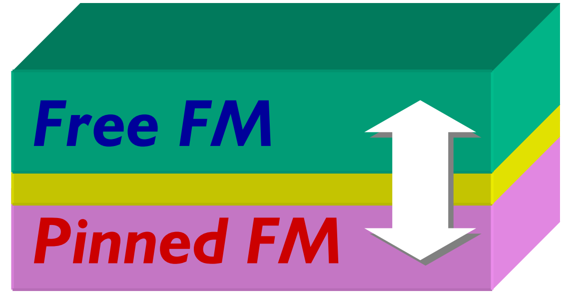
Magnetic Tunneling Junctions: History



1974 Slonczewski - concept proposed

1975 Juliere - first demonstration (CNR-France)

Fe/Ge/Co, $\Delta R/R \sim 14\%$ at 4.2 K

1982 Maekawa and Gafvert (IBM post-docs)

Ni/NiO/Ni, Fe, Co, $\Delta R/R \sim 0.4\text{-}2\%$ at 4.2 K

1990~1993 Miyazaki et al. (Tohoku University)

NiFe/Al-Al_2O_3/Co, $\Delta R/R \sim 2.7\%$ at room temperature (RT)

1995 Miyazaki *et al.* (Tohoku University) - first large MR at RT

Fe/Al-Al_2O_3/Co, $\Delta R/R \sim 18\%$ at RT

1995 Moodera *et al.* (MIT) - large RT MR

Co-Fe/Al-Al_2O_3/Co, $\Delta R/R \sim 10\%$ at RT

1995 Gallagher and Parkin – proposal for MRAM using MTJs

1996 Parkin *et al.* - large RT MR

>25% in shadow masked and patterned junctions; reproducible

1998 Parkin *et al.* - extraordinarily large RT MR; high thermal stability

>35% in sub-micron junctions; >47% in shadow masked junctions

specific resistances ~60 to $>10^9\ \Omega(\mu m)^2$; thermal stability (>300 °C)

1999-2000 Scheuerlein et al. – First MTJ MRAM demonstration

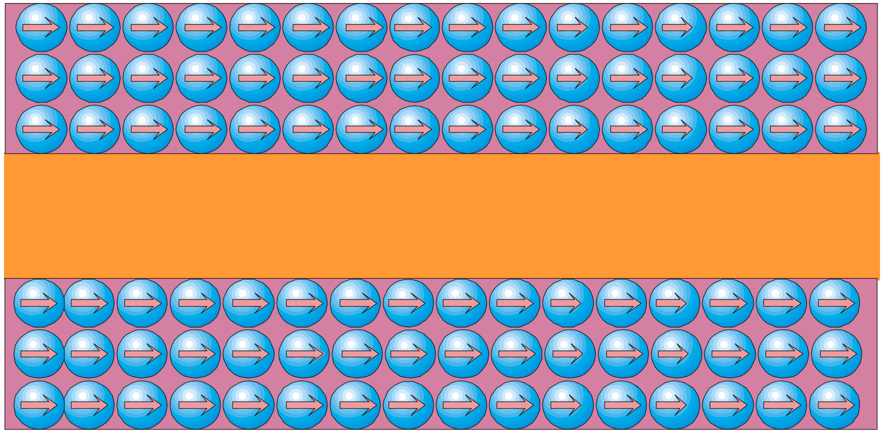
<3 ns read and write

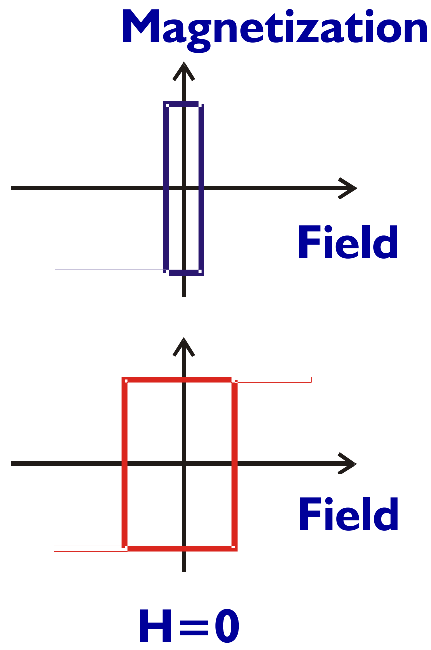
2001-2003 Parkin *et al.* – giant MR using novel tunnel barrier (>220% at RT)

2002 Durlam *et al.* – 1 Mbit MRAM in 0.6 μm technology

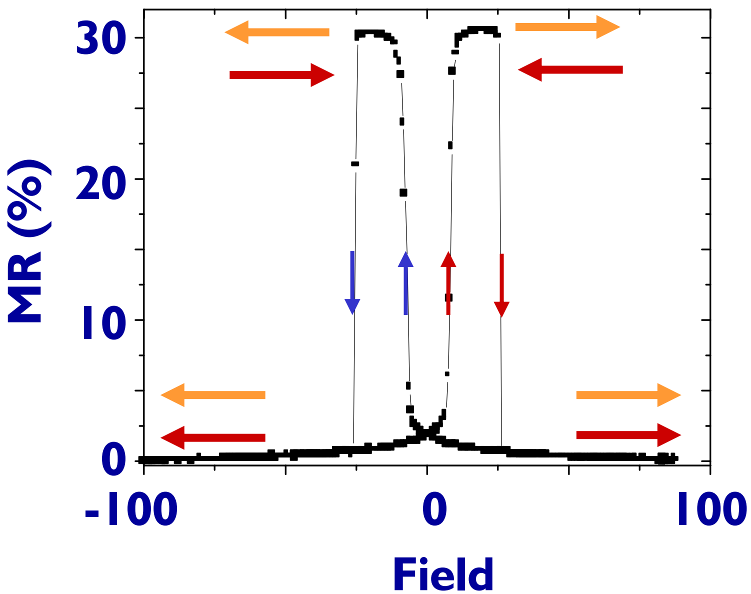
2003 Sitaram *et al.*; Bette *et al.* – 128 kbit MRAM core in 0.18 μm technology

