# Journal 5: Spintronics

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Spintronics is a field in solid state physics and material science that exploits the intrinsic spin of the electron and its associated magnetic moment. It utilises the spin as an additional degree of freedom, allowing us to gain and store more information in spintronics systems. This is why quantum dots, which function on the property of spin of the electron, are used in quantum computation and quantum mechanical systems.

An electron is a fermion, having 1/2h spin angular momentum.
Spintronic devices utilize an imbalance on the net spin of a collection of electrons in a material. For example, in ferromagnetic materials, electron spins get permanently aligned when acted upon by a strong magnet or magnetic force.

Spintronic devices may be generated using a variety of methods: most use the Zeeman effect, in which a material is placed in a large magnetic field. Others use the exchange energy of electrons in which electrons exchange their positions in degenerate orbitals of the subshell, such as in the case of ferromagnets. A third method is to force the material system out of equilibrium of spins.

A simple technique of using spintronics in devices is to pass current through ferromagnetic material. In a ferromagnet-spacer-ferromagnet sandwich, we get low resistance when the magnetization vectors of the ferromagnet get aligned, and high-resistance when they are anti-aligned. This manipulation of alignment and misalignment is used in Giant Magneto Resistance, which finds applications in memory devices such as Magnetic RAM, spin valve sensors, and there is a lot of research going on in spin transistors.

**Spin Valve Sensor**

A spin valve device consists of a non-magnetic material sandwiched by two ferromagnets, one of which is made into a hard-layer by an antiferromagnetic material which elevates its magnetic coercivity. The other ferromagnet is thus a ‘soft’ layer, which changes its polarity at lower magnetic fields than the hard one, due to the difference in their coercivities. (Parkin et al.)
It is the ability of the soft layer to change polarity which is used in the *valve.* Depending on the magnetic field applied, the polarity may be parallel to the polarity of the hard layer, giving rise to a low-resistance state, or anti-parallel, giving rise to a high-resistance state.
Thus, this impacts the way current may be passed through the device, with electrons having aligned spins passing through unhindered in the low-resistance state, and facing resistance in the high-resistance, anti-parallel state.

Depending on the spin polarization in the ferromagnetic materials, the electrons passing through the device carry charge as well as a spin component, the extra degree of freedom which can be used in sensing and detection of magnetic fields.

Thus, spin valves find good application in sensing. Before the widespread use of solid state devices, they were extensively used in hard drives, mainly in detecting minute magnetic impulses. Moreover, the function of the spin valve depends on nonmagnetic material thickness, antiferromagnetic material strength, and the strength of the magnetic field, allowing us to calibrate the soft ferromagnet to become polarized at extremely low magnetic field strengths. This property and variability of spin valves makes them ideal to sense magnetic biomolecules, which are low in concentration and produce very weak magnetic fields.

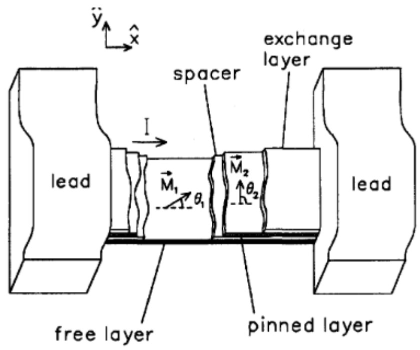

Fig. 1. Unshielded spin valve sensor.

**(Heim et al., 1994)**

The spin valve sensors designed by Heim et al. are fabricated using NiFe/Co/Cu/Co/NiFe nano-layers and NiFe/Cu/Co nanolayers. Sensors using Giant Magneto-Resistance are show greater sensitivity than those using Anisotropic Magneto-Resistance. GMR introduces coupling between adjacent magnetic layers interjected by the nonmagnetic (spacer) layer. The coupling is weakly ferromagnetic in spin valves due to the soft ferromagnetic layer being unpinned.

Here, the pinned layer is magnetized at θ=90°,making the output completely linear. This is how a completely linear spin valve is fabricated. The nanolayer-type spin valve has a free layer/spacer layer/pinned layer structure.

