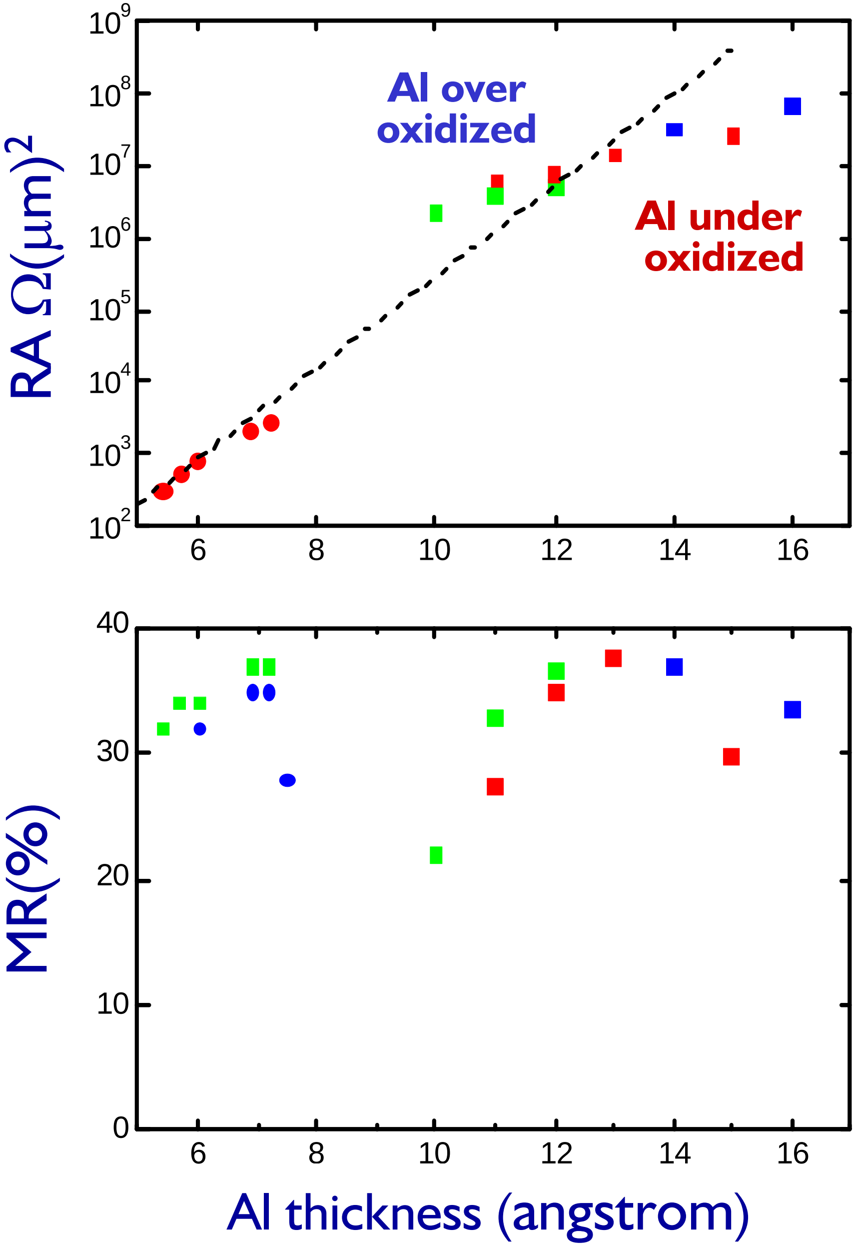
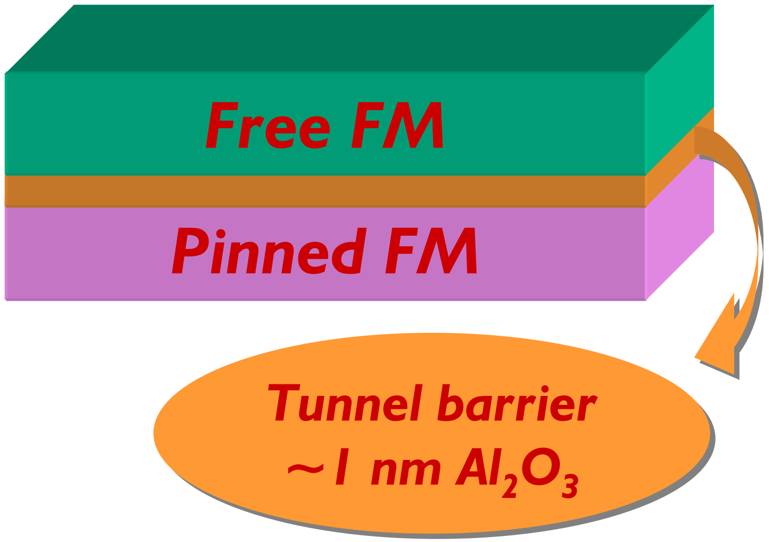
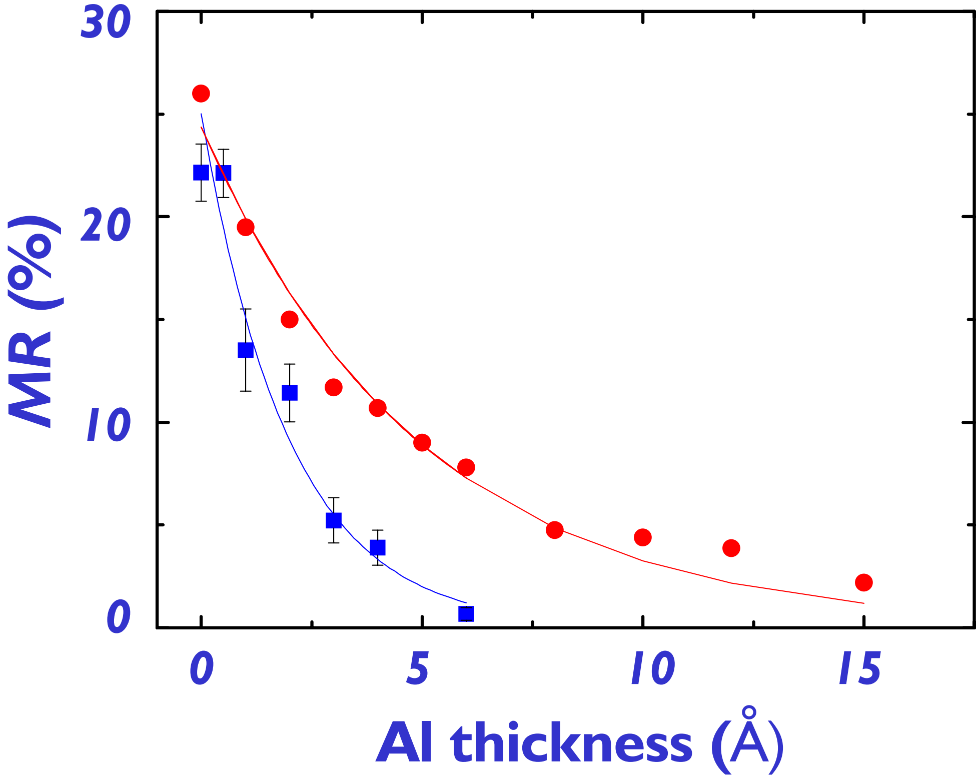
Dependence of MR and R on Al thickness



- Resistance increases exponentially with Al-O thickness
- MR independent of barrier thickness
  - assuming barrier completely oxidized
  - no oxidation of underlying ferromagnetic electrode

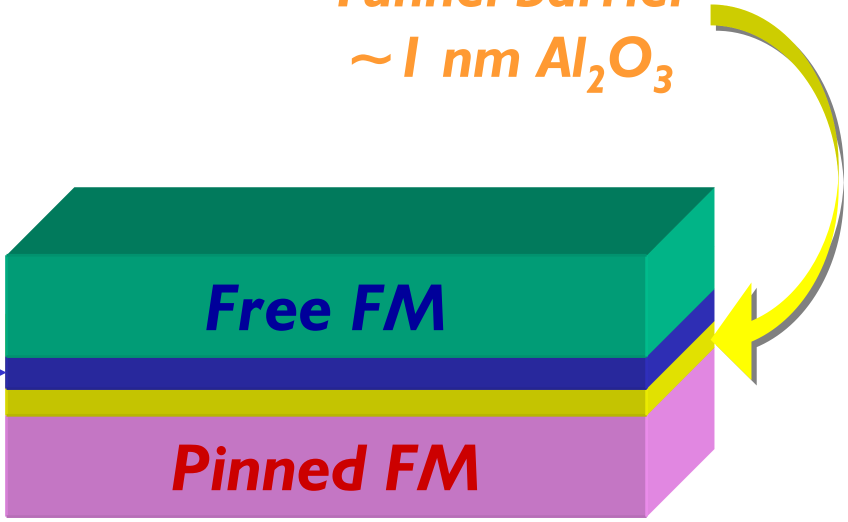


Sensitivity of MR to Interface Structure



Free FM	Decay length
$Ni_{40}Fe_{60}$	$\lambda=2.3$ Å
$Co_{84}Fe_{16}$	$\lambda=5.0$ Å

