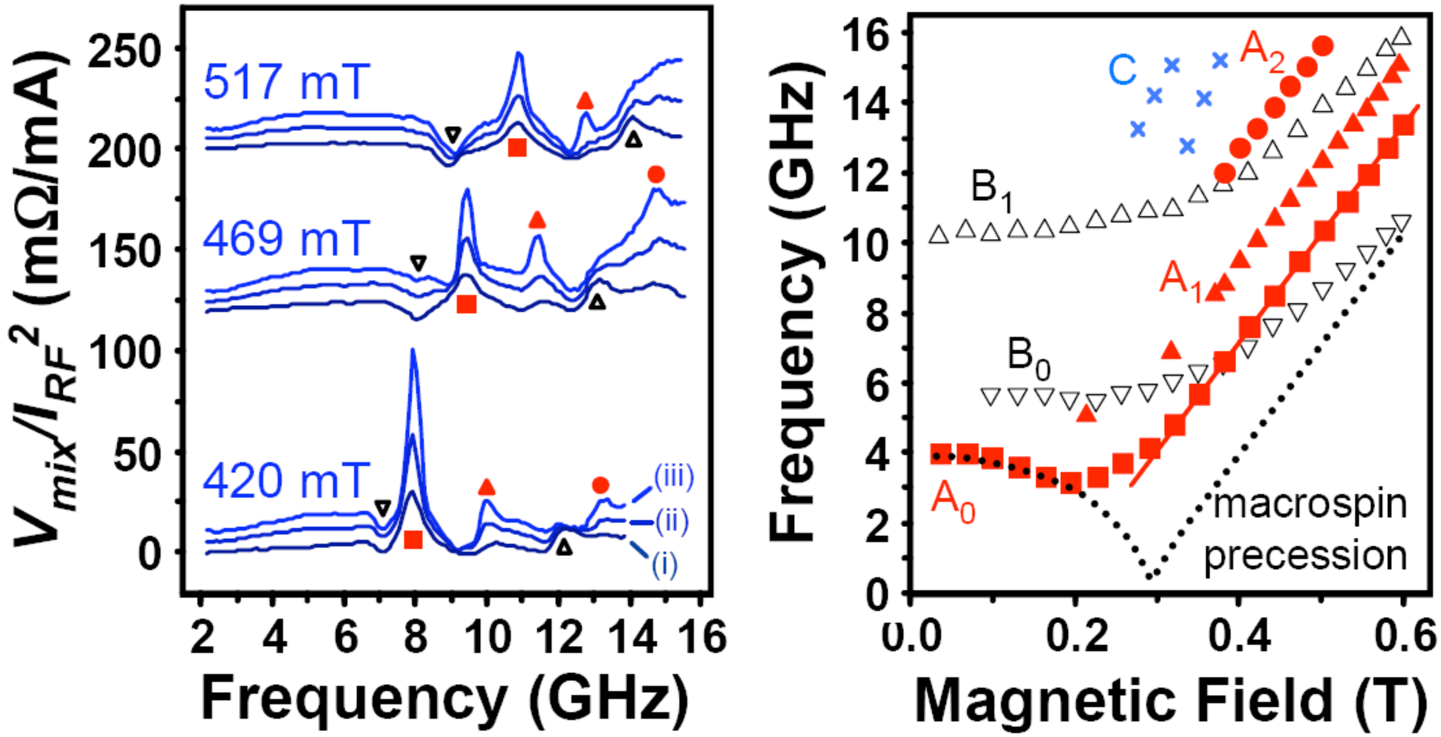
$$= \frac{1}{2} I_{RF}\Delta R\left[\cos(\delta) + \cos(2\omega t + \delta)\right]$$

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

Resonant resistance oscillations generate a DC voltage component by mixing

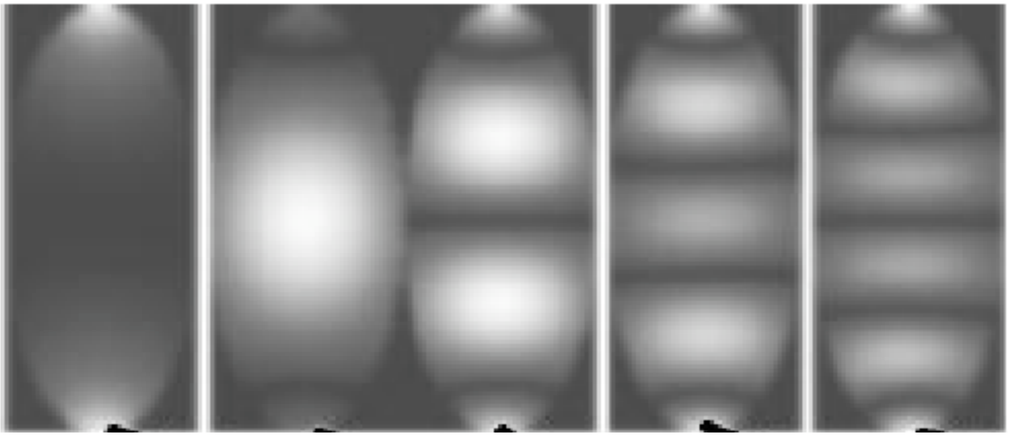
(similar technique used for radio-frequency detection by Tulapurkar et al., Nature **438**, 339 (2005))

# *Measuring Normal Modes in a Single Nanomagnet*

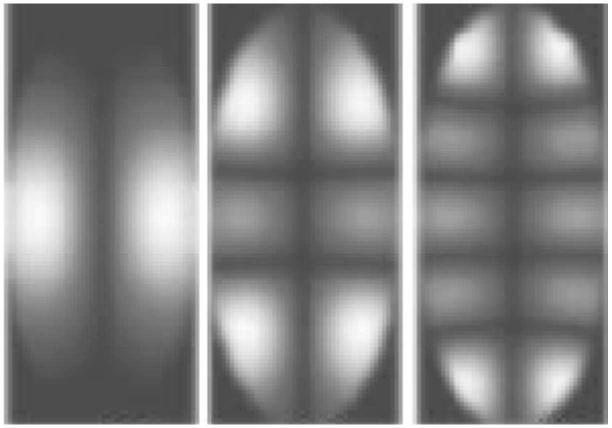


Sankey et al., submitted to PRL (cond-mat/0602105)

