Giant Magnetoresistance

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What is GMR?

- Way to control electrical resistance at the nanoscale using magnetic field
- Nonmagnetic metal sandwiched between magnetic layers
- Apply magnetic field
  → parallel magnetization
  → decreased resistance

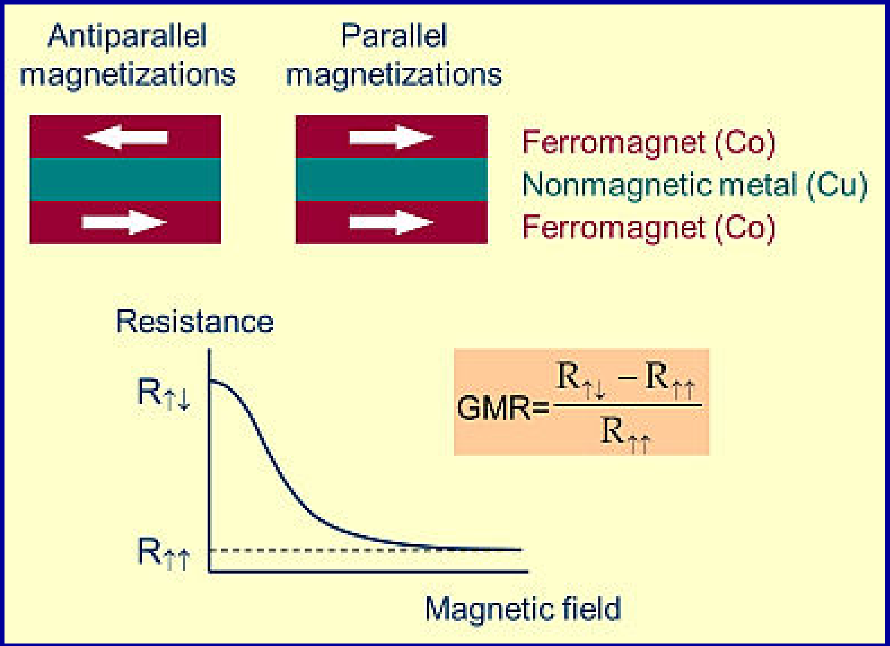

Figure 1. Fundamentals of GMR

Nobel Prize in Physics (2007)

- Awarded jointly to Albert Fert and Peter Grünberg
- Discovered independently in 1988
- Product of nanotech revolution of 1980's
- Revolutionized hard drives/data storage

Figure 2. Albert Fert

Figure 3. Peter Grunberg

Outline

- Background
- Discovery of GMR
- Some basic theory
- Applications: magnetic field sensors, hard drive read heads, magnetic RAM

Background

- Ordinary magnetoresistance (OMR) discovered in 1856 by Lord Kelvin
- Resistance of iron changes up to 5% with external magnetic field
- Little progress in MR effect through 1980

