2008 Nobel Prize in Physics

The Discovery of Giant Magnetoresistance

the laureates:
Albert Fert, Universite Paris Sud & Thales
Peter Gruenberg, Forschungszentrum Juelich
Enabling technology: MBE
“Spray-painting with atoms:” semiconductor heterostructures

Semiconductor superlattice: GaAs/AlAs

Quantum wells, etc (!)

pioneers, Bell Labs ~1978
Other things to do with the MBE chamber

Metal superlattices?

1980's: **X-ray mirrors (W/Si)**; studies of diffusion (Ni/Cu).. studies of plasticity (Ag/Ni).. Finite size effects on superconductivity (Nb/Cu) ...

1985- **perpendicular magnetic anisotropy** (Co/Pd, Co/Au) (MO disks)

*(1991 Review): “The commercial applications of metallic multilayers so far are belittled by the development of semiconductor multilayers, which have created the new field of bandstructure engineering and revolutionized semiconductor device design...”*
Macroscopic magnets are built of atomic moments

Magnetization is average:
\[ \mathbf{M} = N \mathbf{v} \mu \]

from internal electrons orbiting

or spinning

Magnetization is average:
\[ \mathbf{M} = N \mathbf{v} \mu \]
All atoms are magnetic…

(esp. in 10 T superconducting magnet)

Some diamagnetic:
\[ M = \chi H, \]
\[ \chi < 0 \]

Some paramagnetic:
\[ M = \chi H, \]
\[ \chi > 0 \]
Only a few “ferromagnetic elements”
Prehistory of GMR:
"long-range" magnetic interactions in Gd/Y (4/1986)

Observation of a Magnetic Antiphase Domain Structure with Long-Range Order in a Synthetic Gd-Y Superlattice

C. F. Majkrzak
Brookhaven National Laboratory, Upton, New York 11973

J. W. Cable
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830

J. Kwo, M. Hong, D. B. McWhan, Y. Yafet, and J. V. Waszczak
AT&T Bell Laboratories, Murray Hill, New Jersey 07974

and

C. Vettier
Institut Laue-Langevin, 38042 Grenoble Cédex, France
(Received 15 April 1986)

FIG. 4. The oscillatory dependence of (a) $\sigma/\sigma(0)$, and (b) $H_s$, on $N_Y$ in two series of superlattices with $N_{Gd}=4$, and $N_{Gd}=10\pm 1$. The dashed lines are to guide the eyes. (c) The calculated functional dependence of $J_{Gd-Y}(r)$ on $N_Y$. 

Antiferromagnetic
Ferromagnetic
Antiferromagnetic coupling was be essential for the observation of GMR!
Observation of GMR
Who was first? Grunberg (5/1988); Fert (8/1988)

Enhanced magnetoresistance in layered magnetic structures with antiferromagnetic interlayer exchange

G. Binasch, P. Grünberg, F. Saurenbach, and W. Zinn
Institut für Festkörperforschung, Kernforschungsanlage Jülich G.m.b.H., Postfach 1913, D-5170 Jülich, West Germany
(Received 31 May 1988; revised manuscript received 12 December 1988)

The electrical resistivity of Fe-Cr-Fe layers with antiferromagnetic interlayer exchange increases when the magnetizations of the Fe layers are aligned antiparallel. The effect is much stronger than the usual anisotropic magnetoresistance and further increases in structures with more than two Fe layers. It can be explained in terms of spin-flip scattering of conduction electrons caused by the antiparallel alignment of the magnetization.

