Spin-Dependent Tunneling in Magnetic Tunnel Junctions

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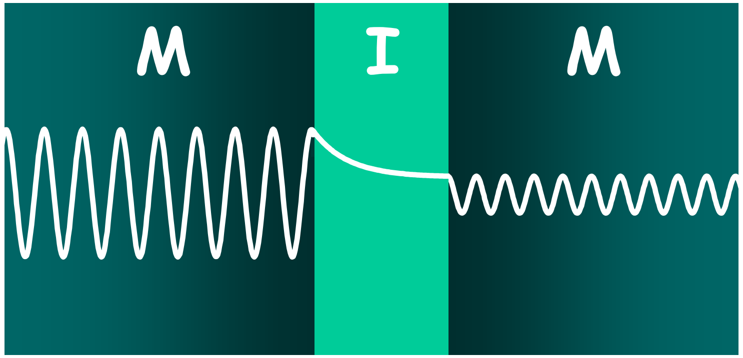
Electron Tunneling

Tunnel junction



- quantum-mechanical effect
- observed in tunnel junctions

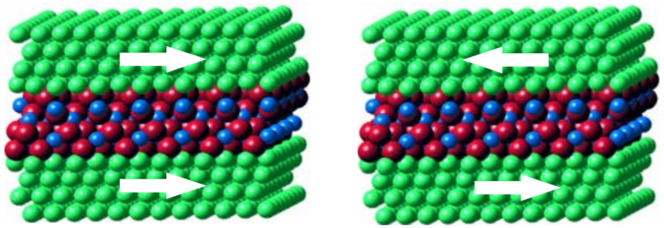
Some applications:

- Scanning tunneling microscopy (STM)
- Josephson junctions: superconducting quantum interference devices (SQUIDs)
- Field emission (Fowler-Nordheim tunneling): electron source in flash memories, electron microscopy and field emission displays
- Magnetic tunnel junctions: magnetic field sensors, magnetic random access memories (MRAM)

Tunneling magnetoresistance (TMR)

Magnetic tunnel junction (MTJ)

$$TMR = \frac{G_{AP} - G_P}{G_{AP}}$$



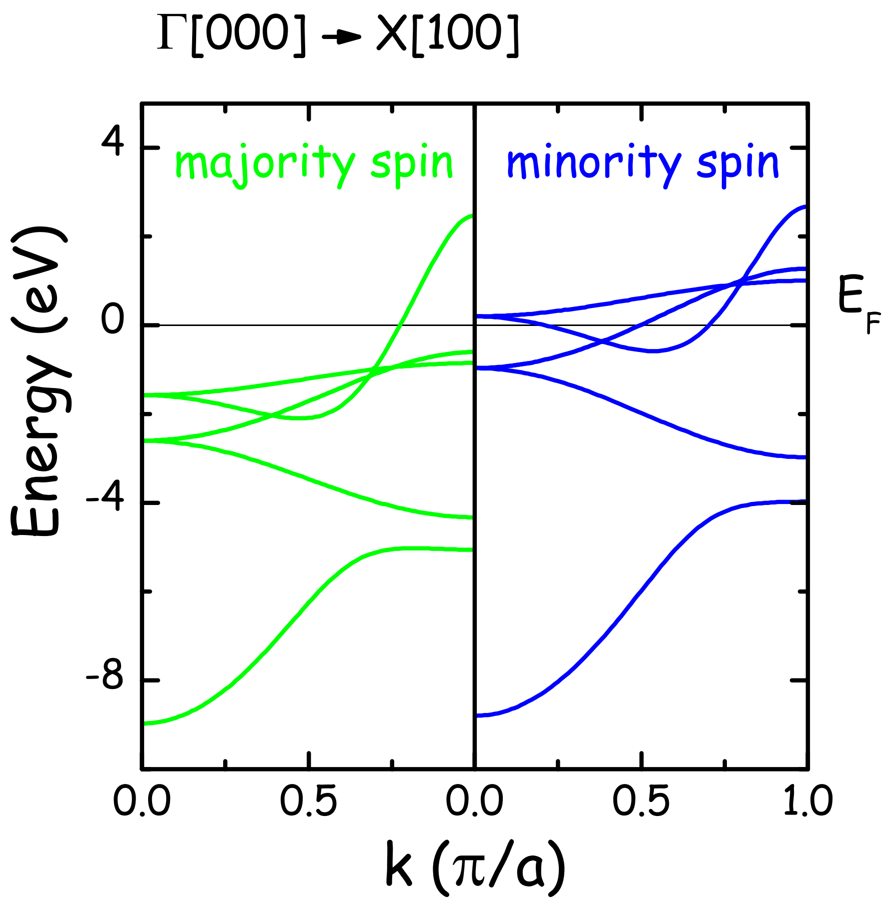
Ferromagnet
Insulator
Ferromagnet

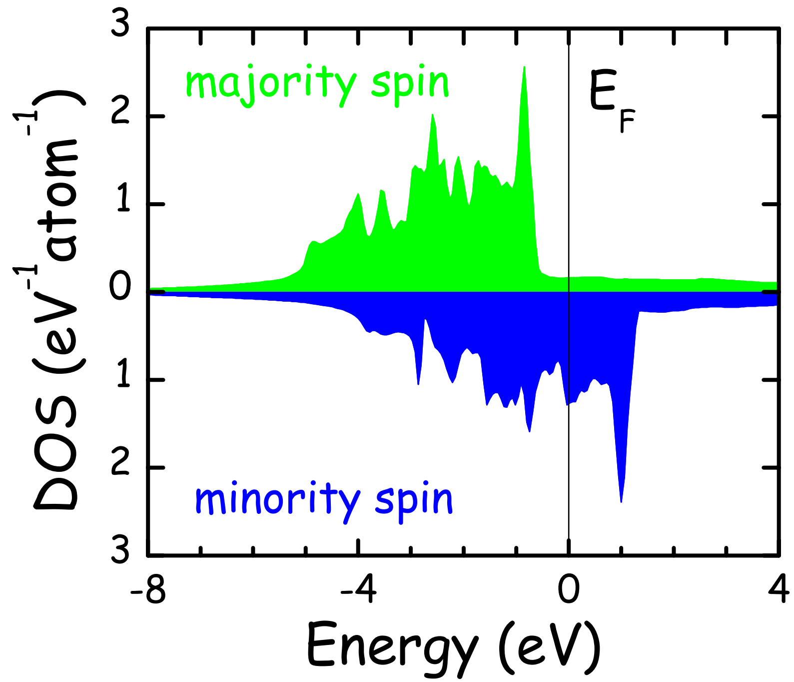
Jullière, Phys. Lett. A 54, 225 (1975) – realization of a MTJ
Maekawa and Gäfvert, IEEE Trans. Magn. 18, 707 (1982) – TMR-magnetization switching correlation
Miyazaki and Tezuka, JMMM 139, L231 (1995) – large TMR
Moodera et al., PRL 74, 3273 (1995) – large reproducible TMR
Parkin et al., Nat. Mat. 3, 862 (2004) – giant TMR, MgO-based MTJ
Yuasa et al., Nat. Mat. 3, 868 (2004) - giant TMR, MgO-based MTJ

FM|Al_2O_3|FM MTJs: TMR~70%

FeCo|MgO|FeCo MTJs: TMR>300%

Band structure of Co





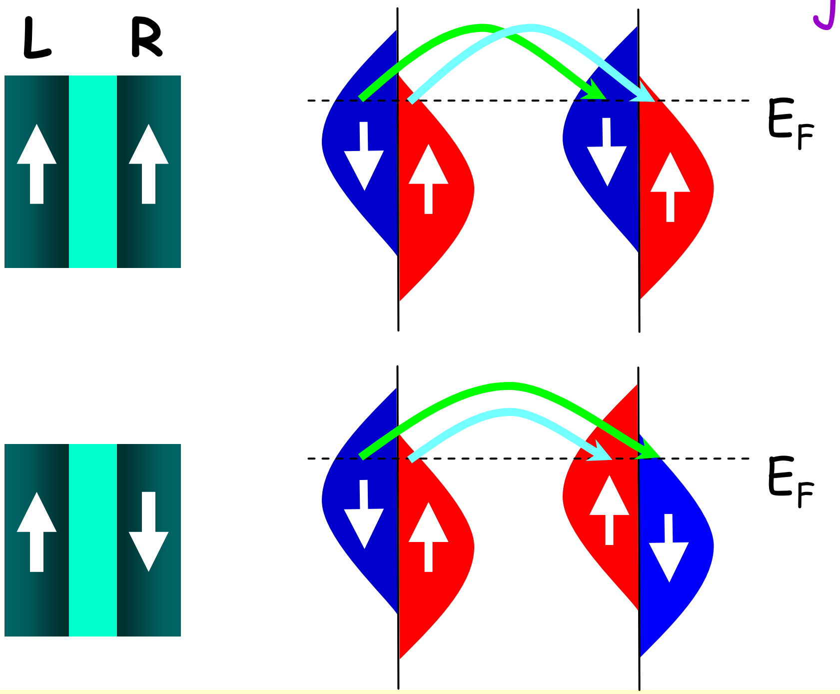
$3d^7 4s^2$ $n = 9$ $n_\uparrow = 5.3$ $n_\downarrow = 3.7$

$$m = (n_\uparrow - n_\downarrow) m_s = 1.6 \mu_B$$

- Majority- and minority-spin electrons
- Exchange-split bands

Origin of TMR

Jullière, Phys. Lett. A **54**, 225 (1975)



$$G_{\uparrow\uparrow} \propto n_L^{\uparrow} n_R^{\uparrow} + n_L^{\downarrow} n_R^{\downarrow}$$

$$G_{\uparrow\downarrow} \propto n_L^{\uparrow} n_R^{\downarrow} + n_L^{\downarrow} n_R^{\uparrow}$$

Jullière's formula:

$$TMR \equiv \frac{G_{\uparrow\downarrow} - G_{\uparrow\uparrow}}{G_{\uparrow\downarrow}} = \frac{2P_L P_R}{1 - P_L P_R}$$

Tunneling spin polarization of ferromagnets:

$$P_L = \frac{n_L^{\uparrow} - n_L^{\downarrow}}{n_L^{\uparrow} + n_L^{\downarrow}} \qquad P_R = \frac{n_R^{\uparrow} - n_R^{\downarrow}}{n_R^{\uparrow} + n_R^{\downarrow}}$$