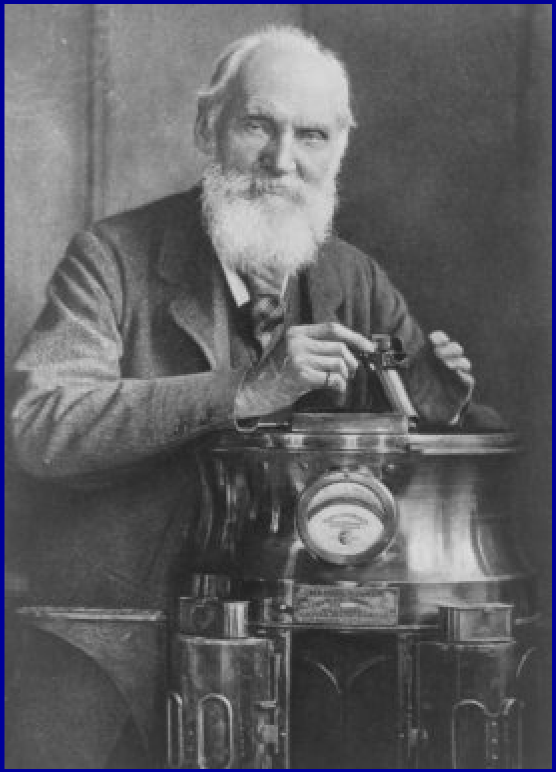

Figure 4. Lord Kelvin

Discovery

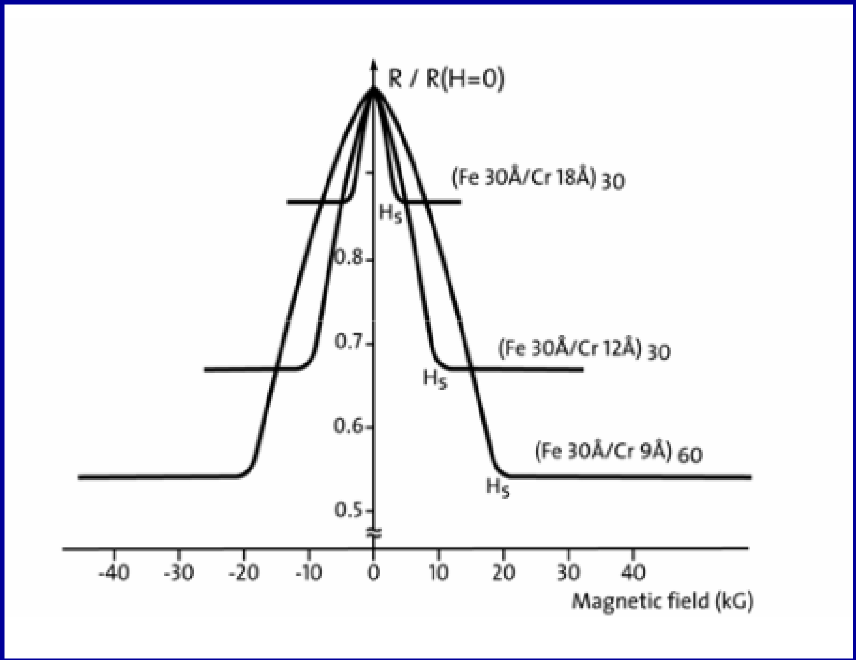

Figure 5. Albert Fert's experimental data (1988)

- Multilayers of Fe/Cr prepared by molecular beam epitaxy
- Fe is **ferromagnetic:** can be permanently magnetized
- Cr is nonmagnetic
- Magnetoresistive effect ~50% (vs. 5% previously)

Basic Mechanism

- Electron spin & atom magnetic moments in parallel → weak scattering
- Antiparallel → strong scattering
- More scattering = higher electrical resistance

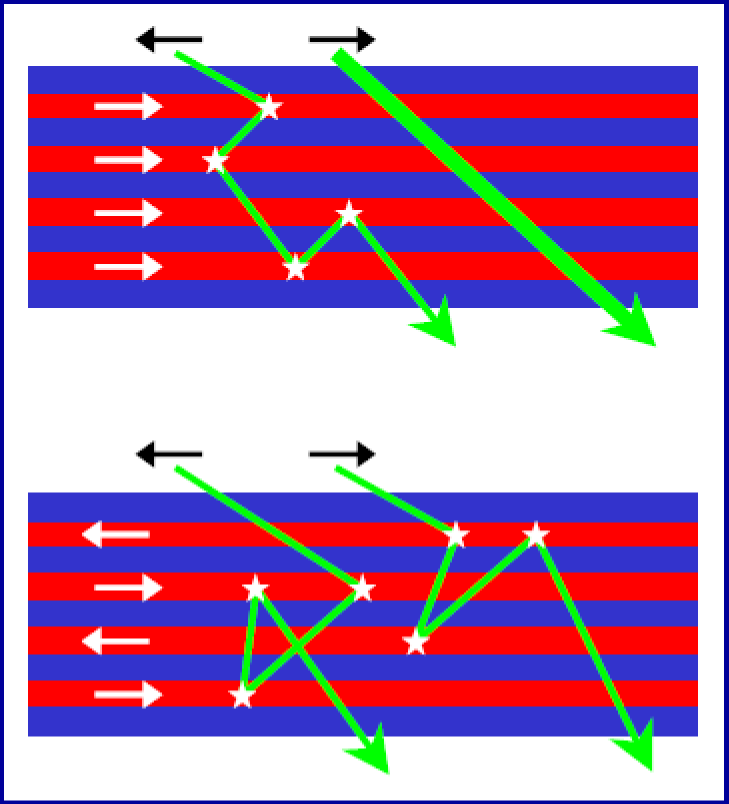

Figure 6. Schematic of Spin-Dependent Scattering

Ferromagnetic Density of States (DOS)

