Fabricated Magnetic Structures

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LECTURE 3

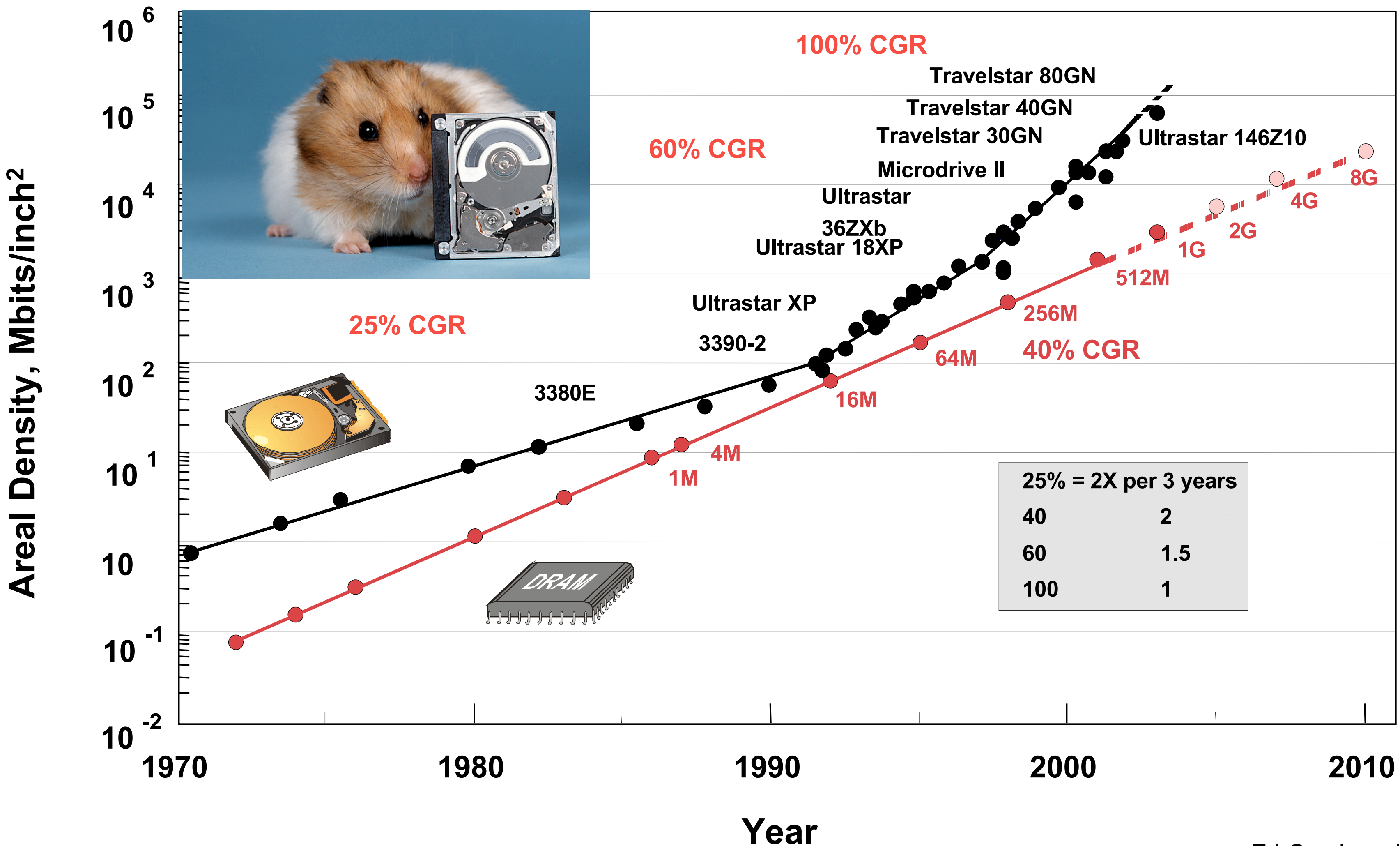
Magnetic Junction Devices

BOULDER SUMMER SCHOOL

Lectures on Fabricated Magnetic Structures

- Introduction
- Synthesis and fabrication techniques for magnetic structures
- Magnetic behavior in small magnetic structures
- Magnetic Junction Devices
  - Patterning of Junction Devices
  - Spin Polarization
  - Interfaces

Areal Density of Magnetic HDD and DRAM



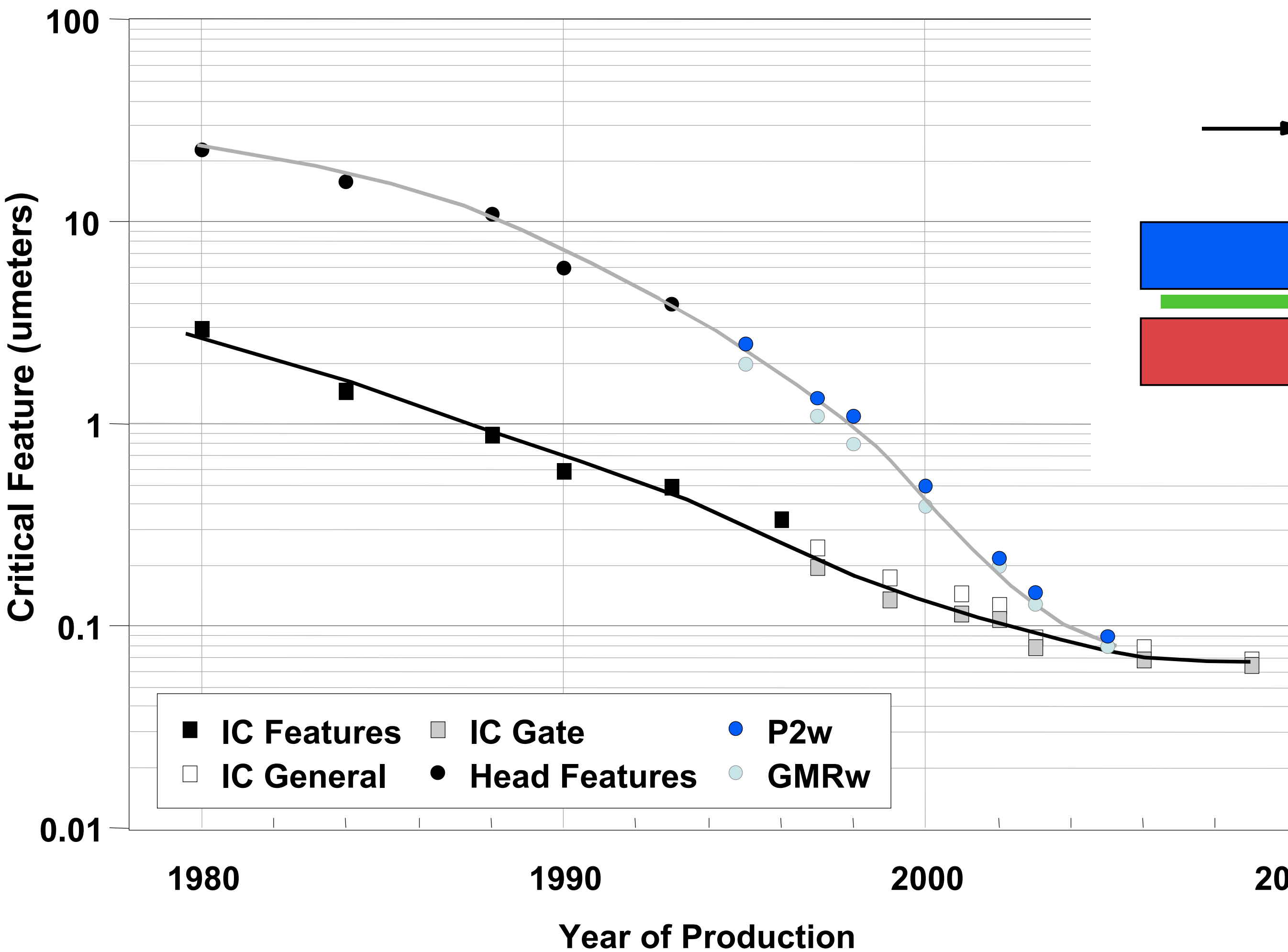
DRAM projections after 2001 are based on industry capacities and constant chip area

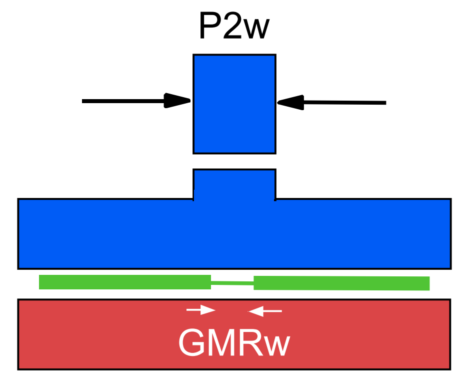
Ed Grochowski

BOULDER SUMMER SCHOOL

AREAL2002Eh.PRZ

Lithographic Critical Feature Roadmap for GMR Heads and Semiconductor IC



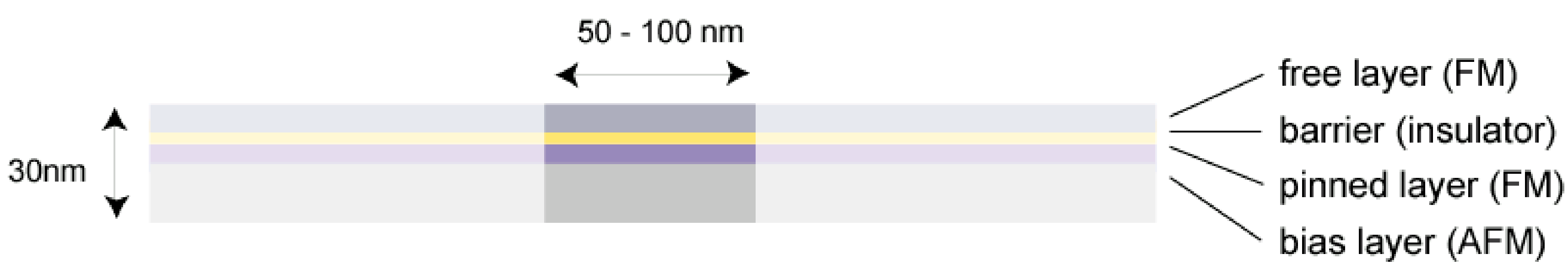


Robert Fontana

Linewidth2002c.prz

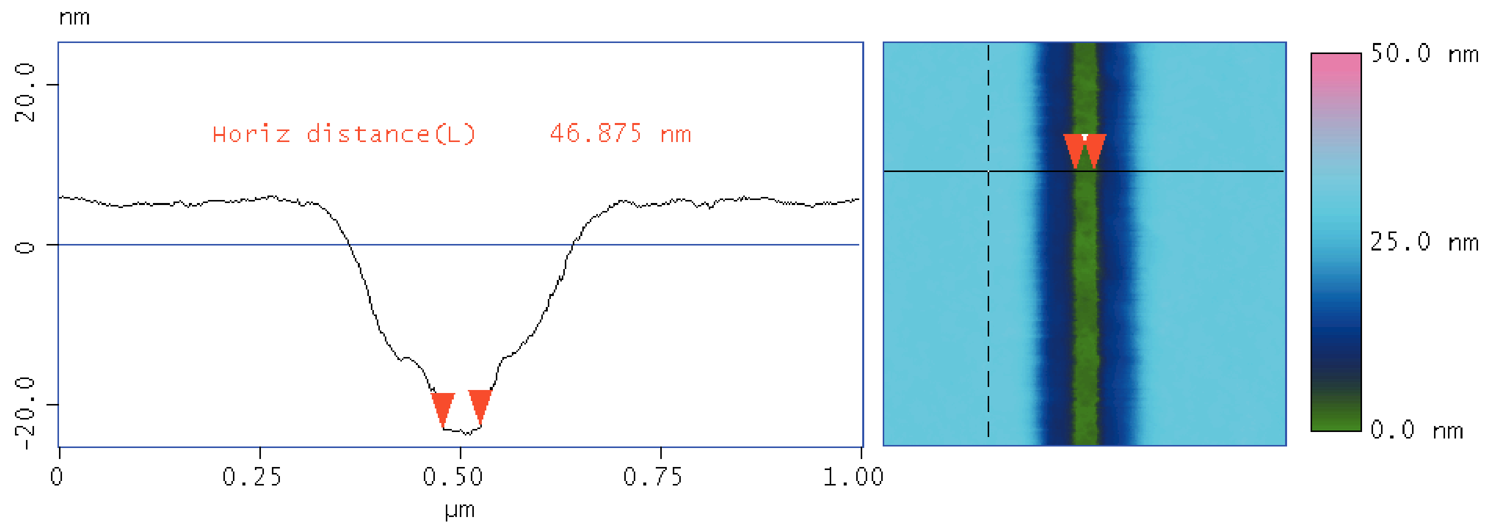
Fabricating Magnetic Heterostructures with length scales below 100nm

- lithographic processes to create small structures from continuous
  magnetic multilayers
  - optical lithography, incl. DUV
  - e-beam lithography
  - Au particles as milling masks



