Harnessing Spin for Solid State Devices: Spintronics

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This writeup talks about an active field of research in today's world, spintronics. We'll start with introducing what spintronics is, followed by a brief discussion on electron spin, which is the key quantum mechanical concept involved and then we will see why spintronics has lately attracted a lot of attention in the technological domain and some of the spintronic systems in use today.

This topic was chosen based on my realization as a CSE student, how fundamentally important spintronic devices are in the upcoming future. The discussion of applications of quantum mechanical phenomena in technology during the lectures was an important contributing factor. Spintronics is based majorly on the property of intrinsic spin of an electron which is a key concept in quantum physics.

INTRODUCTION

Spintronics, also known as spin electronics, is the study of intrinsic spin of the electron and its associated magnetic moment, in addition to its electronic charge in solid-state device[1]. It differs from traditional electronics as in traditional electronics, whereas spintronics focuses on utilizing both the charge and the spin of electrons which leads to advantages such as zero standby leakage, low power consumption, a good read-write performance, non-volatile nature etc.

HISTORY

The idea of electron spin was introduced in 1925, much before the first integrated circuit, but due to the technological limitations and lack of understanding not much progress was made in implementing it. The field of spintronics emerged as a result of scientific advancements and discoveries in the late 20th century. Some key milestones that contributed to the emergence of spintronics were Giant Magnetoresistance (GMR), Spin injection and detection, spin transfer torque etc. The use of semiconductors for spintronics began with the theoretical proposal of a spin field-effect-transistor by Datta and Das in 1990. These discoveries have been talked about further in upcoming sections. The following figure illustrates the key junctures in spintronics research.

[1] A solid-state device is an electronic device in which electricity flows through solid semiconductor crystals.

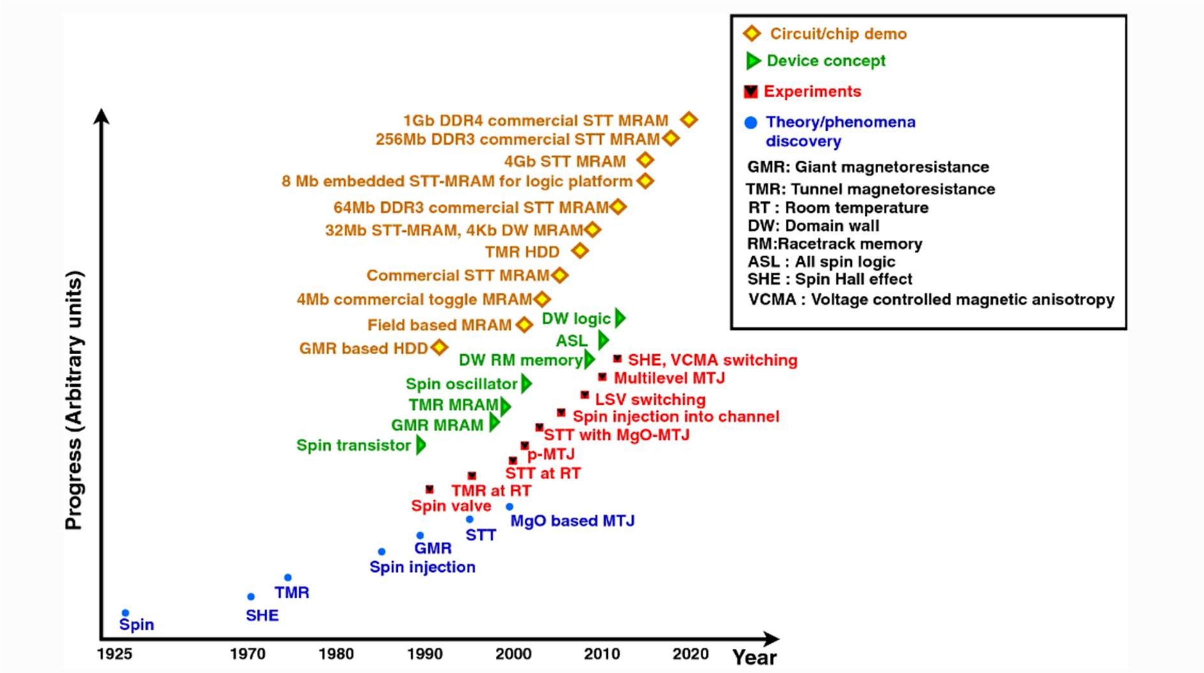

Figure 1 Historical developments in spintronics research

Before talking further about spintronics, let us discuss what this ‘spin’ is.

