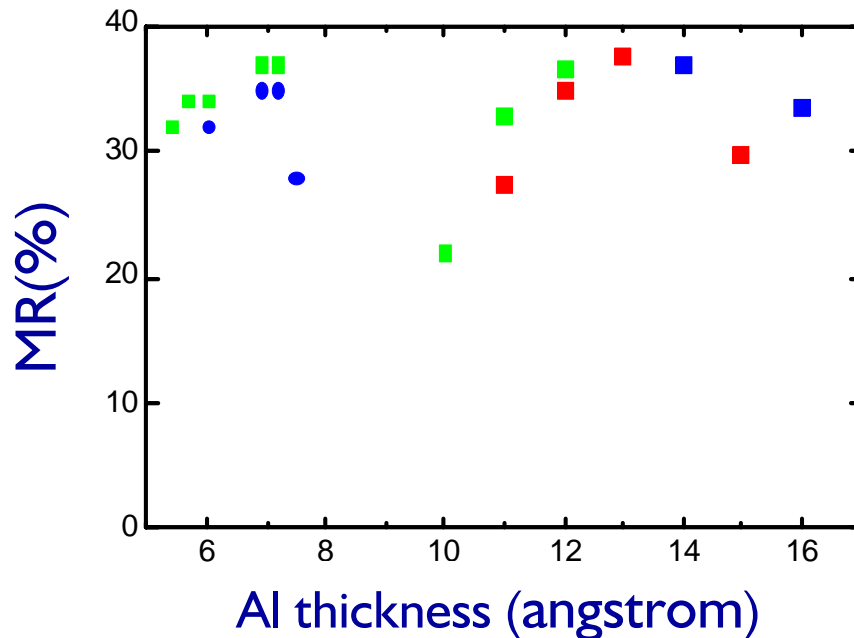
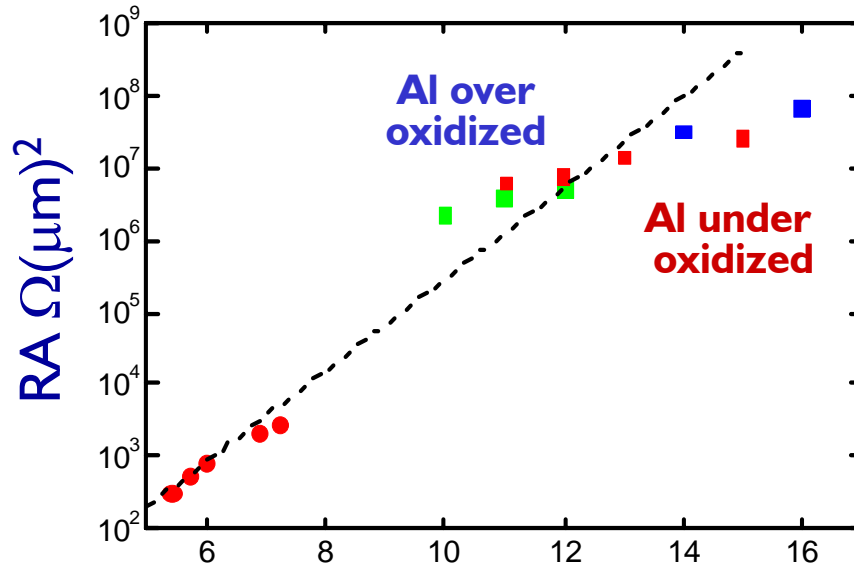
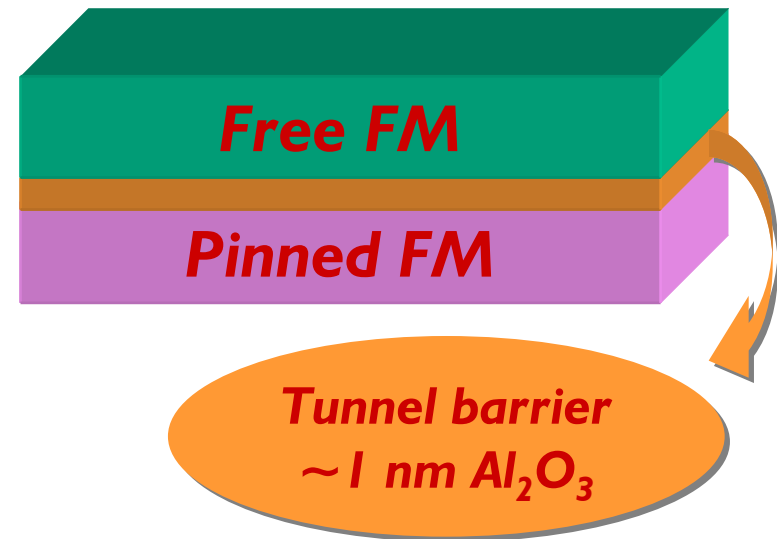