Liesl Folks
HGST

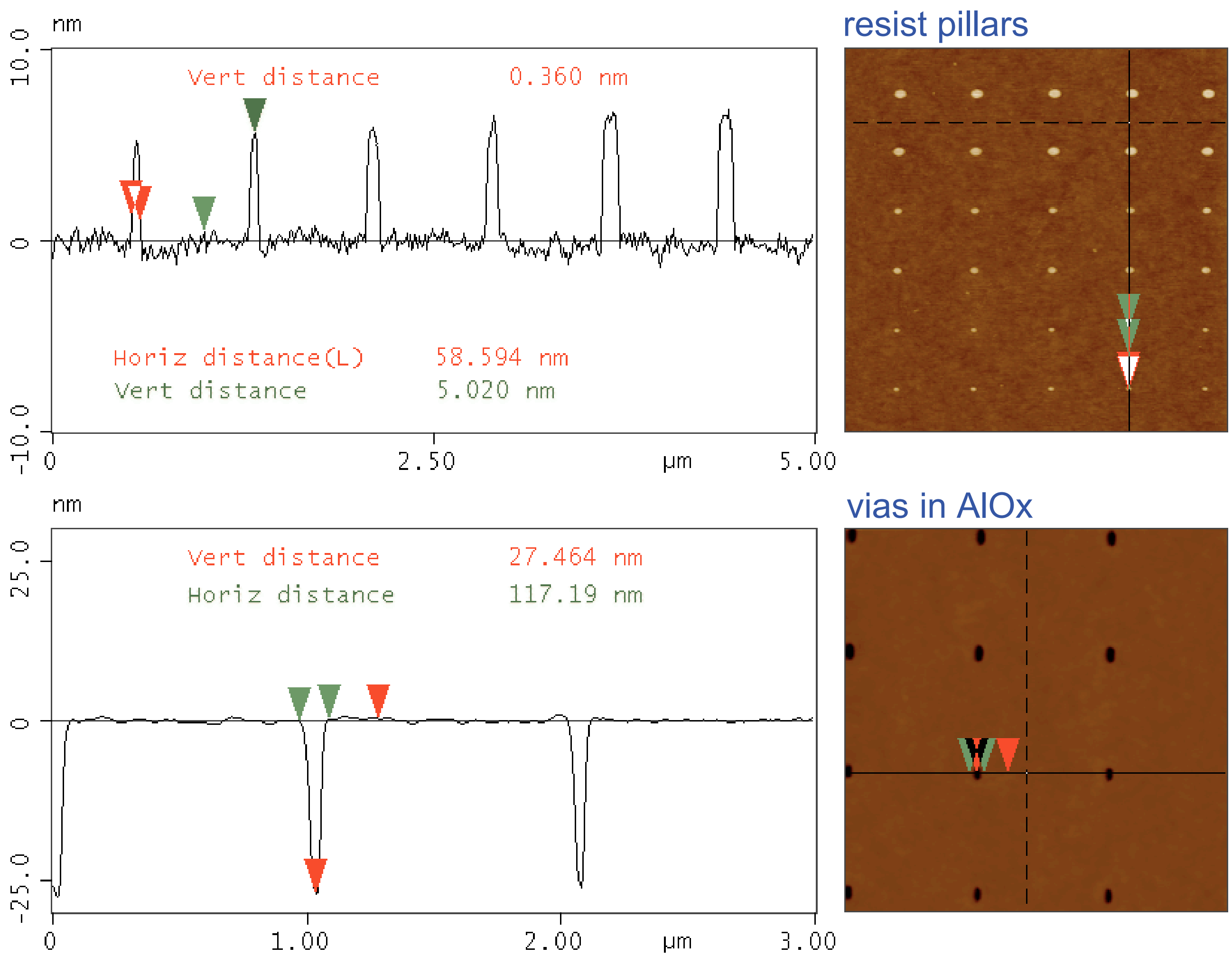
Deep UV lithography



- manufacturable, but slow and expensive
- not good for materials testing

Marie-Claire Cyrille
HGST

e-beam Lithography

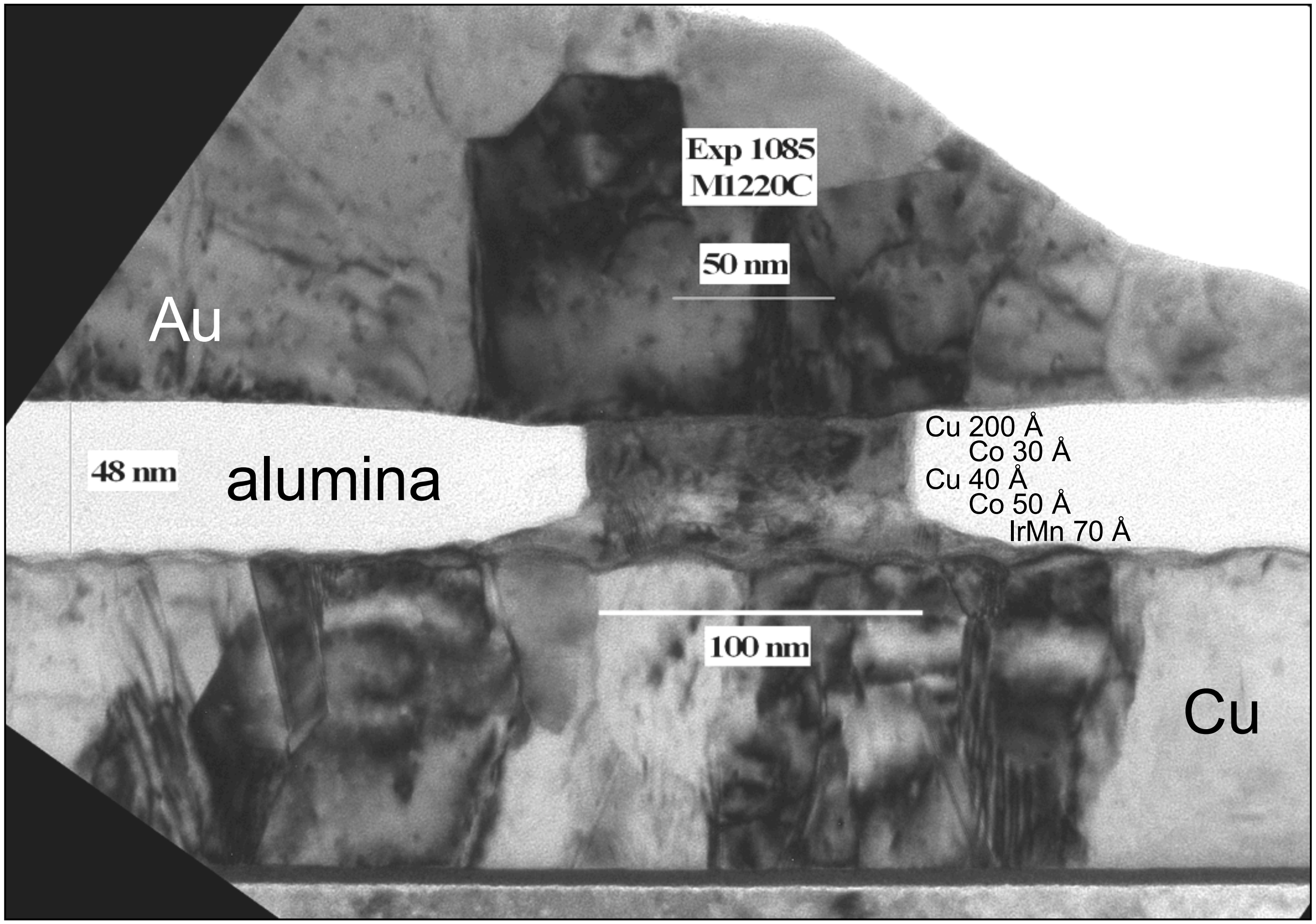


- fast, expensive, very effective

Jordan Katine

HGST

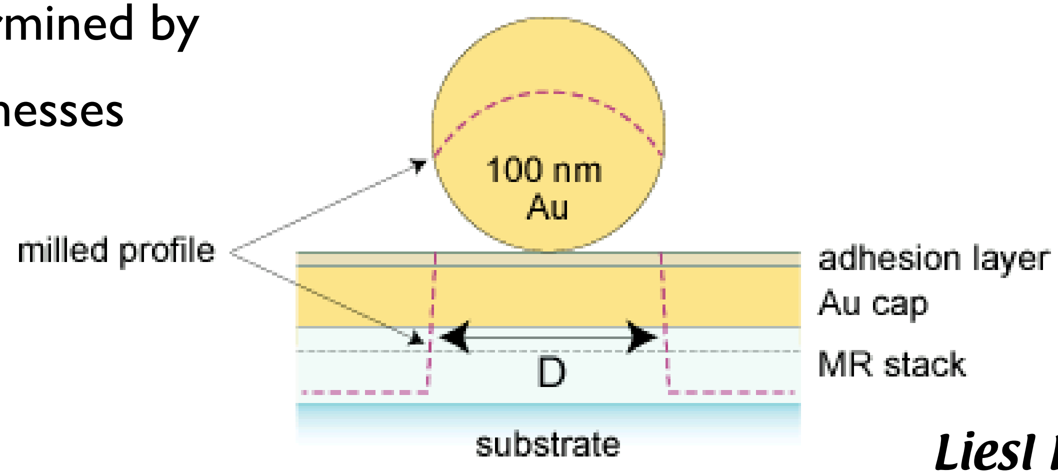
TEM Cross-section of Spin-transfer Device



Jordan Katine
HGST

Au spheres as milling masks for creating small pillars

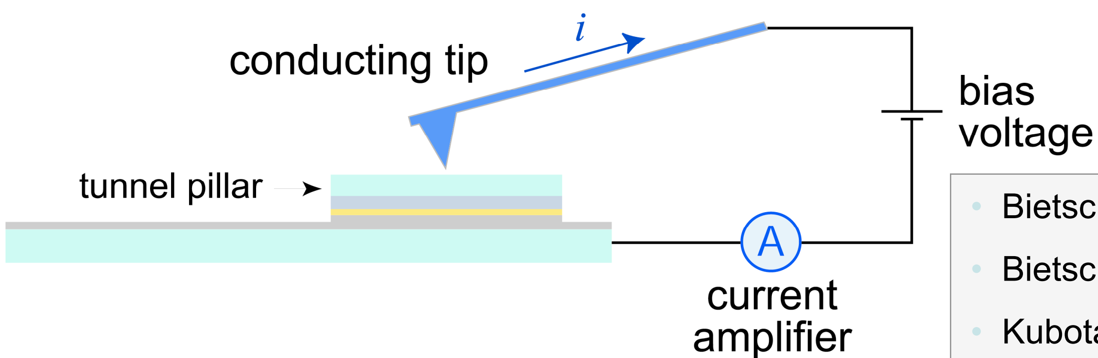
- rapid process for pillar formation:
  - attach gold particles (50 - 150 nm) to Au-coated full-film CPP sample
    - Lewis et al., JVST B **16** (1998) 2938
  - ion mill into MR stack to define pillars
  - lift off Au particles
- minimum diameter determined by layer mill rates and thicknesses



Liesl Folks
HGST

Scanning Imaging/Conductance Probe

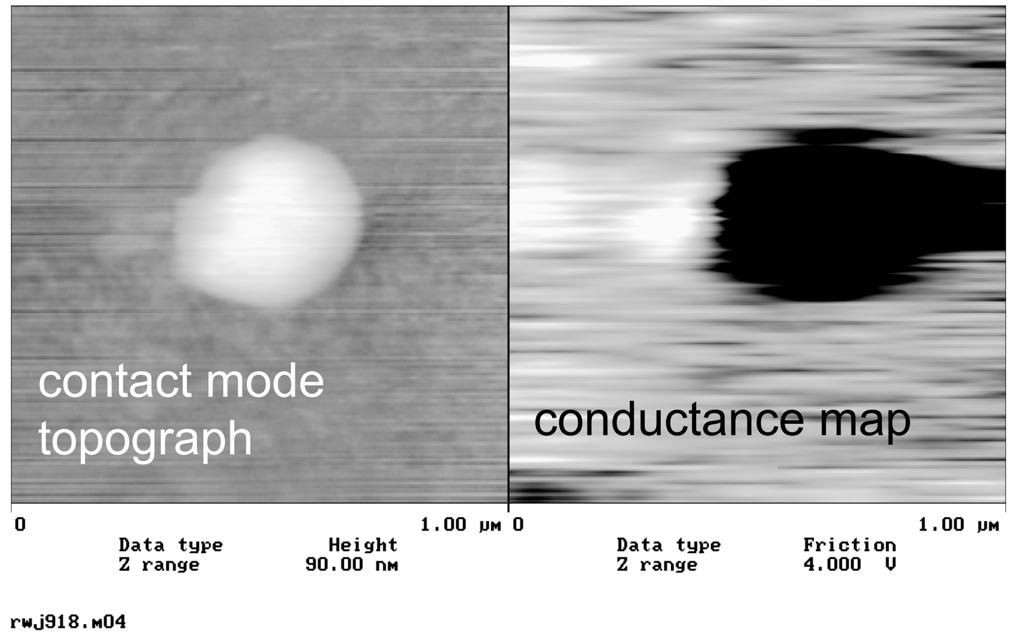
- imaging of pillars (tapping or contact mode AFM)
- IV curves measured with stationary conducting probe
- tunnel magnetoresistance TMR curves measured with conducting AFM (c-AFM) in applied fields
    - require contact + lead resistance < 100 Ω
    - ideally, contact + lead resistance << 100 Ω
- conductance maps with c-AFM

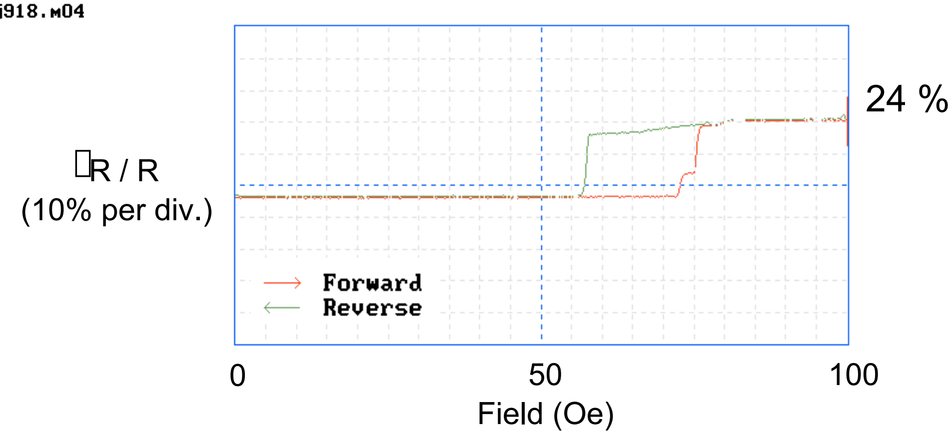


- Bietsch et al., JVST B **18** 1160 (2000)
- Bietsch & Michel, APL **80** 3346 (2002)
- Kubota et al., Jpn. JAP **41** L 180 (2002)
- Worledge & Abraham, APL 82 4523 (2003)