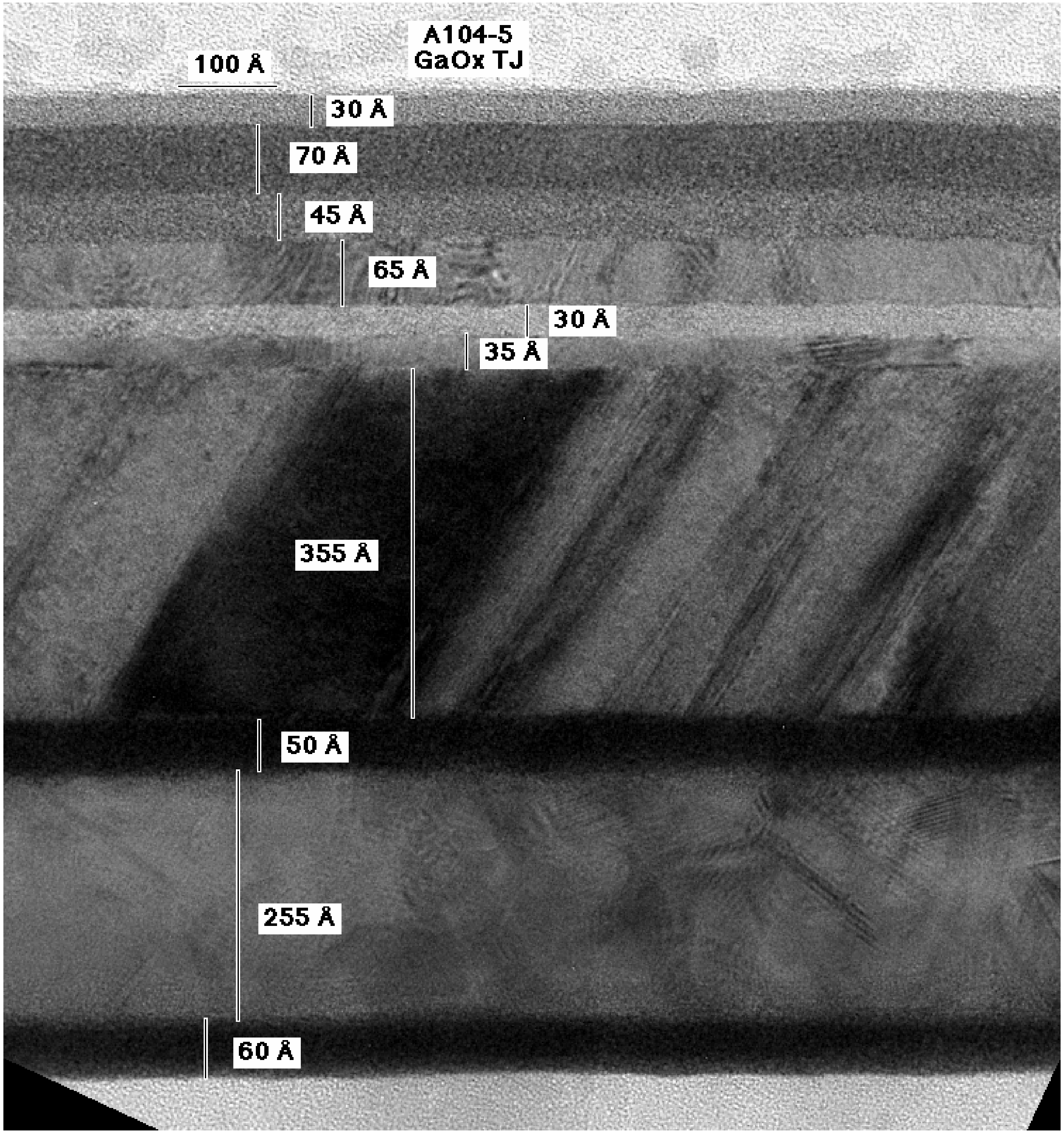
Al interface layer



Tunnel barrier

~1 nm Al_2O_3

XTEM of Typical MTJ



10CoFe/50Py (Free FM)

Barrier Ga_2O_3

20CoFe/15Fe
(pinned FM)

275IrMn
(Antiferromagnet)

50Ta

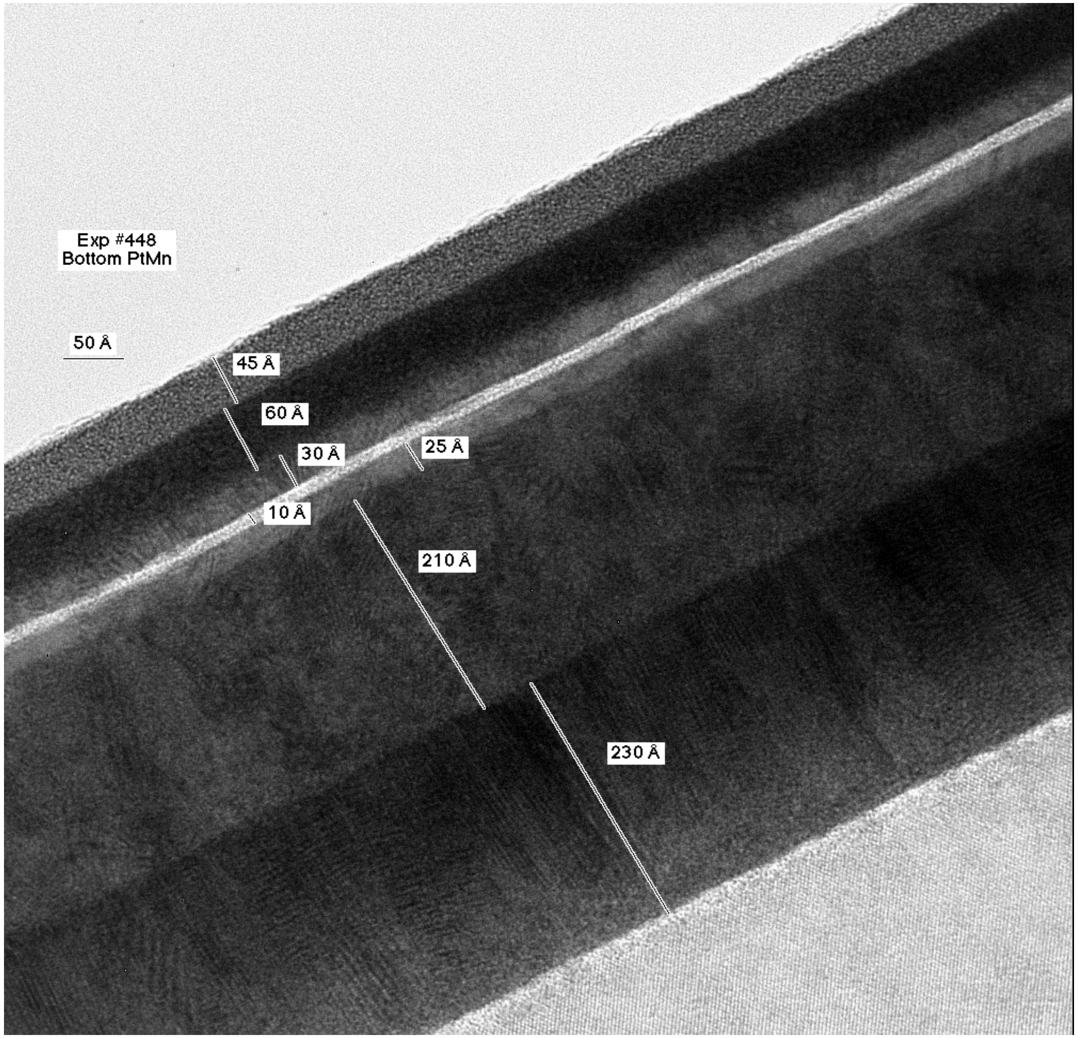
200Cu

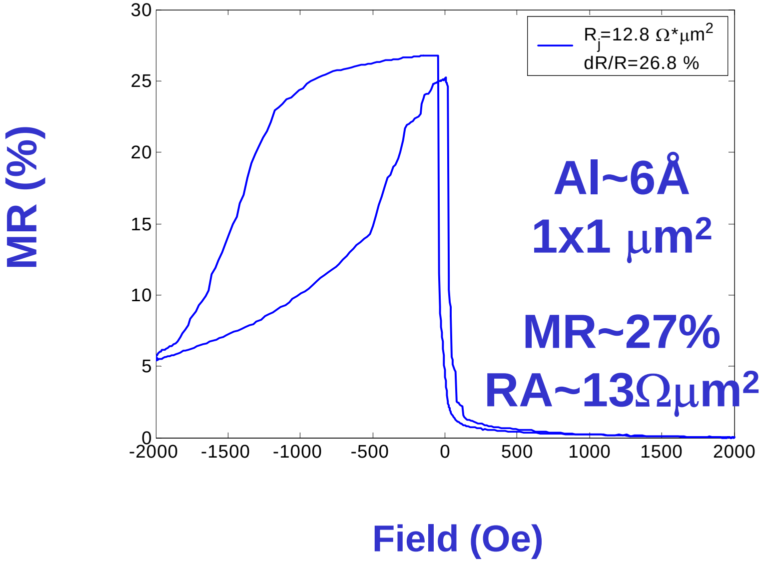
50Ta

Stuart Parkin
July 7, 2003

PtMn Exchange Biased MTJ with RA~12$\Omega\mu m^2$

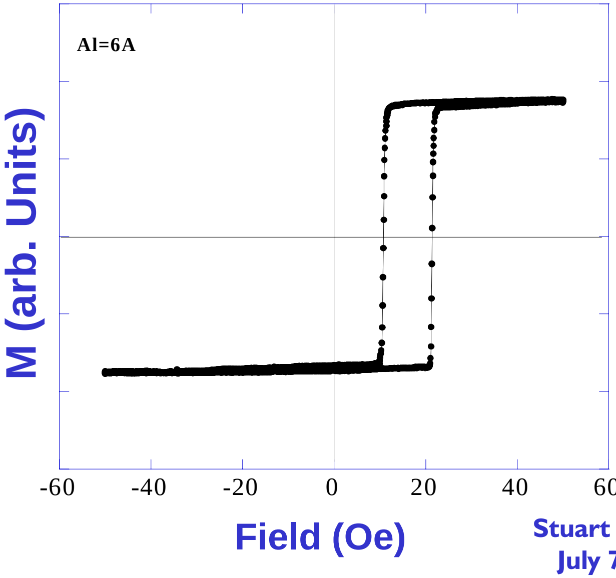
$Ta(200Å)/PtMn(250Å)/Co_{80}Fe_{20}(15Å)/Al(6Å)+O_2/Co_{80}Fe_{20}(10Å)/Ni_{81}Fe_{19}(46Å)/Ta(100Å)$