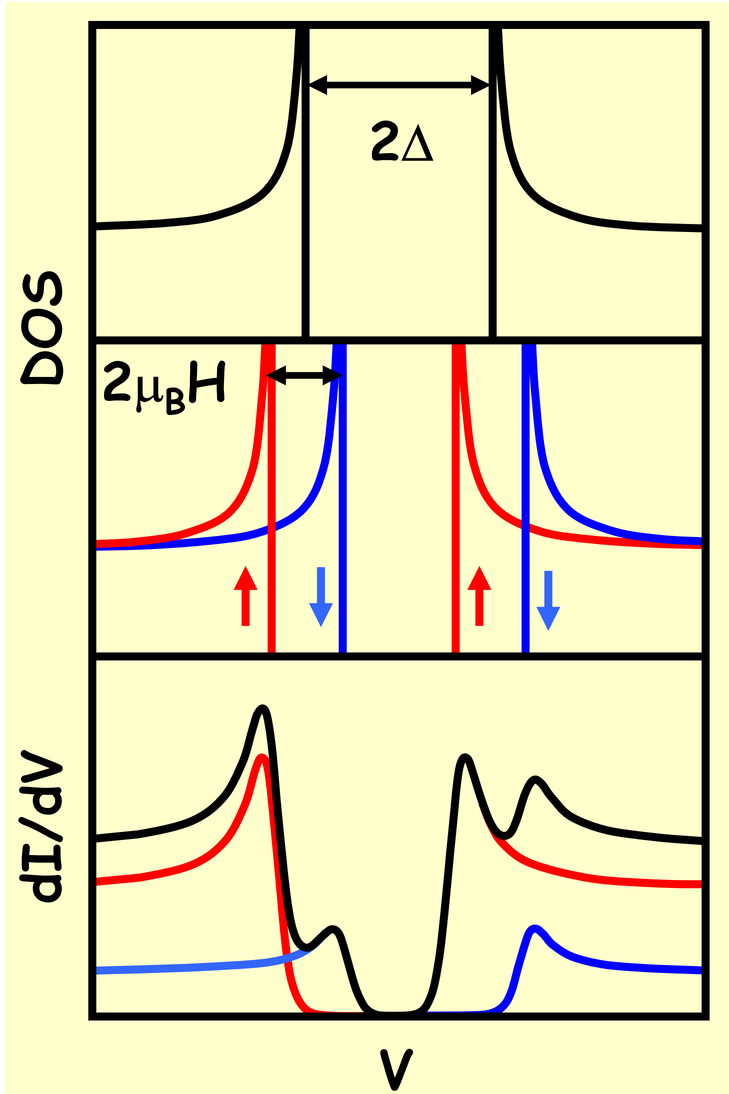
Spin-polarized tunneling

Tedrow and Meservey PRL 26, 192 (1971)

- Quantum tunneling
- Spin-split bands of ferromagnets
- DOS of superconductors

Tunneling spin polarization:

$$P_{exp} = \frac{G^{\uparrow} - G^{\downarrow}}{G^{\uparrow} + G^{\downarrow}}$$

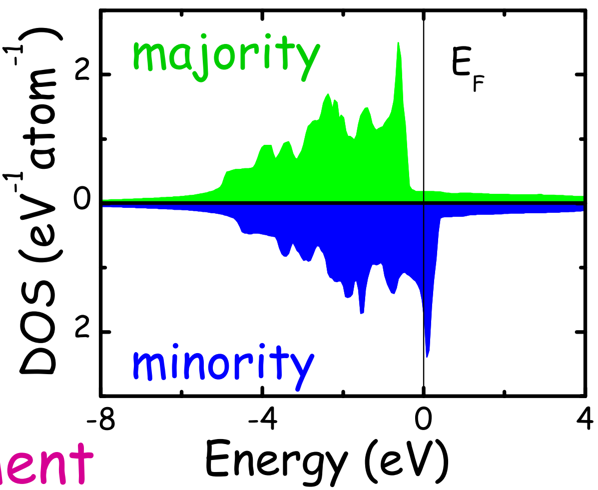


Spin polarization and TMR

Spin polarization

FM	$P_{exp} = \frac{G^{\uparrow} - G^{\downarrow}}{G^{\uparrow} + G^{\downarrow}}$	$P_{calc} = \frac{n^{\uparrow} - n^{\downarrow}}{n^{\uparrow} + n^{\downarrow}}$
Fe	+45%	+61%
Co	+42%	-77%
Ni	+32%	-81%

Ni DOS



- Contradiction between theory and experiment

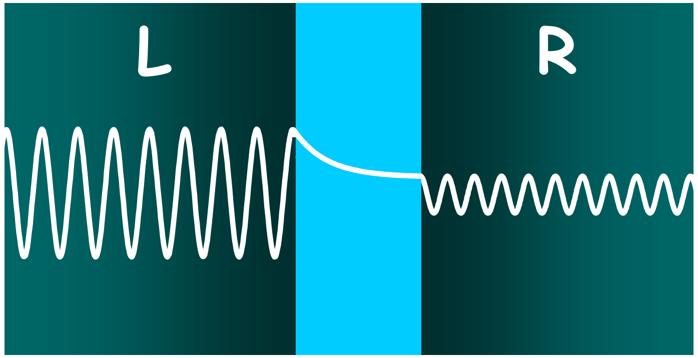
Tunneling Magnetoresistance

MTJ	Julliere	Experiment
$Ni/Al_2O_3/Ni$	25%	23%
$Co/Al_2O_3/Co$	42%	37%
$Co_{75}Fe_{25}/Al_2O_3/Co_{75}Fe_{25}$	70%	69%
$Co_{70}Fe_{30}/MgO/Co_{70}Fe_{30}$	520%	~600%

- Consistency between measured SP and TMR values

Interface Transmission Function

Belashchenko et al., PRB **69**, 174408 (2004)



$$G^\sigma = \frac{e^2}{h}\sum_{k_\parallel} T^\sigma(k_\parallel)$$ - conductance

$$T^\sigma(k_\parallel) = T_L^\sigma(k_\parallel)e^{-2\kappa(k_\parallel)d}T_R^\sigma(k_\parallel)$$

$T_L^\sigma(k_\parallel),\ T_R^\sigma(k_\parallel)$ - interface transmission functions (ITF)

$$T_{L,R}^\sigma(k_\parallel) = \frac{4\kappa k_{L,R}^\sigma}{\kappa^2 + k_{L,R}^{\sigma 2}}$$ - for free electrons

- Tunneling spin polarization is largely controlled by ITF

for thick crystalline barrier

$$P_{L,R} = \frac{T_{L,R}^\uparrow(0) - T_{L,R}^\downarrow(0)}{T_{L,R}^\uparrow(0) + T_{L,R}^\downarrow(0)}$$

for amorphous barrier

$$P_{L,R} = \frac{\langle T_{L,R}^\uparrow\rangle - \langle T_{L,R}^\downarrow\rangle}{\langle T_{L,R}^\uparrow\rangle + \langle T_{L,R}^\downarrow\rangle}$$

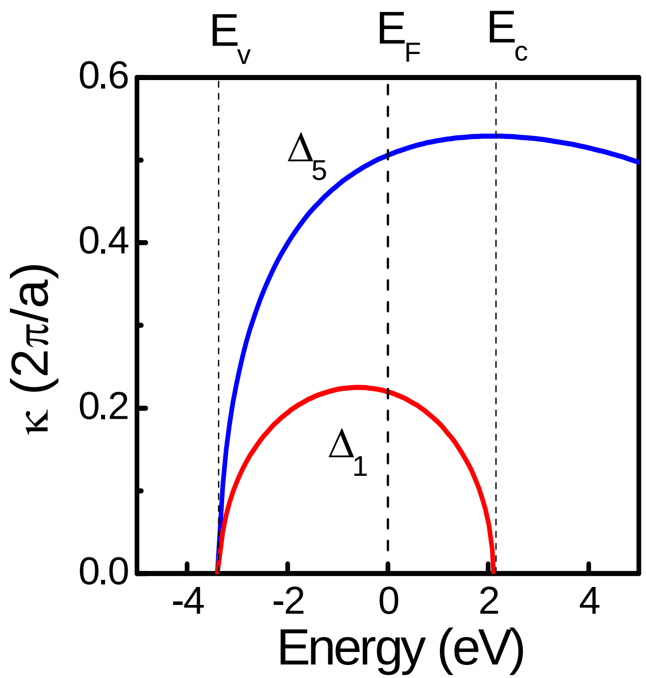
Symmetry of bands

Mavropoulos et al., PRL 85, 1091 (2000)

Insulator

Complex band structure:

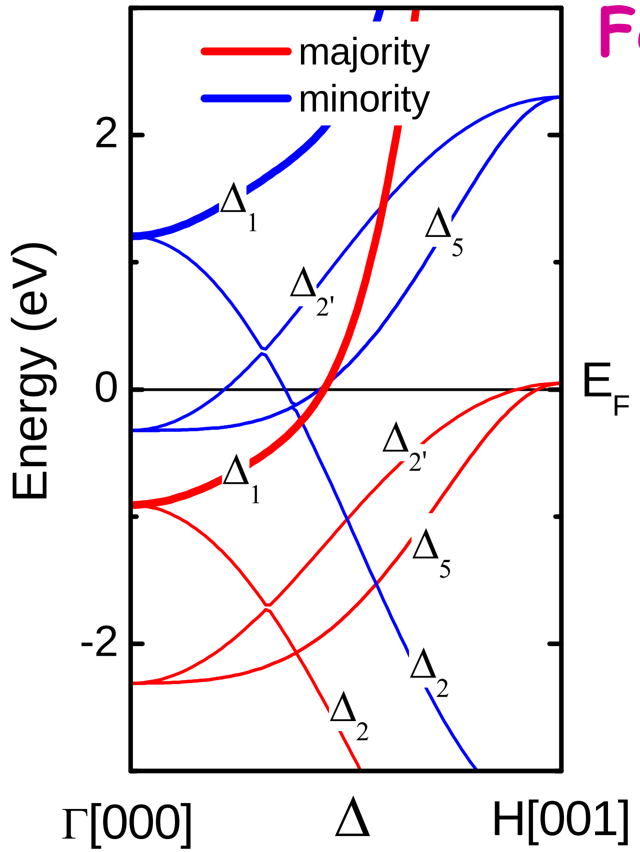
$E=E(k_{||},k_z)$, where $k_z=q+i\kappa$, $\psi \propto e^{-\kappa z}$



