Spintronics

INTRODUCTION

- Conventional electronic devices ignore the spin property and rely strictly on the transport of the electrical charge of electrons

- Adding the spin degree of freedom provides new effects, new capabilities and new functionalities

Future Demands

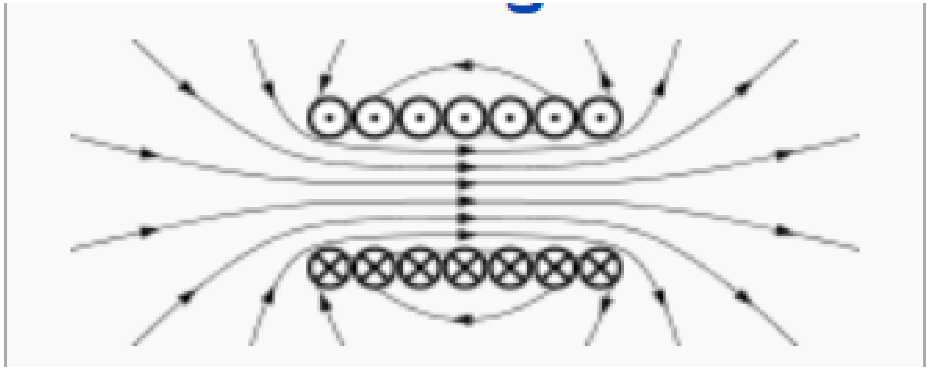
- Moore's Law states that the number of transistors on a silicon chip will roughly double every eighteen months
- As electronic devices become smaller, quantum properties of the wavelike nature of electrons are no longer negligible
- Spintronic devices offer the possibility of enhanced functionality, higher speed, and reduced power consumption

Advantages of Spin

- Information is stored into spin as one of two possible orientations
- Spin currents can be manipulated
- Spin devices may combine logic and storage functionality eliminating the need for separate components
- Magnetic storage is nonvolatile
- Binary spin polarization offers the possibility of applications as qubits in quantum computers

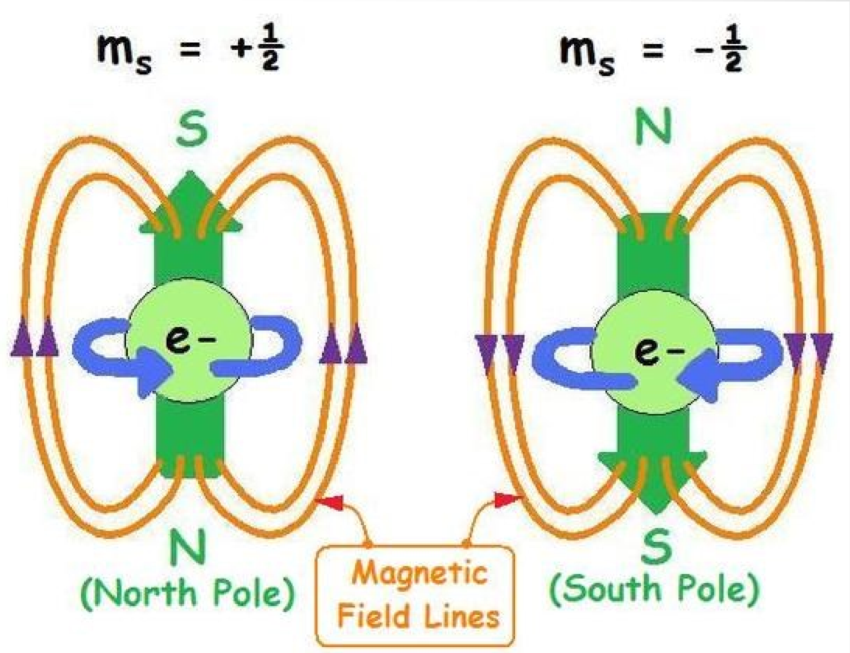
WHAT IS MAGNETIC MOMENT

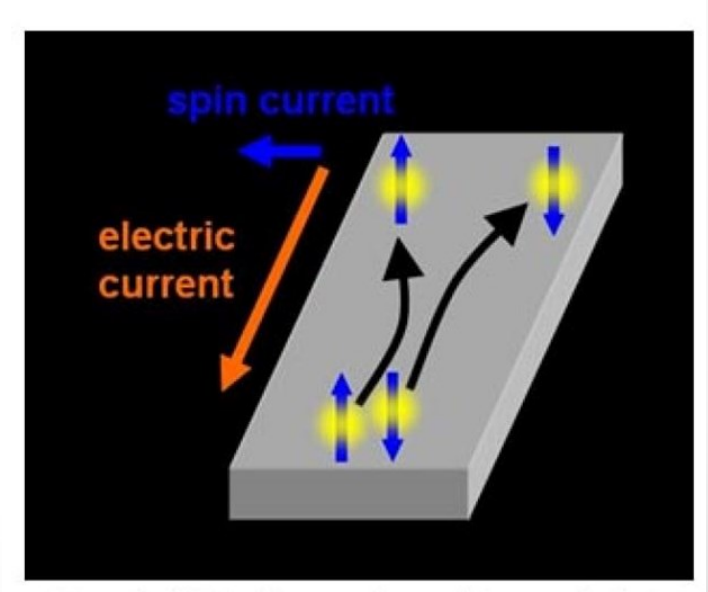
- The **magnetic moment** of a magnet is a quantity that determines the torque it will experience in an external magnetic field. A loop of electric current, a bar magnet, an electron, a molecule, and a planet all have magnetic moments.
- The **magnetic moment** may be considered to be a vector having a magnitude and direction. The direction of the magnetic moment points from the south to north pole of the magnet. The magnetic field produced by the magnet is proportional to its magnetic moment.



What is Spintronics?

- Utilizes the bizarre property of spin of electron.
- Intrinsic angular momentum is spin.
- Two arbitrary orientations, and its magnitudes are $\pm \hbar / 2$ ($\hbar$ is Plank constant).
- Directional and coherent motion of electron spin circulates a spin current, which will carry or transport information and control quantum spin in an spintronic device.





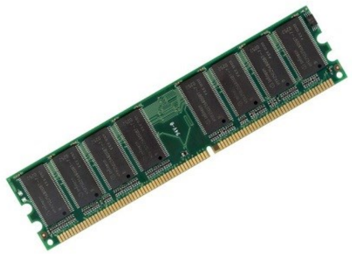
Why Spintronics?

Motivation:
Spintronics-Information is carried not by electron charge but by it's spin.

