THE EVOLUTION OF MAGNETIC SENSING TECHNOLOGY:
FROM HALL EFFECT TO TUNNELING MAGNETORESISTANCE (TMR)

As advanced products move into portable, battery-operated devices, leading manufacturers are looking to Tunneling Magnetoresistance (TMR) as today's leading magnetic sensor technology. Competing with yesterday's solutions, TMR inspires and empowers designers of emerging technologies requiring the lowest power consumption coupled with the highest sensitivity and the tiniest of size.

Solid state magnetic sensors have long been regarded as a highly-reliable solution for position sensing applications because these types of sensors are actuated by magnetic field flux; no physical contact is required. Due to that reliability, various advanced magnetic sensing technologies have materialized over the last 70+ years. Even today, Hall effect sensors continue to enjoy a healthy market share due to developed Si-based CMOS processes. However, with the emergence of so many exciting, new, innovative devices, design engineers are looking past Hall effect for a smarter sensor solution with lower power consumption, higher sensitivity, better accuracy, and stable performance. Developed decades ago, but only commercially available over the last 5-10 years, TMR delivers on those more advanced requirements; TMR-based sensors are fast becoming the new "rising star" technology expected to capture the market share currently enjoyed by Hall effect and lesser-used magnetic technologies.

The Hall Effect Sensor

The Hall effect was discovered by Edwin Hall in 1879. The modern Hall effect sensor is comprised of Hall cells and CMOS circuitry (preamplifier, regulator, comparator and FET). The Hall cell is the basic sensing component within the Hall effect sensor (Fig. 1a). Current, which moves through the Hall cell plane, will undergo Lorentz force while a magnetic field exists. A voltage difference – known as the "Hall Voltage" or (V_H) – will then be produced across the Hall cell plane (Fig. 1b).

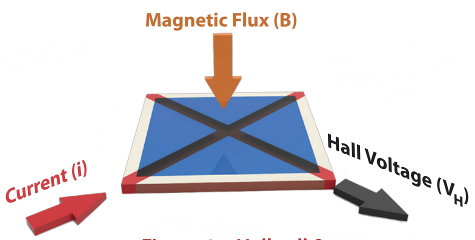


Figure 1a: Hall cell & Hall effect mechanism

$V_H = R_H * I * B / t$
V_H: Hall voltage
R_H: Hall effect coefficient
I: current
B: magnetic flux
t: Hall cell thickness

Figure 1b: Hall voltage equation

R_H is the Hall Effect coefficient and is determined by the Hall cell material. Over the last few decades, a Silicon-based Hall cell has been widely used to produce the Hall effect sensor. With the highly integrated CMOS process and subsequent drop in cost, the Hall effect sensor has long enjoyed a majority share of the magnetic sensor market.

In actuality, Silicon is NOT an ideal material to make a Hall cell due to its low R_H. The Hall voltage (V_H) of Si-based Hall effect sensors is typically only a few microvolts. Additionally, the offset voltage of Hall cell geometry and the piezoelectric effect during the assembly process makes it exceedingly difficult to achieve high accuracy, high sensitivity, or stability. Although various techniques such as chopper stabilization or dynamic offset cancellation have been developed to moderate offset voltage, these techniques make the power consumption of Hall effect sensors even higher. Sometimes, dual or quad Hall cells are designed to balance geometry offset voltage; dynamically-changed current direction is also used to minimize offset voltage (Fig. 2).

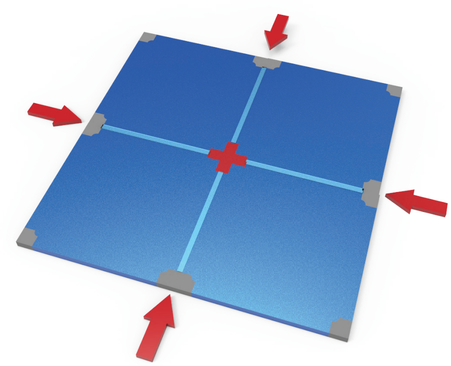


Figure 2: Quad Hall cell design & dynamic offset cancellation

With their inherent limitations, Hall effect sensors cannot meet the requirements of many of the newer, more demanding applications. In the late 1990's, "magnetoresistance" sensors (MR) began to enter the market. Different types of MR sensors, such as "anisotropic" MR (AMR) and "giant" MR (GMR) were developed specifically to improve upon the disadvantages of Hall effect sensors.