- **Exchange interaction:** QM consequence of Pauli principle
- Electrons with parallel spin spatially separated by exchange interaction → reduced electrostatic energy
- Exchange interaction stronger than competing dipole-dipole interaction

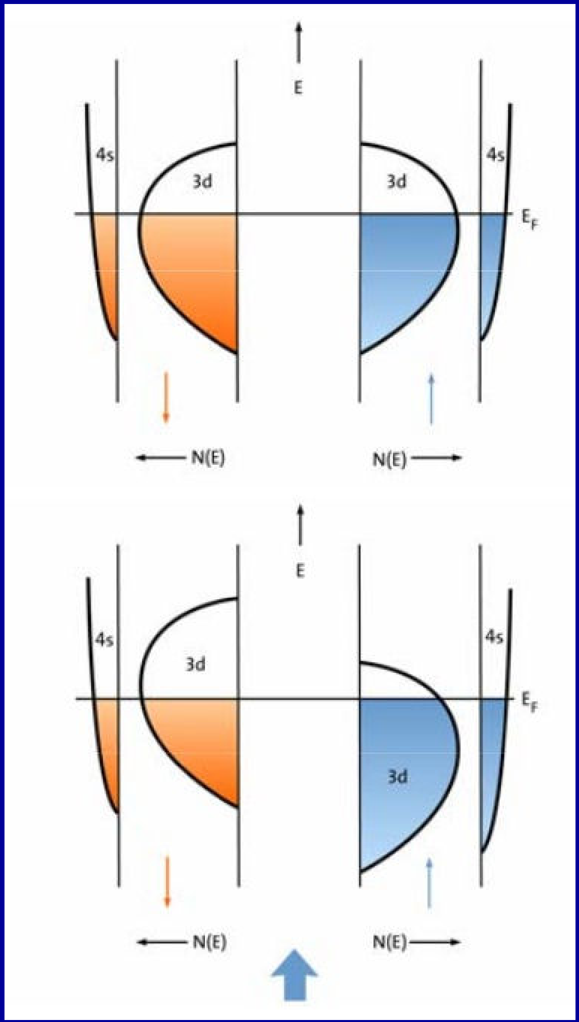

Figure 7. Ferromagnetic DOS

Spin-Dependent Scattering

- 4s electrons more responsible for conduction (more overlap)
- 3d DOS at E_F larger for minority-spin electrons than majority-spin electrons
- Higher DOS of 3d states → Stronger scattering

