PHN-006 : Quantum Mechanics and Statistical Mechanics

SPINTRONICS : FUTURE OF ELECTRONICS AND ITS DEVICE APPLICATIONS

Name: AYUSH RANJAN
Enrollment Number: 22114018
Batch Number: O1
B. Tech CSE, IIT Roorkee

1. Reason for choice of this topic :

Spintronics is one of the most important emerging research areas with an immense potential to provide high speed, low power and high density logic and memory electronic devices, and attempts to overcome some of the major challenges faced by the semiconductors-based technologies. It has huge applications ranging from mass storage devices to medicine, where it can be very useful for the detection of cancer cells using various scanning techniques based on spintronics.

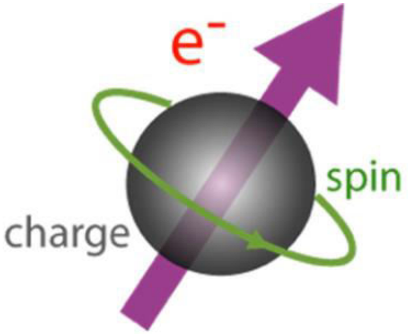
2. Its relevance to the course :

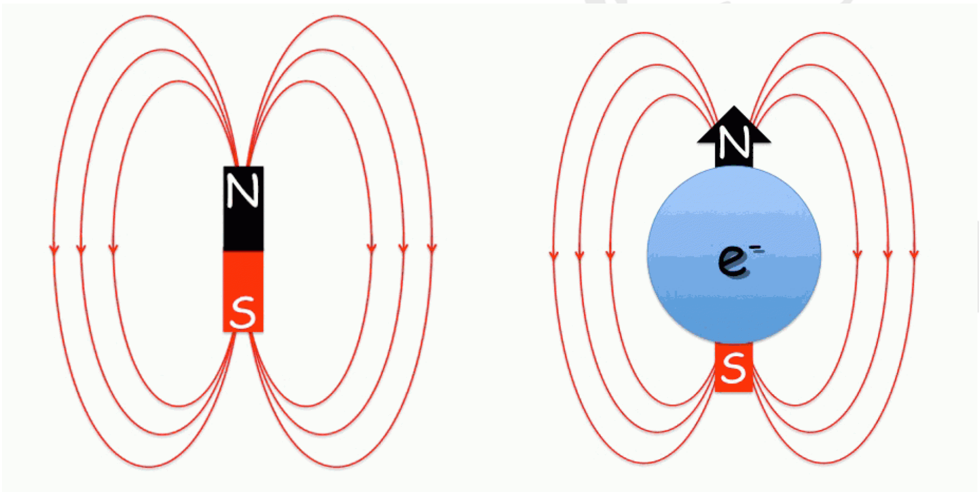
This topic combines various theoretical concepts put forward in the Quantum Mechanics and Statistical Mechanics course and tries to connect it to the real world phenomena by extracting some practical applications out of it, and how these can help create better and more advanced technologies.

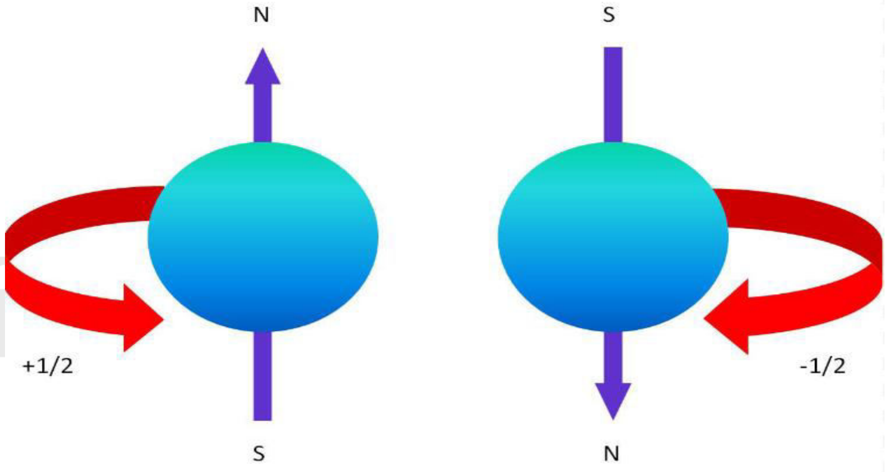
What is Spintronics

- **Spintronics** (meaning spin transport electronics), also known as **spin electronics**, is the study of the intrinsic spin of the electron and its associated magnetic moment, in addition to its fundamental electronic charge.

- Spintronics fundamentally differs from traditional electronics in that, in addition to charge state, electron spins are used as a further degree of freedom, with implications in the efficiency of data storage and transfer.







Electronics - Charge

Binary states represented by High and Low voltages

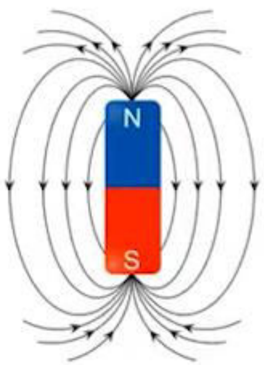
+5 V

0 V

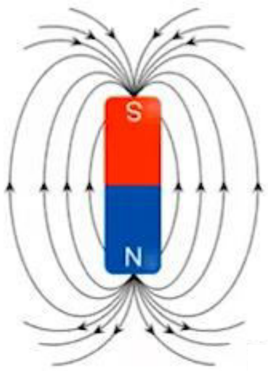
+5V represents logic 1 and 0V represents logic 0

Spintronics – Spin/angular momentum

Binary states represented by Magnetization direction



This can be used to represent logic 1



This can be used to represent logic 0

What is Spin

Credit : SCIENCE PHOTO LIBRARY

Photograph of George Uhlenbeck (left) and Samuel Goudsmit, Dutch-American physicists, taken in 1926.In 1925 they discovered electron spin, the fourth quantum dimension used to describe the electron.