AlO_x MTJ pillar

- good contact (R = 50 W) on exposed PtMn surface
- pillar resistance R_J = 650 W
  RA = R_J * 0.05 = 32 W mm^2
- TMR loop recorded during 30 second field sweep
- c.f. properties measured by conventional means:
  TMR = 20% and RA = 25 W mm^2

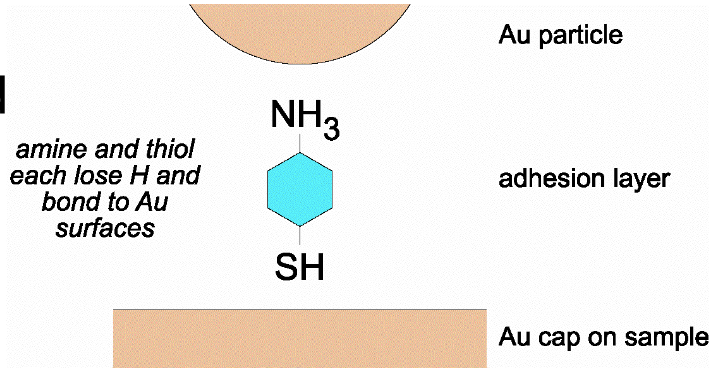


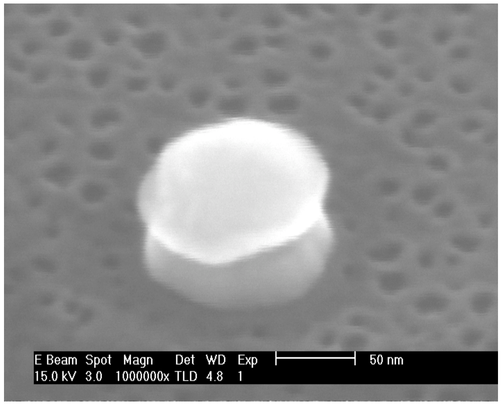


Liesl Folks
HGST

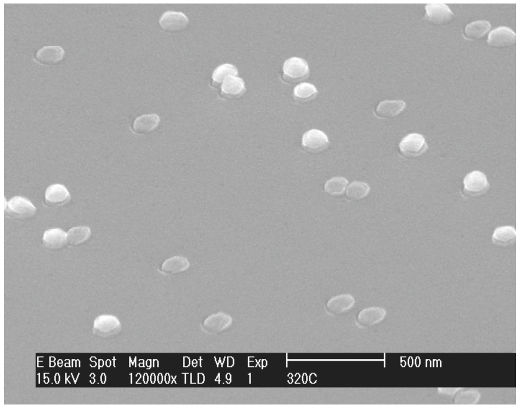
Au Bead Patterning Technique

- Attach Au spheres by decorating CPP magnetic films with colloidal gold particles by immersion into aqueous suspension
- Use bifunctional molecular linkers to attach particles to surface
- Ar ion milling



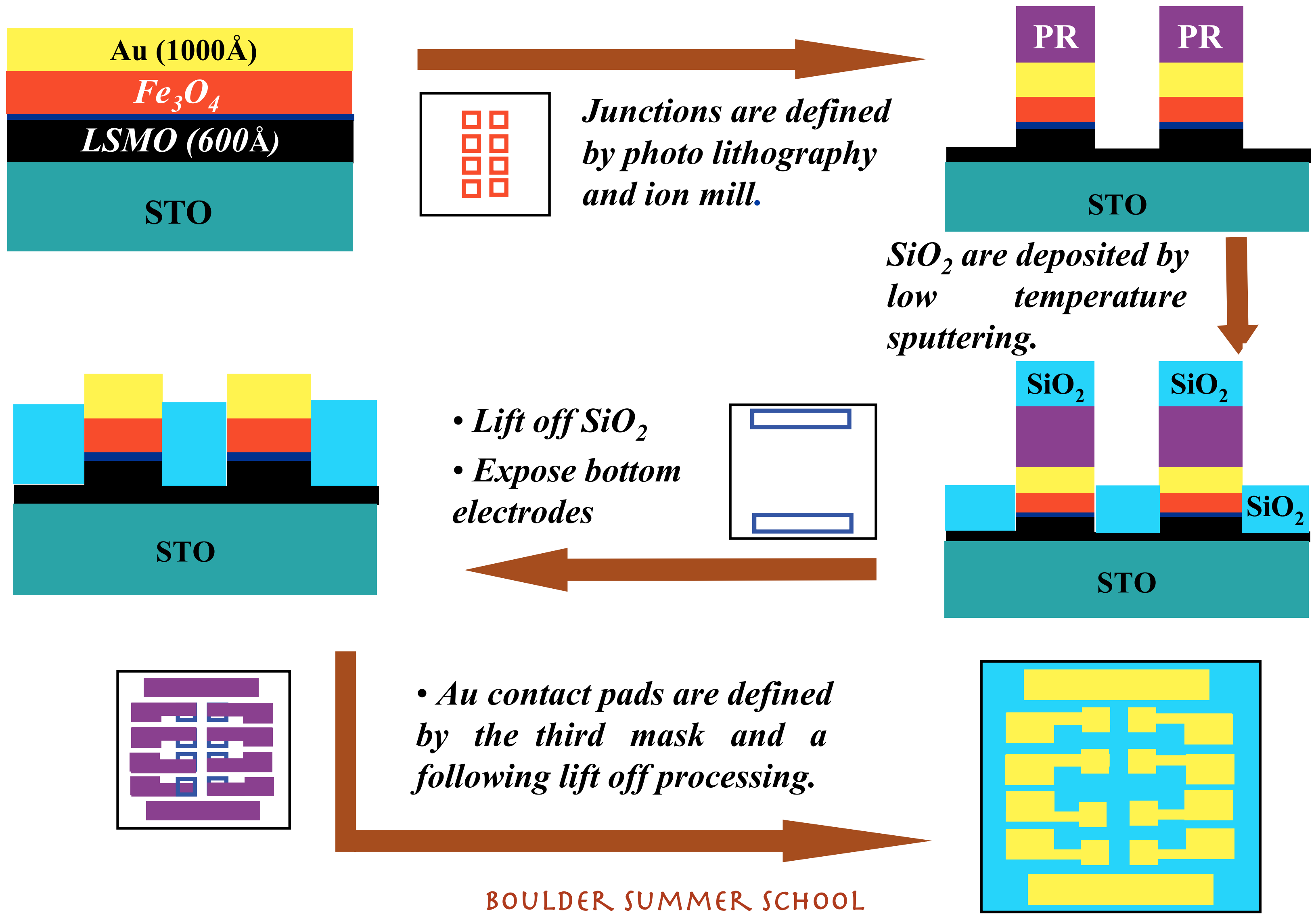


- AlOx overcoat and subsequent Au lift-off



Liesl Folks
HGST

Fabrication of Magnetic Junctions

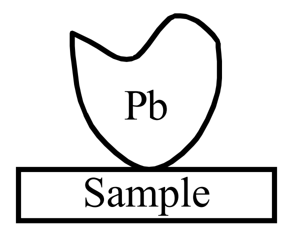


Spin Polarized Thin Film Materials

Material studied	Point	Base	N	P_T (%)	P_C (%)
NiFe	Nb	$Ni_{0.8}Fe_{0.2}$ film	14	25 ± 2	37 ± 5
Co	Nb	Co foil	7	35 ± 3	42 ± 2
Fe	Ta	Fe film	12	40 ± 2	45 ± 2
	Fe	Ta foil	14		46 ± 2
	Nb	Fe film	4		42 ± 2
	Fe	V crystal	10		45 ± 2
Ni	Nb	Ni foil	4	23 ± 3	46.5 ± 1
	Nb	Ni film	5		43 ± 2
	Ta	Ni film	8		44 ± 4
NiMnSb	Nb	NiMnSb film	9	–	58 ± 2.3
LSMO	Nb	$La_{0.7}Sr_{0.3}MnO_3$ film	14	–	78 ± 4.0
CrO_2	Nb	CrO_2 film	9	–	90 ± 3.6

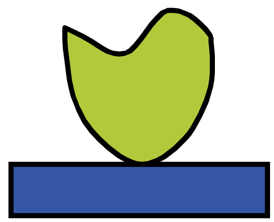
Soulen *et al.*, Science 282, 85 (1998).

Spin polarization as measured by Andreev reflection



Spin Polarization

Andreev Reflection



superconductor

spin polarized material

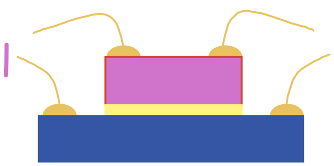
S-I-F junction

superconductor

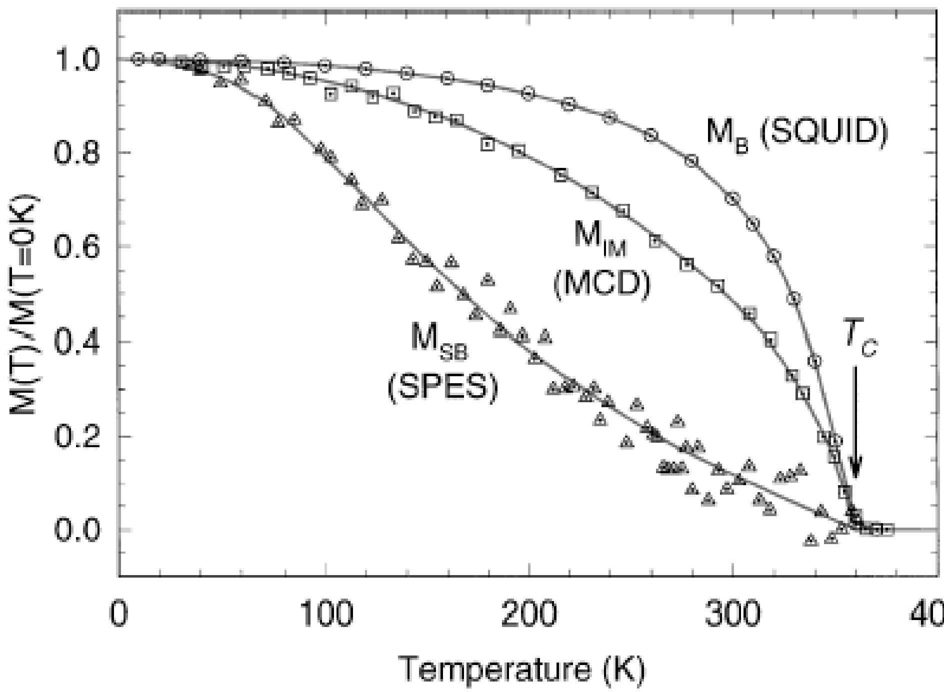
spin polarized material

spin polarized material

F-I-F' junction



Magnetism at Surfaces and Interfaces



Bulk, intermediate length scale (50Å) and surface (5Å)magnetization are probed by SQUID, magnetic circular dichroism and spin polarized photo-emission. Park et al. PRL 81 1953 (1998)

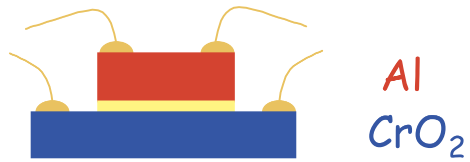
- intrinsic nature of ferromagnetism at surfaces and interfaces

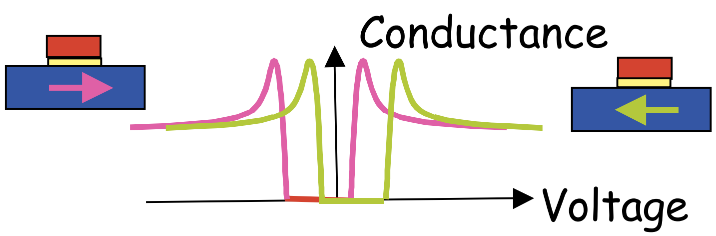
- surface/interface roughness
- magnetic domain walls
- electrode quality
- barrier quality
- interface quality