Combining the best of both worlds

Ferro magnets
- Stable Memory
- Fast switching
- High ordering temp
- Spin transport

- Technological base (magnetic recordings)



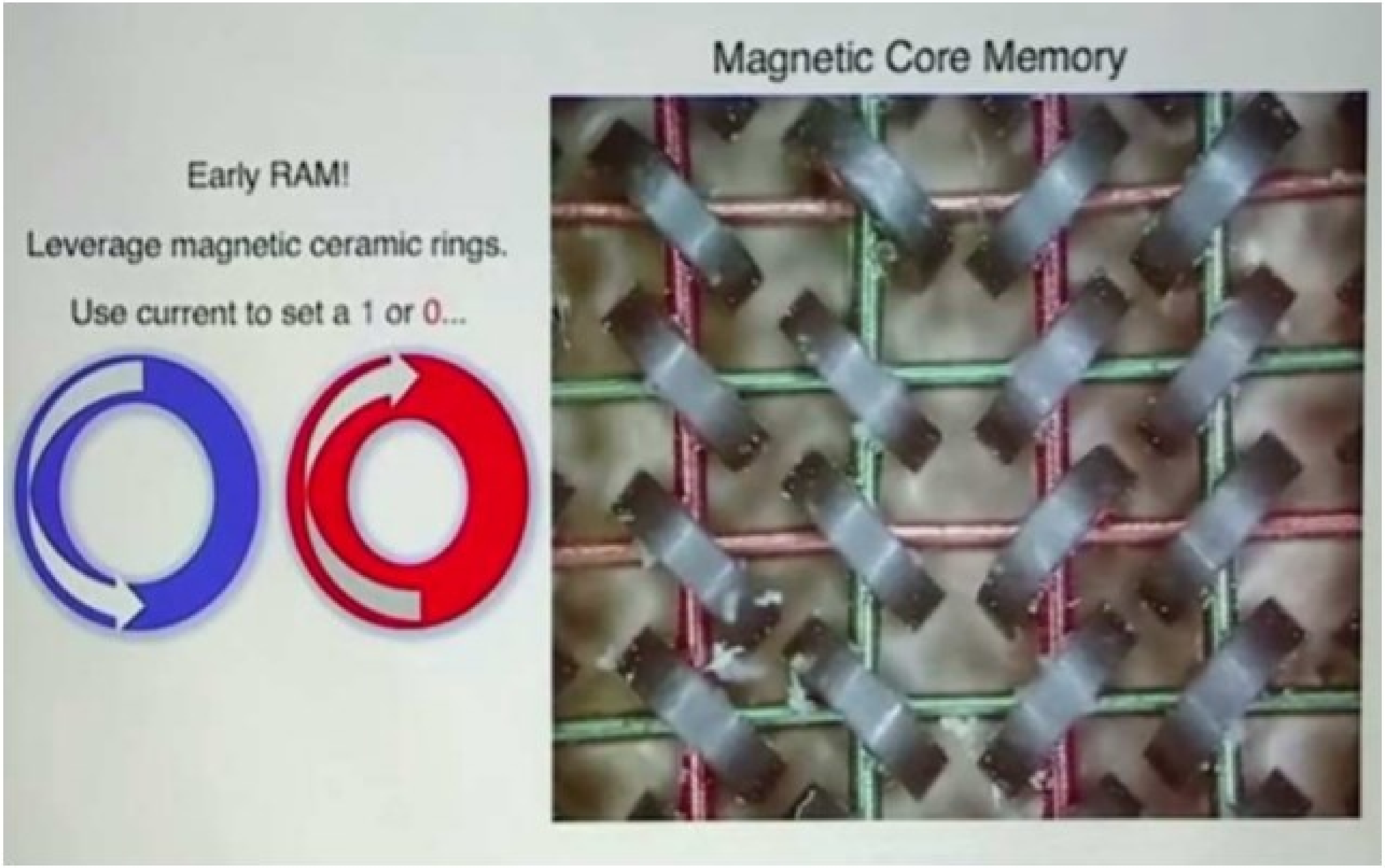
Semiconductors
- Bandgap engineering
- Carrier density & type
- Electrical gating
- Long spin lifetime

- Technological base (Electronics)

Can we develop spin based transistors , switches and logic circuits?

How to create control propagate spin information in semiconductor structures?

• MAGNETIcs & Storage



- Spin is a quantum mechanical property
- The rotational moment creates a small magnetic field
- The electron spin given a direction up or down
- The up and down direction given a of (1) or (0) same thing as the electron positive or negative charge correspond to those values
- Key concept is controlling the spin of electrons

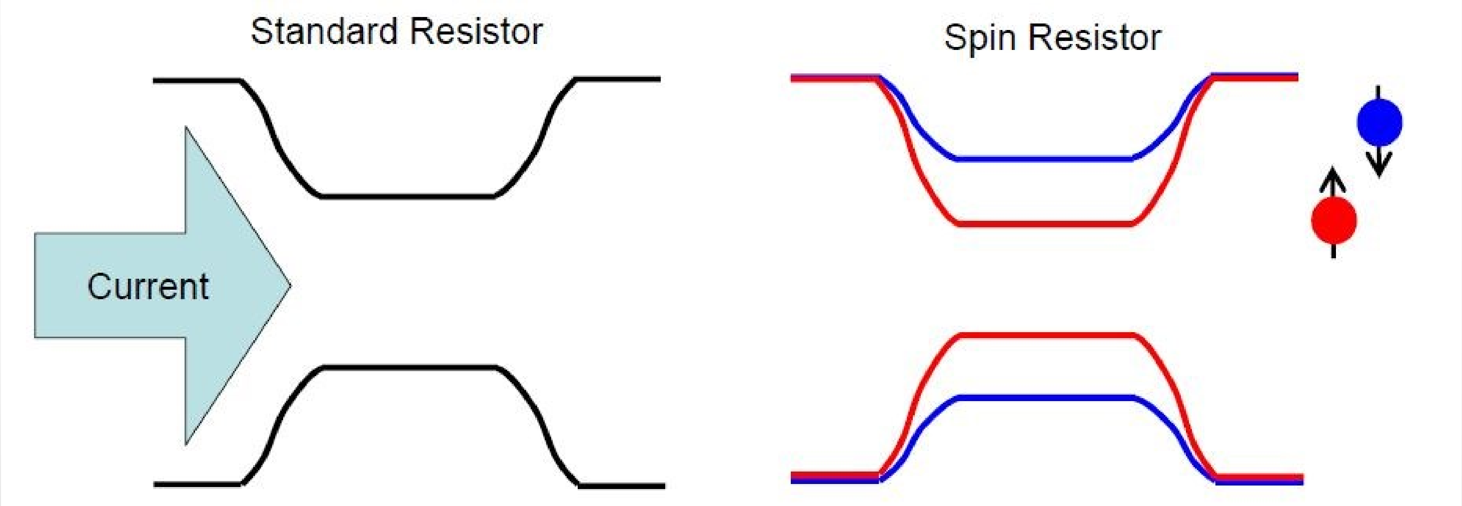
Why We Need Spintronics !

Failure of Moore‟s Law :

- Moore‟s Law states that the number of transistors on a silicon chip will roughly double every eighteen months.
- But now the transistors & other components have reached nanoscale dimensions and further reducing the size would lead to:
  - 1. Scorching heat making making the circuit inoperable.
  - 2. Also Quantum effects come into play at nanoscale dimensions.
- So the size of transistors & other components cannot be reduced further.

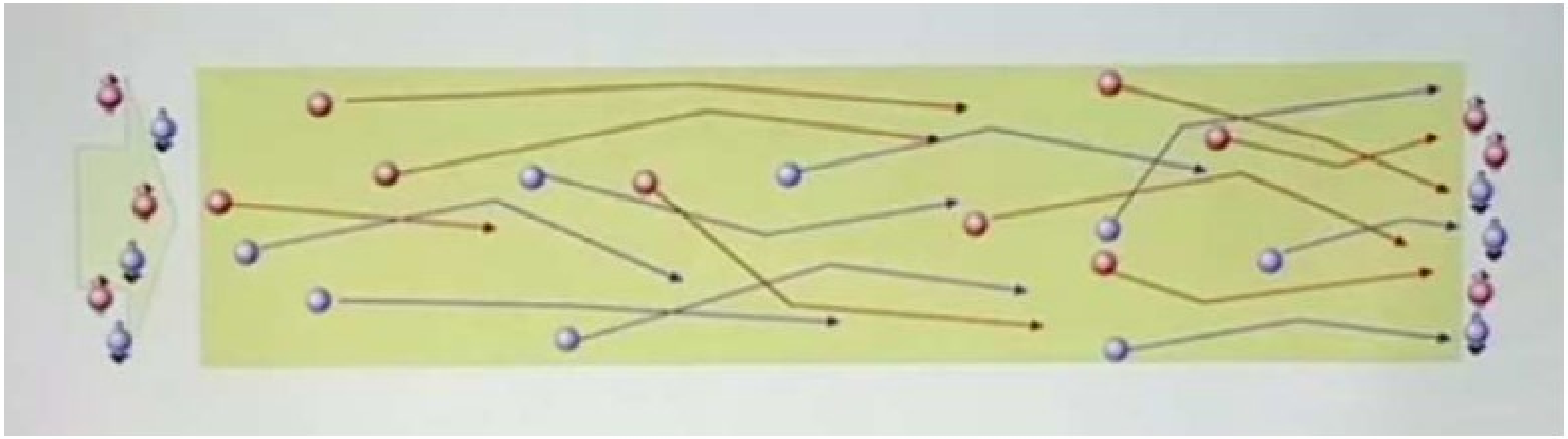
The Giant Magneto Resistance (GMR)

