Spintronic Applications
HDD read heads, MRAM, Logic

Spintronic Effects
GMR, MTJ, spin-FET, STT

Spintronic Materials
GaMnAs, MnAs, Co2MnAl
quantum wells, nanowires, nanodots

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Young Ju Park – MIT/ Korea
Jagadeesh Moodera – MIT

NSF Sponsored
Spintronic Applications

Hard Drive
Read Heads
Giant MagnetoResistance
Magnetic Tunnel Junction

Logic Elements
Spin-FET
Lower Power

Nonvolatile Memory
Magnetic MRAM

Spin TRANSISTOR
Spintronics

Electron has:

- Mass
- Charge
- Spin-1/2 – *magnetic moment*
N. F. MOTT

The Electrical Conductivity of Transition Metals

“A theory is given to account for the fact that the resistance of nickel decreases in a magnetic field, and an expression for the decrease obtained, which is of the same order of magnitude as that observed.”

Magnetic moments of ions scatter electrons more efficiently than do charged ions.
In Richard Feynman’s 1959 address to the American Physical Society

“There’s Plenty of Room at the Bottom”

He envisioned and challenged listeners,

- “sequence the bases in the DNA”
- computers with wires “10 to 100 atoms in diameter”
- a microscope that could “see the individual atoms“
- machines “maneuvering things atom by atom“
- “systems involving the quantized energy levels“
  or the interactions of quantized spins“

http://www.zyvex.com/nanotech/feynman.html
Spintronic Effects

GMR
Giant MagnetoResistence
FM-Metal-FM
Magnetic field sensor

pinned moment
翻可动的时刻
flipable moment

Albert Fert 1988
Peter Grunberg 1988
2007 Nobel Prize
Spintronic Effects

GMR
Giant MagnetoResistance
FM-Metal-FM
Magnetic field sensor

Albert Fert 1988
Peter Grunberg 1988
2007 Nobel Prize

hard disk
Giant Magnetoresistance (GMR)

Electron Spin
Red – spin right
Blue – spin left

Antiparallel Ferromagnets
High resistance

Parallel Ferromagnets
Low resistance

Hard Drives

0.5 MB ← 1975
500 GB → 2005
1TB/$100 → 2009
Spintronic Effects

**GMR**
Giant MagnetoResistance
FM-Metal-FM
Magnetic field sensor

**MTJ**
Magnetic Tunnel Junction
FM-Insulator-FM
Magnetic field sensor

Albert Fert 1988
Peter Grunberg 1988
2007 Nobel Prize

Moodera 1996
2009 Buckley Prize
MR2A16A MRAM from Freescale, Inc.

4Mbit MRAM device
MR2A16ATS35C

- **35 ns** read/write cycle time
- **Unlimited** read/write endurance
- 3.3V ± 10 percent power supply
- Greater than **20-year retention**
- Magnetically shielded to 25 gauss
Spintronic Effects

**GMR**
Giant Magnetoresistance
FM-Metal-FM
*Magnetic field sensor*

**MTJ**
Magnetic Tunnel Junction
FM-Insulator-FM
*Magnetic field sensor*

**Spin-FET**
Spin Transistor
FM-Semiconductor-FM

Albert Fert 1988
Peter Grunberg 1988
2007 Nobel Prize

Moodera 1996
2009 Buckley Prize

Datta and Das 1990
Spin Transistor

**Off**
- $V_{\text{gate}} = 0$
- $I_{\text{collector}} = 0$

- $\mathbf{v} \times \mathbf{E} \rightarrow B_{\text{effective}}$

**On**
- $V_{\text{gate}} > 0$
- $I_{\text{collector}} > 0$

*Datta and Das 1990*
**Spintronic Effects**

**GMR**
Giant MagnetoResistance
FM-Metal-FM
Magnetic field sensor

**MTJ**
Magnetic Tunnel Junction
FM-Insulator-FM
Magnetic field sensor

**Spin-FET**
Spin Transistor
FM-Semiconductor-FM

**STT**
Spin Transfer Torque
FM-Metal-FM

- GMR
  
  Albert Fert 1988
  Peter Grunberg 1988
  2007 Nobel Prize

- MTJ
  
  Moodera 1996
  2009 Buckley Prize

- Spin-FET
  
  Datta and Das 1990

- STT
  
  Slonczewski 1996
Spin Transfer Torque (STT)