# *What are the Expected Normal Modes?*



from numerical modeling

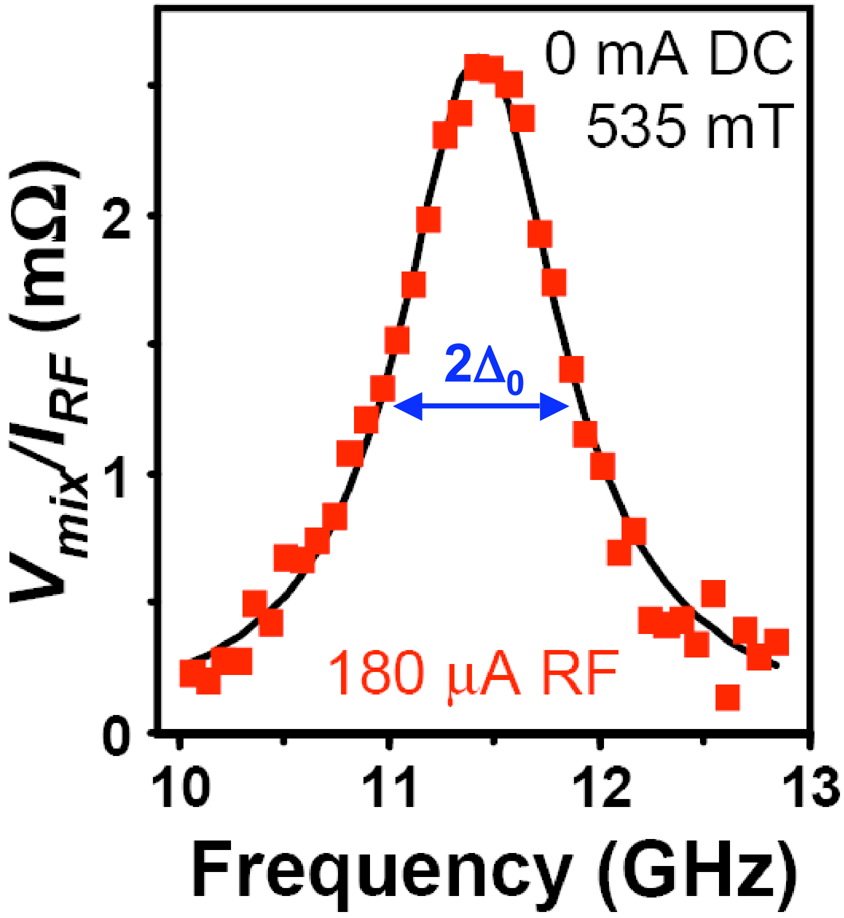


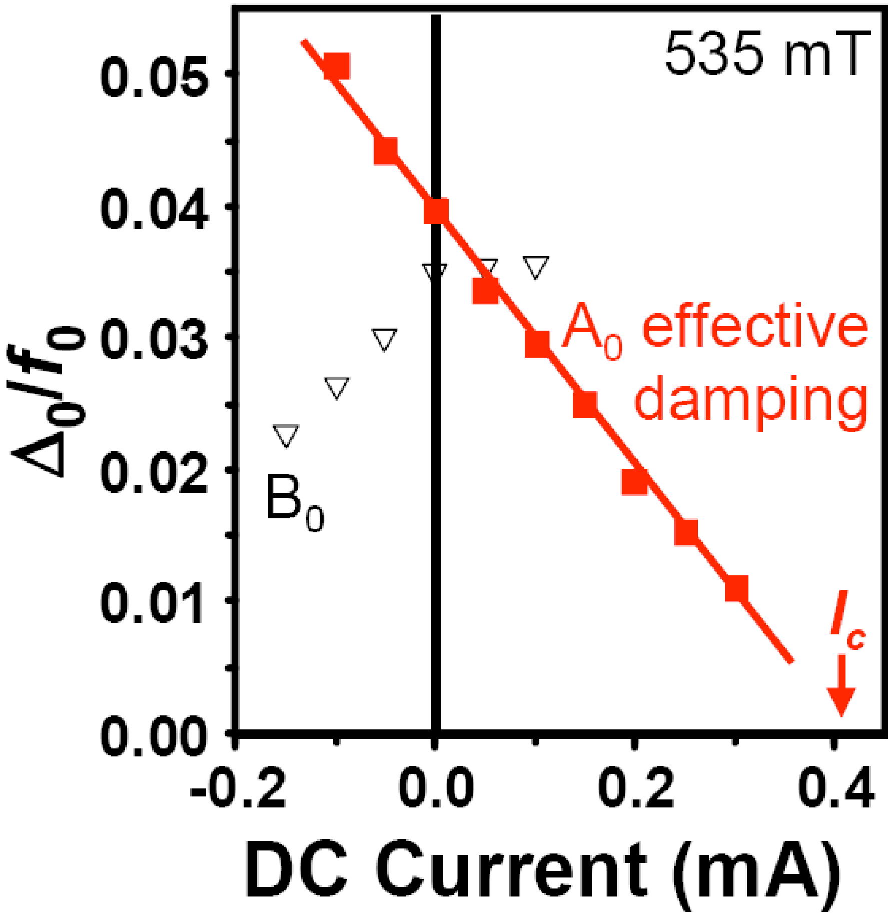
**Measured frequencies and frequency spacings are in reasonable qualitative agreement with simulation.**

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

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

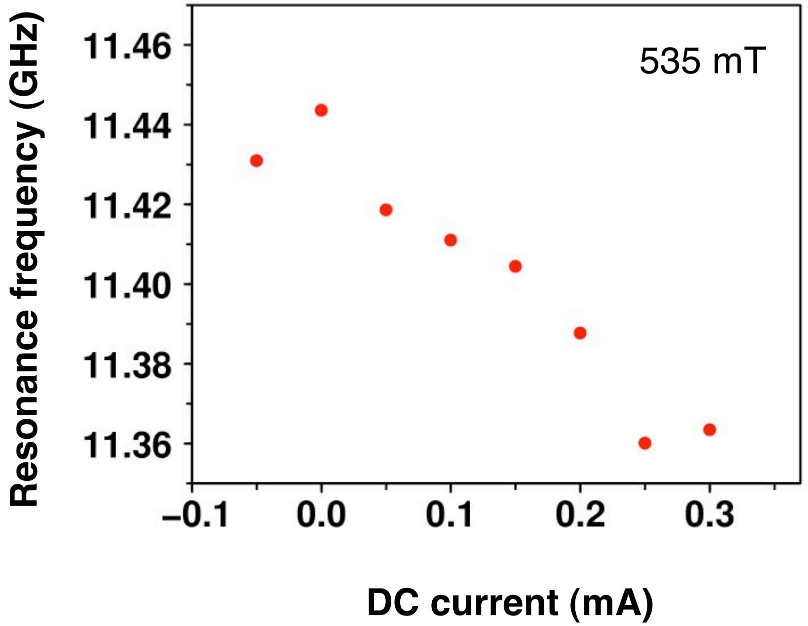
# *The width of the resonance curves gives a measure of the damping coefficient for the oscillations*





# *Very Weak Dependence of Precession Frequency on DC Current*

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

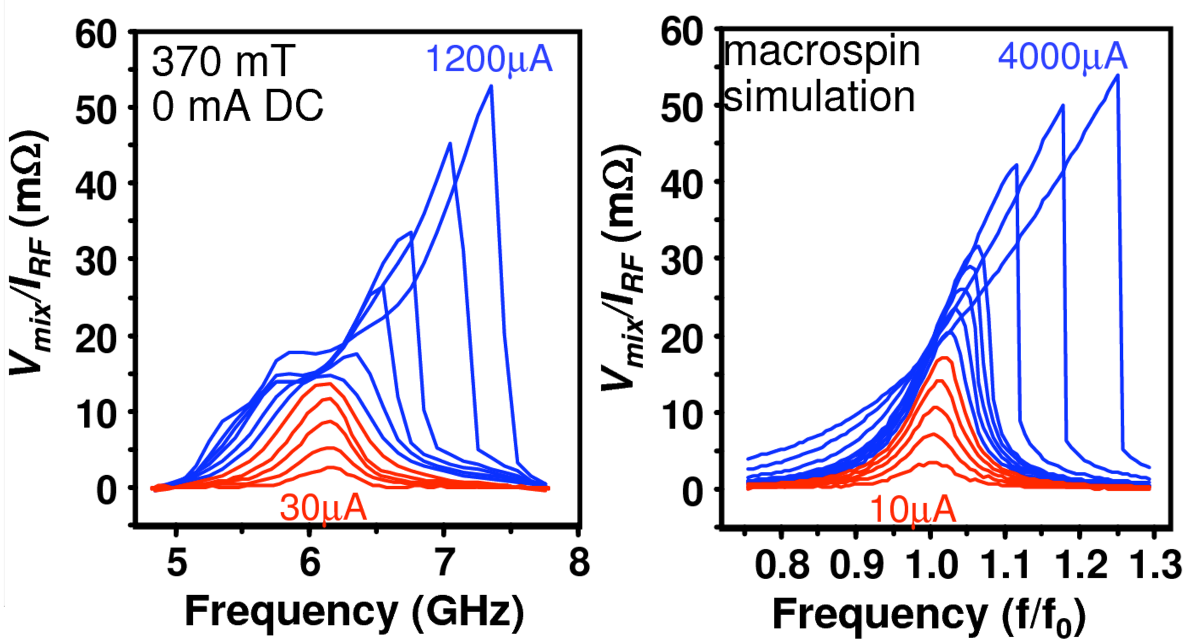


➡ Limits on the Effective-Field Contribution of Spin Transfer
< 15% of the “Slonczewski Torque”

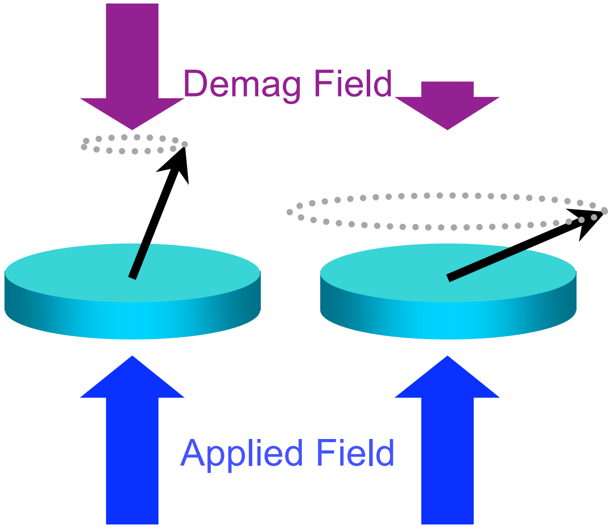
(The measured shift is probably dominated by a changing dipole interaction between the magnetic layers, as their relative angle changes slightly, or by the Oersted field, not by an effective field from spin transfer.)