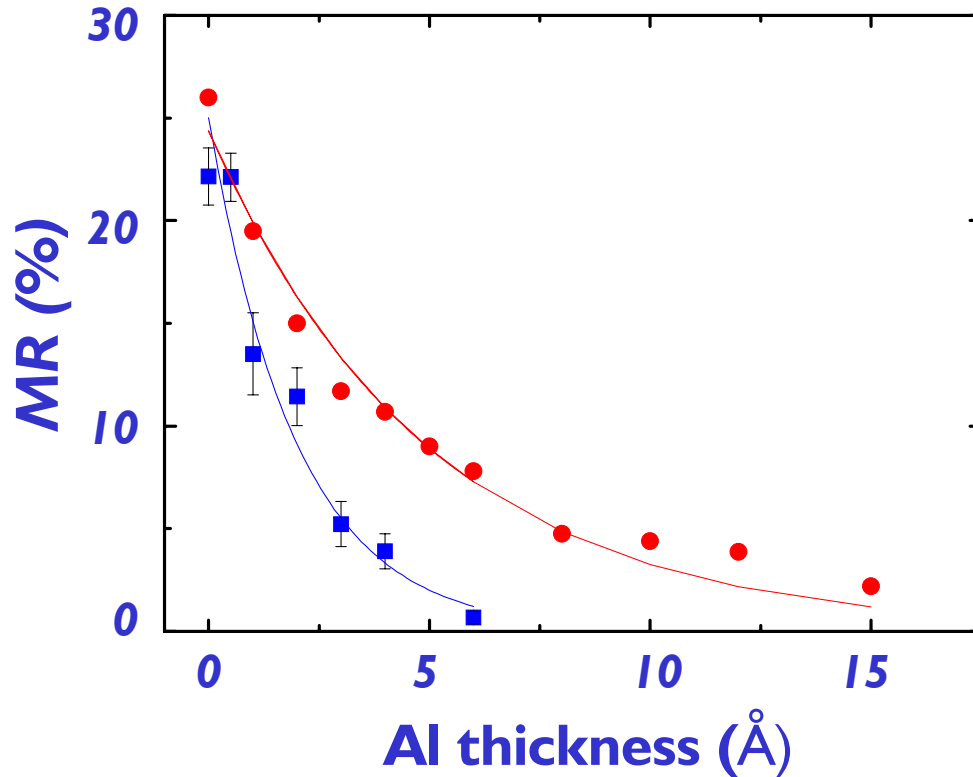
Dependence of MR and R on Al thickness



- ◆ 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

$\text{Ni}_{40}\text{Fe}_{60}$

$\text{Co}_{84}\text{Fe}_{16}$

Decay length

$\lambda = 2.3 \text{ \AA}$

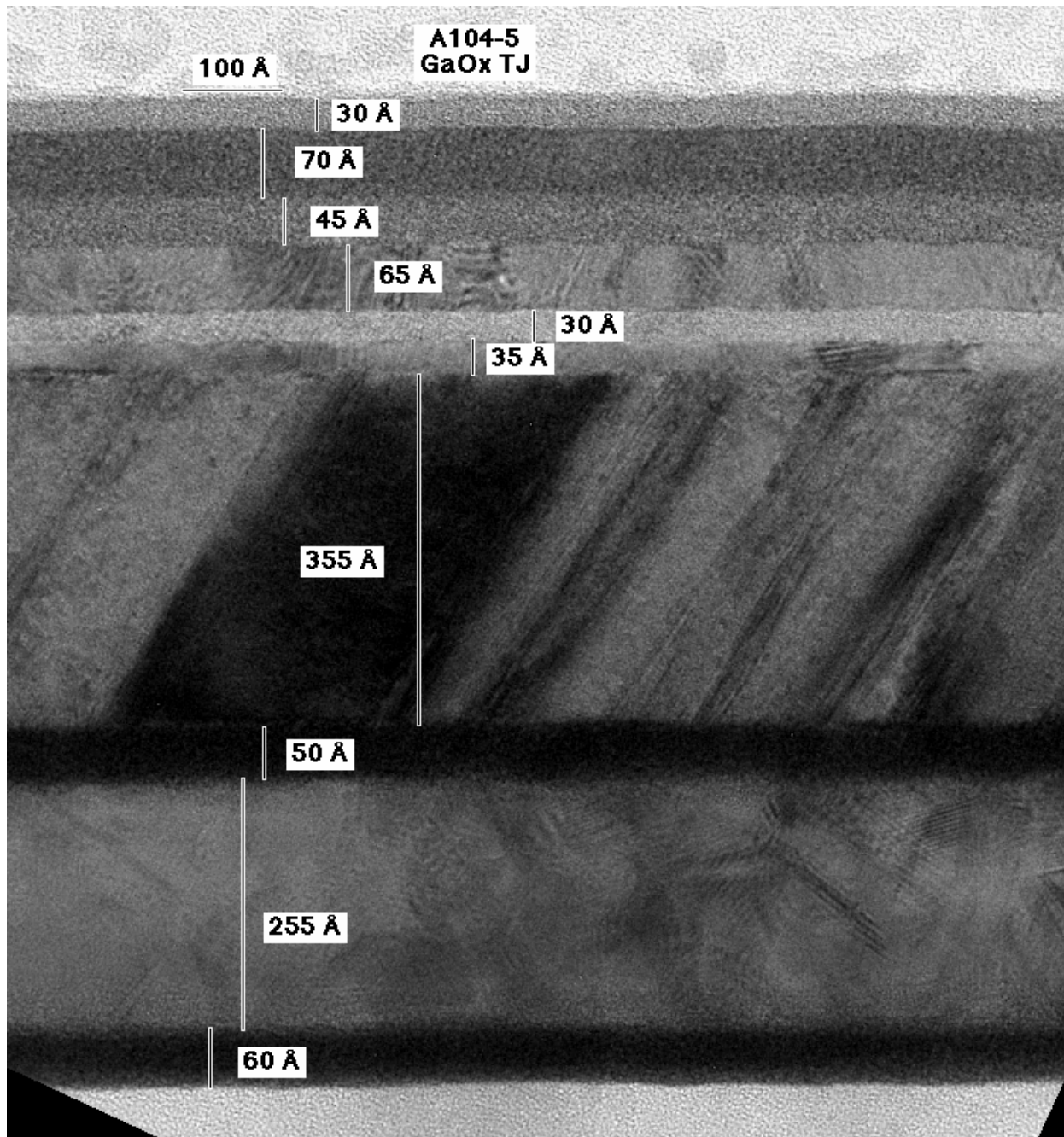
$\lambda = 5.0 \text{ \AA}$

Tunnel barrier
 $\sim 1 \text{ nm Al}_2\text{O}_3$

Al interface layer



XTEM of Typical MTJ



10CoFe/50Py (Free FM)

Barrier Ga_2O_3

20CoFe/15Fe
(pinned FM)

275IrMn
(Antiferromagnet)

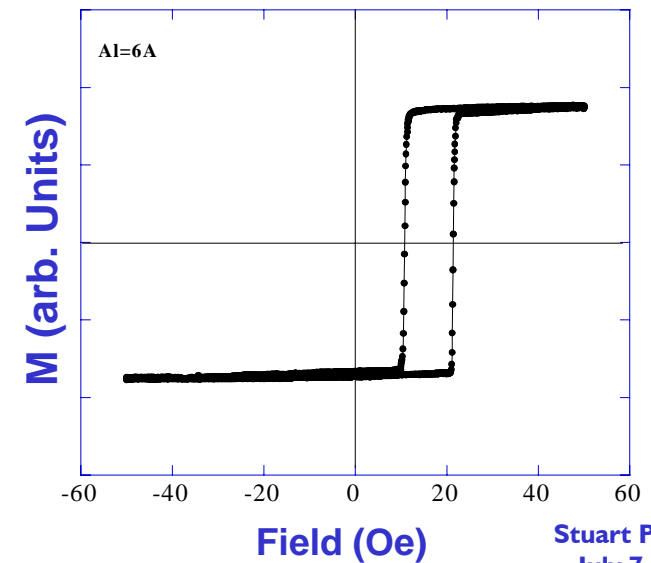
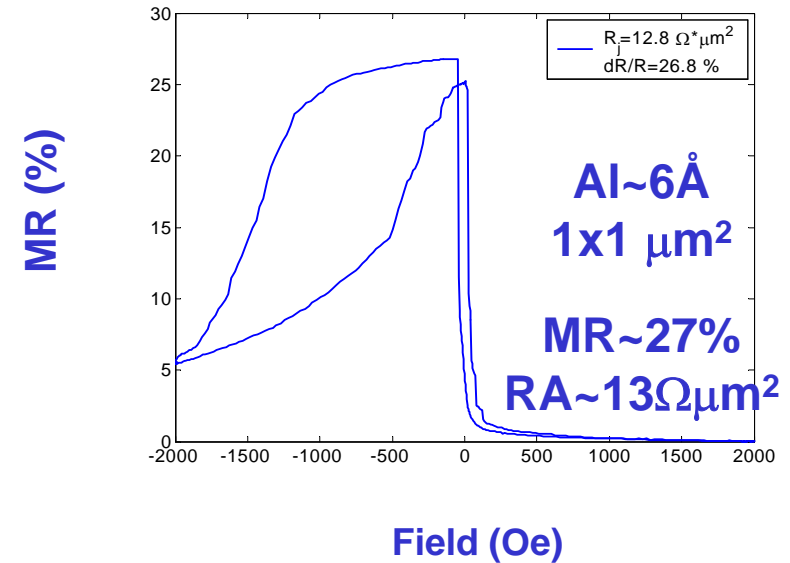
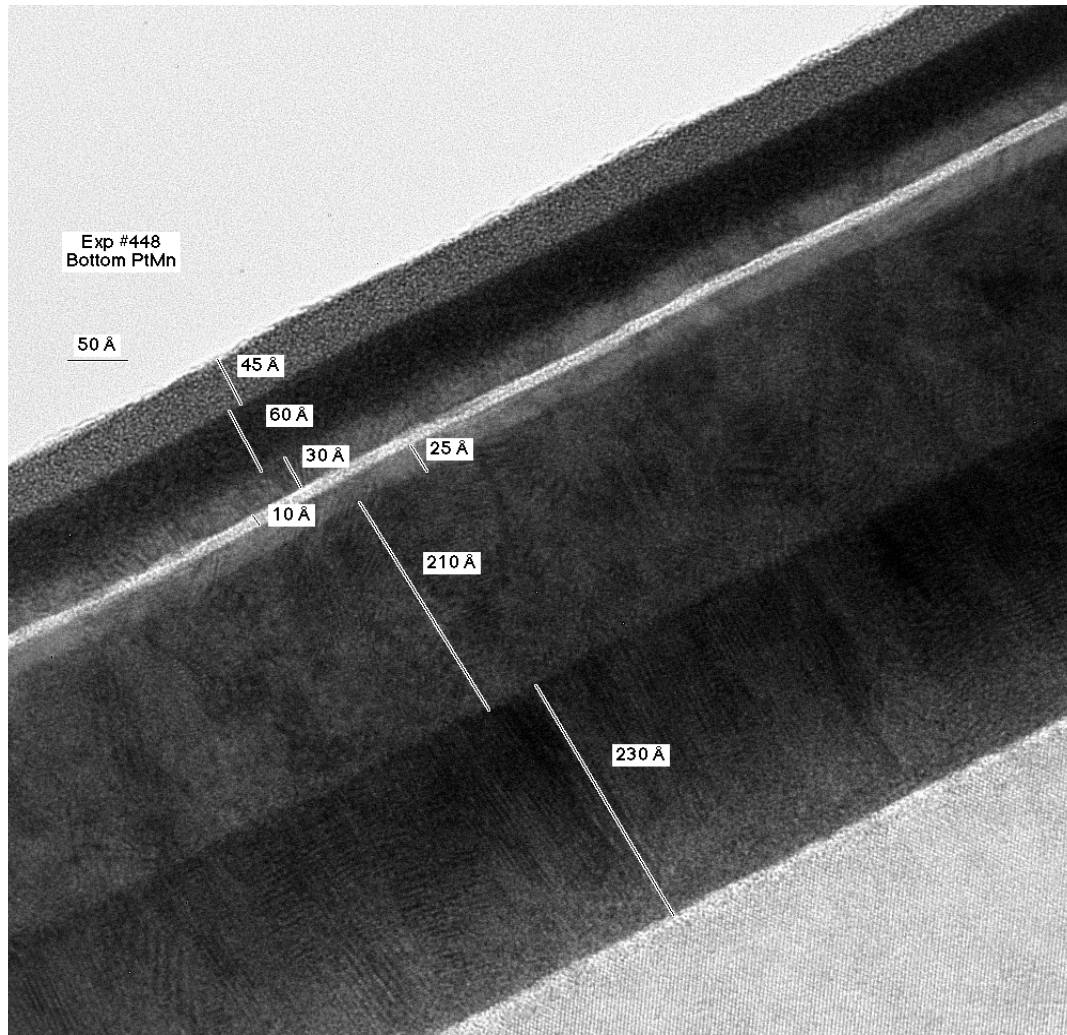
50Ta

200Cu

50Ta

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

Ta(200Å)/PtMn(250Å)/Co₈₀Fe₂₀(15Å)/Al(6Å)+O₂/Co₈₀Fe₂₀(10Å)/Ni₈₁Fe₁₉(46Å)/Ta(100Å)