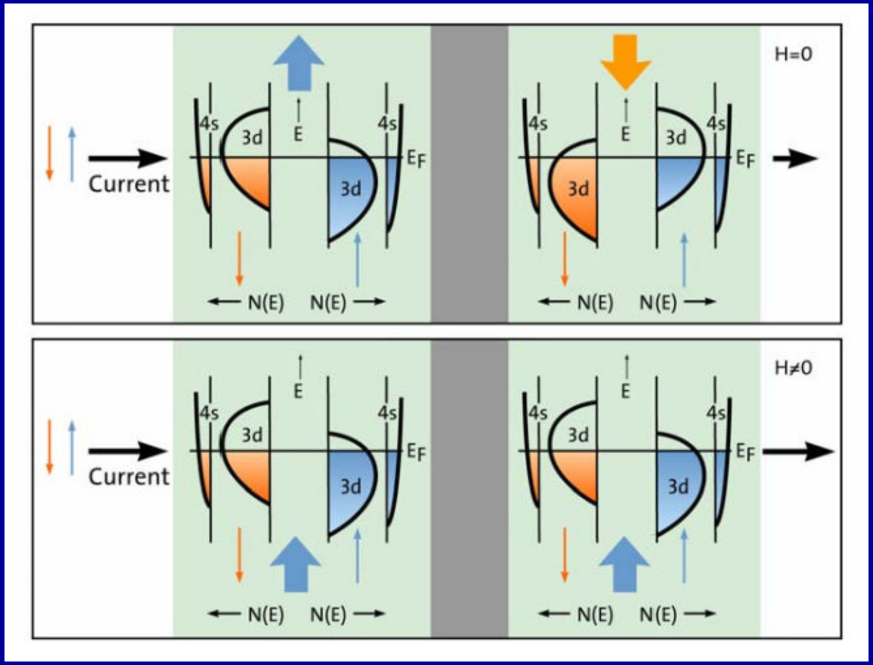

Figure 8. Ferromagnetic DOS and Spin-Dependent Scattering

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Why Nanoscale?

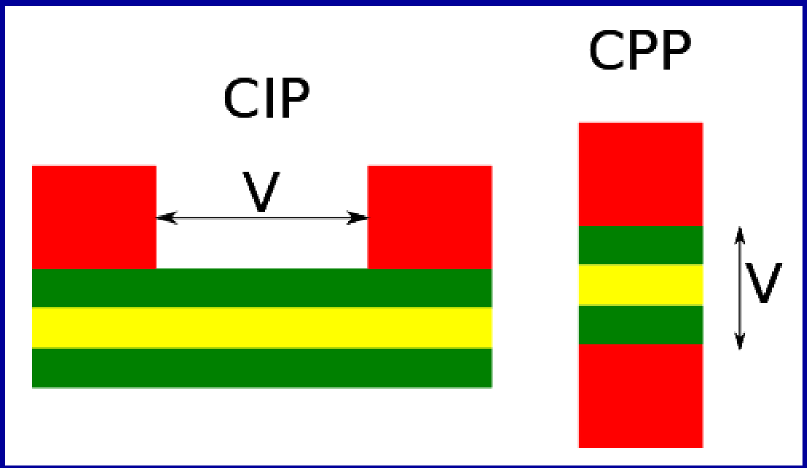

Figure 9. CIP vs. CPP geometries

- Most scattering occurs at interface of ferromagnetic and nonmagnetic layers
- Electron mean free path (~10-100 nm) must be greater than interlayer separation
- Current-perpendicular-plane (CPP) more effective than current-in-plane (CIP)—also more difficult to achieve

Nonmagnetic Layers

- Provide coupling mechanism between magnetic layers
- Decaying oscillatory exchange coupling in nonmagnetic metals
- Optimal thickness → adjacent ferromagnetic layers have antiparallel magnetization

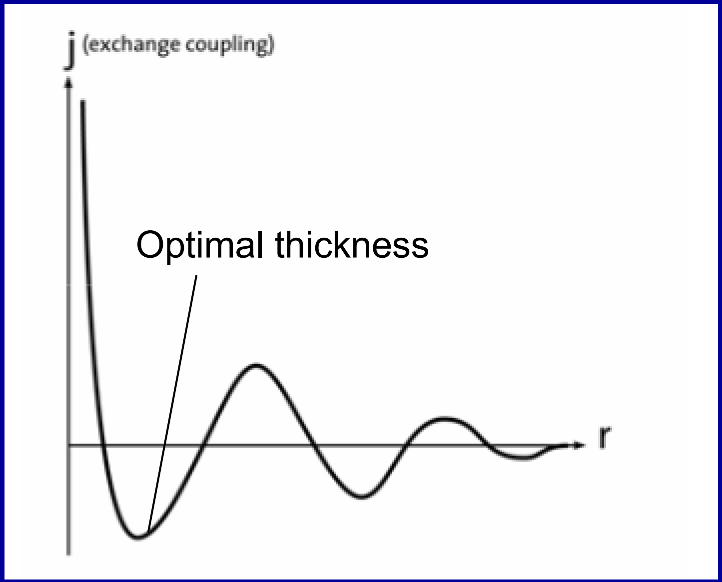

Figure 10. Exchange coupling in nonmagnetic metals

Applications

Spin-Valve Sensors

- Layers
  1. Silicon substrate
  2. Free layer (3 nm Fe)
  3. Non-magnetic layer (1-3 nm Cu)
  4. Fixed layer (3 nm Fe)
  5. Protective layer
- Find magnetic field by measuring electrical resistance