THE SPIN

The theory of atom which was developed by solving the Schrodinger equation for an electron in hydrogen atom cannot account for several well-known experimental observations. One is the fact that many spectral lines, observed in spectrum when an electron makes transition from a higher energy state to a lower energy state, consist of two separate lines that are very close together (this is called **fine structure**). Another failure of the simple quantum mechanical theory was in explaining the **Anomalous Zeeman Effect**, i.e., why does a spectral line splits into more than three lines when an atom is put in a constant homogeneous magnetic field.

In order to account for these discrepancies, Goudsmit and Uhlenbeck in 1925 proposed that

> Every electron has an intrinsic angular momentum, called spin, whose magnitude is the same for all electrons. Associated with this angular momentum is a magnetic moment.

They pictured an electron as a charged sphere spinning on its axis. This leads to the electron having a magnetic moment $\boldsymbol{\mu}_s$ which will be opposite in direction to its angular momentum vector **S** (since electron is negatively charged).[2] This proved to be successful in explaining a wide variety of atomic effects. Later in 1929 the nature of electron spin was confirmed by Paul Dirac.

The quantum number s describes spin angular momentum of the electron. Only value taken by s is $s = \frac{1}{2}$, which follows from spectral data and spin-statistics theorem.

The magnitude S of the angular momentum due to electron spin is given in terms of spin quantum number s by

$$S = \sqrt{s(s+1)}\hbar = \frac{\sqrt{3}}{2}\hbar$$

[2] This picture of a ‘spinning electron’ may not be true, as it leads the electron to have angular momentum so high that the equatorial velocity of the imagined spherical ball is many times larger than the speed of light. We really don’t know what type of internal motion in electron causes the presence of spin angular momentum and spin magnetic moment.

Space quantization of electron spin is described by spin magnetic quantum number m_s. The spin angular momentum vector can have orientations specified by $m_s = +\frac{1}{2}$ ("spin up") and $m_s = -\frac{1}{2}$ ("spin down").

The component S_z of the spin angular momentum of an electron along magnetic field in the z direction is determined by the spin magnetic quantum number, so that

$$S_z = m_s\hbar = \pm\frac{1}{2}\hbar$$

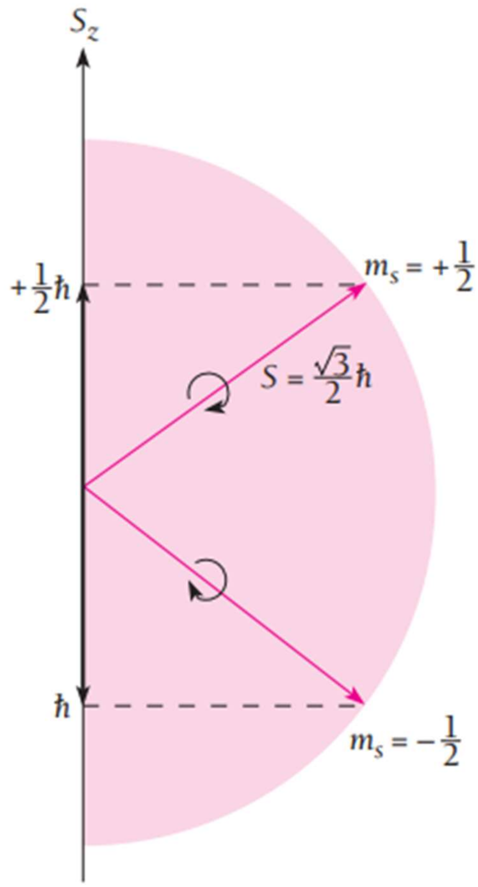

Figure 2 The two possible orientations of the spin angular momentum are "spin up" and "spin down".