**SWITCHING**
Reverse magnetic moment via current
ST-RAM memory

**MICROWAVE OSCILLATOR**
Generate electrical oscillations via current
STO spin-transfer oscillators
Spintronic Research and Applications

<table>
<thead>
<tr>
<th>GMR</th>
<th>MTJ</th>
<th>MRAM</th>
<th>STT</th>
</tr>
</thead>
<tbody>
<tr>
<td>research</td>
<td>device</td>
<td>research</td>
<td>device</td>
</tr>
<tr>
<td>2005</td>
<td>2010</td>
<td></td>
<td></td>
</tr>
<tr>
<td>research</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

GMR - Giant magnetoresistance - HDD read heads
MTJ - Magnetic Tunnel Junction - HDD read heads+MRAM
MRAM - Magnetic RAM - nonvolatile memory
STT - Spin Transfer Torque - MRAM+oscillator

spin-FET
spin-LED

Co₂MnAl-Co MTJ
D. Heiman, T. Santos, J.S. Moodera
Research on Spintronic Materials

- MBE Growth
- Magnetic Semiconductors
  (Ga,Mn)As
- Half-Metallic Ferromagnets
  Fe$_3$O$_4$, CrO$_2$, Co$_2$MnAl
- Nanostructures – Wires/Dots
Molecular Beam Epitaxy
Molecular Beam Epitaxy

- UHV: 10^{-10} torr
- GaMnAs
- Substrate
- Heater
- GaAs
- Ga, Mn, As
- Shutters
- Effusion cells
- RHEED screen
Molecular Beam Epitaxy

- Ga, Mn, As
- Shutters
- Effusion cells
- RHEED screen
- UHV \(10^{-10}\) torr
- Substrate heater
- GaMnAs

Substrate located within high vacuum chamber.
Can we make semiconductors ferromagnetic?

Add Fe or Mn to Si
Can we make semiconductors ferromagnetic?

Add Fe or Mn to Si GaAs

Ga$_{1-x}$Mn$_x$As, $x \sim 0.1$ $T_c \sim 170$ K

$T_c < \text{room temperature}$

II-VI DMS EuX III-V DMS

GaMnAs $T_c = 110$ K

H. Ohno -- 1996
Can we make semiconductors ferromagnetic?

---

Add Fe or Mn to Si GaAs

---

Ga1-xMnxAs, x~0.1 Tc~170 K

GaN, ZnO

GaMnAs Tc=110 K

H. Ohno -- 1996
Half-Metallic Ferromagnets

Half-Metallic FM

- Fe$_3$O$_4$ magnetite
- CrO$_2$
- Heusler FM
  - Ni$_2$MnGa
  - Co$_2$MnAl

Half-Metals have Higher Spin Polarization

Transition Metals
- Fe, Co, Ni
- polarization~0.5

Half Metals
- Co$2$MnAl
- polarization=1
Magnetic Nanostructures

- Grow Nanowires with MBE
- Fabricate Magnetic Nanodots
  - annealing
  - masking
MBE Growth of GaAs Nanowires

VLS GROWTH
Vapor – Liquid - Solid

[Diagram of VLS growth process]

[SEM images of GaAs nanowires]
**MnAs in GaAs**

\[ \text{Ga}_{0.9}\text{Mn}_{0.1}\text{As} \] grown by MBE

Anneal at 650°C to nucleate MnAs nanoparticles in GaAs

*Ben Chaprut, Radhika Barua, Laura Lewis, Don Heiman*
Fabricate GaMnAs Quantum Dots

Etch Quantum Dots into GaMnAs using Nanoporous Alumina Templates

Steve Bennett, Latika Menon, Don Heiman
Superparamagnetism of GaMnAs Quantum Dots

Steve Bennett
Zhen Wu, Latika Menon, and Don Heiman
Appl. Phys. Lett. 2007
Spintronic Applications

- Hard Drive
  - Read Heads
  - Giant MagnetoResistance
  - Magnetic Tunnel Junction

- Logic Elements
  - Spin-FET
  - Lower Power

- Nonvolatile Memory
  - Magnetic MRAM

- SPIN TRANSISTOR
End