FROM HALL EFFECT TO TMR

By Allegro MicroSystems

ABSTRACT

This paper compares legacy Hall-effect technology to xMR technology, specifically tunnel magnetoresistance (TMR) from Allegro MicroSystems.

INTRODUCTION

Historically, there have been many systems to transduce a magnetic field to a proportional voltage. These sensors vary by industry application and include magnetic-encoder, e-compass, absolute angle-sensor, simple on/off-switch, and current sensing.

The most popular of these were Hall-effect sensors, discovered by Edwin Hall in 1879. Yet, after more than a century of development, these legacy sensors have finally reached their limits. Today, system designers require new technologies with improved power consumption, sensitivity, accuracy, and cost.

Increasingly, the solution is TMR technology, the natural evolution of older technologies like giant magnetoresistance (GMR) and anisotropic magnetoresistance (AMR). This paper provides a high-level introduction to these different technologies and a look at the Allegro TMR solution.

THE PHYSICS

Hall Effect

A Hall-effect demonstrator requires a thin plate of conductive material, carrying current (I) generated by a DC voltage supply and a voltmeter connected to the sides of the conductive plate, as illustrated in Figure 1.

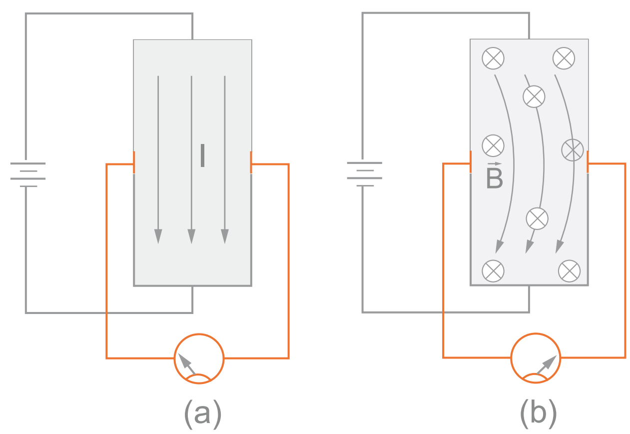

Figure 1: The Hall Effect in a Thin Plate

When a magnetic field is not present, the voltmeter should read 0 V, as shown in Figure 1 (a). However, when a magnetic field—perpendicular to the current flow—is applied to the plate, a small voltage appears across the plate, which can be measured by the voltmeter, as illustrated in Figure 1 (b).

The separation of charge establishes an electric field that opposes the migration of further charge, so a steady electrical potential is established for as long as the electrons are flowing. The force that pushes charged particles (such as electrons) is called the Lorentz force and is described by:

Equation 1: Lorentz Force Equation

$$\vec{F} = q_0\vec{E} + q_0\vec{v} \times \vec{B},$$

where F is the resultant force, E is the electric field, v is the velocity of the charge, B is the magnetic field, and q is the magnitude of the charge.

This equation represents two separate effects: the response of a charge to an electric field and the response of a moving charge to a magnetic field. When a magnetic field is applied to a moving charged particle, it experiences the Lorentz force.

Hall Effect in Semiconductors

The thin plate used in the creation of the Hall effect can be implemented in a CMOS process. This enables semiconductor companies to develop products based on the Hall effect.

Typically, the conducting plate is grown directly on the substrate by doping the silicon with different materials to create either N-type or P-type carrier regions. The doped region is then connected to the rest of the circuit with a metal vertical interconnect access (VIA).

The top view of a Hall-effect plate implemented on CMOS substrate is shown in Figure 2 (a). The cross section where there is N-epi doped silicon is shown in Figure 2 (b).

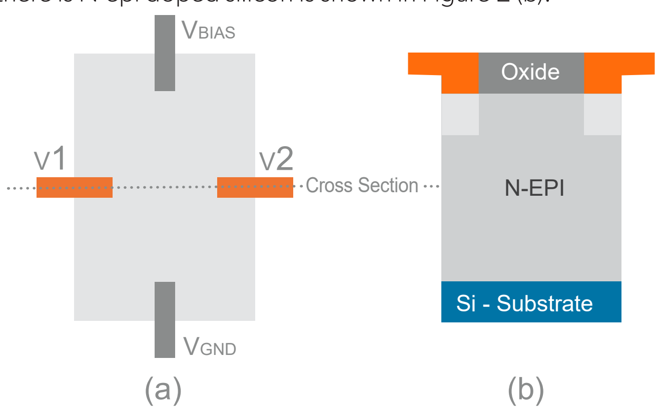

Figure 2: Cross Section of a Single Hall Element

Magnetoresistance

Magnetoresistance is the property of a device to change its electrical value under a magnetic field.