MgO

Ferromagnet

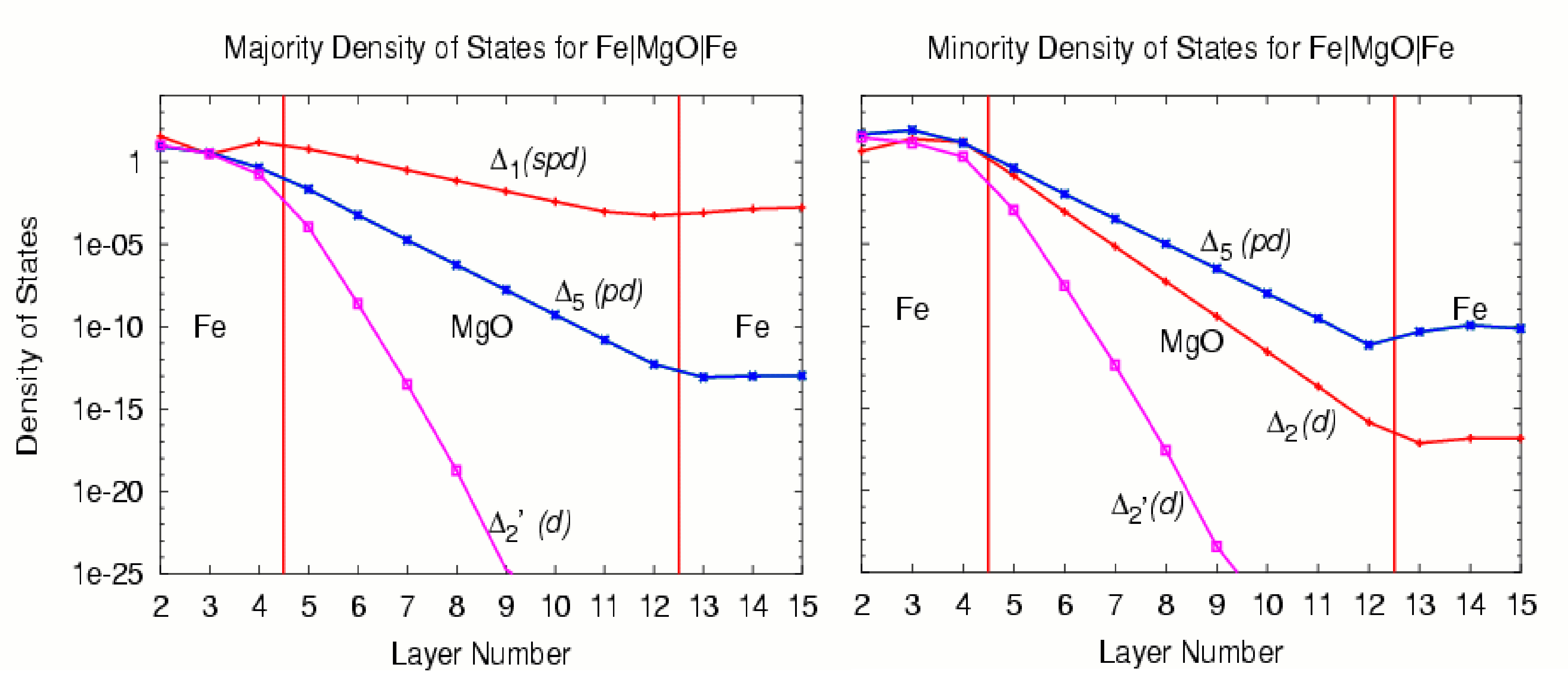
Fe



- Fe(001) behaves as a half metal if coupled with MgO

Fe/MgO/Fe junctions

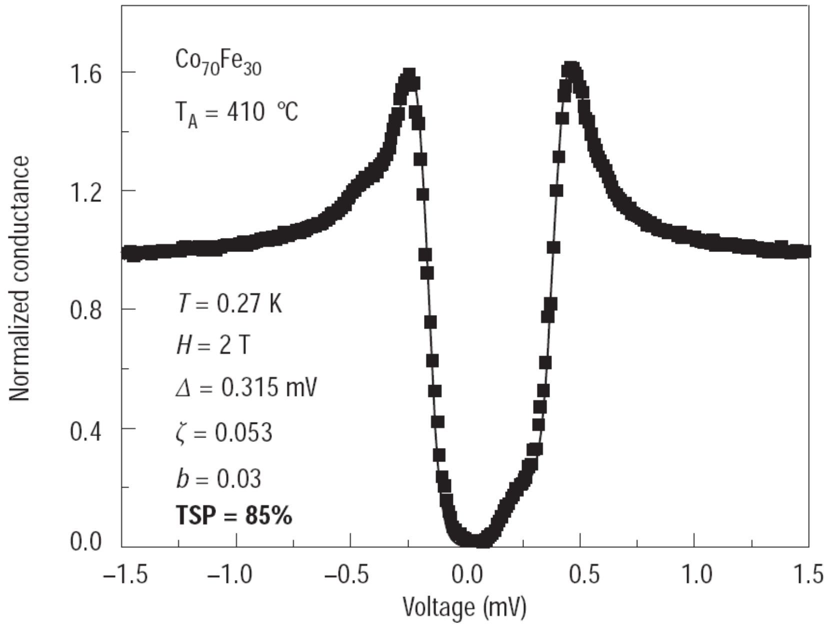
Butler et al., PRB 63, 054416 (2001)



- Giant TMR for Fe/MgO/Fe (001)

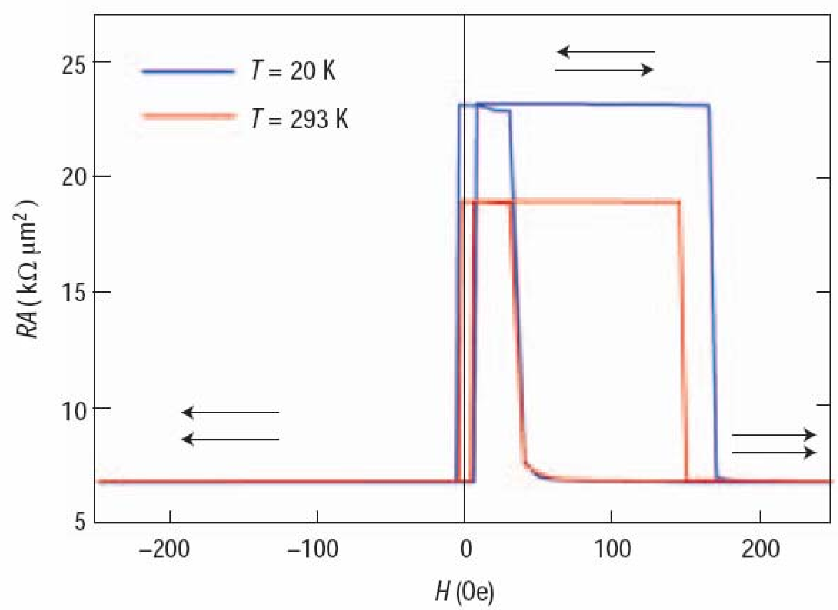
Experimental results on Fe(Co)/MgO/Fe(Co)

Parkin et al., Nat.Mat. 3, 862 (2004)



SP = 85%

Yuasa et al., Nat.Mat. 3, 868 (2004)

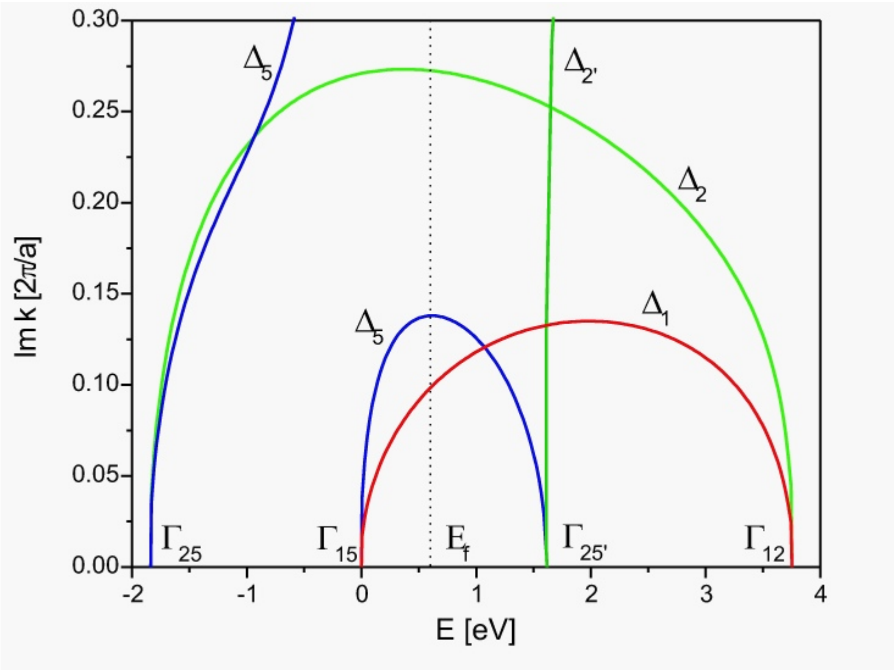


TMR = 250%

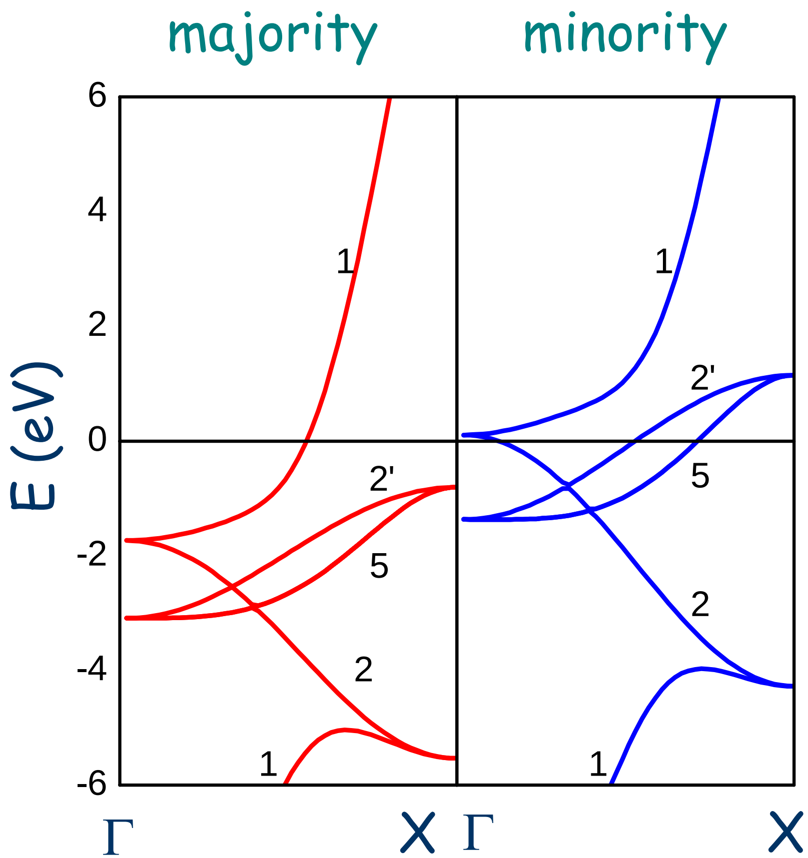
Co/SrTiO$_3$/Co junctions

Velev et al., PRL 95, 216601 (2005)

