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

- 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)

Figure 5. Albert Fert’s experimental data (1988)
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
Why Nanoscale?

- 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.

Figure 9. CIP vs. CPP geometries
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](image)
Hard Drives

- 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

**Figure 12.** Hard Disk Drive (HDD)
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)

- Grid of spin-valves
- Stored bits encoded in magnetization direction of sensor layers

Advantages:
- Independent of power supply
- Low power consumption
- High speed

Figure 15. MRAM prototype
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

• “Giant Magnetoresistance.” http://physics.unl.edu/tsymbal/reference/giant_magnetoresistance/index.shtml
Questions?