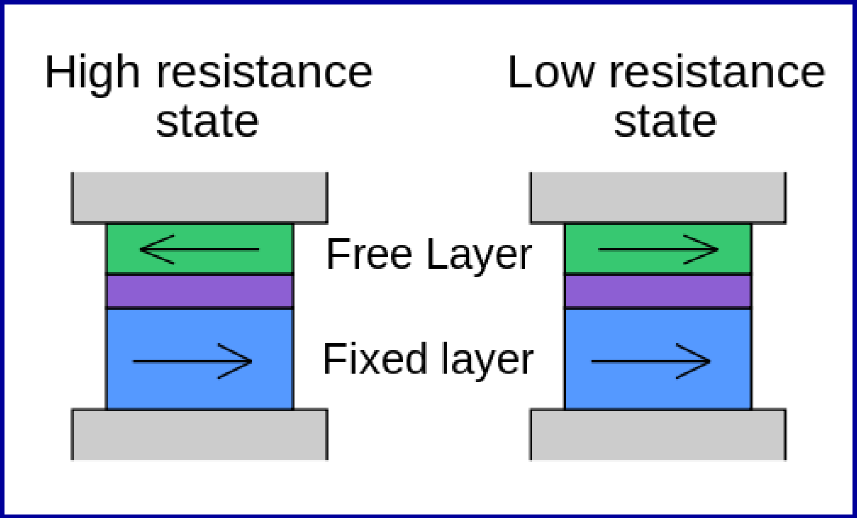

Figure 11. Magnetic Field Sensor

Hard Drives

Figure 12. Hard Disk Drive (HDD)

- Information encoded in magnetic domains
- Spin up/down corresponds to logic levels 0 and 1
- Read heads sense magnetic fields: relay information as electrical signals
- Before GMR, used induction coils and OMR

IBM Spin-Valve Sensor

- Mass market commercial debut of GMR effect in 1997
- Functions at room temperature, used sputtering (cheaper)
- IBM Deskstar 16GP Titan: 16.8 GB
- 2000: Used in 100% of hard drives
- Advantages
  - Increased storage density
  - Faster readout

Figure 13. HDD with GMR read head

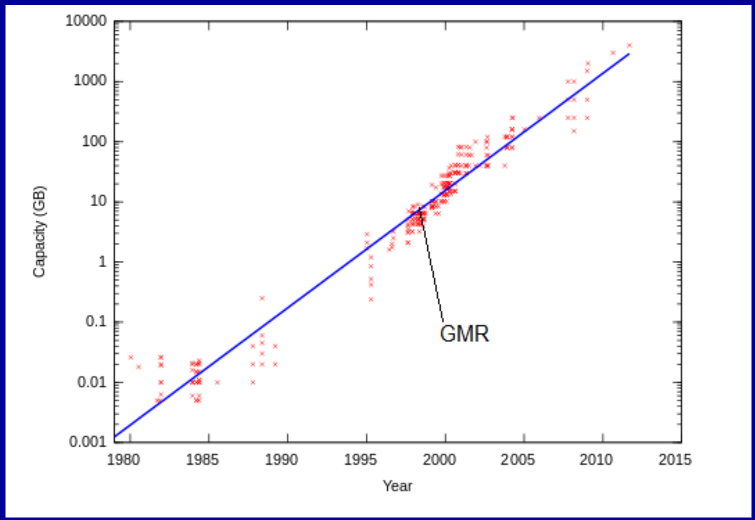

Figure 14. Storage Capacity of HDDs

Magnetic RAM (MRAM)

Figure 15. MRAM prototype

- Grid of spin-valves
- Stored bits encoded in magnetization direction of sensor layers
- Advantages:
  - Independent of power supply
  - Low power consumption
  - High speed

Summary

- Up to 50% change in resistance under external magnetic field
- Nonmagnetic metal sandwiched between antiferromagnetically coupled layers
- Result of spin-dependent scattering, intrinsically quantum effect
- Huge impact on magnetic field sensors and hard drives

References

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Questions?