- **Spin** is *intrinsic* angular momentum associated with elementary particles.

- It is a purely quantum mechanical phenomenon without any analog in classical physics. Spin is quantized, and can only take on discrete values.

- The conventional definition of the **spin quantum number** is $s = n/2$, where n can be any non-negative integer. Hence the allowed values of s are 0, 1/2, 1, 3/2, 2, etc.

- The **spin angular momentum** S of any physical system is quantized. The allowed values of S are

$$S = \hbar\sqrt{s(s+1)} = \frac{h}{2\pi}\sqrt{\frac{n}{2}\frac{(n+2)}{2}} = \frac{h}{4\pi}\sqrt{n(n+2)},$$

- An electron has spin, even though it is believed to be a point particle, possessing no internal structure. For the electron $s = 1/2$ and $S^2 = (3/4)\hbar^2$.

- The spin angular momentum of an electron, measured along *any* particular direction, can only take on the values $\hbar/2$ or $-\hbar/2$.

Idea of Spin : Stern-Gerlach Experiment

- **Stern-Gerlach experiment** was performed in the early 1920s by the German physicists Otto Stern and Walther Gerlach.

- The Stern–Gerlach experiment demonstrated that the spatial orientation of angular momentum is quantized. Thus an atomic-scale system was shown to have intrinsically quantum properties.

- It involved sending silver atoms through a non-uniform magnetic field and observing their deflection.

- Particles with non-zero magnetic moment are deflected from a straight path, due to the magnetic field gradient.

- The screen reveals discrete points of accumulation, rather than a continuous distribution.

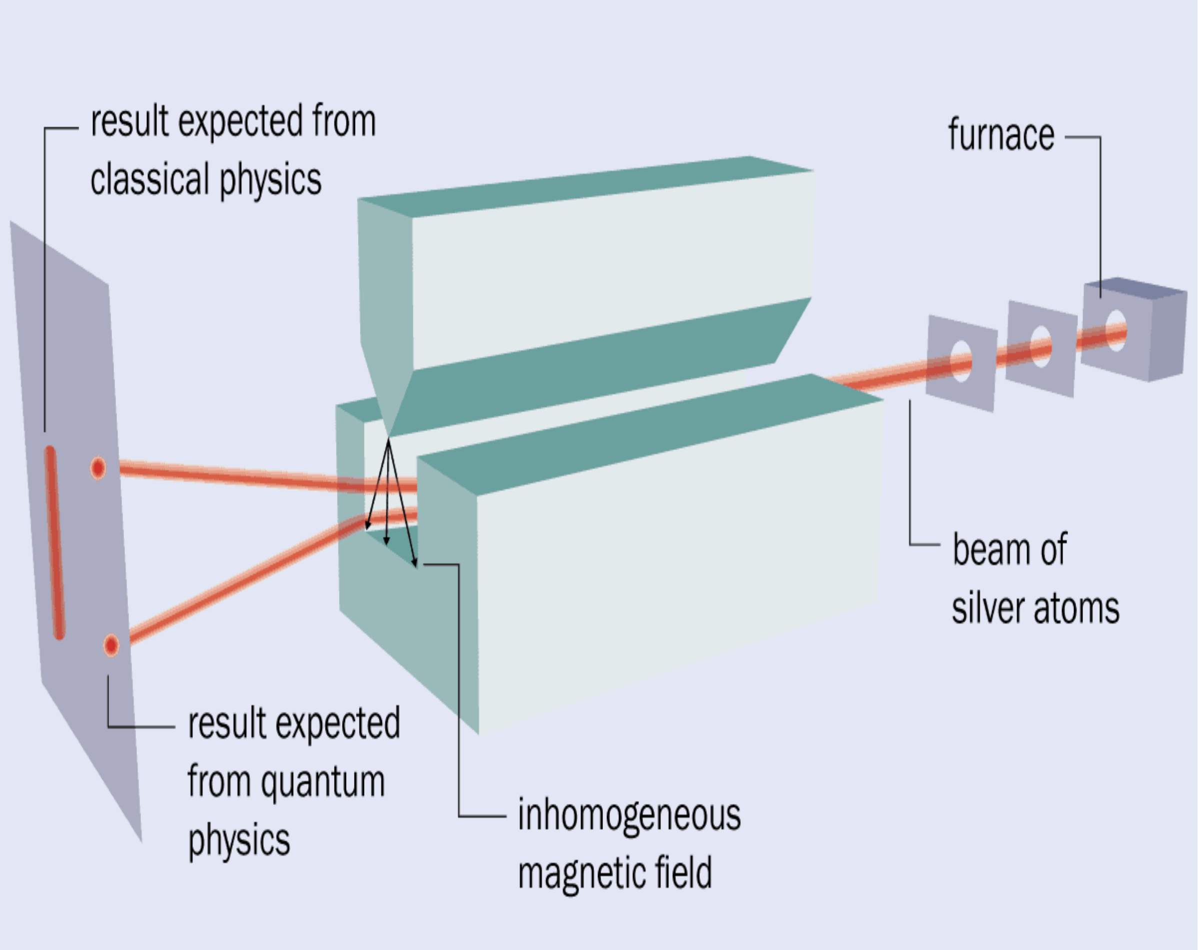


Fig. Illustration of Stern-Gerlach Experiment

This experiment discovered two surprising things.

- The atoms—specifically, the unpaired outer electron—did have a magnetic dipole moment. In effect, in addition to being charged, electrons acted like tiny bar magnets.
- Electrons are called *spin-1/2* particles.
- These have only two possible spin angular momentum values measured along any axis $+\hbar/2$ or $-\hbar/2$.

