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.

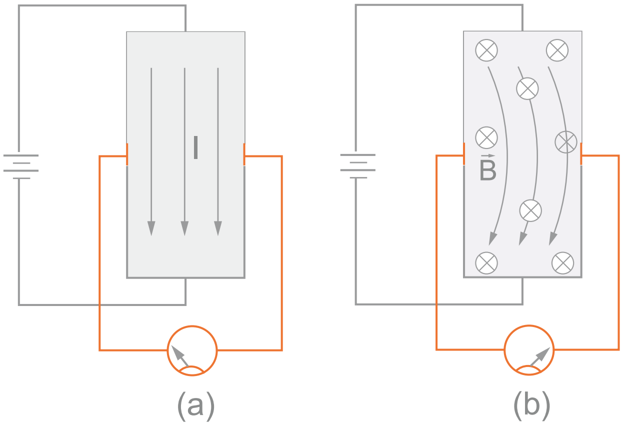

Figure 1: The Hall Effect in a Thin Plate

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).

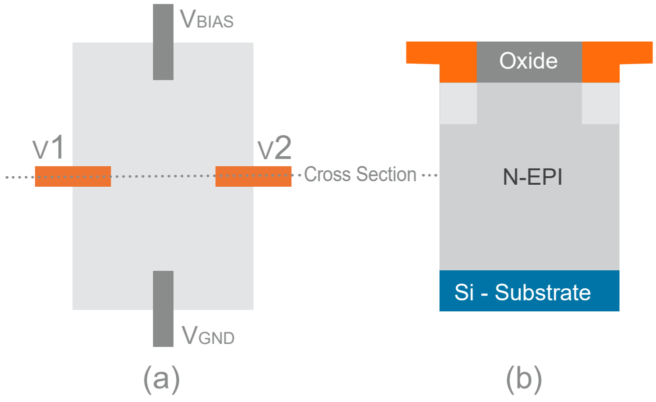

Figure 2: Cross Section of a Single Hall Element

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.

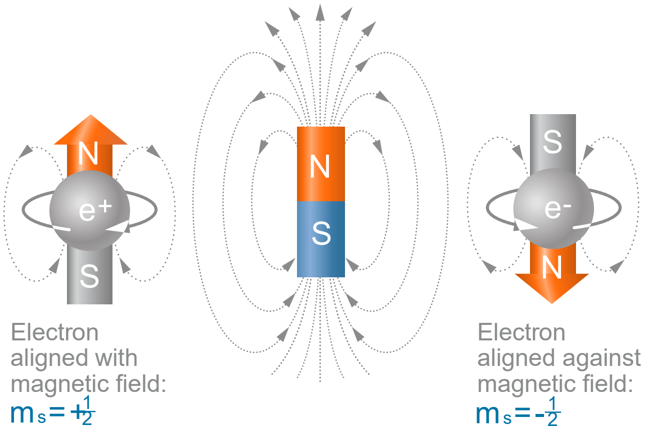

Figure 3: The Two Possible Spin Positions of an Electron

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.

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.

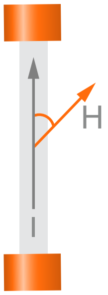

Figure 4: Single AMR Element

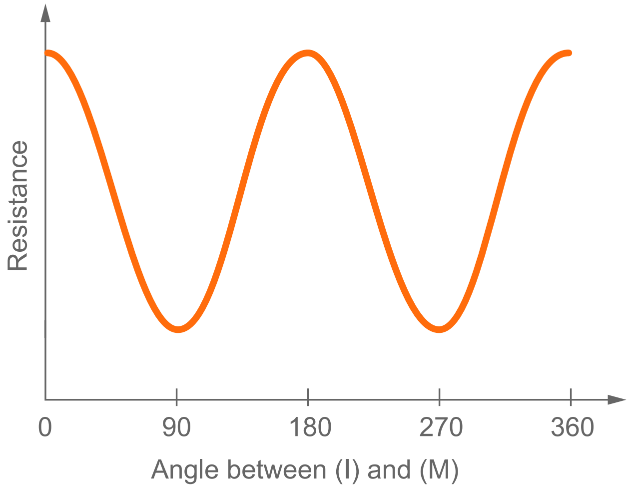

Figure 5: AMR Element Resistance Change Under Rotating Magnetic Field

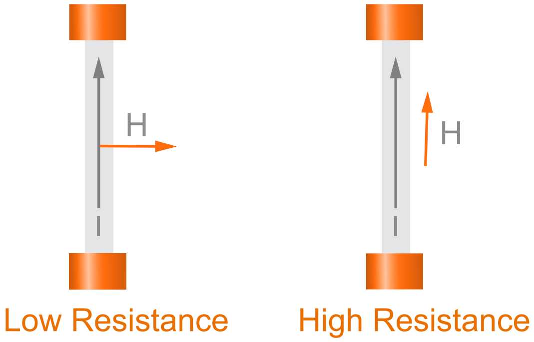

Figure 6: Two AMR Elements Under Different Magnetic Fields

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