Al~6Å
1x1 μm^2

MR~27%
RA~13Ωμm^2

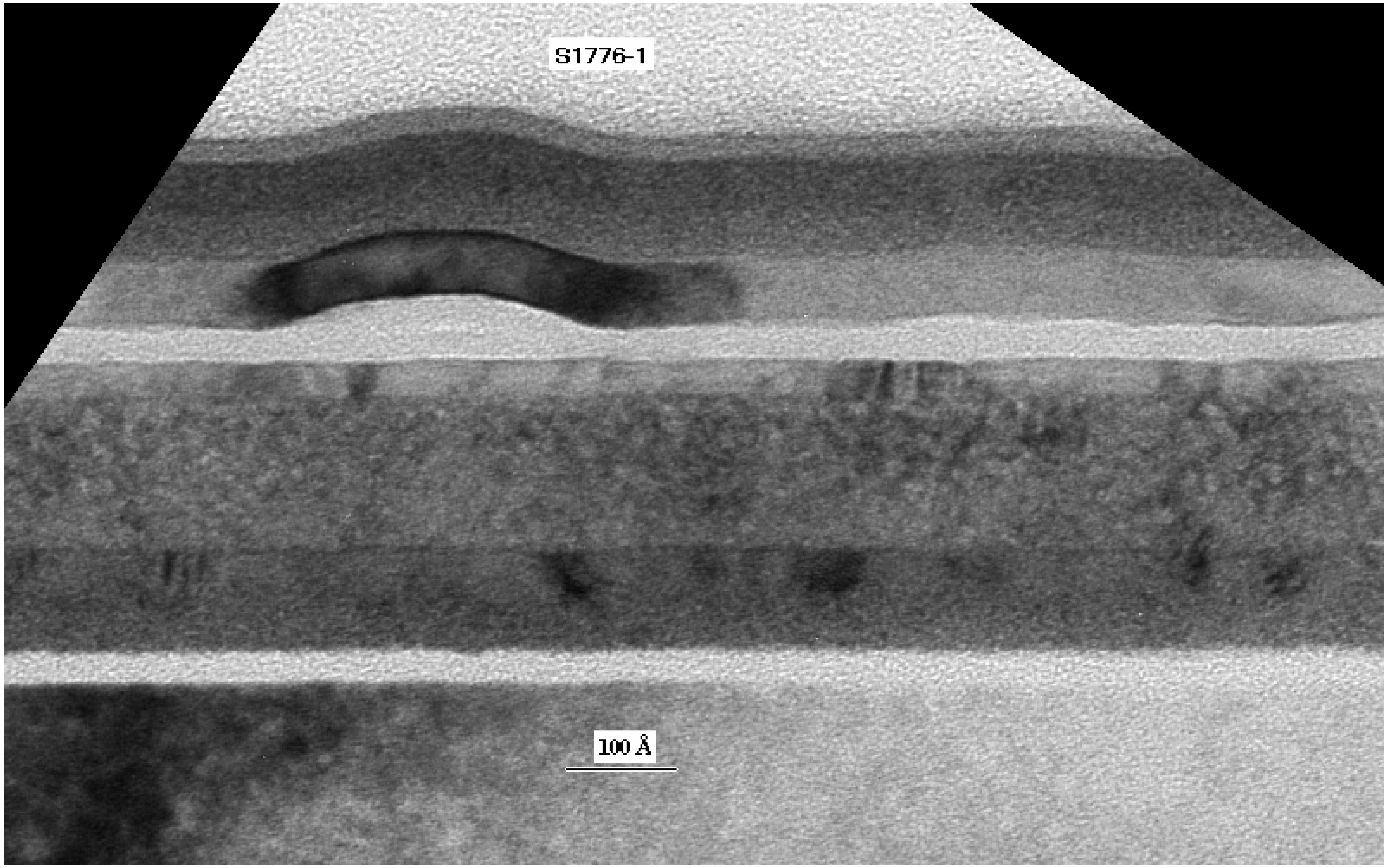


Aluminum Oxide Tunnel Barrier

Best tunnel barrier: oxidized Al metal films

- Aluminum wets Ni, Fe, Co etc
  - Plasma or thermal oxidation gives rise to dense oxide (fills pinholes)
    - Al metal diffuses through oxide layer
  - Typically reactively sputtered Al_2O_3 less dense
    - Smaller breakdown voltage…
- Limits to Al_2O_3 thickness
  - 1/3 unit cell of crystalline Al_2O_3 ~4.3 Å!
  - Defects, non-uniformity in thin layers, oxidation of FM
    - Defects form defect band of states (Buhrman- BEEM)
  - Image charge effects: rounding of barrier
  - Very difficult to probe structure of ultra thin oxide layers
    - One of the best probes is transport
      - IV and temperature dependence measurements

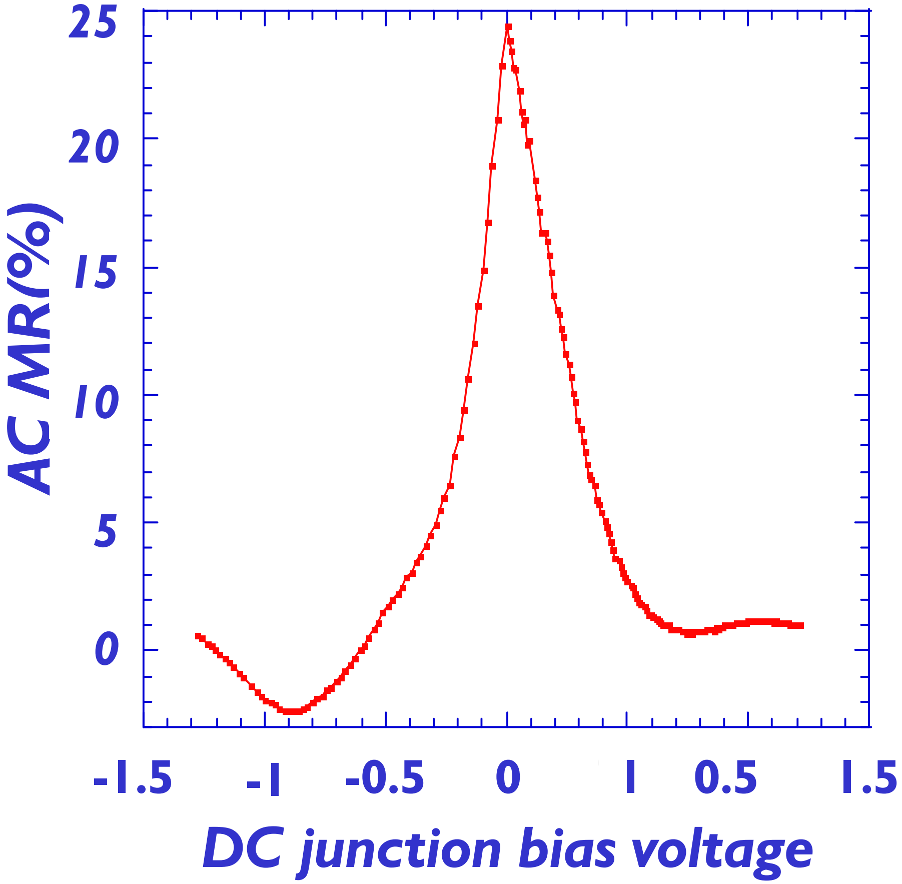
"Lumpy" Al_2O_3 Tunnel Barrier



Questions

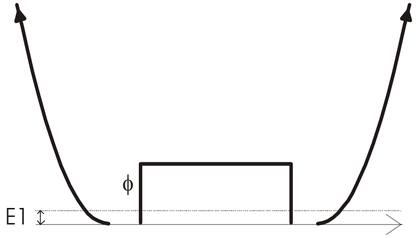
- What determines tunnel barrier height?
  - How can we measure tunnel barrier height?
  - Experimentally, strong decrease of barrier height with decreasing Al_2O_3 thickness from IV curves
  - Can we reduce barrier height by work function engineering, adding defects…
- How can we measure structure of thin tunnel barriers?
  - Interfaces very critical
  - Defects in thin layers very important
- Can we improve growth of thin dielectric layers?
  - Surfactants
  - Ultra smooth underlayers
  - Deposition temperature
  - Assist ion source
- What determines voltage dependence of MR?
  - Can we significantly reduce decrease of MR with voltage?
- What determines dependence of MR on magnetic material?

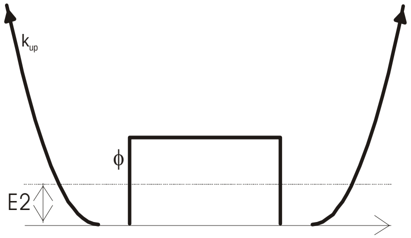
Oscillatory variation of MR with Bias Voltage

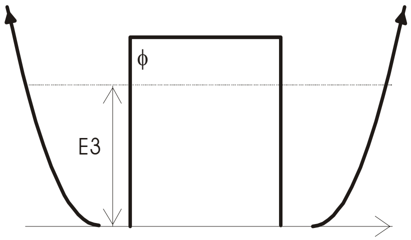

Si/ 70Å Pd/100ÅCo/20Å Al_2O_3 / 300Å NiFe

- Magneto-conductance determined from ac conductance vs dc bias voltage curves for parallel and anti-parallel alignment of ferromagnetic layers
- MR oscillates through zero MR for negative bias voltage
- Weak MR oscillation for positive bias voltage

Exact Free Electron Model of Tunneling

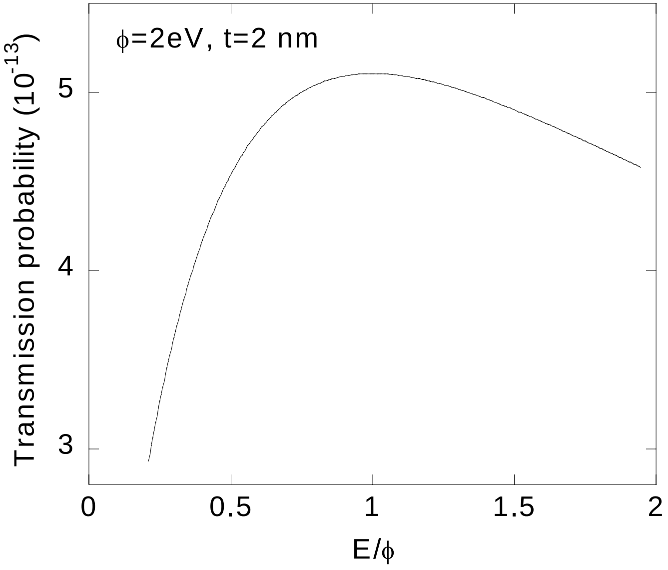






Transmission probability depends on electron energy relative to barrier height

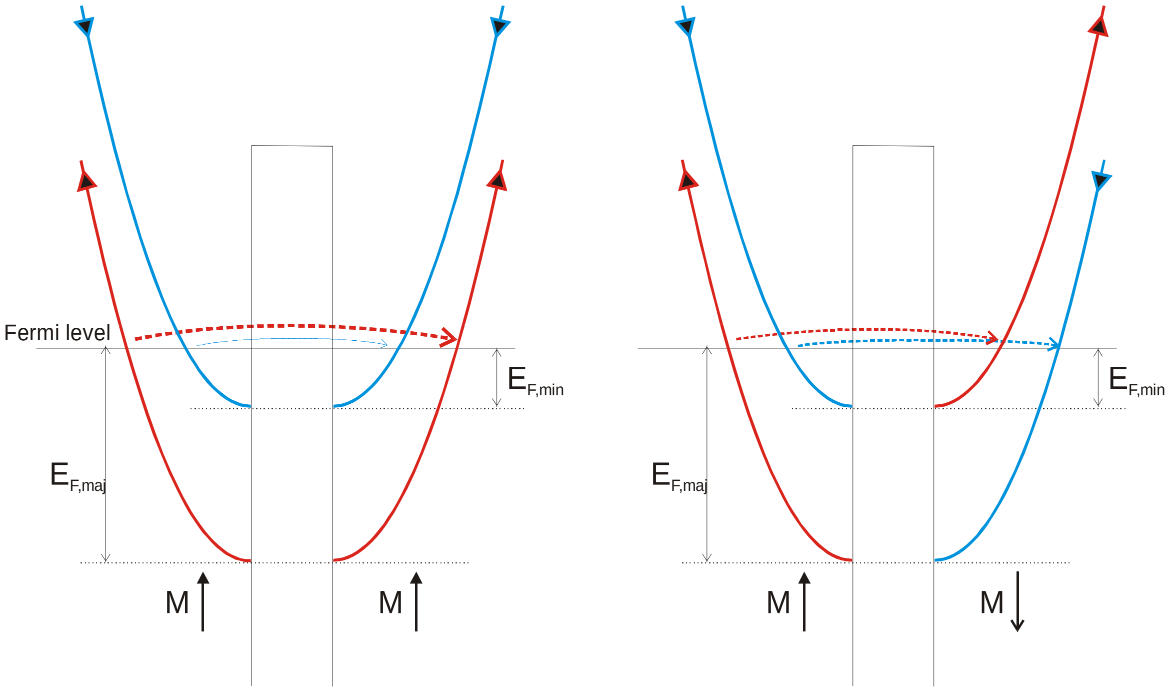
Transmission probability vs E/φ



Transmission probability maximized when

$$k_x = \sqrt{\frac{2mE_x}{\hbar^2}} = i\kappa_x = i\sqrt{\frac{2m\phi}{\hbar^2}}$$