- A Nano scale phenomena .
- Giant refers to giant change in resistance due to current.
- It is a quantum mechanical magneto resistance effect observed in thin-film structures composed of alternating ferromagnetic and non-magnetic layers.



- EVOLUTION

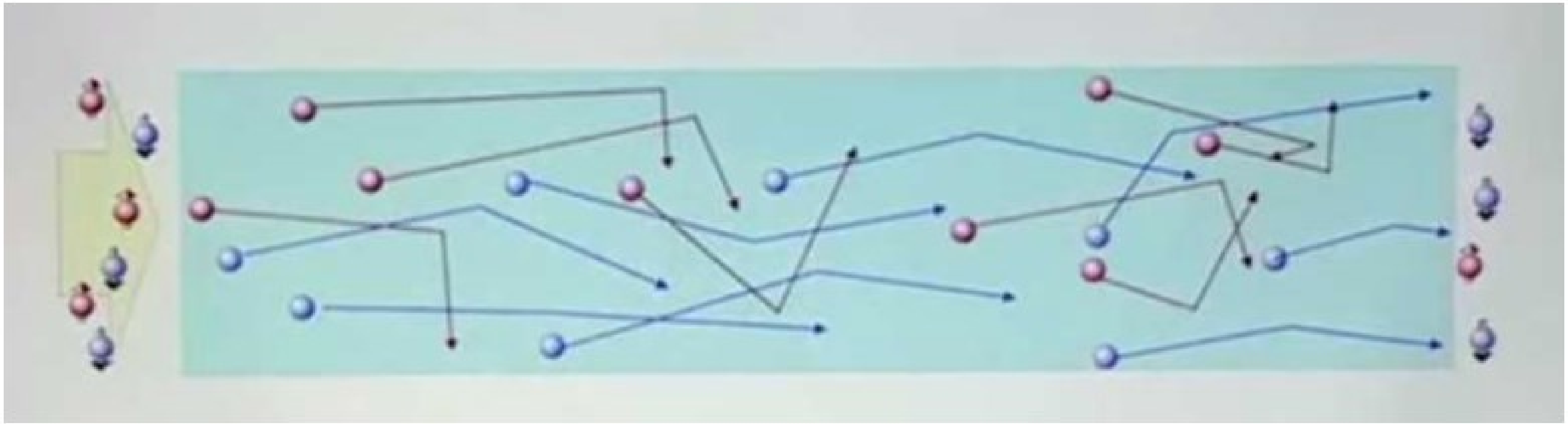
CURRENT IN A METALIC CONDUCTOR



In a non magnetic conductor , electron scatters the same amount regardless of spin as a current flow.

How much they scatters determines the resistance of device.

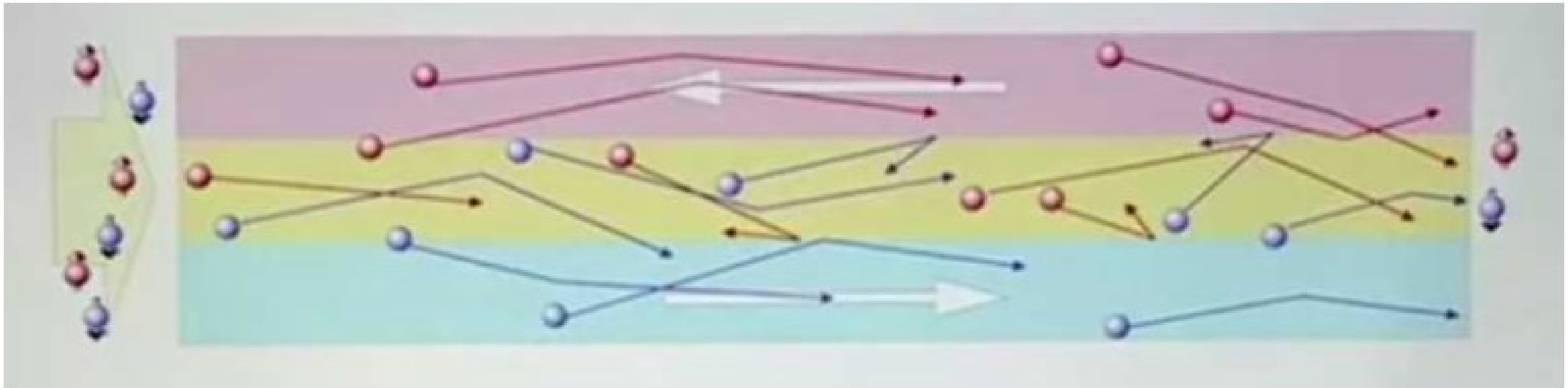
CURRENT IN A FERROMAGNETIC CONDUCTOR



In a ferromagnetic conductor , however , electrons scatters differently depending on whether they are spin up or spin down.

In this Case , spin up electrons are scatters strongly while the spin down electrons are scattered only weakly.

