PAST, PRESENT, and FUTURE of MRAM

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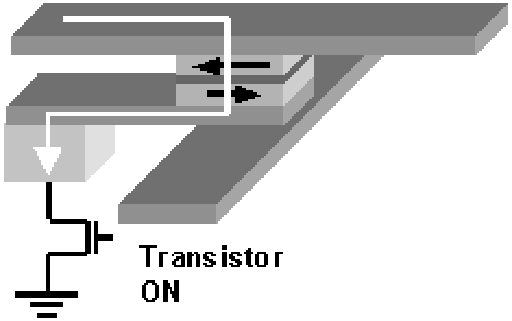
Outline



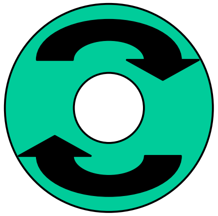
- Introduction

- Basics of MRAM operation

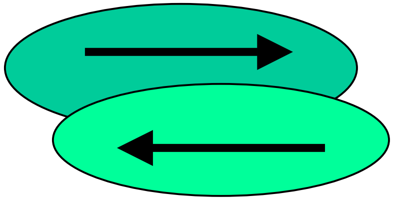
- Prototype MRAM design

- Possible Future Directions
  - Magnetization Dynamics
  - Spin Momentum Transfer

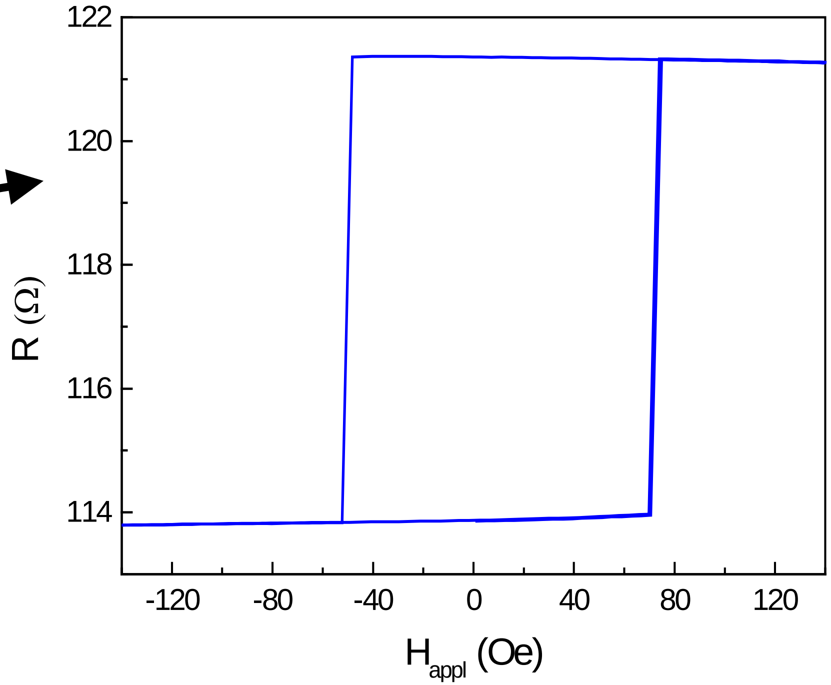
Beginnings



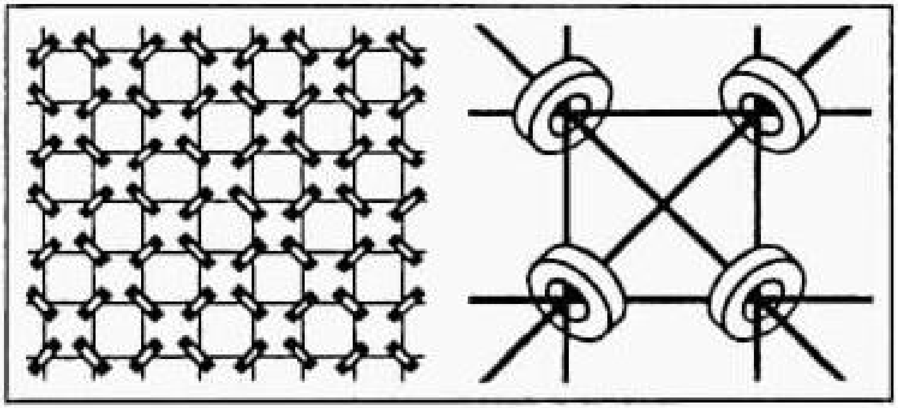
ferrite toroid

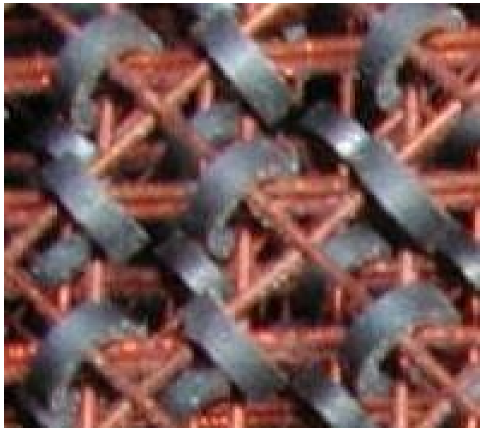


Spintronics:
GMR, TMR



Non-Volatile Magnetic Memory c.a. 1950
(but a destructive read!)





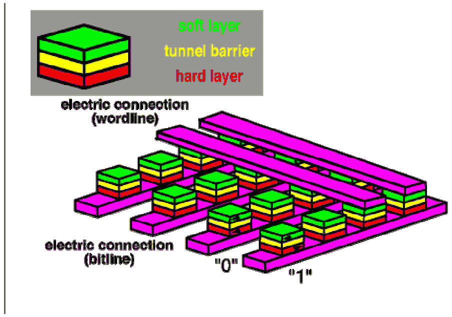
Why Now?

Memory market dominated by pure semiconductor technology

DRAM $16 billion LEAKY
SRAM $ 4 billion BIG
FLASH $ 9 billion (Non-Volatile) SLOW

MRAM (spintronics technology)

May be able to compete!



Universal Memory

*but maybe first embedded memory

Desired non-volatile, fast, low power memory, low cost, technology widely being sought.

MRAM : IBM, Motorola, Infineon, Toshiba, Cypress, Micron, . . .

FRAM : Ramtron, Texas Instruments, Fujitsu, Samsung, NEC, …

Other Options – Ovonics, Polymer Ferroelectric memory, Nanotubes, PMC, …???FLASH???

MRAM (Attractive) Properties

- Non-Volatile
- High Density
- High Speed
- Non-Destructive Read

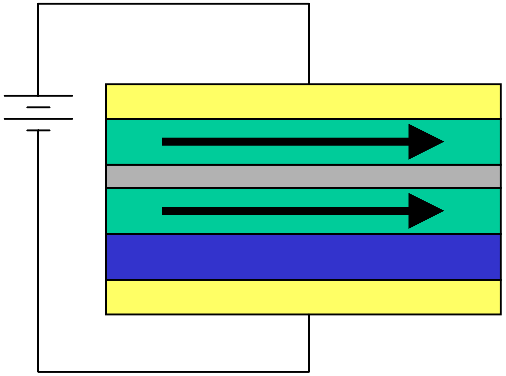
- Low Voltage Operation
- Unlimited Endurance
- Scalable?
- Reliable?