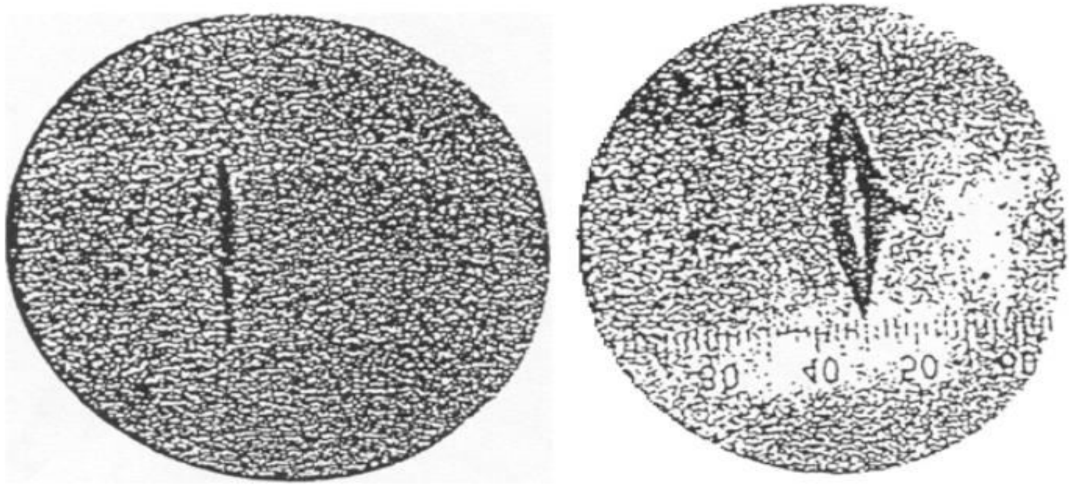


FIGURE 13. The experimental result of the Stern-Gerlach experiment. The beam has split into two components. From Gerlach and Stern (1922a).

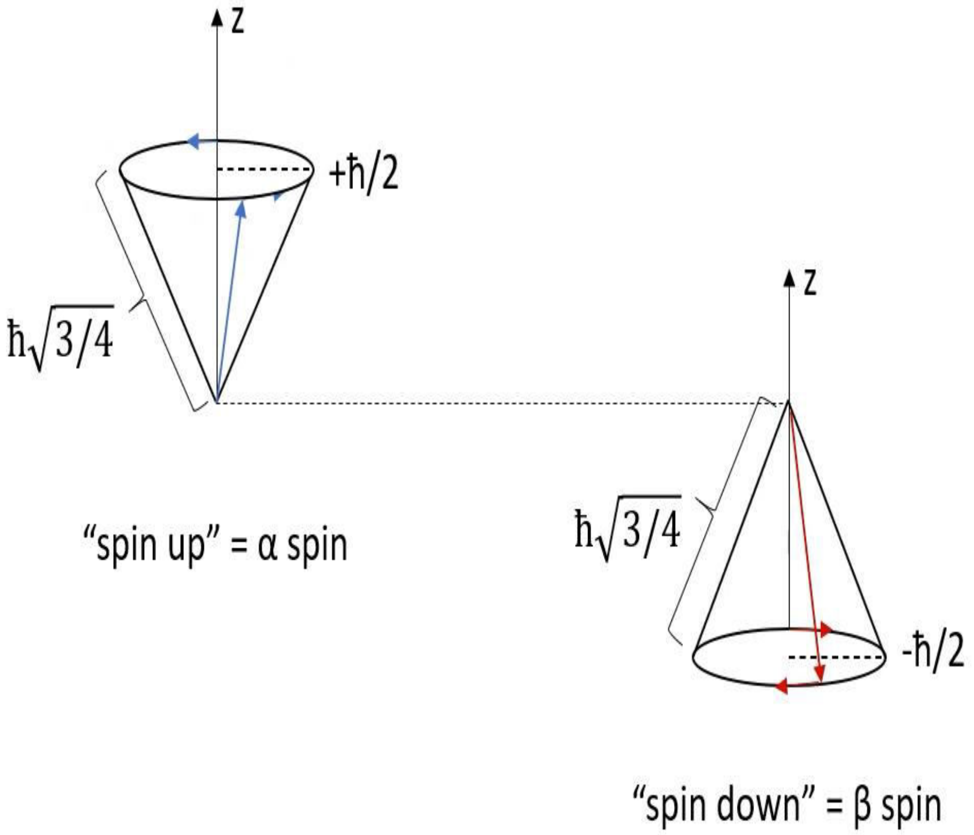
- The second surprising thing was how much the path of the electrons was deflected. If electrons were really bar magnets, they could be oriented in any direction.

- The component oriented along the magnetic field gradient (say the Z direction) would determine the force on the electron, and hence how much it would be deflected.

- If electrons were like ordinary magnets with random orientations, they would show a continuous distribution of paths.

- What was observed was quite different. The electrons were deflected either up or down by a constant amount, in roughly equal numbers.

- Apparently, the Z component of the electron's spin is quantized. It can take only one of two discrete values. We say that the spin is either up or down in the Z direction.



Why Spintronics : Post-Silicon Endeavours

- Limitations to Moore's Law: Moore's law is the observation that the number of transistors in an integrated circuit doubles about every two years.
- As electronics devices are reaching increasingly small size, intense heat is becoming a major problem.
- Also as size keeps on reducing, Quantum properties of the wavelike nature of electrons remains no longer negligible.
- Spintronics devices offer the possibility of enhanced functionality, higher speed and reduced power consumption.