This effect is observed in ferromagnetic materials (materials that have magnetic properties). Metals like iron (Fe), nickel (Ni), and cobalt (Co) are ferromagnetic, while copper (Cu) is not. Changing the magnetization of the material affects how the electrons travel, altering the electrical resistance of the device.

Electron Scattering

Every electron has two key parameters: charge and spin. While every electron has the same charge of -1.602×10^{-19} C, an electron can have either an up-spin or a down-spin. This was experimentally proven in 1922, confirming that electrons possess an intrinsic angular momentum and a magnetic moment.

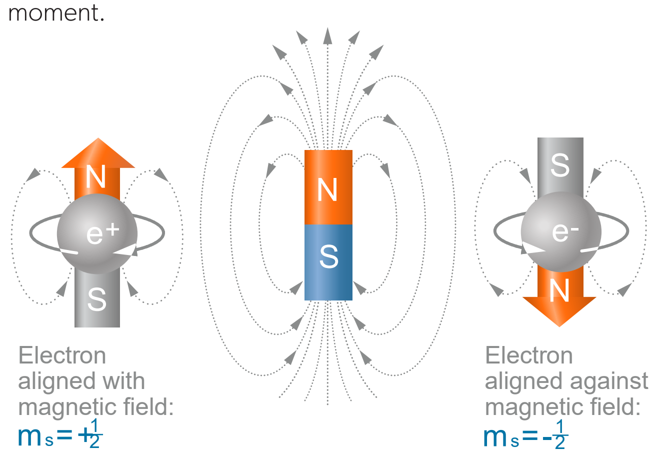

Figure 3: The Two Possible Spin Positions of an Electron

While the Lorentz force acts on the electrons due to their charge, the magnetoresistive phenomenon is due to the spin of the electrons.

When travelling inside a conductive material, electrostatic forces in the material can cause electrons to scatter or otherwise deviate from the normal trajectory.

The Lorentz force appears on a charged moving particle (i.e., electron) within a conductive material when subjected to a magnetic field. This force affects any particle with a charge and is independent of the spin direction of the electrons.

When electrons travel inside a ferromagnetic material (i.e., material with a certain magnetization), the spin of electrons (either up or down) increases or decreases scattering within the magnetized material. This is the origin of the magnetoresistance (MR) effect.

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AMR

The anisotropic magnetoresistance (AMR) effect was discovered in 1856 by William Thomson.

This effect can be easily demonstrated using a ferromagnetic material and a biasing current under an external magnetic field.

When the magnetization (M) is parallel to the current (I), the resistance reaches its maximum value as electronic orbits are perpendicular to current. This increases the spin-dependent scattering, thus increasing the electrical resistance. Conversely, when the magnetization (M) is perpendicular, the electronic orbits are parallel to the current. This reduces the spin-dependent scattering, thus leading to a lower resistance value.

Because of the simplicity and ease of CMOS integration of this phenomenon, multiple semiconductor companies employ this technology.

The biggest limitation of AMR technology is the MR effect itself, which typically limits the maximum and minimum values to a 5% change in resistance.

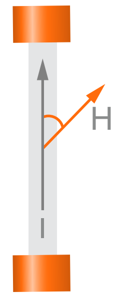


Figure 4: Single AMR Element

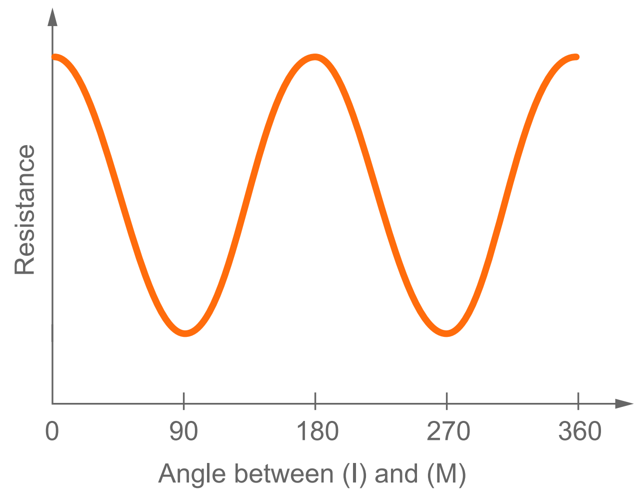


Figure 5: AMR Element Resistance Change Under Rotating Magnetic Field

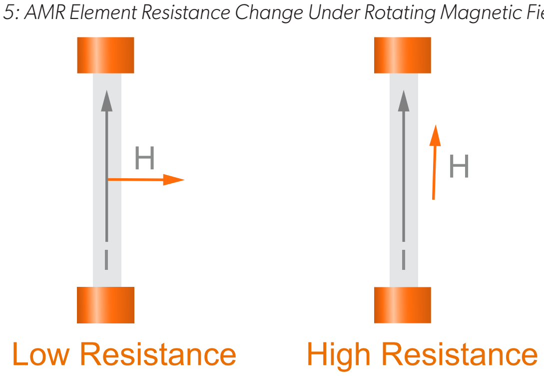


Figure 6: Two AMR Elements Under Different Magnetic Fields

GMR

Giant magnetoresistance (GMR) was first discovered in 1988 independently by Albert Fert and Peter Grünberg. Both were later awarded the Nobel Prize in 2007 for this discovery.

GMR is observed in thin-film structures composed of alternating ferromagnetic and nonmagnetic conductive layers.

The magnetization of both ferromagnetic layers impacts the spin-dependent scattering of electrons travelling inside the junction.

Electrons traveling through the ferromagnetic layer have a much weaker interaction when their spin directions are opposite to the magnetization of the material compared to when they are parallel to it.

GMR revolutionized hard drives by making the reading head smaller than the usual coil. This allowed for smaller storage magnets on the hard disk, leading to higher storage capacities.

However, like AMR, GMR is limited by the percentage change between high- and low-resistance states, typically approximately 20%.

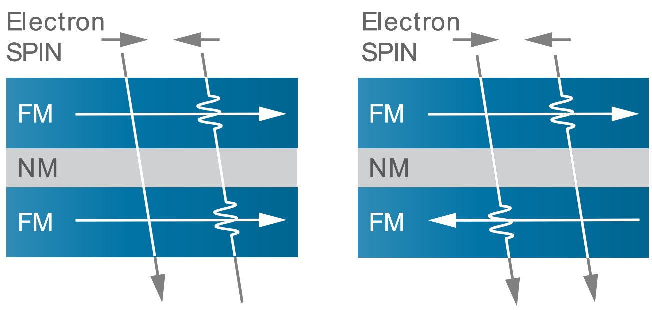


Figure 7: GMR Structures Showing Spin-Dependent Scattering

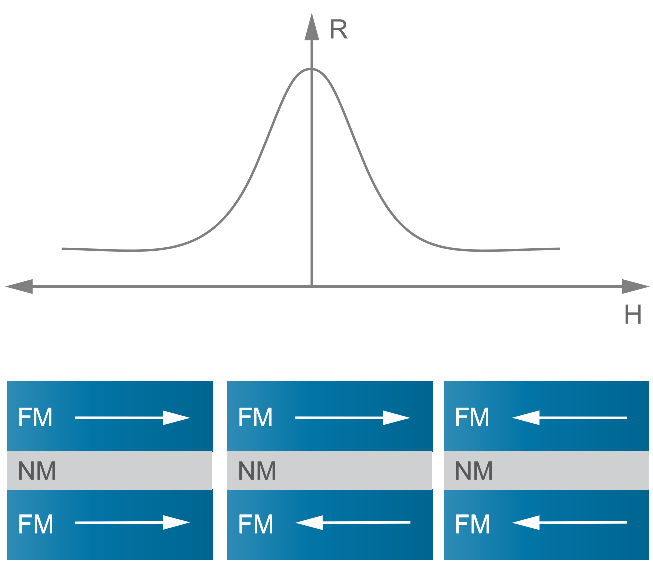


Figure 8: GMR Element Response Under Different Configurations

TMR

Tunnel magnetoresistance (TMR) was first discovered in 1991 by Terunobu Miyazaki. The main difference between GMR and TMR is in the nonmagnetic layer.

TMR requires extremely thin, nonmagnetic, nonconducting insulation between ferromagnetic layers. If the insulating layer is thin enough (typically a few nanometers), electrons can tunnel from one ferromagnet to the other. (Because this process is forbidden in classical physics, TMR is a strictly quantum mechanical phenomenon.)

The MR effect in TMR junctions can reach more than 100% in production. In lab conditions, levels upwards of 1,000% have been achieved.

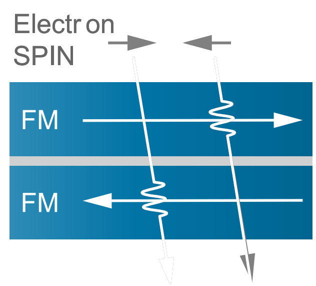


Figure 9: TMR Junction Showing Two Ferromagnets and a Tunnel Barrier

Signal Amplitude—MR Effect

TMR offers the best sensitivity compared to Hall, AMR, and GMR, as shown in Figure 10, which presents the change of resistance or the magnetoresistance when a rotating magnetic field is applied.