Spin Polarization of CrO_2

- Meservey-Tedrow junctions

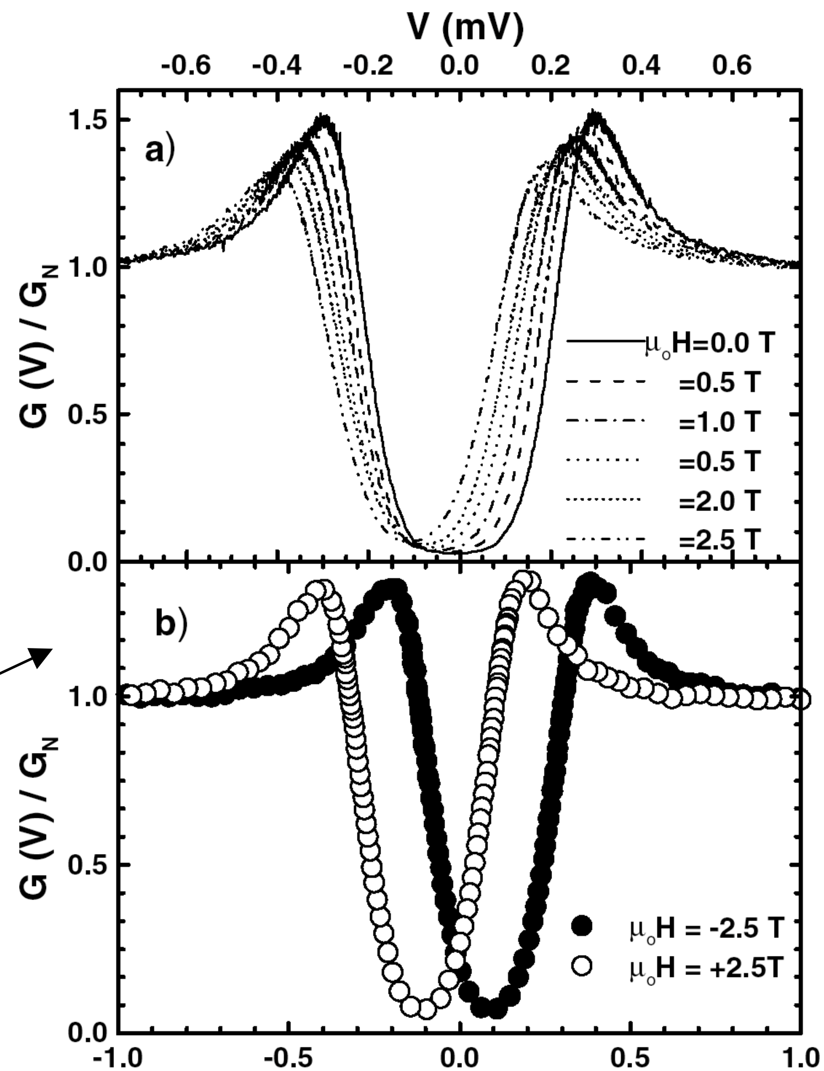
(superconductor-insulator-ferromagnet)





*Parker et al. PRL **88** 196601 (02)*

P=90-94%



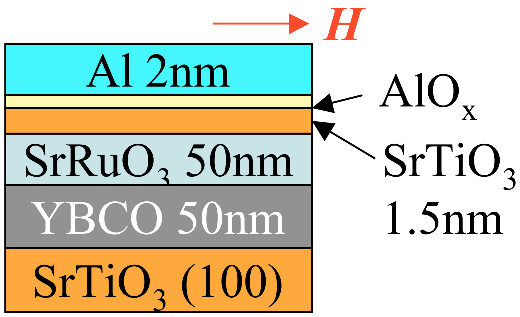
- Point contact Andreev reflection

*Ji et al. PRL **86** 5585 (01)*

P=96%

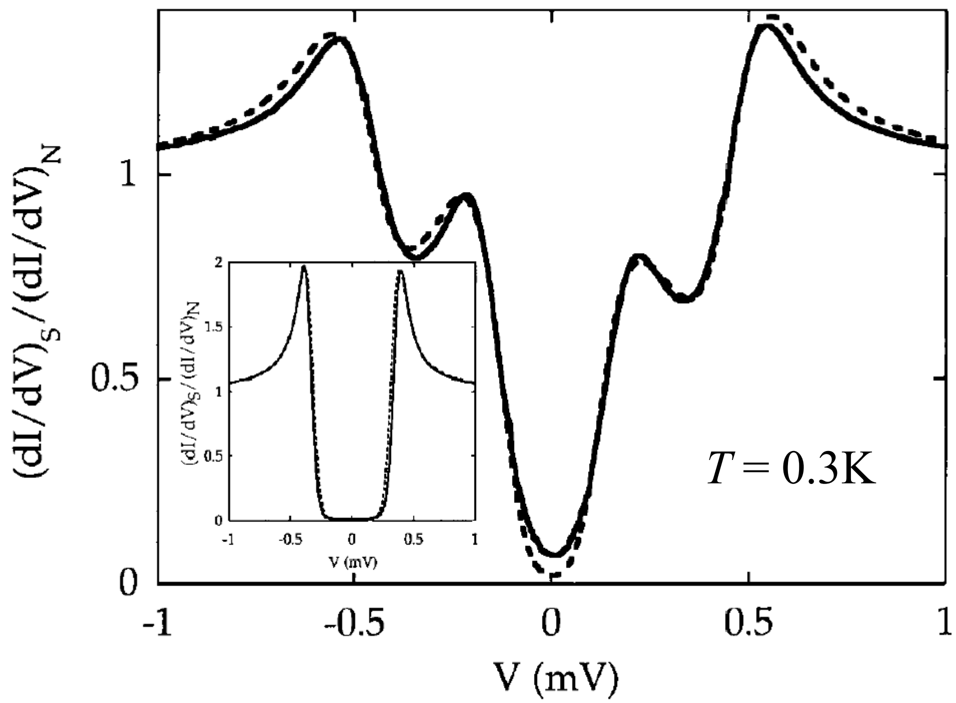
Spin Polarization of $SrRuO_3$

- Negatively spin-polarized $SrRuO_3$:



P = -0.095

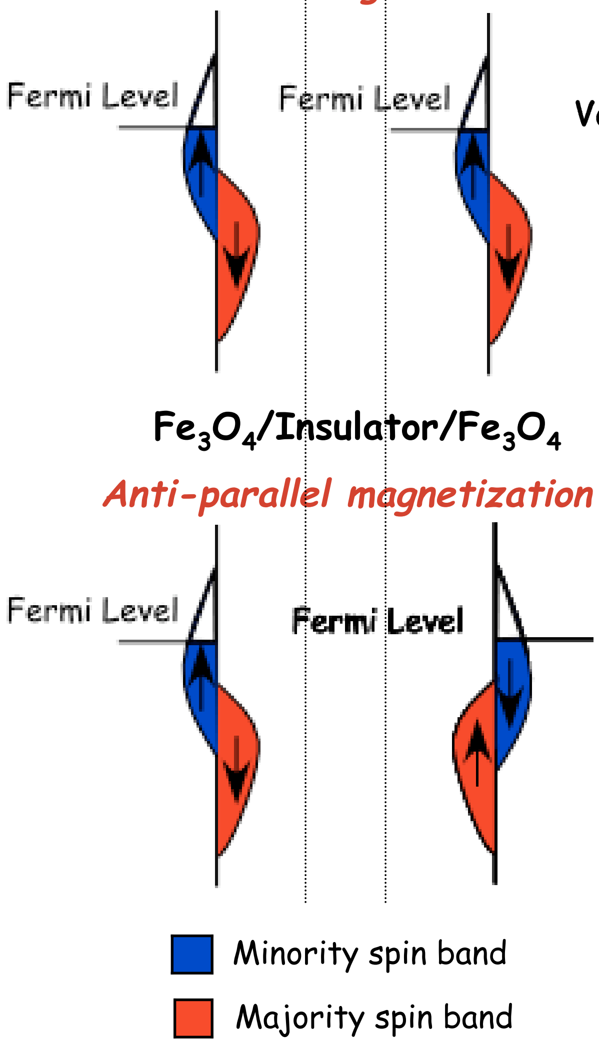
- A weak negative spin polarization.

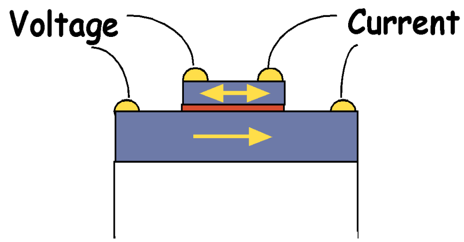


D. C. Worledge and T. H. Geballe, PRL 85, 5182 (2000)

Magnetic Tunnel Junctions (MTJ)

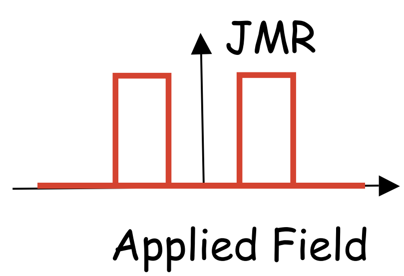
Parallel magnetization





Junction magnetoresistance……

$$JMR = \frac{R_{AP}-R_P}{R_{AP}}$$



Tunnel resistance

$$\square_P = 1/R_P \ \mu \ N_{1\uparrow}N_{2\uparrow} + N_{1\downarrow}N_{2\downarrow}$$

$$\square_{AP} = 1/R_{AP} \ \mu \ N_{1\uparrow}N_{2\downarrow} + N_{1\downarrow}N_{2\uparrow}$$

$N\uparrow$, $N\downarrow$ --- densities of majority and minority spin states at Fermi level

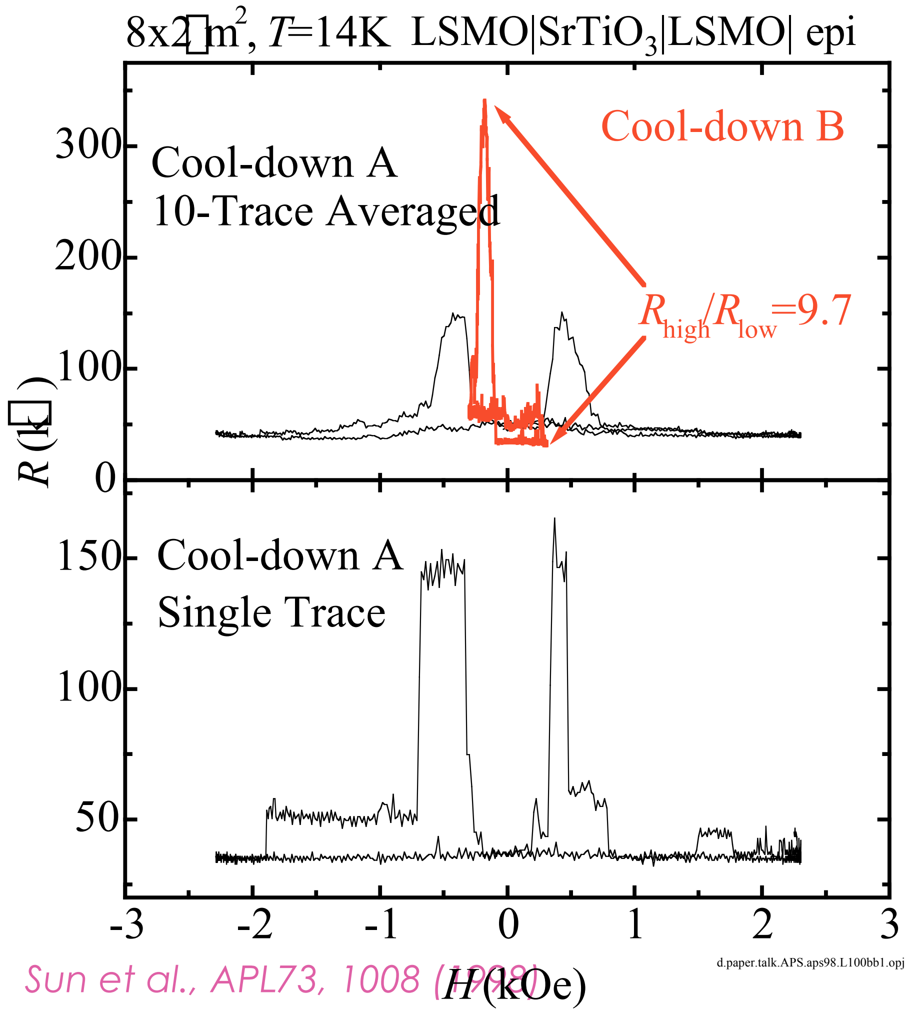
Degree of spin polarization

$$P = \frac{N\uparrow - N\downarrow}{N\uparrow + N\downarrow}$$

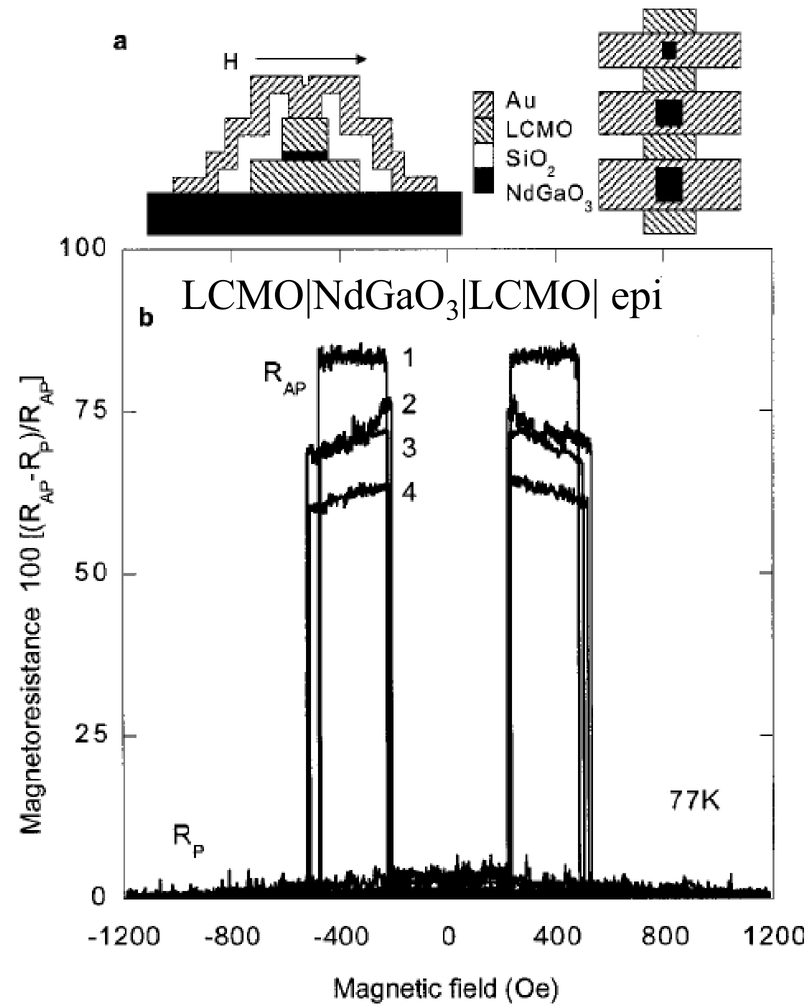
$$JMR = \frac{R_{AP} - R_P}{R_{AP}} = \frac{2P_1P_2}{1+P_1P_2}$$

For half metals where P=1, JMR=1 !