!!! Instant-ON computers !!!

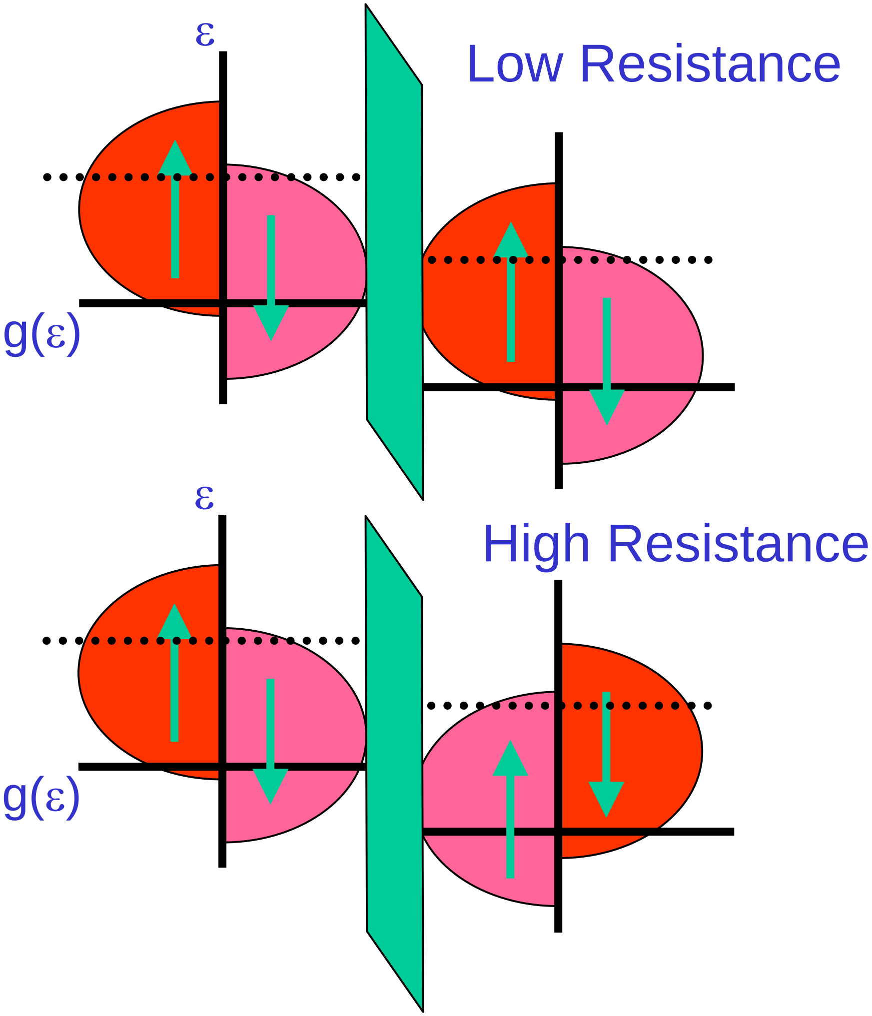
MRAM Elements (Bits)

Magnetic Tunnel Junctions

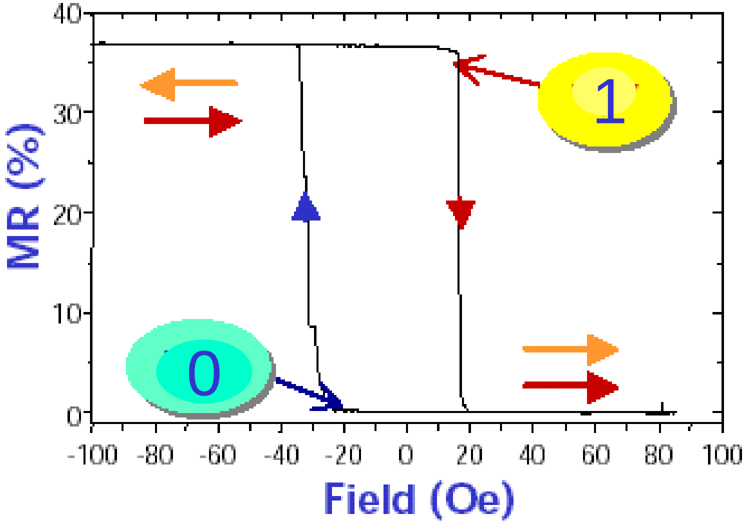
FM/Insulator/FM/AFM



Spin-Dependent Tunneling



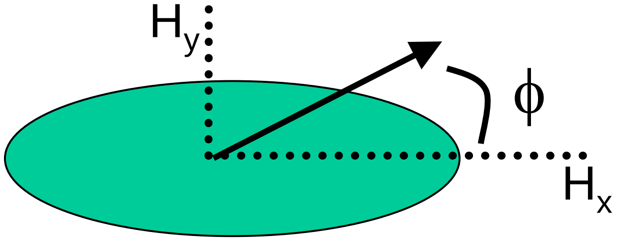
Large Resistance Change

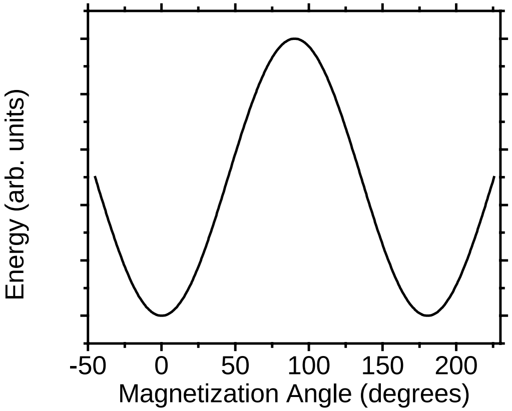


Cross Point Architecture

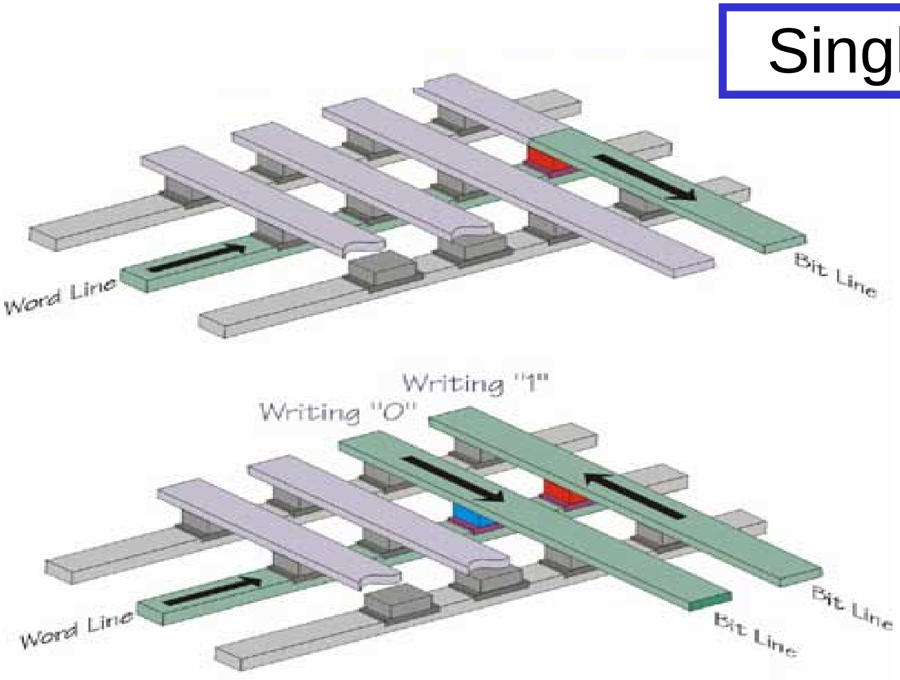
Programming Method

$$u = \frac{1}{2}\mu_0 M_s H_K \sin^2\phi - \mu_0 \mathbf{M} \bullet \mathbf{H}_{app}$$