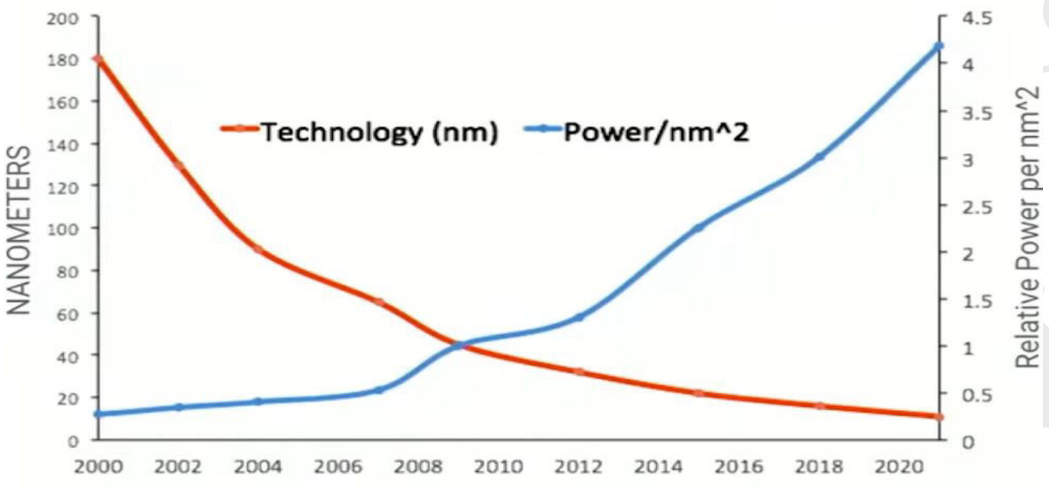


Fig. Power density over the years

It becomes difficult to control the power consumption as size of chips and transistors reduces. Also the leakage current gets increased.

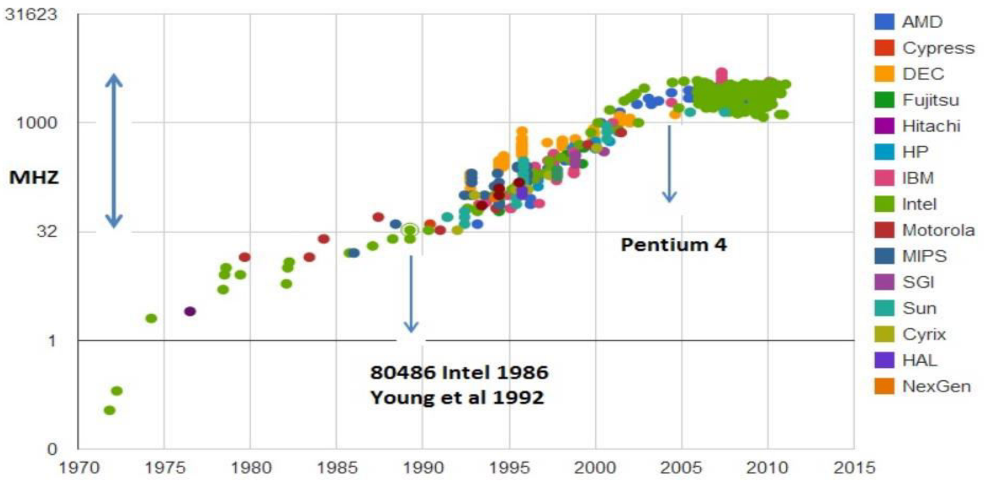


Fig. Stagnation in processor clock frequency due to increasing
power consumption and heat.

Source: Wikipedia

Low Power Spintronics Technology

- Spintronics is one of the emerging technology which has extended the Moore’s law and industry is trying to put more than Moore.
- Any technology can replace the current world of electronics if it reduces any one of the very large scale integration (VLSI) cost functions like area, power consumption and speed etc.
- Thankfully, Spintronics promises to reduce heat dissipation and power consumption significantly.
- In charge based device to switch from logic ‘0’ to logic ‘1’ the magnitude of the charge must be changed in the active region of the device due to which current flows from Source to Drain. It is not possible with charge based electronics to reduce the power (or heat) dissipation since charge is a scalar quantity and the presence or absence of charge gives logic ‘1’ or logic ‘0’.
- Spin unlike charge is a pseudo vector quantity which has a fixed magnitude of $h/4\pi$ with a variable polarization.
- The binary states in digital electronics can be achieved with a polarization parallel and antiparallel to the field which encode logic 1 and logic 0 respectively. In that case switching is accomplished by flipping the polarization of spin without any change in flow of current. This may result in significant energy saving.

Spin Polarization

- **Spin polarization** is the degree to which the spin, i.e., the intrinsic angular momentum of elementary particles, is aligned with a given direction.

- This property may pertain to the spin, hence to the magnetic moment, of conduction electrons in ferromagnetic metals, such as iron, giving rise to spin-polarized currents.

- The spin polarization has been calculated theoretically by the given relation :

$$P_n = \frac{n_\uparrow - n_\downarrow}{n_\uparrow + n_\downarrow}$$

- If $n_\downarrow = 0; P_n = 1$, in this case only majority spins are there and the spin polarization is 100%. Such materials are known as ferromagnetic half metals or heusler alloys with 100% spin polarization.

- Heusler alloys (or half metals) are ferromagnetic metal alloys based on a heusler phase [13]. One example of half metals is strontium doped lanthanum manganate (LSMO), well known for its colossal magneto resistive behavior and has 100% spin polarization at low temperature (0 K).

- If $n_\uparrow = 0; P_n = -1$, if $n_\uparrow = n_\downarrow;\ P_n = 0$ (only for paramagnetic or normal metal).