Manganite Junctions



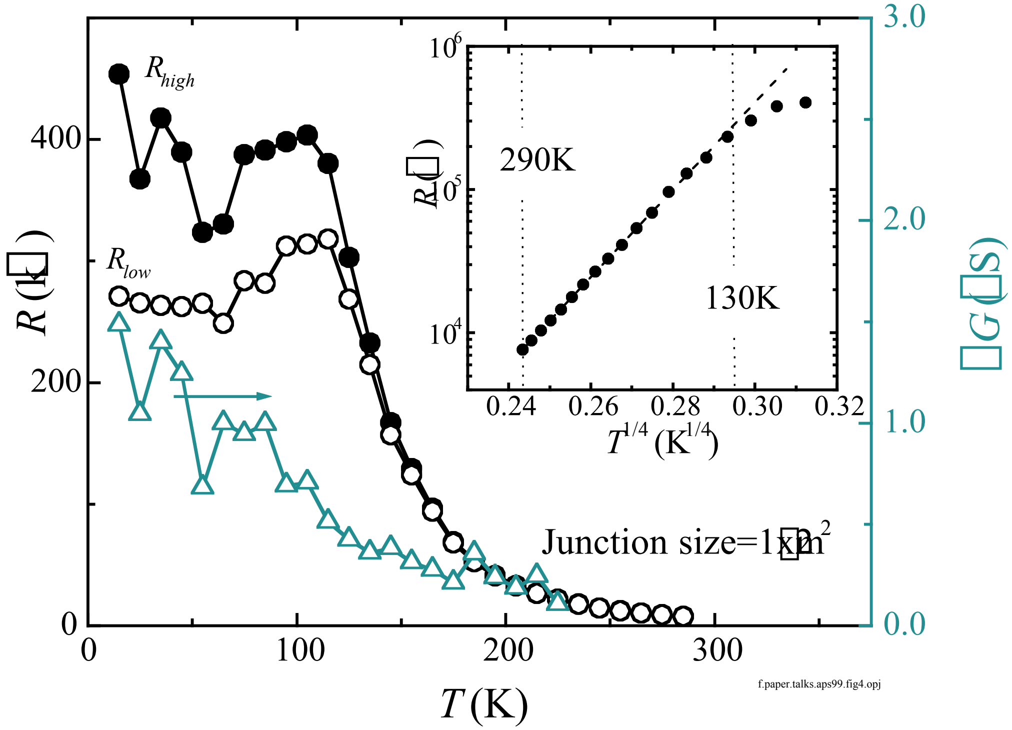
Sun et al., APL73, 1008 (1998)

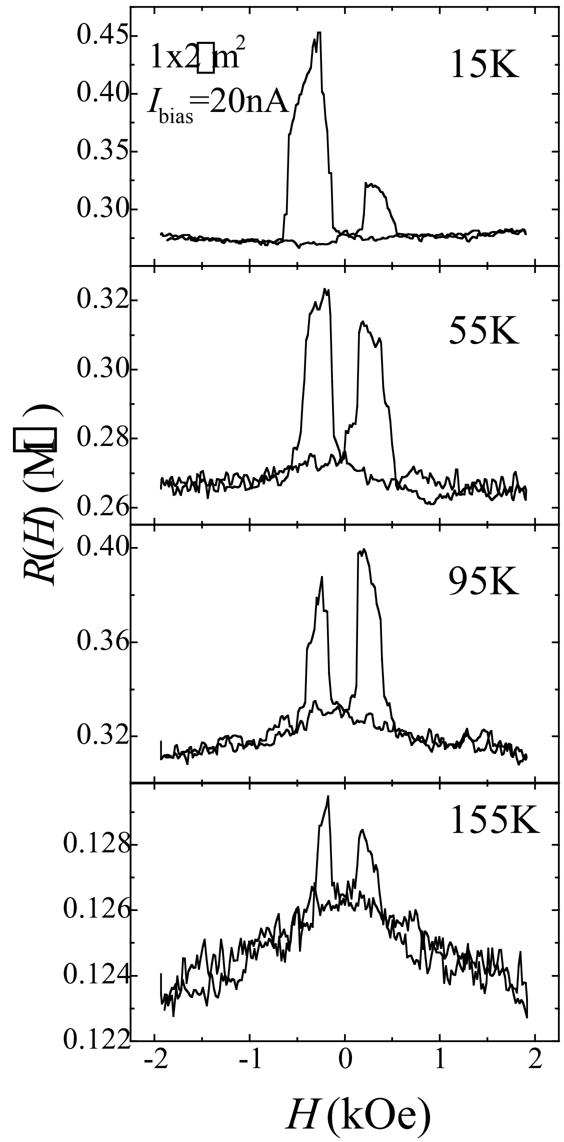


Jo et al., PRB61, R14905 (2000)

Manganite Junctions

Strong decrease of MR upon increasing *T*.



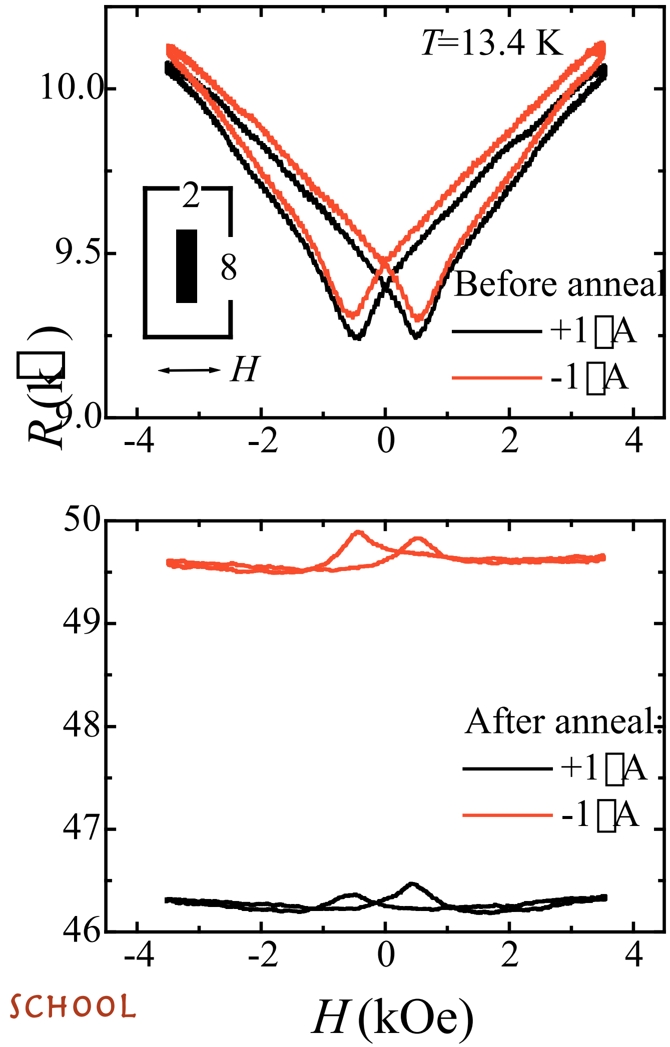


Sun et al., APL ***73****, 1008 (1998)*

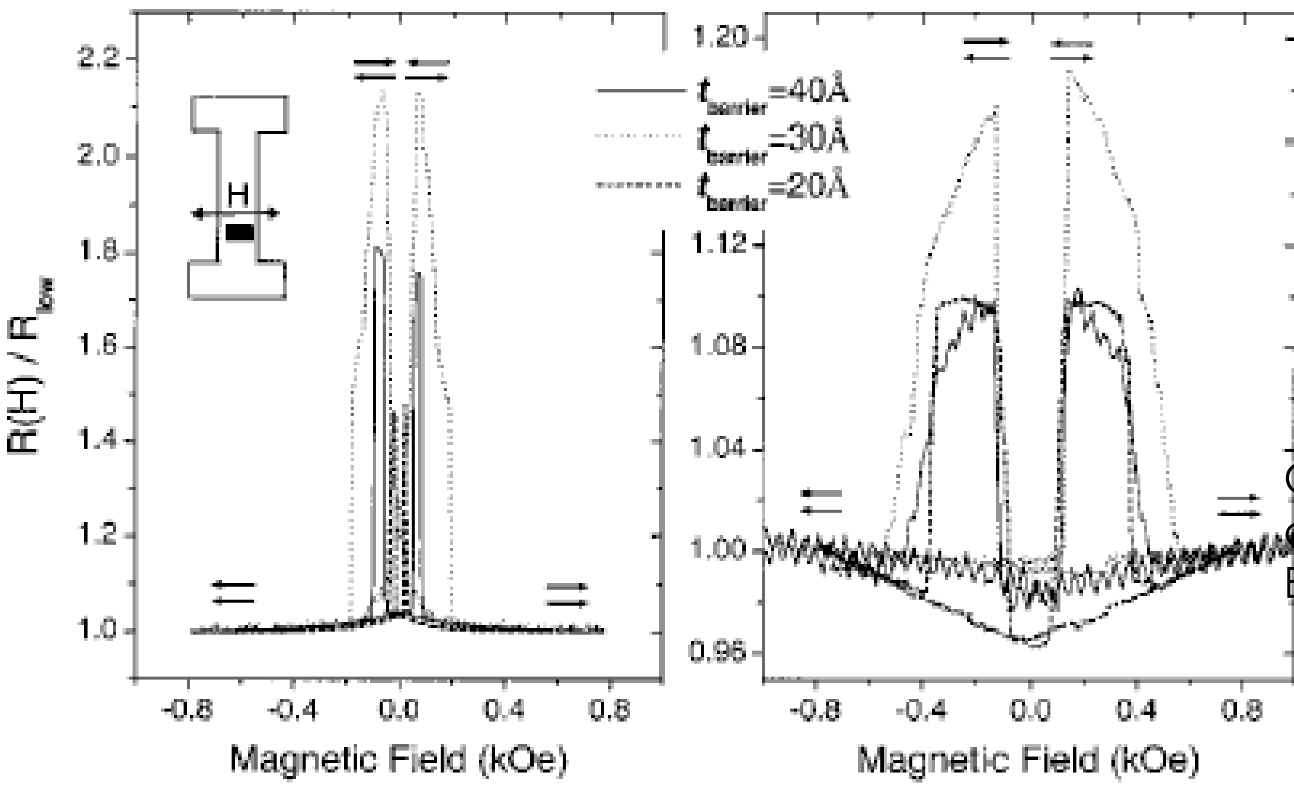
Interface Stability

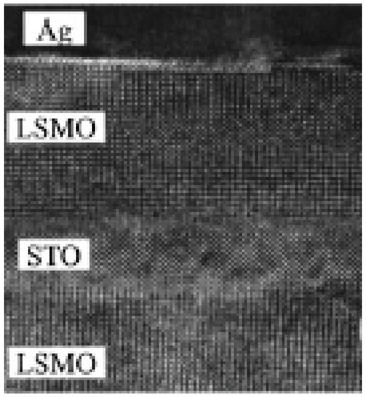
- LSMO/STO/Fe junction
- Before/after 220C/15min:
  - 5´ increase of R_J.
  - Becomes asymmetric
  - ***MR changes sign!***
- Junction interface unstable against moderate heat treatment.
- Interface FeO_x formation!

J. Z. Sun, et al., PRB 61 11244 (2000)



Manganite Junctions

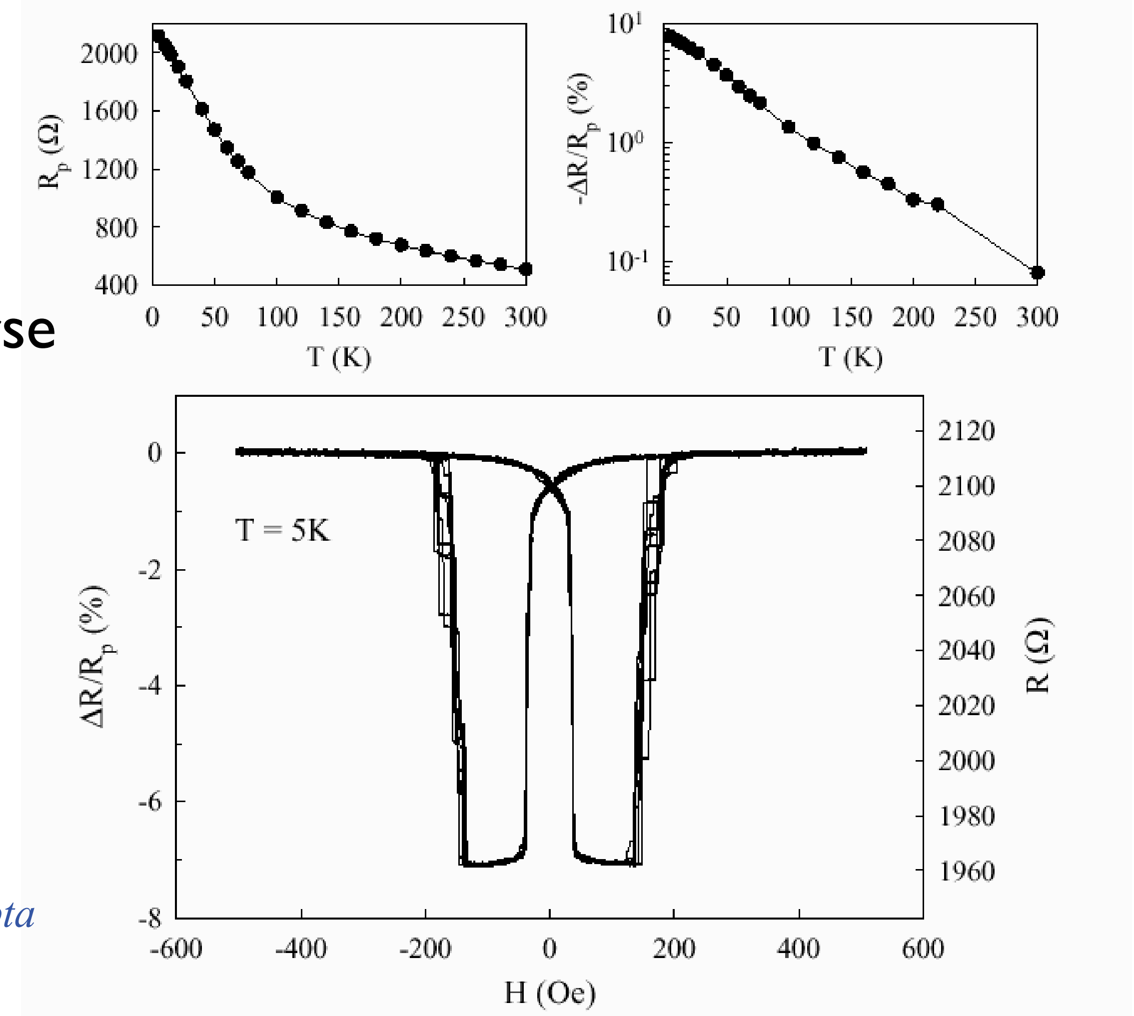




Cross-sectional TEM of junction 30Å $SrTiO_3$ Barrier.