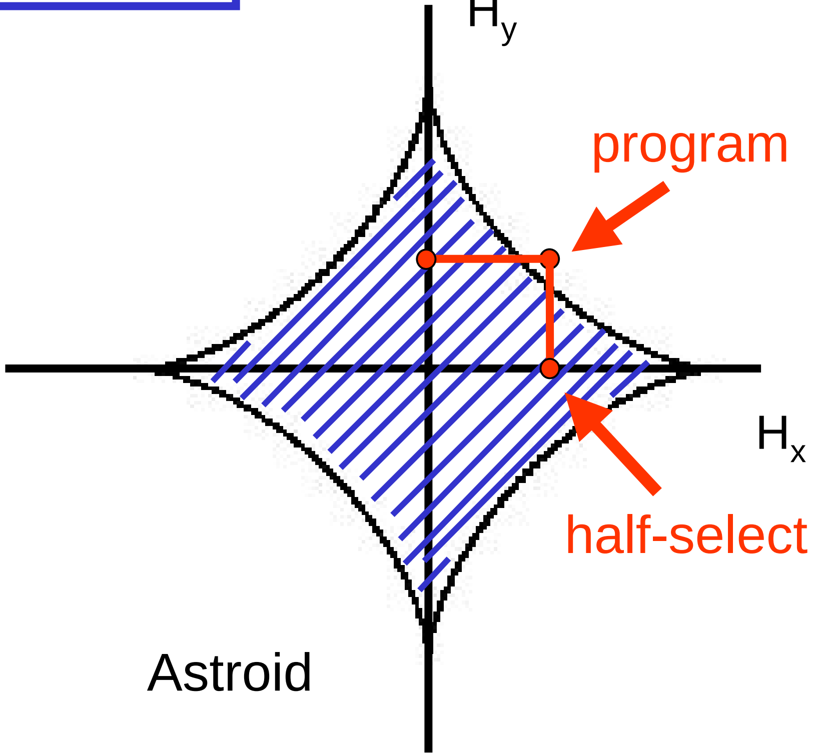




Single Domain



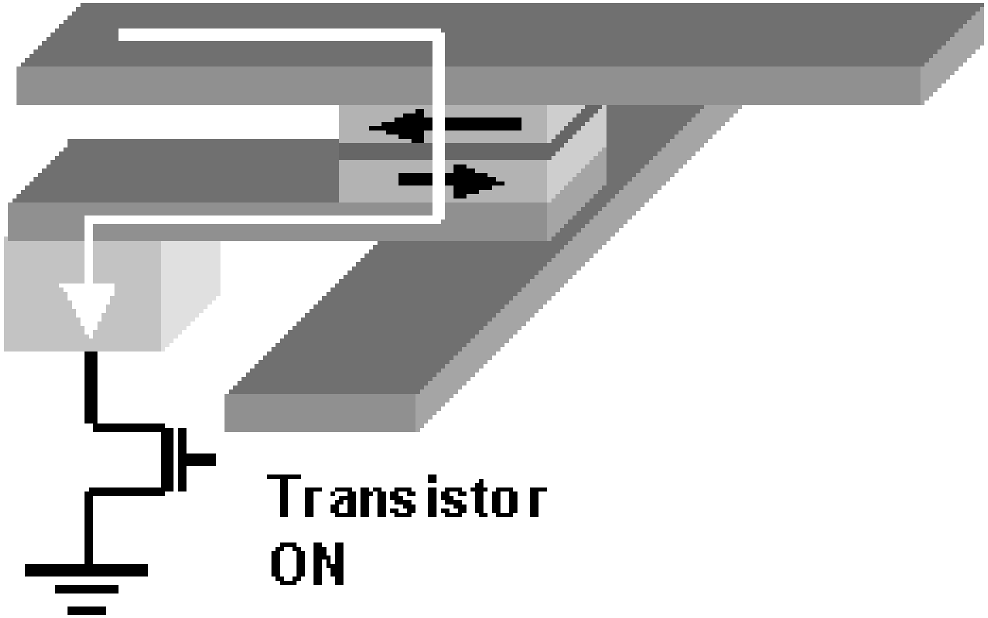
IBM



Bit Sense

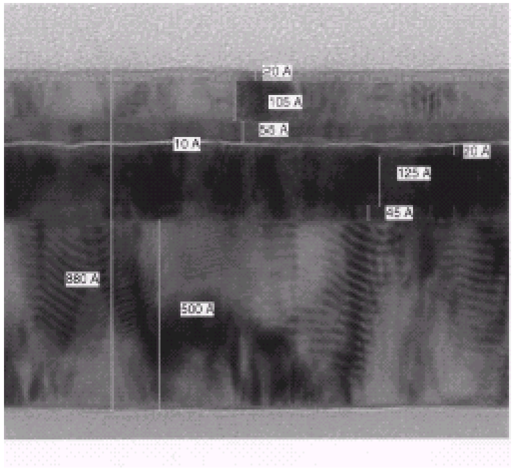
1 Transistor and 1 MTJ element per unit cell

Allows for a non-destructive read process



Bit cell size < 1 μm^2 using 0.18 μm technology

Complications

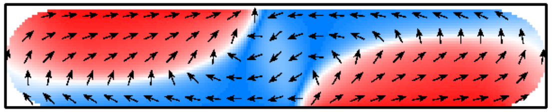


Tunnel Barrier

- very thin (< 2 nm); R, ΔR depends on barrier thickness
- ΔR depends on interfaces to the barrier
- Pinholes and roughness are problems

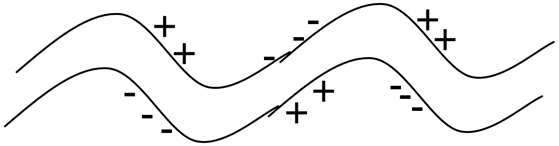
Micromagnetic Effects

- magnetization not exactly single domain
- switching fields sensitive to device shape



Layer Coupling Effects

- edge charges on FM layers cause AP ground state
- film roughness leads to Neel coupling – Parallel state



Thermal Stability Issues for small bits

- caution for half-selected bits switching via thermal activation

State of the art

Motorola* 1Mbit MRAM chip in 2002

0.6 μm process technology, 7.2 μm cell size, 50 ns read access time, 24 mW at 3V 20 MHz