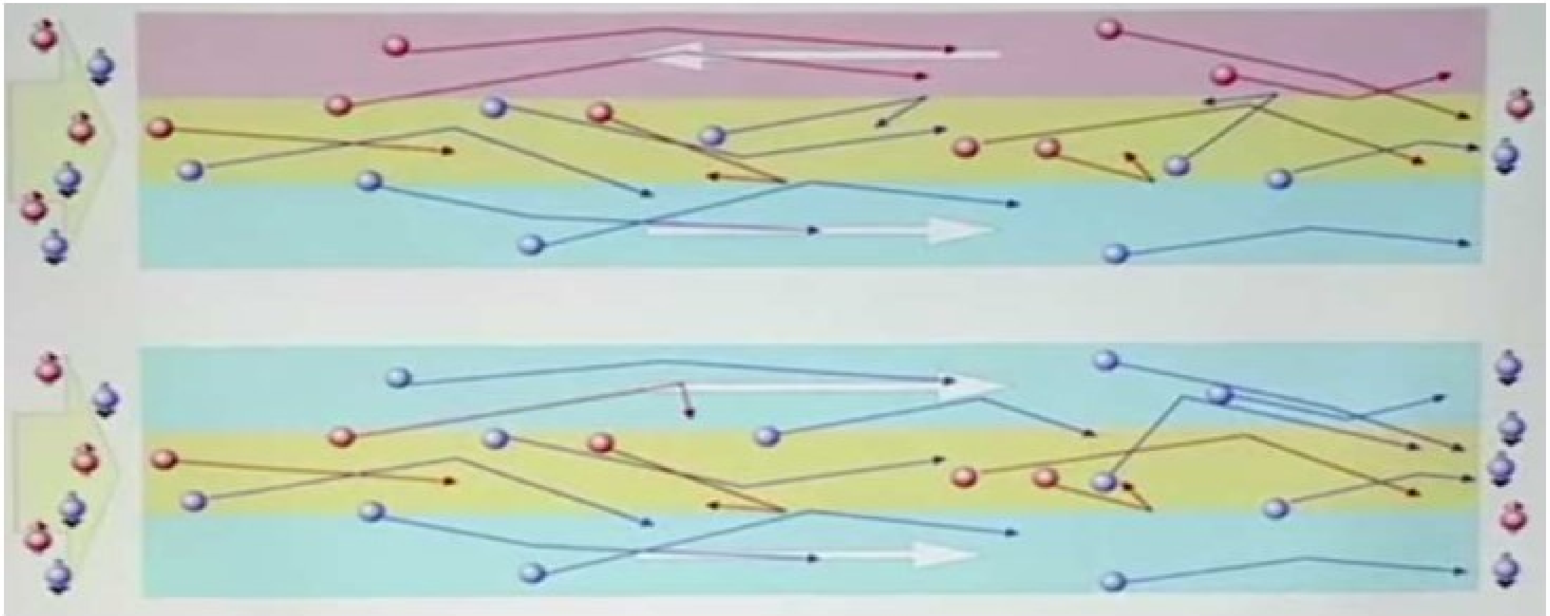
SPIN-DEPENDENT SCATTERING



If a non-magnetic conductor is sandwiched between two oppositely magnetized ferromagnetic layers, a number of electrons will scatter strongly when they try to cross between the layer.

→This gives high resistance.

SPIN-DEPENDENT SCATTERING



If the ferromagnetic layers are magnetized in same direction , far fewer electrons are strongly scattered and more current flows.

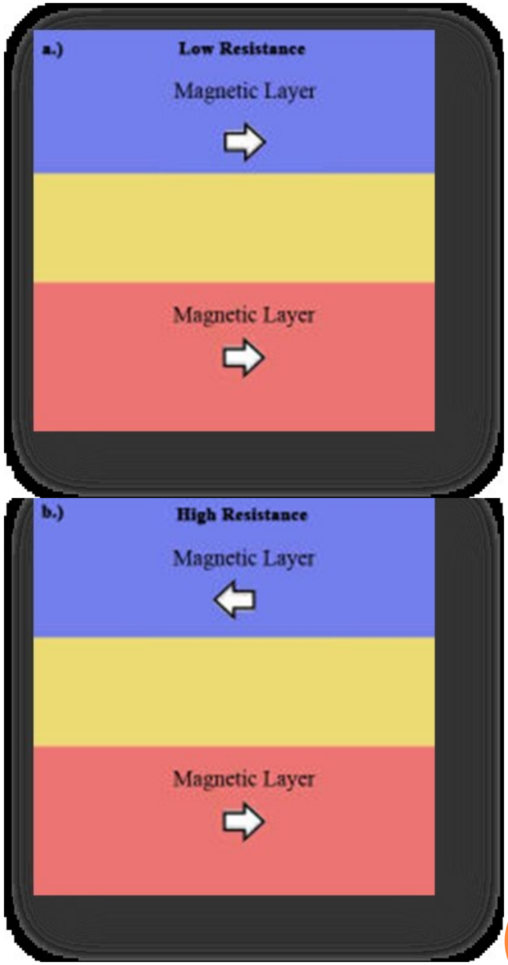
This is measured as a low resistance.

→Useful foe sensing magnetic fields or as a magnetic memory element

→ **SPIN-VALVE** magnetic sensor

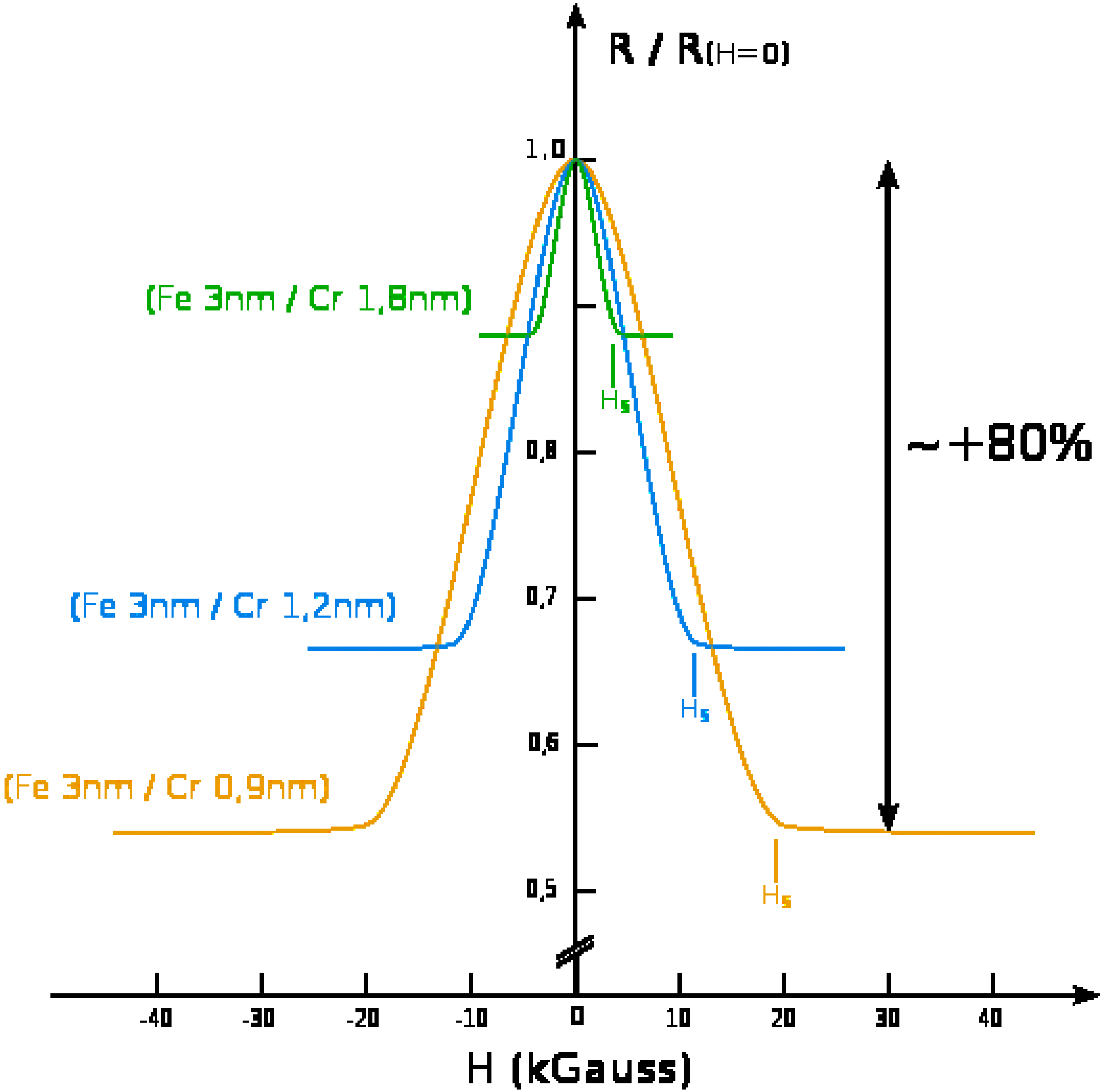
GMR

- 1988 France, GMR discovery is accepted as birth of spintronics
- The 2007 Nobel Prize in Physics was awarded to Albert Fert and Peter Grünberg for the discovery of GMR.
- A Giant MagnetoResistive device is made of at least two ferromagnetic layers separated by a spacer layer
- When the magnetization of the two outside layers is aligned, lowest resistance
- Conversely when magnetization vectors are antiparallel, high R