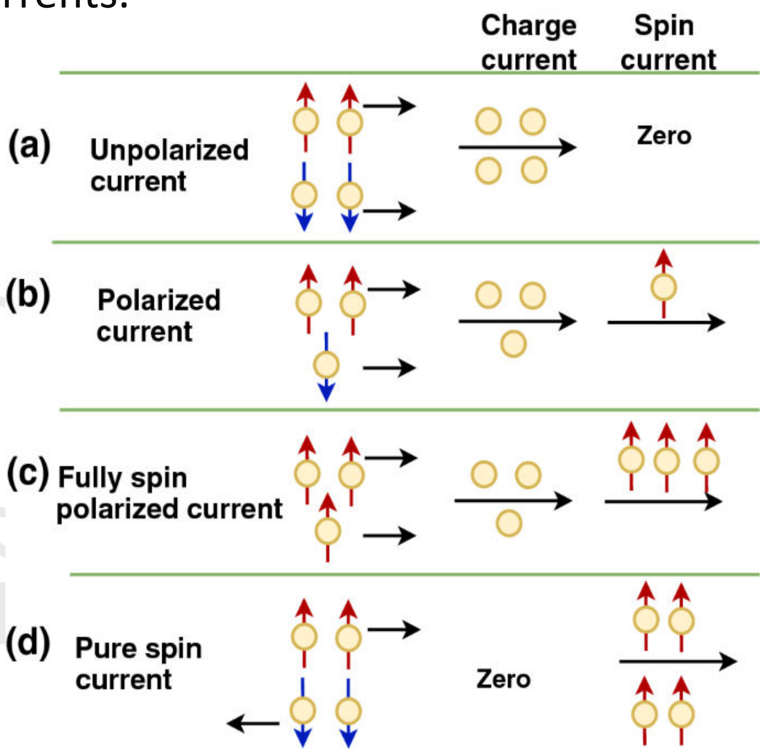


Fig. Illustration of **a** unpolarized current, **b** spin-polarized current, **c** fully polarized current, and **d** pure spin current

- These three cases has been shown in Fig. 1, using Stoner-Wohlfarth (SW) model of ferromagnet.

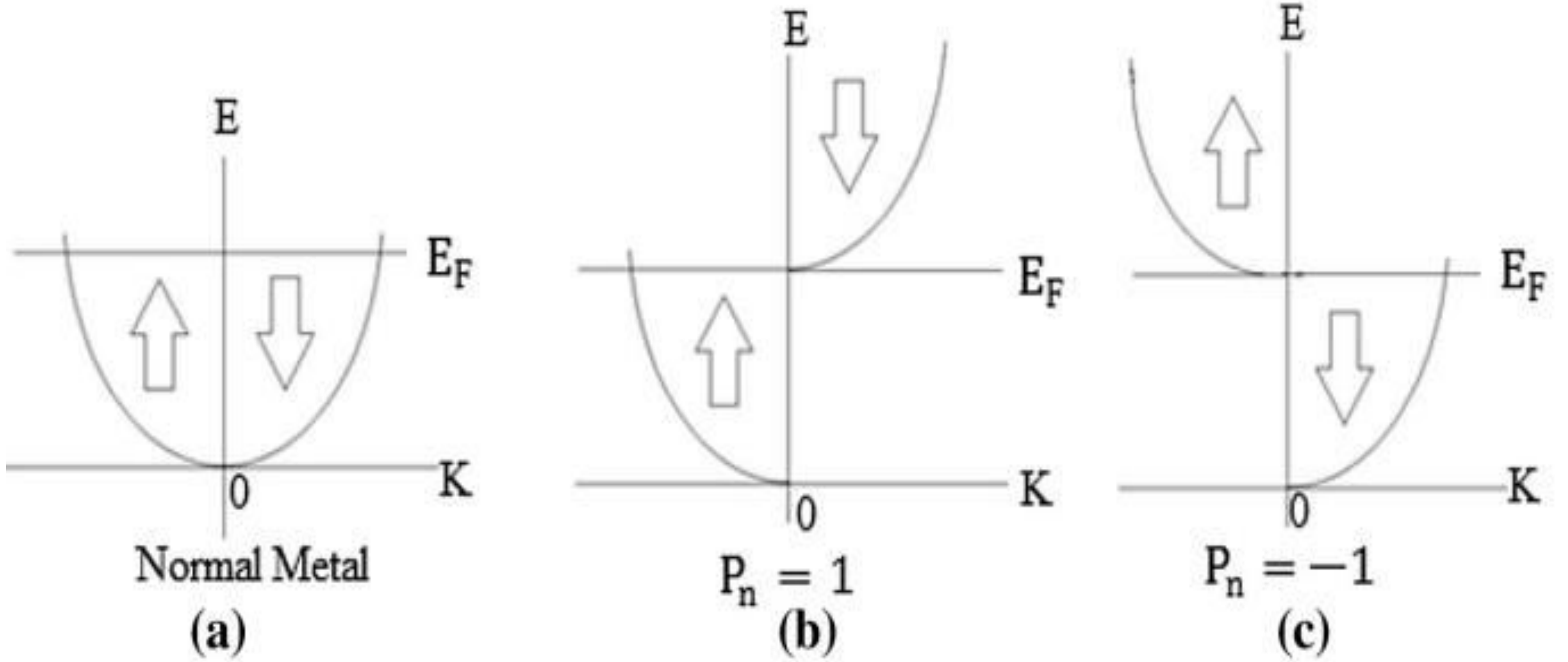
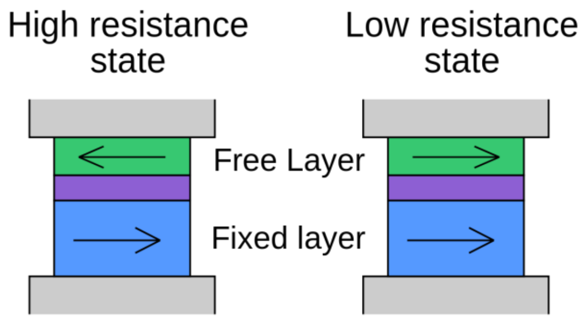


Fig. 1. Energy level (E-K) diagram using SW model (a) In normal metal both up spin and down spin are equal (b) if $n_\downarrow = 0$, and $n_\uparrow$ is 100% spin polarized has $P_n = 1$ (c) here $n_\uparrow = 0$, and $n_\downarrow$ is 100% spin polarized has $P_n = -1$

Spin Valve

- A **spin valve** is a device, consisting of two or more conducting magnetic materials, whose electrical resistance can change depending on the relative alignment of the magnetization in the layers.
- Generally spin valve structure consists of four layers.



I. Free layer-the first sensing layer of ferromagnetic material at top.

II. Spacer layer- the second layer of ultra-thin (of size about 1nm) non-magnetic material which separates free and fixed layer.

