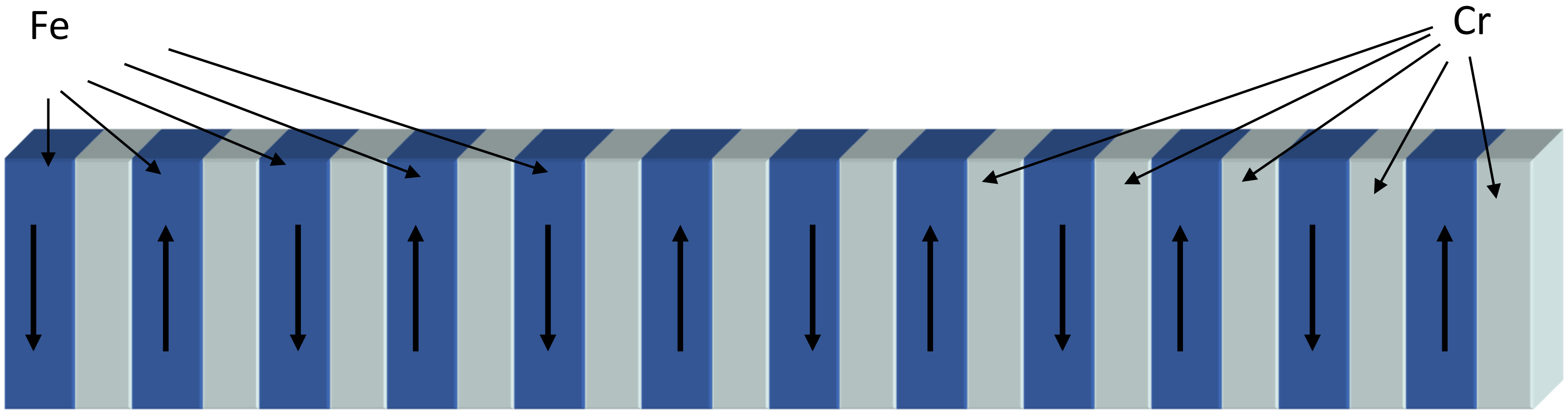
# Magnetic multilayers show strong MR effect

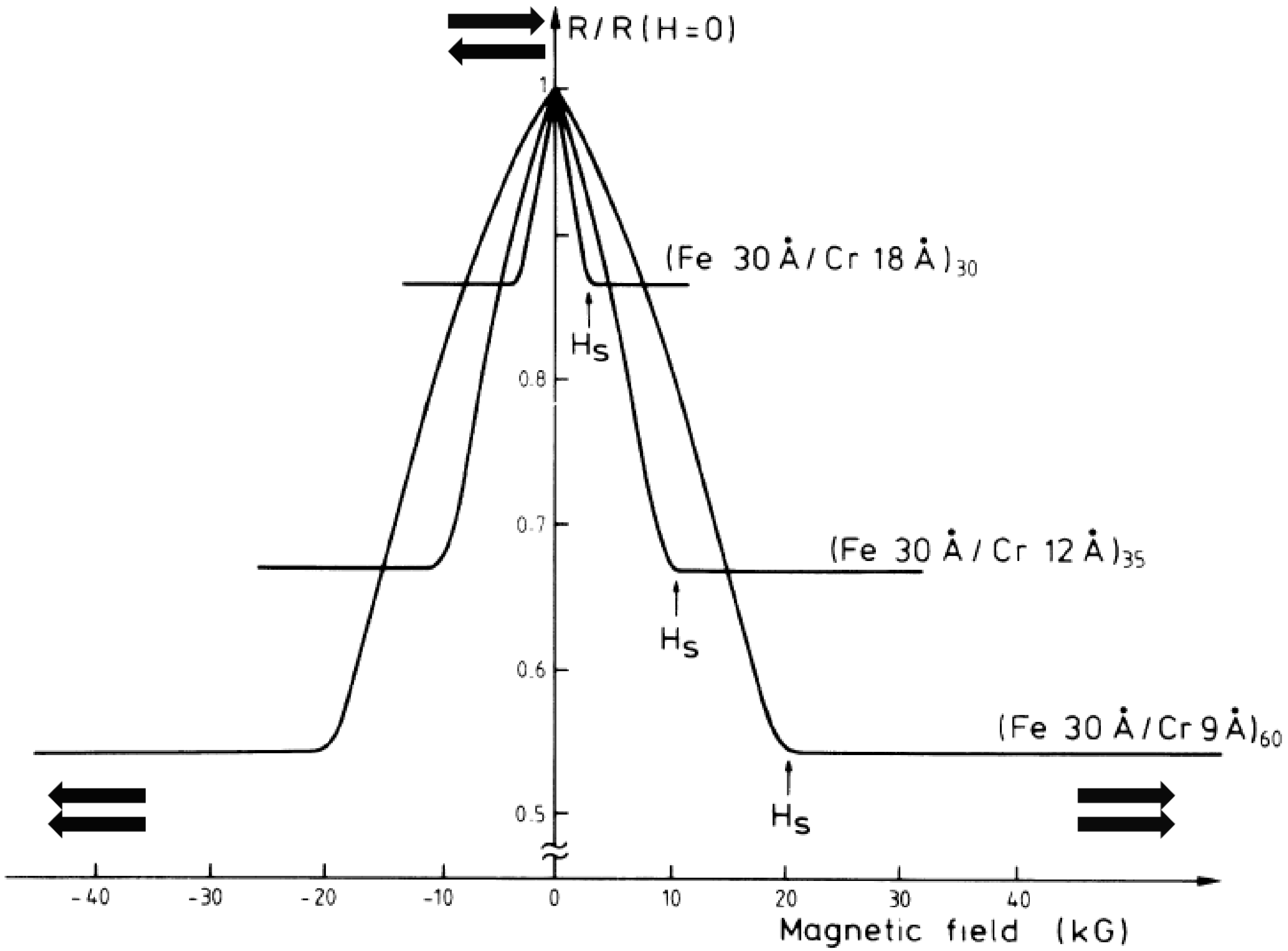
- Fe/Cr Multilayer structure – Each layer is a few nm thick