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

# Nonlinearities at Large Precession Angle



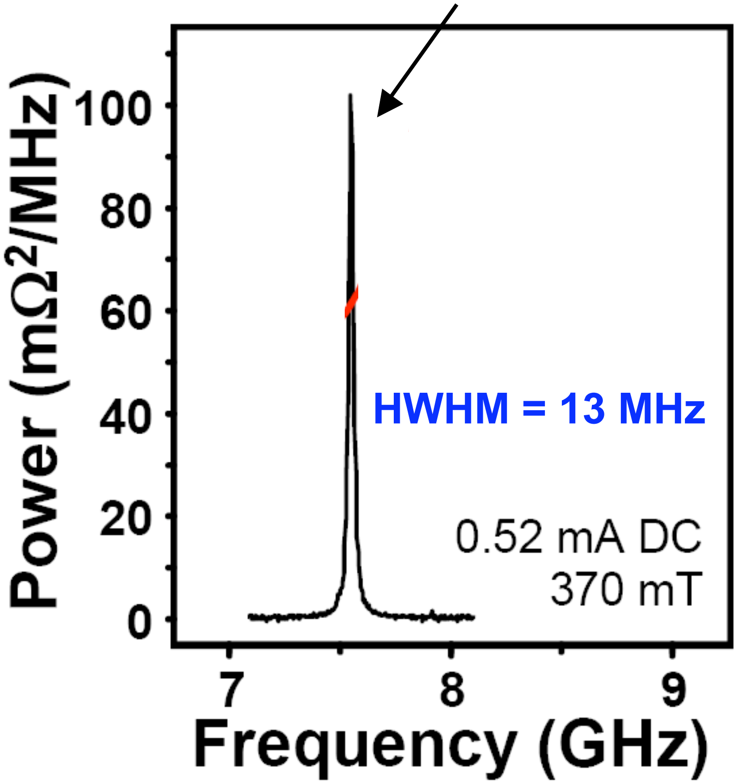
Largest precession angle observed experimentally ~ 40º



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

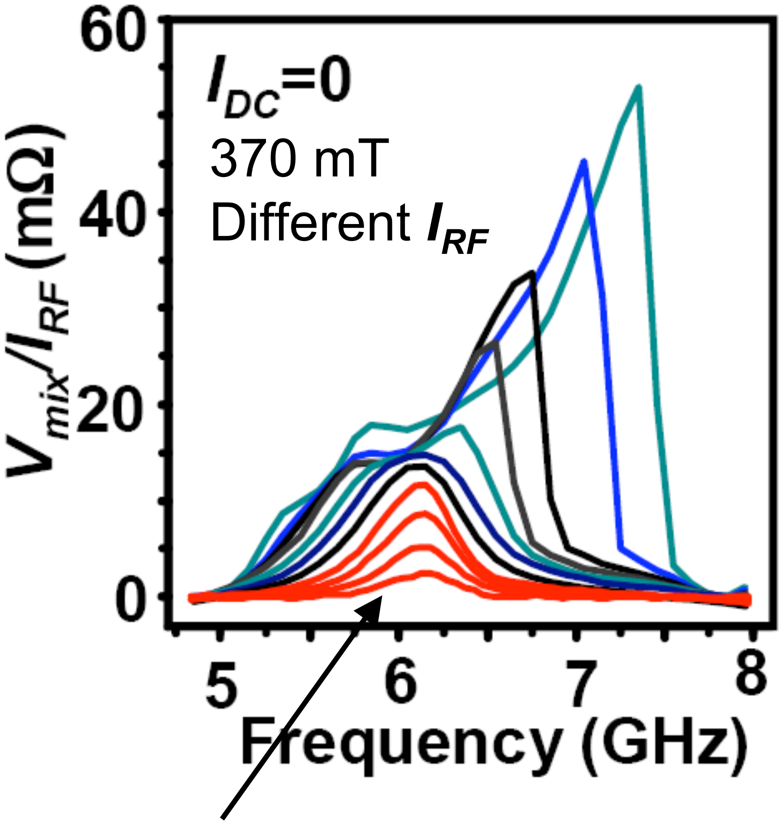
T = 10 K

DC-driven



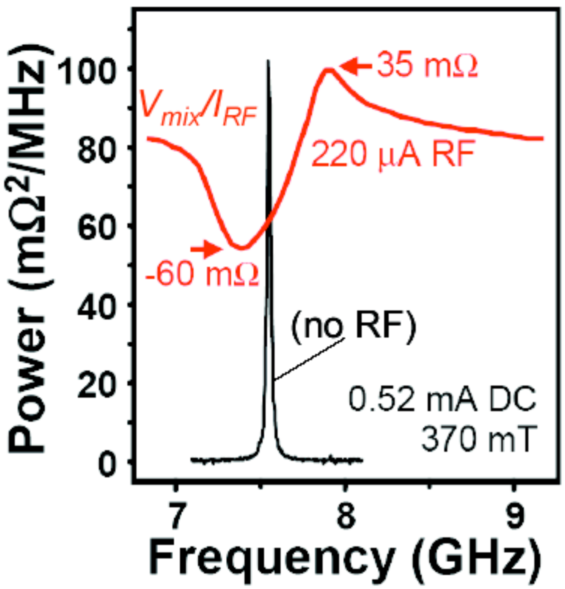
**HWHM = 13 MHz**

FMR

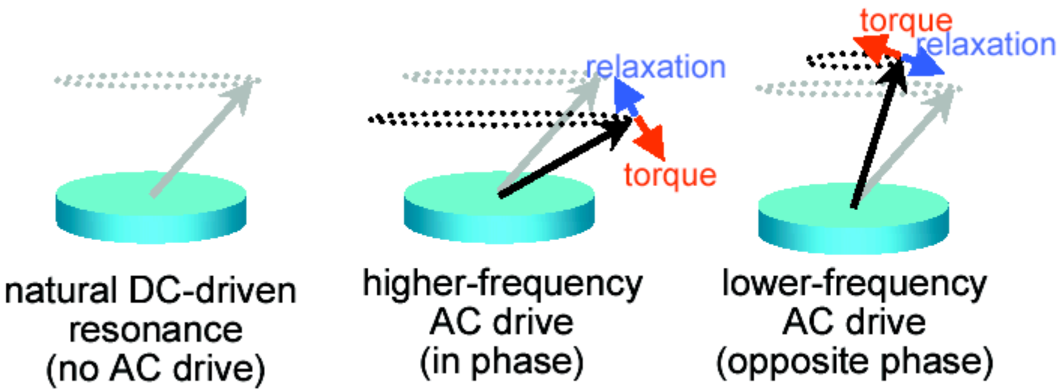


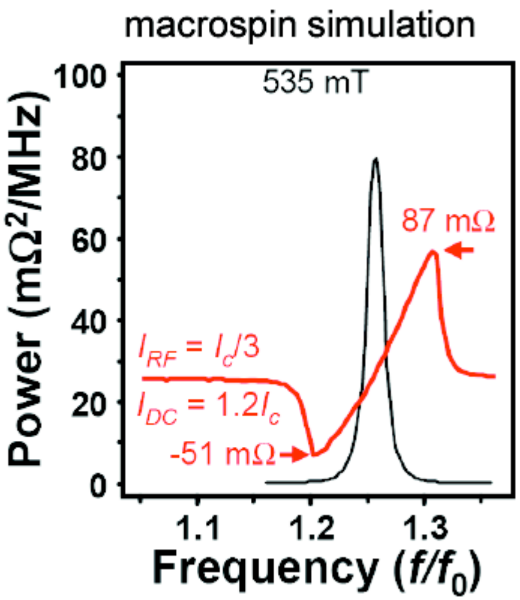
**HWHM = 250 MHz**

# *Peak Shape in the Phase-Locking Regime*



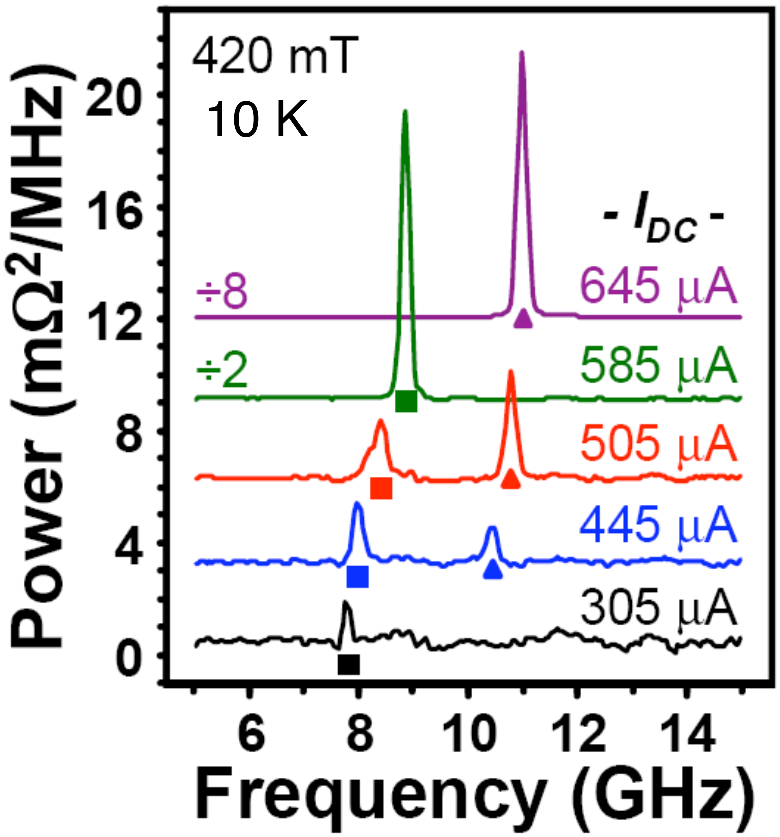
- Peak shape for the phase-locking regime has a negative response on low-frequency side.
- Dip below the natural frequency: The RF drive forces smaller amplitude precession, phase locking ~180° out of phase with precession
- Macrospin simulation confirms this picture