Finally, sometime during the first decade of the 21st century, TMR technology further developed as a solution to the new advanced requirements of modern devices. TMR sensing technology provides superior performance in power consumption, sensitivity, accuracy, and stability as well as tiny package size.

Tunneling Magnetoresistance

A tunneling magnetoresistance (TMR) sensor is comprised of a magnetic tunneling junction (MTJ) element and CMOS circuitry. A MTJ element is a multilayer, thin-film stack which is composed of a sandwiched structure with a free layer, a spacer layer, and a pinned layer. (Fig. 3) The spacer layer (made of dielectric oxide material) separates the ferromagnetic free layer and pinned layer from one another. The electrons moving within the free layer and pinned layer planes are unable to cross the spacer layer to the opposite side. However, if magnetic flux is applied to the MTJ, the magnetism direction of both ferromagnetic layers can be switched between anti-parallel and parallel orientation. In the parallel magnetism orientation, electrons can make a quantum leap to tunnel through the spacer layer; a tunneling current will be observed across the MTJ structure and the relative resistance of the MTJ will be changed between high resistance and low resistance.

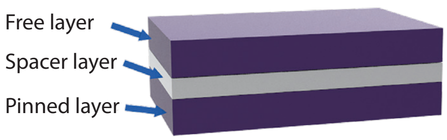
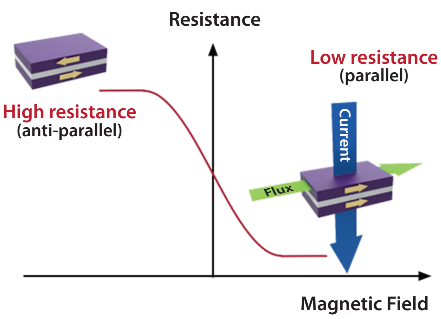


Figure 3: Magnetic tunneling junction (MTJ) structure

The difference of relative resistance is the "TMR ratio" (Fig. 4). TMR ratio can reach approximately 40% at room temperature, and it is comparatively larger than other MR technologies. This feature, which is a implementation of quantum physics, makes the ingenious TMR sensor possible, with higher sensitivity, lower power consumption, and more stable characteristics.



TMR ratio = $(R_{ap} - R_p)/R_p$
R_{ap}: resistance of anti-parallel orientation
R_p: resistance of parallel orientation

Figure 4: Tunneling magnetoresistance mechanism & TMR ratio formula

Comparison

Both Hall effect and TMR are highly compatible with modern CMOS technology. Both are readily available with monolithic TMR sensors (such as Coto Technology's RedRock™ series TMR magnetic sensor) now attainable in the market. However, for certain applications, TMR technology has obvious advantages over Hall effect - especially for battery-powered systems. Below is the table (Figure 5) comparing the two technologies. TMR offers definite advantages such as smaller package size, lower power consumption, better thermal stability, better resolution and higher sensitivity. Amazingly, TMR provides 1000 times more sensitivity than Hall effect while consuming only a few micro ampere current. With its uniquely positive features, the TMR sensor has the potential to replace Hall effect sensors in most applications.

	Hall Effect	TMR
Structure	Hall cell + CMOS	MTJ + CMOS
Sensing Orientation	Perpendicular	In Plane
Field Sensitivity (mV/V/Oe)	~0.05	~20
Power Consumption (mA)	5~10	0.001~0.01
Chip Size	Medium	Small
Package Size	Small	Smallest
Thermal Stability	Medium	High
Thermal Range (ºC)	~150	~200
Switching Speed	High	High

Figure 5: Hall Effect vs. TMR Comparison

Figure 6 (see page 3) compares the magnetic characteristics between a commercial Hall effect sensor and Coto's RedRock™ series TMR sensor. Coto's RedRock™ TMR sensor outperforms the Hall effect sensor on the sensitivity distribution range; as this is accomplished through high TMR ratio, controlling sensor characteristics becomes easier. In other words, Coto's RedRock™ series TMR sensor can not only deliver high sensitivity and low power consumption, but the quality is extremely consistent part-to-part.

