Giant magnetoresistance in magnetic metallic multilayers

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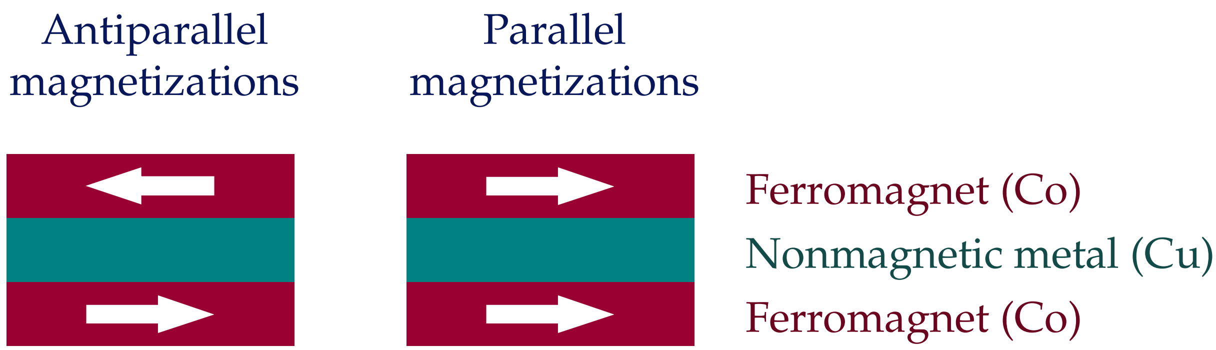
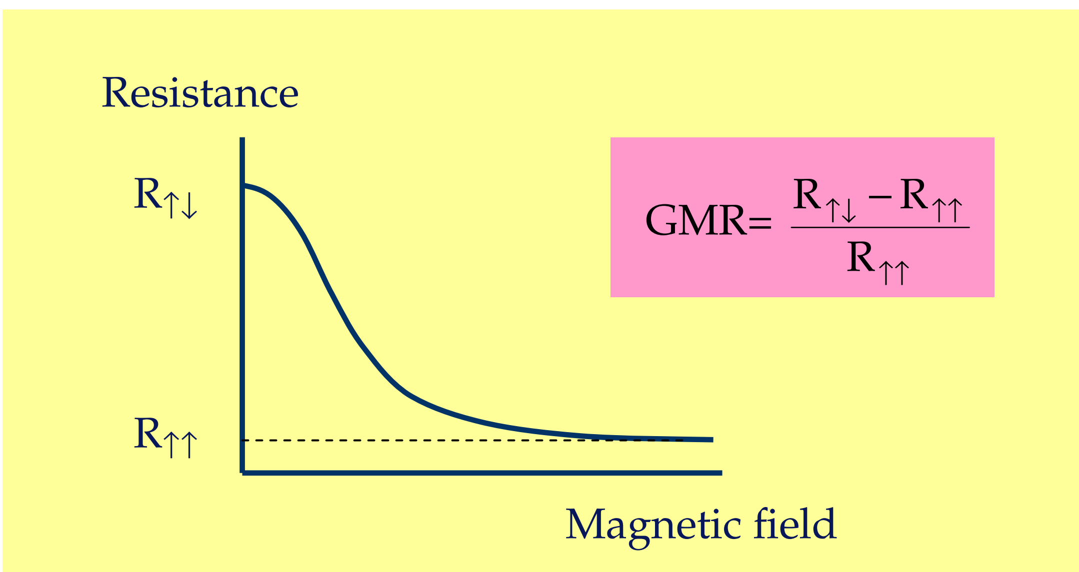
Synopsis

- Introduction
- Physical origin
- The theoretical model
- Co/Cu and Fe/Cr multilayers
- Application to experiments:

  Thermoelectric power
  Thickness-dependent conductance
  Interface resistance
- Conclusions

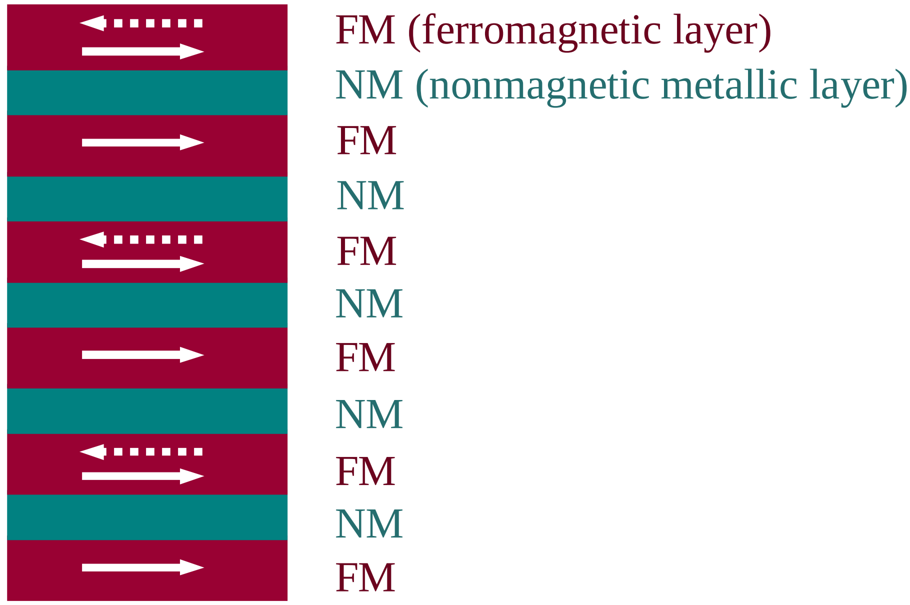
Giant magnetoresistance (GMR)





GMR structures

Magnetic multilayer



- antiferromagnetic exchange coupling
- highest values of GMR, in Co/Cu and Fe/Cr multilayers ~ 100%