Simplest MTJ: Hard-Soft





MTJ comprised of two FM layers with different coercivities



Pd
80Å $Co_{84}Fe_{16}$
16Å Al-180s
24Å $Co_{84}Fe_{16}$
100Å $Ir_{22}Mn_{78}$
200Å Ti

Problems:
- difficult to control magnetics:
- difficult to find FM layer with very high H_c and S

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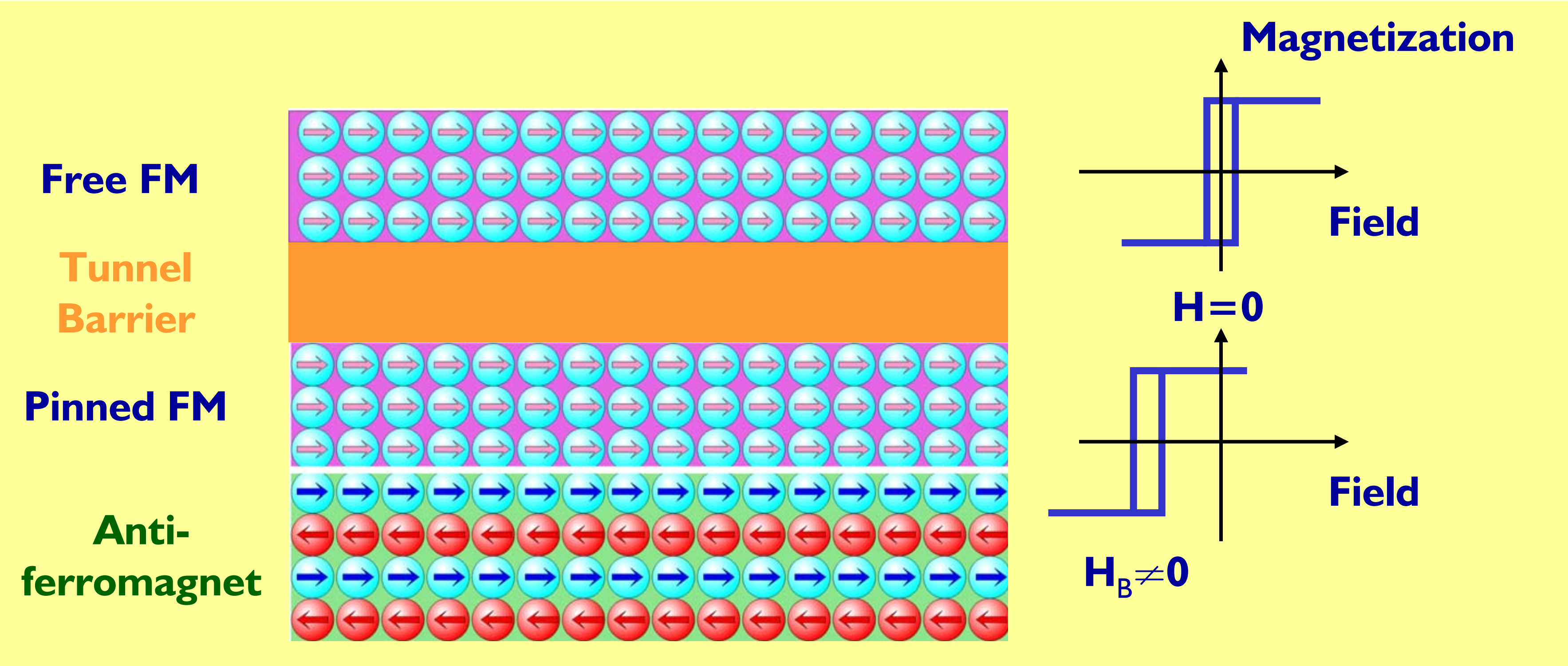
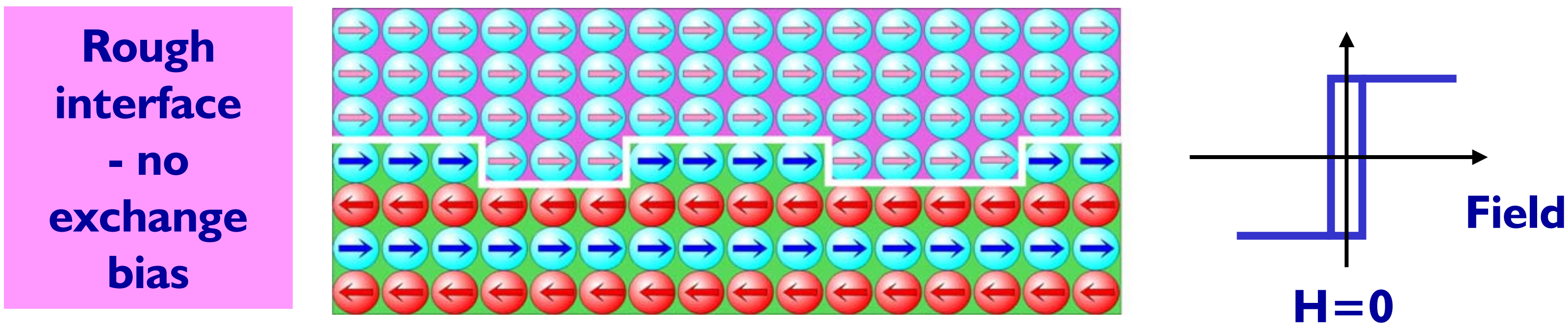
Spin Valve Structure using Exchange Bias