The spin magnetic moment μ_s of and electron is related to its spin angular momentum **S** by

$$\mu_s = -\frac{e}{m}\mathbf{S}$$

The spin of many electrons acts together to affect the magnetic and electric properties of a material.

Now, let us return to our topic and see why we need spintronics.

WHY SPINTRONICS?

Over the past few decades, the CMOS technology, the major technology used in present integrated circuits has been continuously downscaled, consistently improving performance and reducing size of circuits. The current bulk CMOSFETs are evolving towards nanoscale ultrathin body silicon-on-insulator (SOI) structures as reducing the thickness of the silicon body on top of the buried oxide leads to better electrostatic control.

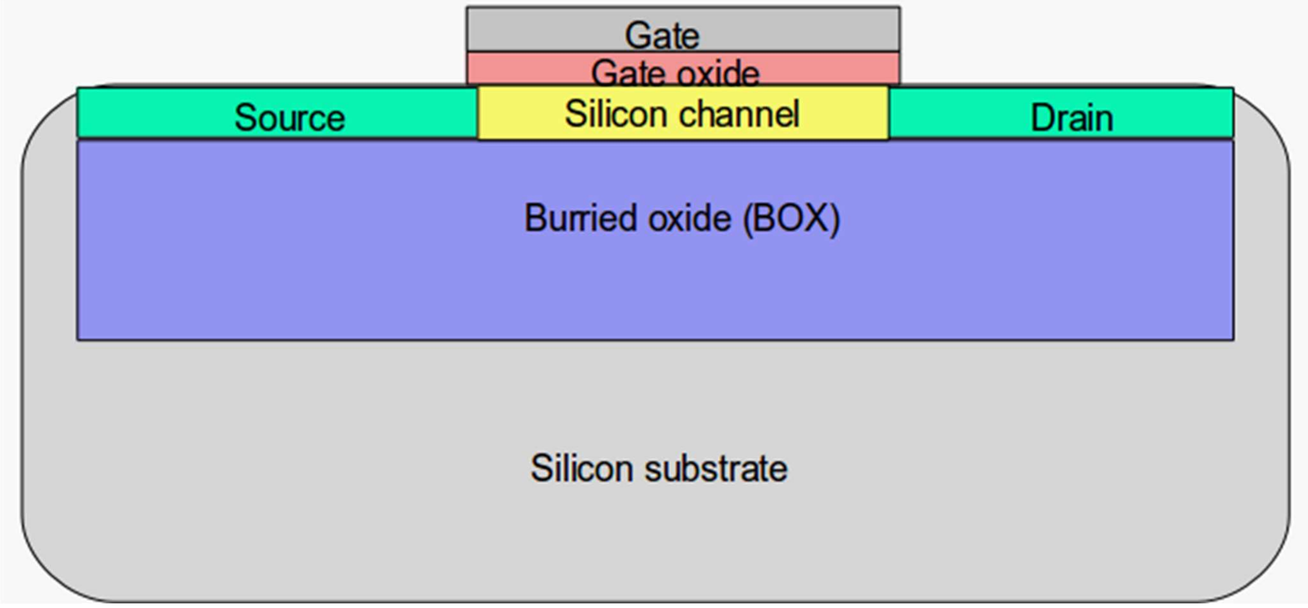

Figure 3 A silicon-on-insulator (SOI) structure

However, further scaling is becoming extremely difficult as the transistor size reaches a few atomic layers, quantum effect starts to kick in. The expected gate length in future is 5nm, because of that, off leakage current will be too high for the entire chip. This arises due to quantum tunnelling of electrons which depends exponentially on oxide thickness.

Various techniques to reduce the off-chip power are in use currently, the most promising ones being double gate MOSFET (DG-MOSFET), fin-FET and Si-nanowire MOSFET. Carbon nanotube FET (CNTFET) is another feasible nanodevice. The problem with all above mentioned logics is that they are all **volatile**. Spin logics improves battery life by consuming less power and are also non-volatile in nature as spin and magnetization of an electron are retained indefinitely in spintronic device.