IBM/Infineon 128 kbit MRAM

0.18 μm technology, write/read access ~2ns

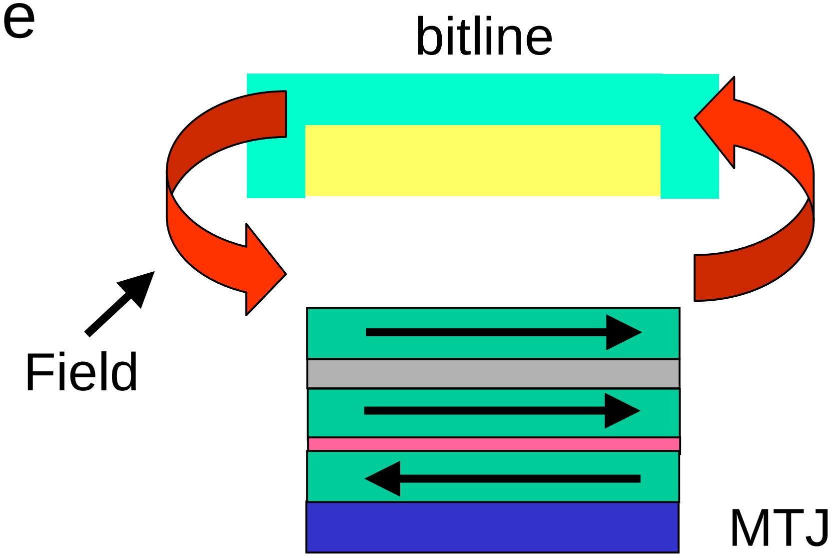
Cypress 64 kb and 256 kb product data sheets on website

70 ns access time

Innovations

-SAF pinning structure

-Flux concentrating-cladded Cu lines



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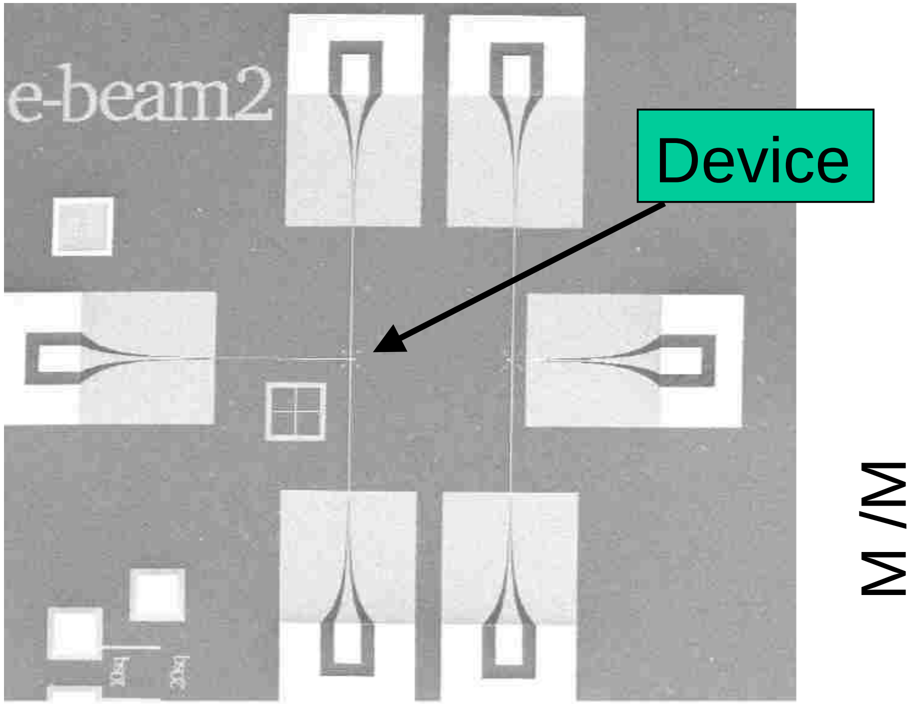
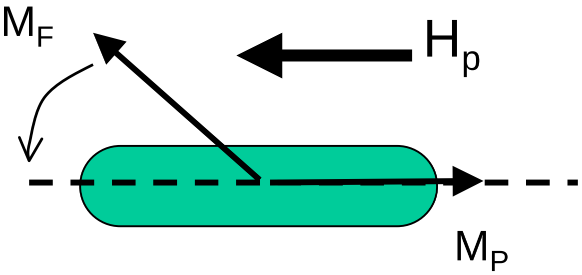
* IEEE J. Solid State Circ. 38 769 (2003)

High Bandwidth Magnetic Measurements

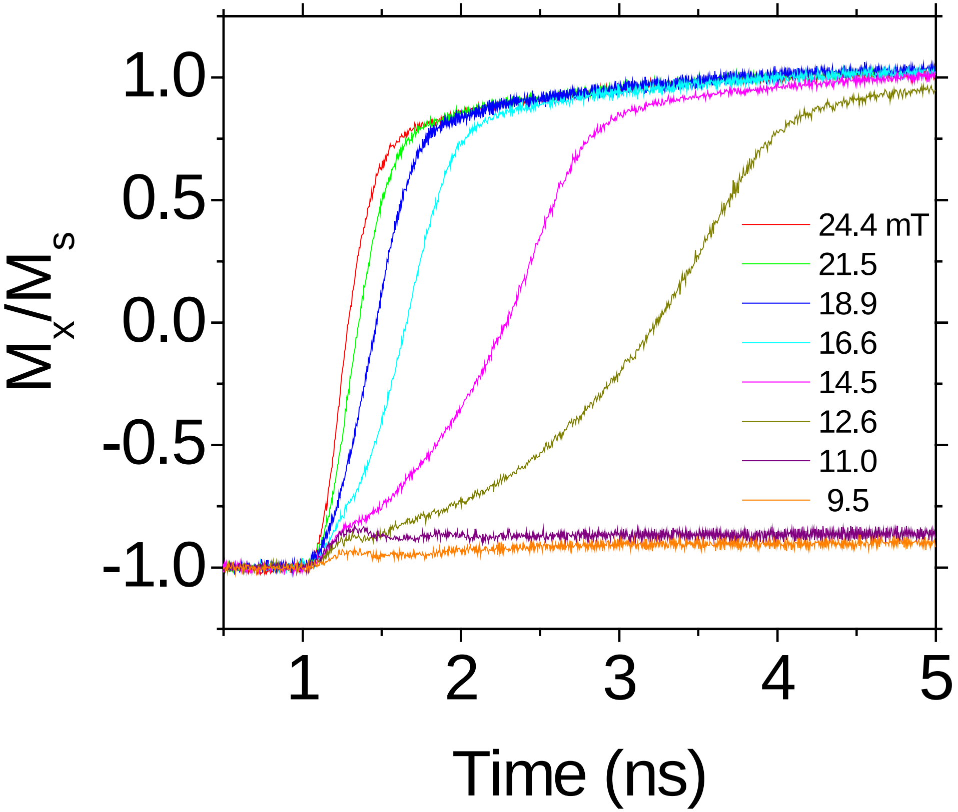
Test structure with CPW and μ-strip lines; sub-μm device