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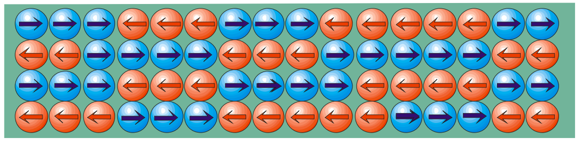
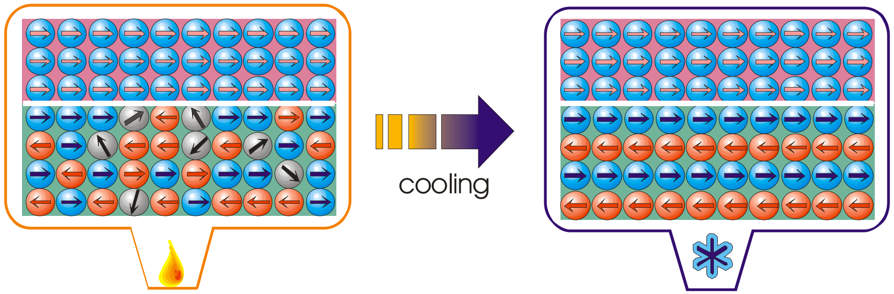
Establishing Exchange Bias

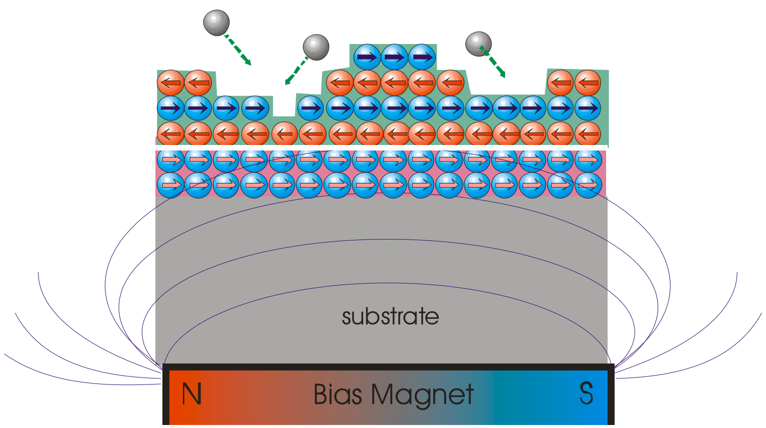
An antiferromagnet grown in the absense of
a magnetic field has no long-range magnetic order



A disordered antiferromagnet layer adjacent to a ferromagnetic layer
may be magnetically ordered by heating above its blocking temperature
and subsequently cooling



Antiferromagnet film deposition onto a ferromagnetic layer biased by an
external applied field will yield a uniformly antiferromagnetically ordered layer



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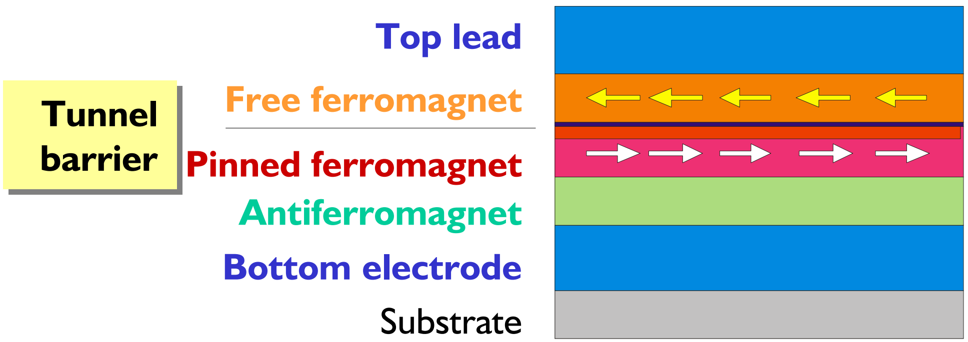
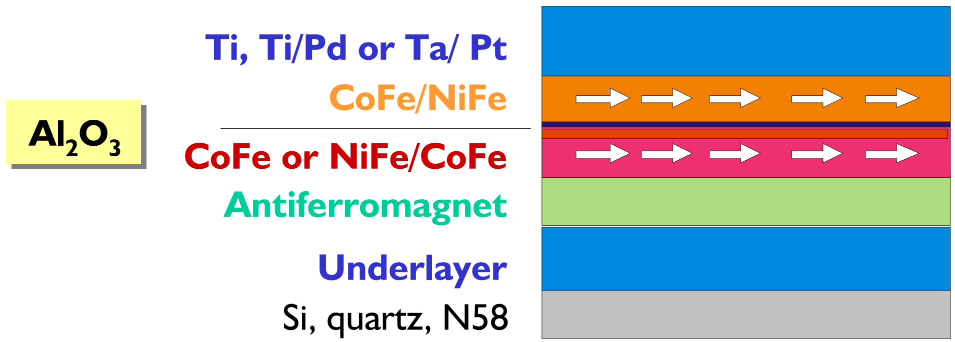
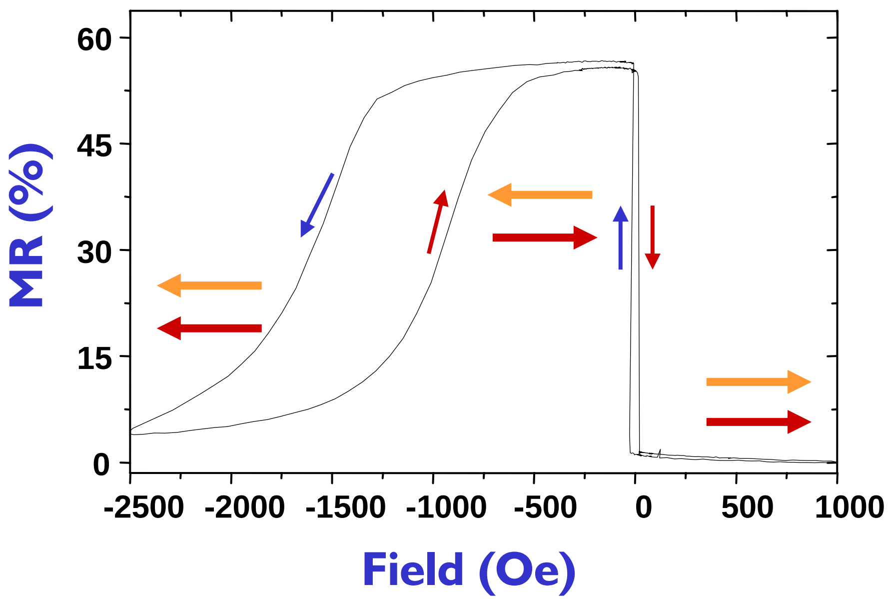
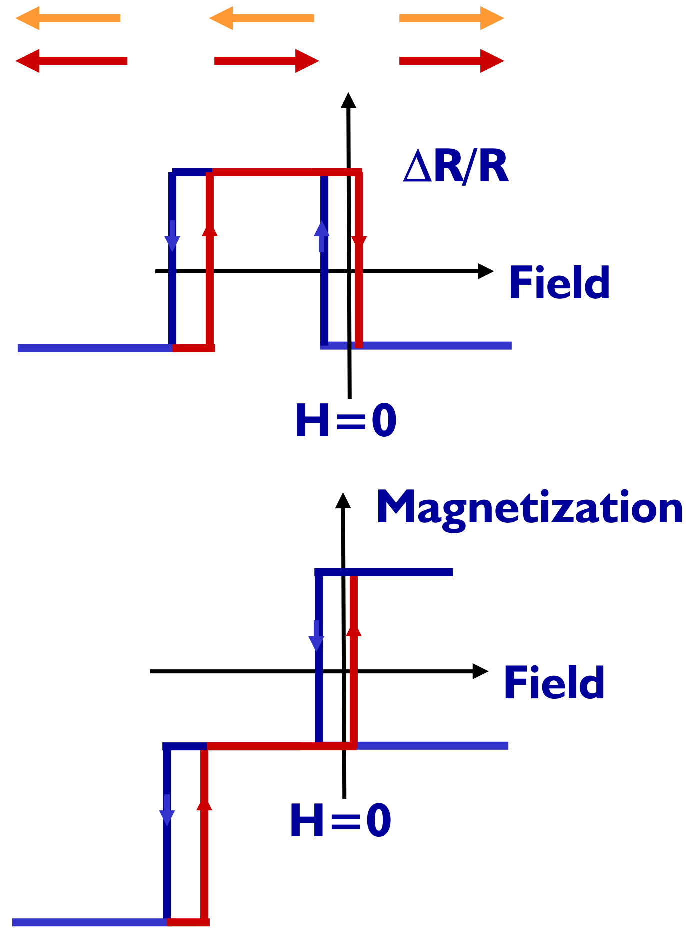
Exchange-Biased Magnetic Tunnel Junction