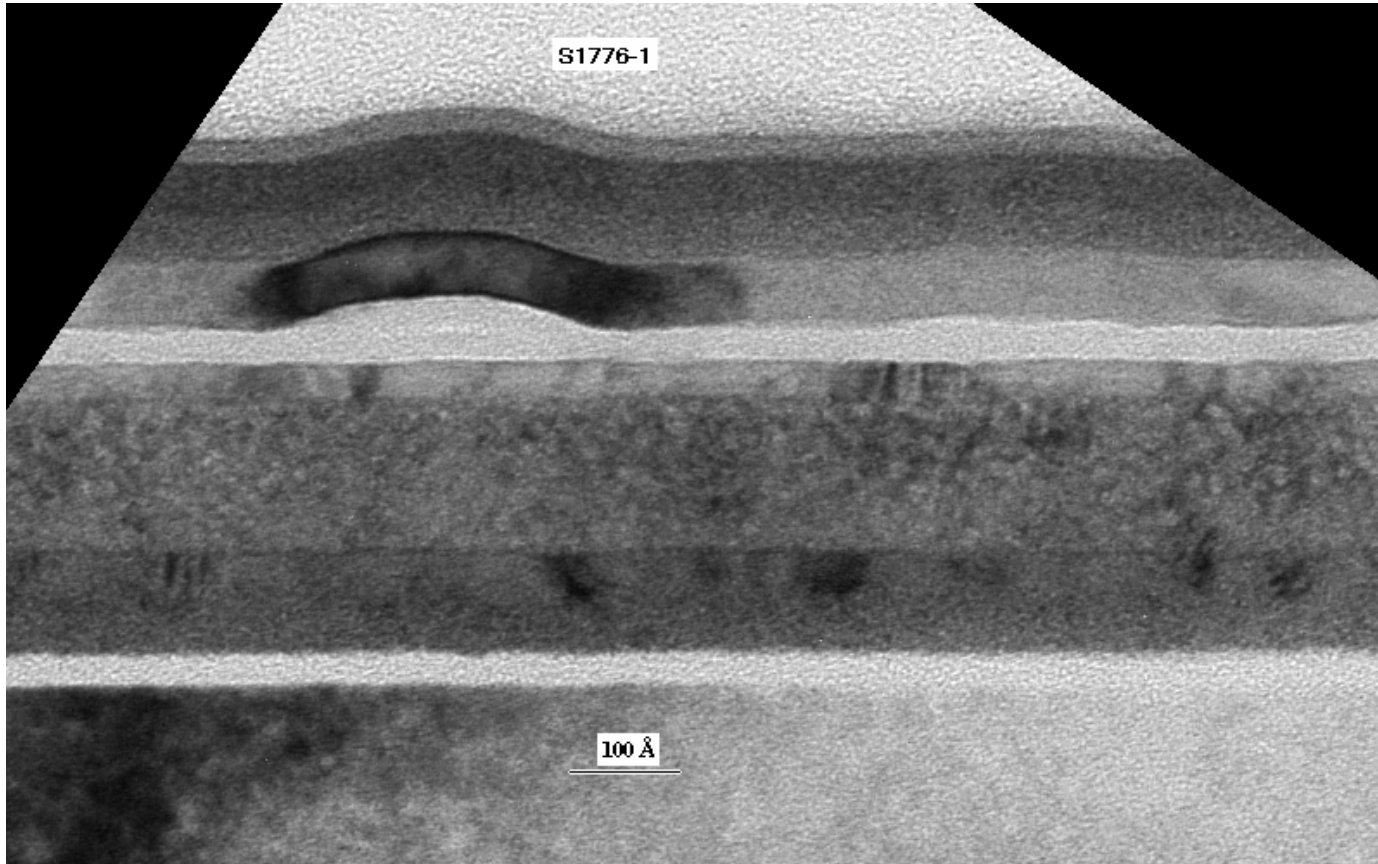


Aluminum Oxide Tunnel Barrier

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 $\text{Al}_2\text{O}_3 \sim 4.3 \text{ \AA}$!
 - ◆ 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

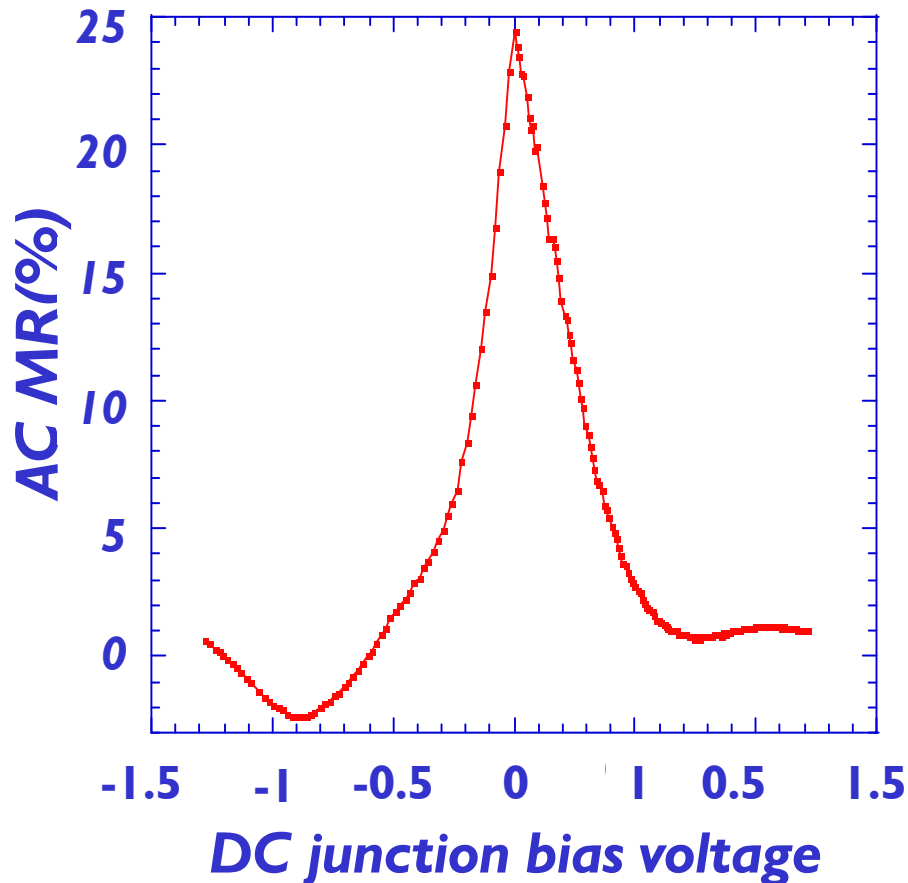


Questions

- ◆ 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?

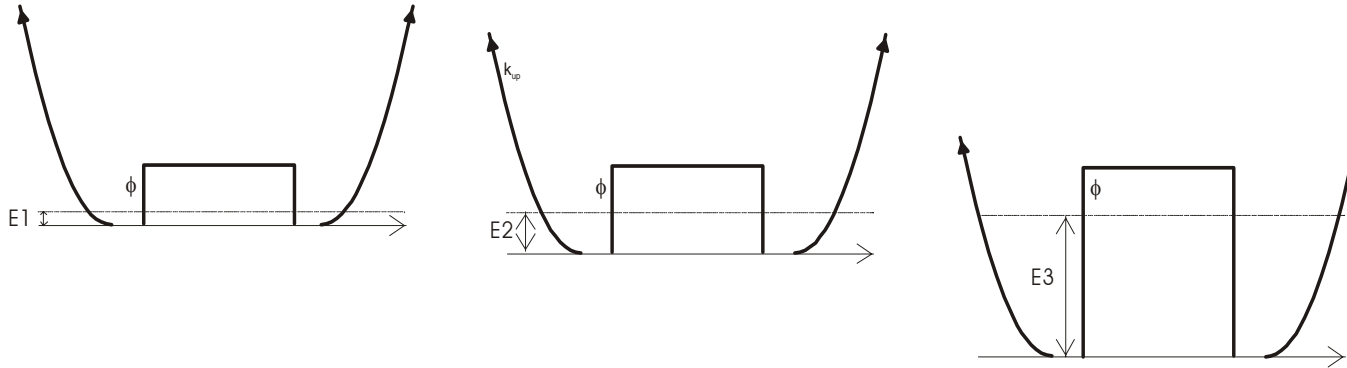
Oscillatory variation of MR with Bias Voltage

Si/ 70Å Pd/100ÅCo/20Å Al₂O₃ / 300Å NiFe



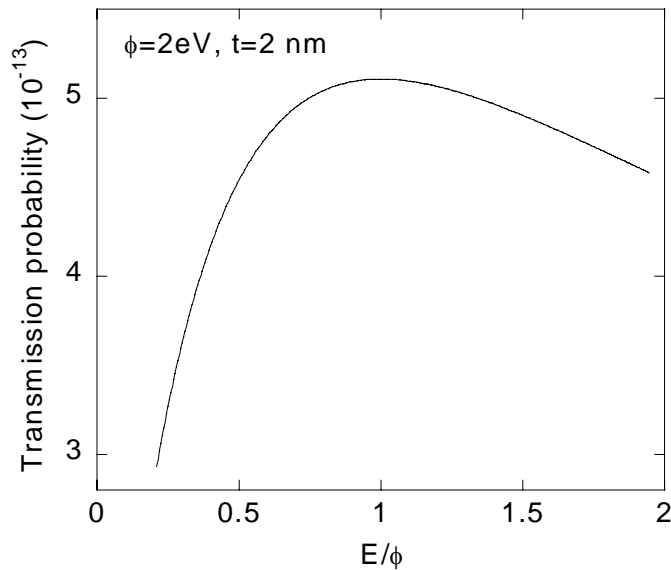
- Magneto-conductance determined from ac conductance vs dc bias voltage curves for parallel and anti-parallel alignment of ferromagnetic layers
- MR oscillates through zero MR for negative bias voltage
- Weak MR oscillation for positive bias voltage