III. Pinned layer- the third layer of magnetic materials known as fixed layer.

IV. Exchange layer- the fourth layer of antiferromagnetic materials that fixes the magnetic orientation of pinned layer

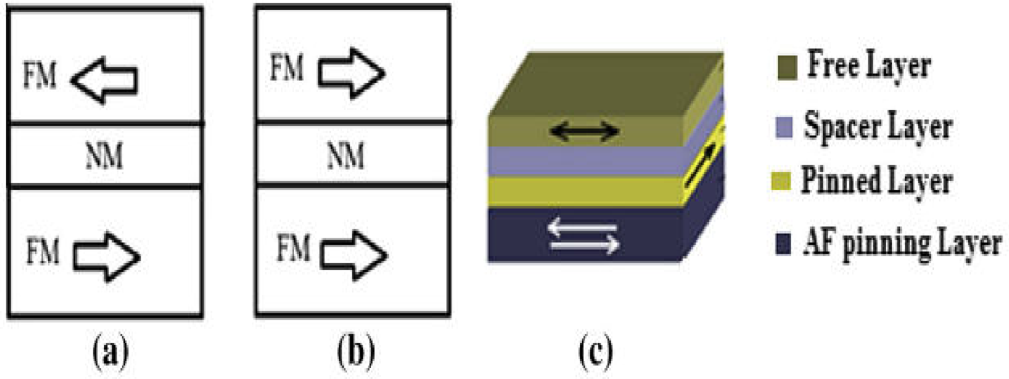


Fig. (a) Represents antiparallel resistance while (b) represents parallel resistance. (c) Schematic of a simple 4 layer spin valve structure.

- Sir Neville Mott first presented a simple two current model to understand the spin valve operation.

- It has been verified experimentally that there is a difference in resistance when the magnetizations are either parallel or antiparallel

- A sufficient biased voltage is applied between the electrodes and the electron can tunnel through the non-magnetic region.

- Tunneling magnetoresistive (TMR) effect is a consequence of spin dependent tunneling.

- The effect by which electron tunnel through one end to another end is a quantum mechanical effect and is known as TMR effect. TMR is calculated by Eq.

$$\mathrm{TMR} = \frac{R_{AP} - R_P}{R_P}, \text{ here } R_{AP} = \frac{R + r}{2} \text{ and } R_P \approx 2r$$

Here R, r is the resistance when channel and contact spin are in antiparallel and parallel direction respectively. Here R is more than r.

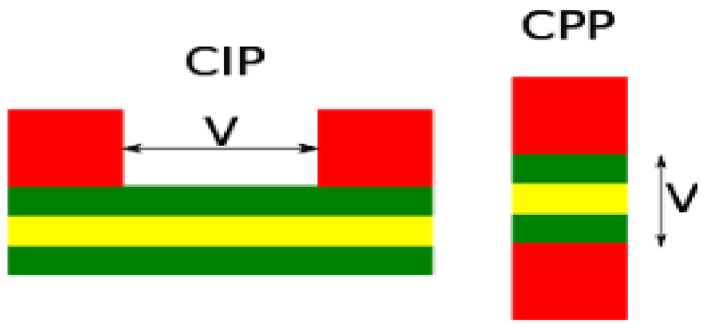


Fig. Spin valves in the reading head of a sensor in the current in plane (CIP) (left) and current perpendicular to plane (CPP) (right) geometries.

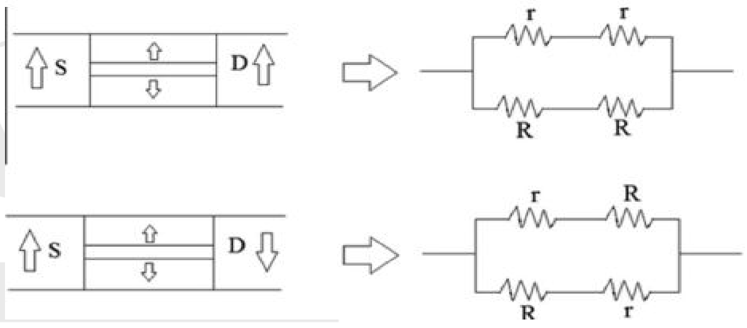


Fig. Parallel and antiparallel spin valve using Mott's resistor model

Giant Magnetoresistance

- **Giant magnetoresistance** (**GMR**) is a quantum mechanical magnetoresistance effect observed in multilayers composed of alternating ferromagnetic and non-magnetic conductive layers.

- There is a significant change in the electrical resistance depending on whether the magnetization of adjacent ferromagnetic layers are in a *paralle*l or an *antiparallel* alignment.

- The overall resistance is relatively low for parallel alignment and relatively high for antiparallel alignment.

- The effect is based on the dependence of electron scattering on spin orientation.

- Magnetoresistance is the dependence of the electrical resistance of a sample on the strength of an external magnetic field. Numerically, it is characterized by the value :

$$\delta_H = \frac{R(H) - R(0)}{R(0)}$$

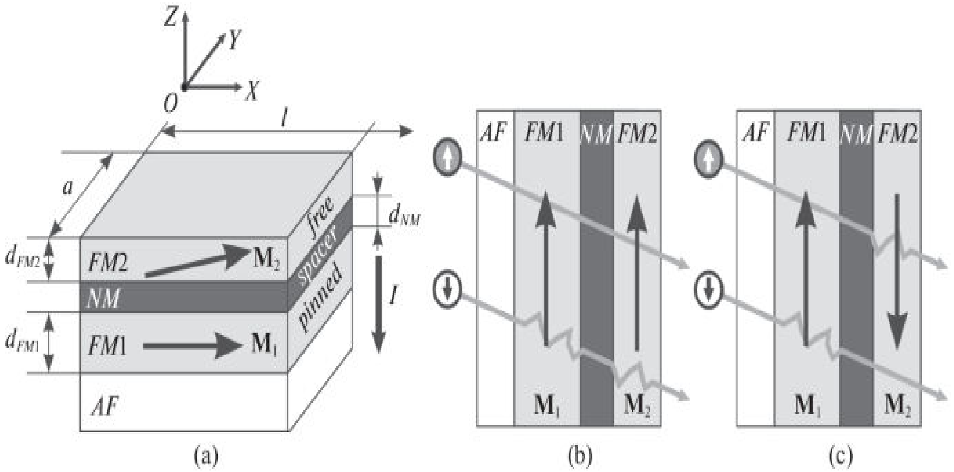


Fig. (a) Spin valve. Schematic of the GMR mechanism for a spin valve in (b) the parallel and (c) antiparallel states.