MR ~ 50%

Switching field of free layer ~ 3 Oe

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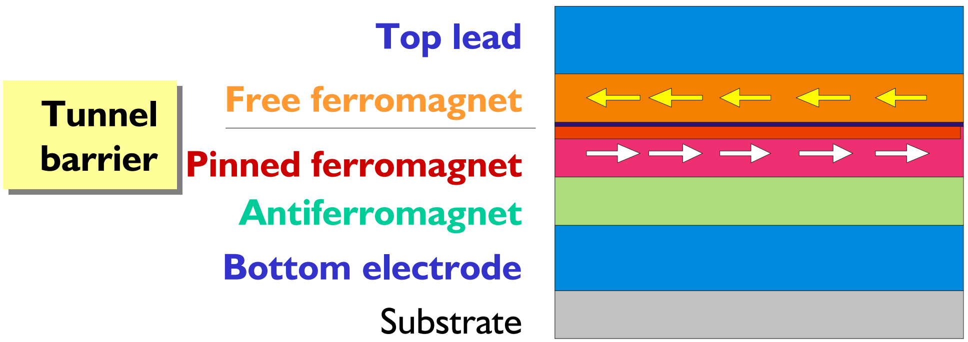
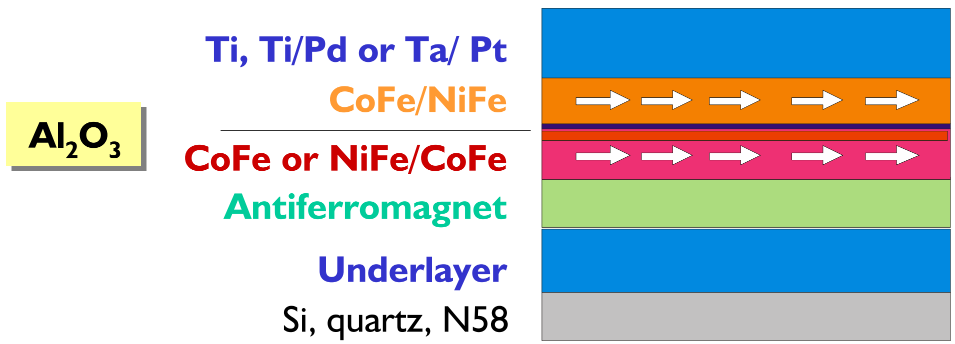
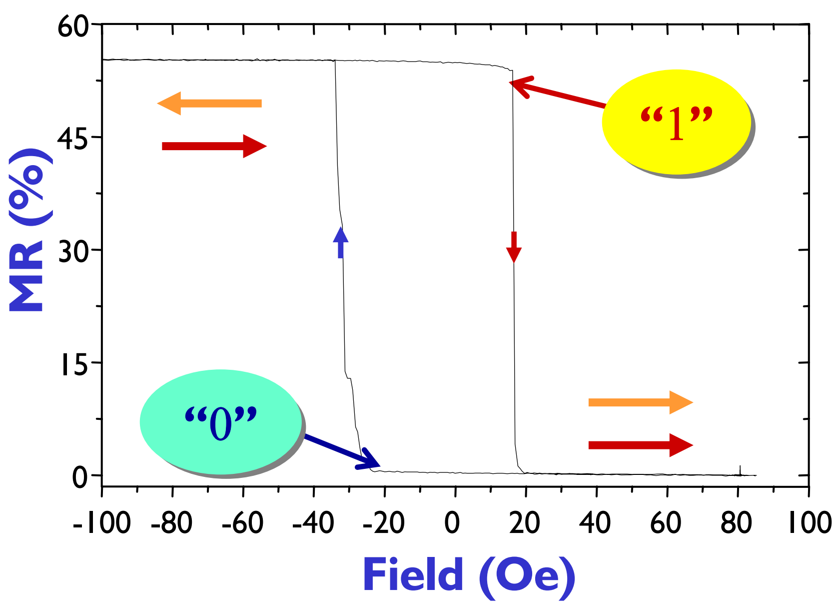
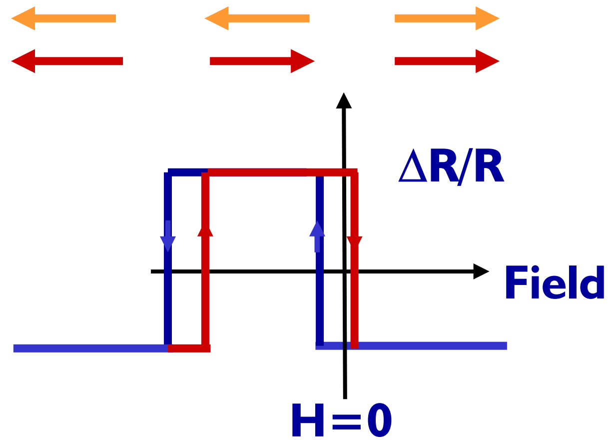
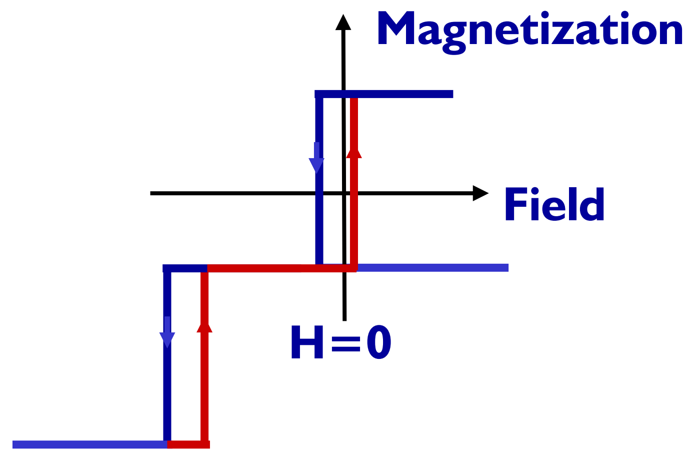
Exchange-Biased Magnetic Tunnel Junction (MTJ)