The materials used for each layer are ($Ni_{80}Fe_{20}$ 60 A)/(Co 10 A)/(Cu 25 A)/(Co 10 A)/($Ni_{80}Fe_{20}$ 30 A). (Heim et al., 1994)

The Co layers are thinner than the others, making them nanolayers, and are part of the free and pinned layers respectively.

The second type of valve is simpler, with ($Ni_{80}Fe_{20}$ 60 A)/(Cu 25 A)/(Co 50 A). Due to the additional Co 10 Angstrom, the first type of valve showed higher magnetoresistance than the latter. This happens because the Co needs to polarize similarly to the NiFe free layer, and both need to be aligned to NiFe pinned layer for a non-resistive effect.

Here, the spin valve layers are composed using sequential lithography, and the trackwidth, which determines the pattern type, is defined by the separation of the lead metallurgy on the face of the structure.

When the sensor is placed in material with low magnetic fields, such as material with disparate, moving ferrous particles, a magnetoresistance output is recorded according to variations in magnetic fields. With integration of current lines atop the sensor layers, the variation and presence of the fields can be detected. Variation in magnetoresistance output of the spin valve sensor represents the variations in input (detected) magnetic field.

**Magnetoresistive RAM**

State-of-the-art MRAM devices utilize Magneto Tunnel Junctions to toggle between two magnetoresistances. Similar to the spin valve, an MTJ uses free and pinned layers to result in the magnetoresistance. The resistance is lower when the free and pinned layers are aligned, and higher for when they are misaligned. The Magnetoresistance Ratio (MR) determines the difference in the resistances of these two states.

MRAM devices are preferred over traditional memory storage devices because of their durability and non-volatility. Memory bits are stored using the magnetoresistance property of the device -- 1 for high resistance, 0 for low resistance.(Bedair et al., 2010)

An MRAM memory element is composed of two ferromagnetic electrodes and an $Al_2O_3$ tunnel barrier. The electrode layers are elliptical in shape, and their magnetic moments are always along the long axis in the trilayer. Because this type of structure utilizes a tunnel barrier, the resulting magnetoresistance is also known as Tunneling Magnetoresistance.
An NiFe compound is usually used as the ferromagnetic material, with the thickness of the layers ranging from 20 to 50 A. The spacer placed between the ferromagnets is Co/Ru/Co $Co_{90}Fe_{10}$/Ru/$Co_{90}Fe_{10}$. (Bhatti et al., 2017)
After film deposition for the ferromagnetic-nonmagnetic sandwich structure, patterning is carried out using Chemical Mechanical Polishing, which also allows for interconnects between the memory element and transistors.

In this device, the bottom ferromagnetic layer is pinned by an antiferromagnetic layer. The top layer is free/soft. The readout is conducted by a transistor which is connected to each MRAM memory element, and is done so by clamping the bitline to a fixed voltage and activating the worldline.The resulting current varies between a small current for bitstate ‘high’ (due to higher resistance), and large current for bitstate ‘low’ (due to smaller resistance). The output is stored by using a current sense amplifier to compare the output current to a reference current.

The shape of the layer is kept elliptical for its magnetic anisotropy, which ensures the magnetic moment stays along the longer axis. The linear orientation of the moment helps generate magnetic poles at the ends of the structure. Rectangular layers give rise to very strong magnetic dipoles. (Chung et al., 2016,)
The magnetic anisotropy helps in retention of the bit state. This is because each bit state is represented by the spin state of the electrons, and anisotropy ensures the spins don’t change with changes in magnetic field applied across the structure.

Writing into the memory element is done by passing an electric current through the pinned ferromagnetic layers, which induces a spin change on the electrons within the memory element. A spin up electron is considered to be of value 1 and a spin down electron of value 0.

The current technology requires a very small current, by virtue of Spin-Transfer Torque, in which spins of neighboring electrons are flipped using spin polarized current (current with electrons having spins polarized to the ferromagnetic material they are passing through). (Bedair et al., 2010)

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