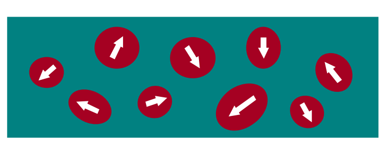
Pseudo spin valve

- different coercivities

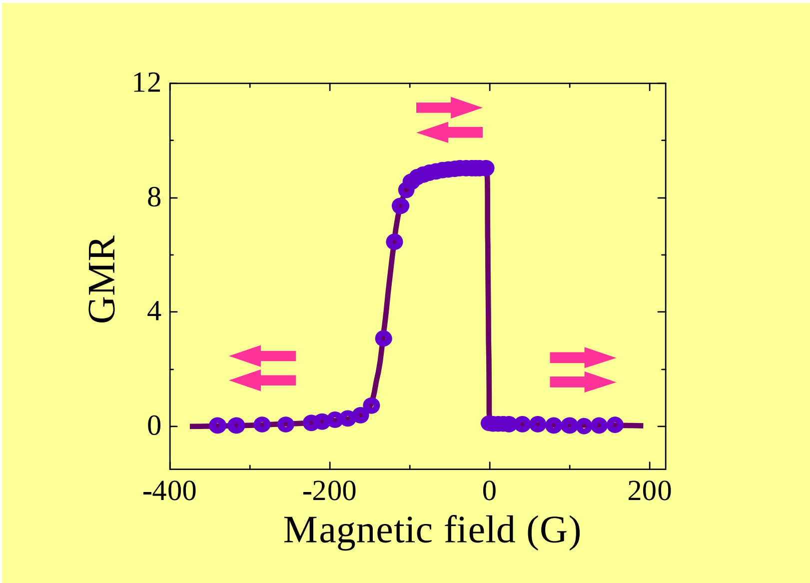
Spin valve

- exchange biasing

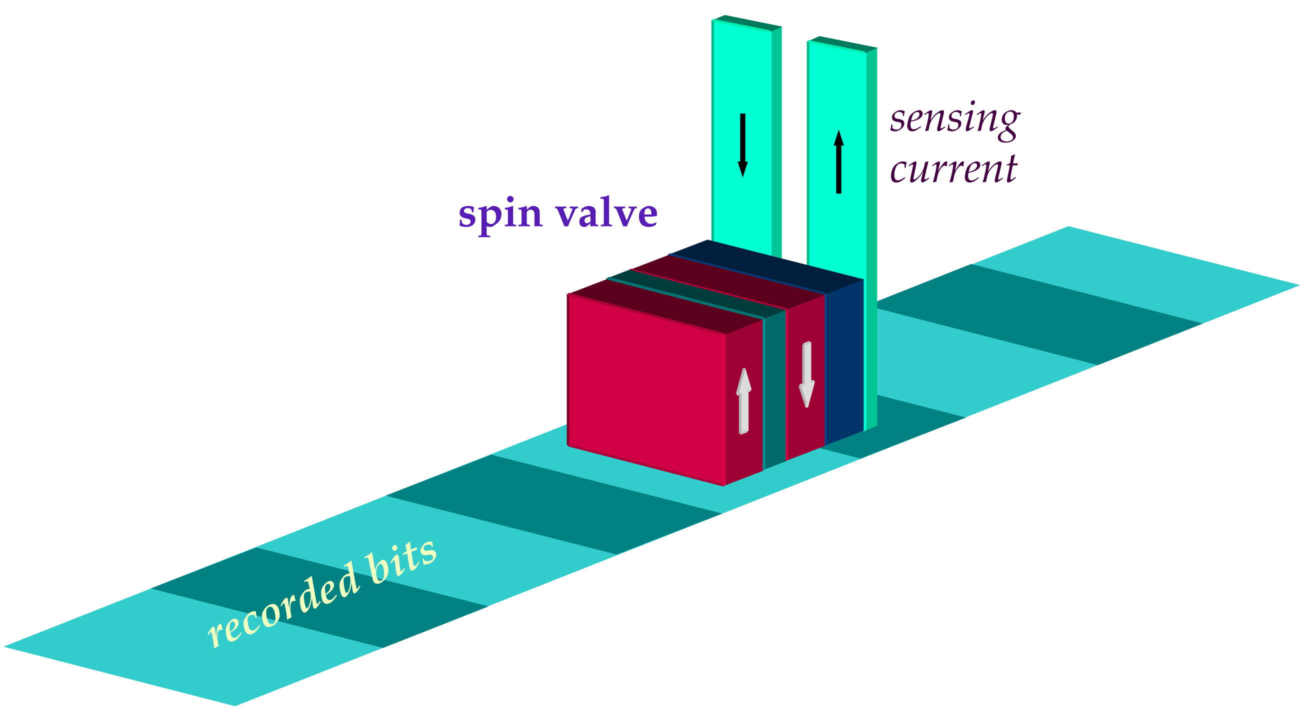
Granular material



Spin valve

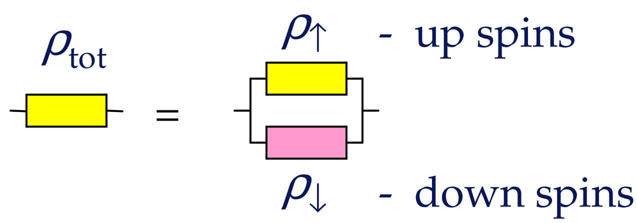


Magnetic field sensor

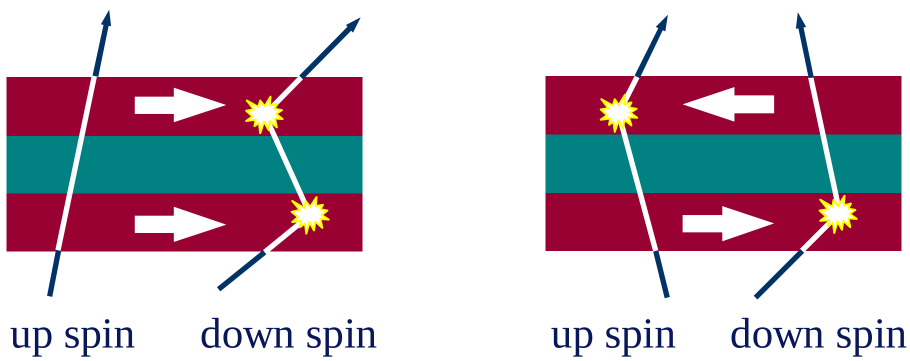


Simple model for GMR

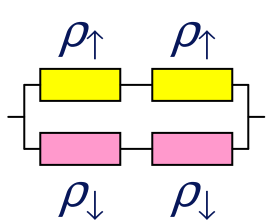
Two-current model:



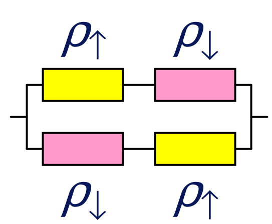
In ferromagnets $\rho_\uparrow \neq \rho_\downarrow$



$R_{\uparrow\uparrow}=$



$R_{\uparrow\downarrow}=$



$$\text{GMR}=\frac{(\rho_\downarrow-\rho_\uparrow)^2}{4\rho_\downarrow\rho_\uparrow}=\frac{(\alpha-1)^2}{4\alpha}$$

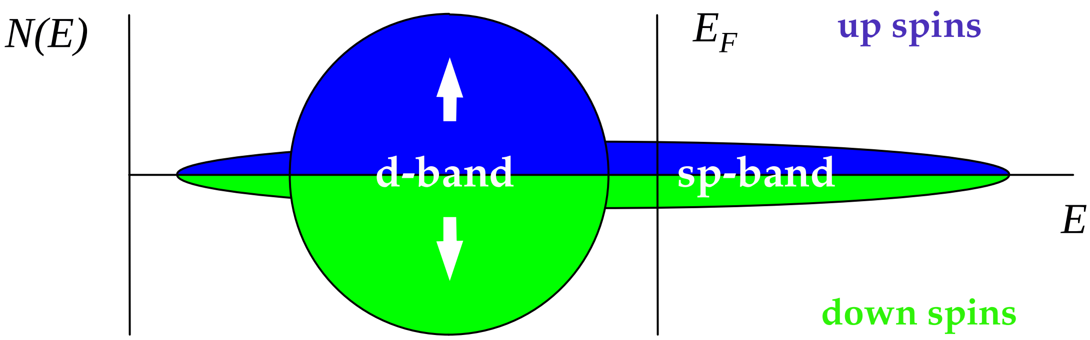
$\alpha=\dfrac{\rho_\downarrow}{\rho_\uparrow}$ is spin asymmetry parameter

Electrical conduction in metals

Drude formula $$\sigma = \frac{ne^2\tau}{m} = \frac{e^2}{\pi\hbar}\frac{k_F^2}{3\pi} l_{mfp}$$

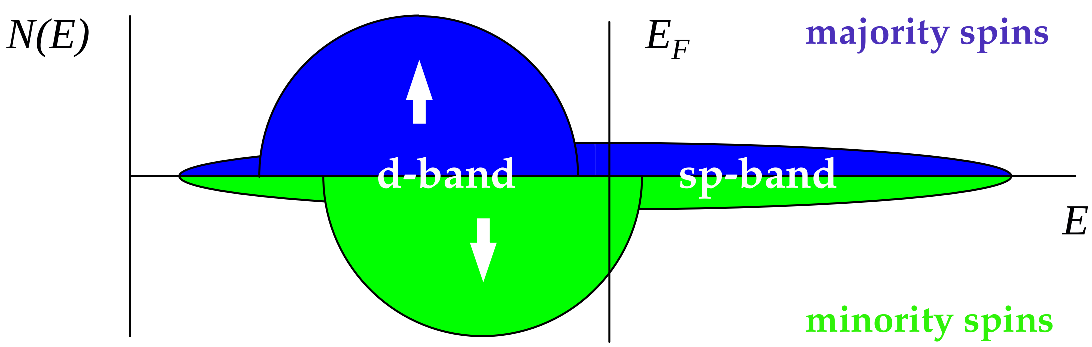
Mean free path $$l_{mfp} = v_F \tau = v_F \frac{\hbar}{2\pi}\frac{1}{V_{scat}^2 N_F}$$

Nonmagnetic metal (Cu)