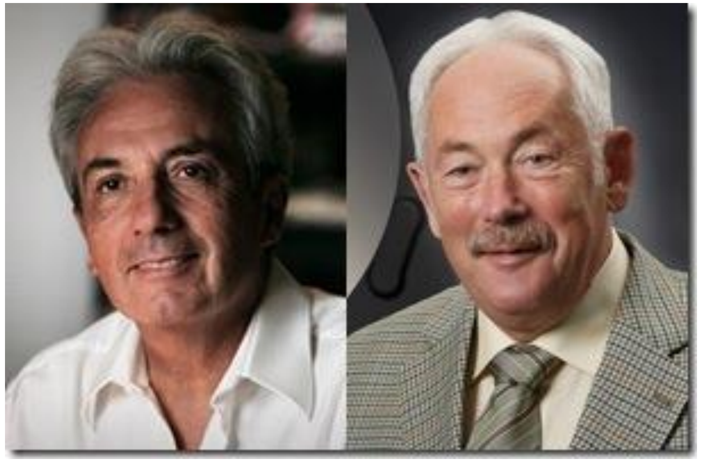


Fe layers can be either parallel or antiparallel to each other.
Drastic difference in resistance is observed between these configurations

# Giant Magnetoresistance Effect

## First observed in Fe/Cr superlattices (FM/M/FM)



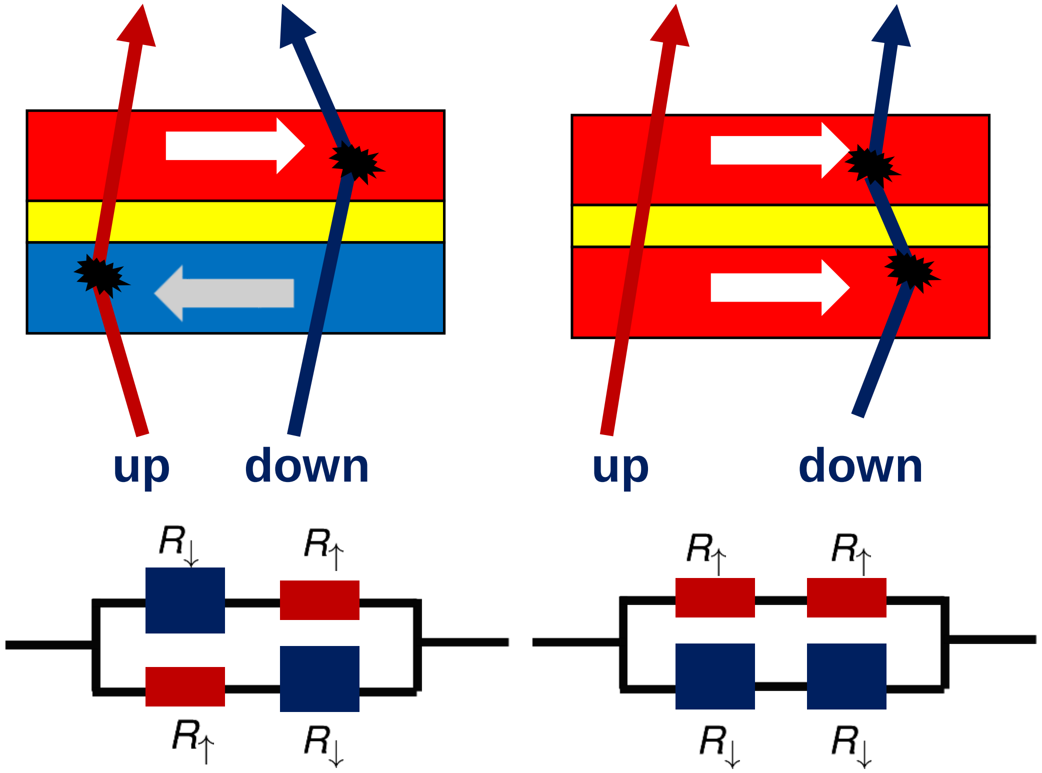


**A.Fert and P. Grunberg**
**2007 Physics Noble Prize**

**Baibich *et. al.* PRL (1988)**

**20% effect at RT**

# Two resistor model of GMR

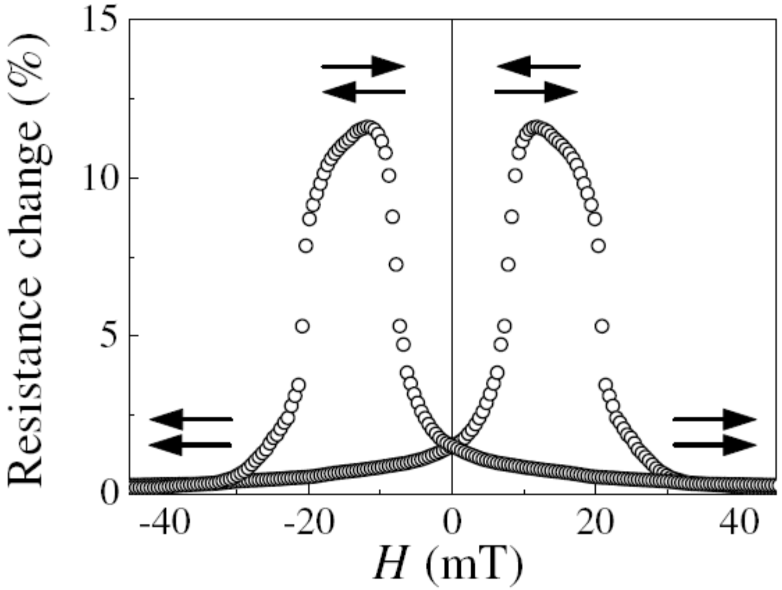


$$MR = \frac{R_{\uparrow\downarrow} - R_{\uparrow\uparrow}}{R_{\uparrow\uparrow}} = \frac{(\alpha - 1)^2}{4\alpha};\ \alpha = \frac{R_\downarrow}{R_\uparrow}$$

# Tunnel magnetoresistance device

- Replace Cr layer in GMR device with an insulator like Al2O3 or MgO.
- Device is called Tunnel magnetoresistance or Magnetic tunnel junction

**1975 – Julliere observes 14% TMR at 4.2K**
**1993 – Room temperature TMR ~ 3% (Miyazaki)**
**1995 - *substantial RT MR (>10%) was reported***



***Moodera et al. (1995)***

# Spintronics with insulating barrier

Quantum Tunneling - Ability of electrons to overcome classically forbidden potential barrier