Exact Free Electron Model of Tunneling



Transmission probability depends on electron energy relative to barrier height

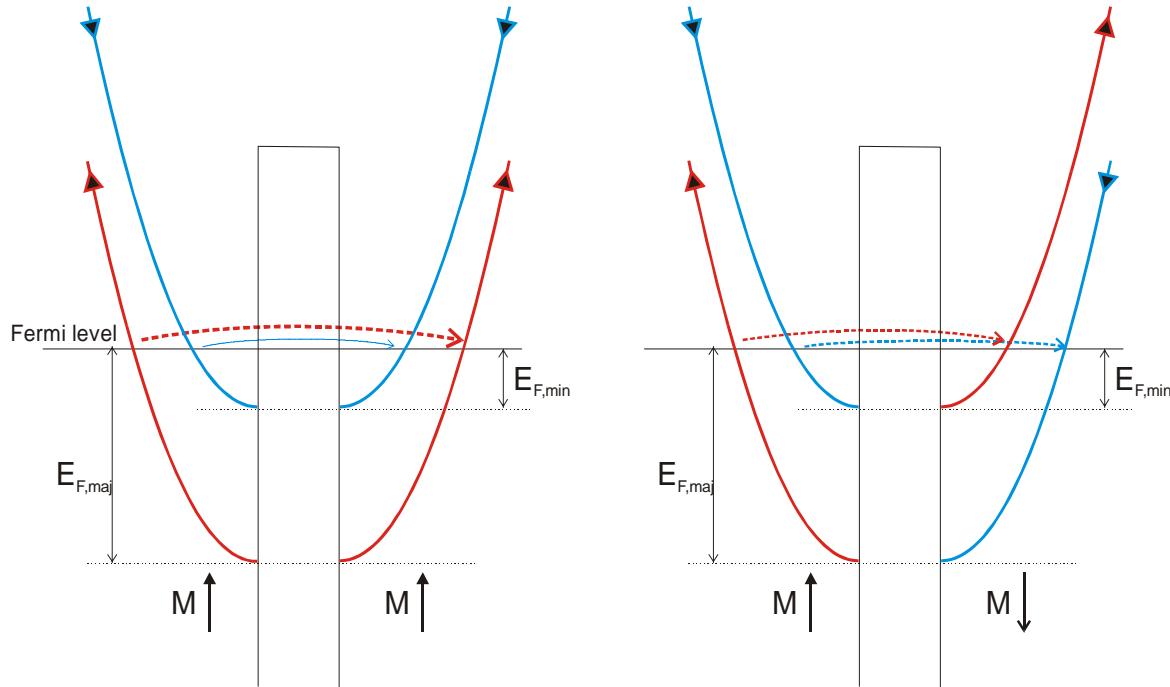
Transmission probability vs E/ϕ



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



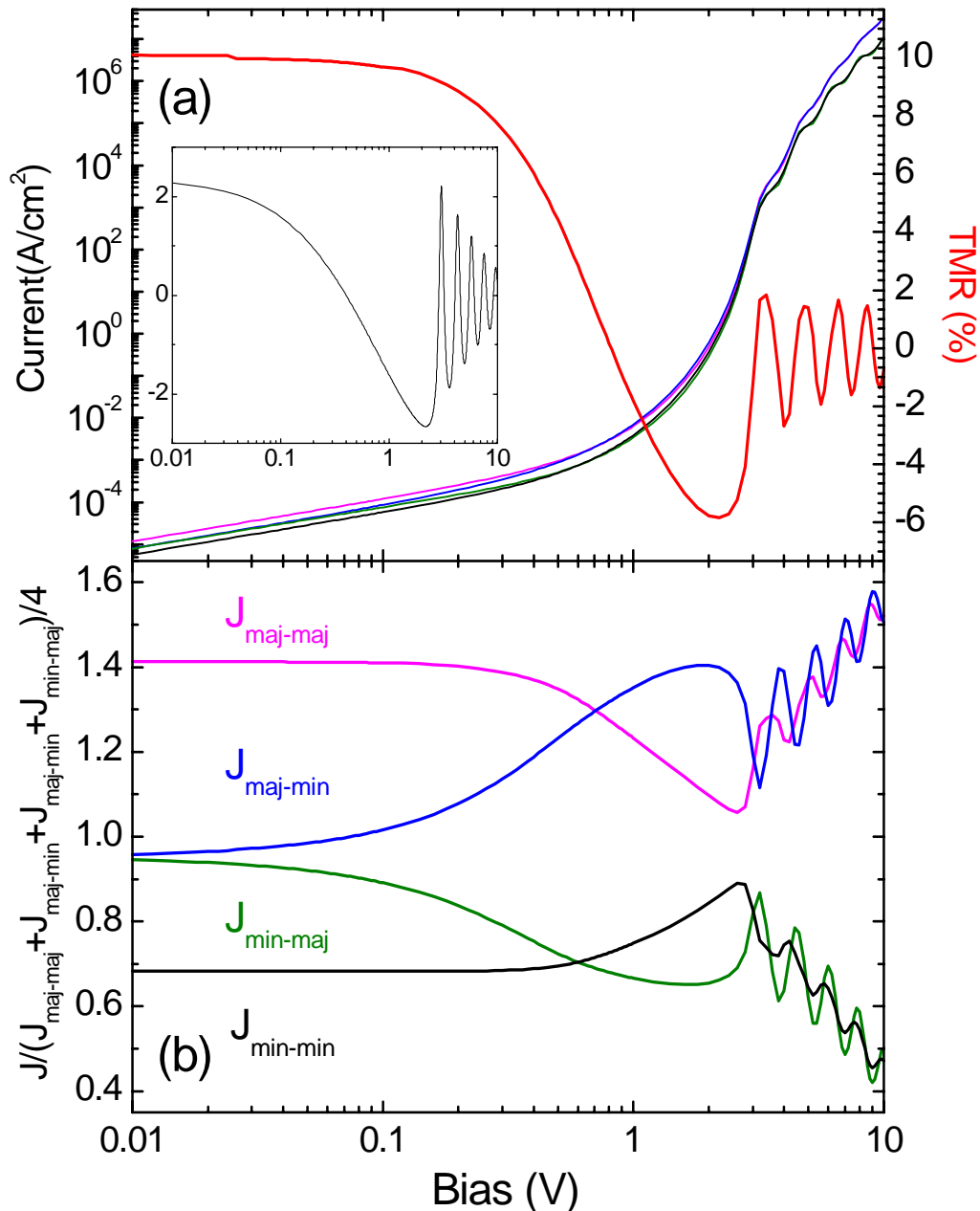
Assume exchange split parabolic bands in Ferromagnet:
Majority and minority bands have different Fermi energies

Transmission probability maximized when

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

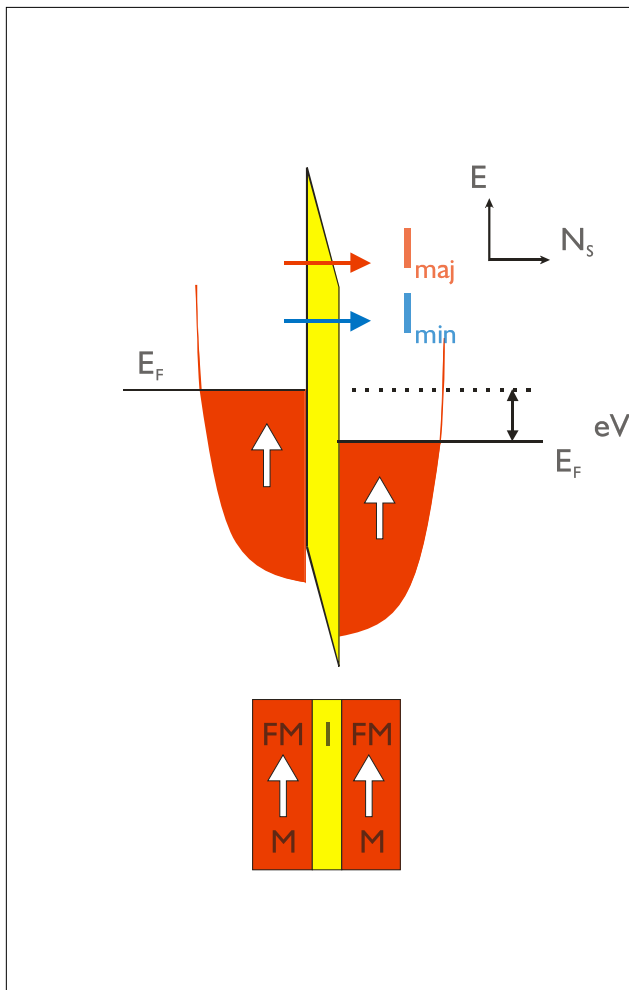
Or for band with Fermi energy closest to barrier height B

Bias Dependence of MR: Exact Free Electron Model

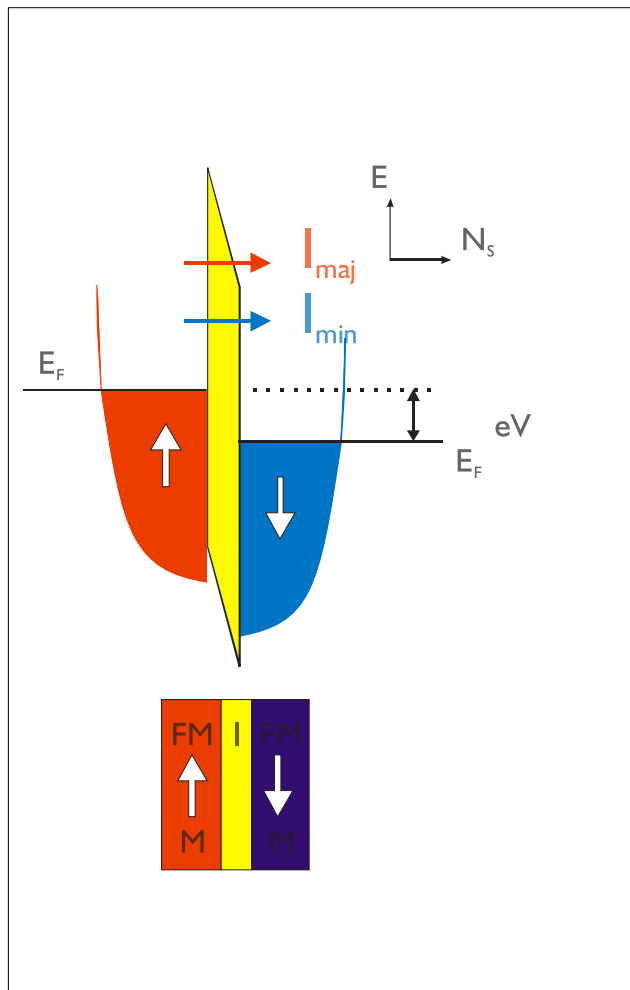


- Model shows TMR decreases with bias and changes sign
 - Resonances in insulator conduction band
- Bias dependence of MR caused by different bias dependence of spin polarized currents