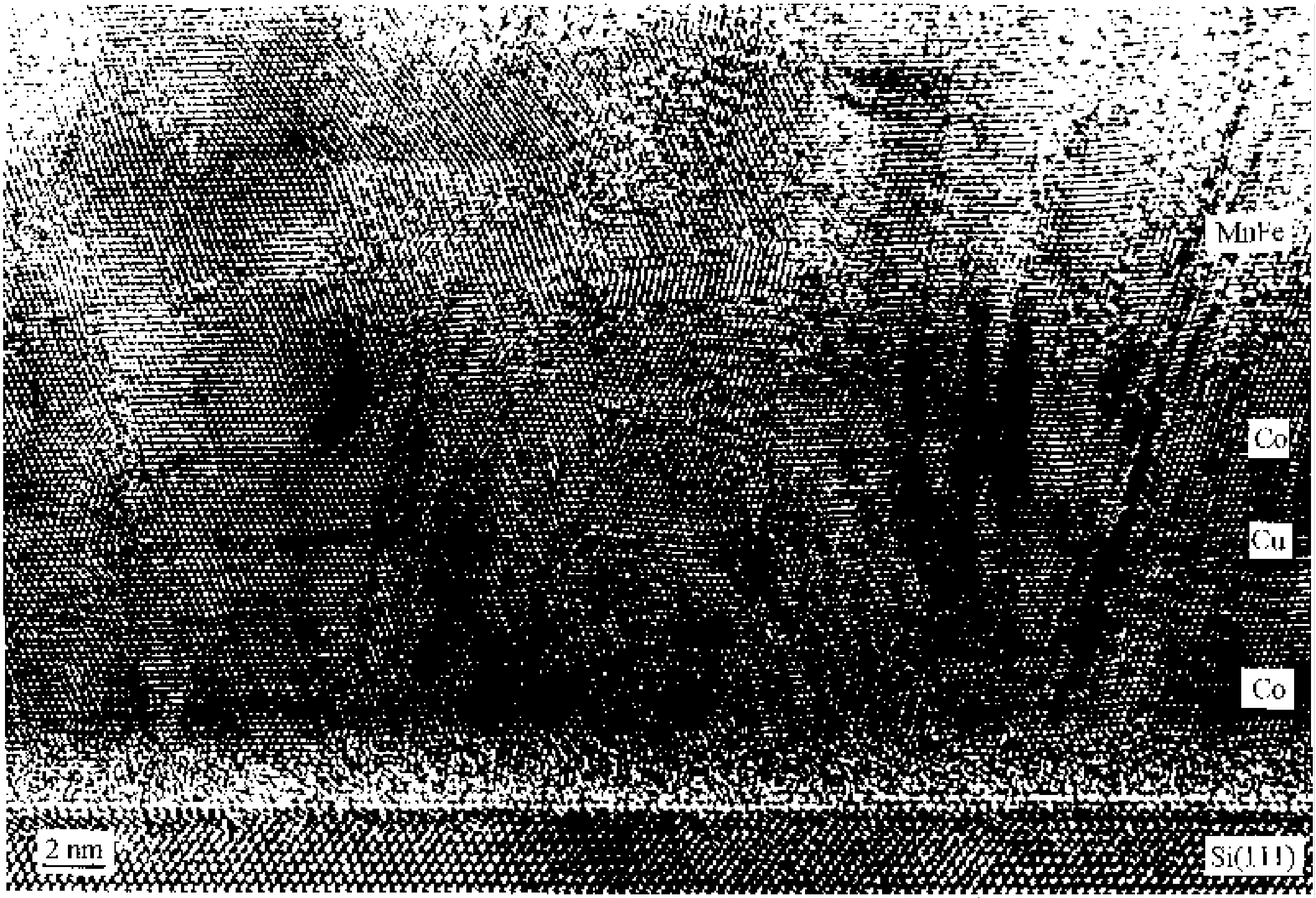
$\sigma_\uparrow = \sigma_\downarrow$

Magnetic metal (Co)



$\sigma_\uparrow >> \sigma_\downarrow$

High resolution electron micrograph of Co/Cu spin valve



Si(111)/Co(6nm)/Cu(2.8nm)/Co(4nm)/MnFe(12nm)

P.Baile-Guillemaud, A.K.Petford-Long

The theoretical model for GMR

Phys.Rev.B ***54****, 15314 (1996)*

- Realistic electronic band structure
- Scattering is due to structural defects within a multilayer

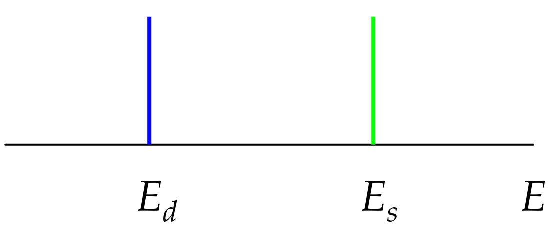
Kubo-Greenwood formula:

$$\sigma = \frac{\pi\hbar e^2}{\Omega} Tr\langle \mathrm{v}\delta(E_F - H)\mathrm{v}\delta(E_F - H)\rangle$$

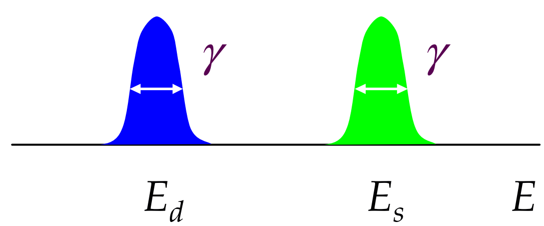
$$H = H_0 + V_{scat}$$

V_{scat} - scattering potential
effecting on-site atomic energy levels randomly

Perfect lattice:

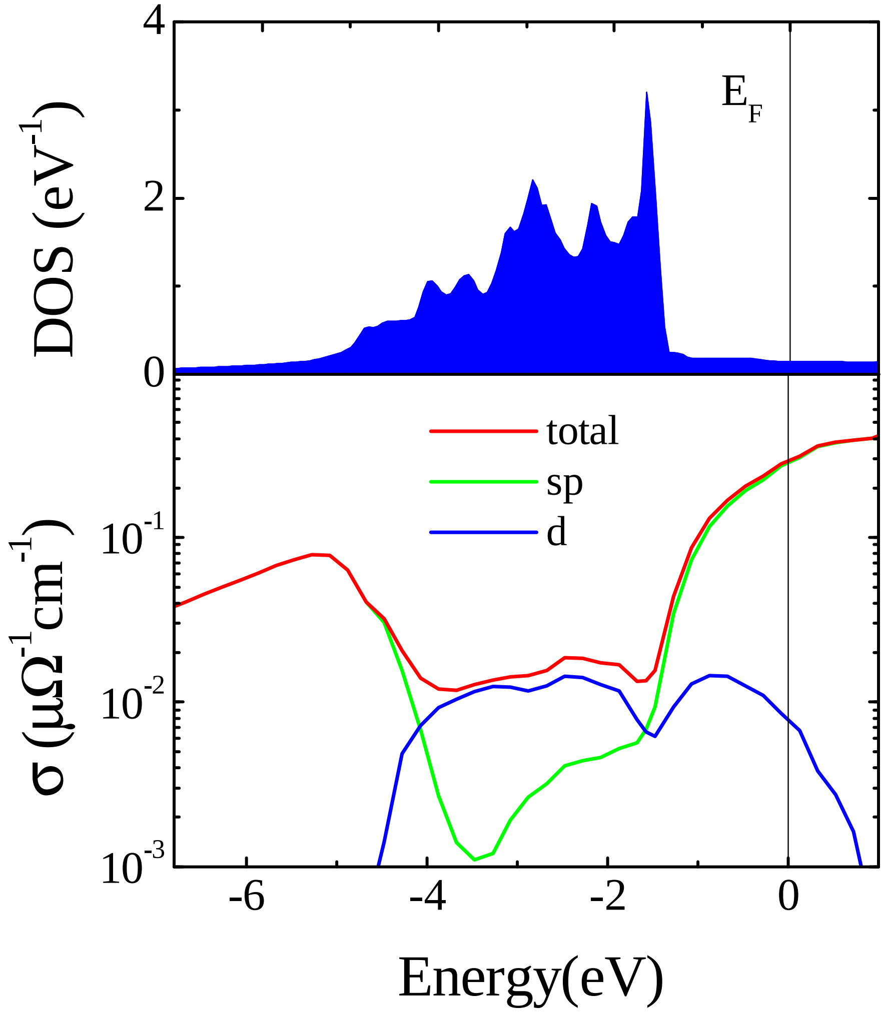


Defective lattice:

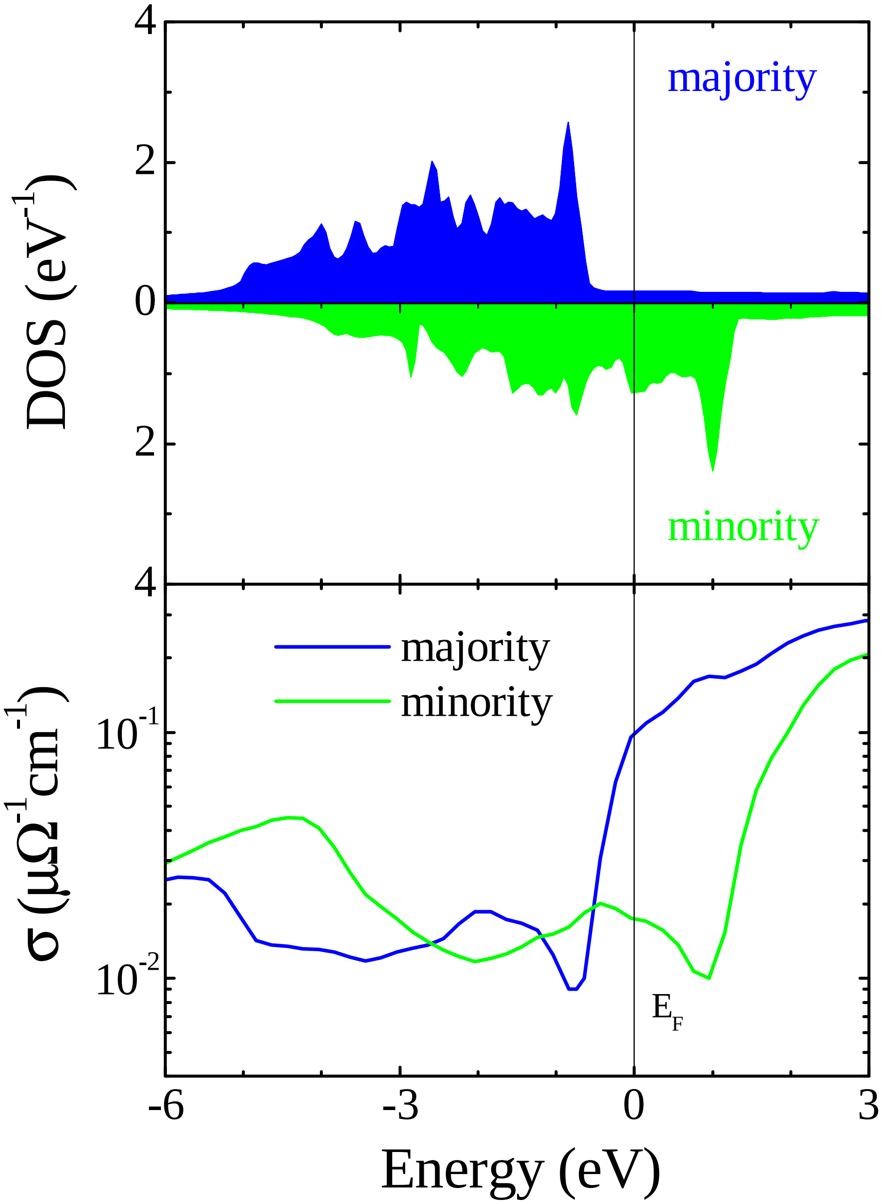


- γ is assumed to be spin-independent

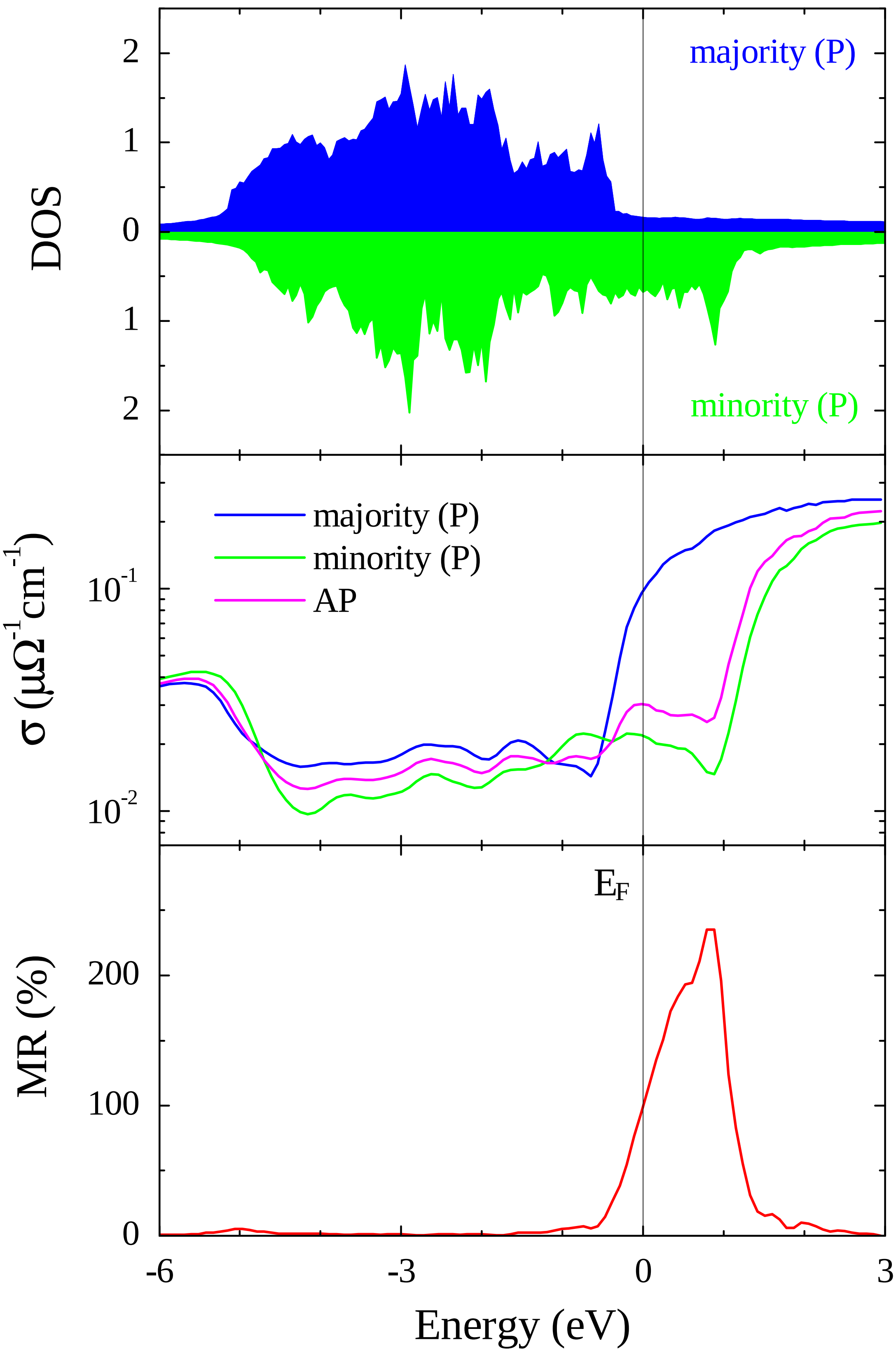
Conductivity of bulk Cu



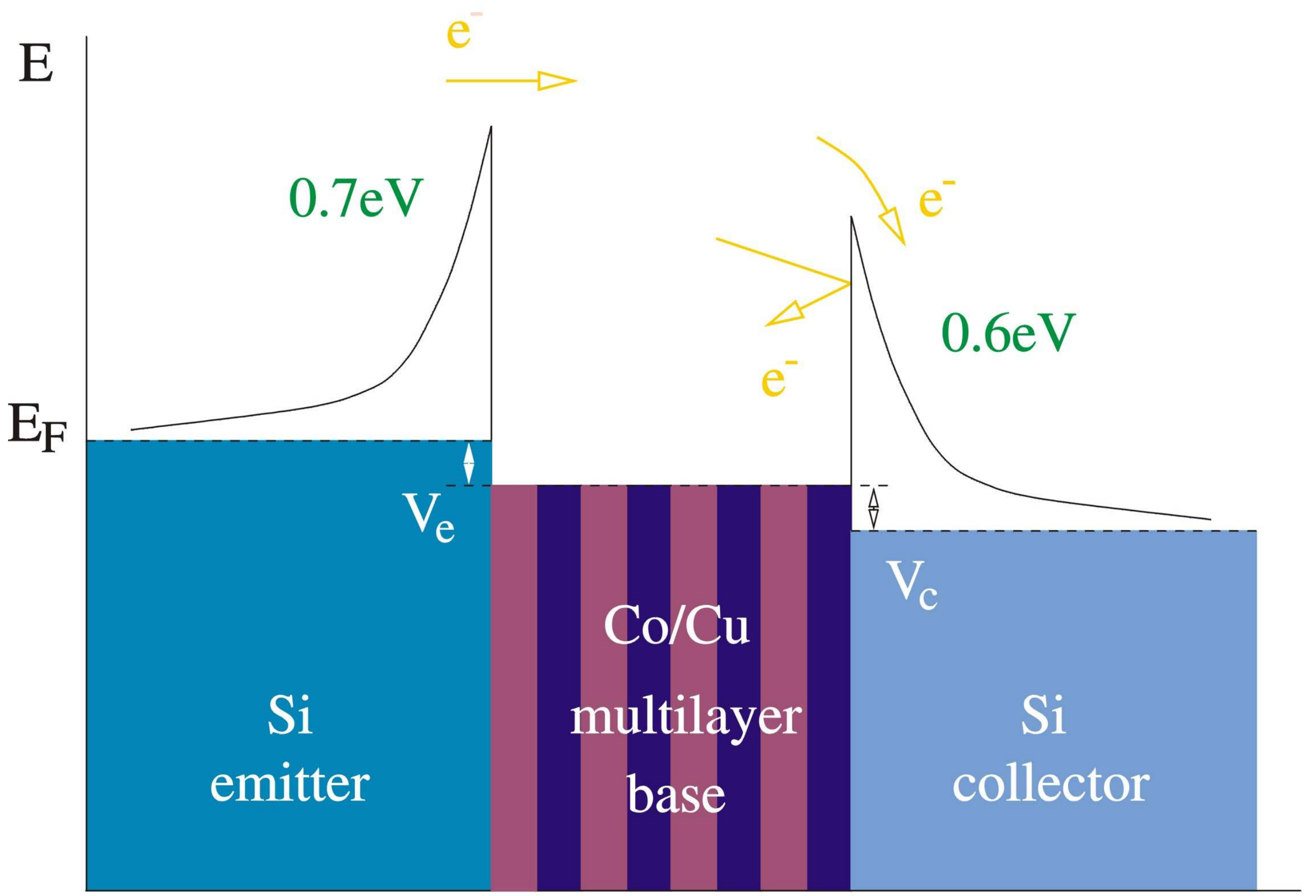
Conductivity of bulk Co



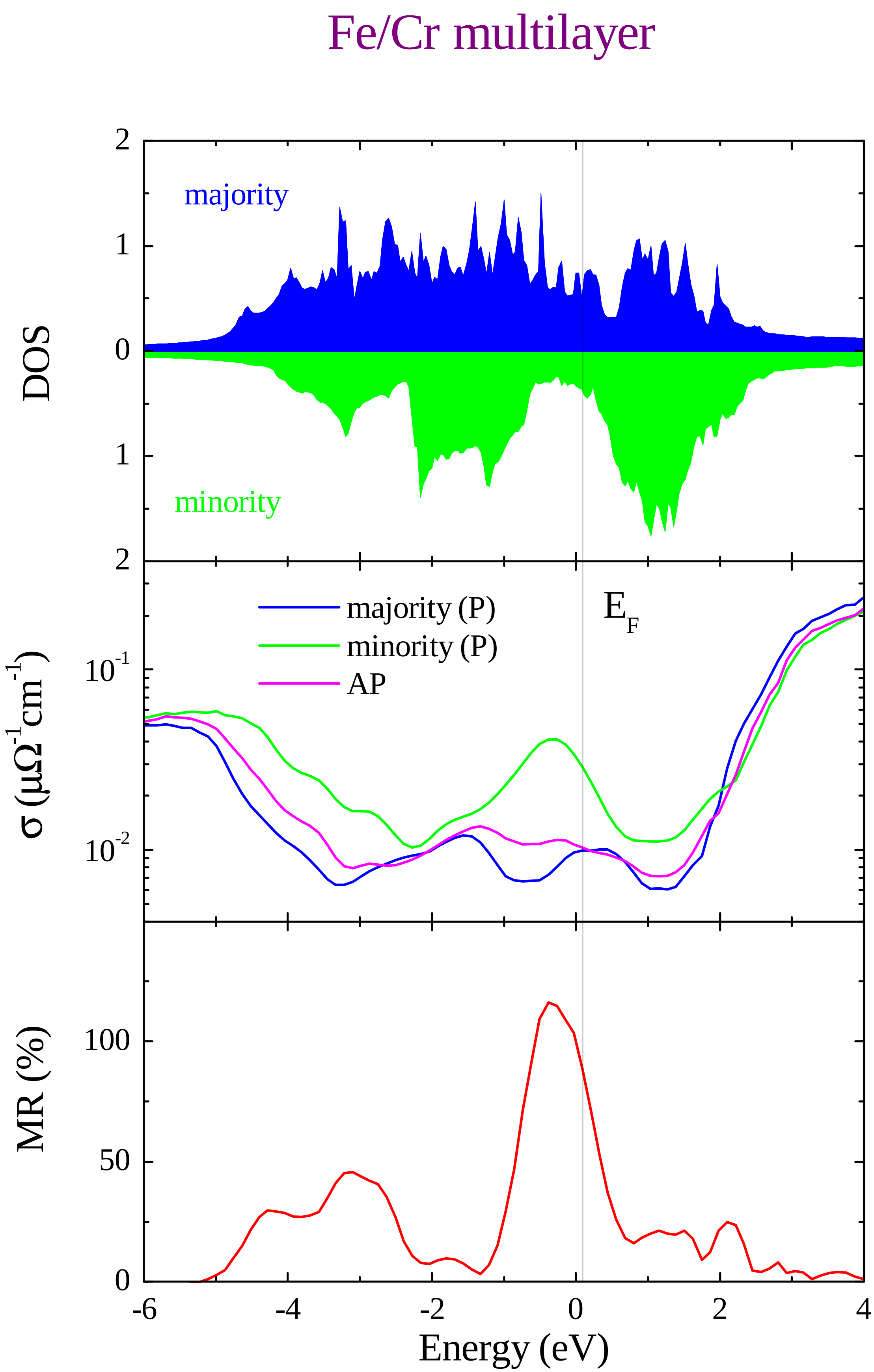
Co/Cu multilayer



Spin-valve transistor

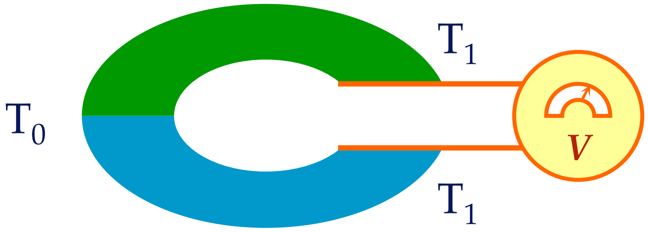


D.J.Monsma et al, Phys.Rev.Lett. 74, 5260 (1995)


Fe/Cr multilayer
majority
minority
DOS
2
1
0
1
2
majority (P)
minority (P)
AP
E$_F$
σ (μΩ^{-1}cm^{-1})
10^{-1}
10^{-2}
MR (%)
100
50
0
-6
-4
-2
0
2
4
Energy (eV)

Thermoelectric power (TEP)