*Noh et al. APL **79** 234 (01)*

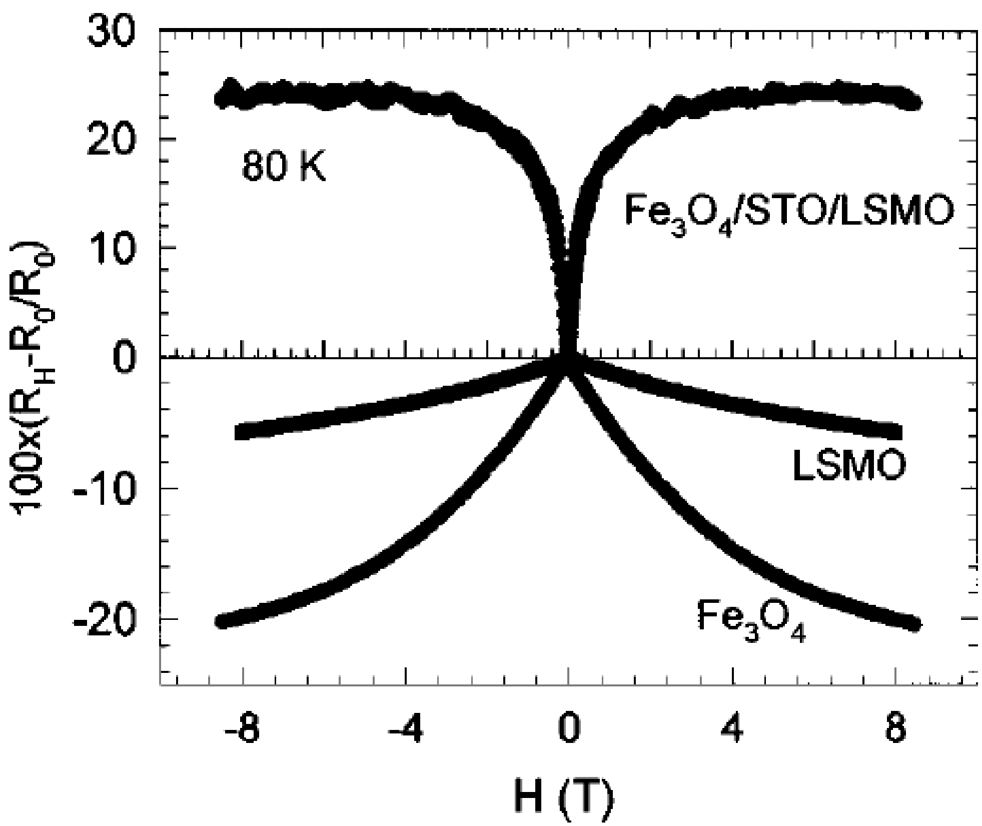
CrO_2 | Natural barrier | Co trilayers

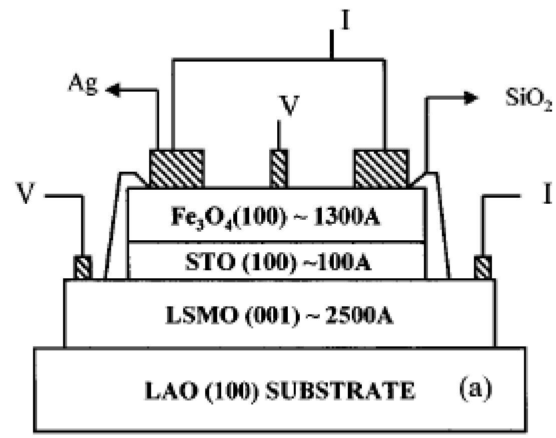


- Observation of an inverse magnetoresistance

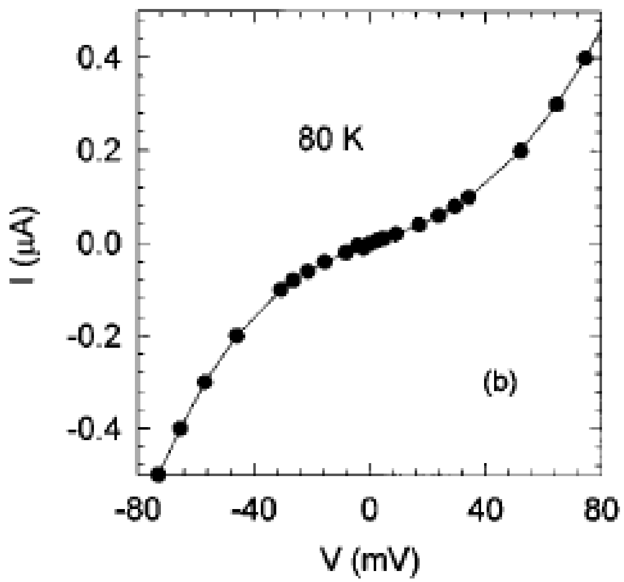
X. W. Li, Ph. D. Thesis, 1999 (Brown Univ. w. Prof. Gang Xiao and A. Gupta at IBM).

$Fe_3O_4/SrTiO_3/(La,Sr)MnO_3$ Junctions



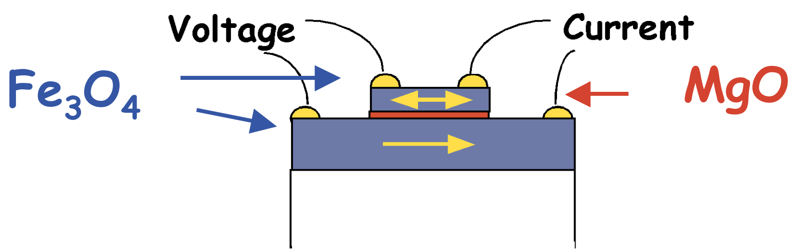


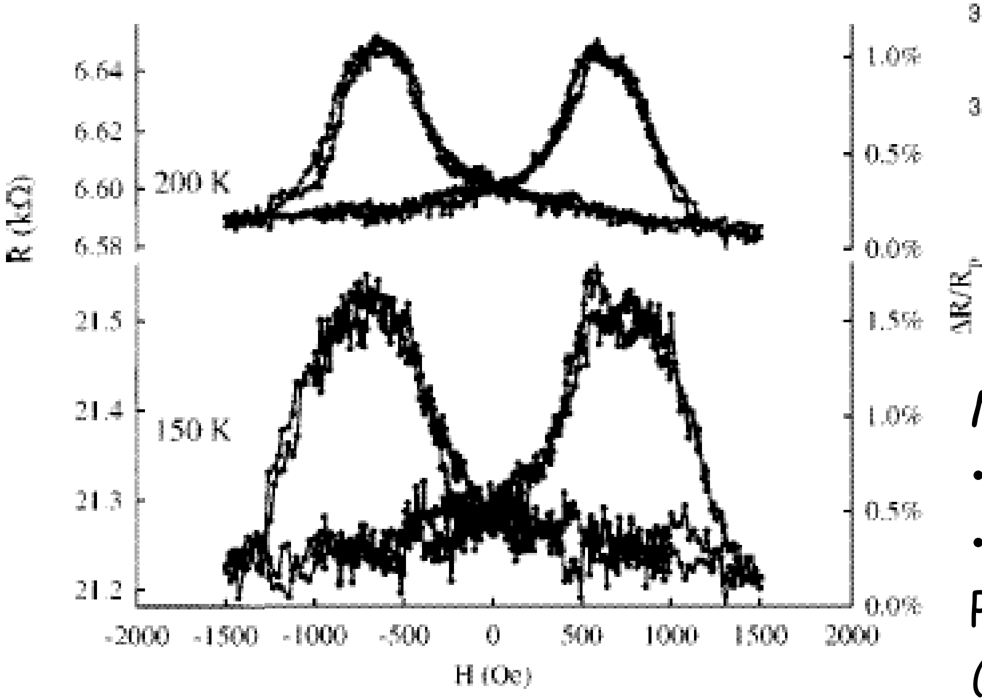
CPP-MR measurement configuration



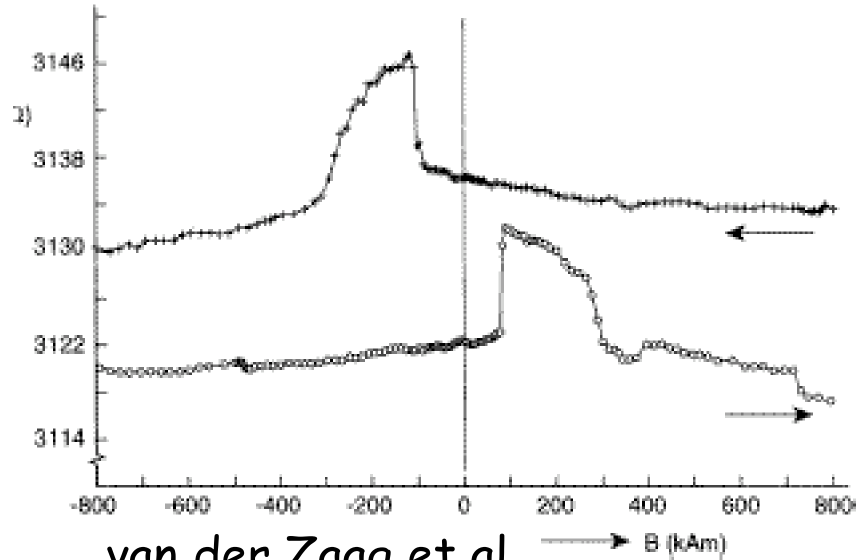
Ghosh et al., APL 73, 689 (1998).

Fe_3O_4 based Epitaxial Oxide MTJs





Li et al. APL **73** 3282 (1998)



van der Zaag et al.
JMMM **211** 301 (2001)

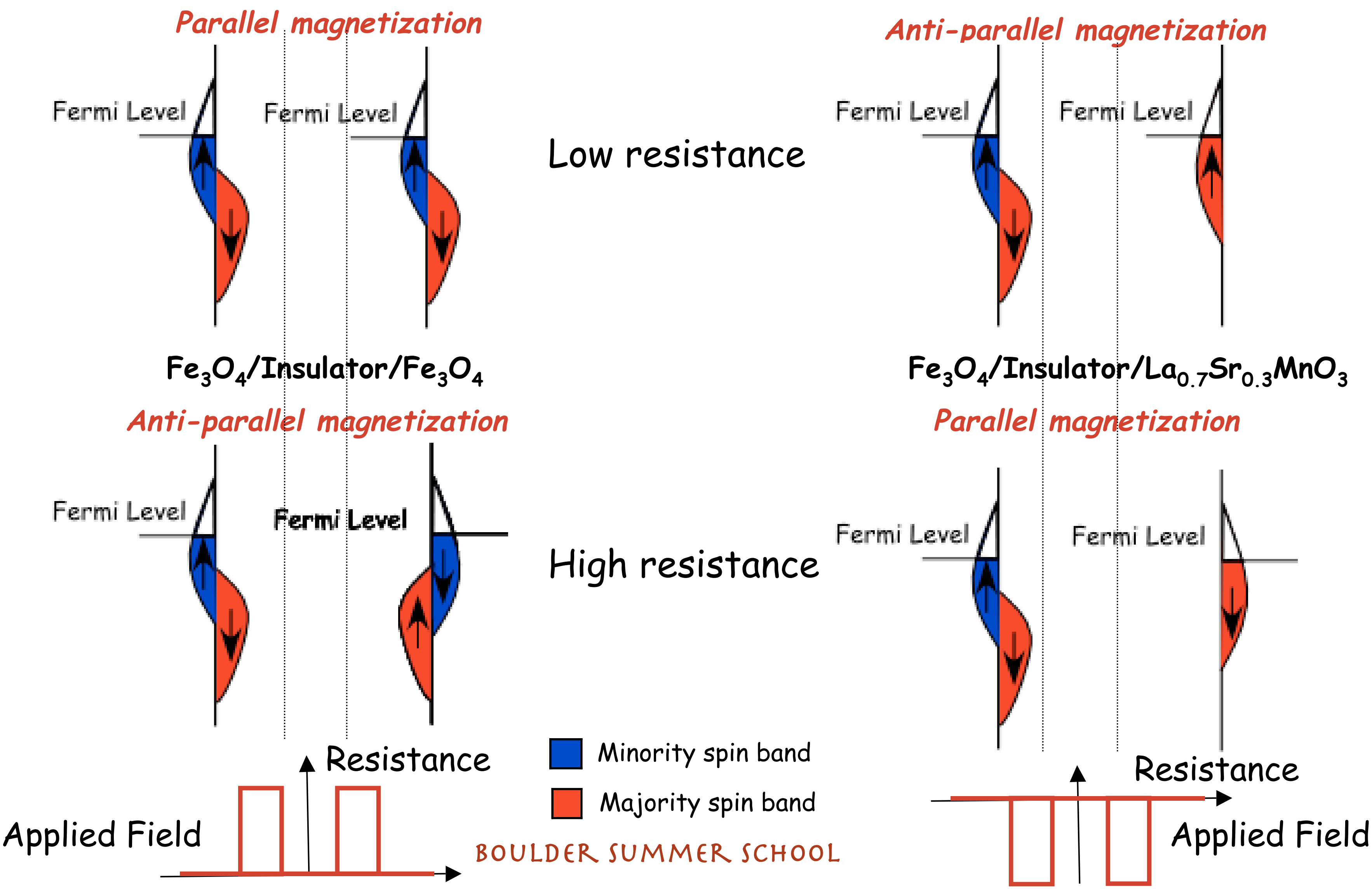
MR of 1.5% at 150K and <1% at 190K

- small coercivity difference
- tunnel barrier choice

Poly Fe_3O_4 junctions
(Panchula et al. unpublished)