3 mm X 3 mm
SEM Micrograph

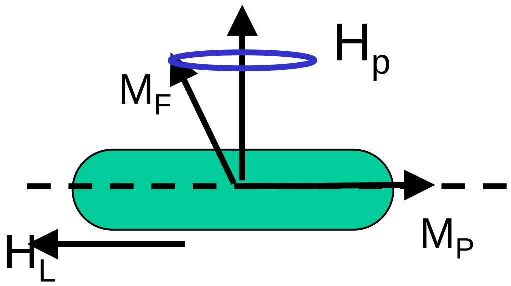


Easy-axis field switching data



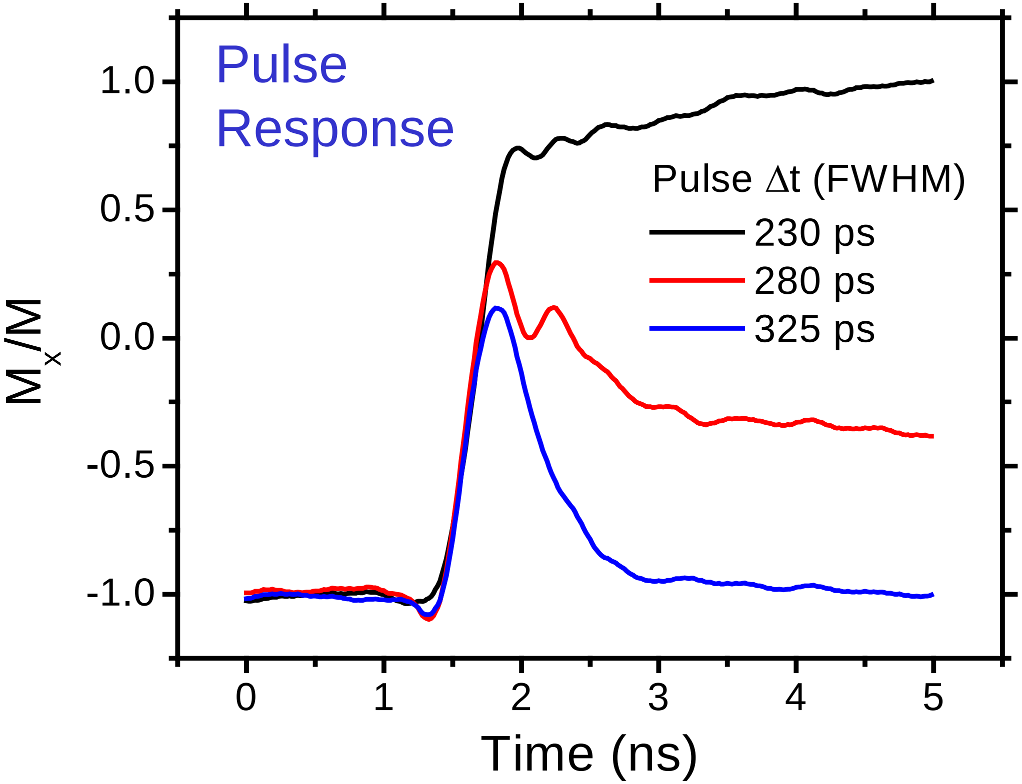
Precessional Switching

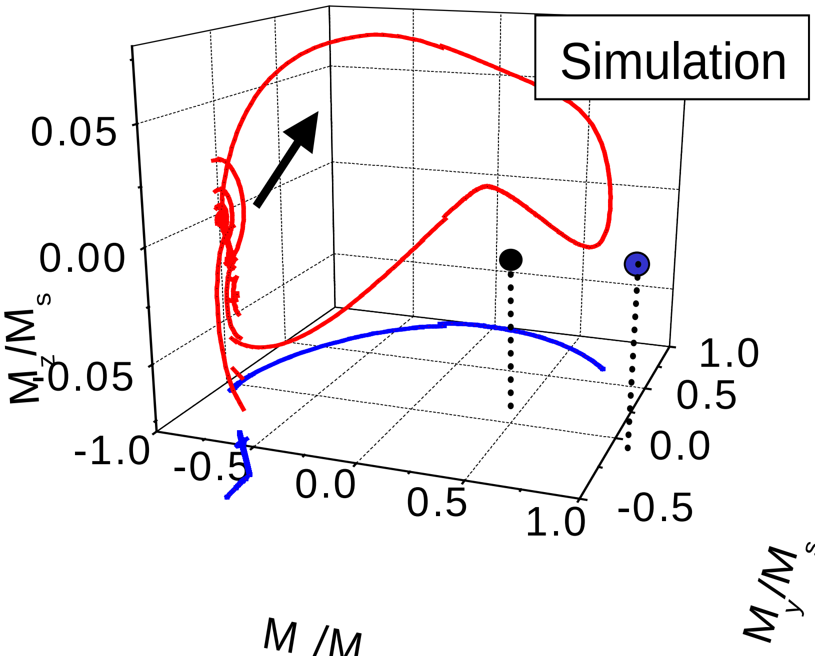
*APL **80** 2958 (2002)*



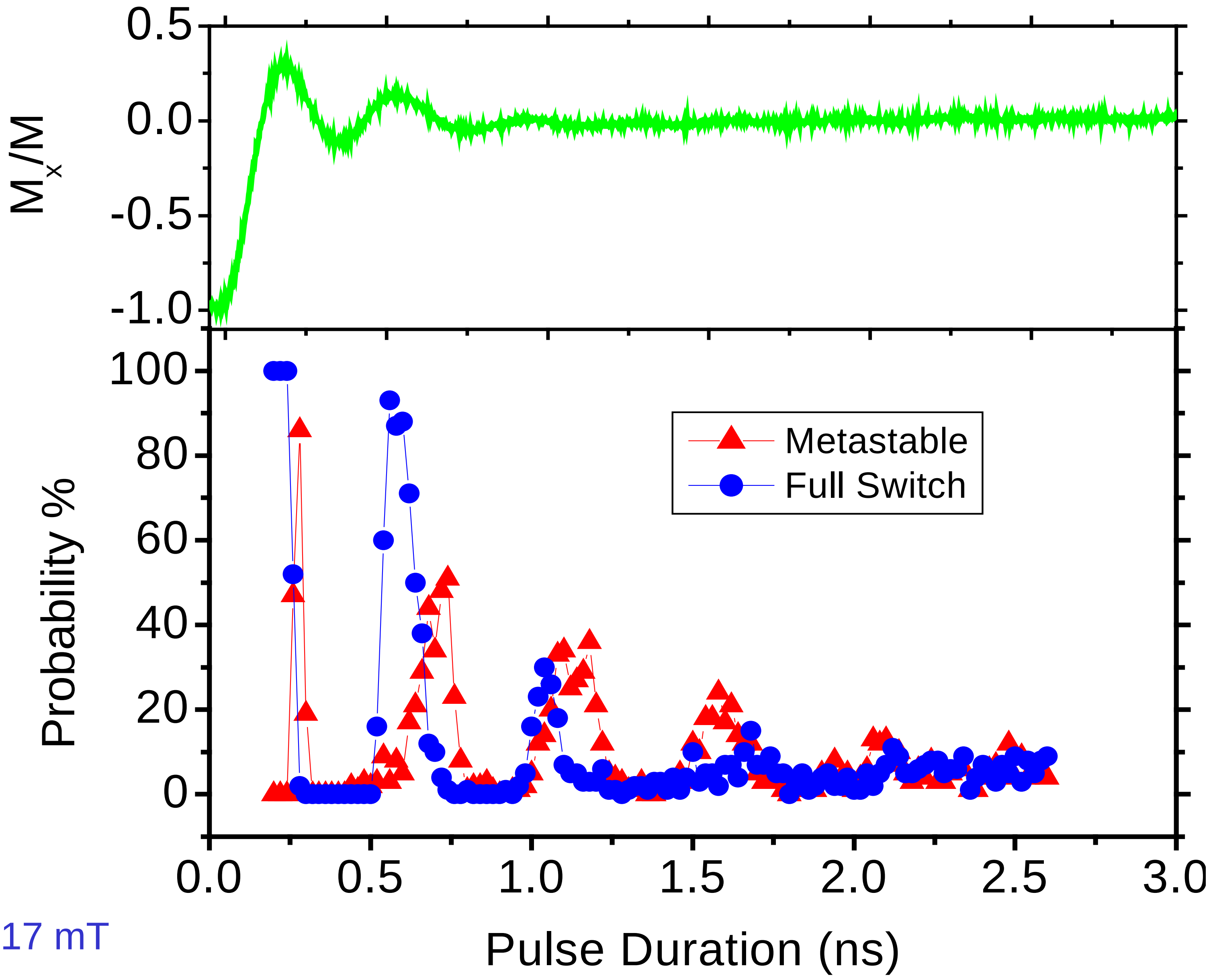
Landau-Lifshitz equation - dynamics

$$\frac{d\mathbf{M}}{dt} = -\mu_0\gamma\,\mathbf{M}\times\mathbf{H}_{eff} - \alpha\frac{\mu_0\gamma}{\mathbf{M}}\mathbf{M}\times(\mathbf{M}\times\mathbf{H}_{eff})$$





Precessional Switching – Resulting Remanent States

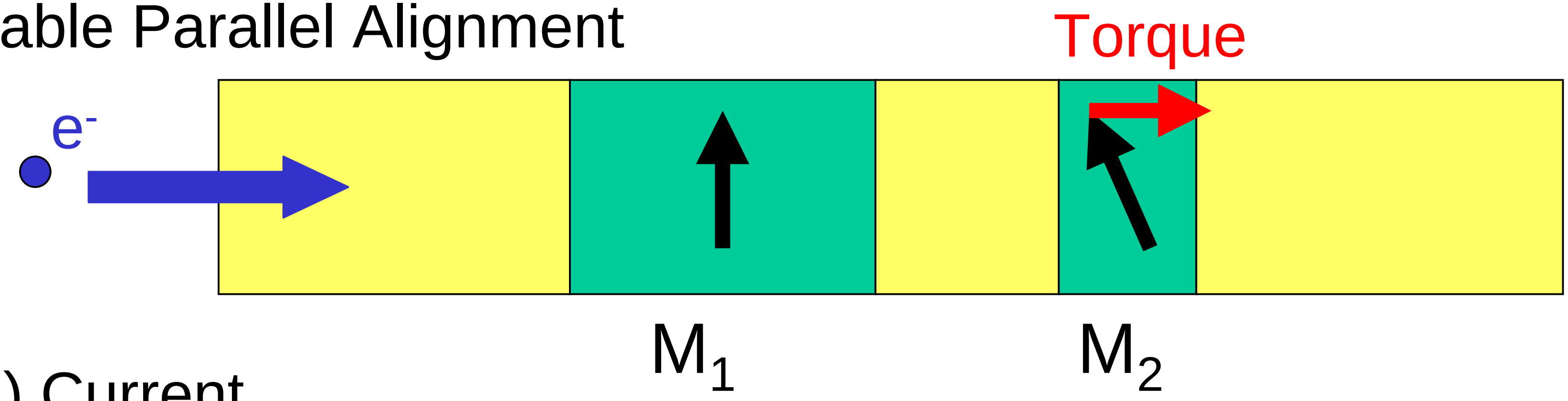


H_p = 17 mT

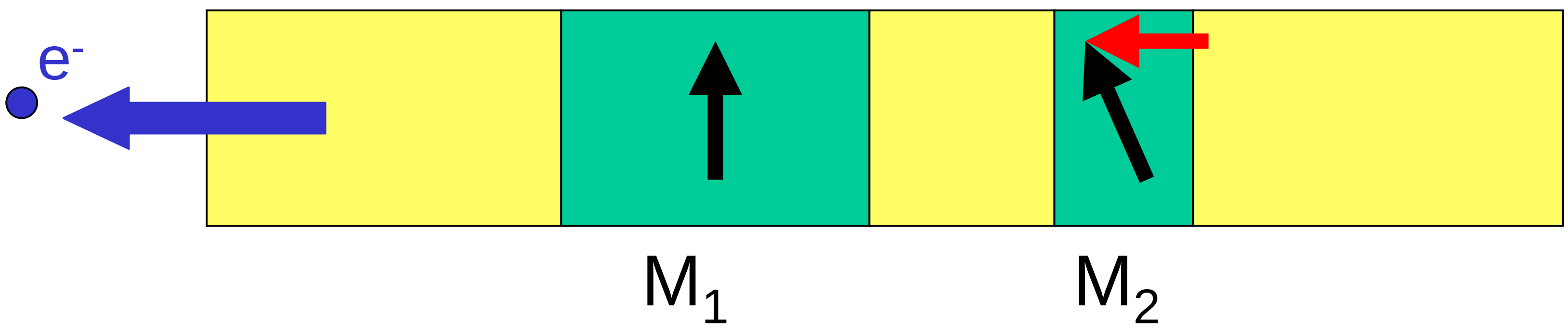
The Spin Momentum Transfer Effect

$$\boxed{\tau_2 \propto I\ \mathbf{M}_2\ X\ (\mathbf{M}_1\ X\ \mathbf{M}_2)\ ;\ I \sim 10^7 A/cm^2}$$