Another advantage that TMR (and GMR) offers compared to AMR is the ability of the magnetic junction to sense a 360° applied field. This enables a great advantage when designing an absolute angle sensor.

(Note that, to be able to show the sinusoidal signal of AMR, Figure 10 is not to scale. The percentages on the graph represent the change of resistance from R_{MIN} to R_{MAX} for every signal.

Another method to visualize the difference in sensitivity between the three main MR technologies is shown in Figure 11.

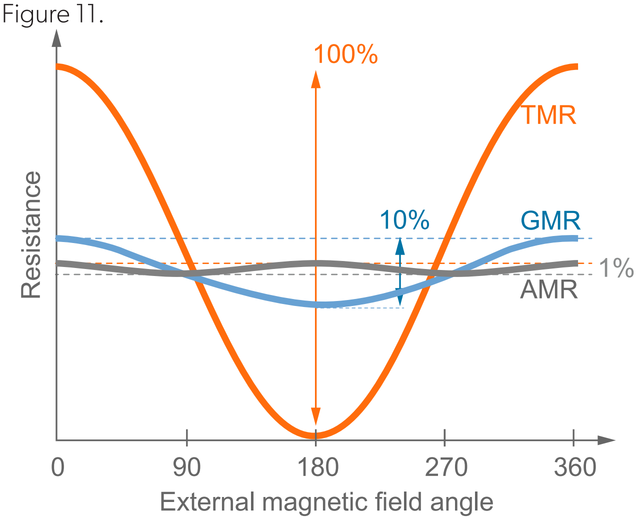


Figure 10: Signal Amplitude Comparison of AMR, GMR, and TMR (not to scale)

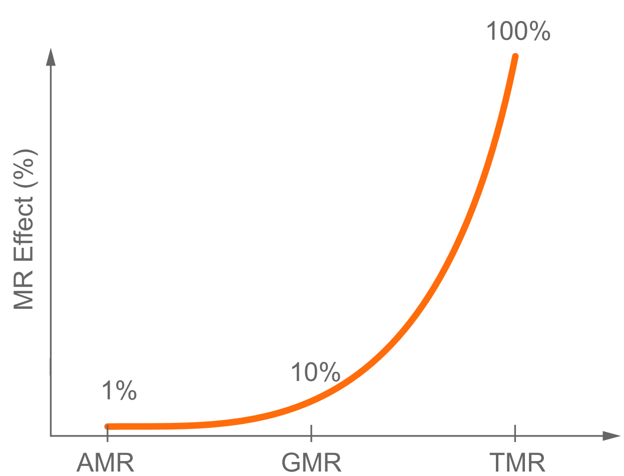


Figure 11: MR Effect Comparison

TMR FROM ALLEGRO

Many teams worldwide have demonstrated TMR junctions in their labs. However, very few companies have implemented this technology into full-fledged products. Allegro has done exactly this.

There are key aspects that differentiate Allegro TMR from other TMR-based products.

CMOS Process Agnostic

One advantage of Allegro TMR is that it is deposited during back-end-of-line (BEOL) processing. In contrast, Hall-effect sensors are deposited during front-end-of-line (FEOL) processing, taking precious space on the substrate. Allegro has also developed extensive expertise in depositing the TMR sensor between metal layers, especially dealing with mechanical stress over the junctions.