Non-Volatile Memory!

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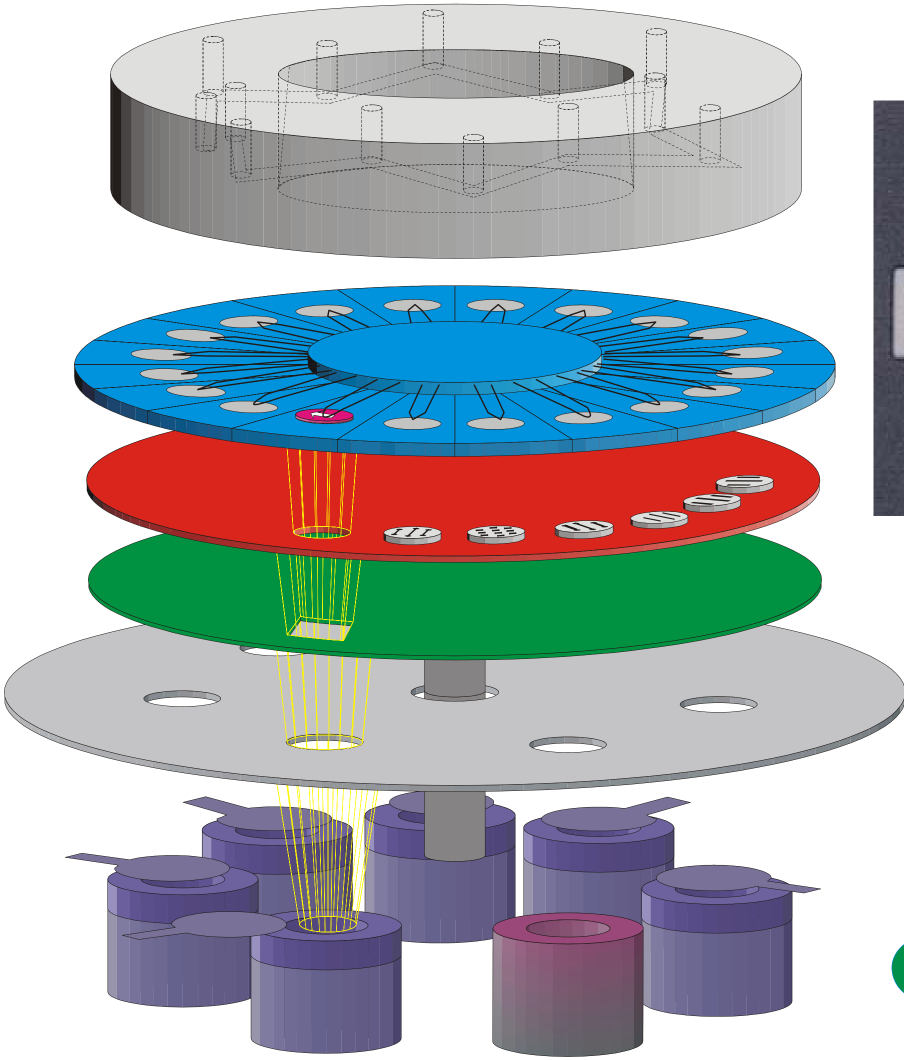
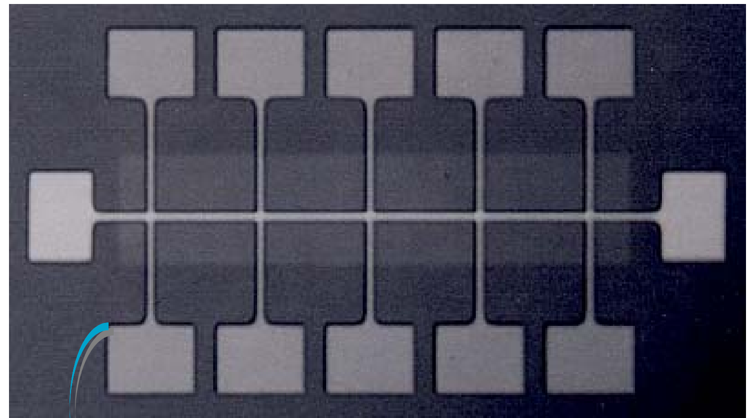
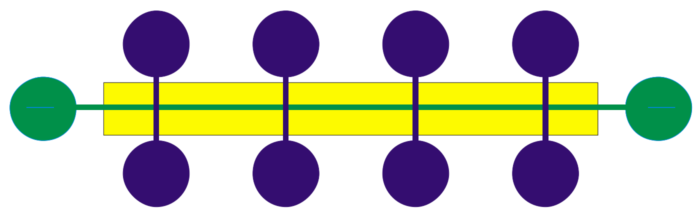
Shadow-Masked Structures Prepared by Sputter Deposition