GMR

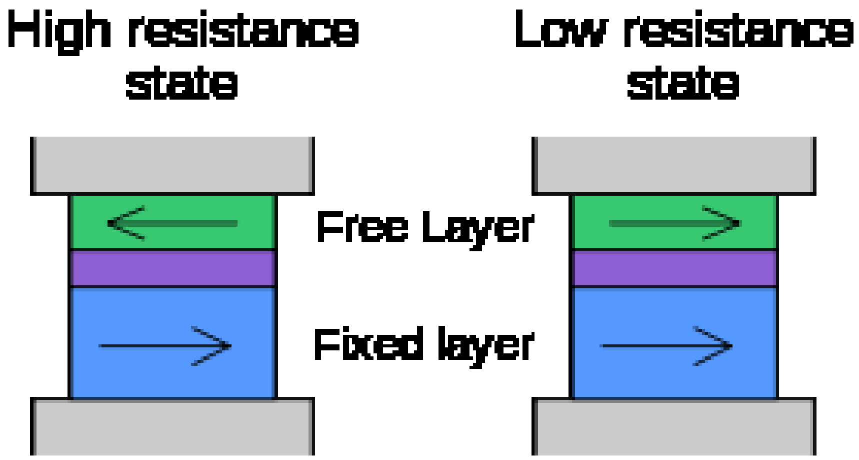
- Small fields can produce big effects
- parallel and perpendicular current
- The magnetization direction can be controlled, for example, by applying an external magnetic field.
- The effect is based on the dependence of electron scattering on the spin orientation.
- Has shown 200% resistance difference between zero point and antiparallel states
- Most commonly used in magnetic read heads



R / R(H=0)
1,0
0,8
0,7
0,6
0,5
(Fe 3nm / Cr 1,8nm)
(Fe 3nm / Cr 1,2nm)
(Fe 3nm / Cr 0,9nm)
Hs
Hs
Hs
~+80%
-40
-30
-20
-10
0
10
20
30
40
H (kGauss)

Spin Valve

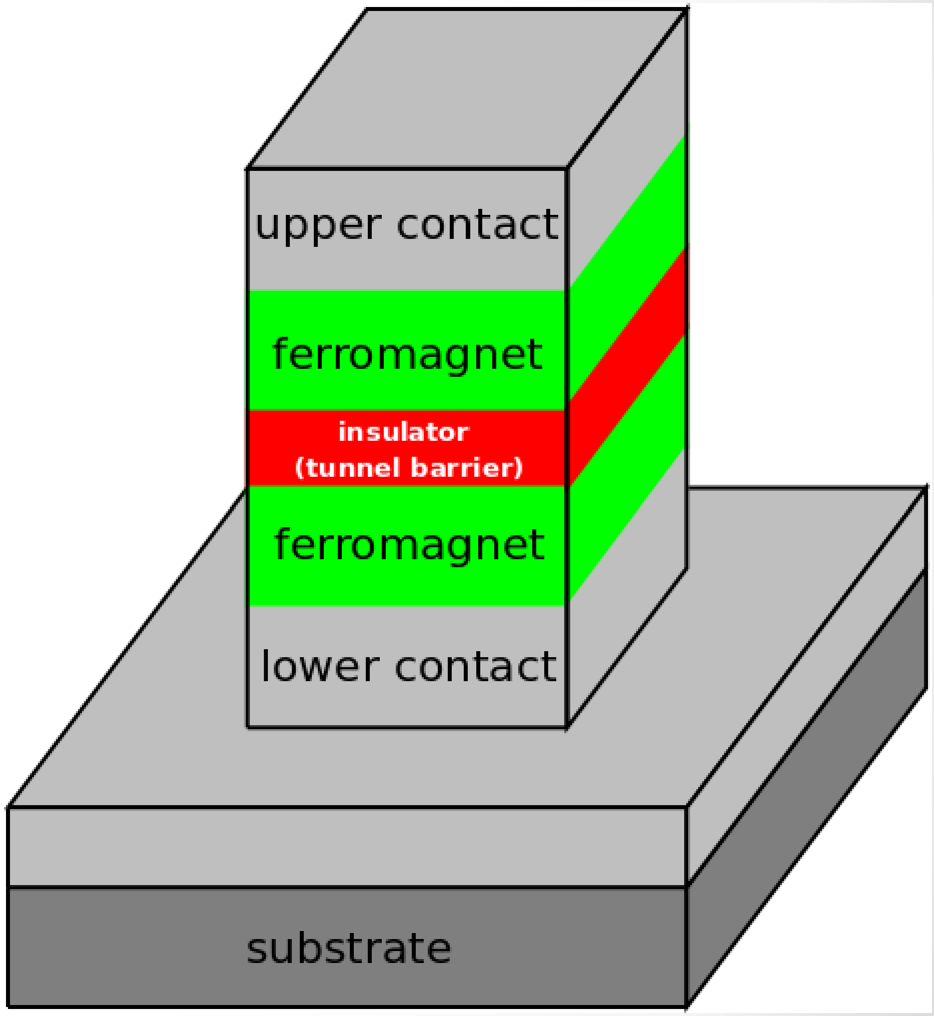
- Simplest and most successful spintronic device
- Used in HDD to read information in the form of small magnetic fields above the disk surface



A schematic diagram of a pseudo spin valve. The free layer is magnetically soft and the fixed layer is magnetically hard. When the magnetic layers are antiparallel the electrical resistance is higher than when they are aligned.

Magnetic tunneling junction

- Like GMR but better.
- More sensitive
- Multilayer junction filter
- Quantum mechanical principle
- Tunneling effect
- 2 layers of magnetic metal, separated by an ultrathin layer of insulator, about 1 nm.



Tunnel Magnetoresistance

- **Tunnel magnetoresistance** (TMR) is a magnetoresistive effect that occurs in a **magnetic tunnel junction** (MTJ), which is a component consisting of two ferromagnets separated by a thin insulator.
- Tunnel Magnetoresistive effect combines the two spin channels in the ferromagnetic materials and the quantum tunnel effect
- TMR junctions have resistance ratio of about 70%
- MgO barrier junctions have produced 230% MR

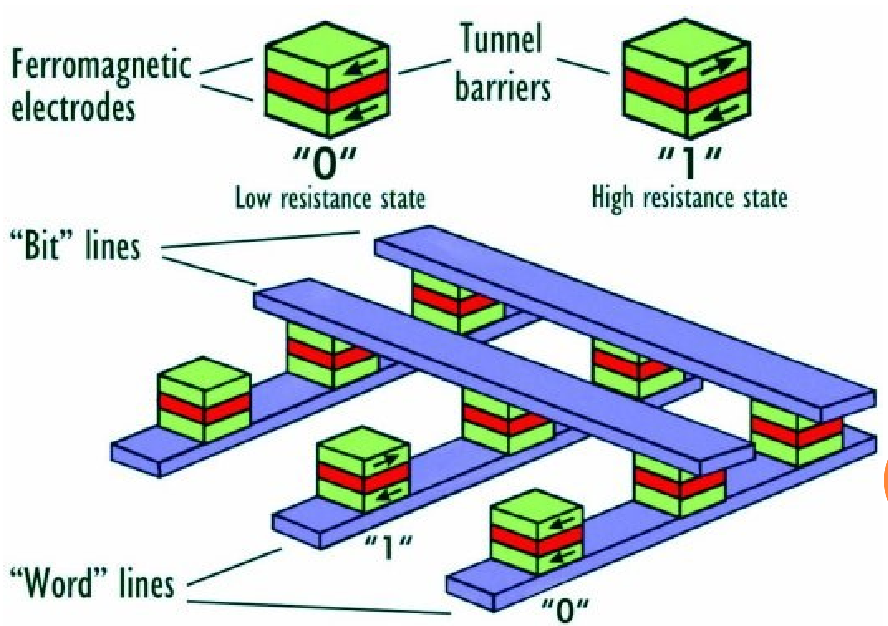
Application

The read-heads of modern hard disk drives work on the basis of magnetic tunnel junctions. TMR, or more specifically the magnetic tunnel junction, is also the basis of MRAM, a new type of non-volatile memory.