Giant Magnetoresistance of (001)Fe/(001)Cr Magnetic Superlattices

M. N. Baibich, (a) J. M. Broto, A. Fert, F. Nguyen Van Dau, and F. Petroff
Laboratoire de Physique des Solides, Université Paris-Sud, F-91405 Orsay, France

P. Etienne, G. Creuzet, A. Friederich, and J. Chazelas
Laboratoire Central de Recherches, Thomson CSE, B.P. 10, F-91401 Orsay, France
(Received 24 August 1988)

We have studied the magnetoresistance of (001)Fe/(001)Cr superlattices prepared by molecular-beam epitaxy. A huge magnetoresistance is found in superlattices with thin Cr layers. For example, with \( t_{\text{Cr}} = 9 \text{ Å} \), at \( T = 4.2 \text{ K} \), the resistivity is lowered by almost a factor of 2 in a magnetic field of 2 T. We ascribe this giant magnetoresistance to spin-dependent transmission of the conduction electrons between Fe layers through Cr layers.

PACS numbers: 75.50.Rr, 72.15.Gd, 75.70.Cn

Gruenberg, sort of!
Observation of GMR: the phenomenon

What happened?

The electrical resistance drops a lot when the Fe magnetizations are aligned.
Origin of the GMR effect:
spin-dependent electrical resistance (scattering) in a FM

The electrical resistance in a conductor arises when electrons scatter against irregularities in the material so that their forward movement is obstructed.

In a magnetic conductor the direction of spin of most electrons is parallel with the magnetization (red). A minority of electrons have spin in the opposite direction (white). In this example electrons with antiparallel spin are scattered more.
Origin of the GMR effect:
spin-dependent electrical resistance (scattering) in a FM

Fert & Campbell, J. Phys F (1976)

Resistivity of ferromagnetic Ni and Fe based alloys

Table 5. The residual resistivity per at%_p, the parameter $\alpha = \rho_0/\rho_{1}$ and the spin ↑ and spin ↓ residual resistivities per at% for impurities in iron.

<table>
<thead>
<tr>
<th>Impurity</th>
<th>Ti</th>
<th>V</th>
<th>Cr</th>
<th>Mn</th>
<th>Co</th>
<th>Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho_0 (\mu\Omega \text{cm/at%}_p)$</td>
<td>29</td>
<td>1.4</td>
<td>2.6</td>
<td>1.7</td>
<td>2</td>
<td>1.8</td>
</tr>
<tr>
<td>$\alpha = \rho_0/\rho_{1}$</td>
<td>$\frac{1}{3}$</td>
<td>$\frac{1}{3}$</td>
<td>$\frac{1}{3}$</td>
<td>$\frac{1}{3}$</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>$\rho_{0\uparrow} (\mu\Omega \text{cm/at%}_p)$</td>
<td>14.5</td>
<td>13.5</td>
<td>18</td>
<td>21</td>
<td>20</td>
<td>24</td>
</tr>
<tr>
<td>$\rho_{0\downarrow} (\mu\Omega \text{cm/at%}_p)$</td>
<td>3.6</td>
<td>1.6</td>
<td>3</td>
<td>1.9</td>
<td>2.0</td>
<td>7.2</td>
</tr>
</tbody>
</table>

In a magnetic conductor the direction of spin of most electrons is parallel with the magnetization (red). A minority of electrons have spin in the opposite direction (white). In this example electrons with antiparallel spin are scattered more.
Introduction to GMR: origin of spin-dependent scattering

3d ferromagnets (Fe, Co, Ni): $s \rightarrow d$ scattering

- $sp$-electrons carry current
- scattering into empty $d$-states: (final states)
  - $D \downarrow (E_f)$: large high scattering rate: $\rho \downarrow \text{high}$
  - $D \uparrow (E_f)$: small low scattering rate: $\rho \uparrow \text{low}$
Introduction to GMR: optical analogy

GMR:

unpolarized light

polarized light

Orthogonal P: Dim

(Parallel P, Bright)

spin-unpolarized current

spin up current

Antiparallel M: High Resistance

Parallel M: Low Resistance

ferromagnetic (FM) #1 "pinned layer"

ferromagnetic (FM) #2 "free layer"

noble metal (NM) "spacer"
Observation of GMR
Who got it right?

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with antiferromagnetic interlayer exchange

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Observation of GMR
Who got the patent?