SrTiO$_3$



bcc Co



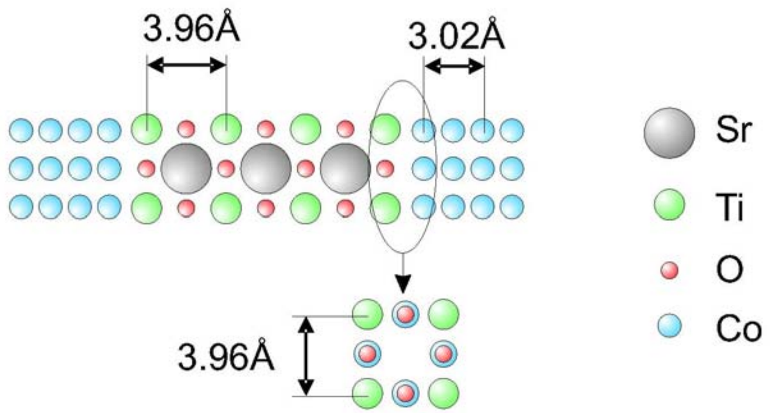
- Significant contribution to conductance from Co d bands

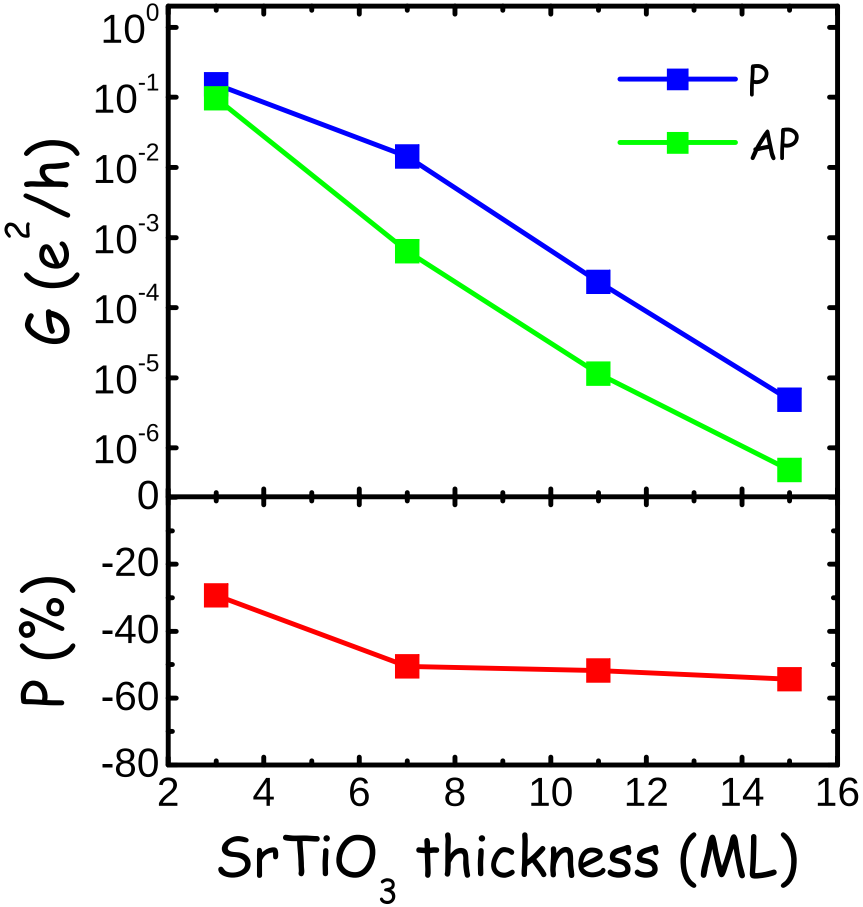
Conductance and spin polarization

Velev et al., PRL 95, 216601 (2005)

$SrTiO_3$ - perovskite, TiO_2 terminated

Co - bcc coordination

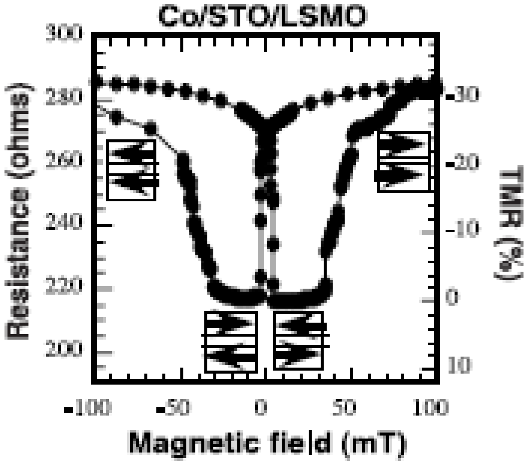


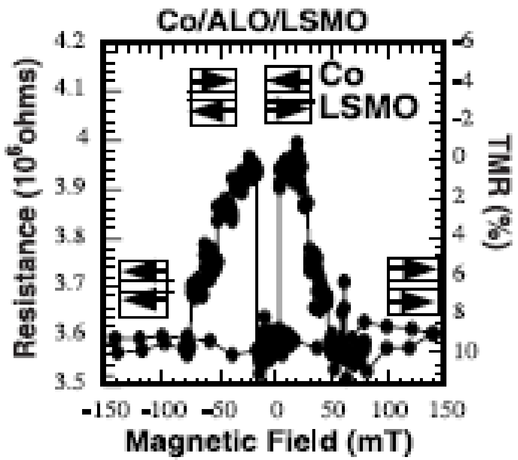


- Negative spin polarization and a very large TMR

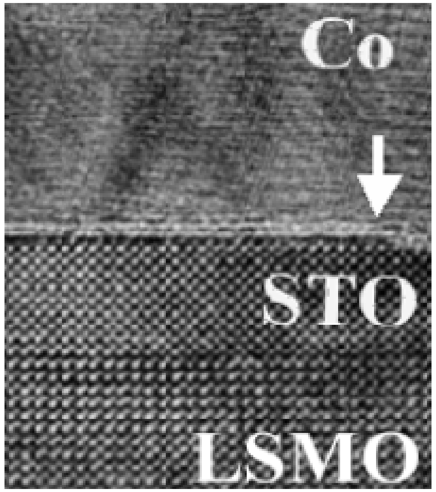
Transport spin polarization of $Co/SrTiO_3$ interface

De Teresa et al., Science 286, 507 (1999)





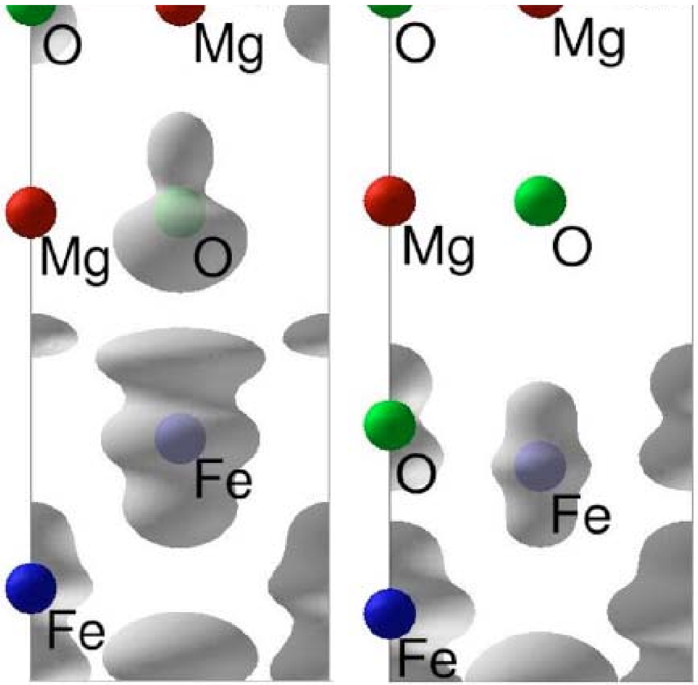
- LSMO as spin analyzer (100% positive SP)
- large inverse TMR (-50%) for $Co/SrTiO_3/LSMO$
- negative spin polarization for $Co/SrTiO_3$



Detrimental effect of O and B at the interface

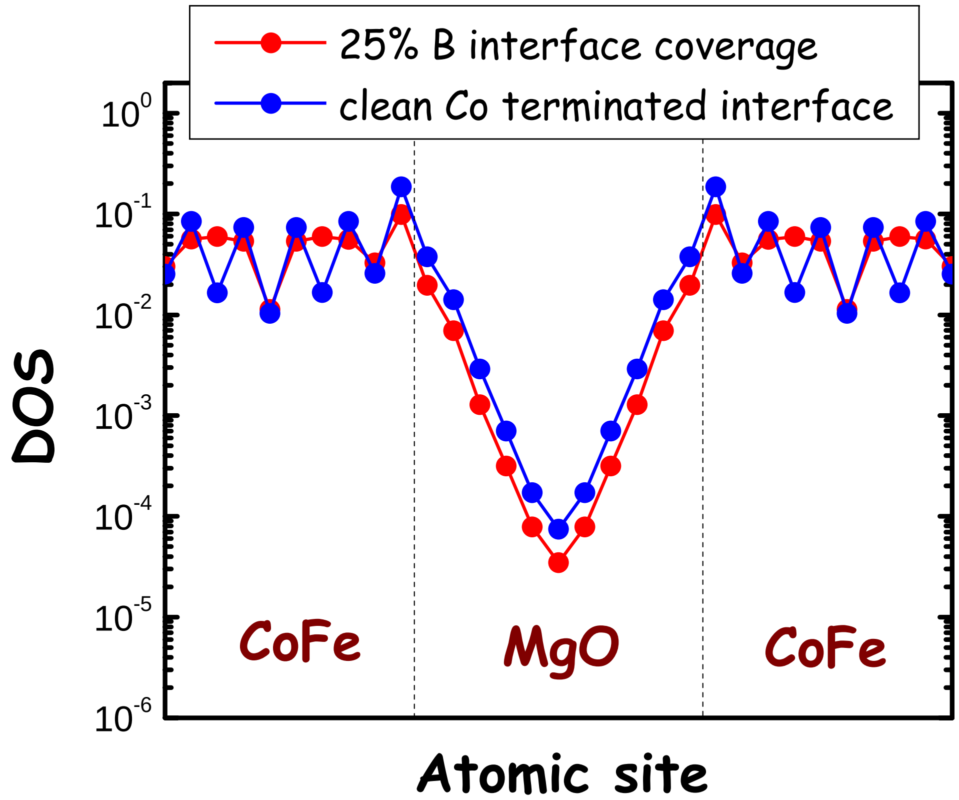
Zhang et al., PRB 68, 092402 (2003)