20x20 μm^2

Tunnel barrier



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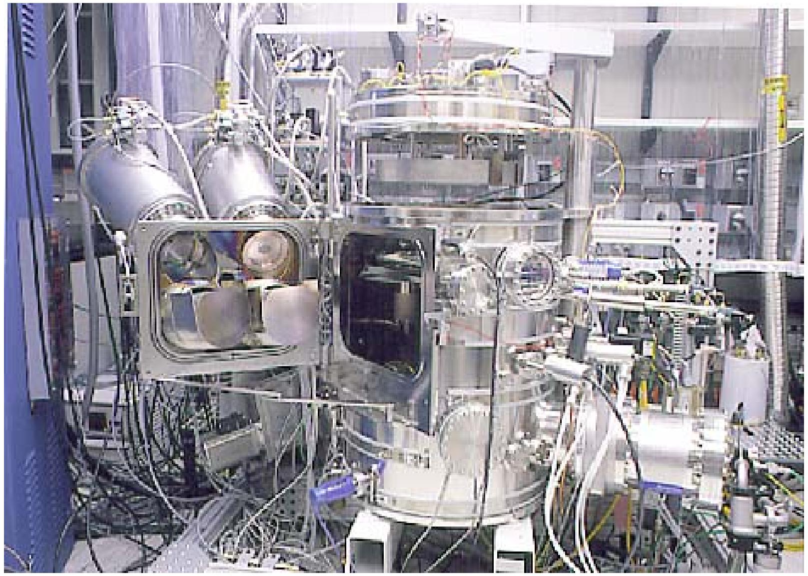
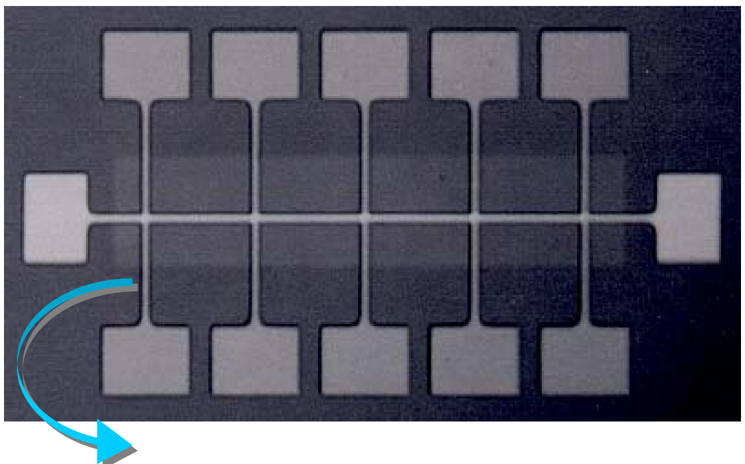
Shadow-masked MTJs prepared by sputter deposition





Tunnel barrier

20x20 μm^2

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Lecture II: Magnetic Tunnel Junctions and MRAM