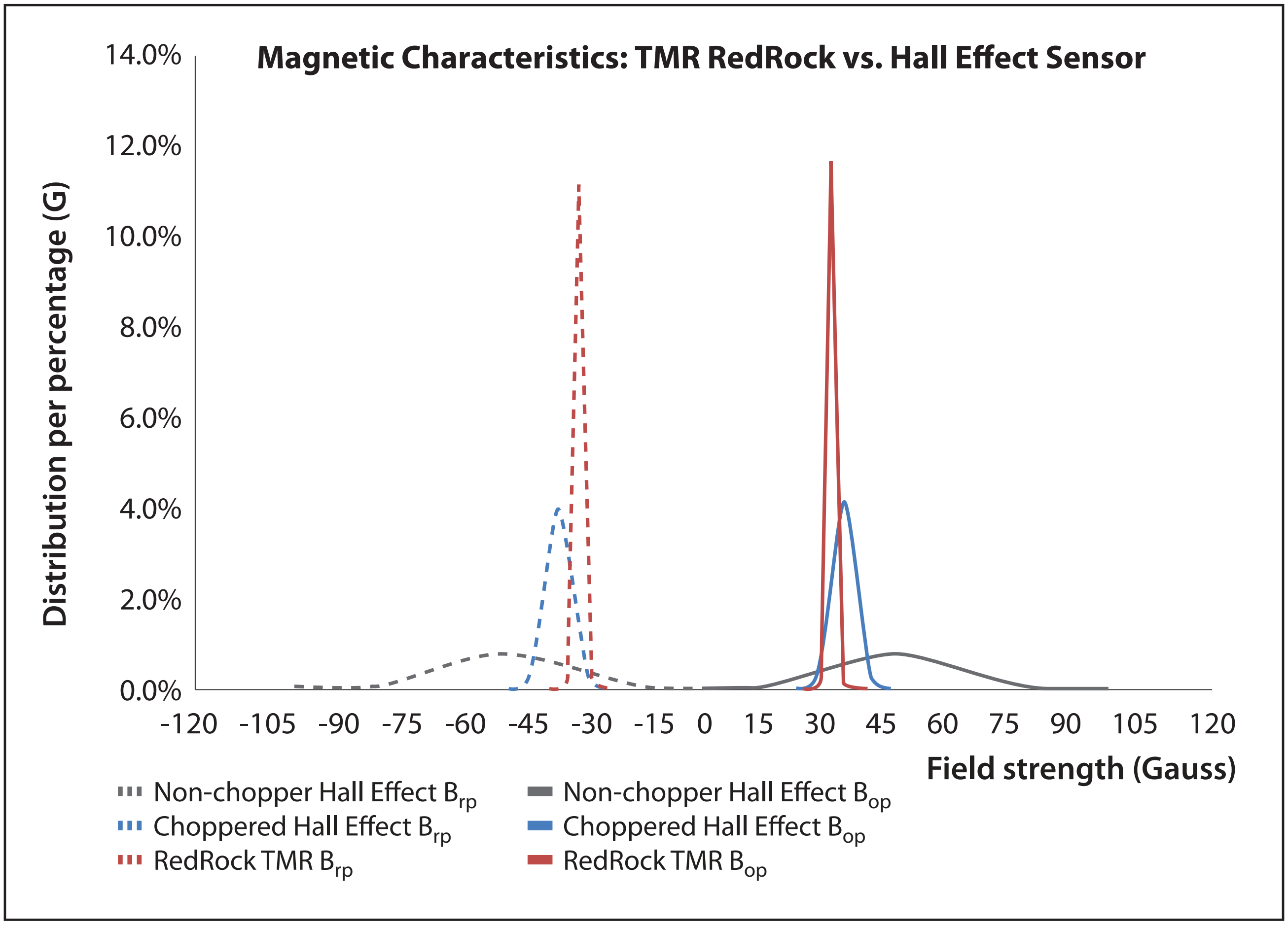


Figure 6: Magnetic characteristics comparison between Hall effect and RedRock TMR sensors

Conclusion

Tunneling Magnetoresistance represents a huge leap in technology as compared to the now-dated Hall effect. As investments continue to accelerate in advanced devices within the medical, industrial and consumer markets, electronic engineers are searching for more sophisticated components that will help them reach the next milestone in the development of products that will both perform and delight. TMR sensors are now becoming the new go-to solution to drive the advanced precision, consistency, high sensitivity, low power consumption, and tiny package size required for tomorrow's advanced devices.

For more information about Coto Technology and its RedRock™ Series TMR magnetic sensor products, visit ***www.cotorelay.com*** *or email* ***appsupport@cotorelay.com.***