Fe/MgO Fe/FeO/MgO



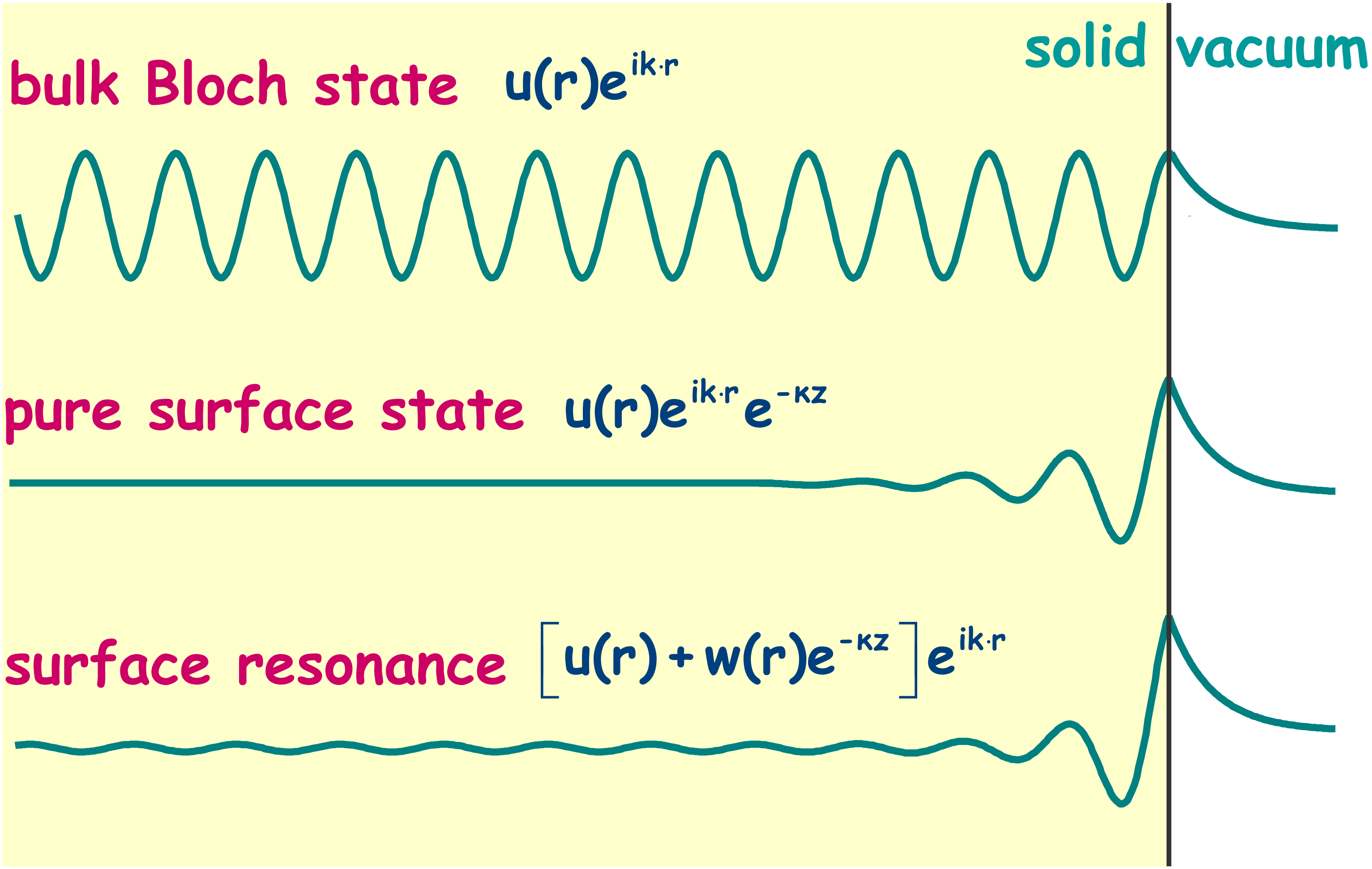
Burton et al., APL (2006)

FeCoB/MgO

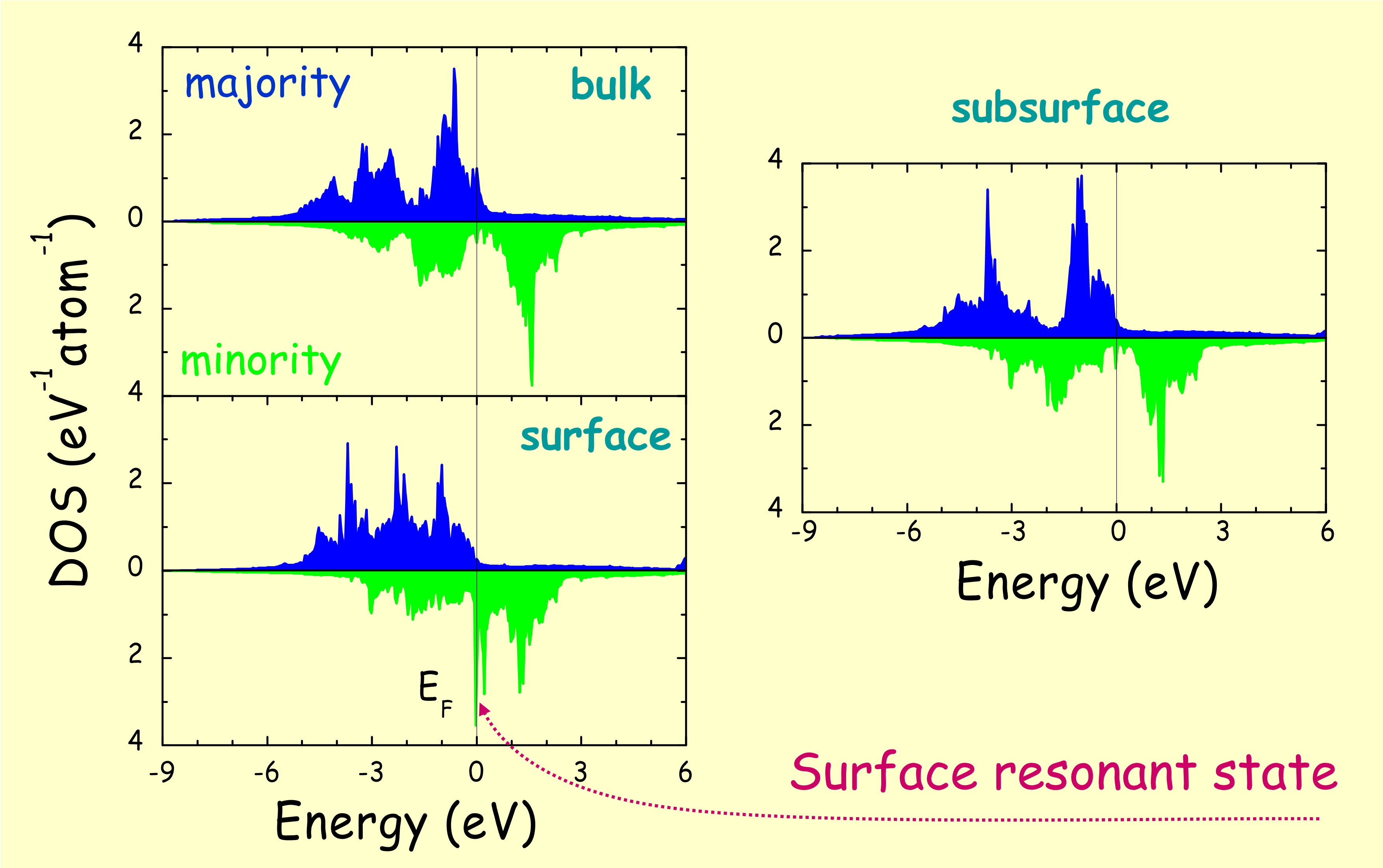


- Bonding at the interface controls the spin polarization

Surface states



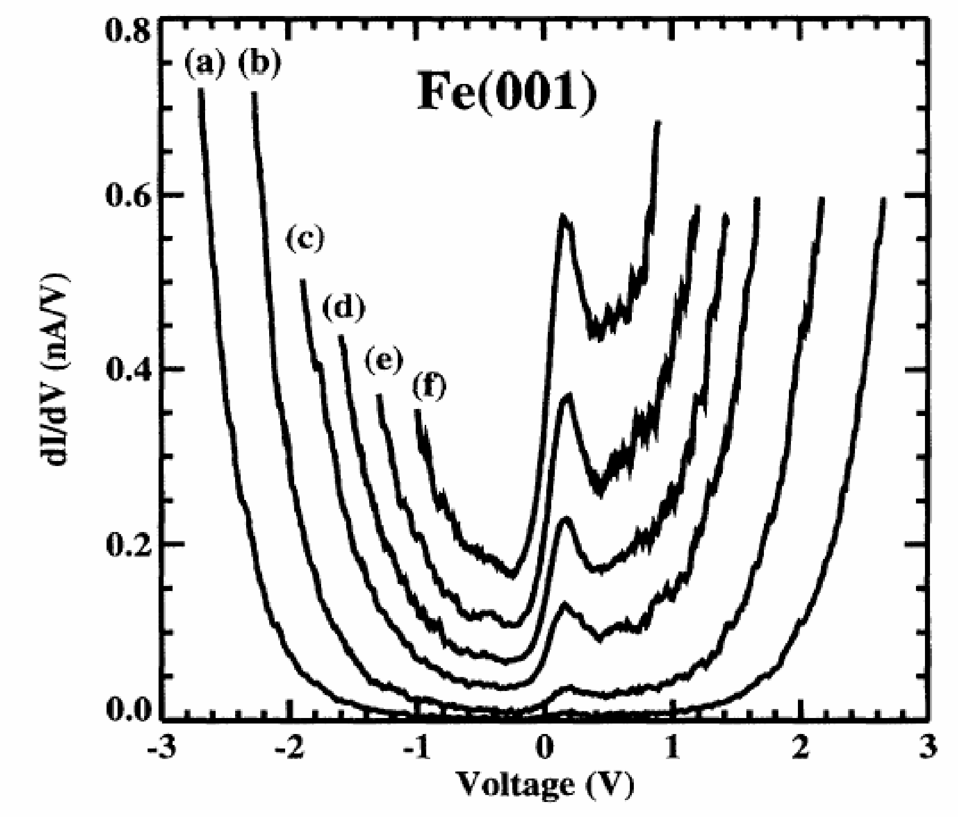
Surface states in Fe(100)