MRAM
MAGNETO RESISTIVE RAM

- MRAM uses magnetic storage elements instead of electric used in conventional RAM
- Tunnel junctions are used to read the information stored in Magnetoresistive Random Access Memory, typically a"0" for zero point magnetization state and "1" for antiparallel state

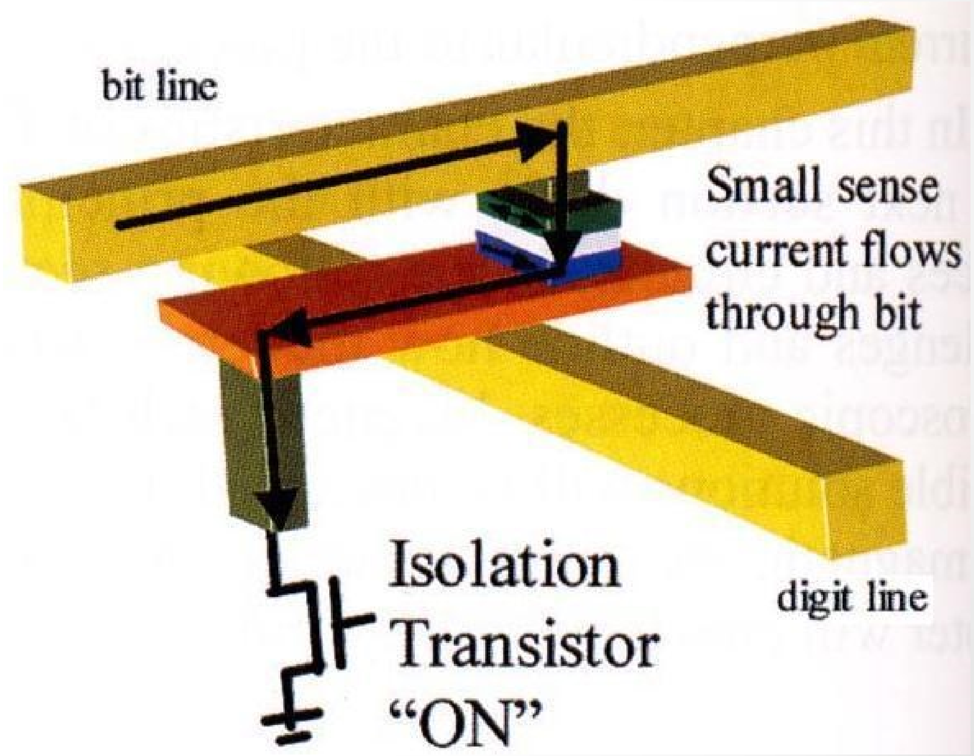
MRAM promises:
- Density of DRAM
- Speed of SRAM
- Non-volatility like flash



MRAM
Magneto resistive RAM

Reading process

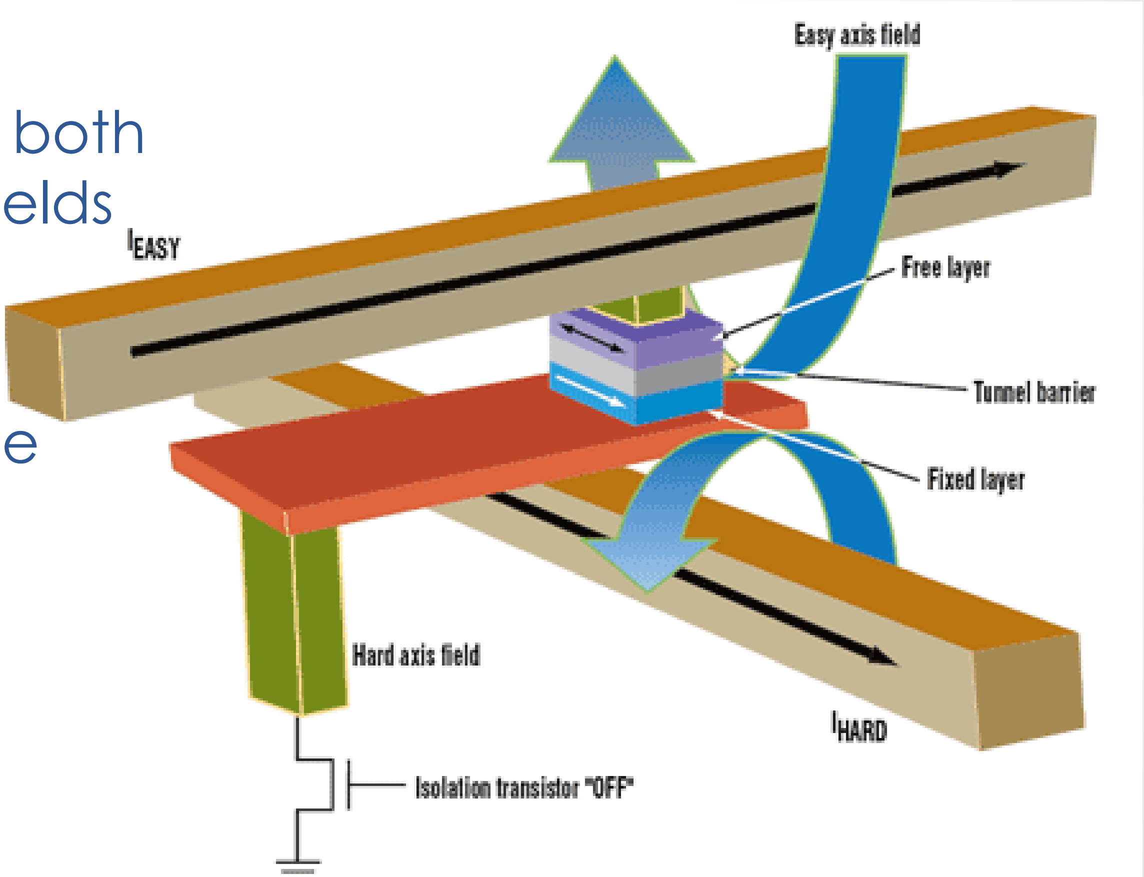
- Measurement of the bit cell resistance by applying a current in the 'bit line'
- Comparison with a reference value mid-way between the bit high and low resistance values