Exact Free Electron Model of Tunneling



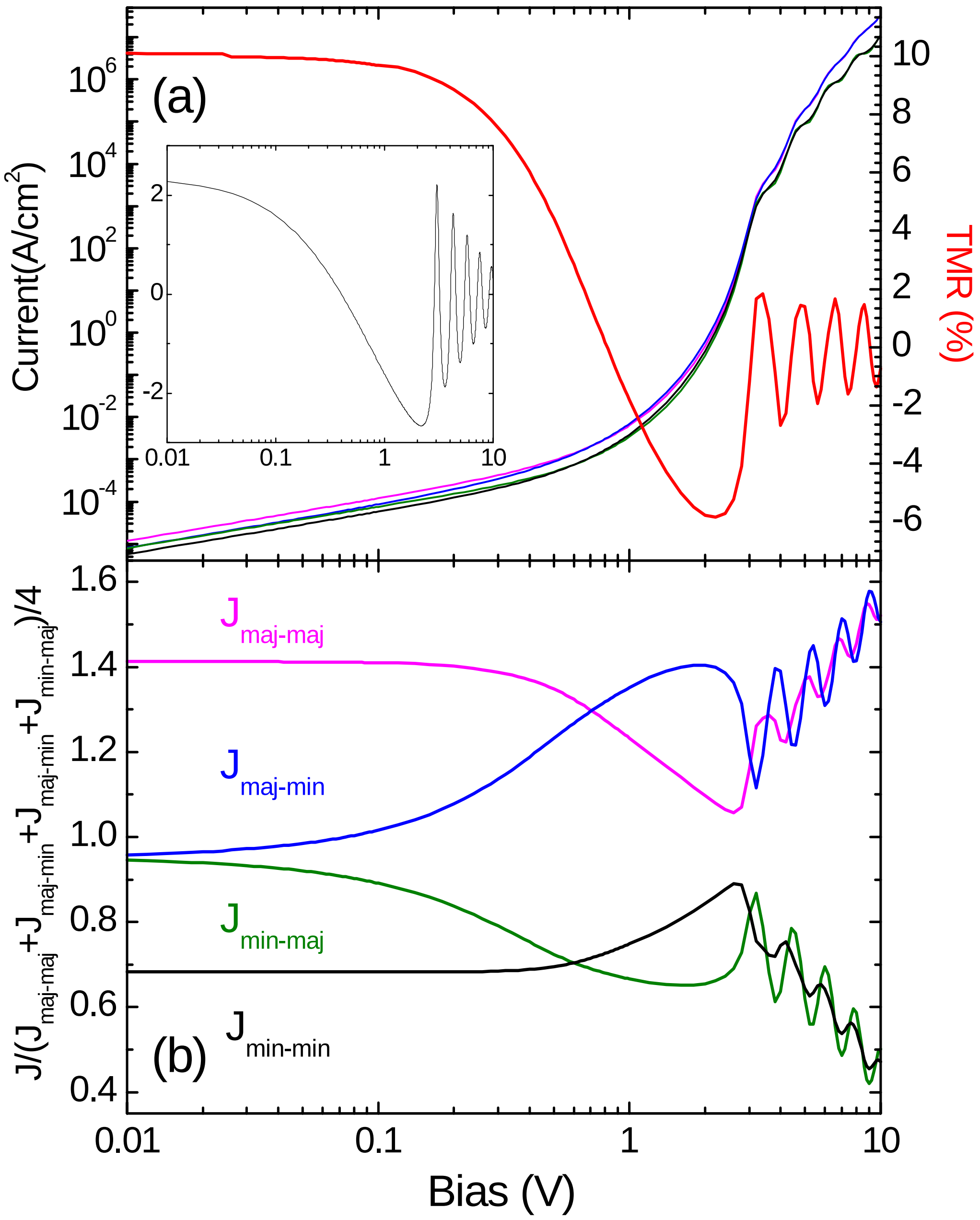
Assume exchange split
parabolic bands in
Ferromagnet:
Majority and minority bands
have different Fermi
energies

Transmission probability
maximized when

$$k_x = \sqrt{\frac{2mE_x}{\hbar^2}} = i\kappa_x = i\sqrt{\frac{2m\phi}{\hbar^2}}$$

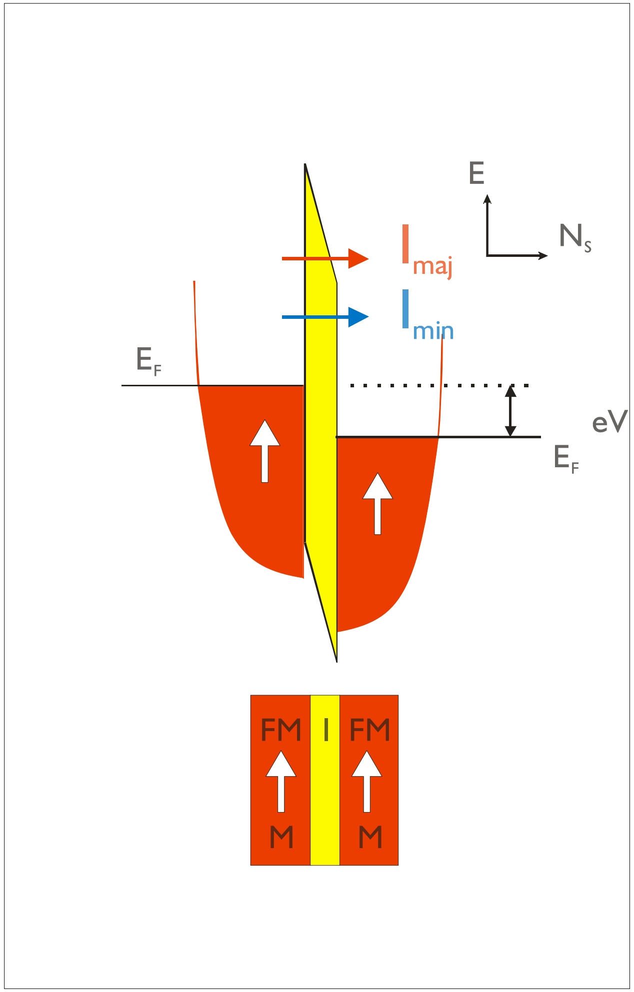
Or for band with Fermi energy
closest to barrier heightB

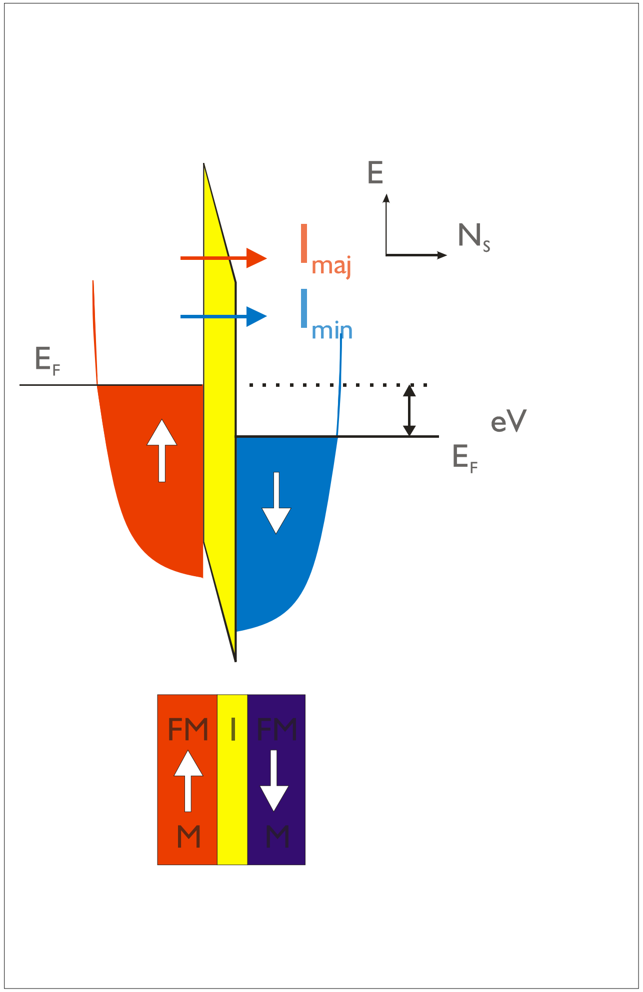
Bias Dependence of MR: Exact Free Electron Model

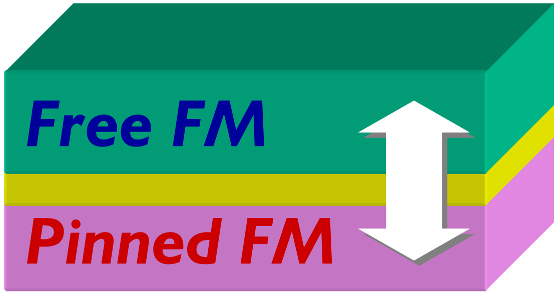


- Model shows TMR decreases with bias and changes sign
    - Resonances in insulator conduction band
- Bias dependence of MR caused by different bias dependence of spin polarized currents