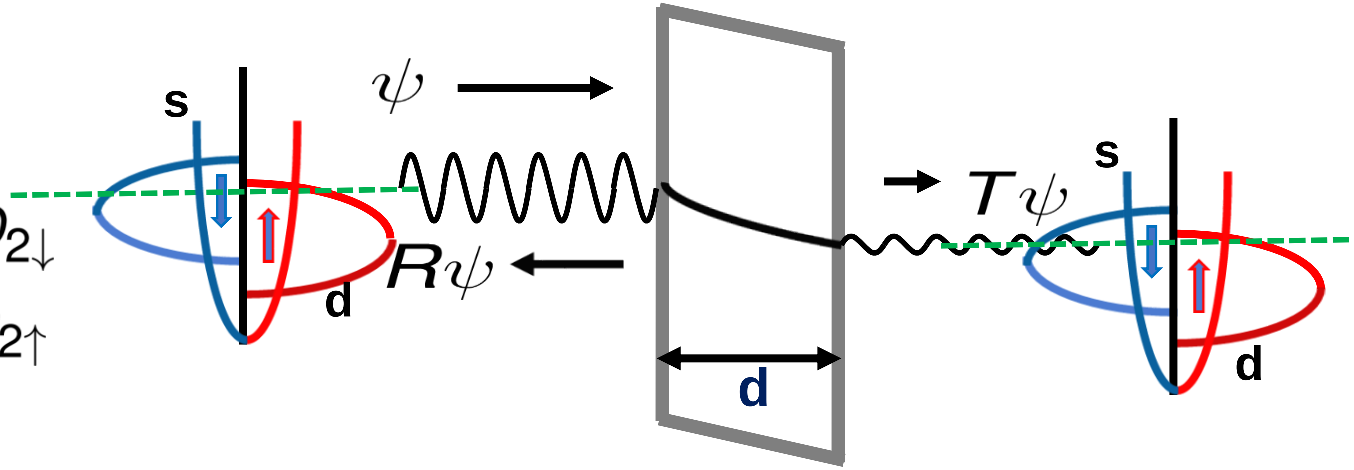
Tunneling probability depends exponentially on barrier thickness, height

$$T \propto e^{-2\kappa d} \quad \kappa = \sqrt{\frac{2m(V-E)}{\hbar^2}}$$

$$I = I_{up} + I_{down}$$

$$T_{\uparrow\uparrow} \propto D_{1\uparrow}D_{2\uparrow} + D_{1\downarrow}D_{2\downarrow}$$

$$T_{\uparrow\downarrow} \propto D_{1\uparrow}D_{2\downarrow} + D_{1\downarrow}D_{2\uparrow}$$



$$TMR = \frac{\sigma_{\uparrow\uparrow} - \sigma_{\uparrow\downarrow}}{\sigma_{\uparrow\downarrow}} = \frac{2P_1P_2}{1-P_1P_2} \quad P_{1(2)} = \frac{D_{\uparrow 1(2)} - D_{\downarrow 1(2)}}{D_{\uparrow 1(2)} + D_{\downarrow 1(2)}}$$

Julliere (1975)

Technology - Completely spin-polarized materials would approach infinite TMR value. Complex oxides have a few of these (e.g. $CrO_2$, LSMO, $Fe_3O_4$) and Heuslers

# TUNNELING BETWEEN FERROMAGNETIC FILMS

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Received 25 June 1975

Fe-Ge-Co junctions conductance G(V) is studied when mean magnetizations of the two ferromagnetic film are parallel or antiparallel. Conductance measurement, in these two cases, is related to the spin polarizations of the conduction electrons.

We have observed zero bias anomalies of the Appelbaum-Anderson type as a systematic feature of the tunneling conductance $G(V)$ of Fe-Ge-Pb and Fe-Ge-Co tunnel junctions, at $T \leqslant 4.2$K. The conductance dip can be due to exchange scattering of the tunneling electrons by magnetic atoms. These atoms are diffused in the semiconductor tunnel barrier or located at the Fe-Ge interface. The anomaly, typically of 4 mV width, is independent of applied magnetic field. This is explained by interactions between localized moments (magnetic atoms) resulting in an large effective magnetic field, as described by Wyatt [3].