USPO 4949039
“Magnetic field sensor with ferromagnetic thin layers having magnetically anti-parallel components”

Fundamental patent on GMR heads.
**Filed 6/16/1988**
9 MEuros in licensing, 14 licensees
(KFJ website)
Making GMR practical: structures

GMR Multilayer (1988)

<table>
<thead>
<tr>
<th>Co</th>
<th>Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Co</td>
<td>Cu</td>
</tr>
<tr>
<td>Co</td>
<td>Cu</td>
</tr>
<tr>
<td>Co</td>
<td></td>
</tr>
</tbody>
</table>

ΔR

R

ΔR

R

etc, x 20

< 110%

H_{sat} ≈ 10 kOe

The Spin Valve (1991)

<table>
<thead>
<tr>
<th>Co</th>
<th>Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Co</td>
<td></td>
</tr>
<tr>
<td>NiO</td>
<td></td>
</tr>
</tbody>
</table>

ΔR

R

ΔR

R

< 20%

AP

P

H_{sat} = 10 Oe
Introduction to GMR: geometries

**Current perpendicular to planes**

**CPP-GMR**

- \( \Delta R/R \) to 300%

Used today.

**Current in plane**

**CIP-GMR**

- \( *1/3\) of motion perpendicular to layers
- \( \Delta R/R \) to 100%

Used five years ago.
Q: Why do trilayers have lower GMR than multilayers?

addition of surfaces

\[ d = t_{Co} \]

decreases GMR by surface scattering


![Graph showing the relationship between \( \Delta G \) and \( t_{Co} \)]

\[ \Delta R/R(\%) \]

multilayers

trilayers

![Graph showing the variation of \( \Delta R/R(\%) \) with \( t_{Co} \)]
The “GMR effect”

- **GMR effect** demonstrated: 67 Gbit/cm²
- **Shipping**: 30 Gbit/cm²

**HAMR**: 10 Tbit/cm²
(Seagate Program)

Areal density (gigabits/cm²)

- **Demonstrated**: 67 Gbit/cm²
- **Shipping**: 30 Gbit/cm²
(Seagate Barracuda, 07)

**Year**
- 1980
- 1990
- 2000
- 2010
Nature: By the end of the 1990s, the technology had become standard across the electronics industry, thanks partly to the work of physicist Stuart Parkin at IBM’s Almaden Research Center in San Jose, California, who came up with a simple way to create the thin multilayers. Although Parkin has shared physics prizes for GMR with Fert and Grünberg in the past, he was not included in the Nobel announcement. Parkin conducted vital work that allowed the effect to be commercialized, but Fert and Grünberg were the ones who discovered it, says Tony Bland, from the University of Cambridge, UK. "I think the field will generally see this as fair," he adds.

Important to be first!
Current work building on GMR effect
Spin-polarized transport phenomena ("spintronics")

1988: First observation of GMR in Fe/Cr (Fert, Grunberg)
1990: General oscillatory coupling in FE/TM (SSP)
1991: Demonstration of the GMR spin valve (SSP, B. Gurney)
1994: Record of 420% GMR in MBE Fe/Cr at 4K (R. Schad)
1995: Record of 110% GMR in epitaxial Co/Cu at RT (SSP)
1995: 15% TMR in MTJ (Moodera)
1996: CPP-GMR experiments interpreted (Fert)
1998: **First GMR read head shipped (IBM)**
1998: Unified theory of CIP-CPP GMR (Fert)
2000: 70% TMR in annealed Co/Al2O3/Co (SSP)

2000: Demonstration of spin torque switching (Cornell)
2004: Demonstration of spin torque oscillator (NIST, Cornell)
2004: 400% TMR at room temperature in epitaxial Fe/MgO/Fe (SSP)
2006: Lateral spin valves demonstrated (RIKEN)
2006: 70% efficient spin polarized current injection into GaAs (SSP)
2006: Demonstration of nonlocal spin torque (RIKEN)
2006: **First MRAM device shipped (Freescale)**