*PRB **59**, 8371 (1999)*

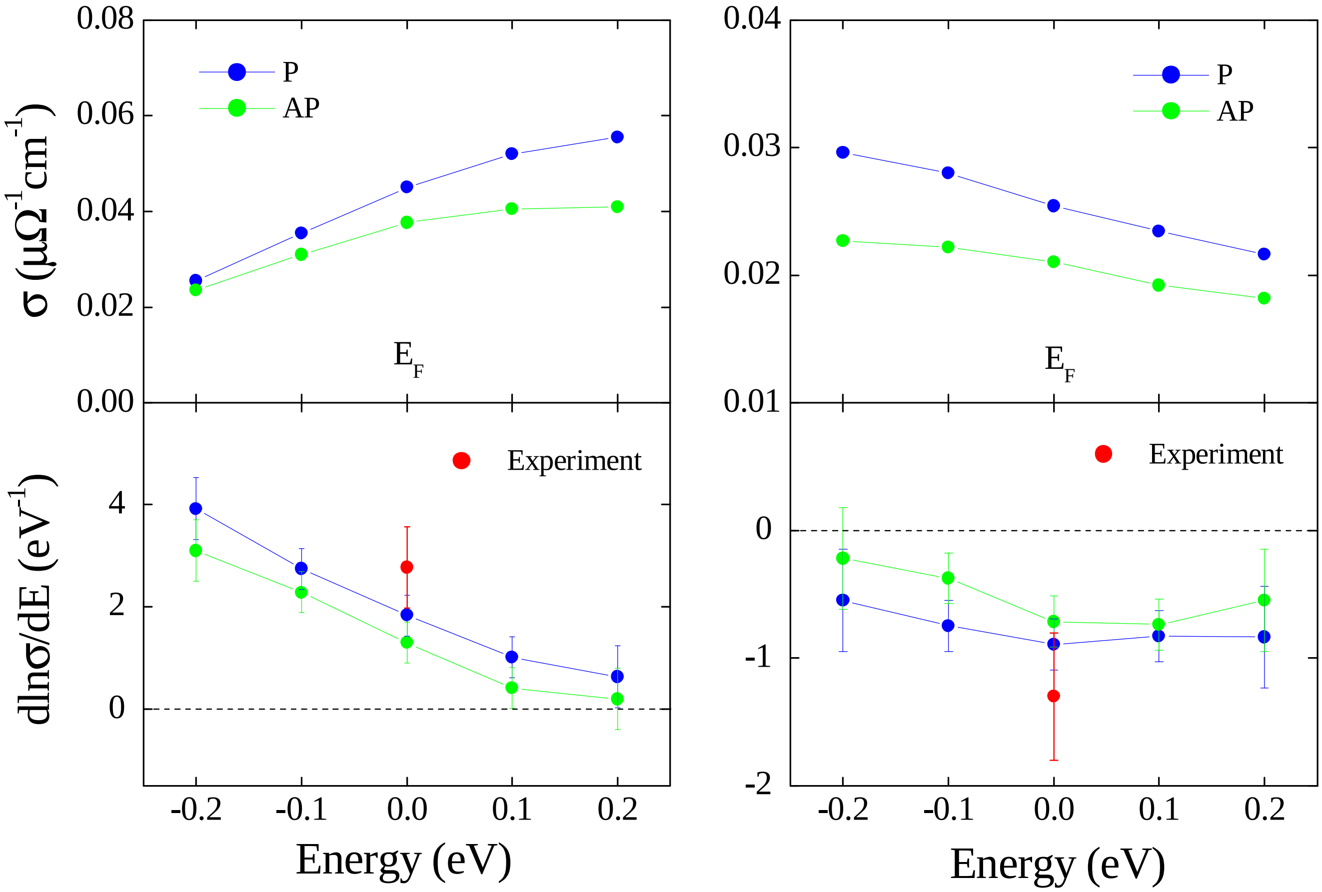


Experiments:
J.Shi, *Motorola Research Labs*
M.Salamon, *University of Illinois*

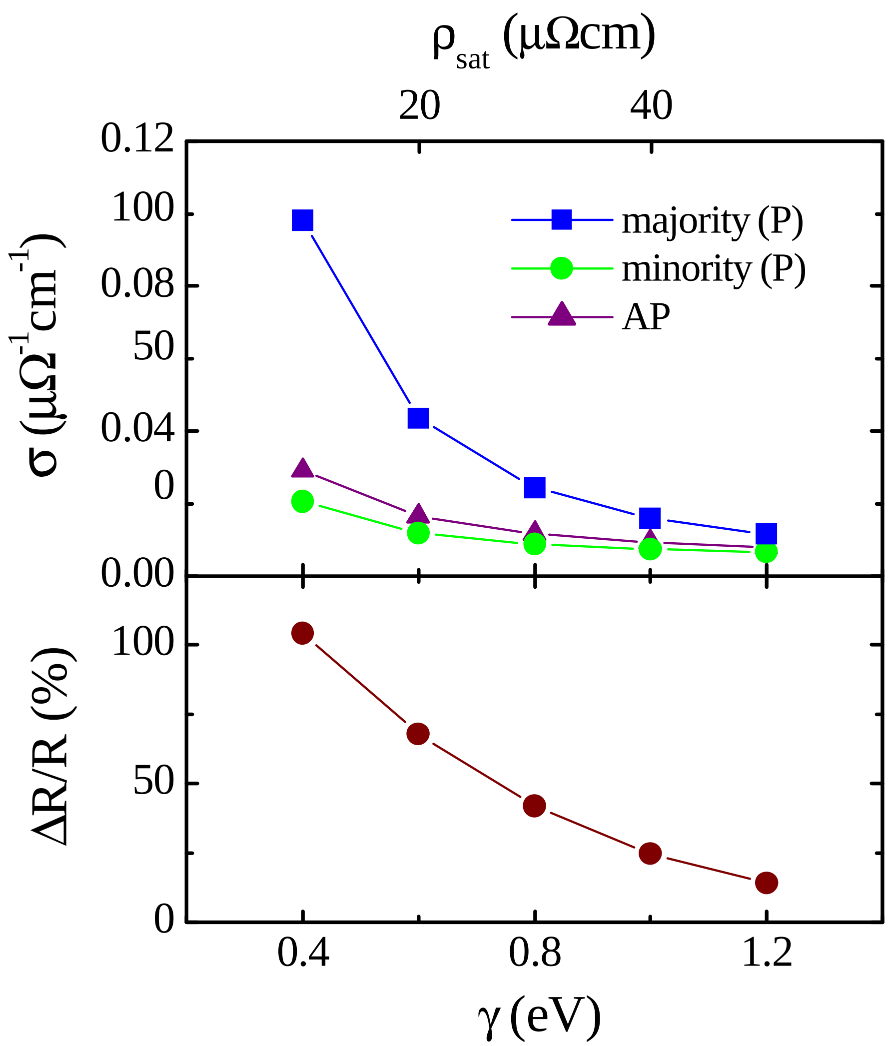
- Experimentally TEP and magneto-TEP is negative for Co/Cu multilayers, but positive for Fe/Cr multilayers

Mott formula:

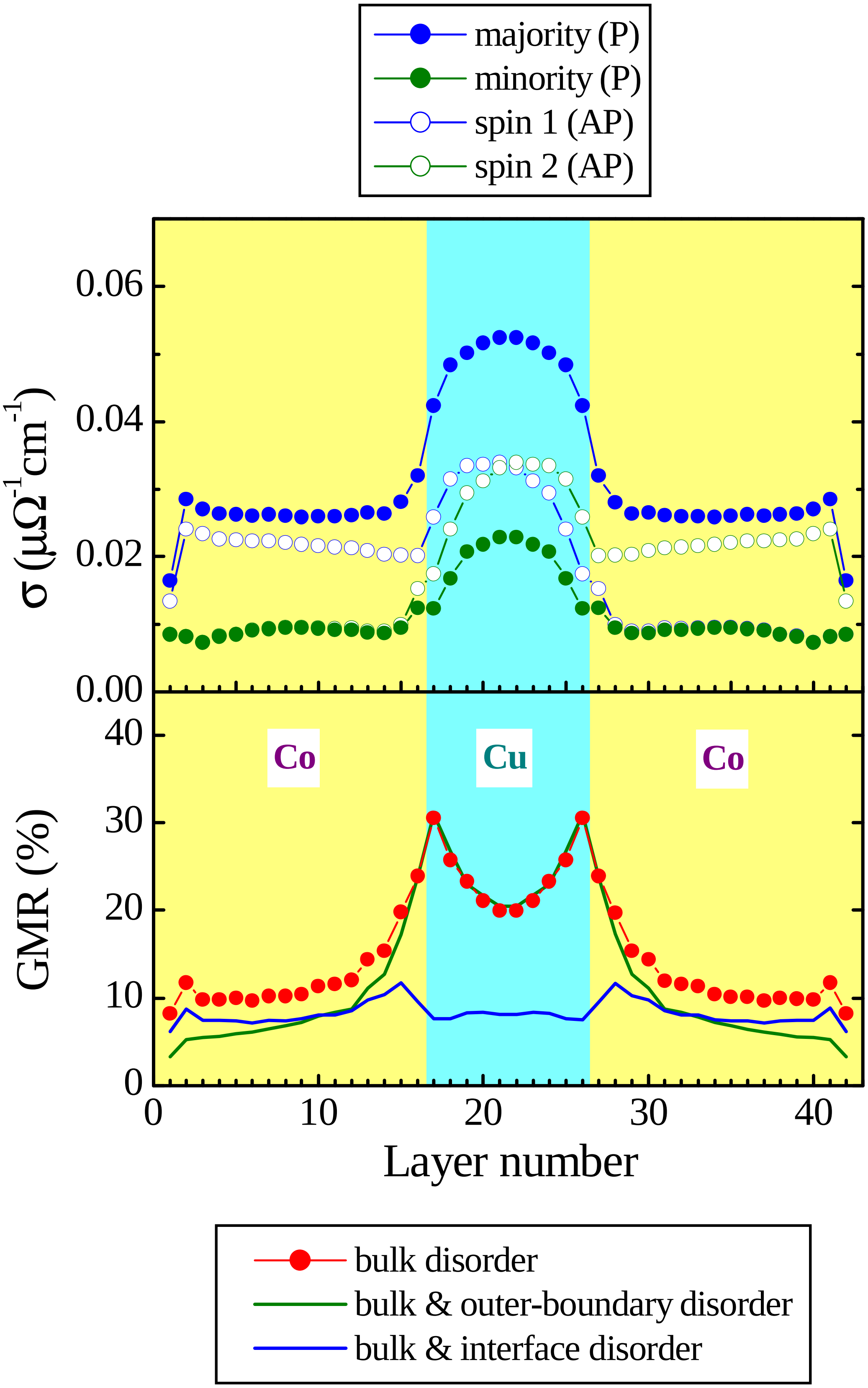
$$S = -\frac{\pi^2 k^2 T}{3e} \frac{\partial \ln \sigma}{\partial E}\bigg|_{E_F}$$



Effect of disorder

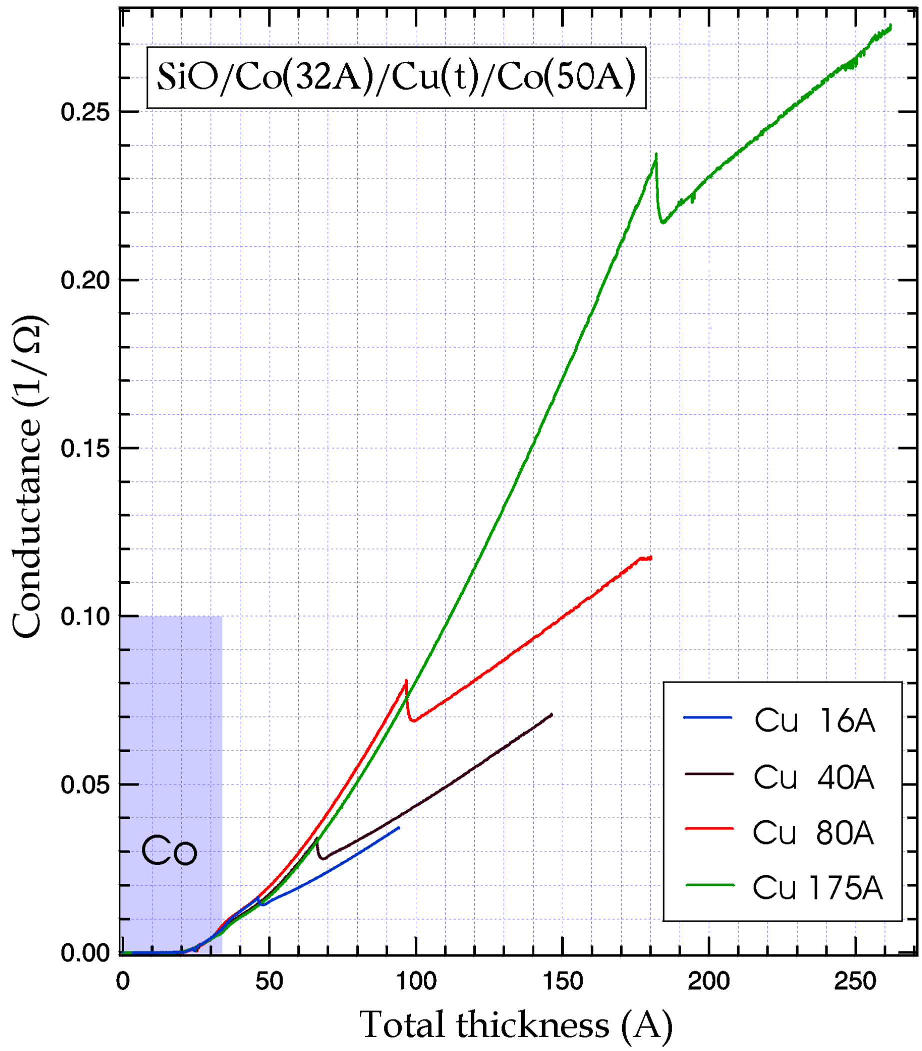


Layer-dependent conductance



Thickness-dependent conductance

*PRB **61**, 1330 (2000)*



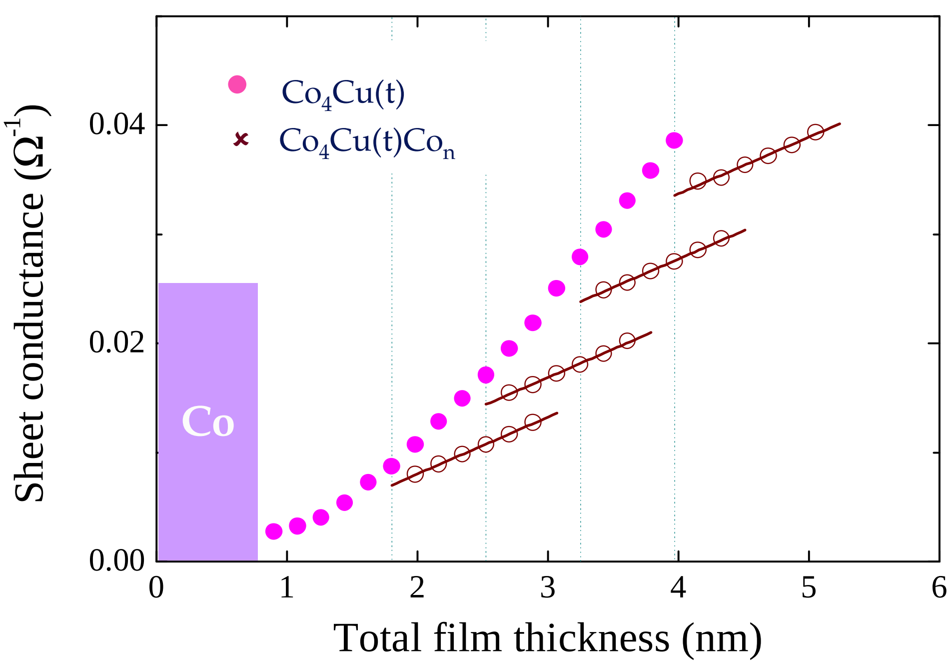
Experiments:

W.Bailey and S.Wang,
Stanford University

Conductance is measured *in situ* during ion-beam deposition

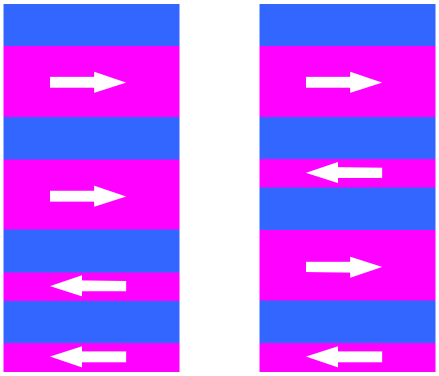
Theory:

Conductance drop results from strong interface scattering, as a consequence of high density of empty Co *d* states at Cu boundaries