MRAM
Magneto resistive RAM

Writing process

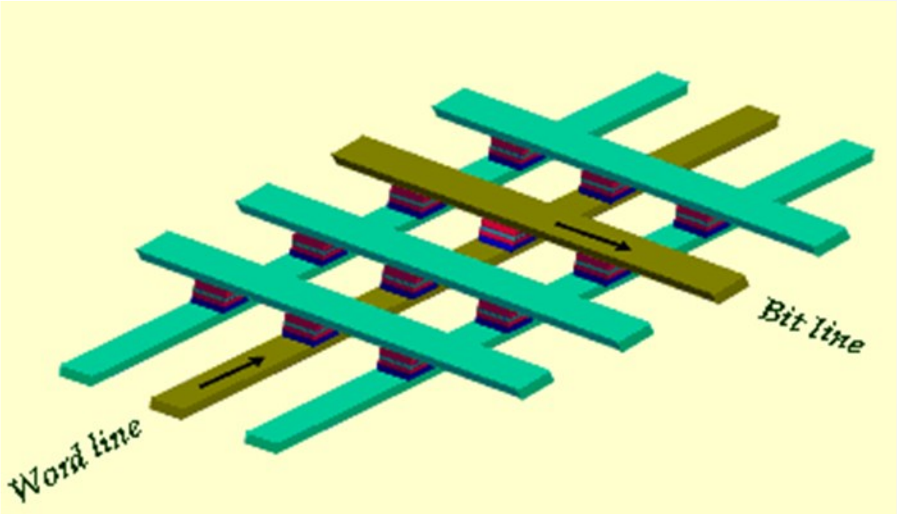
- Currents applied in both lines : 2 magnetic fields
- Both fields are necessary to reverse the free layer magnetization
- When currents are removed : Same configuration



MRAM
Magneto resistive RAM

Array structure of MRAM

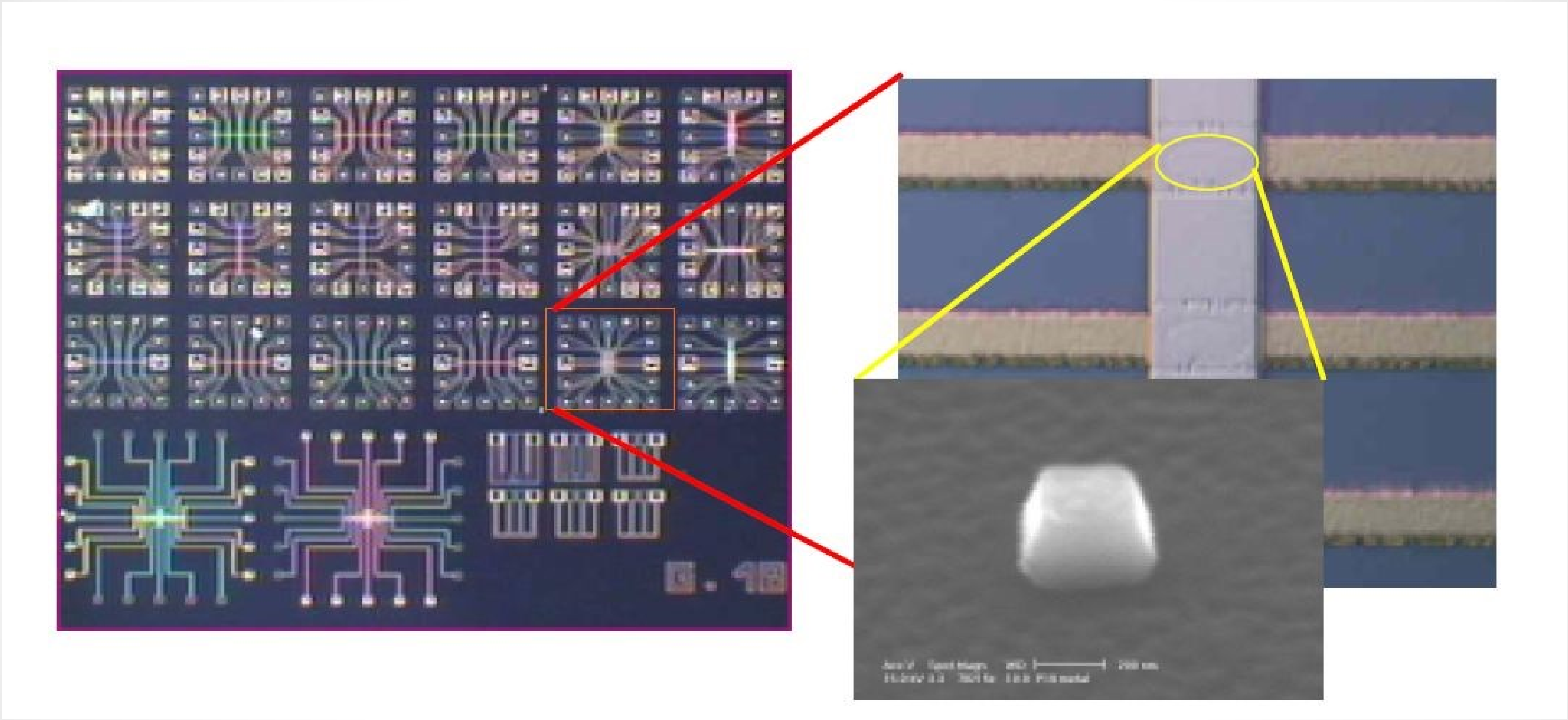
- Reading: transistor of the selected bit cell turned ‘on’ + current applied in the bit line
- Writing: transistor of the selected bit cell turned ‘off’ + currents applied in the bit and word lines
- Need of 2 magnetic fields for writing



MRAM vs …..

	DRAM	SRAM	FLASH	FeRAM	OUM	MRAM
Write speed	Moderate	Fast	Slow	Moderate	Moderate	Fast
Read speed	Moderate	Fast	Fast	Moderate	Fast	Fast
Density	High	Low	High	Medium	High	High
Endurability	Good	Good	Poor	Poor	Good	Good
Power	High	Low	Low	Low	Low	Low
Refresh	Yes	No	No	No	No	No
Retention	No	No	Yes	Partially	Yes	Yes
Scalability	Bad	Good	Good	Medium	Good	Good
Write/Erase	Charge (Capacitance)	CMOS Logic	Charge (Tunneling)	Ferroelectric	Phase transition	Magnetization

MRAM
Magneto resistive RAM



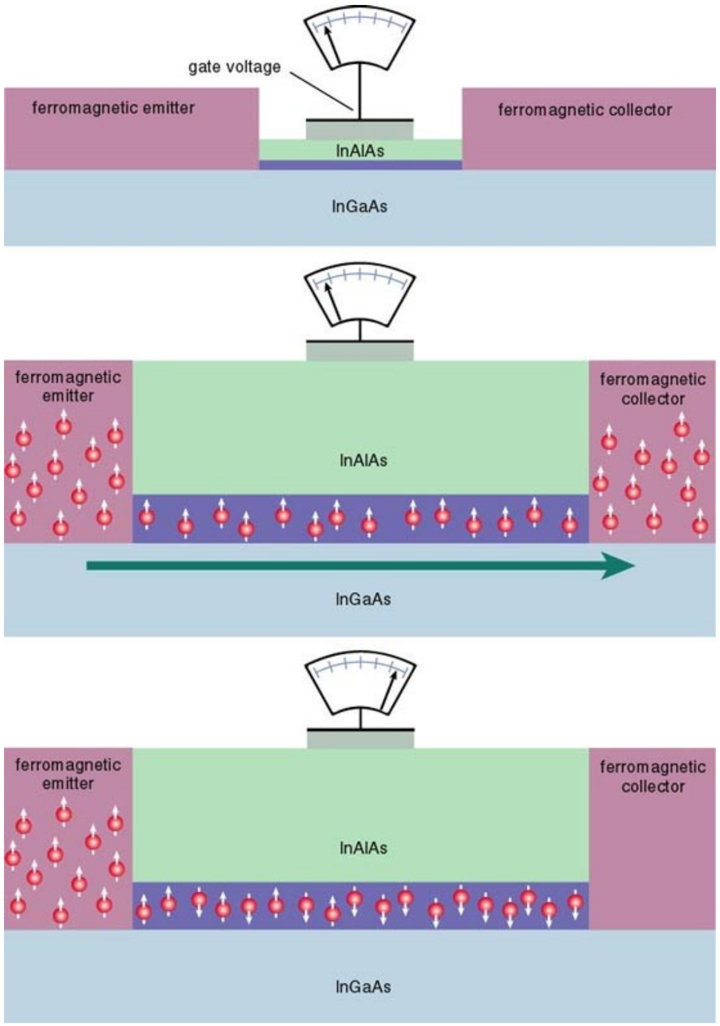
- MTJ test structures developed at SPINTEC: the die area with 1x5 μm
- 0.2 μm width isolated MTJ element after etch

