“Magneto-resistance effects – Physics & Applications in High Density Data Storage Technology”

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5th I.I.T. established in 1961 on pattern of MIT

26 Academic Units

Departments (14)
• Computer Science
• Electrical Engineering
• Mechanical Engineering
• Chemical Engineering
• Bio-chemical Engn & Bio-technology
• Civil Engineering
• Textile Technology
• Applied Mechanics
• Physics
• Chemistry
• Mathematics
• Humanities and Social Sciences
• Management Studies
• Design

Centers, Schools and CoE (12)
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• Center for Energy Studies
• Center for Atmospheric Sciences
• Center for Polymer Science Engn.
• Center for Biomedical Engineering
• Center for Rural Development
• Center for Value Education in Engn.
• School of Biological Sciences
• School of Information Technology
• School of Telecomm Tech & Mgmt
• CoE - Bioinformatics & Computational Biology
• CoE – Cyber Systems & Information Assurance
Programs & Student strength

Programmes (Student strengths)
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- M.Sc. (330)
- M.Tech. (1800)
- M. Design (40)
- MBA (330)
- M.S. Research (40)
- Ph.D. (2400)

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~8000

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- M.Sc. Physics (110)
- M.Tech. Applied Optics (60)
- M.Tech. Solid State Materials (60)
- M.Tech. Optoelectronics & Optical Communication (30)
  - jointly with Electrical Engineering
- Ph.D. (200)

Faculty (45)
- Condensed Matter & Nano-materials
- Magnetism & Spintronics
- Photonics & Fiber Optics
- Plasma and High Energy Physics

~700
Outline

- Introduction to SPINTRONICS
- Magnetoresistance (MR) - Ordinary, AMR, GMR, TMR
- Overview of Magnetism – Material’s perspective
- Spin Valves (SV), Magnetic Tunnel Junctions (MTJs), etc.
- How we prepare/study these multilayer – Ion beam sputtering & Magneto-optic Kerr Effect (MOKE)
- Some of our recent results – TEM, SIMS & MR
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Collaborators

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Magnetic Tunnel Junctions (MTJs)
(Tunnel Magnetoresistance)
Spin Valves (SVs)
(Giant Magnetoresistance)

Introduction

SPINTRONICS
(SPIN based electronics)
Spin + Charge → Multifunctionality

Advantages of Spintronic devices:

➢ Fast switching speed
➢ Nonvolatility
➢ Low power consumption
➢ Scalability at low dimensions

Spin Valves (SVs)
(FM 1
NM metal e.g., Cu(1-2nm)
FM 2
NM insulator e.g., MgO (1-3 nm)
)

Magnetic Tunnel Junctions (MTJs)
(FM 1
FM 2
)
Technology tree for spin-based devices

Spin polarized battery
Spin-LED
Next generation application
Advanced Memory
Quantum computers
Spin FET
Spintronics material technology
Data storage
MRAM
Sensors
Change in resistance of a material in presence of magnetic field

**Magneto Resistance,** \[ MR = \frac{R(H) - R(0)}{R(0)} \times 100\% \]

It can have different origins:

- **Ordinary Magnetoresistance (MR)** \( \sim 0.1 \)
- **Anisotropic Magnetoresistance (AMR)** \( \sim 1-2 \)
- **Giant Magnetoresistance (GMR)** \( \sim 10-50 \)
- **Tunnel Magnetoresistance (TMR)** \( \sim 100-600 \)
“GIANT MAGNETO RESISTANCE (GMR)”

Noble Prize in Physics (2007)

Albert Fert
Univ. of Paris-Sud, FRANCE

P Grünberg
KFA Res. Inst., Jülich GERMANY

Inside Look of a Hard Disk
Storage Media & Read Head
Giant Magneto Resistance

Discovered in 1989 in Fe/Cr Multilayers

FIRST MAJOR APPLICATION OF NANOTECHNOLOGY

Technology Revolutionized: Retrieving Data from Hard Disk

Impact of Technology: IT Industry in ~2000

- New Compact Devices
- High Density Data Storage (~500 Gbits/in², 2007)
  (~1 Gbits/in², 1992)

Future: Spin based Electronics Devices (MRAMs)

GMR Effect: Giant reduction of electrical resistance in presence of applied magnetic field
Overview of Magnetism

Magnetic Dipole

\( \mathbf{\mu}_m = I A \mathbf{u} n \)

- Current
- Unit vector normal to the surface
- Area circled by current
Magnetic moment experiences a **torque** in a magnetic field
Magnetic moment behaves like a magnet