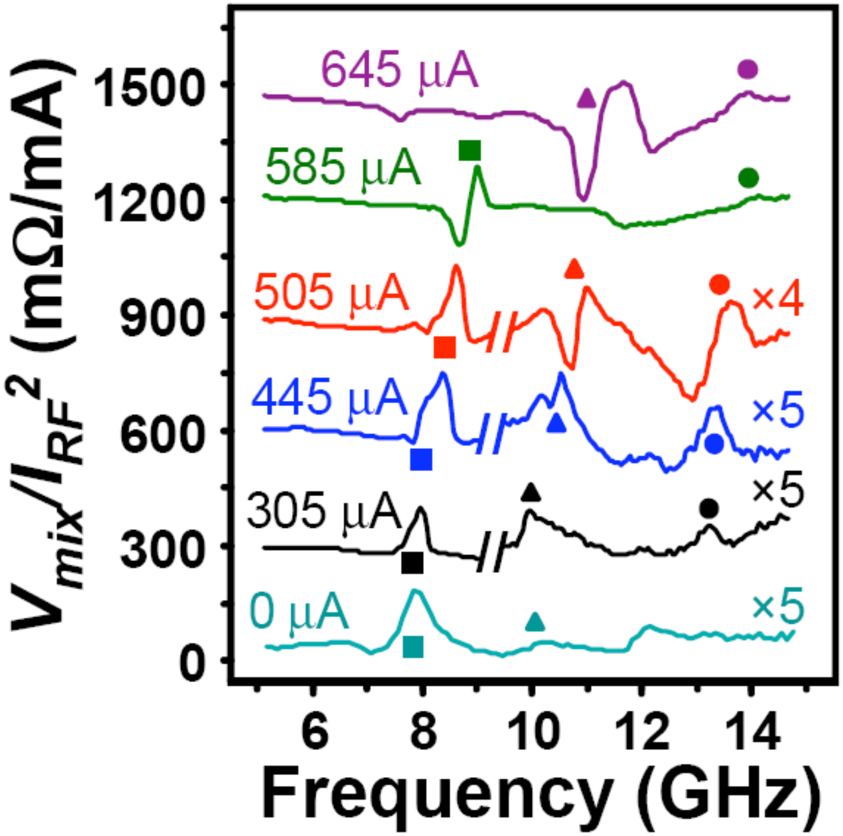


# *What modes are excited in DC-Driven Precession?*

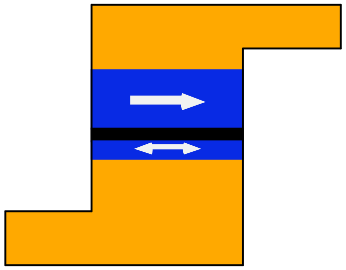
DC-driven signals



FMR spectra

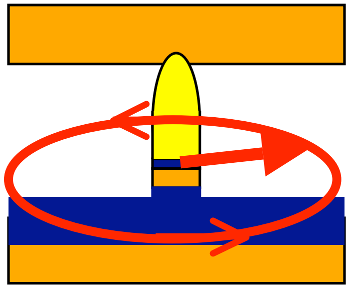


# Summary: Spin-Transfer-Driven Dynamics



## Magnetic Switching

- Considerable recent progress on understanding switching mechanisms and on reducing switching currents to the level required for MRAM applications
(More on this from Bob Buhrman)



## Spin-Transfer Driven FMR

- A new technique allows detailed characterization of magnetic normal modes in samples 1000 times smaller than demonstrated by other techniques
- Provides rapid measurements of magnetic damping

## Magnetic Precession Driven by DC Spin-Transfer Currents

- By comparing to FMR measurements, can identify which magnetic mode is precessing
- Excellent linewidths have been achieved ($f/\Delta f$ ~ 1800 in nanopillars, ~17,000 in point contacts (NIST))
- DC-driven linewidths can be narrower than predictions of macrospin models

# *Can Similar Control of Spin-Transfer-Driven Dynamics be Achieved on Smaller Length Scales?*

**Need:**

- **Nanoscale Magnetic Electrodes with Controllable Moments**
- **Ability to Insert Magnetic Nanostructures**

Caution:

Mechanical stability needs to be a big concern.

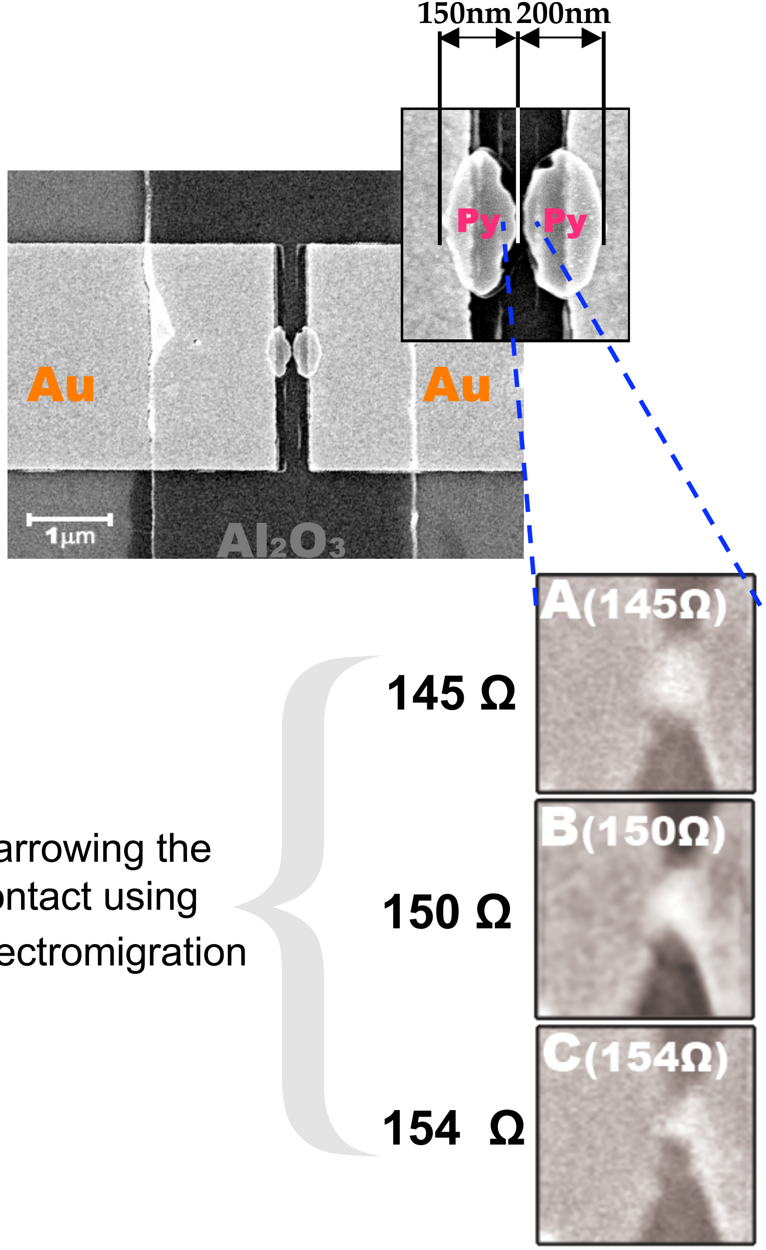
Previous measurements of huge “Ballistic Magnetoresistance” at room temperature in magnetic point contacts (Garcia et al., PRL **82**, 2923 (99); Hua and Chopra, PRB **67**, 060401 (2003)) have been challenged due to artifacts from magnetostriction and magnetostatic forces (Gabureac et al., PRB **69**, 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

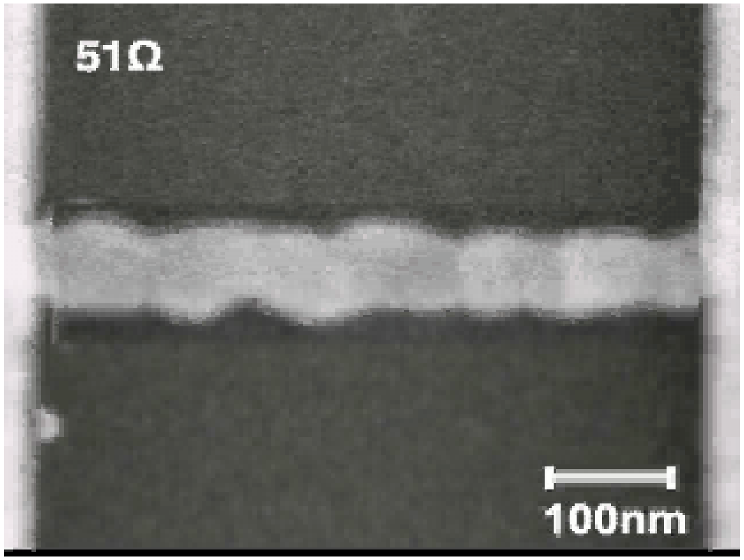
# *Magnetic Electrode Fabrication*

- 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

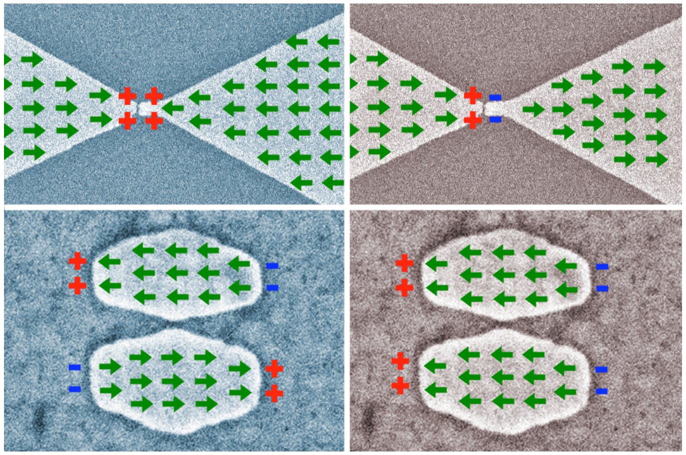
*Electromigration in a test gold device live*