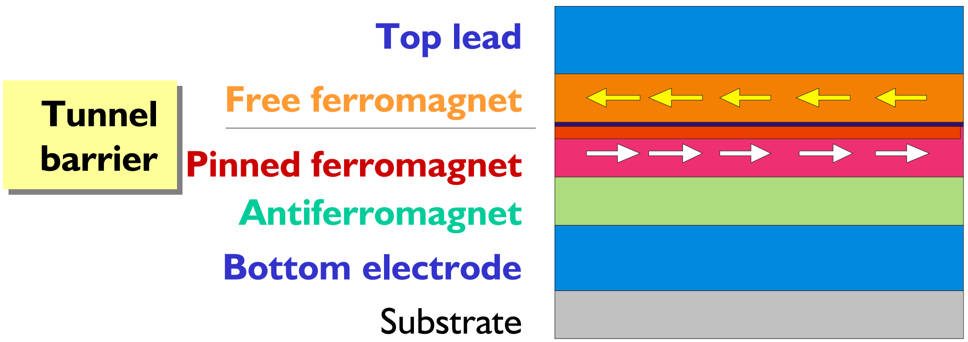
Stuart Parkin

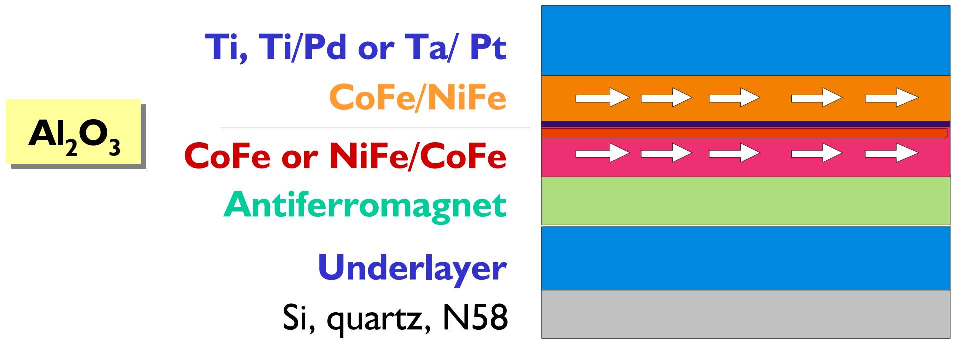
IBM Almaden Research Center, San Jose, California

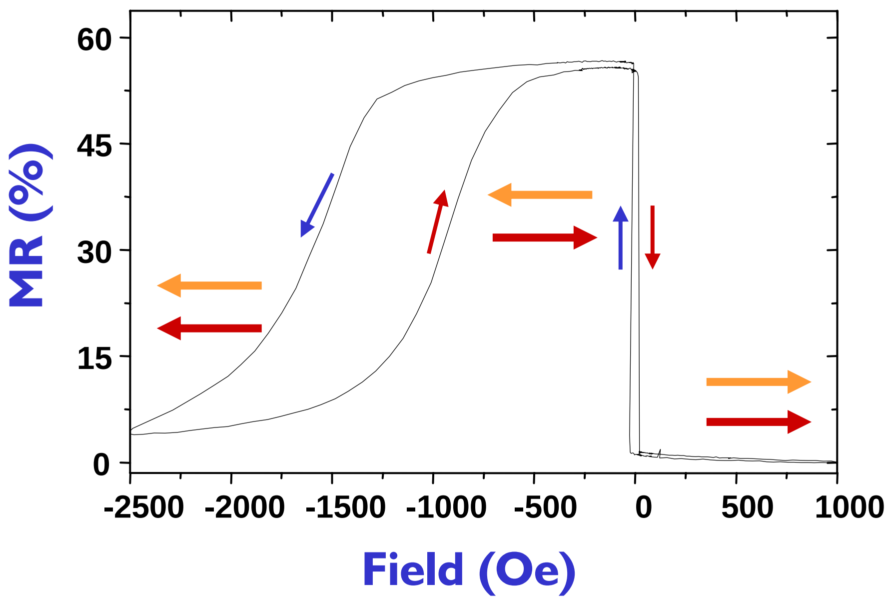
- Magnetic tunnel junctions
  - Magnetic engineering
- Spin polarization of tunneling current
  - ~50% for 3d transition metal ferromagnets/ Al_2O_3
- Magnetic Random Access Memory
  - Attractive: Non-volatile, dense and high-speed
- Magnetic Tunnel Transistor [Lecture 3]
  - Hot electron spin injection into GaAs and Si
  - 3,500% change in collector current → ~100% spin polarized current
  - Optical detection of spin polarized current using QW light emitting diode

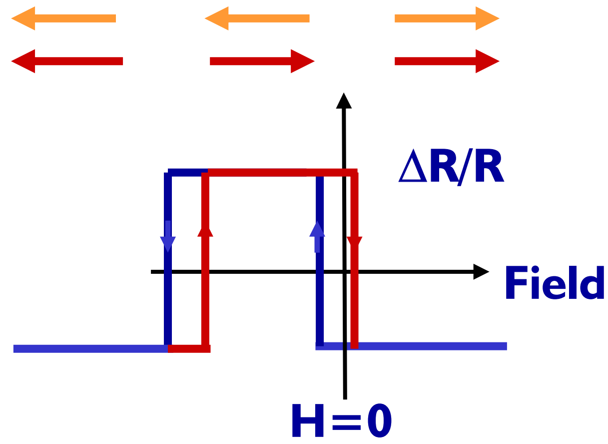
Supported in part by the United States
Defense Advanced Research Project Agency (DARPA)

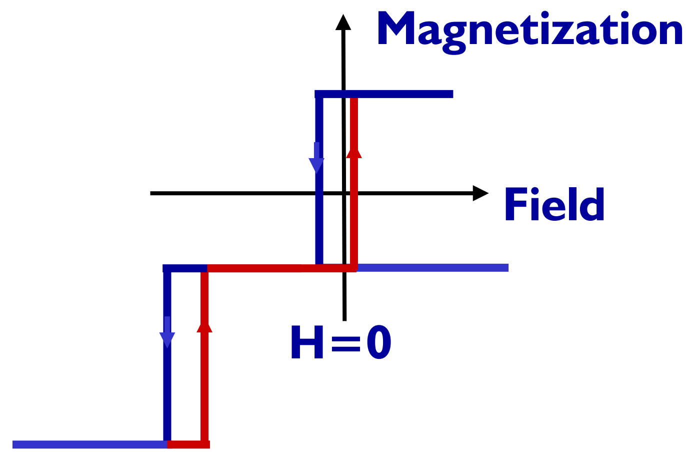
Exchange-Biased Magnetic Tunnel Junction