- A magnetic dipole moment produces a magnetic field (just like a bar magnet)
- The field $B$ depends on $\mu_m$
Microscopic Theory of Magnetization: Orbital angular momentum and magnetic moment

An orbiting electron is equivalent to a magnetic dipole moment $m_{\text{orb}}$

Mass Property: ORBITAL ANGULAR MOMENTUM (L)

\[ L = (m_e \nu) r = m_e \omega \ r^2 \]  \hspace{1cm} (1)

Magnetic Property:

\[ I = \frac{\text{charge flowing}}{\text{time}} = -\frac{e}{(2\pi / \omega)} = -\frac{e \omega}{2\pi} \]
Magnetization of an atom/solid

- Orbital motion of e\(^{-}\)s: In a closed shell, for every L, there is \(-L\), hence net contributions is zero
- Spin motion of e\(^{-}\)s: In a closed shell, similarly S and \(-S\) yield ZERO
- Only unfilled subshells contribute to magnetization (Paramagnetic)

\[ \mu_{\text{atoms}} = \sum \text{all the contributions} \]

e.g., An atom has all inner shells as closed, and only has an e- in s-shell (i.e., l=0), then \[ \mu_{\text{atom}} = \mu_{\text{spin}} \]
Classification of Materials

- **Diamagnetic** (Copper)
- **Paramagnetic** (Aluminum)
- **Ferromagnetic** (Iron, Cobalt, Nickel, Gadolinium)
- **Antiferromagnetic** (Chromium)
- **Ferrimagnetic** ($\text{Fe}_3\text{O}_4$)
Diamagnetic Materials

- A diamagnetic material placed in a non-uniform magnetic field experiences a force towards smaller fields.
- This repels the diamagnetic material away from a permanent magnet.
Paramagnetic Materials

(a) Each individual atom possesses a permanent magnetic moment, but due to thermal agitation there is no average moment per atom; $M = 0$

(b) In the presence of an applied field, individual magnetic moments take alignments along the applied field and $M$ is finite and along $B$
In a magnetized region of a ferromagnetic material such as iron, all the magnetic moments are spontaneously aligned in the same direction.

There is a strong magnetization vector $M$ even in the absence of an applied field.
Antiferromagnetic Materials

In this antiferromagnetic BCC crystal (Cr), the magnetic moment of the center atom is cancelled by the magnetic moments of the corner atoms (an eighth of the corner atom belongs to the unit cell)
Ferrimagnetic Materials

Illustration of magnetic ordering in a ferrimagnetic crystal

- All A-atoms have their spins aligned in one direction
- All B-atoms have their spins aligned in the opposite direction
- As the magnetic moment of an A-atom is greater than that of a B-atom, there is net magnetization, $M$, in the crystal
Magnetization and Surface currents

- Elementary current loops result in surface currents.
- There is no internal current as adjacent currents on neighboring loops are in opposite directions. (hence they can be thought to cancel each other)
- Result: the CIRCULATING current is INDUCED SURFACE CURRENT

By def. the total magnetic moment = M (Volume) = MA \ell

If \( K_m \) = Surface Magnetization Current PER UNIT LENGTH OF THE SPECIMEN

Then, total magnetic moment = (Total current) \times (Cross-sectional area) = \( K_m \ell A \)

Equating the two total magnetic moments, we find 

\[ M = K_m \]
Magnetic Susceptibility, $\chi_m$:

$$M = \chi_m H$$

Magnetic Permeability, $\mu$:

Relative Permeability, $\mu_r$:

IN AIR, \[ B_0 = \mu_0 H \implies \mu_0 = \frac{B_0}{H} \]

IN MAG. MATERIAL, \[ B = \mu_0 (H + M) = \mu_0 (H + \chi_m H) = \mu_0 (1 + \chi_m)H \]

Calling, $\mu_0 (1 + \chi_m) \equiv \mu$, \[ B = \mu H \]

$\mu = \text{extent to which a medium is permeable by magnetic field/INDUCTION}$

$$\mu_r = \frac{B}{B_0} = \frac{\mu}{\mu_0} \implies \mu = \mu_r \mu_0$$

$$\mu_r = 1 + \chi_m$$
(a) A long solenoid. With free space as medium inside, the magnetic field is $B_0$.

(b) A material medium inserted into the solenoid develops a magnetization $M$

\[ M = \chi_m H \]

\[ \vec{B} = \mu_0 (\vec{H} + \vec{M}) \]
1. Resistance in a Non-Magnetic Metal/SC

Q: What causes resistance to flow of electrons in ordinary metals?