Spin Transistor

- Ideal use of MRAM would utilize control of the spin channels of the current
- Spin transistors would allow control of the spin current in the same manner that conventional transistors can switch charge currents
- Using arrays of these spin transistors, MRAM will combine storage, detection, logic and communication capabilities on a single chip
- This will remove the distinction between working memory and storage, combining functionality of many devices into one

Datta Das Spin Transistor

- The Datta Das Spin Transistor was first spin device proposed for metal-oxide geometry, 1989
- Emitter and collector are ferromagnetic with parallel magnetizations
- The gate provides magnetic field
- Current is modulated by the degree of precession in electron spin



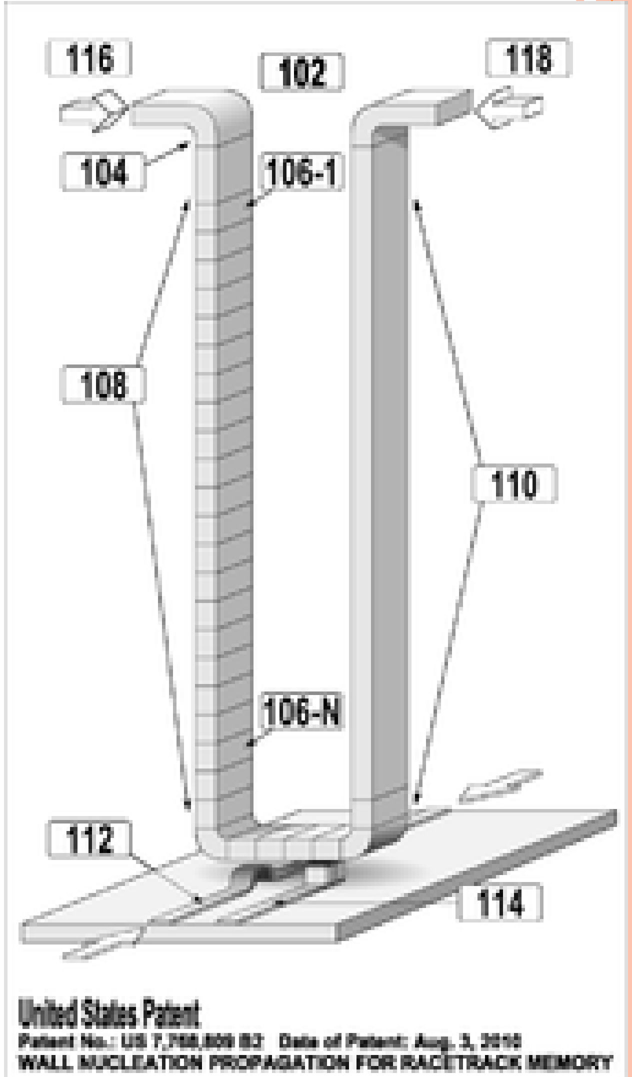
RACETRACK MEMORY

Racetrack memory (or domain-wall memory (DWM)) is an experimental non-volatile memory device under development at IBM's Almaden Research Center.

If it is developed successfully, racetrack would offer storage density higher than comparable solid-state memory devices like flash memory and similar to conventional disk drives, and also have much higher read/write performance.

It is one of a number of new technologies that could potentially become a universal memory in the future.

Racetrack memory uses a spin-coherent electric current to move magnetic domains along a nanoscopic permalloy wire about 200 nm across and 100 nm thick. As current is passed through the wire, the domains pass by magnetic read/write heads positioned near the wire, which alter the domains to record patterns of bits



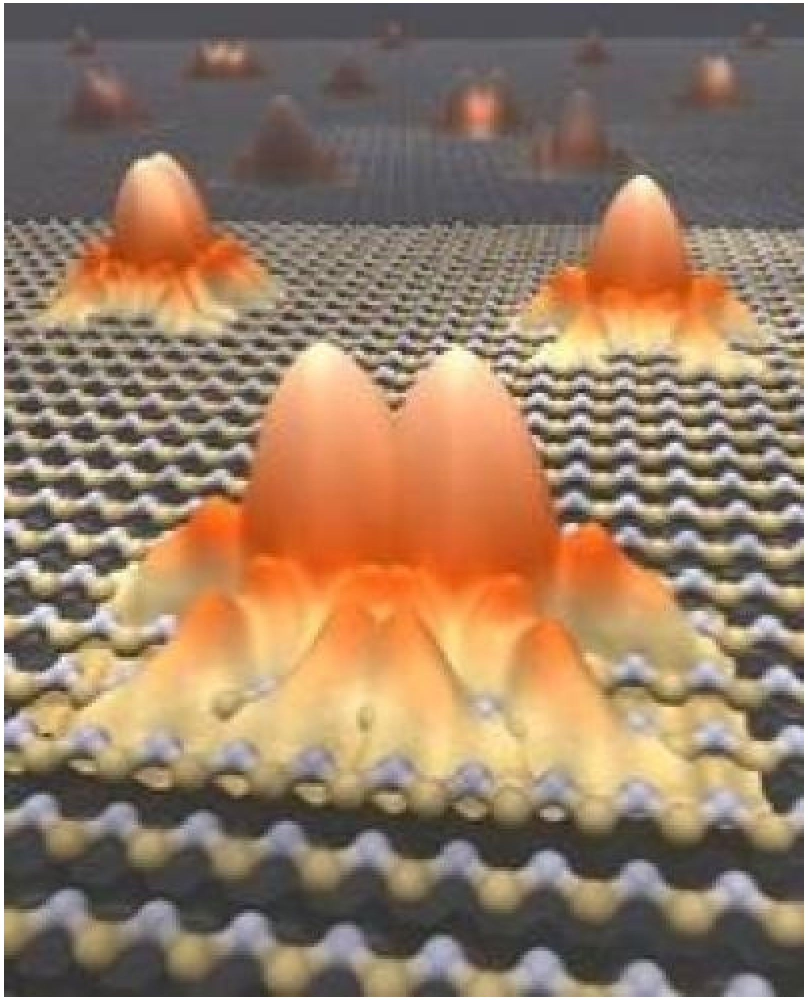
Advantages of Spintronics

- Low power consumption.
- Less heat dissipation.
- Spintronic memory is non-volatile.
- Takes up lesser space on chip, thus more compact.
- Spin manipulation is faster , so greater read & write speed.
- Spintronics does not require unique and specialized semiconductors.

  Common metals such as Fe, Al, Ag , etc. can be used.

Current Research

- Material science
  - Many methods of magnetic doping
- Spin transport in semiconductors



Conclusion

Interest in spintronics arises, in part, from the looming problem of exhausting the fundamental physical limits of conventional electronics.

However, complete reconstruction of industry is unlikely and spintronics is a “variation” of current technology

The spin of the electron has attracted renewed interest because it promises a wide variety of new devices that combine logic, storage and sensor applications.

Moreover, these "spintronic" devices might lead to quantum computers and quantum communication based on electronic solid-state devices, thus changing the perspective of information technology in the 21st century.