Spin Polarized Electron Tunneling: FM-I-FM



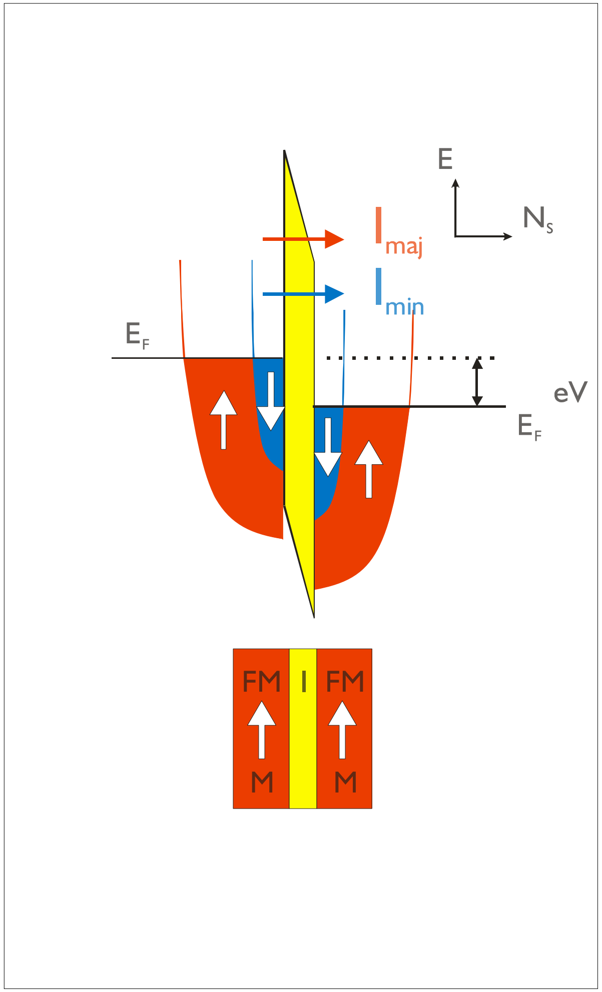


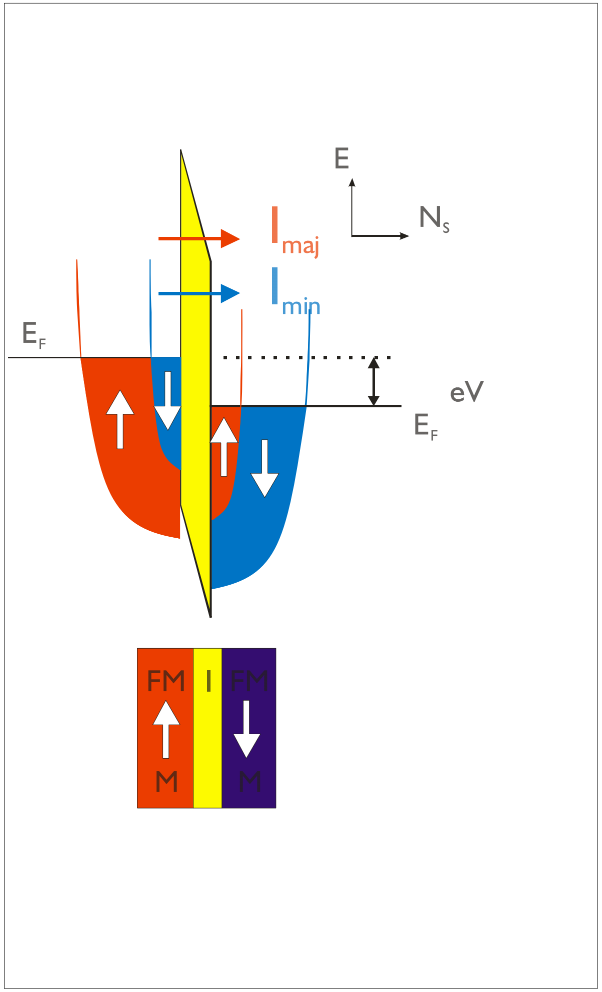


$$I_P \approx N_\uparrow^1 N_\uparrow^2$$

$$I_{AP} \approx N_\uparrow^1 N_\downarrow^2 \approx 0$$

Spin Polarized Electron Tunneling: FM-I-FM





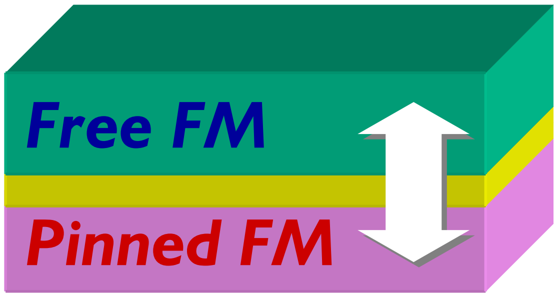
$$I_P \approx N_{\uparrow}^{1} N_{\uparrow}^{2} + N_{\downarrow}^{1} N_{\downarrow}^{2}$$

$$I_{AP} \approx N_{\uparrow}^{1} N_{\downarrow}^{2} + N_{\downarrow}^{1} N_{\uparrow}^{2}$$

Juliere (1975)

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

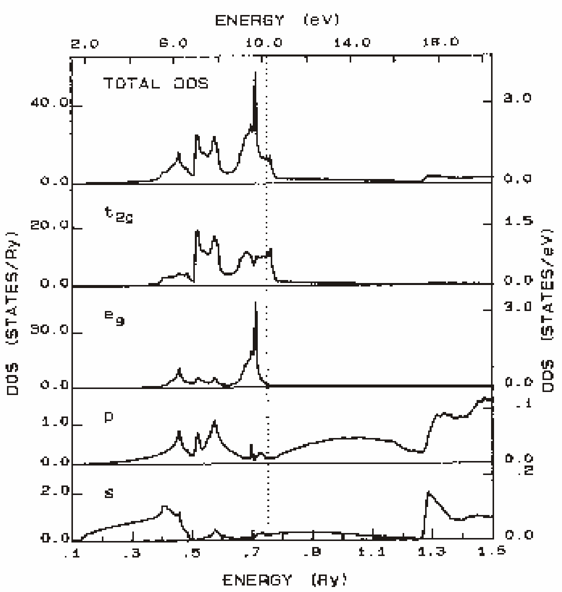
$$\text{with } P = \frac{N_{\uparrow} - N_{\downarrow}}{N_{\uparrow} + N_{\downarrow}}$$



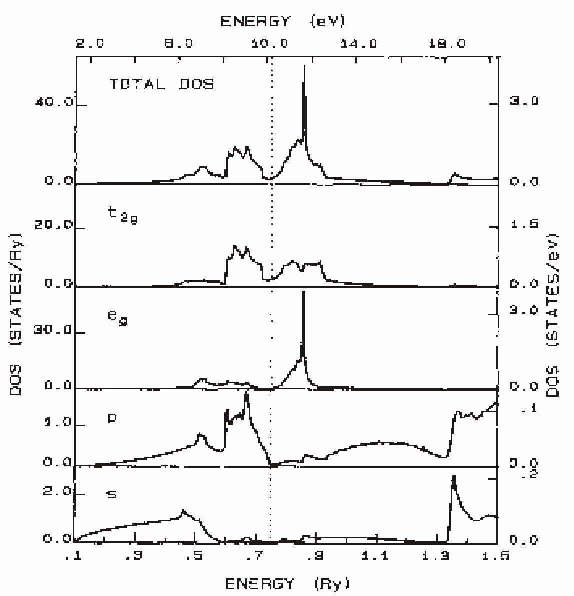
Tunneling (DOS effect)

- In real metals DOS not uniform
- Not all electrons tunnel with equal probability.
  - – T(s-p) > T(d)
    - d-electrons are more localized
- Number of initial and final states determine the net current

Fe(bcc)
Majority Band N(E)



Fe(bcc)
Minority Band N(E)



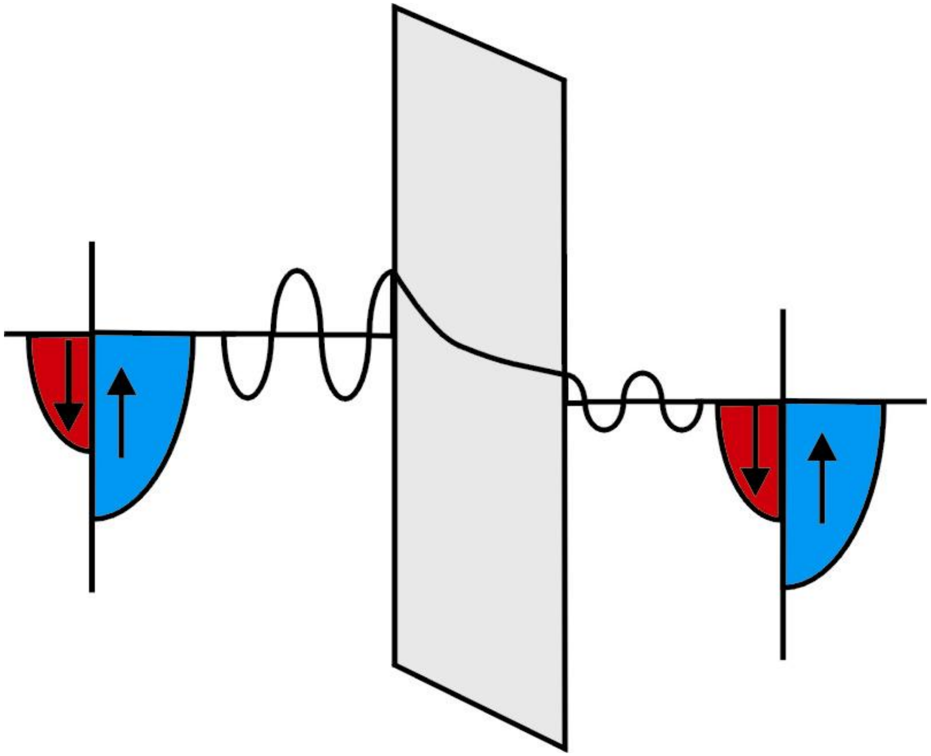
Junctions with:
- –Metals
- –Superconductor
- –Semiconductor

→ Have different IV characteristic which reflect the DOS and relative tunneling probabilities.

Spin polarization in materials (simple picture)

- Spin-bands are exchange split giving rise to different DOS at E_f for Spin up and spin down.
- This spin imbalance in tunneling current then called “Spin Polarized” current
- **In devices, the tunneling spin polarization (TSP) depends on transmission probability and DOS**.

→ Spin polarization is not intrinsic!



→ Spin polarization depends on:

- barrier height
- barrier shape
- degree of disorder in barrier
- bonding at F/I interfaces
- electronic structure of insulator

$$P = \frac{N_\uparrow |T| - N_\downarrow |T|}{N_\uparrow |T| + N_\downarrow |T|}$$

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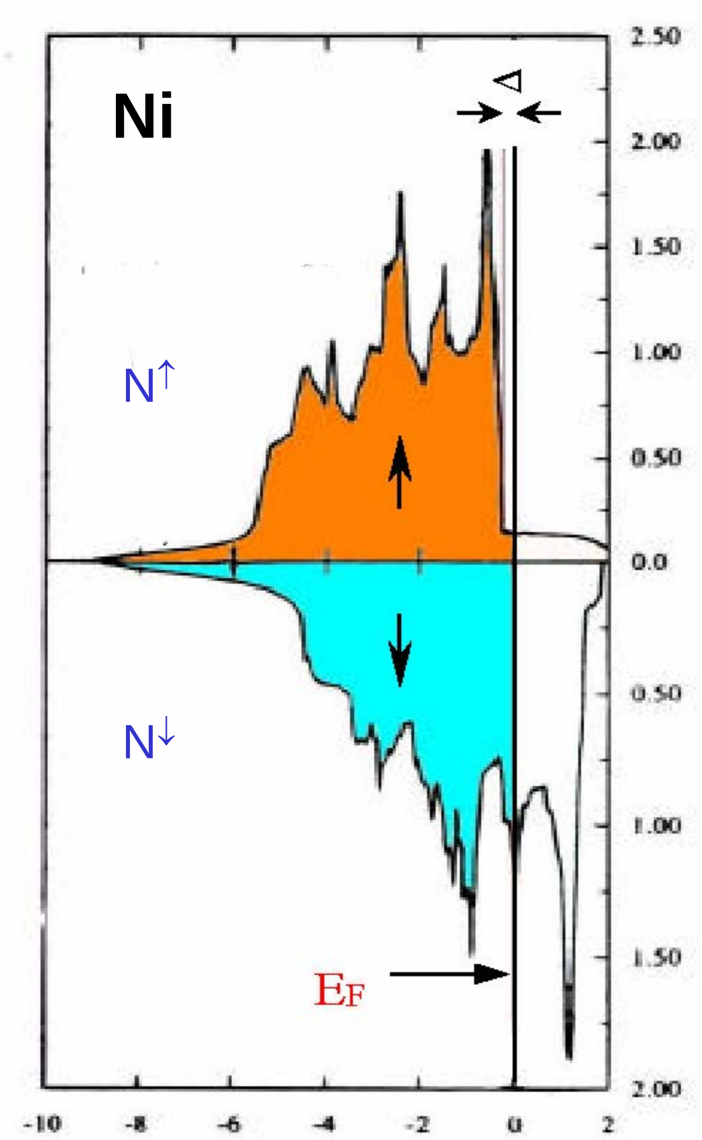
July 7, 2003