# *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

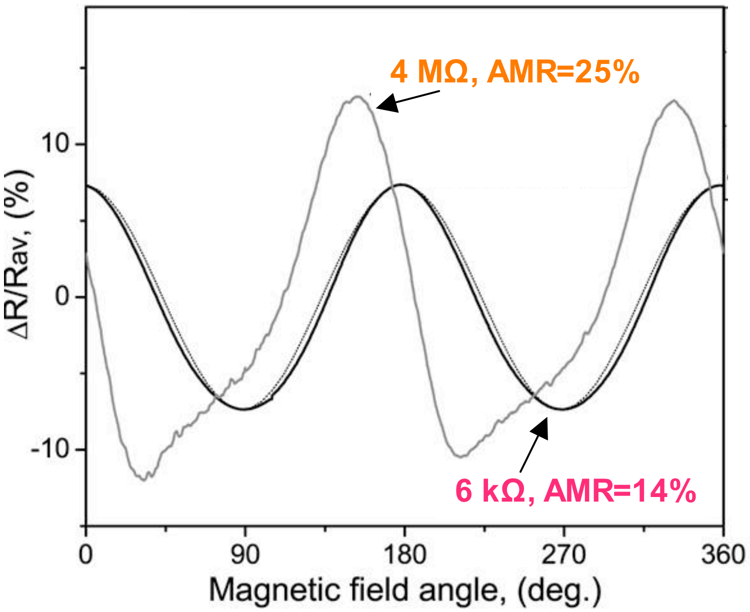


With conventional “bowtie” electrodes, dipole fields act to destabilize the antiparallel configuration.

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

# *An Unanticipated Effect: Large Tunneling Anisotropic Magnetoresistance in Nanometer-Scale Junctions*

When the moments in the two electrodes are forced parallel by a large applied magnetic field, the resistance still depends on the field angle.

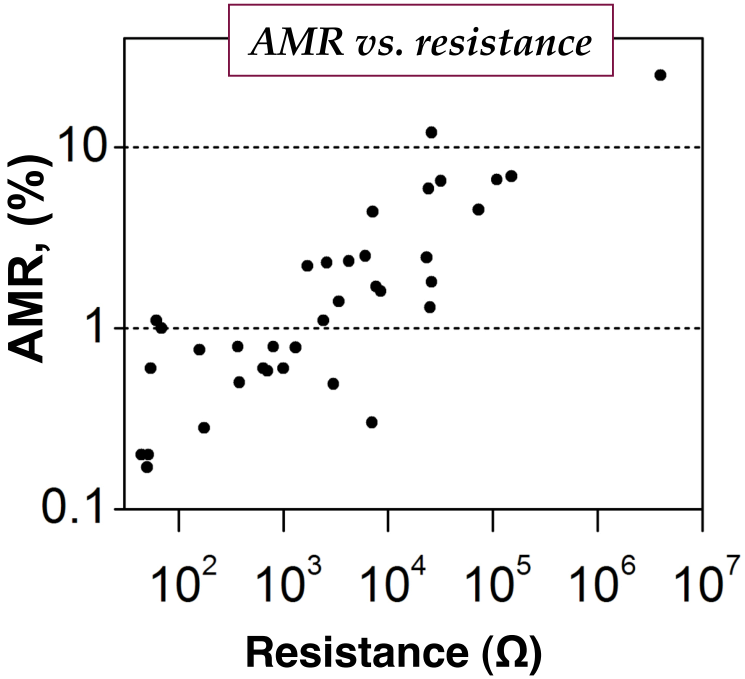


4.2 K, field magnitude = 800 mT

- Large AMR is observed even for the samples in the tunneling regime
- The resistance changes smoothly and reproducibly. Indicates that the large AMR is not a result of mechanical artifacts

K. I. Bolotin et al., submitted to PRL (cond-mat/0602251)

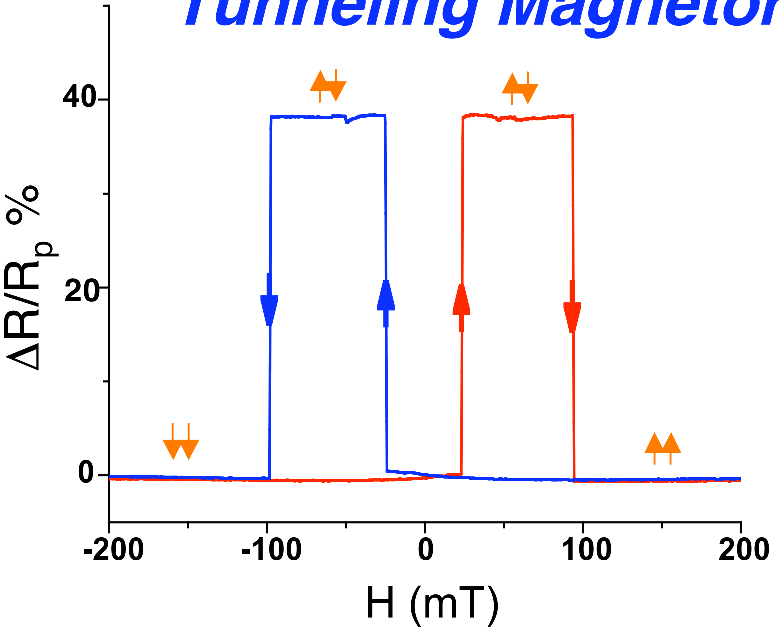
# Dependence of the AMR/TAMR on Resistance



- Probable mechanism: the orbital wavefunction contributing to tunneling is not spherically symmetric -- and it rotates as a function of the angle of the applied field due to spin-orbit coupling.

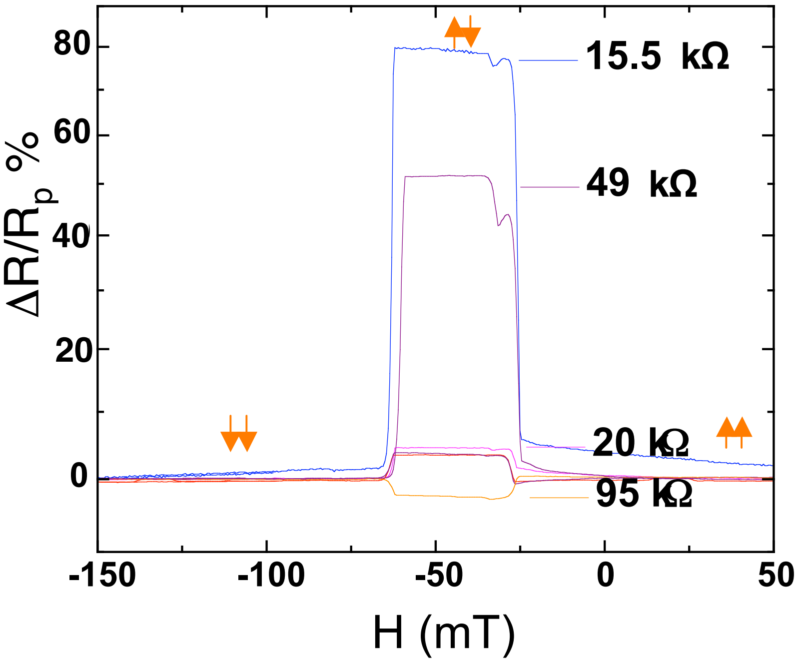
(Similar to effects in GaMnAs junctions, Gould et al., PRL **86**, 043109 (2005).)

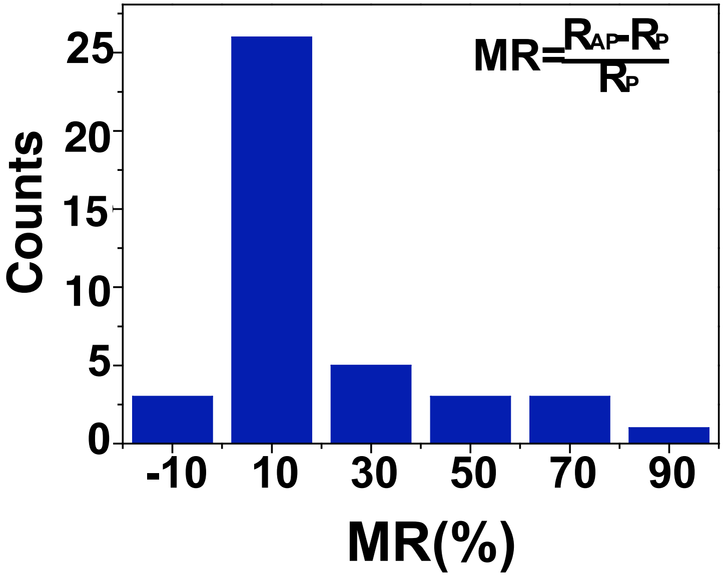
# *Tunneling Magnetoresistance of Bare Junctions*