Spin Polarized Electron Tunneling: FM-I-FM



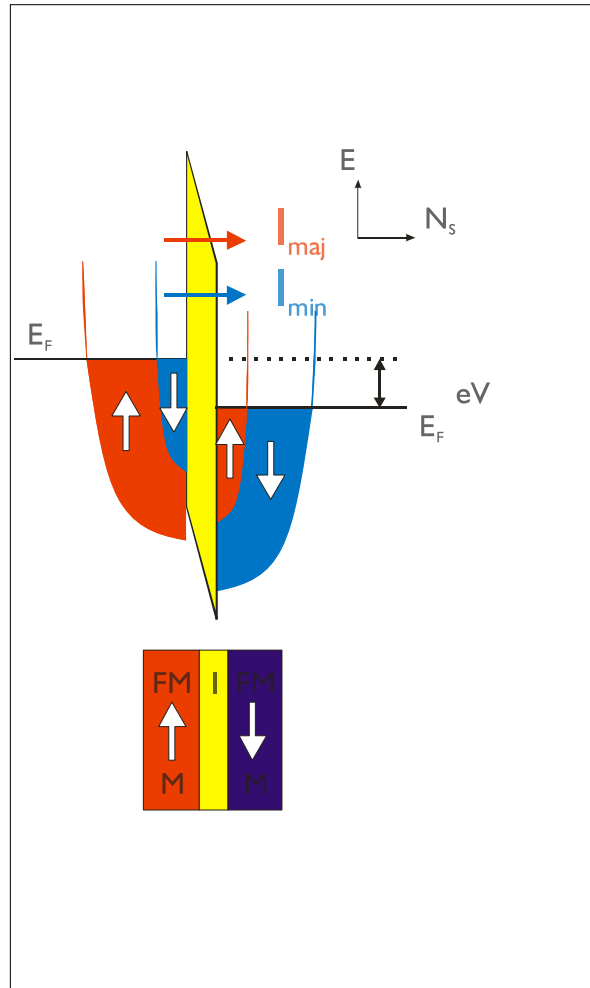
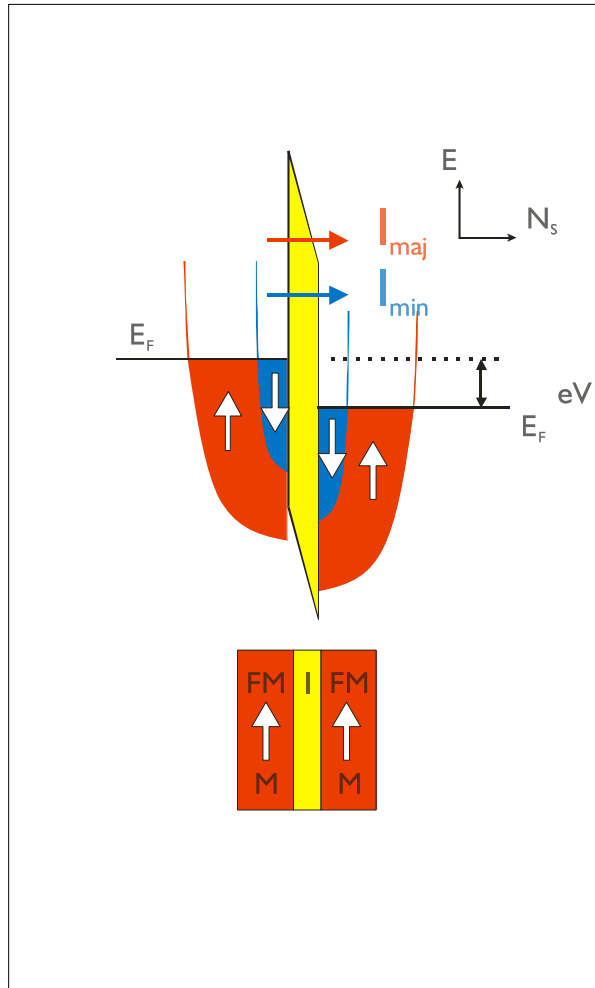
$$I_P \approx N_{\uparrow}^1 N_{\uparrow}^2$$



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



Spin Polarized Electron Tunneling: FM-I-FM



Julliere (1975)

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

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



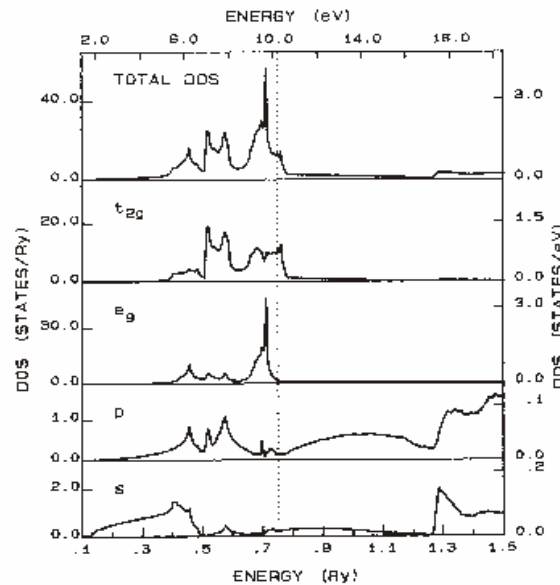
$$I_P \approx N_{\uparrow}^1 N_{\uparrow}^2 + N_{\downarrow}^1 N_{\downarrow}^2$$

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

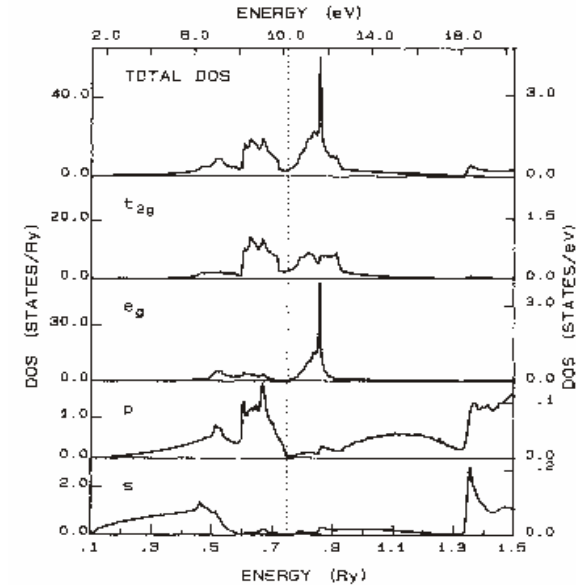
Tunneling (DOS effect)

- 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:

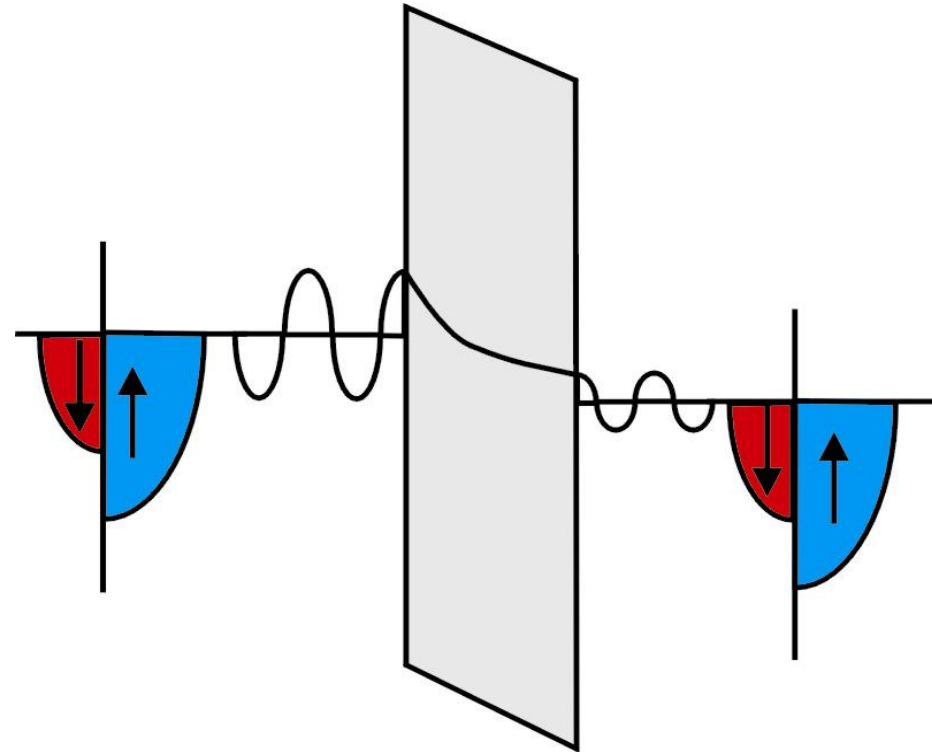
- Metals
- Superconductor
- Semiconductor

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

Spin polarization in materials (simple picture)