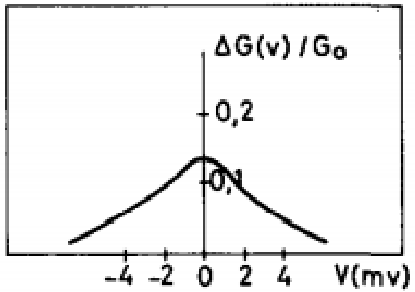
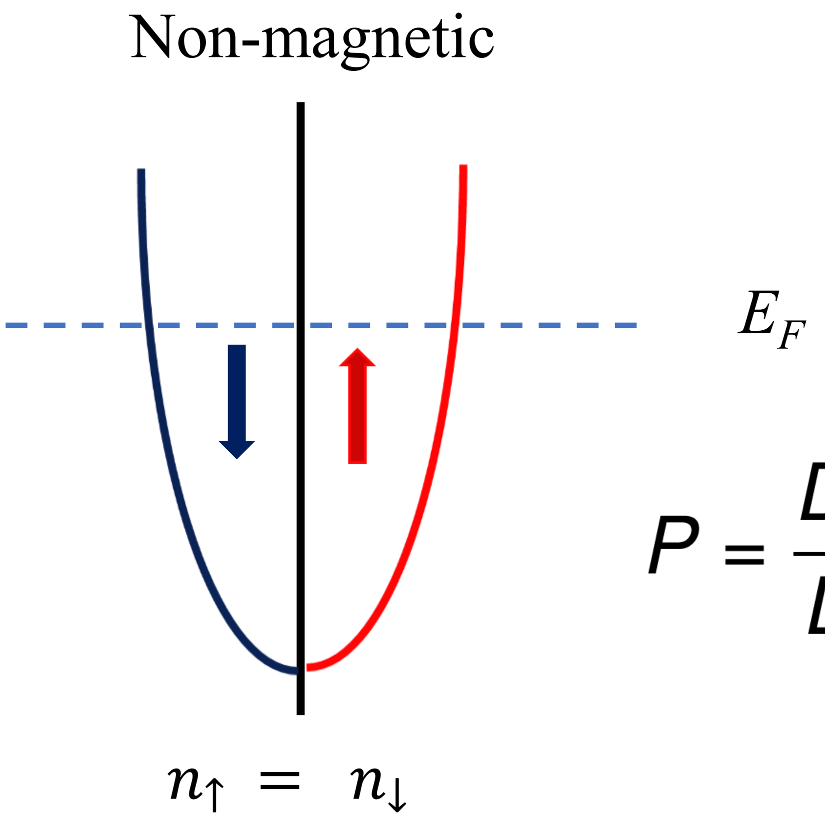


Fig. 2. Relative conductance $(\Delta G/G)_{V=0}$ of Fe-Ge-Co junctions at 4.2K. $\Delta G$ is the difference between the two conductance values corresponding to parallel and antiparallel magnetizations of the two ferromagnetic films.

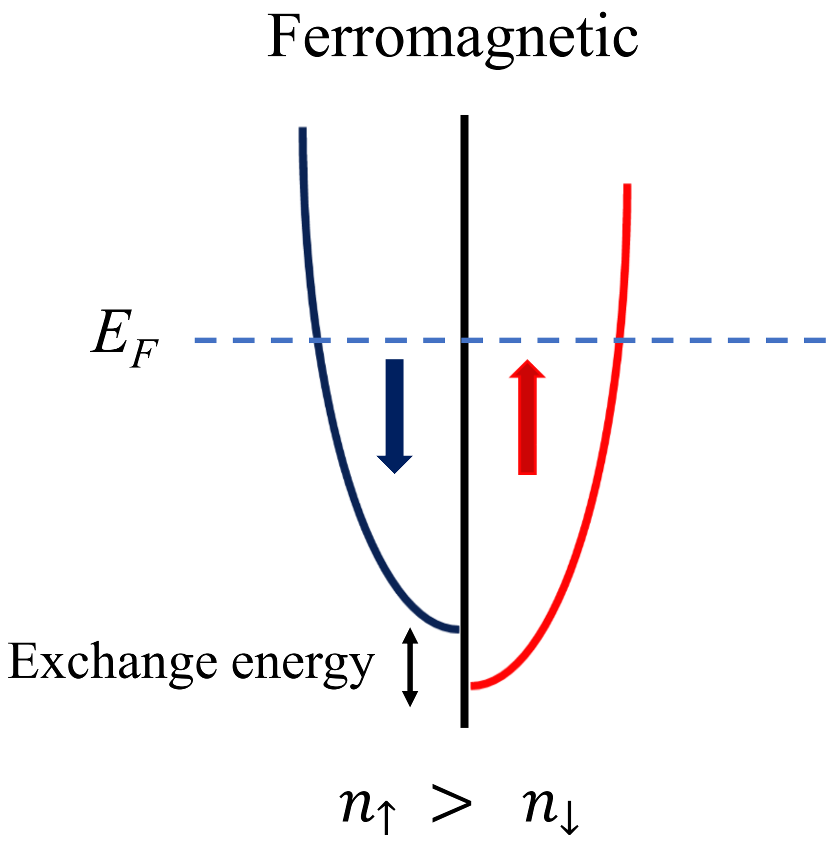
# Spin polarization (P)

- There are more spin-up than spin-down electrons at the Fermi level in a ferromagnet.