Tunneling Spectroscopy of bcc (001) Surface States

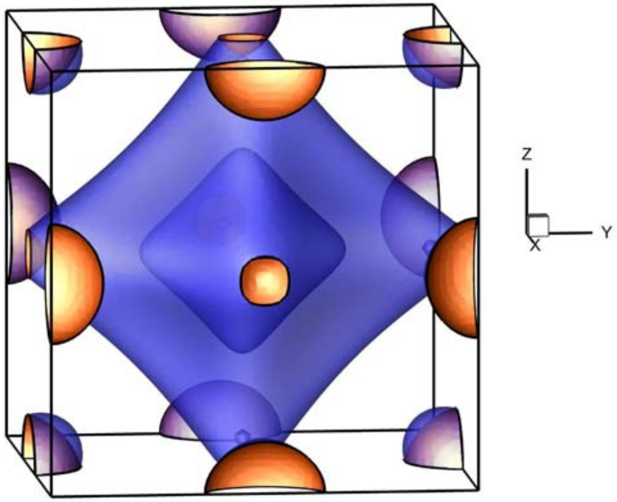
Joseph A. Stroscio, D. T. Pierce, A. Davies, and R. J. Celotta
Electron Physics Group, National Institute of Standards and Technology, Gaithersburg, Maryland 20899

M. Weinert
Physics Department, Brookhaven National Laboratory, Upton, New York 11973

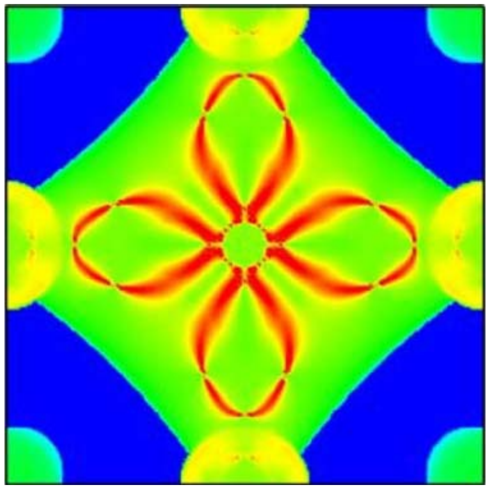


Minority-spin states in Fe(100)

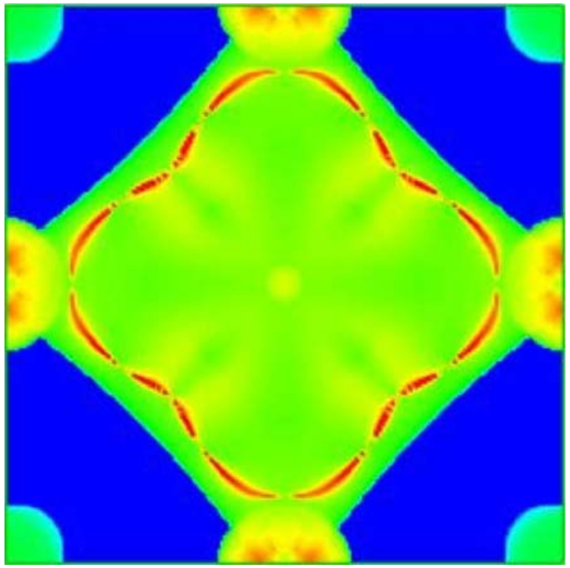
Fermi surface



$K_{||}$-resolved surface DOS at E_F



Energy dependence



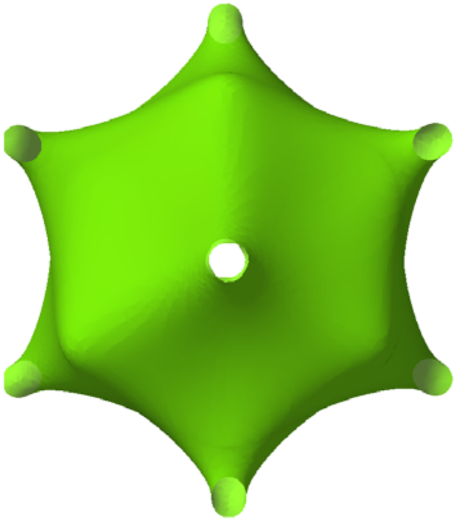
$E = E_F + 0.125eV$

Spin-dependent tunneling from clean and oxidized Co surface

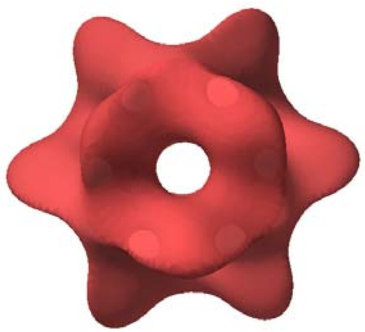
Belashchenko et al., PRB **69**, 174408 (2004)

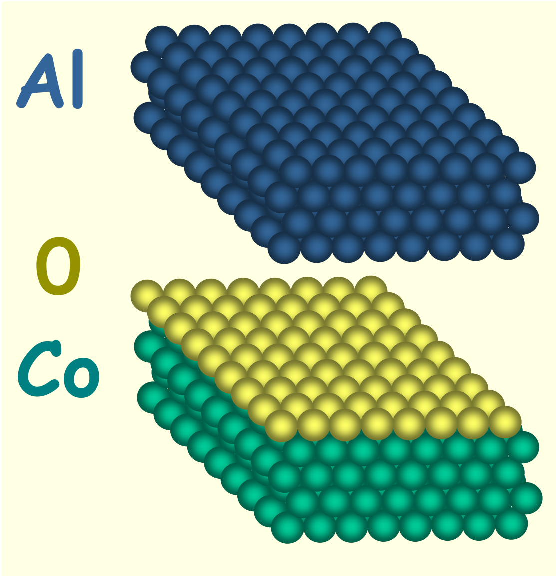
Fermi surface

Majority spin



Minority spin

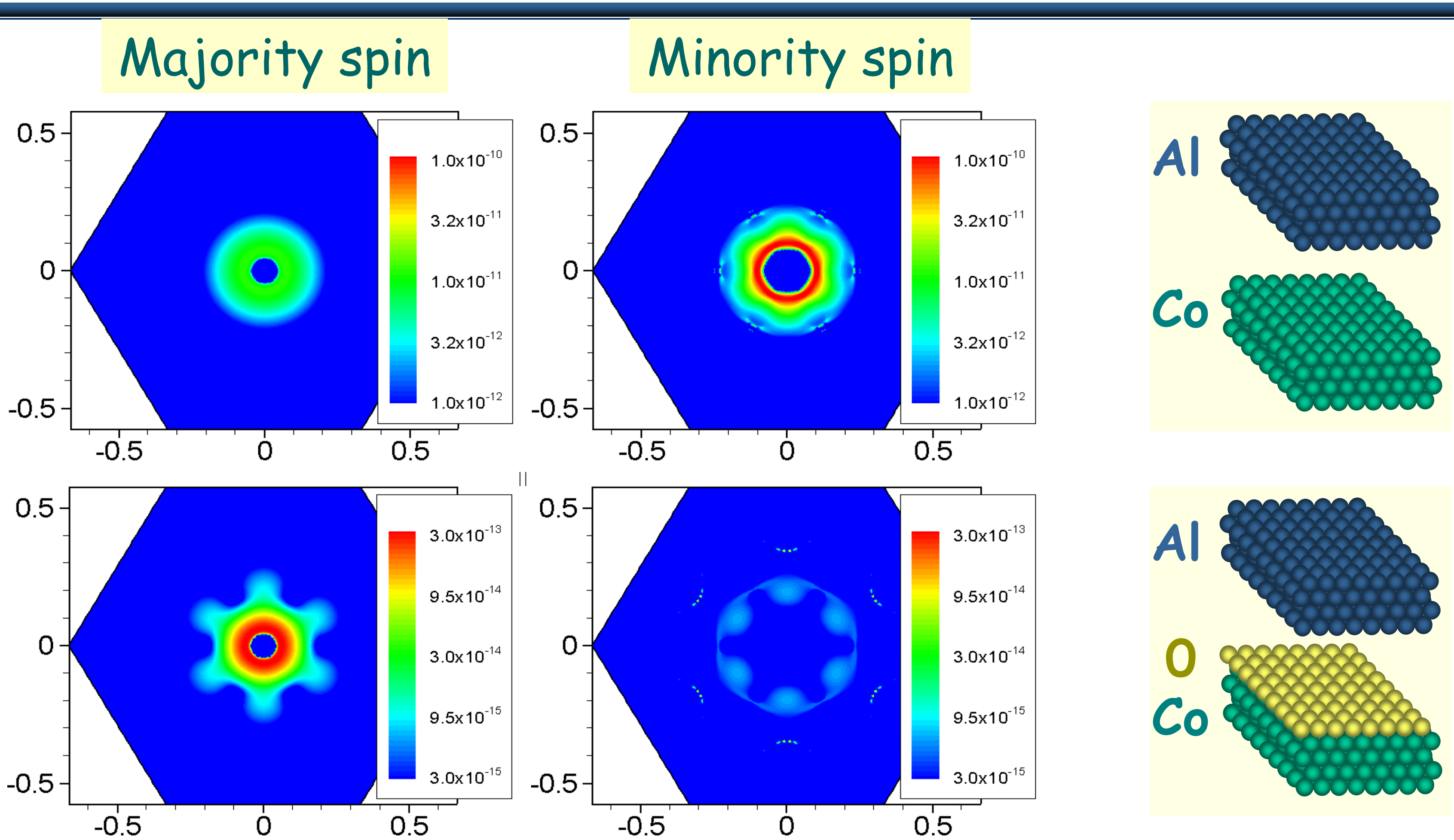




$$\kappa(k_{\parallel}) = \sqrt{\frac{2m}{\hbar^2}U + k_{\parallel}^2}$$ - decay constant in vacuum