Spintronics can also reduce heat dissipation significantly. In traditional charge-based devices, when we switch from logic ‘0’ to logic ‘1’, the magnitude of charge must be changed in the active region of the device due to which current flows from Source to Drain. Charge is a scalar quantity, so it is not possible to reduce the power dissipation. Spin, unlike charge, is a pseudo vector quantity which has a fixed magnitude ($= \frac{h}{4\pi}$) with a variable polarisation. The logic states ‘1’ and ‘0’ can be achieved with a polarisation parallel and antiparallel to the field respectively. Switching is accomplished by flipping the polarisation of spin without any change in flow of current. This may result in significant energy saving.

Let us now look at some spintronics technologies. Two diverse field of low power spintronics technologies are the active and passive devices. I have discussed few active devices like spin valve and magnetic tunnel junction (MTJ). Other two domains under passive devices are monolithic and hybrid technologies. In monolithic spintronics, data storage and communication are done by spin only while in hybrid spintronics it is done by charge only, but its effect is augmented by the presence of spin. It has been shown in literature that hybrid spintronics do not really show significant advantages over BJT or MOSFET transistor.

SPIN VALVE

Spin valves were first developed in 1991 and later changed the landscape of magnetic data storage by dramatically increasing storage capacity. A spin valve is a device, consisting of two or more conducting magnetic materials, whose electrical resistance can change between two values depending on relative alignment of the magnetization in the layers. The resistance change is a result of the giant magnetoresistive effect (GMR)[3].

For a simple picture, consider the spin valve as a sandwich in which a non-magnetic material is sandwiched between two ferromagnets, one of which is fixed (pinned) by an antiferromagnet which acts to raise its magnetic coercivity[4] and behaves as a "hard" layer, while the other is free (unpinned) and behaves as a "soft" layer.

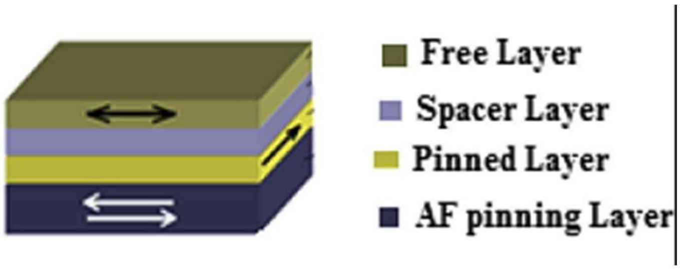

Figure 4 Schematic diagram of a spin valve

The structure can be built horizontally or vertically. I have represented the vertical structure.

The working of a spin valve can be understood by considering the scattering of spin-polarized electrons as it passes through the spin valve. In ferromagnets, there is a net spin polarisation as there is a split in the density of states of electrons at the fermi energy (i.e., there are unequal number of electrons with up and down spins). So, the electric current passing through a ferromagnet carries both charge and spin component. In a normal metal, there are equal number of electrons with spin up and down, so zero net spin component. But when current is passed through a ferromagnet into a normal magnet, it is possible for spin to be transferred. Thus, a normal metal can transfer spin between separate ferromagnets.

Spin transmission depends on the alignment of magnetic moments of the ferromagnets. If a current passes through ferromagnet with majority spin up (say) then electrons with spin up pass through relatively unhindered, while electrons with spin down scatter. Therefore, if the fixed and free layers are polarised in the same direction, the device has relatively low electrical resistance, whereas if the applied magnetic field is reversed and the free layer's polarity reverses, then the device has higher resistance.

A sufficient biased voltage is applied between the ferromagnetic layers and the electron can tunnel through the non-magnetic region. This is known as TMR effect. This allows current to flow through the spin valve.

Spin valves are used in magnetic sensors and hard disk read heads. They are also used in magnetic RAM.