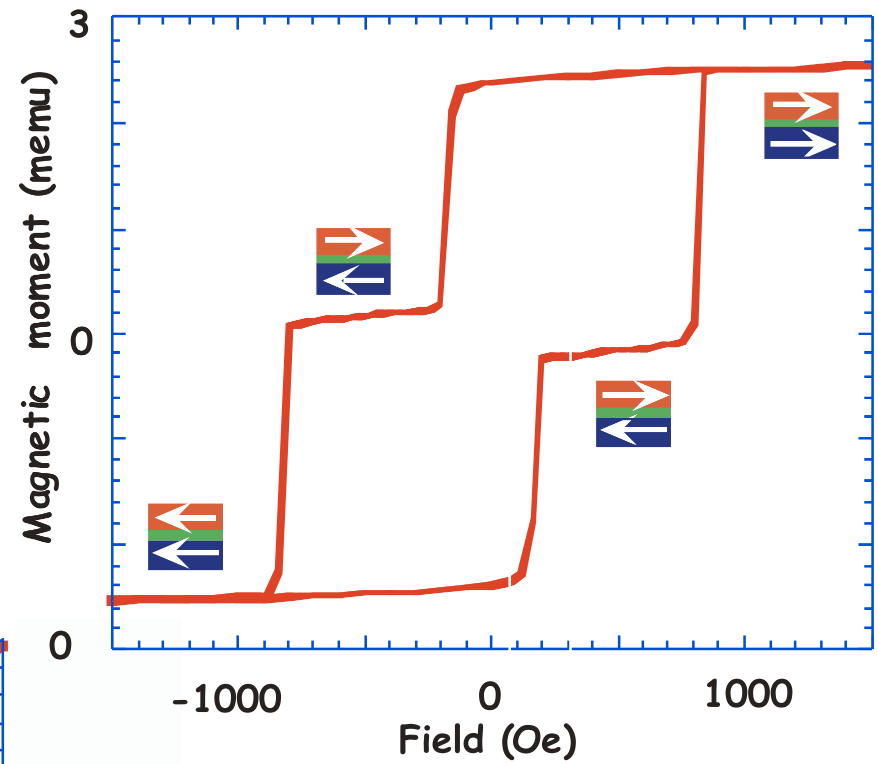
- JMR= -44% at low T

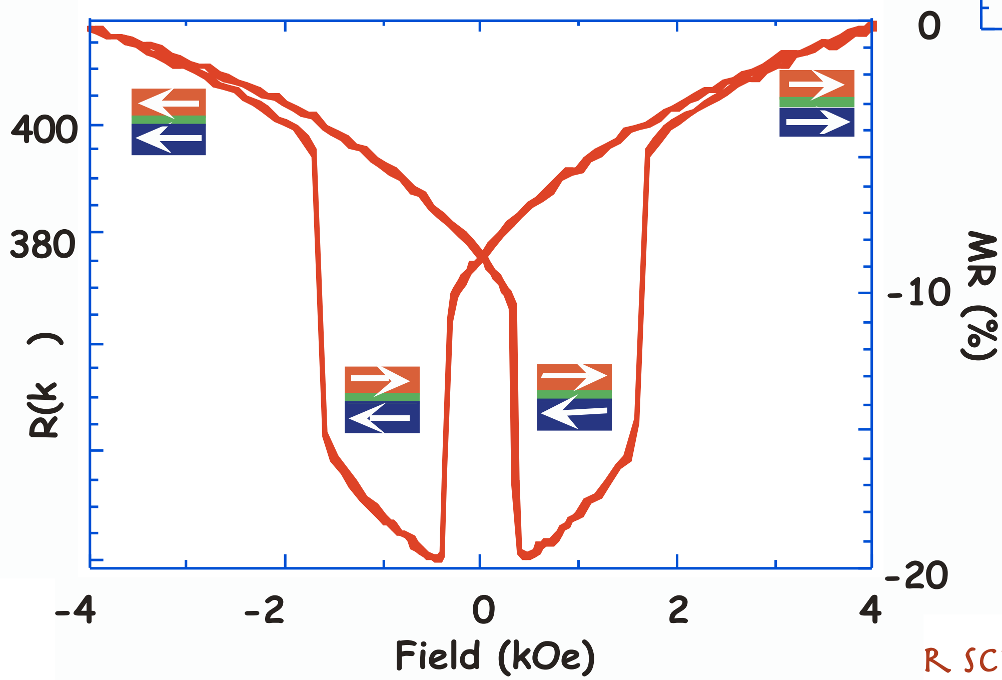
Magnetic Tunnel Junctions (MTJ)

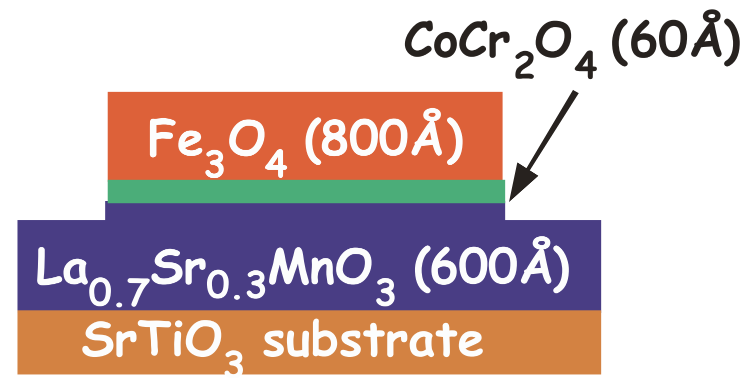


Magnetoresistance and Magnetics in Oxide Junctions

- well defined parallel and antiparallel states
- magnetoresistance as high as 30%







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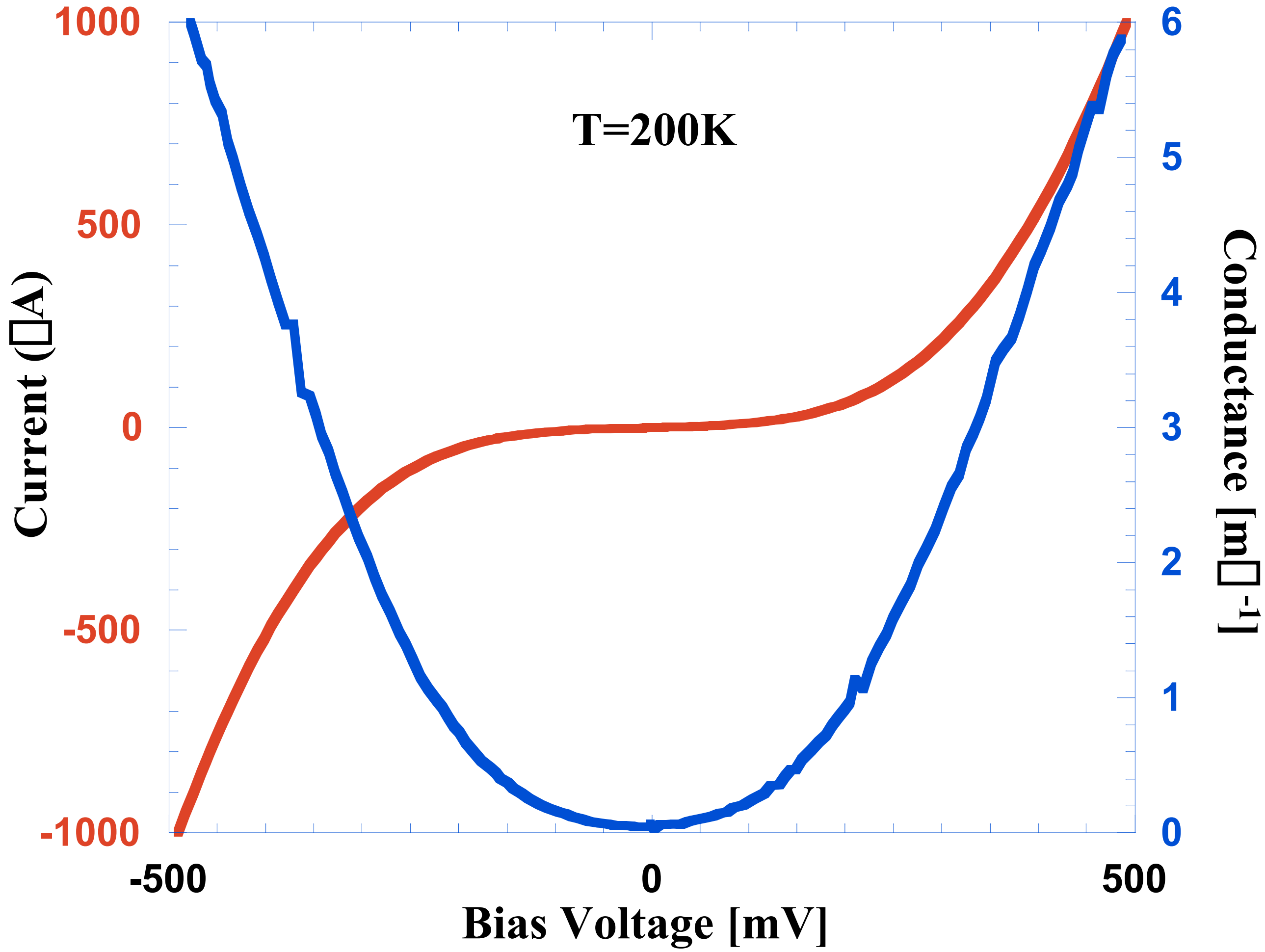
I-V characteristics of the MTJ

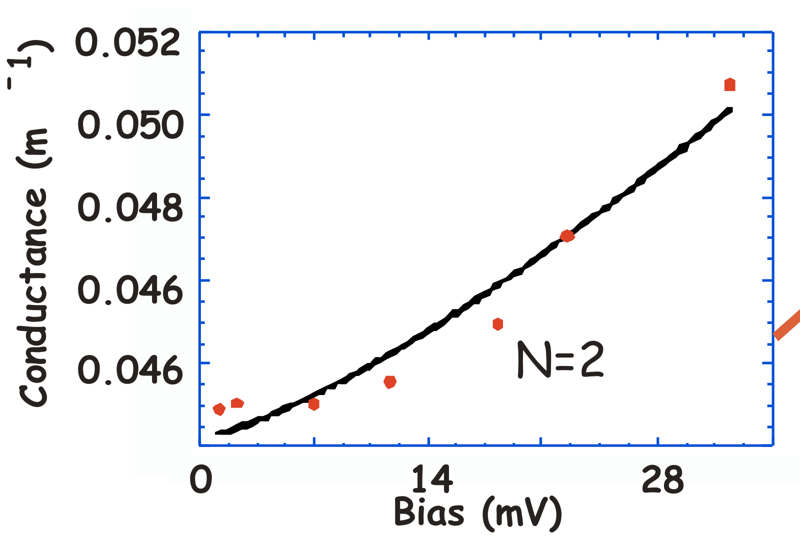


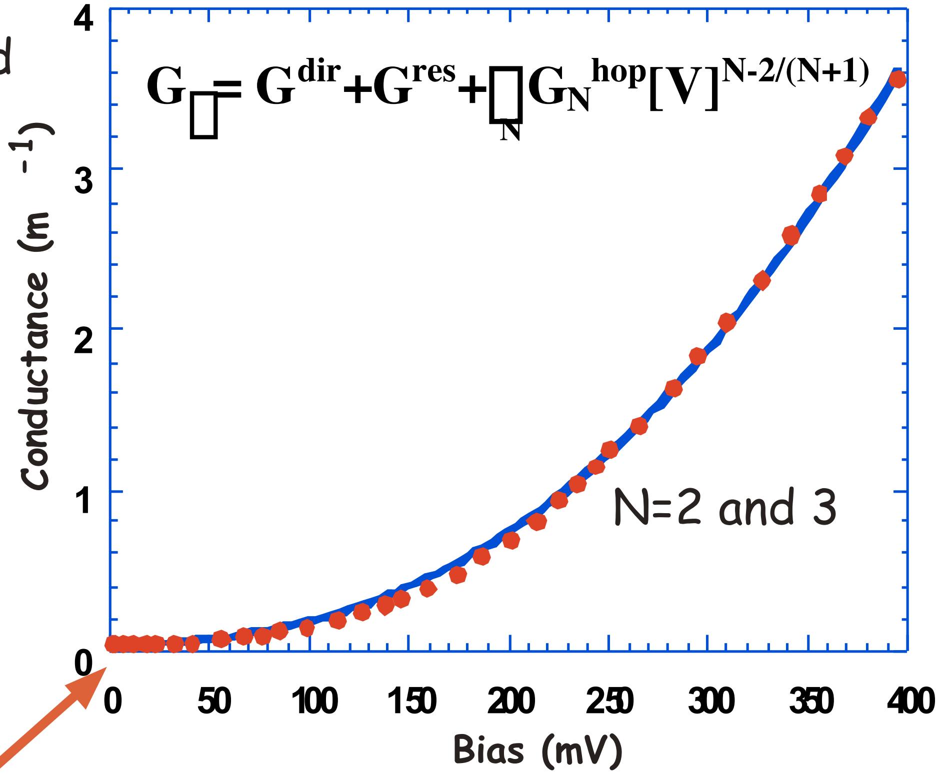
- *By fitting the I-V data with Simmons's tunnel equation for intermediate-voltage range ($V<\phi_0/e$), we obtain the following results:*