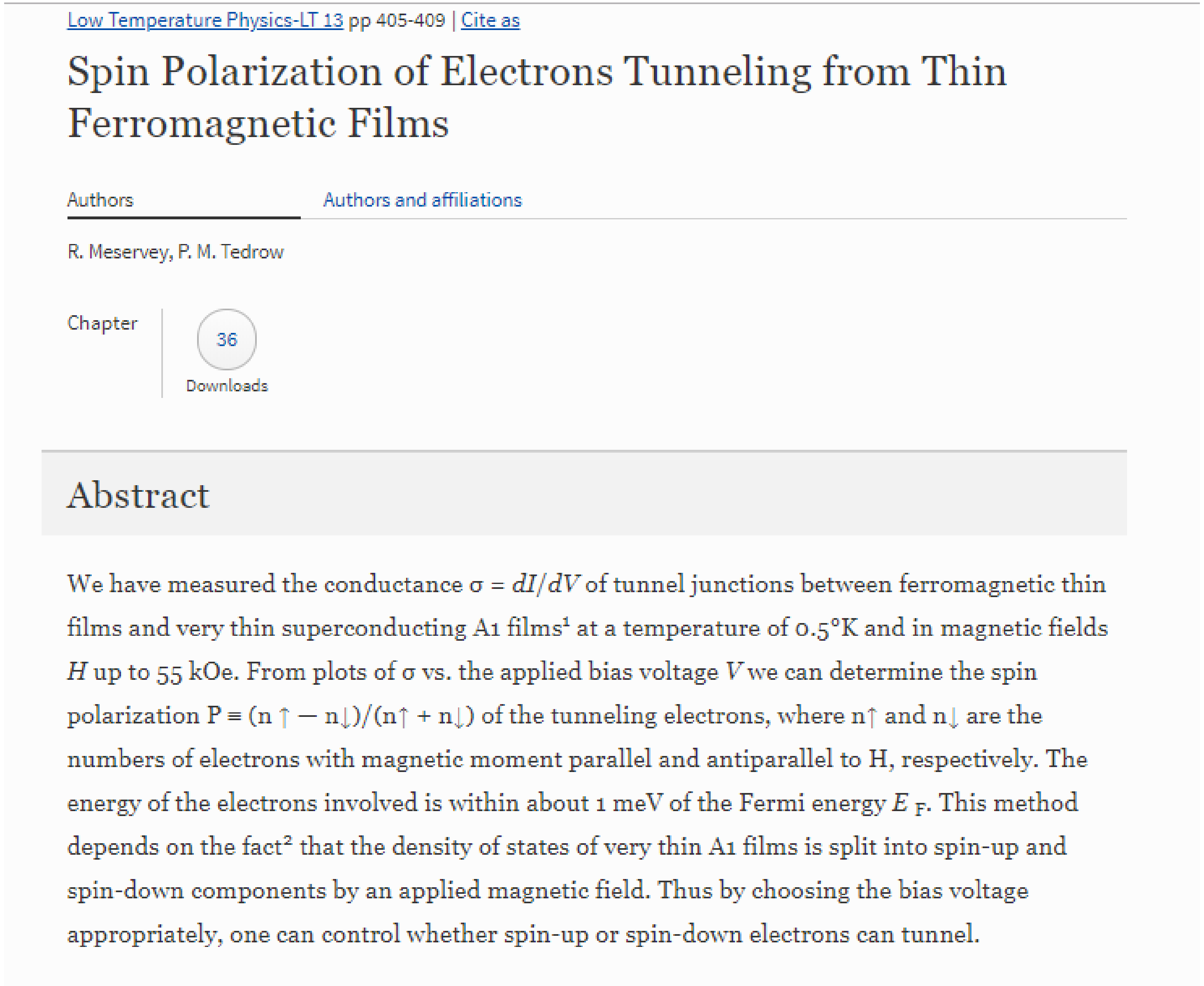
$$N = n_{\uparrow} - n_{\downarrow}$$



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



# Meservey-Tedrow spin-polarization experiments (1971-75)



Low Temperature Physics-LT 13 pp 405-409 | Cite as

## Spin Polarization of Electrons Tunneling from Thin Ferromagnetic Films

Authors | Authors and affiliations

R. Meservey, P. M. Tedrow

## Abstract

We have measured the conductance $\sigma = dI/dV$ of tunnel junctions between ferromagnetic thin films and very thin superconducting A1 films[1] at a temperature of 0.5°K and in magnetic fields $H$ up to 55 kOe. From plots of σ vs. the applied bias voltage $V$ we can determine the spin polarization $P \equiv (n\uparrow - n\downarrow)/(n\uparrow + n\downarrow)$ of the tunneling electrons, where $n\uparrow$ and $n\downarrow$ are the numbers of electrons with magnetic moment parallel and antiparallel to H, respectively. The energy of the electrons involved is within about 1 meV of the Fermi energy $E_F$. This method depends on the fact[2] that the density of states of very thin A1 films is split into spin-up and spin-down components by an applied magnetic field. Thus by choosing the bias voltage appropriately, one can control whether spin-up or spin-down electrons can tunnel.

# TMR with amorphous $Al_2O_3$ tunnel barrier

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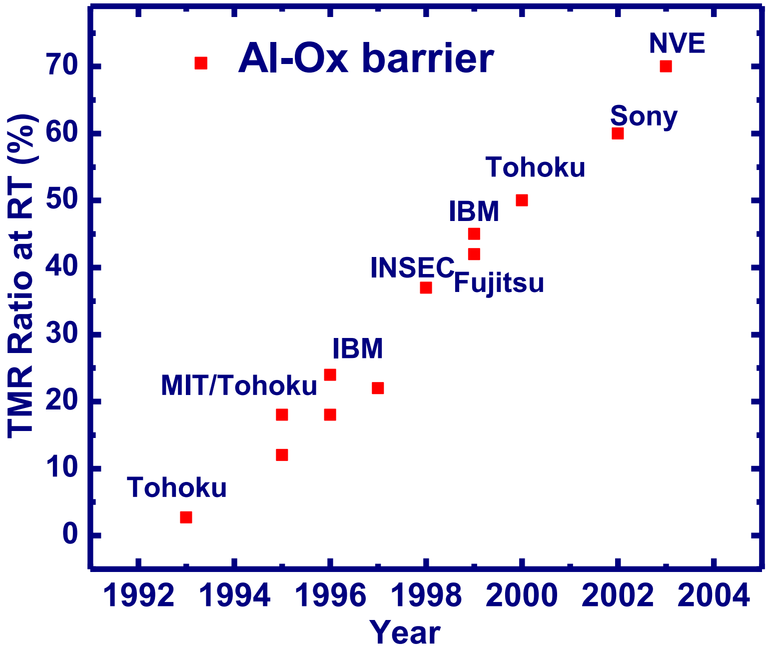

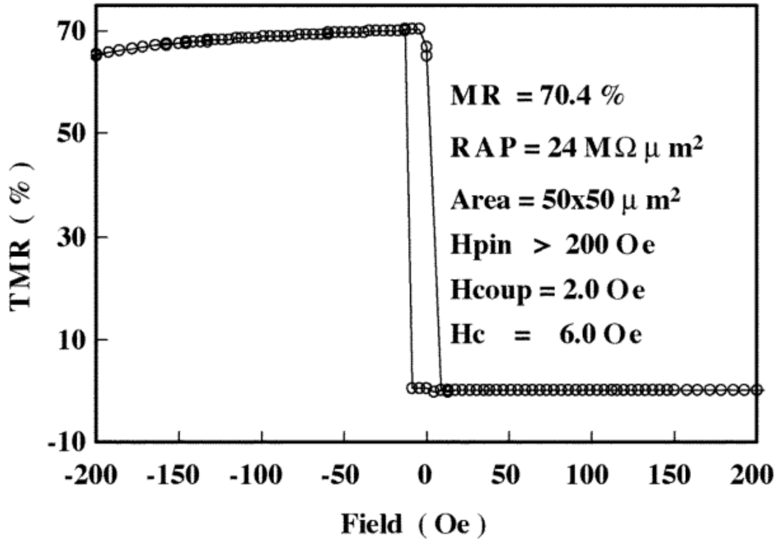

*Wang et al. IEEE (2004)*

**Technology hitting physical limits with amorphous barriers**

**MR – 20- 70 %**

**P=0.5 → MR ~ 67% (Julliere's formula)**