**We can tune the tunneling gap:**

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

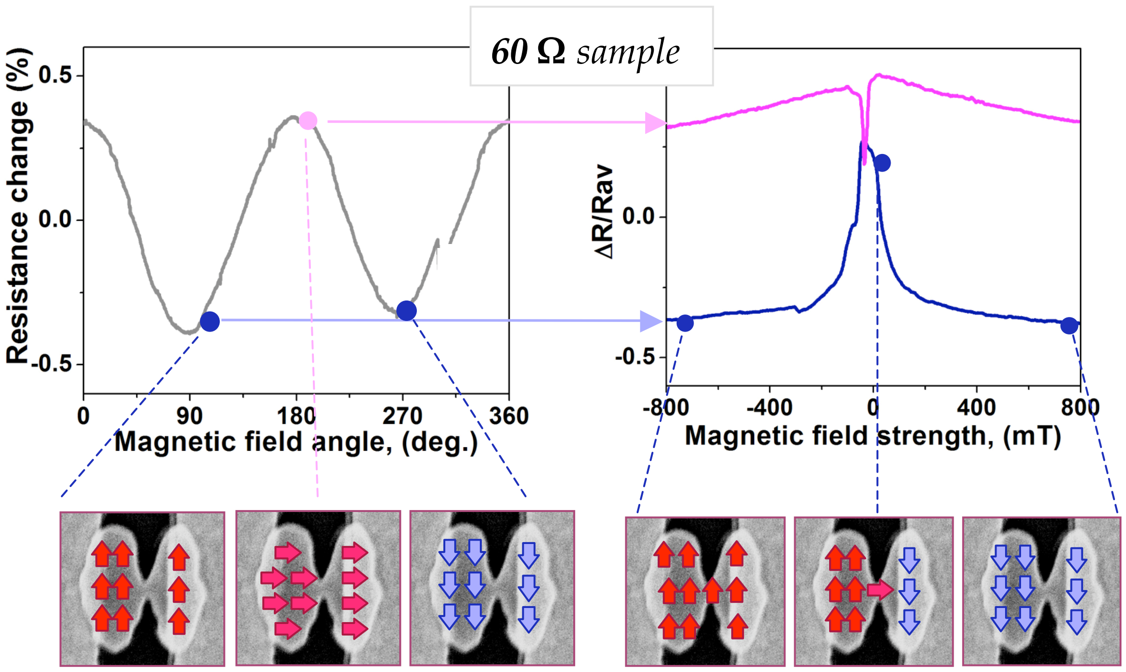




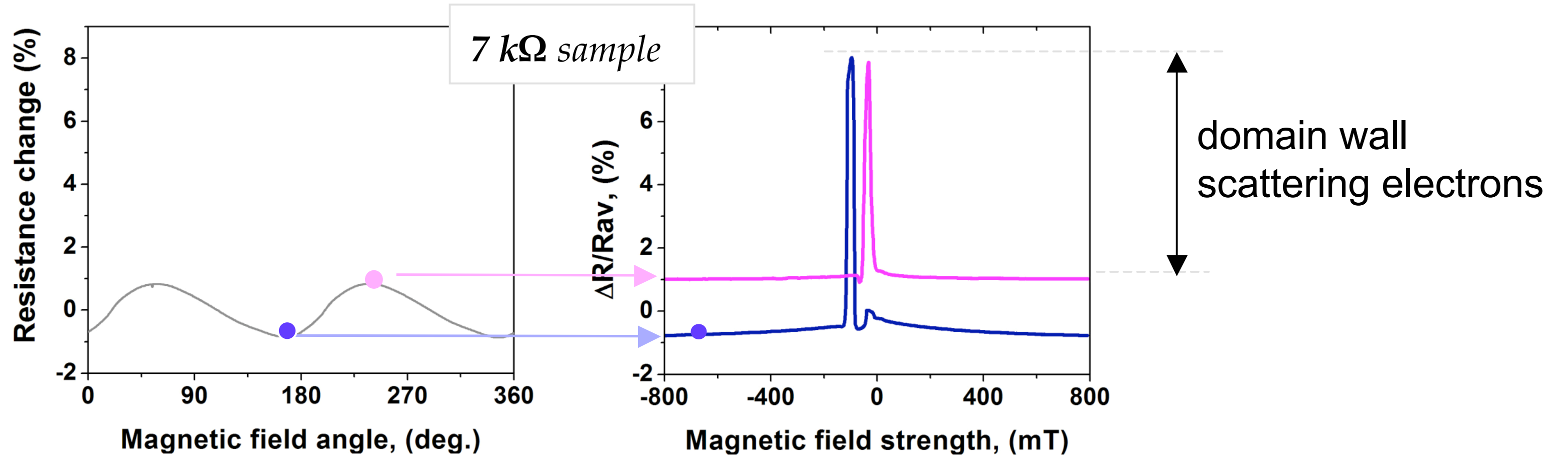
Bolotin et al., Nano Lett. **6**, 123 (2006)

see also Keane, Lu, Natelson, APL **88**, 062514 (2006)

# Domain walls in atomic-scale contacts

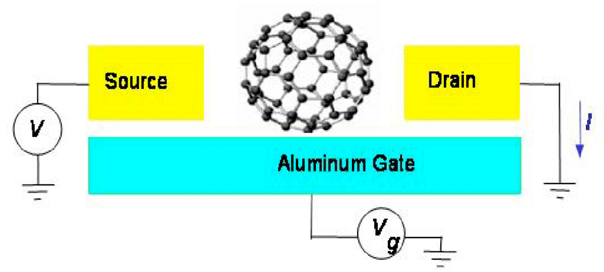


- AMR explains the domain wall resistance in low-resistance samples
- Only when DW gets narrow we observe larger contribution not accounted for by AMR

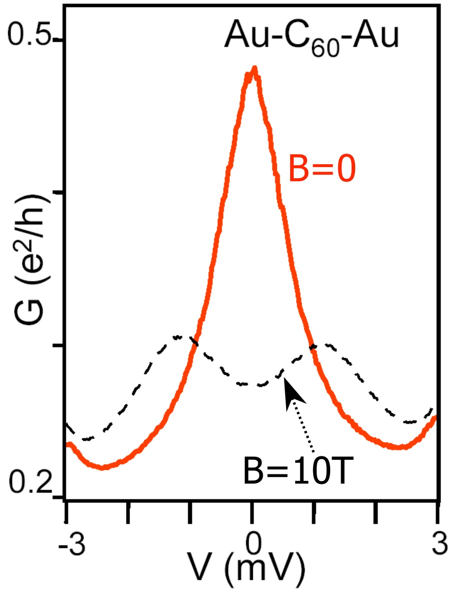


domain wall scattering electrons

# Kondo effect in $C_{60}$ molecules with Magnetic Electrodes



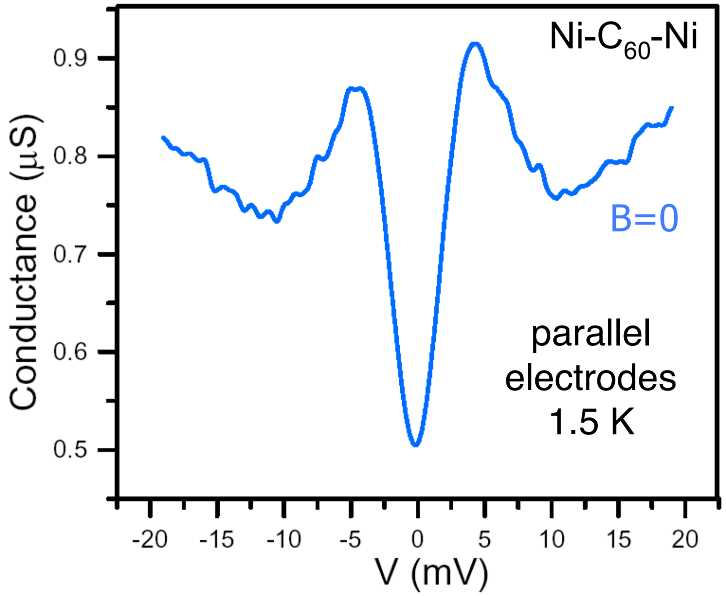
- Au – $C_{60}$ – Au



No splitting for B=0

(see also Natelson group, Nano Lett. 4, 79 (2004))