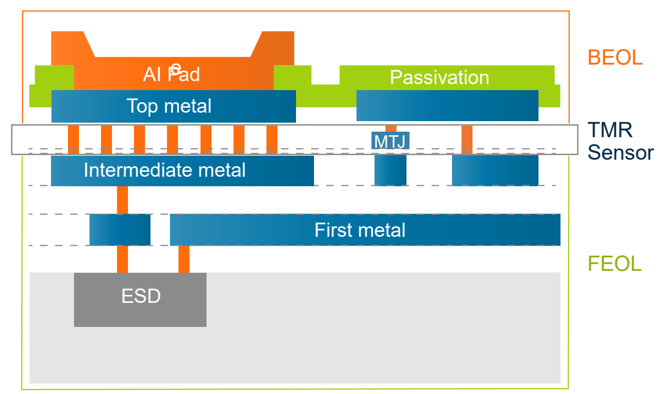


Figure 12: Typical CMOS Structure

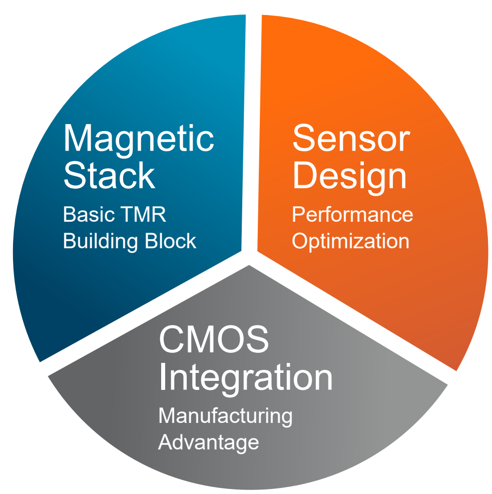
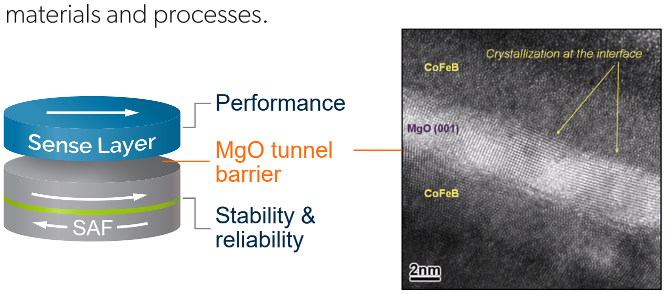


Figure 13: Why Allegro TMR Technology Excels

Magnetic Stack

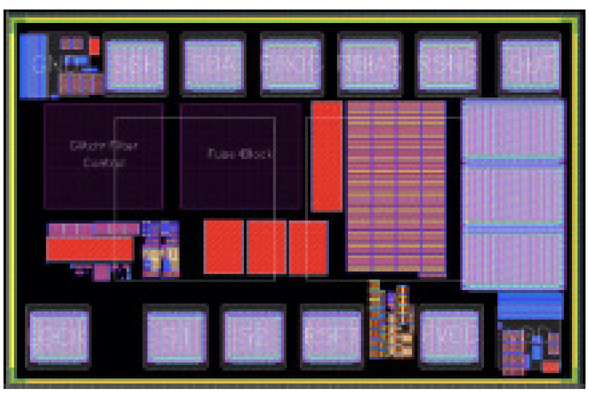
A magnetic TMR stack is expertly designed to provide the exact performance targets of the sensor, including sensitivity range, temperature drift characteristics, and reliability. A dedicated team at Allegro focuses solely on TMR development and continues to push the frontier by developing new materials and processes.

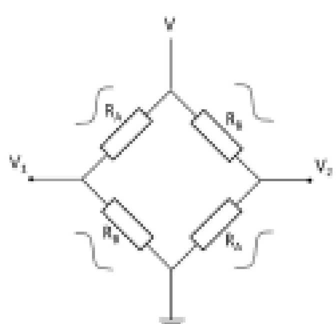


C. Park et al, JAP (2006)

Sensor Design

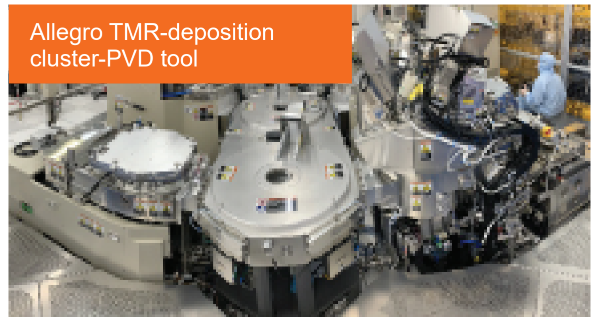
The sensor design leverages the magnetic TMR stack to build a half-bridge or a full-bridge structure using multiple interconnected stacks. This allows for enhanced temperature drift performance and reliability. It also delivers unparalleled noise optimization.





CMOS Integration

CMOS integration gives a decided manufacturing advantage to Allegro enabling monolithic, single-die products with integrated analog front end (AFE) to leverage the half- or full-bridge TMR sensor design using Allegro-proprietary circuit design and integration IP.



CONCLUSION

Allegro TMR offers superior performance and total cost of ownership compared to legacy magnetic sensors. Allegro TMR performance delivers low power consumption, high sensitivity, and low noise, while CMOS integration enables monolithic, single-die products for a competitive cost structure.

Revision History

Number	Date	Description	Responsibility
1	November 16, 2023	Document rebrand and minor editorial corrections	J. Henry