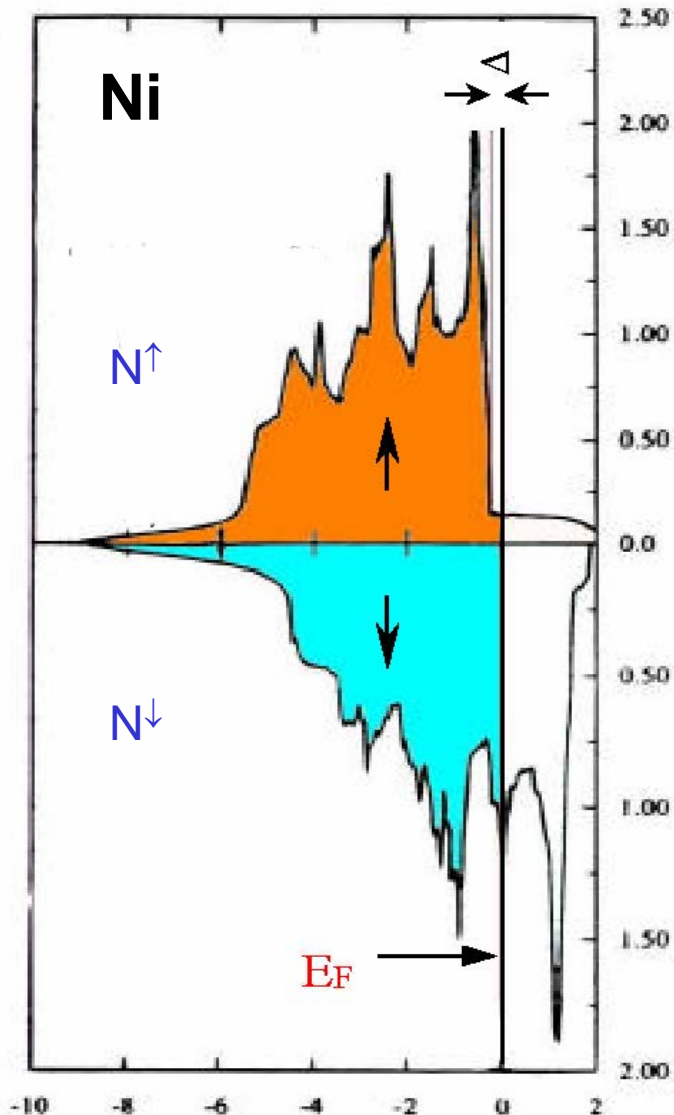
- Spin-bands are exchange split giving rise to different DOS at E_f for Spin up and spin down.
 - This spin imbalance in tunneling current then called “Spin Polarized” current
 - **In devices, the tunneling spin polarization (TSP) depends on transmission probability and DOS.**
- Spin polarization is not intrinsic!

- Spin polarization depends on:
- barrier height
 - barrier shape
 - degree of disorder in barrier
 - bonding at F/I interfaces
 - electronic structure of insulator



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

Spin-Dependent Tunneling and Density of States



- ◆ Julliere:
$$\text{TMR} = \frac{P_1 P_2}{1 - P_1 P_2}$$

How can P be related to the properties of the material?

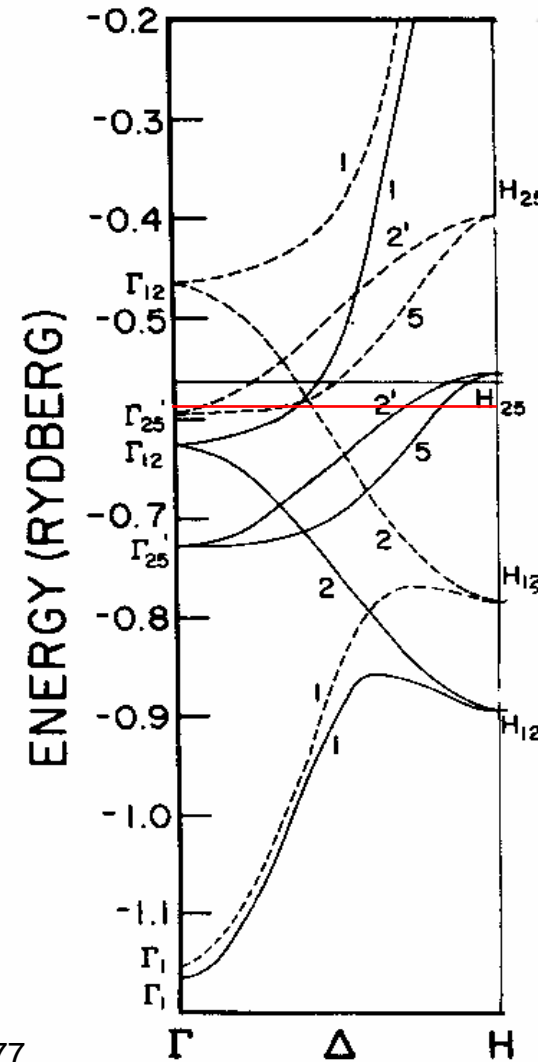
- ◆ First idea: Spin polarization P equals the spin-polarization of all electrons at the Fermi energy of the ferromagnet:

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

- ◆ 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

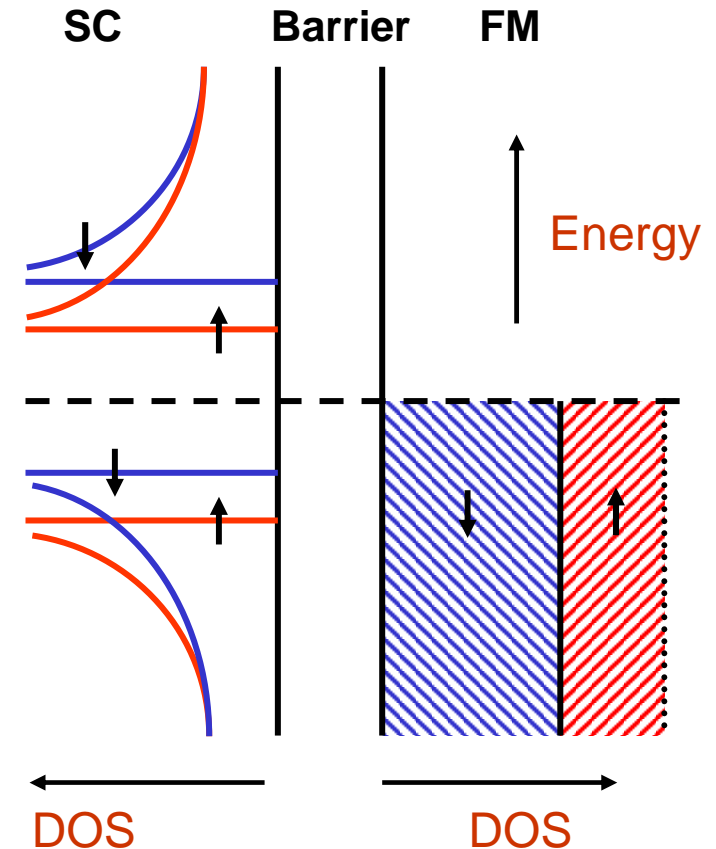
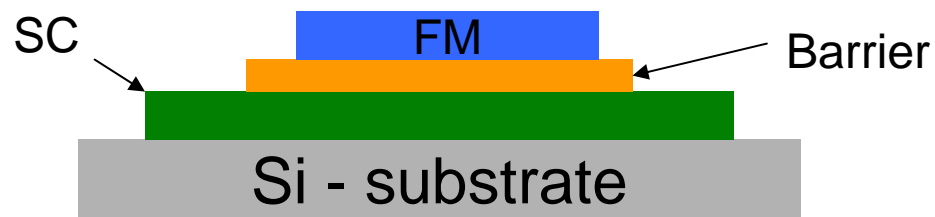
- Spin polarization can be measured with variety of techniques
 - What is T for each measurement technique?
- Photoemission
 - Measures DOS with $\mathbf{T} \sim \mathbf{I}$
- Point Contact Andreev Reflection (PCAR)
 - Measures with $\mathbf{T} = \mathbf{v}_f$
- Tunneling in Superconductors (STS)
 -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

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

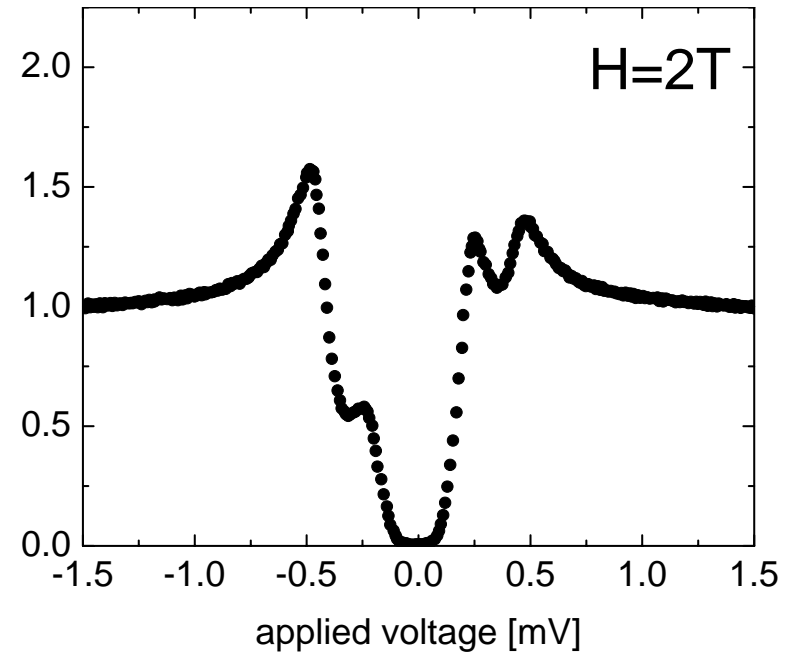
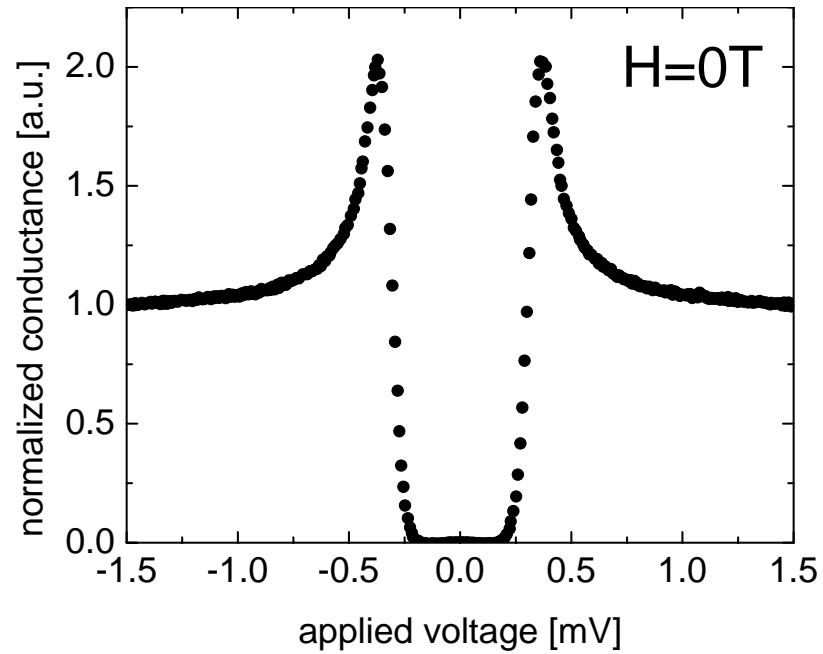
Nadygorny Phys Rev B **63** 184433