Ans. The Structural Irregularities, Defects and Impurities offer resistance to the flow of electrons (=Current)

⇒ Magnetic field (H) causes electrons to move in circular trajectory (Lorentz Force), rather than linear in zero field

\[ F = q (v \times B) \]

More scattering & hence higher \( R(H) \)
2. Resistance in a FerroMagnetic Metal

The intrinsic rotation of the electron gives rise to a magnetic moment – the quantum mechanical property called SPIN. Two effects occur:

1. Electrons distribute themselves in 2 varieties, Anticlockwise - ↑SPIN & Clockwise ↓SPIN
2. The ↑SPIN scatter less compared to ↓SPIN

Magnetism
Spin dependent Resistance
2. Ferromagnetic Metals: Anisotropic Magnetoresistance (AMR)

(a) Origin of AMR: The electrons traveling along the field experience more scattering than those traveling perpendicular to the field.

(b) Resistivity depends on the current flow direction (red arrows in (a)) with respect to the applied magnetic field (black arrow in (a)).

AMR $\equiv$ Spin-orbit coupling
3. GMR in Multilayers \equiv \text{Interplay between Resistance and Magnetization}

- **High Resistance State** (H=0)
  - 1, 3 – Magnetic (Fe)
  - 2 – Nonmagnetic (Cr)

- **Low Resistance State** (H\neq 0)
  - Applied field aligns both the magnetic layers

**Quantification:**

\[
\text{MR} \% = \left( \frac{\Delta R}{R_P} \right)_{\text{GMR}} \times 100\% = \frac{R_{AP} - R_P}{R_P} \times 100\%
\]
Enhanced magnetoresistance in layered magnetic structures with antiferromagnetic interlayer exchange

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(Received 31 May 1988; revised manuscript received 12 December 1988)

Although the microscopic origin of this AF coupling up to now remains somewhat unclear, we found that such structures display novel and unique magnetic properties both in their static and dynamic behavior.

It is clear that this is an attractive aspect for applications, such as magnetoresistive field sensors. The magnitude of MR ~1.5%, much larger than the 0.2% value for isolated magnetic metals.

FIG. 2. (a)–(b) MOKE hysteresis curves and (c)–(d) magnetic ferromagnetic coupling. Also, (d) displays the anisotropic MR effect.

A Trilayer Structure on GaAs

Fe (12 nm)
Cr (1 nm)
Fe (12 nm)
GaAs (~1 mm)
“…We propose that this magnetoresistance arises from spin-dependent transmission of the conduction electrons through the thin Cr layers….”

“…GMR in Fe/Cr is promising for applications to magnetoresistive sensors……”
Resistance of the multilayer structure depends on the relative orientations of magnetization in the two FM layers.

$$\frac{\Delta R}{R_p} = \left( \frac{\Delta R}{R_p} \right)_{\text{max}} \frac{1 - \cos \theta}{2}$$

$\theta = \text{angle bet FM layer’s M}$

- $\theta = 180^\circ$: largest $R$
- $\theta = 90^\circ$: Intermediate $R$
- $\theta = 0^\circ$: smallest $R$  ‘0’ & ‘1’

Q: How the bottom FM layer’s $M$ is locked/pinned?
A: Via Exchange Bias, e.g. Spin Valve (see next page)
‘Spin Valve’ (A GMR device)

Pinning layer (MnFe)
Fixed M

Co
Cu
FeNi

Free layer

No field
(a)

Applied field
(b)

No applied field

Applied field has fully oriented the free layer magnetization.

Resistance change vs. applied field magnetic field (schematic) for a FeNi/Cu/FeNi spin valve

\[ B_o = \mu_0 H_o \]
Physics of GMR: RKKY Exchange Interaction

In a trilayer FM/NM/FM, the GMR effect depends critically on the relative orientation of magnetization vectors of the two FM layers:

- Quantum Mechanical Phenomenon - **RKKY indirect exchange interaction** between two FM layers (Ruderman-Kittel-Kasuya-Yosida)
- RKKY coupling refers to a mechanism by which localized inner d or f shell electron spins (which can not couple directly) in a metal are coupled by means of an interaction through the conduction electrons

Where

\[ J_{ex} = \frac{(2kr)\cos(2kr) - \sin(2kr)}{r^4} \]

- \( k \) = wave vector of cond. electrons
- \( r \) = distance between two localised moments
Does Interlayer exchange coupling \((J)\) **between 2 FM layers:**

1. decay rapidly with \(t_{\text{spacer}}\)?

2. alternates (between AF & FM type) with change in \(t_{\text{spacer}}\)?