Source: C. Chappert, A. Fert, and F. Nguyen Van Dau, Nat. Mater. 6, 813 (2007).

GMR : The Nobel Prize in Physics 2007

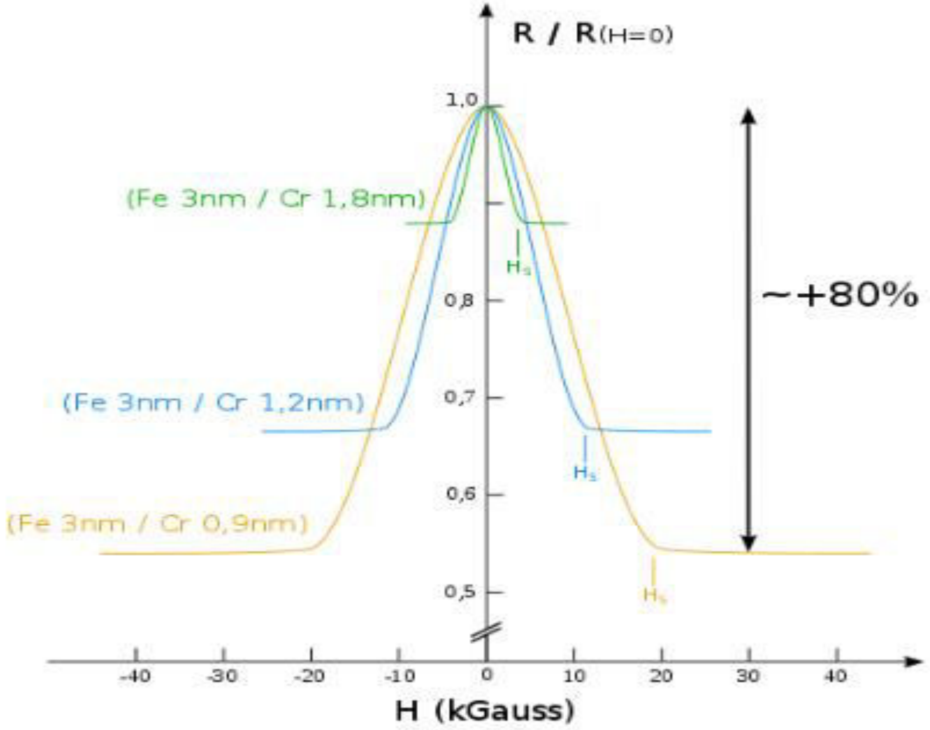


Fig. A sample of the work that led to the 2007 Nobel Prize.

Fig. The Nobel Prize in Physics 2007 was awarded jointly to Albert Fert(right) and Peter Grünberg(left) "for the discovery of Giant Magnetoresistance“.

The founding results of Albert Fert and Peter Grünberg (1988): change in the resistance of Fe/Cr superlattices at 4.2 K in external magnetic field H. The current and applied magnetic field are along the same axis in CIP configuration. The arrow to the right shows maximum resistance change. H_s is saturation field

Source: M.N. Baibich, J.M. Broto, A. Fert, F. Nguyen Van Dau, F. Petroff, P. Etienne, G. Creuzet, A. Friederich, J. Chazelas, Giant magnetoresistance of (001)Fe/(001)Cr magnetic superlattices, Phys. Rev. Lett. 61 (1988).
Image Source: Wikipedia

The World’s First Hard Drive, 1956

IBM unleashed the world's first computer hard drive in 1956. It was bigger than a refrigerator. It weighed more than a ton.

The RAMAC hard drive at the Computer History Museum in Mountain View, California.
Photo: Jon Snyder/WIRED.

Applications of GMR : Read Heads of Hard Disk Drives

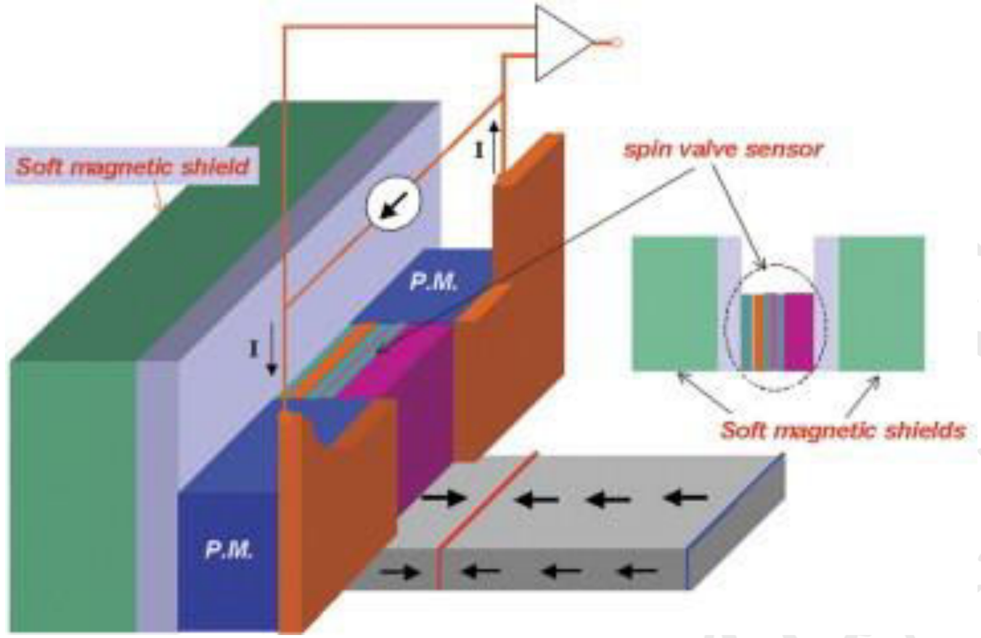
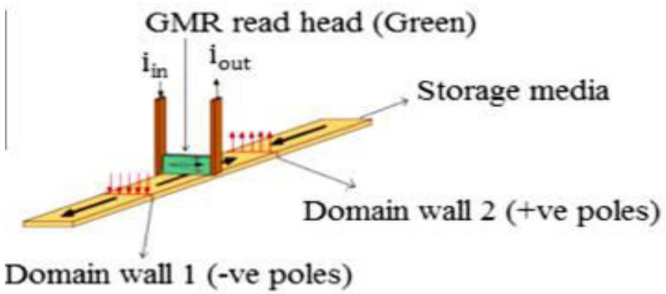