Spin-Dependent Tunneling and Density of States



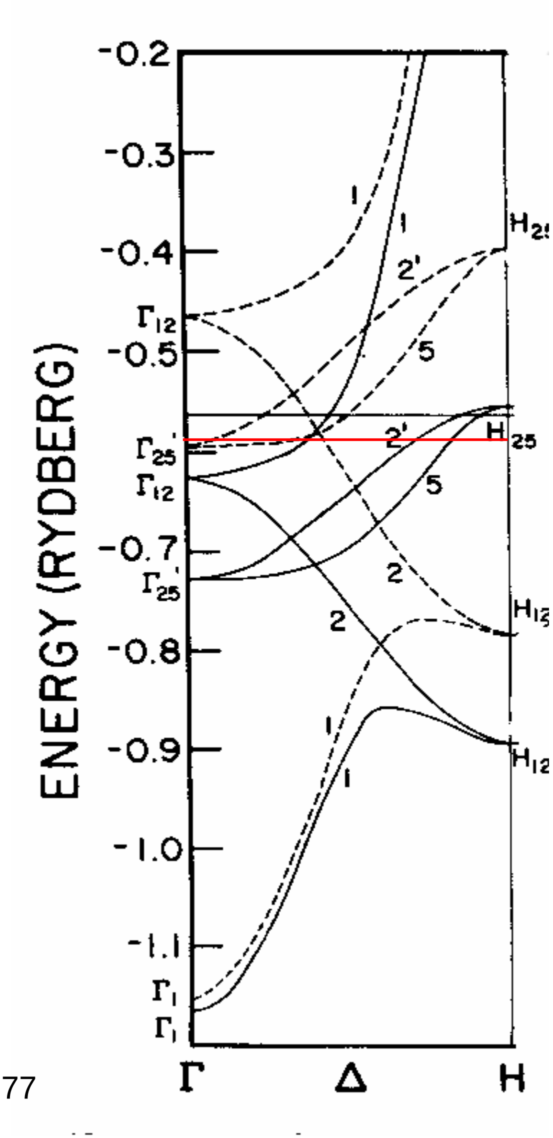
- Julliere: $$\mathrm{TMR} = \frac{P_1P_2}{1 - P_1P_2}$$
  How can P be related to the properties of the material?
- First idea: Spin polarization P equals the spin-polarization of all electrons at the Fermi energy of the ferromagnet:
  $$P = \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$$
- for Ni: P negative (predominantly spin-down electrons at Fermi edge)
  for Fe: P positive
  but: MTJs made of Ni and Fe electrodes show positive TMR !

Spin Polarization of the Tunneling Current

- Responsible for spin-polarization of tunneling current is matrix element for tunneling probability

→ s and p electrons have low DOS at Fermi edge compared to d electrons but are much more mobile: tunneling current in MTJs is dominated by fast sp-electrons

- There are several techniques to measure the “spin polarization” of a ferromagnet that yield different results as different matrix elements play a role



band structure of Fe from Callaway and Wang 1977

Measuring Spin Polarization

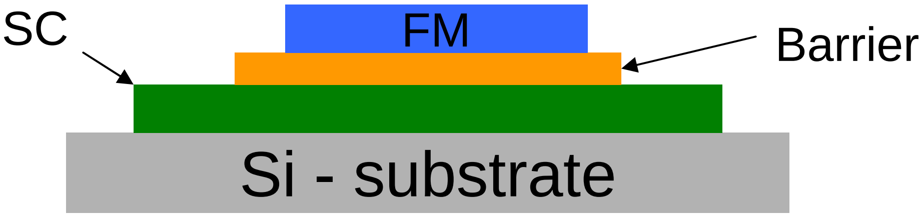
- Spin polarization can be measured with variety of techniques
  - What is T for each measurement technique?
- Photoemission
  - Measures DOS with **T~I**
- Point Contact Andreev Reflection (PCAR)
  - Measures with **T = $\mathbf{v_f}$**
- Tunneling in Superconductors (STS)
  - **T is barrier dependant!**

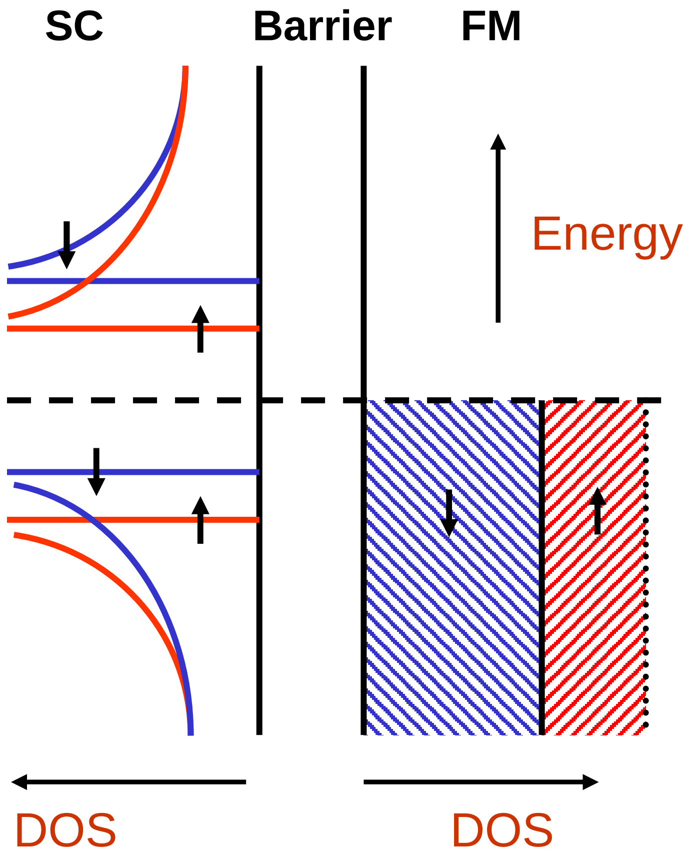
$$P = \frac{N_\uparrow |T| - N_\downarrow |T|}{N_\uparrow |T| + N_\downarrow |T|}$$

Nadygorny Phys Rev B **63** 184433

Superconducting Tunneling Spectroscopy

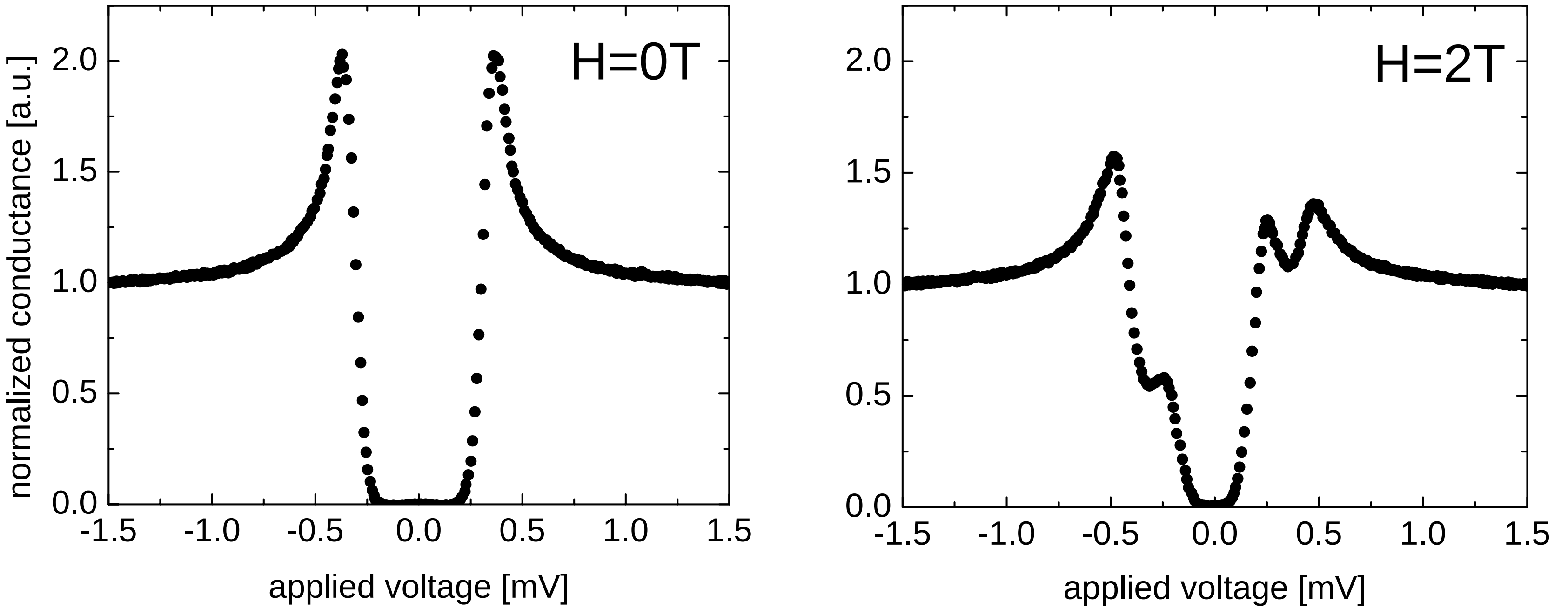
- Cartoon shows DOS for finite field H and zero temperature T
- Dynamic Conductance versus applied field is a measure for spin-polarization at E_F of ferromagnet (FM)
- The spin polarization is dominated by highly itinerant states near the Fermi Energy of the FM
- The structure closely resembles that of an MTJ
- Values for the P only at high field, very low temperature and zero bias





Meservey and Tedrow, Physics Reports **274** (1994)