MR ~ 50%

Switching field of free layer ~ 3 Oe

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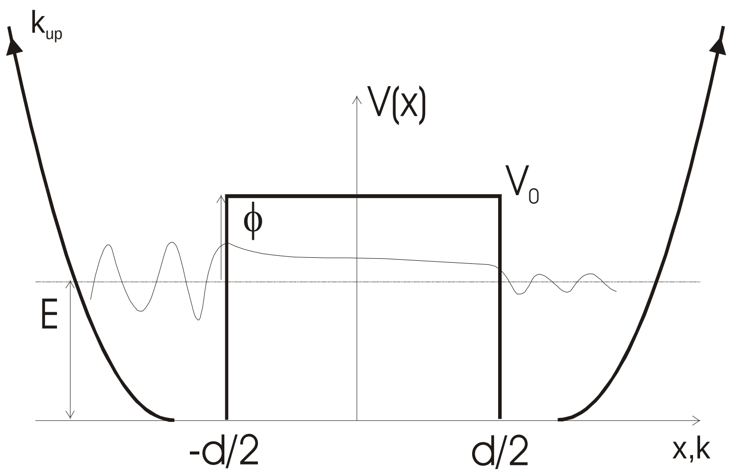
Exact Free Electron Model of Tunneling



Schrödinger equation

$$\frac{-\hbar^2}{2m}\frac{d^2\psi(x)}{dx^2} + \mathrm{V(x)}\cdot\psi(x) = E\cdot\psi(x)$$

$$k = \sqrt{\frac{2mE}{\hbar^2}} \qquad \kappa = \sqrt{\frac{2m(V_0 - E)}{\hbar^2}}$$

$$\psi(x) = e^{ikx} + R\cdot e^{-ikx} \qquad \psi(x) = A\cdot e^{-\kappa x} + B\cdot e^{\kappa x} \qquad \psi(x) = T\cdot e^{-ikx}$$

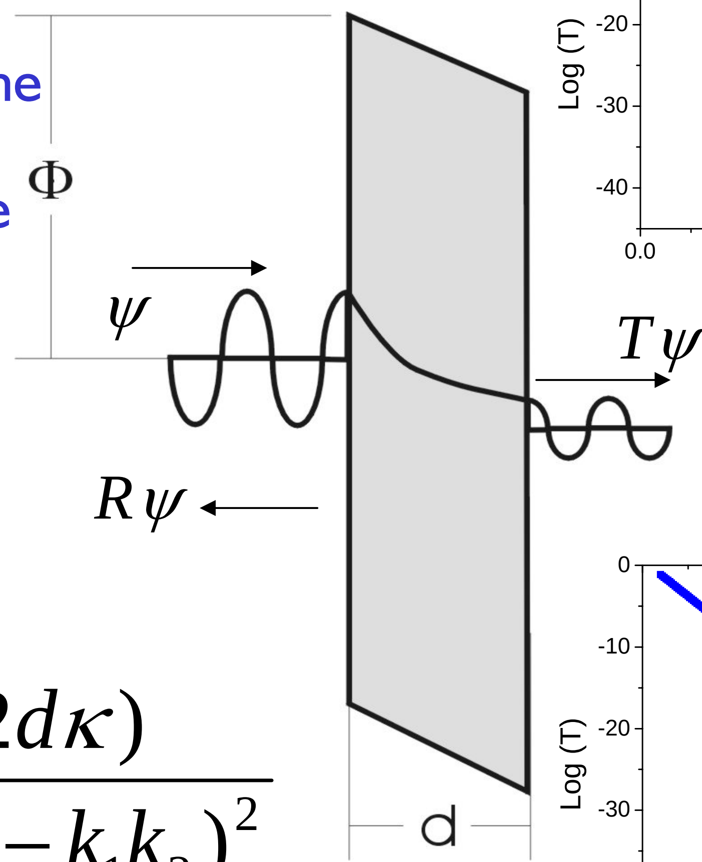
Flux transmission given by:

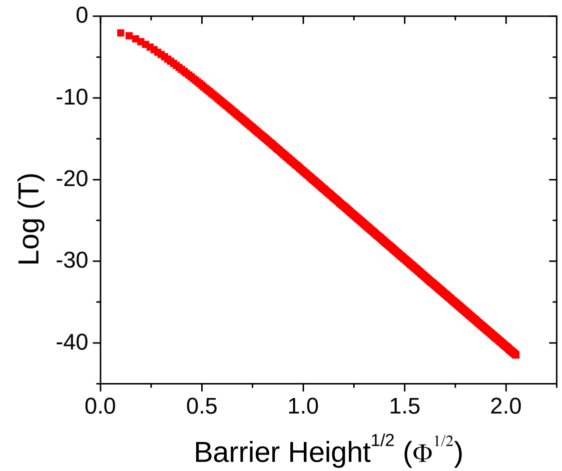
$$|T|^2 = \frac{(2k\kappa)^2}{(k^2+\kappa^2)^2 \sinh^2 2\kappa d + (2k\kappa)^2}$$

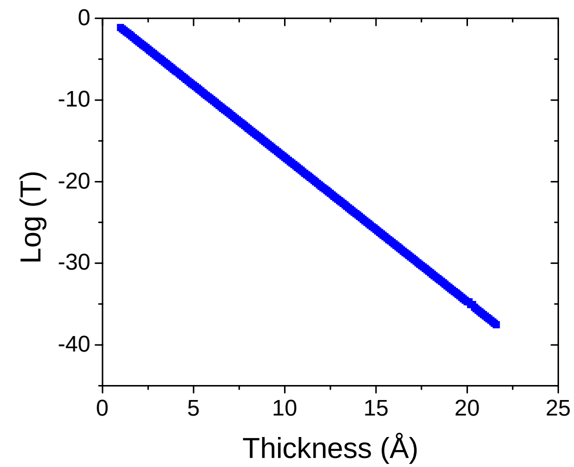
Tunneling Matrix elements

- Tunneling is a quantum mechanical phenomenon
- From basic quantum mechanics, the barrier height (Φ), width (d) and electron energy (k) determine the transmission probability

→ **Exponential decrease with barrier thickness and height**







$$T \sim \frac{16 k_1 k_2 \kappa \exp(-2d\kappa)}{[\kappa(k_1+k_2)]^2 + (\kappa^2 - k_1 k_2)^2}$$

$$\kappa = \sqrt{(2m/\hbar^2)(\Phi - E_f)}$$