Fig. Schematic of a spin valve head structure used in HDDs. A spin valve read sensor stack is placed in between a pair of permanent magnets that provide a horizontal magnetic field in the cross-track direction. Two soft magnetic shields are placed in the down track direction, enabling adequate spatial resolution for high linear recording density.

Fig. A schematic representation of GMR read head that passes over the storage media



Source: Gary A. Prinz, Magnetoelectronics, Science 282 (5394) (1998) 1660–1663.

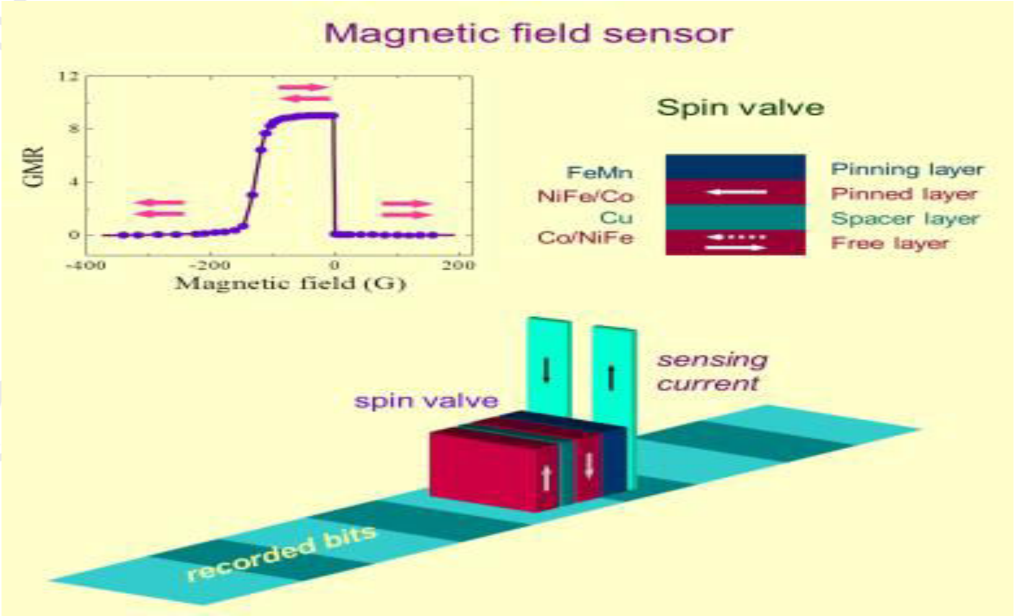


Fig. Magnetic field sensor

Applications of GMR

- The main application of GMR is in magnetic field sensors, which are used to read data in hard disk drives, biosensors, microelectromechanical systems (MEMS) and other devices. GMR multilayer structures are also used in magnetoresistive random-access memory (MRAM) as cells that store one bit of information.

- IBM was first to put on the market hard disks based on GMR technology, and nowadays all disk drives make use of this technology.

- The GMR read head sensor in a hard disk is built using a spin valve. Spin valve resistance demonstrates a steep change in the small field range close to H=0.

- As the magnetic bits on the hard drive pass under the read head, the magnetic alignment of the sensing layer in the spin valve changes resulting in the resistance change.

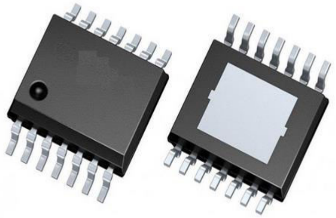


Fig. GMR Sensors

Fig. Read-head in Hard drive

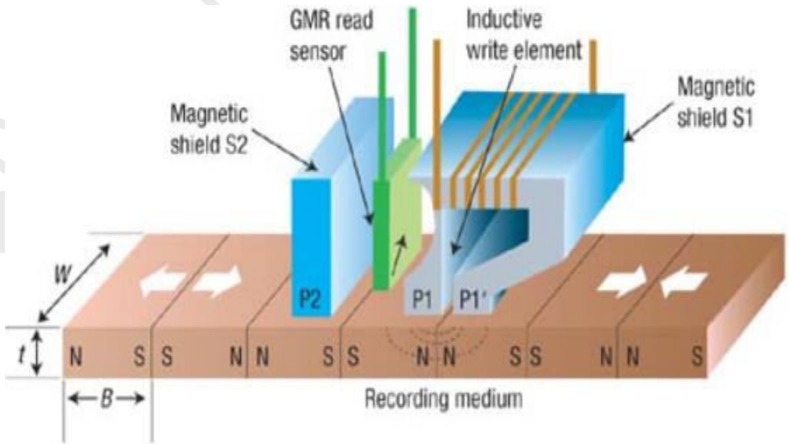


Fig. Magnetoresistive head for hard-disk recording.Schematic structure of the magnetoresistive head introduced by IBM for its hard disk drives in 1991.

References

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SPECIAL THANKS

PHN-006 Course Instructor

Himanshu Fulara, Ph.D. (IIT Delhi)
Assistant Professor
Department of Physics
Indian Institute of Technology Roorkee
Roorkee- 247667, INDIA

THANK YOU