Conductance Curves



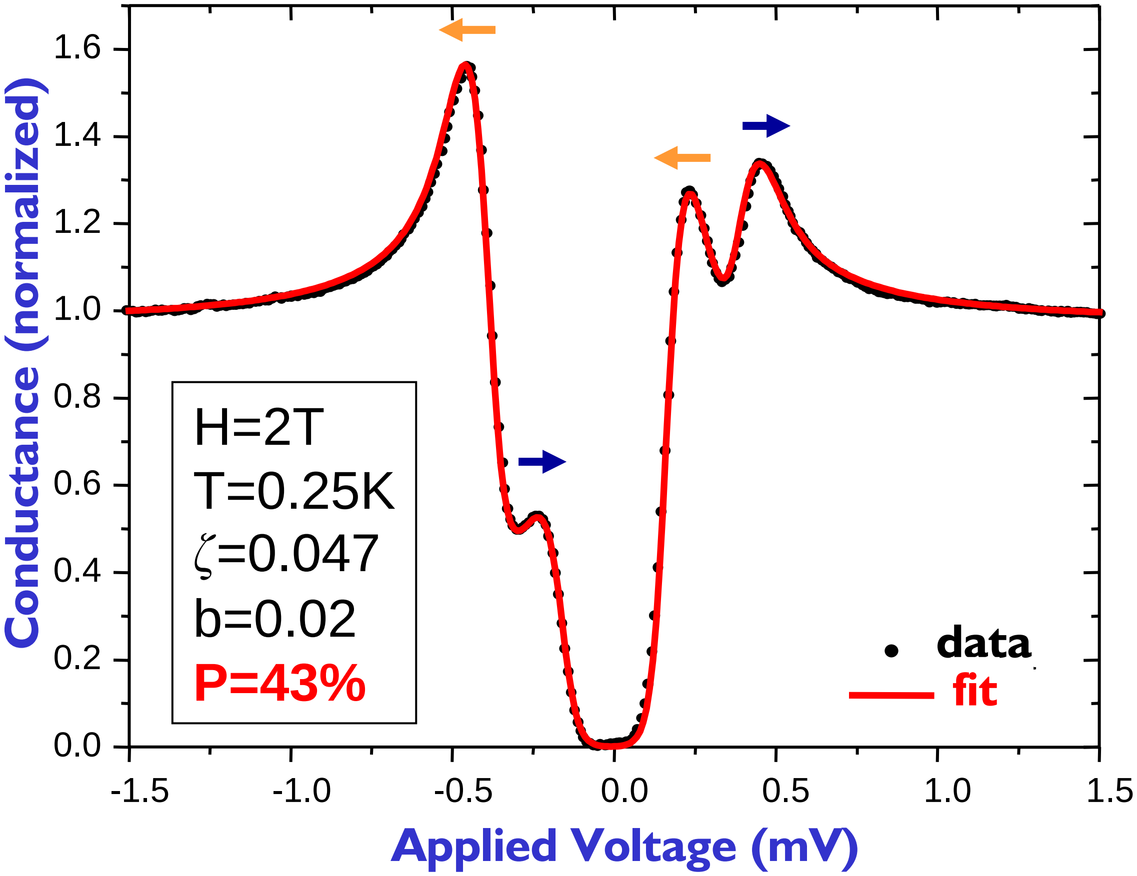
Conductance curves for a $Al|Al_2O_3|Co$ junction

Determination of Spin Polarization: Fitting the Conductance vs. Voltage Curves

Spin-polarization is extracted by fitting the conductance-curves. In the fit we use the superconducting density-of-states derived by Maki.

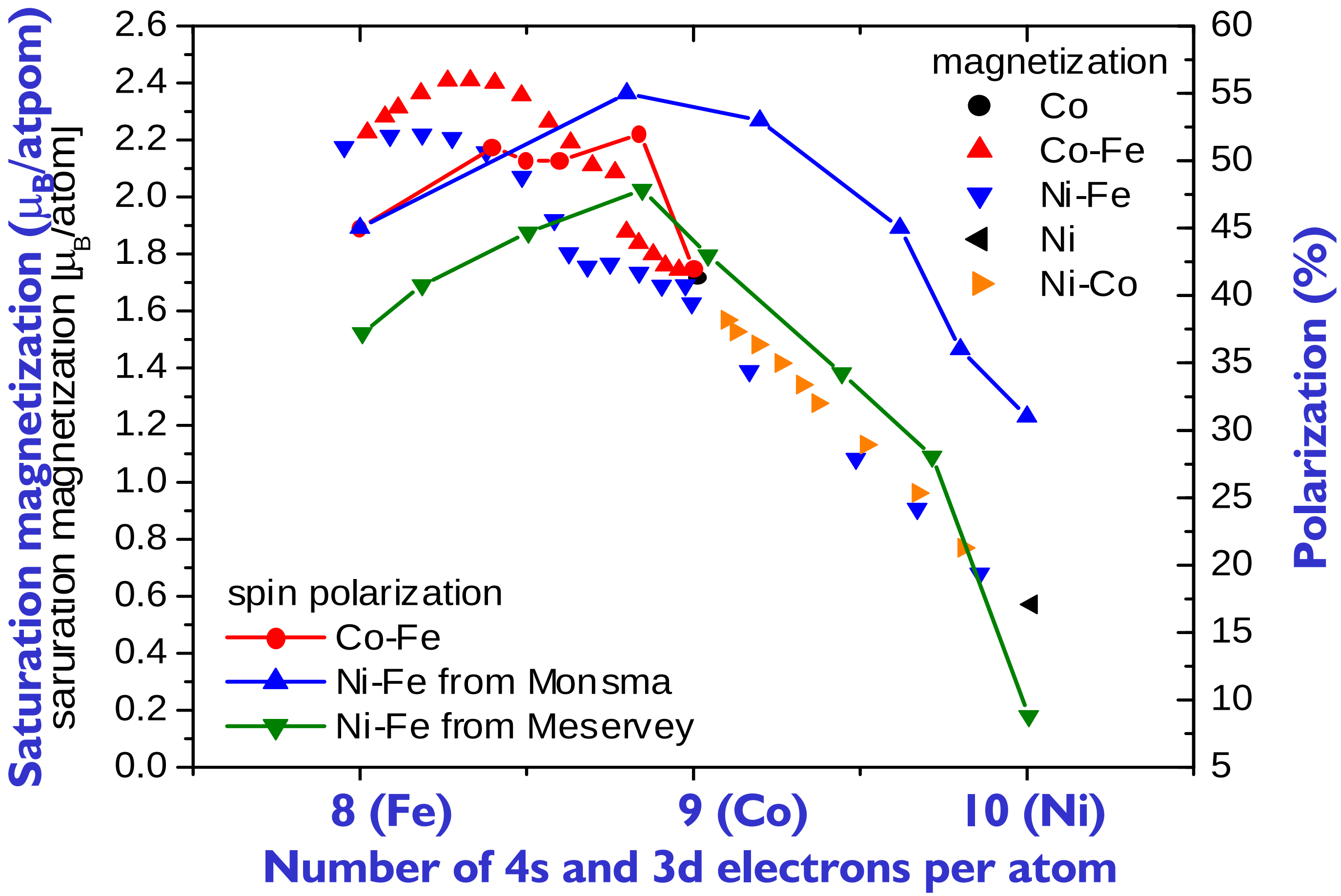
Parameters in fit:

- Temperature T
- Spin-Orbit Parameter b (spin-flip via non-magnetic impurities)
- Depairing parameter ζ (magnetic field tends to depair Cooper-Pairs)
- Spin-polarization P



Fitting procedure: see, for example, Worledge Phys Rev B **62** 447 (2000)

Relationship of Spin Polarization to Magnetization



- Spin-polarization for Fe, Co and Ni and their alloys measured to be positive and around 45%
  - Weak relationship between TMR and magnetization (c.f. $[Co_{70}Fe_{30}]B_{20}$: TMR~60%)
- Results are in contradiction to photoemission results

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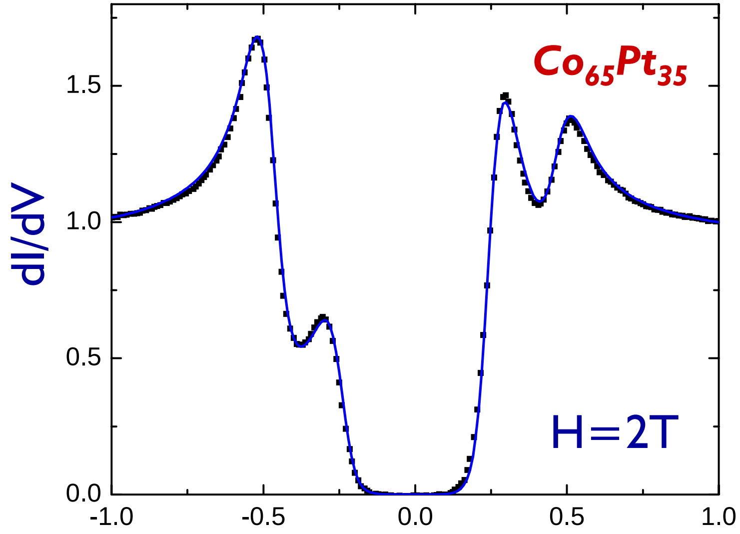
Spin Polarization of Alloys From superconducting Tunneling Spectroscopy