ϕ_0 = 1.0eV, d = 20Å

Hopping Transport in Oxide Junctions

- Inelastic hopping through localized states in the $CoCr_2O_4$ barrier
- Hopping through 2 states in the barrier fits well at low biases while hopping through 2 or 3 states fits well over a larger bias range





Spin Polarization of Fe_3O_4

- Spin polarized photoemission studies of Fe_3O_4:

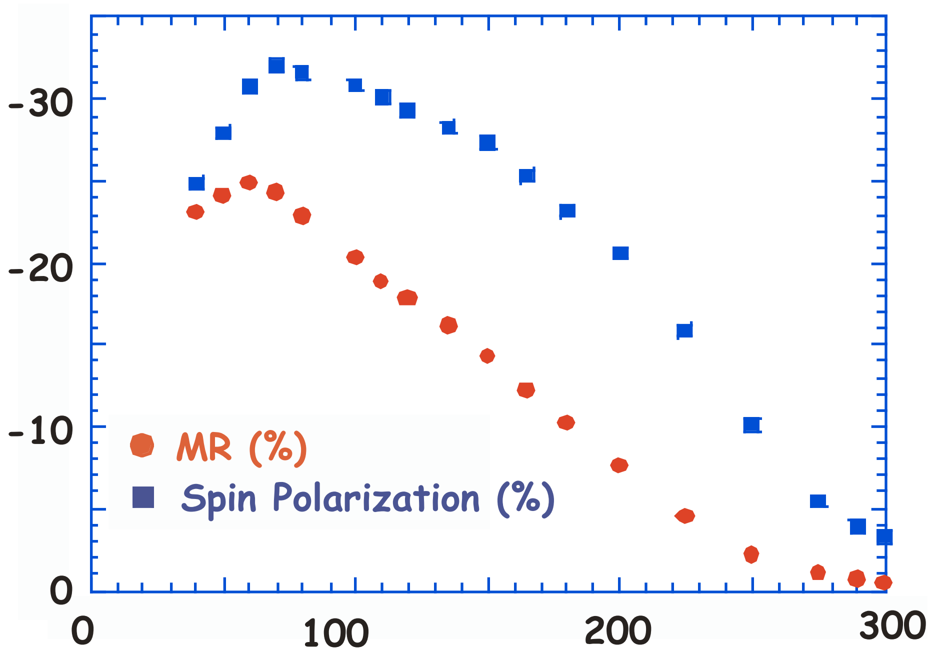
  P=-40% at 10K *Alvarado et al. PRL* ***34*** *319 (75)*

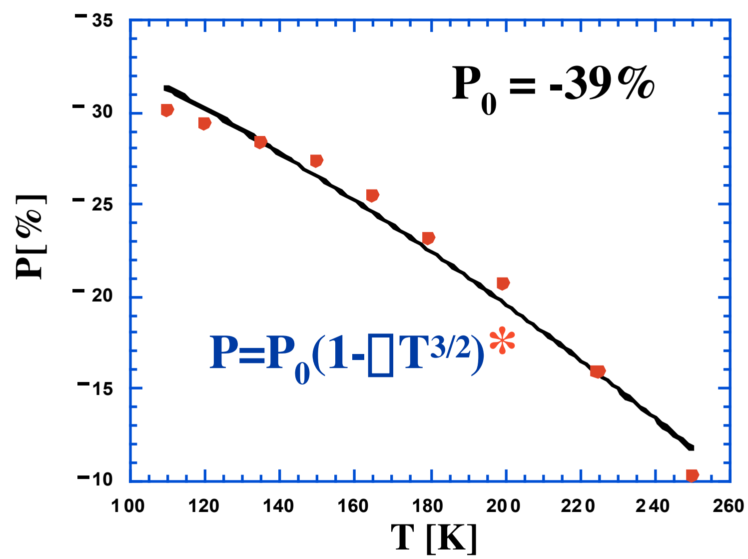
  P=-80% at RT *Dedkov et al. PRB* ***65*** *64417 (02)*

  P=-55% at RT *Huang et al. JMMM* ***239*** *261 (02)*

P_{th}=-67% at 0K
Srinitiwarawong et al. J.Phys.Cond.Matter ***13*** *7987 (01)*

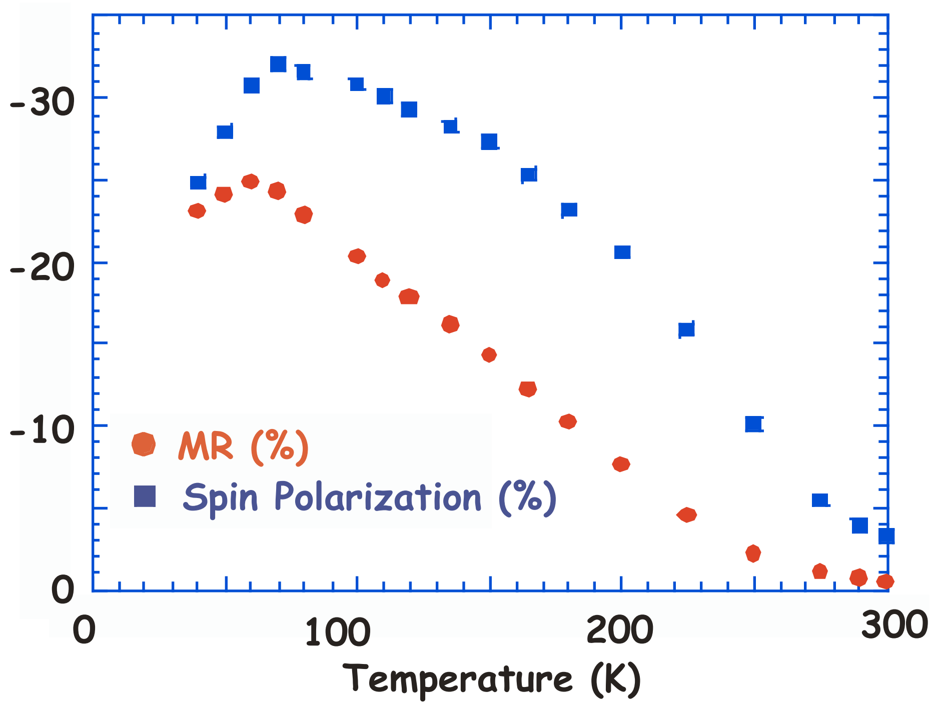
- Fitting high temperature MR(T) to magnon excitations: $P=P_o(1-\square T^{3/2})$

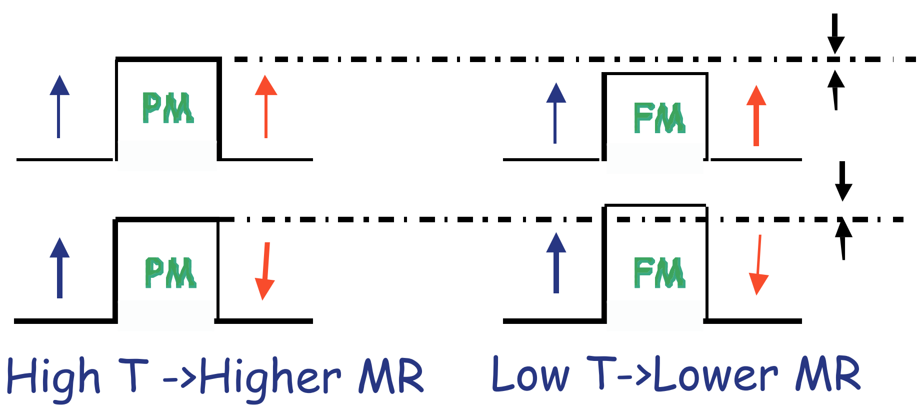




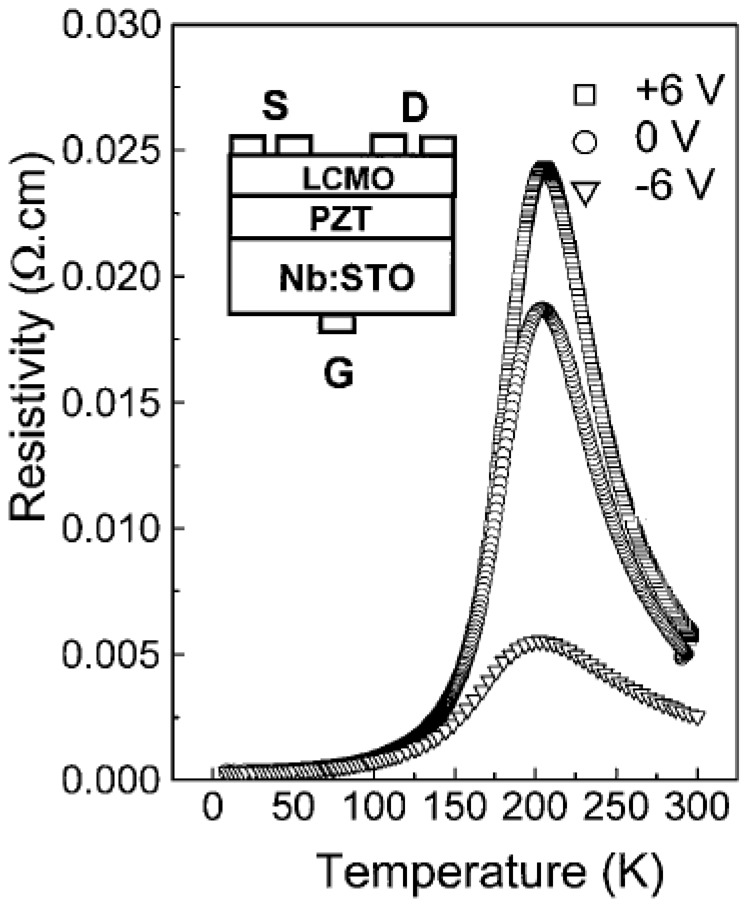
Spin Polarization of Fe_3O_4

Low temperature peak due to .....
- Verwey transition of Fe_3O_4
- Magnetic transition of the $CoCr_2O_4$ barrier





Field-effect-transistor with manganite channel

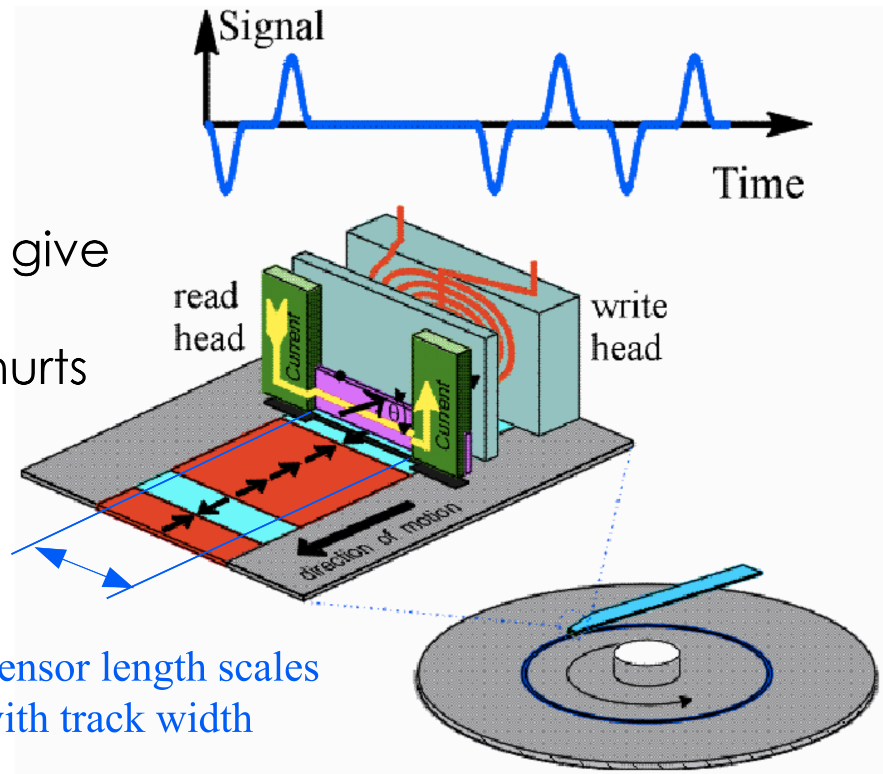


- three terminal device based on manganites
- carrier modulation through PZT gate

T. Wu *et al.*, PRL86, 5998 (2001).

Oxide Devices: Sensors

- Sub-100nm scaling of MR heads challenge existing technology:
  - GMR: too low in resistance to give enough signal.
  - MTJ: too resistive. Shot noise hurts S/N.
- Can oxide MR elements fill the gap???
  - \+ Large MR.
  - \+ Intermediate resistance.
  - \- 300 K performance?
  - \- Switching field control?
  - \- Noise characteristics in deep sub-micron region?
  - \- Processing compatibility?



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