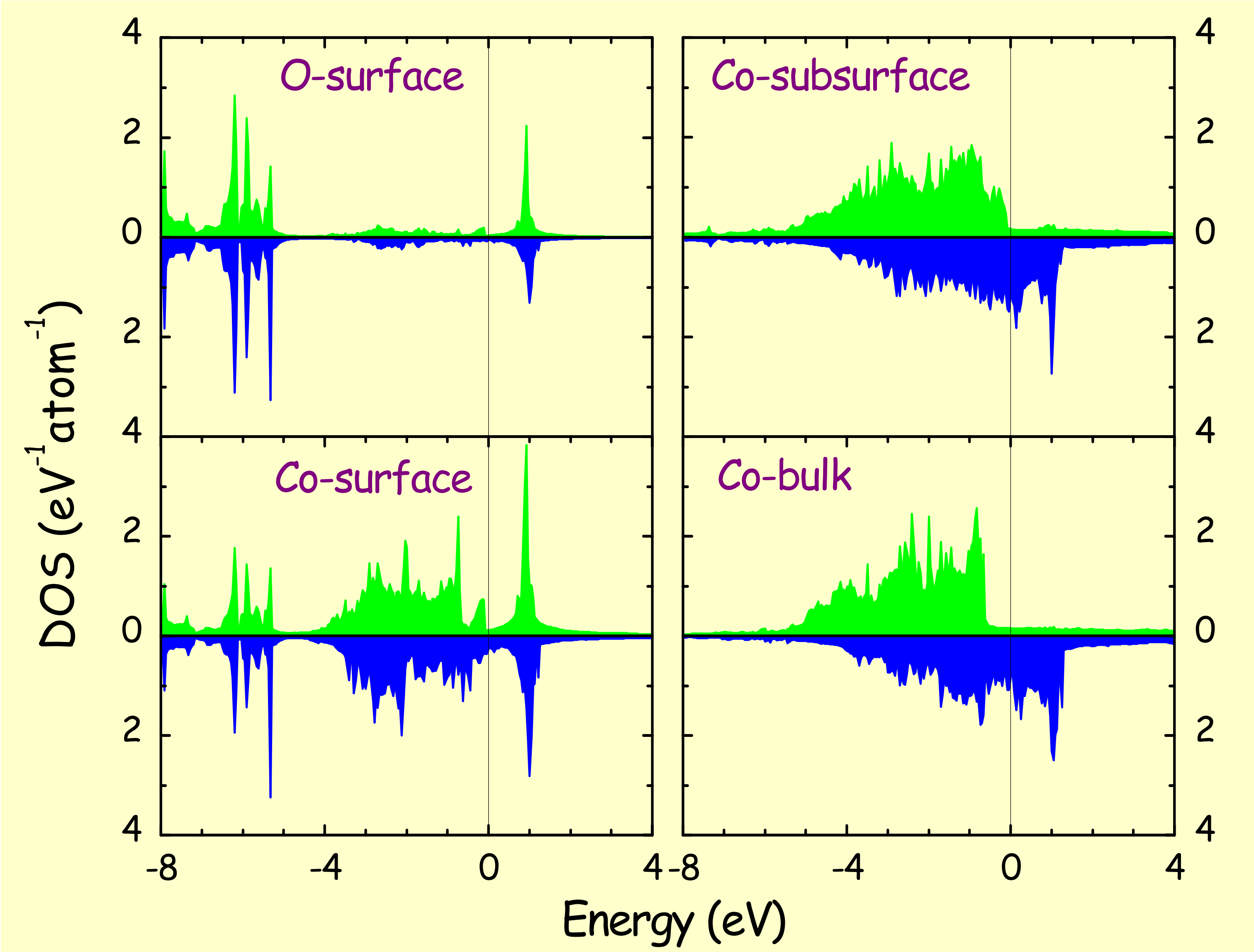
- Majority-spin conductance is expected to dominate in the asymptotic regime of a thick barrier

$k_{||}$-resolved transmission



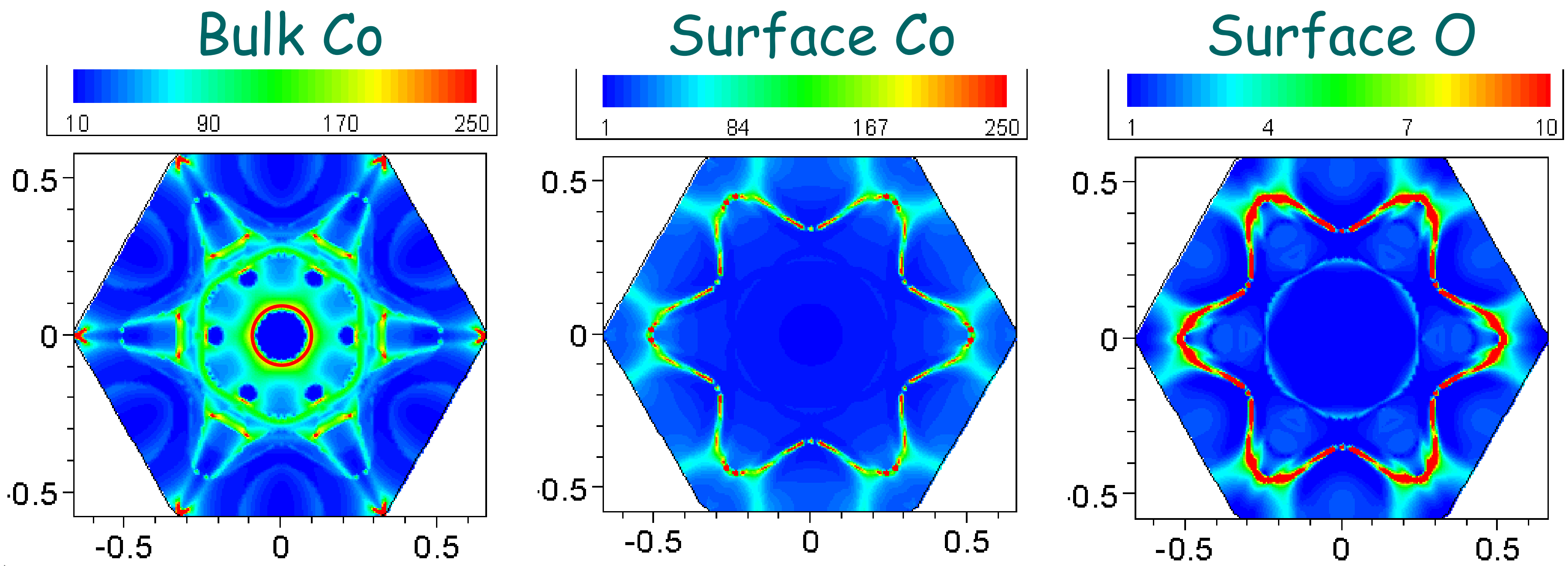
- Minority-spin conductance is filtered out by O layer
- Reversal of spin polarization

Density of states for oxidized Co surface



$k_{||}$-resolved DOS for oxidized Co surface

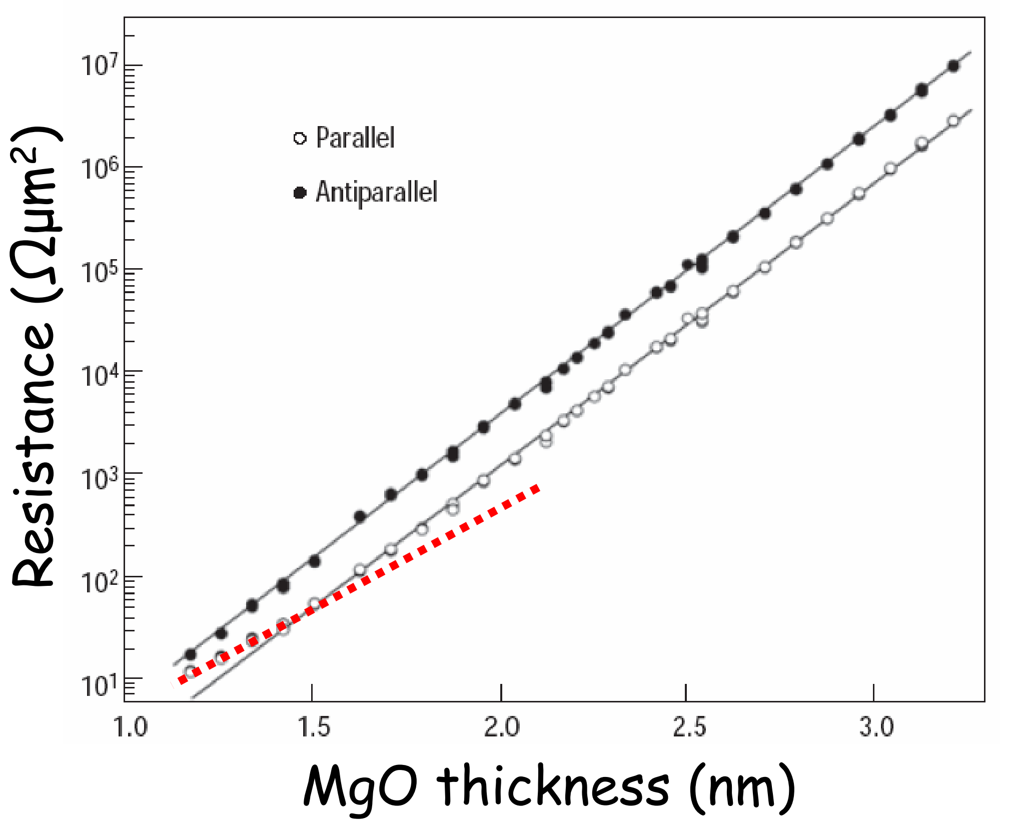
Minority spin



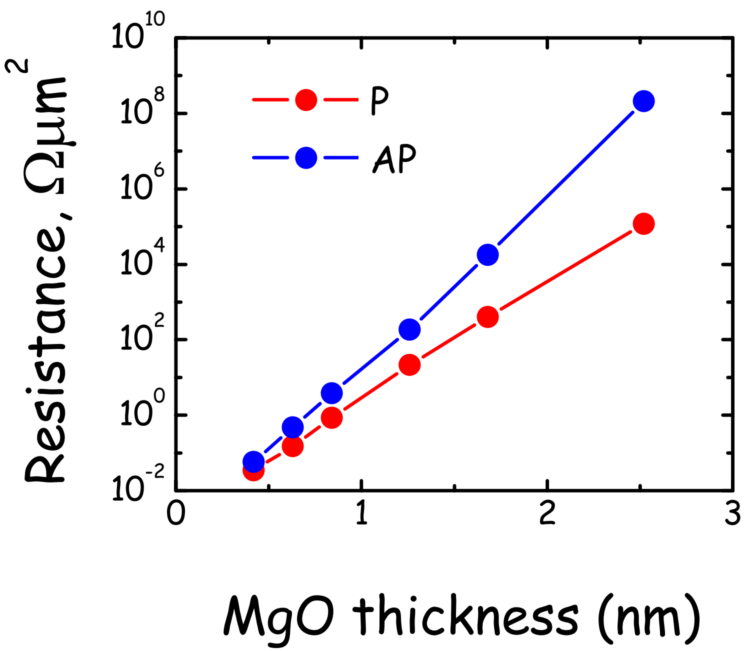
- Surface Co-O antibonding state creates an additional tunneling barrier in minority-spin channel

Ballistic or diffusive ?