(-) Current
Stable Parallel Alignment

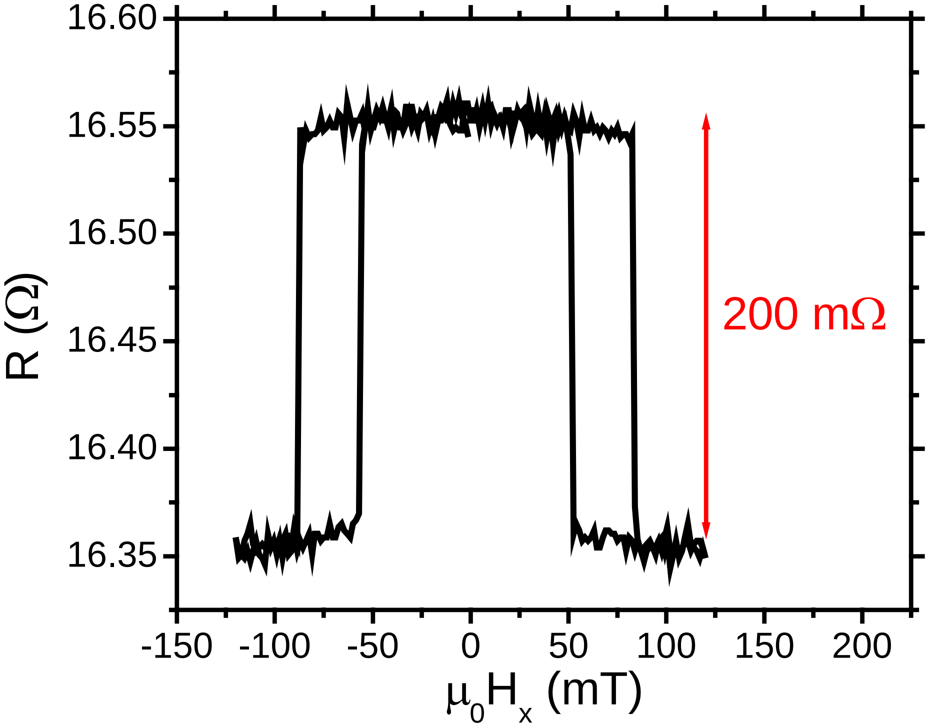


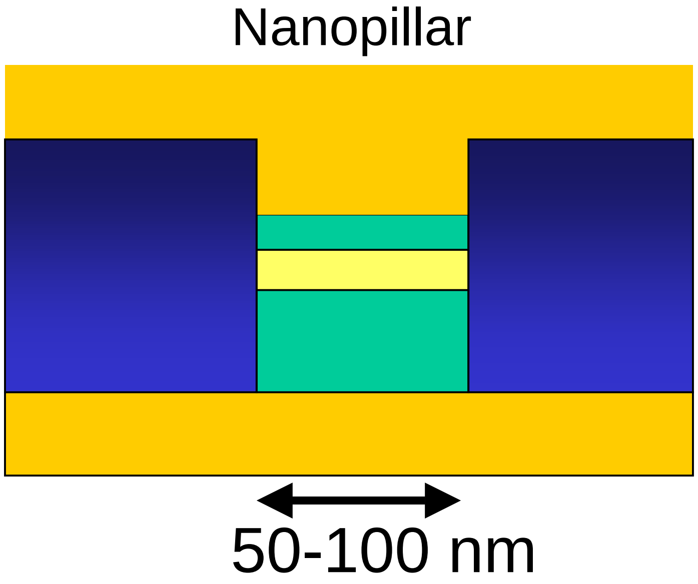
(+) Current
Stable Anti-parallel Alignment

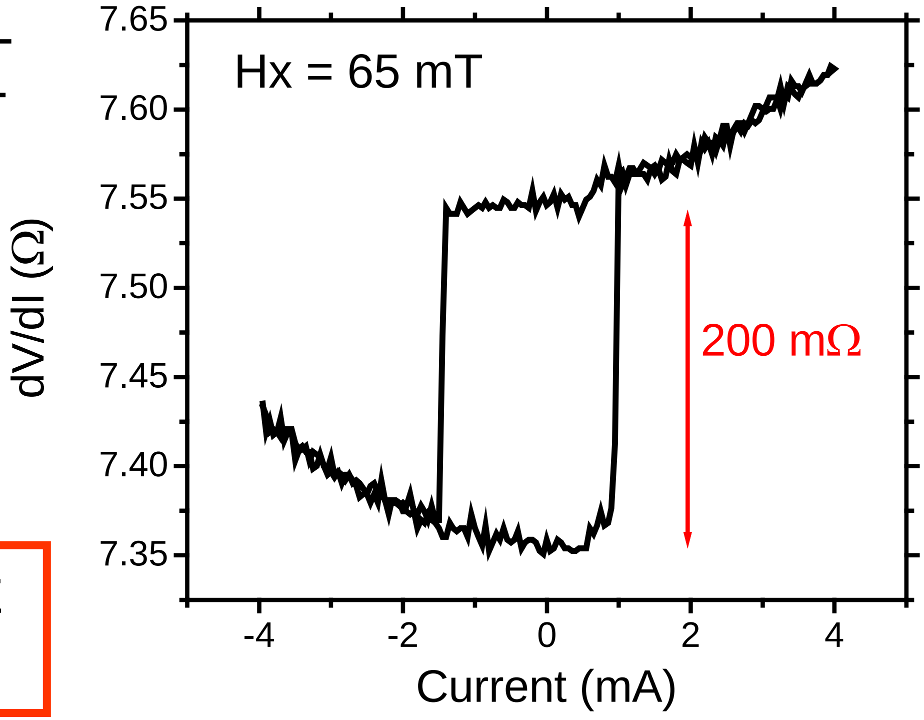


Slonczewski, JMMM ***159*** *(1996)*

The SMT Effect







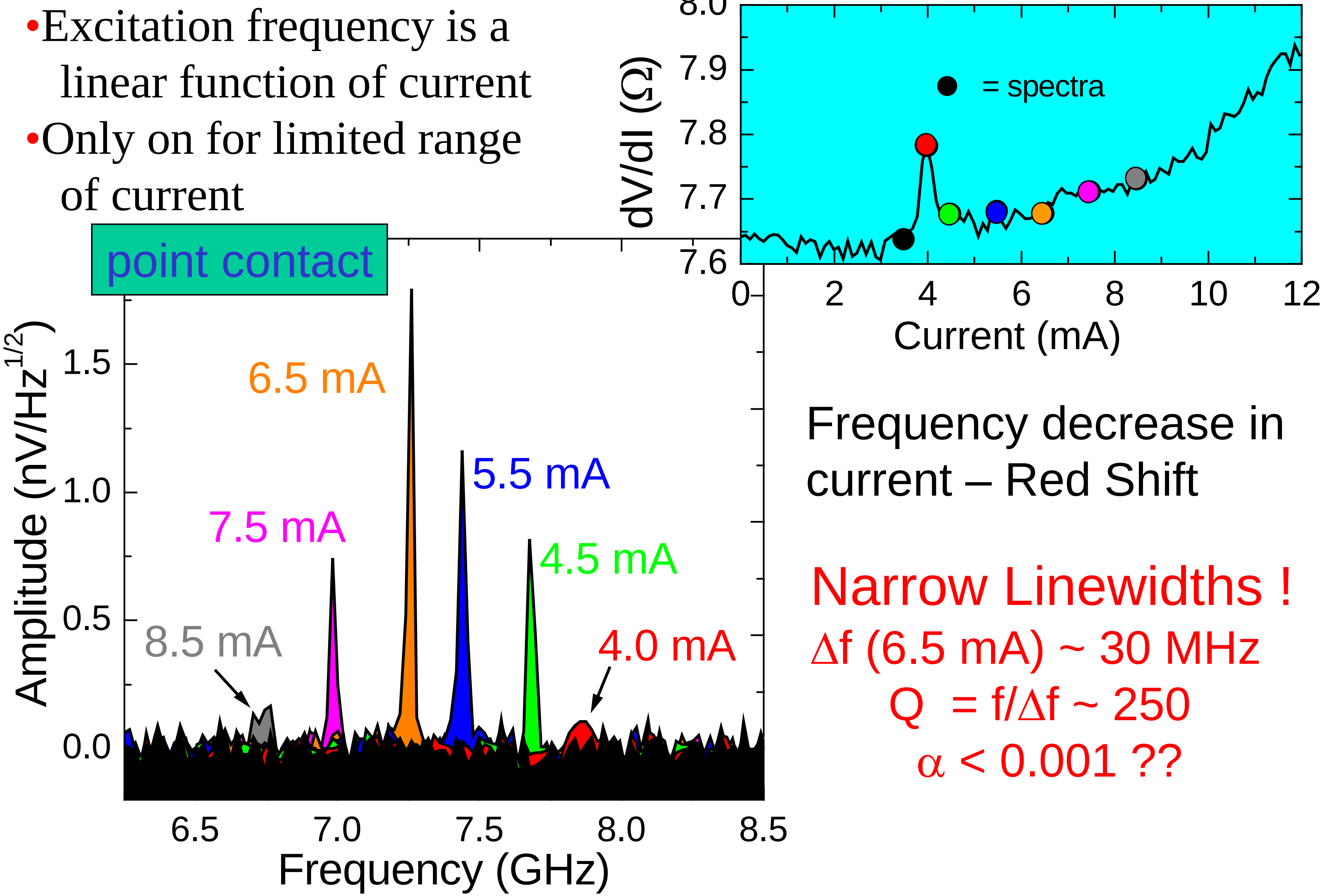
SMT ~ $1/r^2$

Oersted ~ $1/r$

Magnetization control without a magnetic field!