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



Conductance Curves



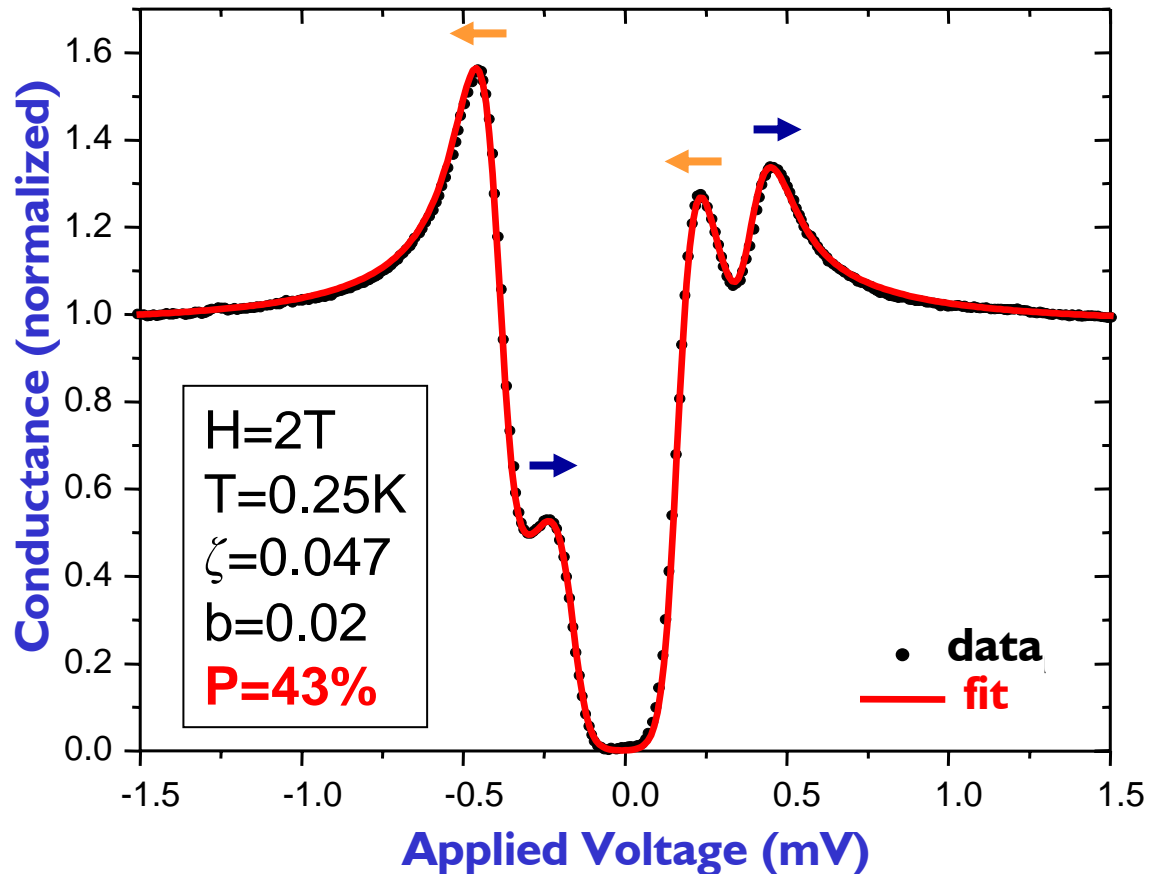
Conductance curves for a $\text{Al}|\text{Al}_2\text{O}_3|\text{Co}$ junction

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.

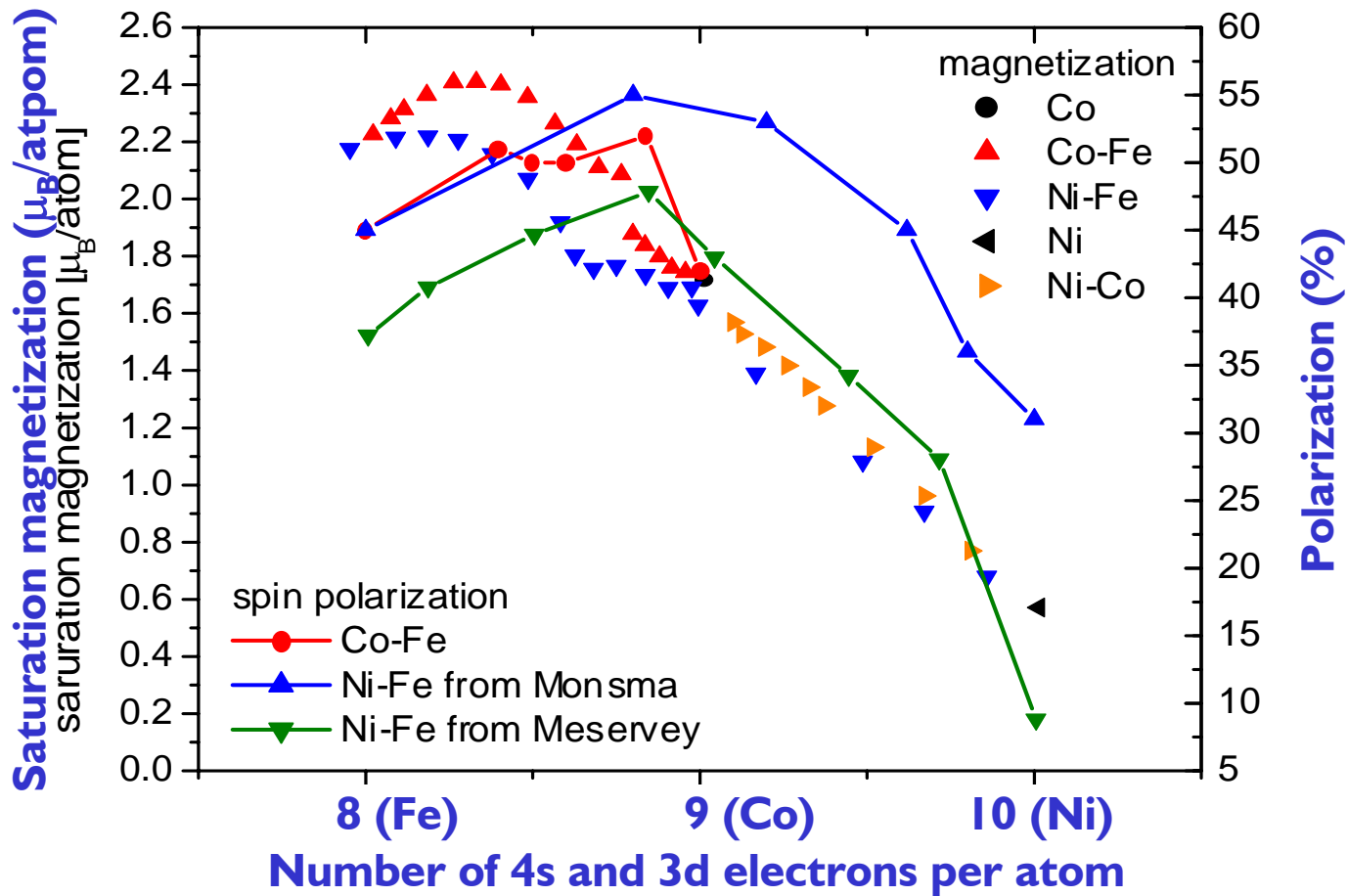
Parameters in fit:

- ◆ 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



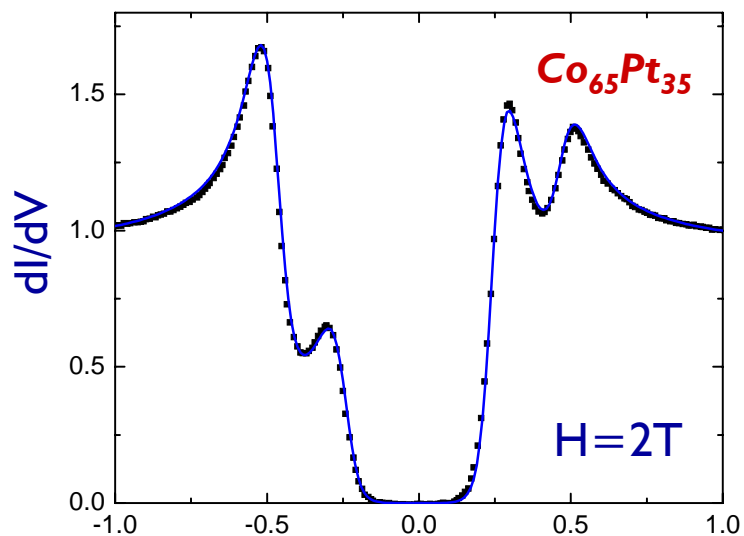
Fitting procedure: see, for example, Worledge Phys Rev B **62** 447 (2000)