Yuasa et al, Nat.Mat. 3, 868 (2004)



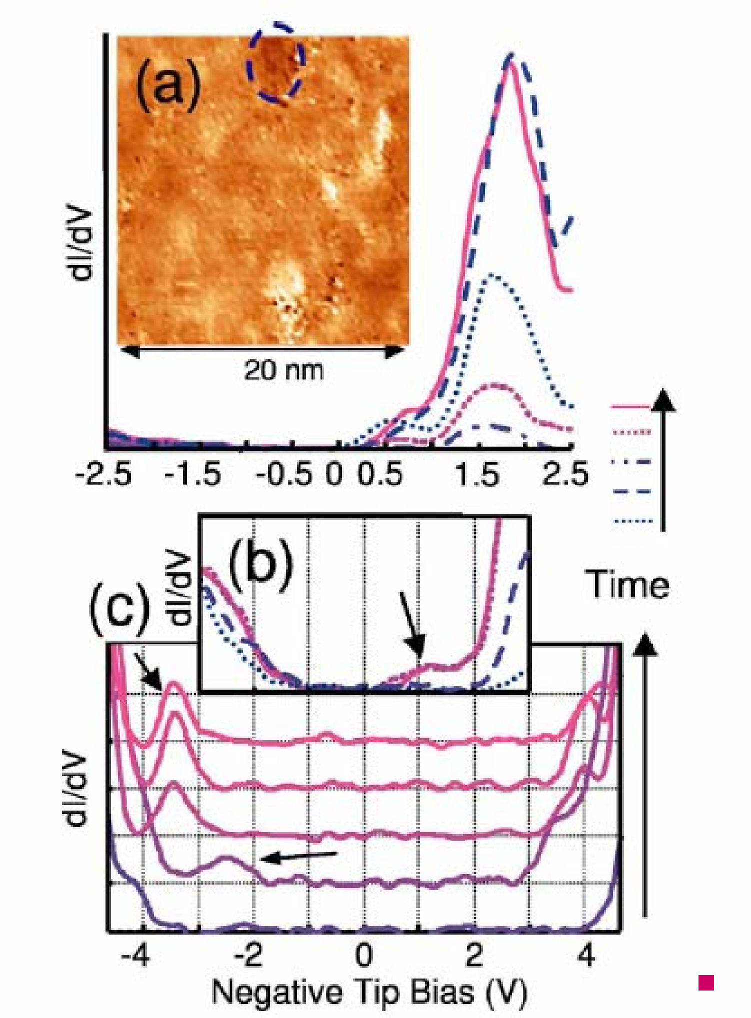
Belashchenko et al.,
PRB 72, R140404 (2005)



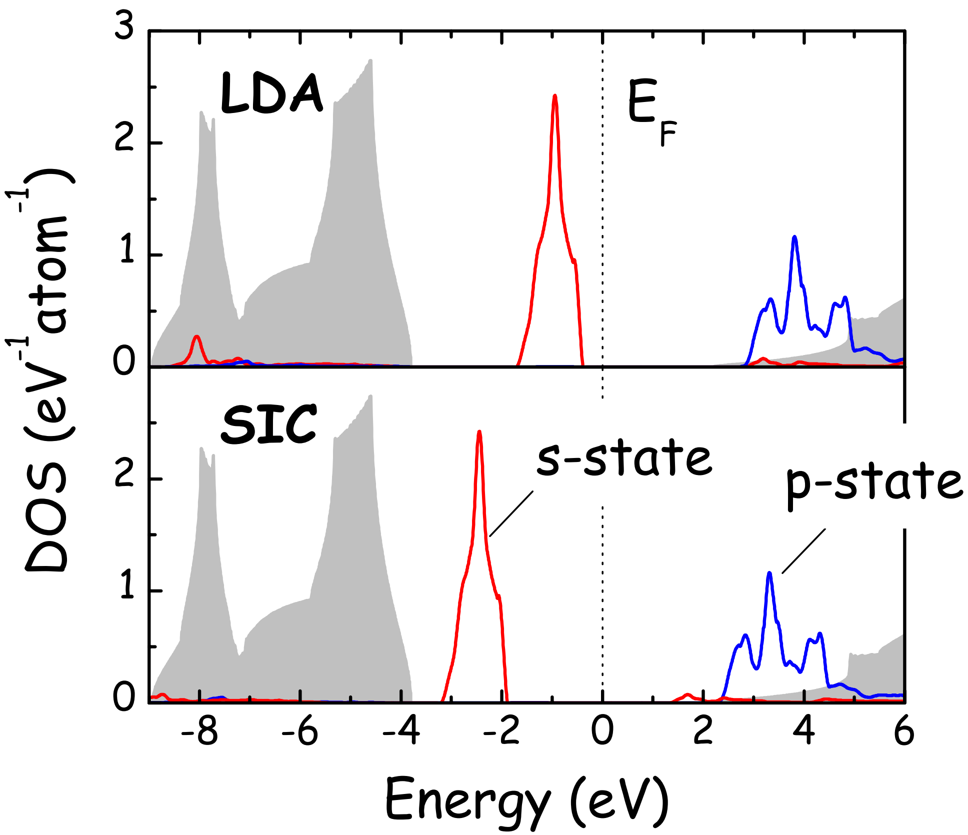
- Ballistic conductance only for thin barriers
- Diffusive transport for MgO thickness above 1.5 nm

O vacancies in MgO

Mather et al., PRB 73, 205412 (2006)



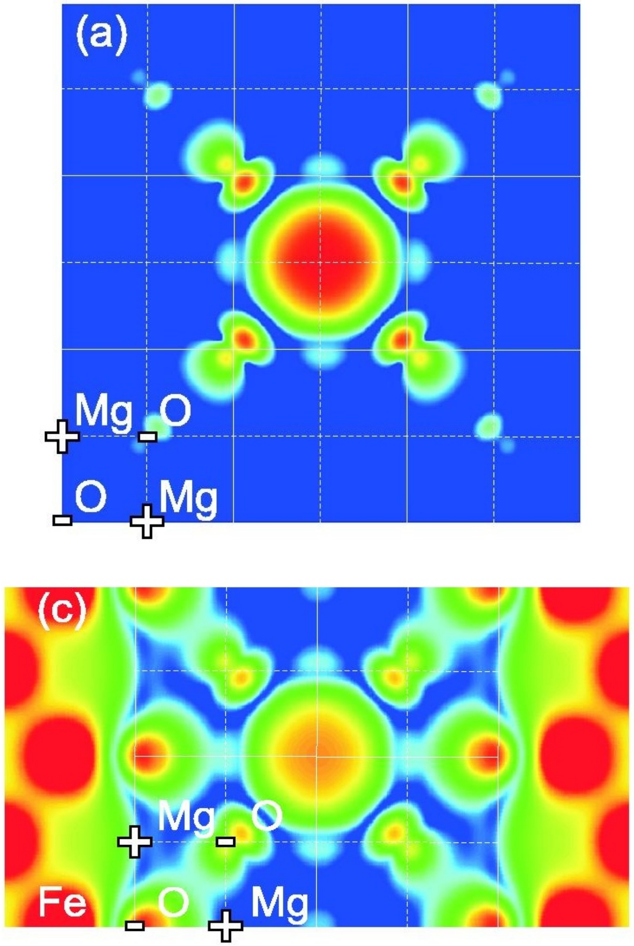
Velev et al., APL (2007)



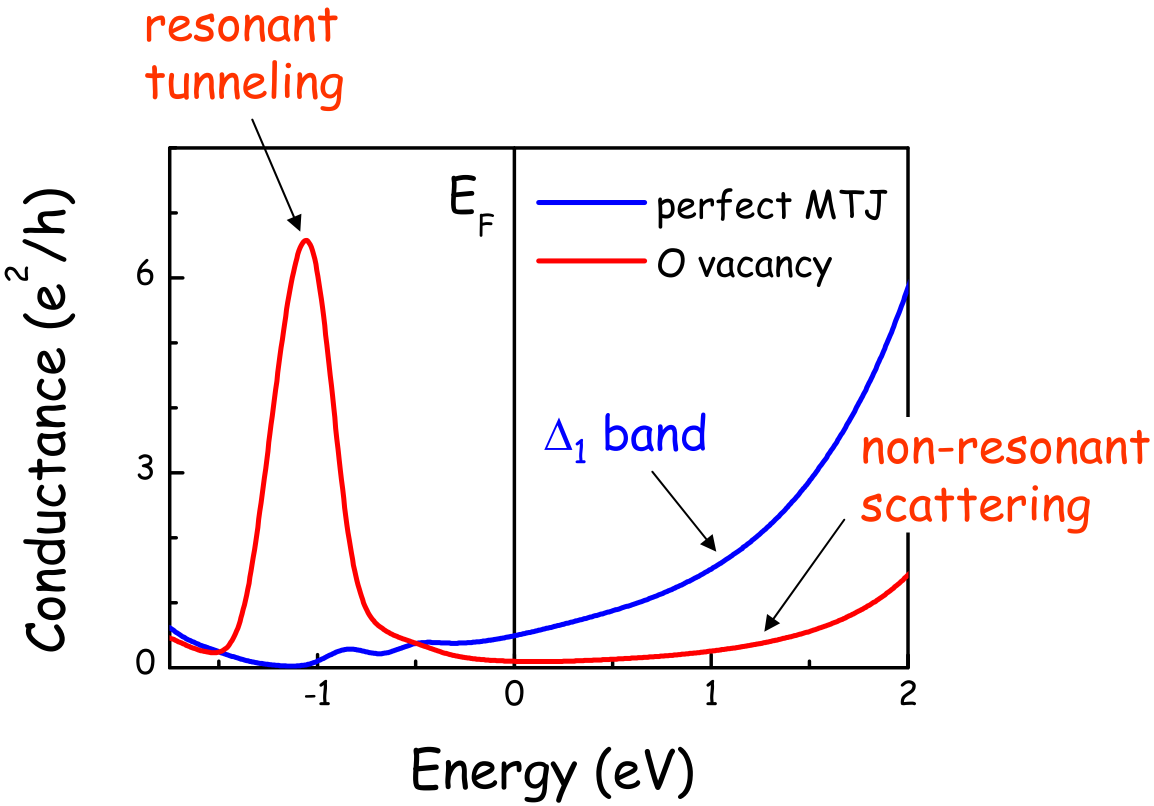
- Agreement between theory and experiment

Effect of O vacancies on transport

Charge density



Velev et al., APL (2007)



- Reduction of TMR due to O vacancies

Conclusions

- Tunneling spin polarization in magnetic tunnel junctions is determined by the interface transmission function which depends on electronic properties of ferro-magnets, insulator and interfaces
- Symmetry arguments, though important, are not sufficient to make overall conclusions regarding the spin polarization in magnetic tunnel junctions
- Critical role of electronic band structure of interfaces: interface bonding and interface states are important
- Diffusive mechanism of tunneling conduction has to be considered to interpret experimental data quantitatively