A structure like spin valve is the **Magnetic Tunnel Junction (MTJ)**. In MTJ, the non-magnetic layer of spin valve is replaced with an insulating barrier layer. The advantage of MTJ is that it can be easily integrated with CMOS circuits. TMR ratio is the primary performance indicator for an MTJ, and it is defined as

$$TMR = \frac{R_{AP} - R_P}{R_P}$$

R_P and R_{AP} represent MTJ resistance in parallel and anti-parallel configuration.

MONOLITHIC SPINTRONICS

Let us now look at how spintronics can be used for data storage and communication using spin only. Here, I explain the single spin logic, more specifically realization of universal NAND gate using SSL.

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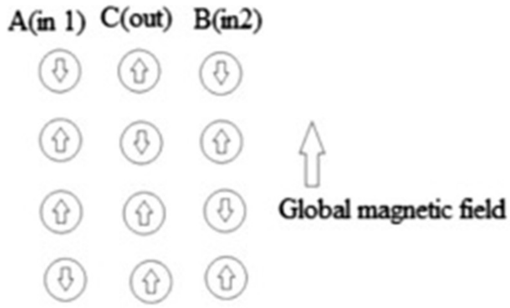
[3] GMR is a quantum mechanical magnetoresistance effect observed in thin film structures composed of alternating ferromagnetic and nonmagnetic layers. The effect manifests itself as a significant decrease (typically 10-80%) in electrical resistance in presence of a magnetic field.

[4] Coercivity gives us a measure of a ferromagnetic material to withstand external magnetic field without getting demagnetized. Here, the antiferromagnetic material increases the coercivity, basically meaning that it fixes the magnetic orientation of the fixed layer.

Consider a linear array of 3 electrons A, B and C containing quantum dots[5].



A(in1)	C (out)	B (in2)
0	1	0
1	0	1
1	1	0
0	1	1

Figure 5 NAND Gate using SSL.

Here A and B are two input and C is the output. Polarization parallel to magnetic field corresponds to logic ‘1’ and antiparallel to magnetic field comprises logic ‘0’. We see that polarization of system is bistable. This can be done by placing the electron in DC magnetic field and allowing the system to relax to thermodynamic ground state. When the spin polarizations of A and B are made to confirm the desired bit inputs and the system is allowed to relax to the ground state, the spin polarizations in C always represent the output. To read and write the input and output pin various methods are used, one of them being spin polarized scanning tunnelling microscope (SPSTM). Any logic can be developed by placing the quantum dots in a 2D array and correct pin configuration of input and output.

CONCLUSION

This write up tried to introduce the idea of spintronics by giving a description of what quantum spin is and how it can be used in solid state devices. It also discussed in brief why spintronics is a better alternative to the existing CMOSFETs. Spintronics, being a vast area of research, is almost impossible to be summed up in a 2000 word write up and I have barely scratched its surface. The reader, if interested, is encouraged to read further about spintronics in the links given below. With further advancements in our technological capabilities, we will possibly live in a world where spintronics find application in almost all our circuits.

REFERENCES

[1] Barla, P., Joshi, V.K. & Bhat, S. **Spintronic devices: a promising alternative to CMOS devices**. *J Comput Electron* **20**, 805–837 (2021). https://doi.org/10.1007/s10825-020-01648-6

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[3] **Concepts of Modern Physics** by Arthur Beiser

[4] **A brief introduction to giant magnetoresistance** Liu Chang, Min Wang , Lei Liu , Siwei Luo2, Pan Xiao, Hycorelle Co., Ltd., Beijing, China Ohio State University, Columbus, OH 43210

[5] https://en.wikipedia.org/wiki/Spintronics

[6] https://en.wikipedia.org/wiki/Spin_(particle_physics)

[7]
https://en.wikipedia.org/wiki/Spin_valve#:~:text=A%20spin%20valve%20is%20a,of%20the%20giant%20magnetoresistive%20effect.

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[5] Quantum dots are tiny semiconductor nanocrystals that exhibit unique electronic and optical properties due to their nanoscale dimensions. They are often referred to as artificial atoms because, at such small sizes, they behave as if they were individual quantum systems, with discrete energy levels.