- Ni – $C_{60}$ – Ni ferromagnetic sample

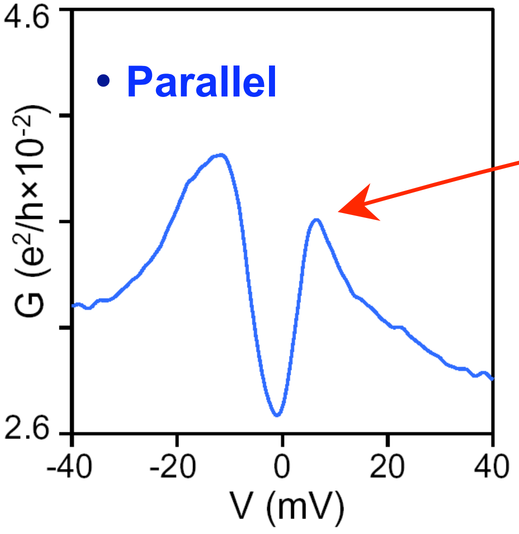


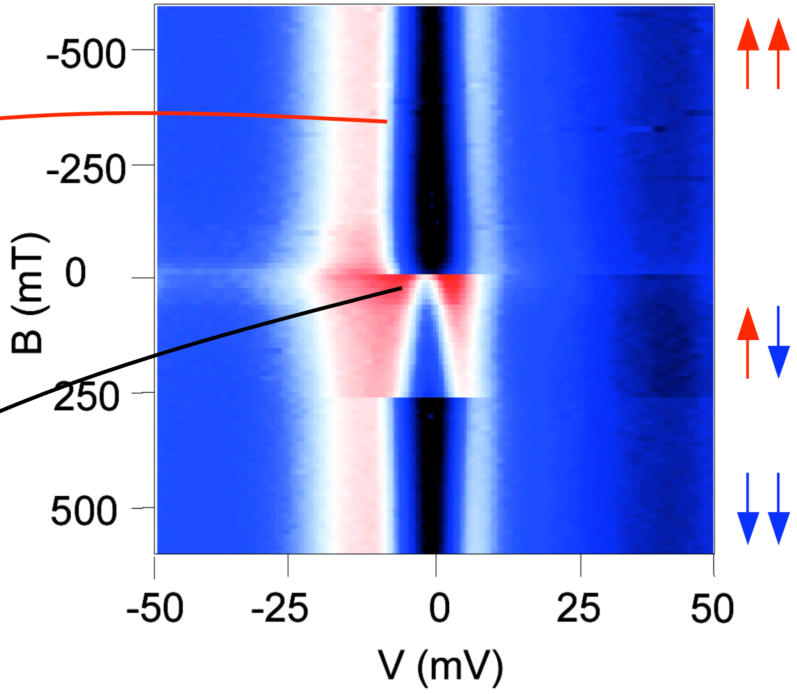
Splitting of zero-bias anomaly due to exchange interaction

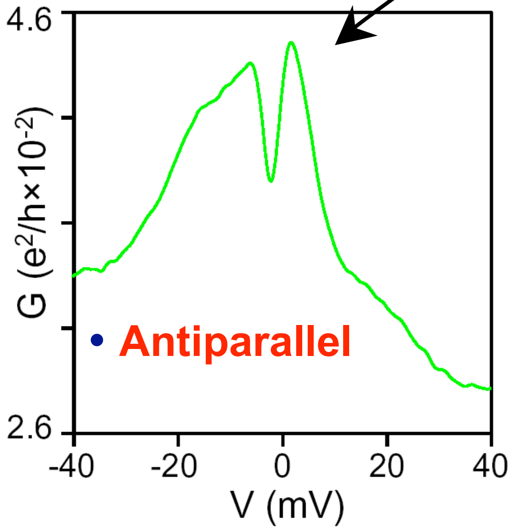
Cannot be due to magnetic field.
5 meV splitting would require >50 T.

A. N. Pasupathy et al., *Science* **306**, 86 (2004).

# *Kondo splitting depends on electrode orientation*



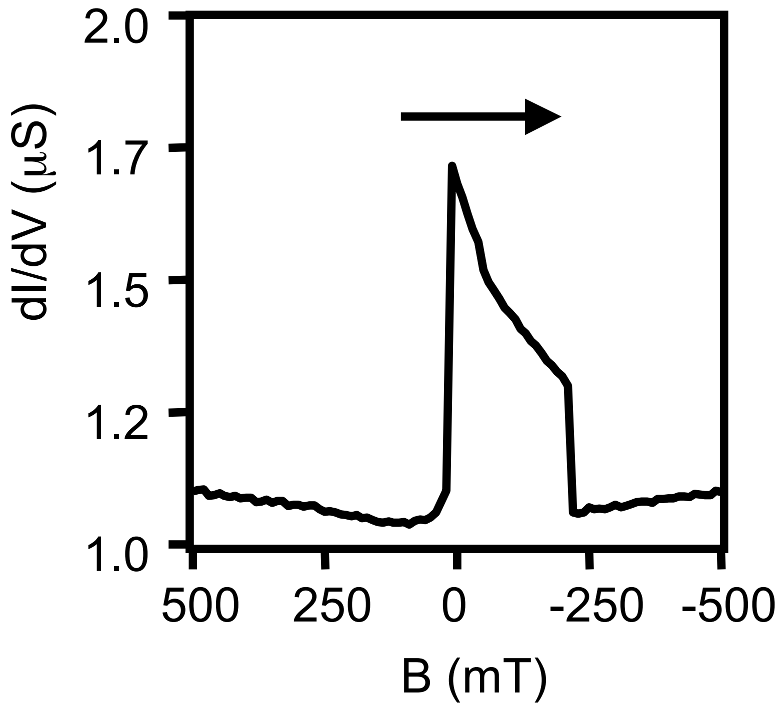


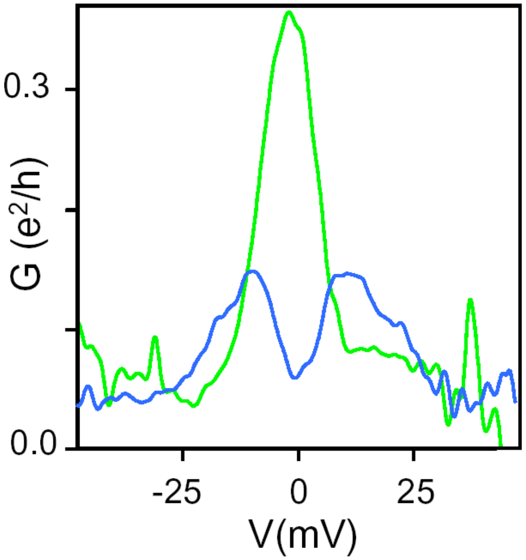


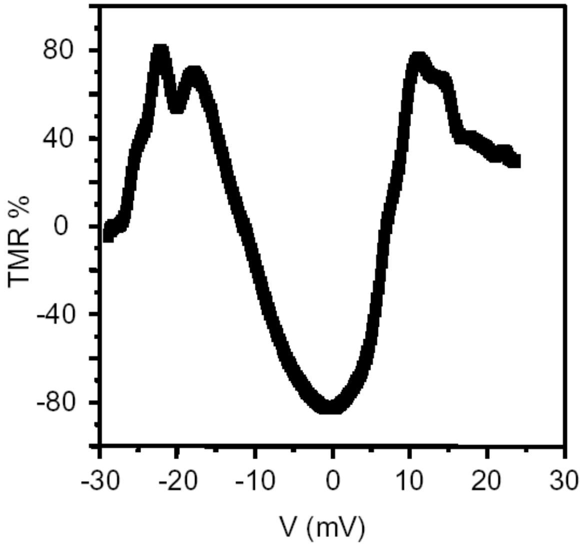
- Large splitting for parallel moments
- Reduction of splitting when moments are antiparallel
- Gradual change corresponds to noncollinear geometry

Good agreement with theory of Kondo effect with magnetic electrodes
(J. Martinek et al., PRL 2003)