Relationship of Spin Polarization to Magnetization

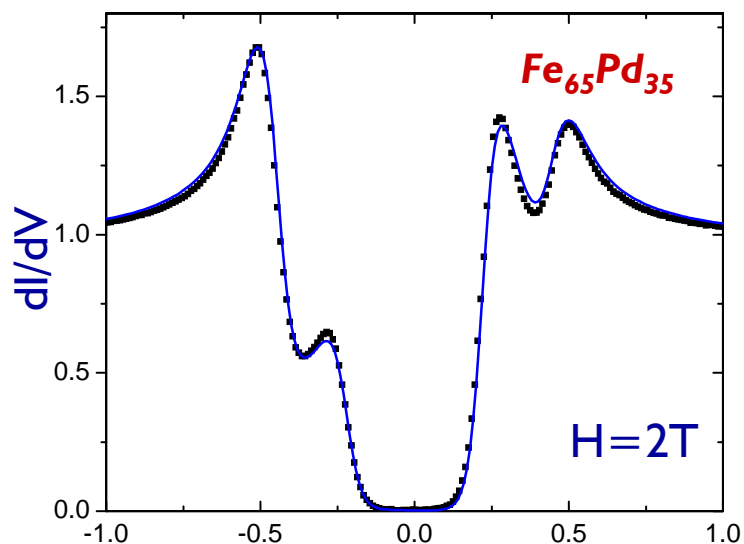
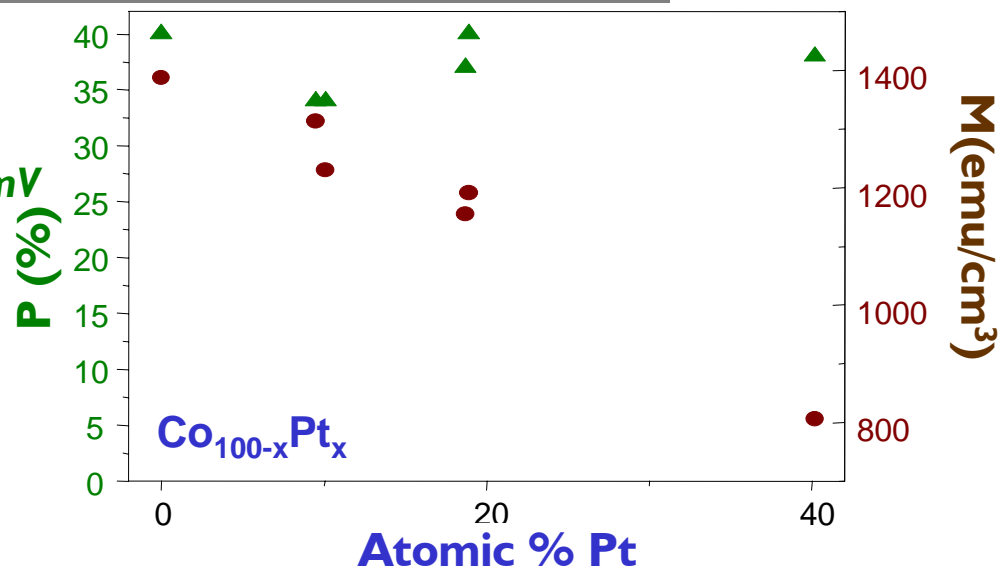


- ◆ Spin-polarization for Fe, Co and Ni and their alloys measured to be positive and around 45%
 - ◆ Weak relationship between TMR and magnetization (c.f. $[\text{Co}_{70}\text{Fe}_{30}]\text{B}_{20}$: TMR~60%)
- ◆ Results are in contradiction to photoemission results

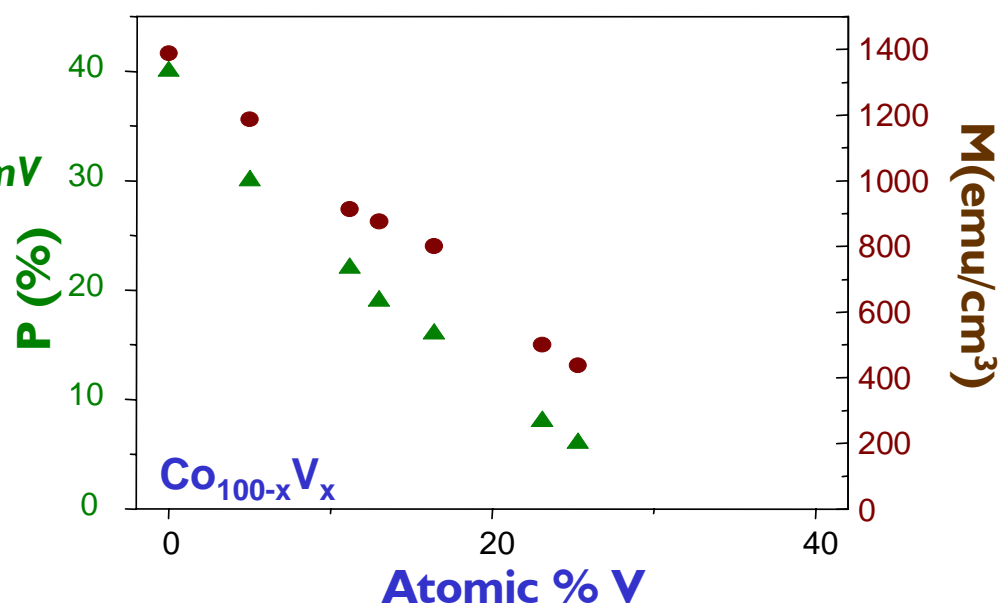
Spin Polarization of Alloys From superconducting Tunneling Spectroscopy



H=2T
T=0.241K
Gap=0.38mV
 $\zeta=0.019$
b=0.037
P=41%



H=2T
T=0.241K
Gap=0.37mV
 $\zeta=0.028$
b=0.03
P=41%



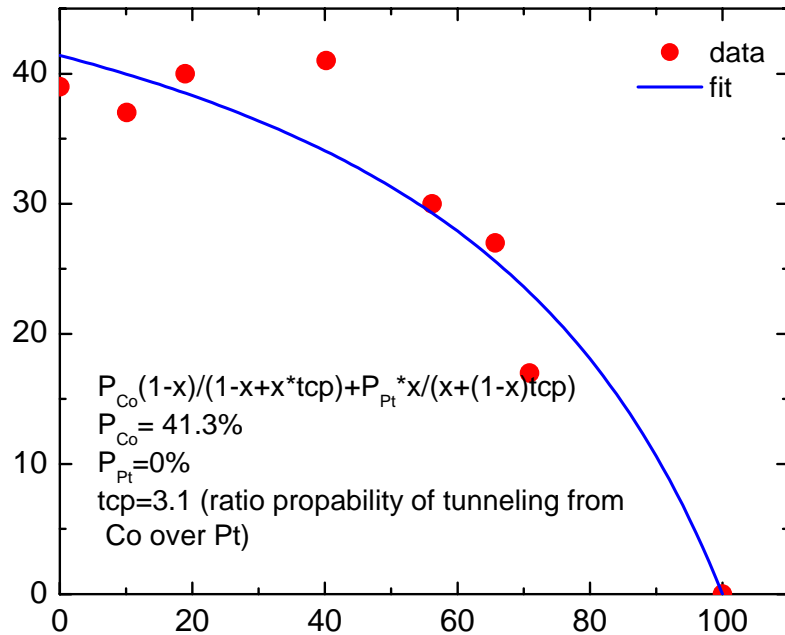
Bias voltage (mV)

Christian Kaiser

Stuart Parkin
July 7, 2003

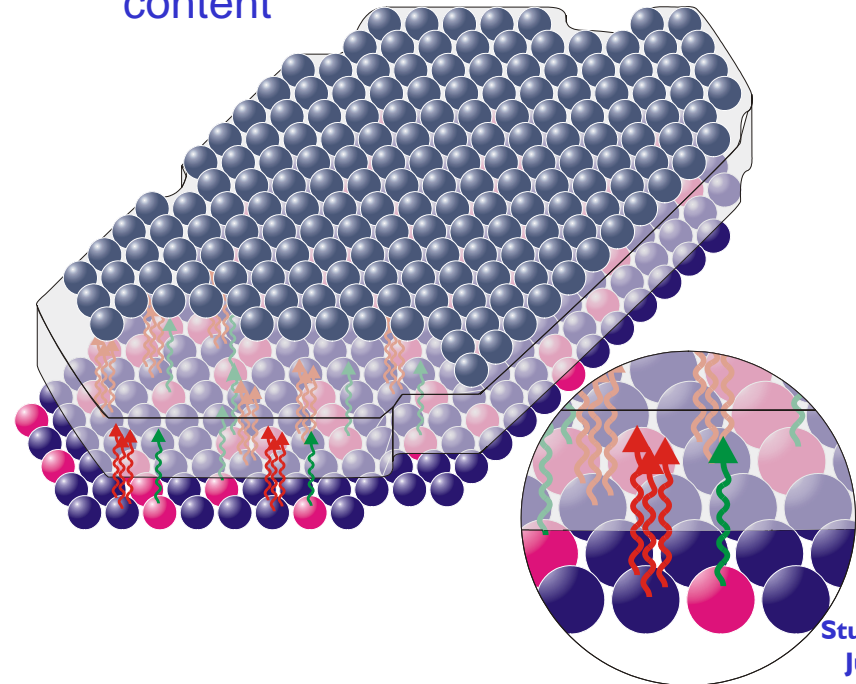
Tunneling Matrix Elements in $\text{Co}_{1-x}\text{Pt}_x$ Alloys

Spin Polarization (%)



x (atomic % Platinum)

- ◆ 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



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 dominated by the spin-polarization of the electrons tunneling from Co sites
- spin polarization independent of composition