Magnetization dynamics at in-plane fixed field (0.1T)

- Excitation frequency is a linear function of current
- Only on for limited range of current



Frequency decrease in current – Red Shift

Narrow Linewidths !

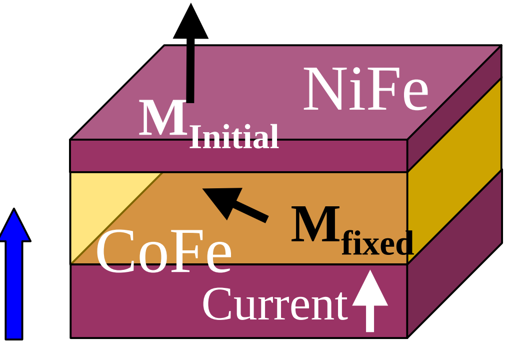
Δf (6.5 mA) ~ 30 MHz

Q = f/Δf ~ 250

α < 0.001 ??

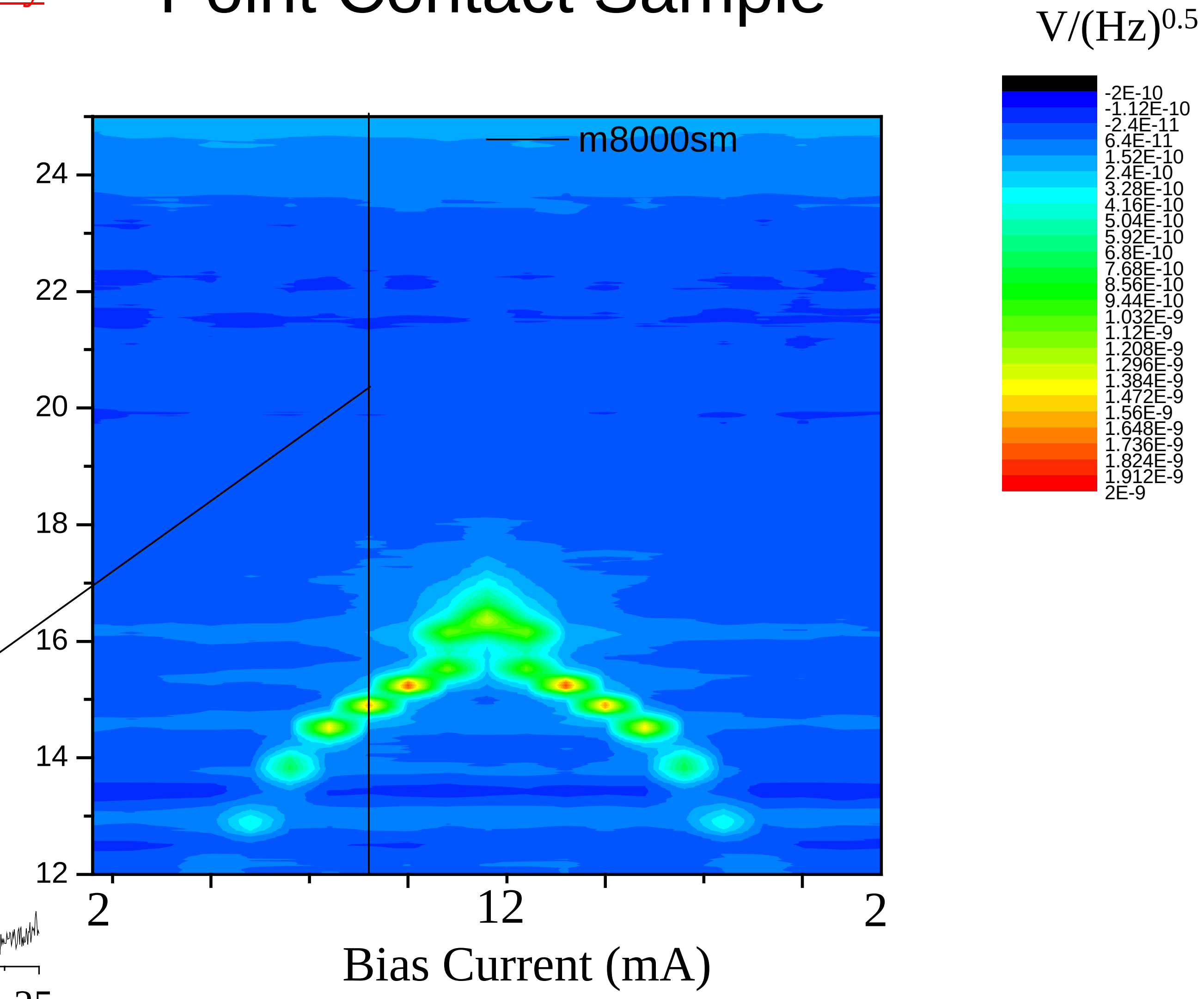
Out of plane precession for out of plane field

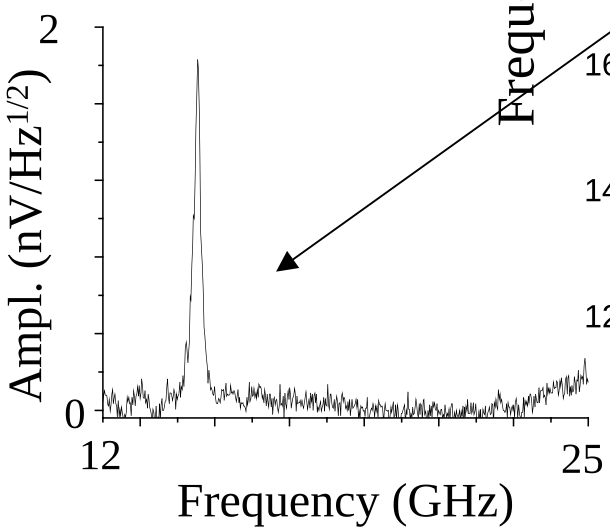
Experimental Geometry



Applied Field 0.8 T

Point Contact Sample





Comparison Chart

	SRAM	DRAM	FLASH	FRAM	MRAM
read time	Fast	Moderate	Fast	Moderate	Moderate/ Fast
write time	Fast	Moderate	Slow	Moderate	Moderate/ Fast
nonvolatile?	No	No	Yes**	Yes*	Yes
refresh	No	Yes	No	No	No
cell size	Large	Small	Small	Medium	Small
low voltage	Yes	Limited	No	Limited	Yes

*Destructive read

** Limited endurance

Motorola

Conclusions

MRAM product will utilize MTJ elements in a cross point architecture

MRAM has attractive properties – maybe capable of surpassing conventional semiconductor memories

Fabrication challenges are being met as MRAM approaches production

Increases in magnetic memory speed performance will require understanding and control of dynamics and damping

Spin Momentum Transfer effect may be utilized in advanced MRAM designs eliminating half-select problem