# Large, Inverted Tunneling Magnetoresistance





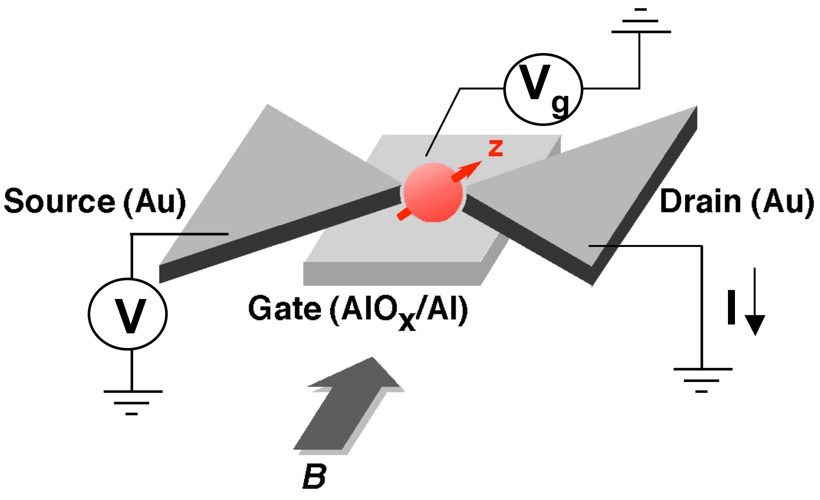


- Julliere magnetoresistance for simple Ni tunnel Junction = 21%

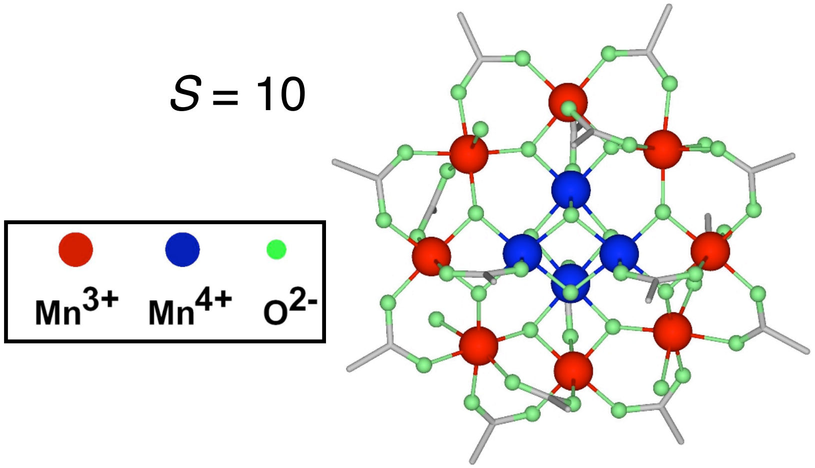
- Our observed MR has much greater

magnitude,
up to -80%

# *Adding Magnetic Molecules: $Mn_{12}$*

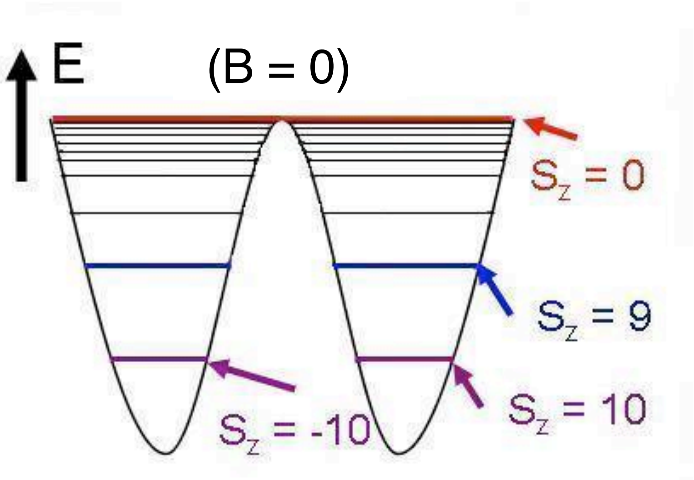


$S$ = 10



(first experiments: nonmagnetic Au electrodes)

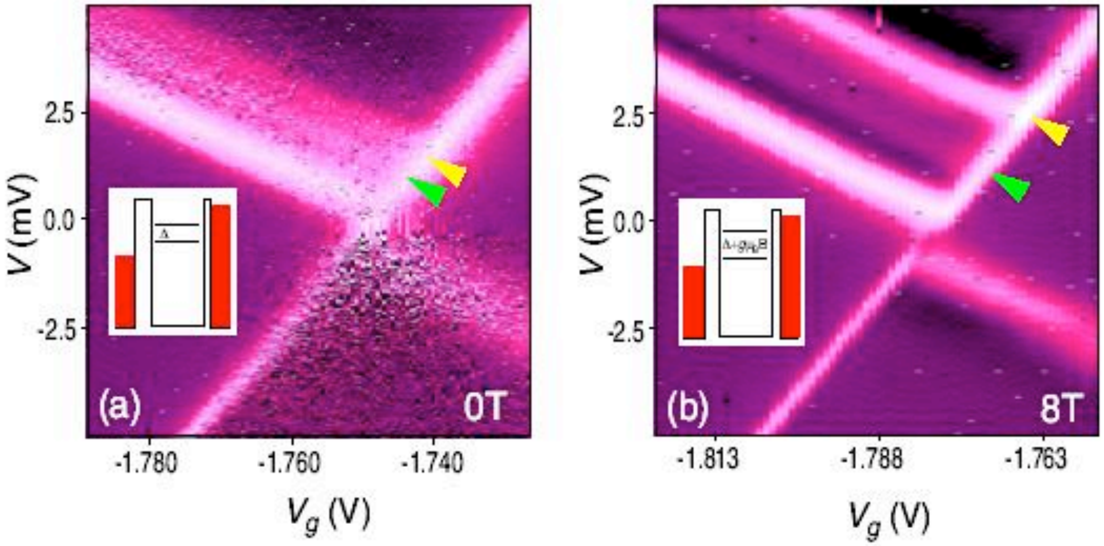
$$H \approx D_N S_z^2 + g\mu_B \vec{B}\cdot\vec{S}$$



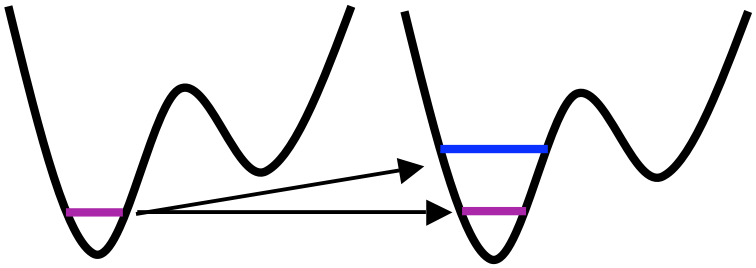
(see also Heersche et al., cond-mat/0510732)

# *Signatures of Magnetic States I: Zero-Field Splittings*

4 of 16 devices that exhibit Coulomb-blockade signals have magnetic excitations with zero-field splittings. (0.25 meV to 1.34 meV)



Yelow state: magnetic excitation with zero-field splitting
Green state: phonon excitation, no shift with field

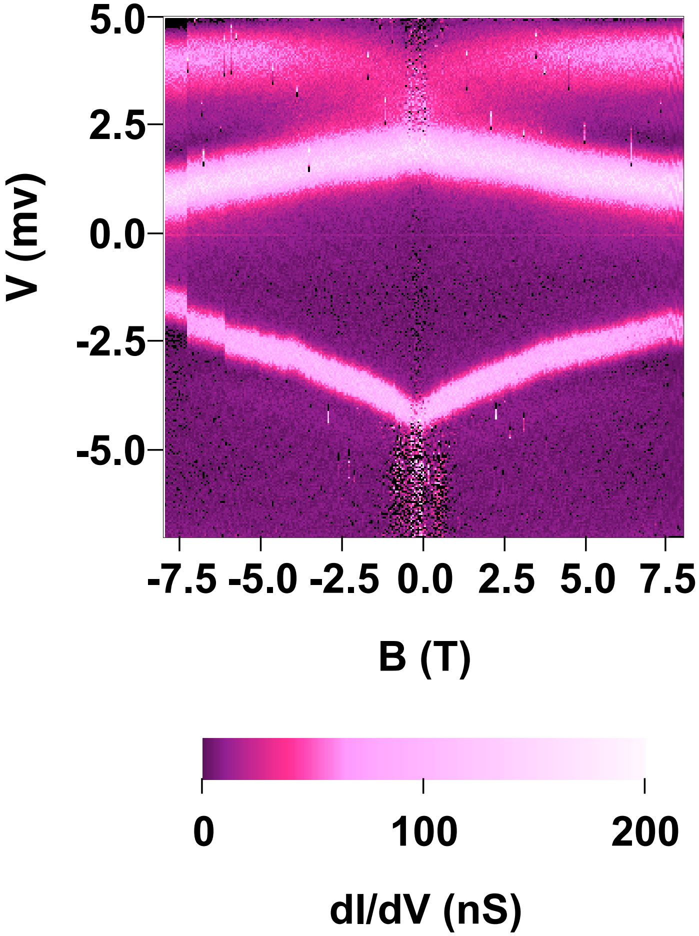


N e$^-$
Spin S

(N ± 1) e$^-$
Spin S+1/2

Moon-Ho Jo, Jacob E. Grose et al., submitted *to Nature Physics* (cond-mat/0603276)

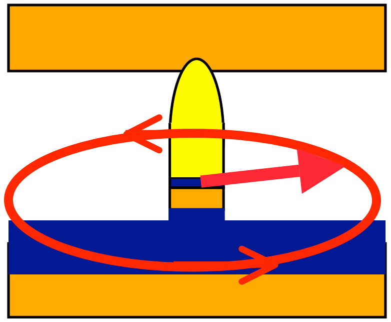
# *Signatures of Magnetic States II: Nonlinear Field Dependence*



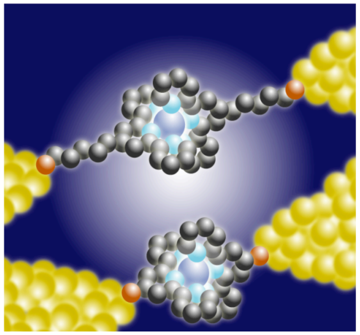
- In modeling, nonlinear evolution of levels vs. magnetic field is generic when the strength of magnetic anisotropy is different for N and N±1 electrons and the field is applied at an angle relative to the magnetic easy axis.

- No hysteresis vs. B. Can tunneling electrons can enhance magnetic relaxation?

(Waintal and Brouwer, PRL **91**, 247201 (2003))



# *Summary of Molecular-Scale Spintronics*



- Nanoscale Magnetic Electrodes: Can use electromigration to fabricate magnetic electrodes with a nanoscale gap appropriate for single molecule studies.
Even simple bare electrodes exhibit some unexpected new physics: large tunneling anisotropic magnetoresistance and fluctuations in magnetoresistance values in the tunneling regime.

- Transport Measurements on Single Magnetic Molecules with Non-Magnetic Electrodes: Accomplished energy-level spectroscopy and found signatures of molecular magnetism.

Spin Transfer measurements of magnetic dynamics in single magnetic molecules are planned.