\(t_{\text{spacer}} = \text{Thickness of non-magnetic (NM) spacer layer}\)

So is GMR

A closer picture of the media

 Courtesy: Hitachi Global Storage Technology
The principle of **longitudinal magnetic recording** on a flexible medium, e.g. **magnetic tape in an audio cassette**
The principle of the hard disk drive magnetic recording

The write inductive head and the GMR read sensor have been integrated into a single tiny read/write head.
How does a Media (HDD) look like?

MFM image of a Disk Media

Transition → ‘1’
Missing Transition → ‘0’
GMR Sensors as Read Heads in PCs/Laptops

Nearly parallel aligned layers (FM) ➞ Lower resistance

Nearly anti-parallel aligned layers (FM) ➞ Higher resistance
GMR: Current Status & Future Directions

- **Status**: The current GMR/Spintronic devices are principally “all-metal” structure (→ signal amplification is not possible)

- **Road Block**: How Ferromagnetic Semiconductor materials can be tailored to obtain energy efficient, ultra fast and multifunctional devices?

- **Future**: Integration of electronics, magnetoelectronics and photonic capabilities on a single chip!
4. Tunnel Magnetoresistance (TMR)*

- The electron’s tunneling through an insulating barrier sandwiched between two FM layers depends upon orientation of the FM layer’s magnetization:
  
  ("Spin-polarized tunneling")

(a) Parallel coupling → High tunneling probability
(b) Antiparallel coupling → Low tunneling probability

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Magnetic Tunnel Junction (MTJ)

TMR effect is much larger than GMR!

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Spin Polarized Tunneling & MTJ

The difference in DOS at Fermi level for $\uparrow$ and $\downarrow$ spins gives rise to TMR

Picture source: "Advance materials in the information technology: Fundamentals and applications"
Material Requirement for high TMR: **Half-metals**?

- Metallic only in one spin channel, say up, (↑)
- Semi-conducting or insulating for the other spin channel, (↓)
- There are few such systems; **Fe₃O₄ (magnetite)** is one such system

\[
P = \frac{N_\uparrow(E_F) - N_\downarrow(E_F)}{N_\uparrow(E_F) + N_\downarrow(E_F)}
\]

(Cu, Ag, Al, ..)

P=0%  P=40-50%  P=100%

Let us now summarize

Switching the **relative Magnetizations** of the FM layers (Parallel ↔ Antiparallel) results in **Magneto-resistance (MR) effect**

"AP"

```
| FM 1 | Nonmagnetic spacer | FM 2 |
```

High resistance

Non-magnetic **Metallic Spacer** (SV) : RKKY coupling of FM layers

Non-magnetic **Insulating Spacer** (MTJ) : Spin-dependent Tunneling

```
MR \% = \left( \frac{\Delta R}{R_P} \right)_{GMR} \times 100\% = \frac{R_P - R_{AP}}{R_P} \times 100\%
```

```
Resistances Changes by \sim 100\% \Rightarrow Efficient Magnetic Sensors
e.g., Read Head Sensors (today), Magnetic RAMs ! (future)
```

“P”

```
| FM 1 | Nonmagnetic spacer | FM 2 |
```
‘Spin valve’ (A GMR device)

No applied field

Applied field has fully oriented the free layer magnetization.

Resistance change vs. applied field magnetic field (schematic) for a FeNi/Cu/FeNi spin valve
Deposition of Multilayers

Ion Beam Sputtering system (NORDIKO 3450)

- Substrate holder & heater assembly
- Shutter
- Deposition of Multilayers
- Accelerating Voltage: +500V
- Negative grid Voltage: -230V
- RF power (6’’ area): 125 W
- Ion beam density: 1.05 mA/cm²
- Target-Subst. distance: ~27 cm
- Working pressure: 5.0 × 10⁻⁵ Torr

Deposition parameters
- Base vacuum ~ 2×10⁻⁷ Torr

Assist ion beam gun
RGA
Sputtering ion beam gun
Experimental set-up for MOKE-MH (Longitudinal configuration)

- He-Ne intensity stabilized laser
- Employed a core-less solenoid
- Accuracy of field: better than 0.1 Oe
Cross-sectional HRTEM characterization

- Sharper interfaces
- CoFeB layers are amorphous
- Crystalline regions in MgO layer
- Assymetric interfaces of MgO
- CoFeB layers are amorphous
- Oriented growth of MgO on amorphous CoFeB
SIMS Characterization - depth profiles

Depth profile for B

Depth profile for Fe
Record high TMR of 140% in Heusler alloy based MTJ!

Thank You for your attention!