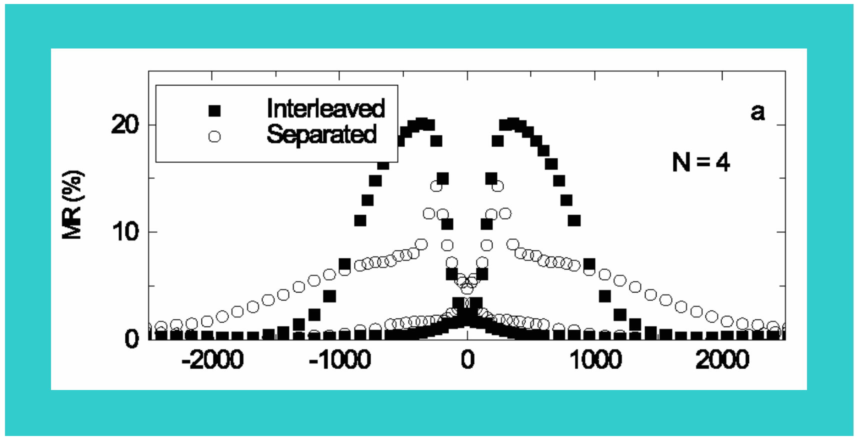
Failure of resistor model for CPP GMR

Experiments: D. Bozec *at al*, University of Leeds

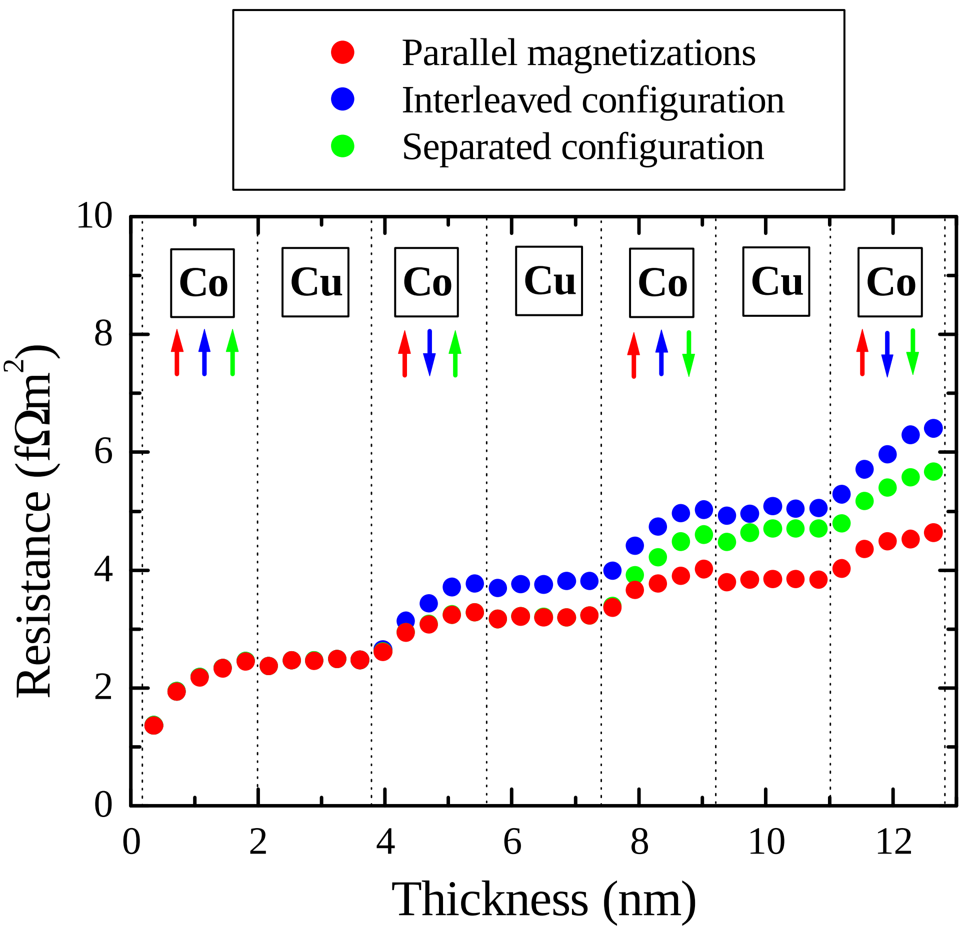


Separated configuration

Interleaved configuration



Theory:

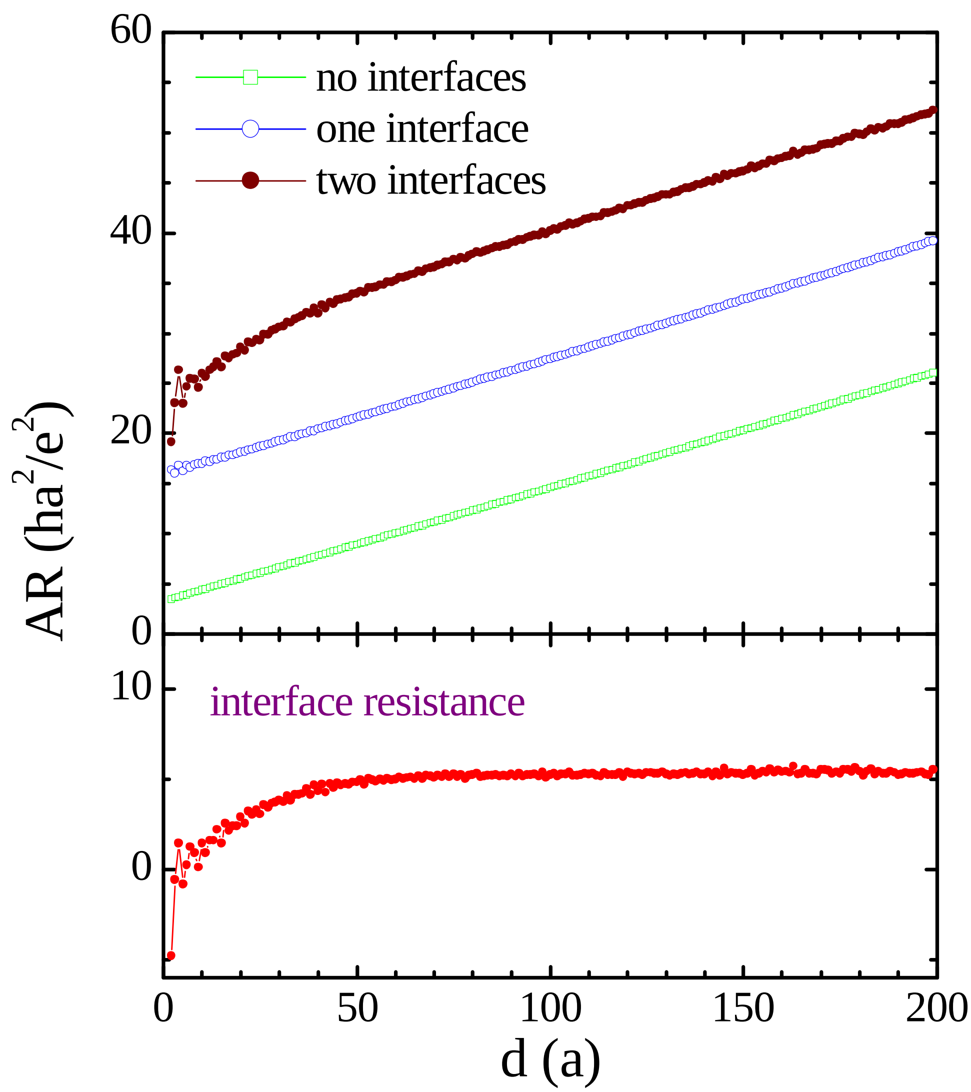


PRL ***85****,1314 (2000)*

Layer-thickness-dependent interface resistance

PRB ***61****, 506 (2000)*

- single-band tight-binding model
- Kubo formula within Anderson model of disorder
- two different metals, characterized by different on-site atomic energies



Conclusions

The model for giant magnetoresistance

predicts

- Decreasing GMR with disorder
- Enhancement of GMR in Co/Cu multilayers for hot electrons; no such enhancement for Fe/Cr multilayers
- Sizeable contribution from the spacer layer in spin valves
- Importance of layer-thickness-dependent interface resistance for CPP GMR

and explains

- Thermoelectric power in Co/Cu and Fe/Cr multilayers
- Conductance of in-situ grown Co/Cu spin valves
- Failure of the resistor model for CPP GMR