H=2T

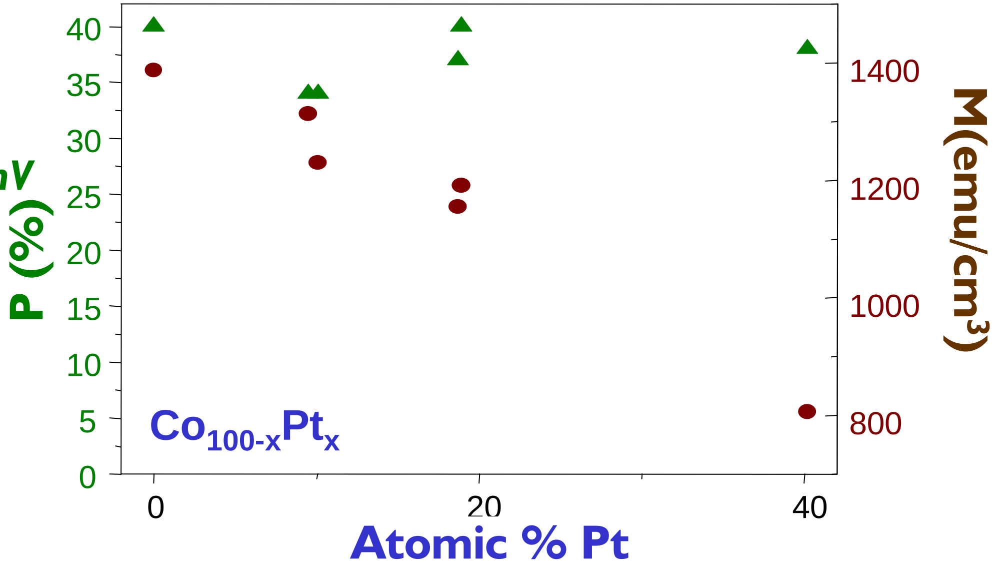
T=0.241K

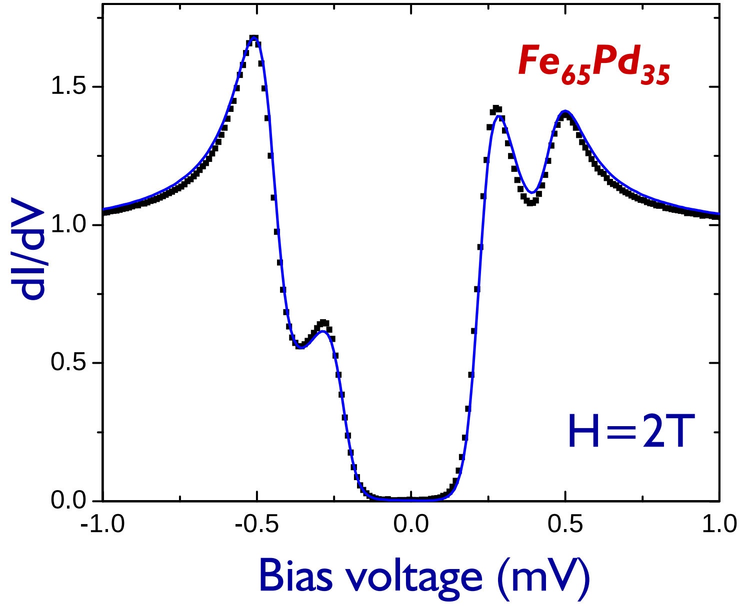
Gap=0.38mV

ζ=0.019

b=0.037

P=41%





H=2T

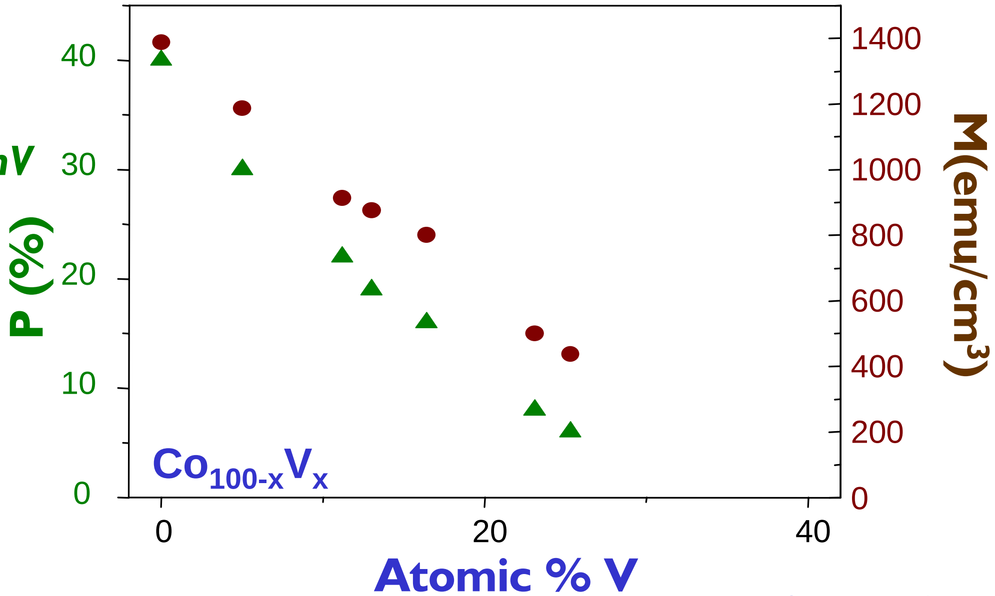
T=0.241K

Gap=0.37mV

ζ=0.028

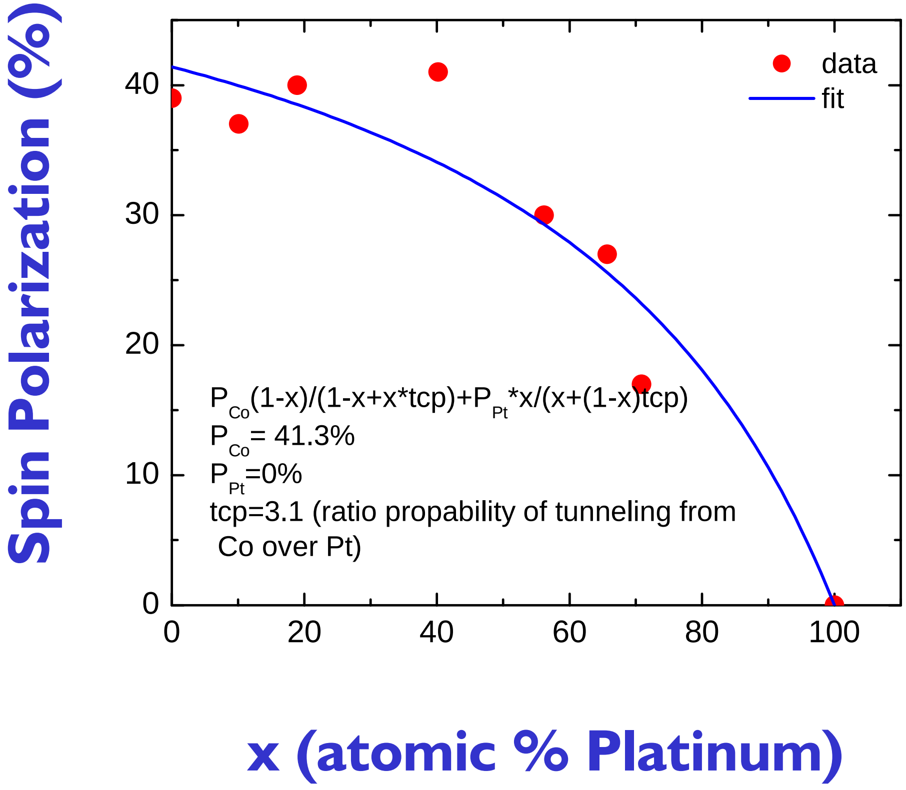
b=0.03

P=41%

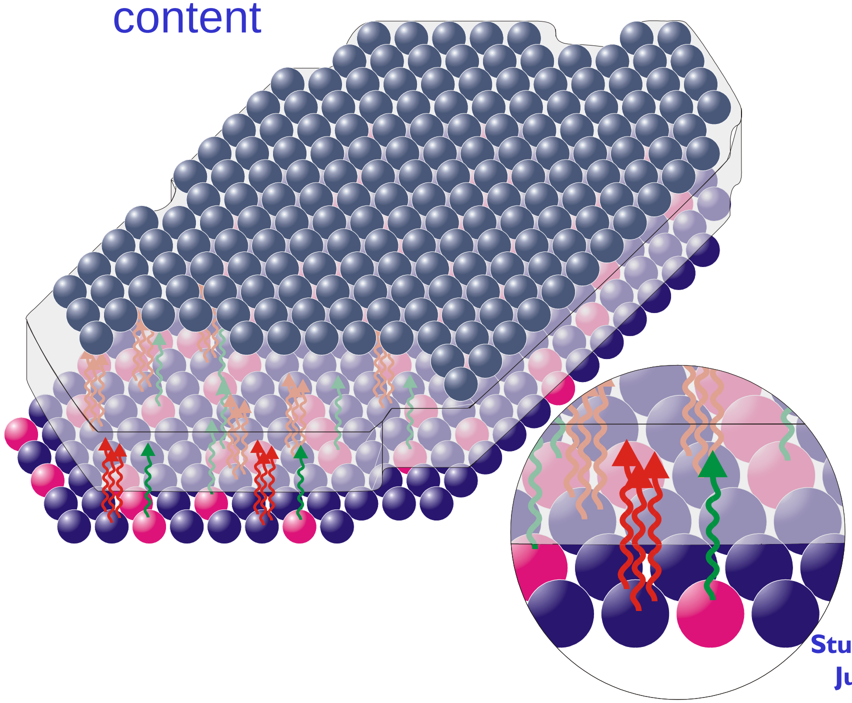


Christian Kaiser

Tunneling Matrix Elements in $Co_{1-x}Pt_x$ Alloys



- Spin-polarization for Co-Pt alloys ~ constant for small Pt but decreases for higher Pt content
- simple model can account for dependence of TMR on Pt content assuming
    - tunneling ~3x more probable from Co than Pt
    - spin polarization from Co independent of Pt content
    - moment decreases linearly with Pt content



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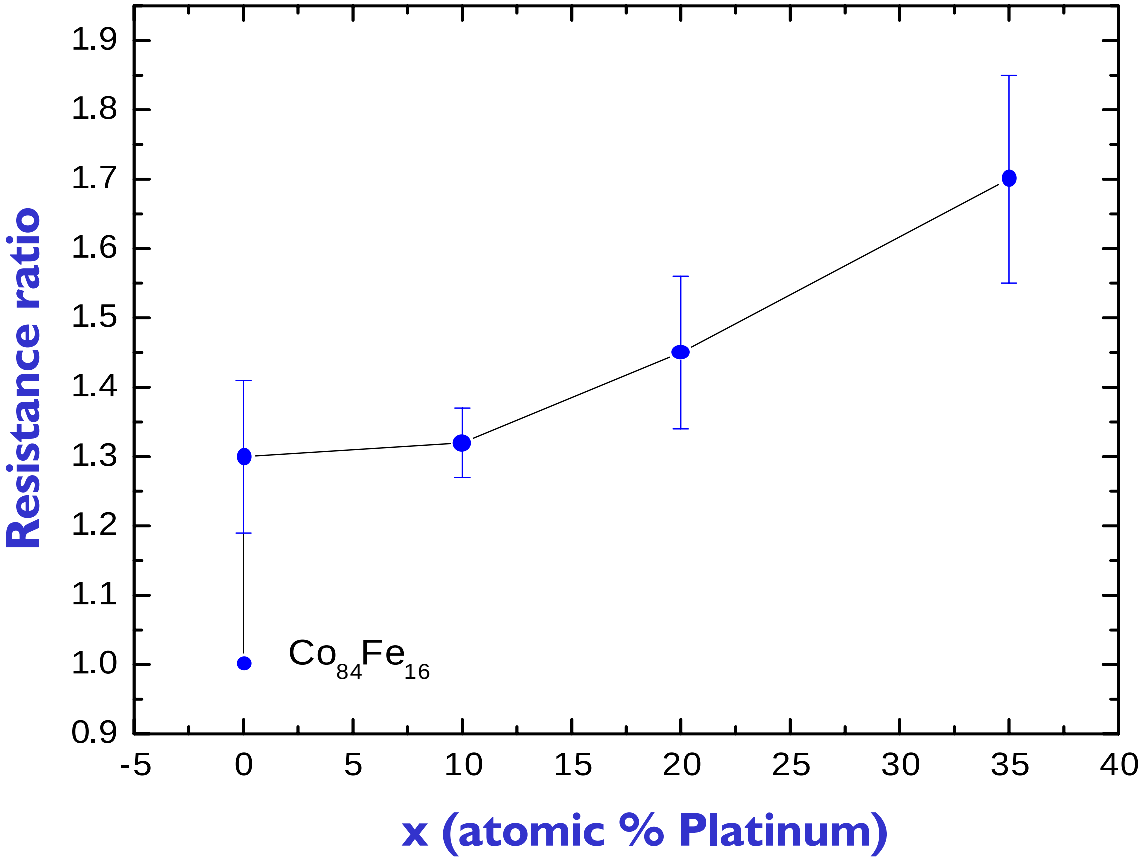
Resistance of MTJs with Co-Pt Alloy Ferromagnetic Electrode

- Tunneling from Pt-sites reduced:

  higher resistance with higher fraction of Pt in the alloy
- Tunneling spin-polarization is domiated by the spin-plarization of the electrons tunneling from Co sites

→ **spin polarization independent of composition**



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