Invented for life

BOSCH

White Paper

Using TMR technology for precision sensing: advancing magnetic sensor performance

A variety of use cases is benefiting from TMR magnetometers. Find out more from page 5.

Table of contents

Executive summary

The magnetic sensor market is at a pivotal point. With the increasing demand for precise, energy-efficient, and compact sensing in consumer electronics, automotive, and industrial applications, traditional magnetometer technologies such as Hall Effect, AMR, and GMR are no longer sufficient for the next generation of devices.

Tunnel Magnetoresistance (TMR) is emerging as a disruptive technology, delivering superior sensitivity, significantly lower power consumption, and greater robustness. This white paper explores the evolution of magnetic sensing technologies, highlights the limitations of legacy approaches, and presents TMR as the transformative alternative. We also examine the Bosch Sensortec BMM350 as a real-world implementation of TMR, demonstrating its potential in enabling new applications and elevating performance standards.

Market evolution and the rise of TMR

According to Yole Group, the global magnetic sensor market is projected to reach nearly $4 billion by 2029[1], driven by the proliferation of smart consumer electronics, electric vehicles, and industrial automation. Devices in these sectors require increasingly compact, power-efficient, and precise sensing capabilities. This market pressure has led to both cost reduction and significant performance improvements across magnetic sensor technologies. In general, a magnetometer is a device that measures a magnetic field or magnetic dipole moment. Different types of magnetic sensors measure the direction, strength, or relative change of a magnetic field at a particular location. A compass is such a typical device, which measures the direction of an ambient magnetic field, in this case, the Earth's magnetic field.

Hall sensors have dominated this market due to their low cost and manufacturing maturity. However, they are reaching the limits of their performance capabilities—particularly in accuracy, noise levels, and power efficiency. Similarly, AMR and GMR sensors offer some improvements but introduce challenges such as packaging complexity, sensitivity limits, and higher current demands.

As new applications in AR/VR, indoor navigation, and wearables demand better performance and integration, the market is shifting toward more advanced sensing technologies. TMR has emerged as the most promising candidate, offering breakthroughs in both efficiency and functionality.

The magnetometer landscape: limitations of legacy technologies

Hall effect sensors

The Hall sensor has long enjoyed considerable market share, owing to its well-developed and low-cost production. A Hall effect sensor is an electronic device that is designed to detect the Hall effect, and convert its findings into electronic data, either to switch a circuit on and off, provide a measurement of a varying magnetic field, or be processed by an embedded ASIC in a sensor package.

The Hall effect means that if a magnet is placed perpendicular to a conductor with a steady flow of current, the electrons flowing within the conductor are pulled to one side, thus creating a potential difference in charge (i.e. voltage). The Hall effect, then, is indicative of the presence and magnitude of a magnetic field near a conductor.

[1] https://www.yolegroup.com/product/report/magnetic-sensors-2024/

This movement of charge carriers is a result of the magnetic force they experience passing through the semiconductor material. The output voltage, called the Hall voltage, (VH) of the basic Hall Element is directly proportional to the strength of the magnetic field passing through the semiconductor material (output $\propto$ H).

Hall sensors exhibit relatively low sensitivity, require higher currents to function reliably, and tend to suffer from high noise levels and offset errors. Their temperature stability is also inadequate for many emerging applications, particularly those demanding reliable performance across wide environmental ranges. These limitations make Hall sensors increasingly unsuitable for advanced consumer devices or industrial-grade applications where precision, stability, and efficiency are critical.

AMR and GMR sensors

Anisotropic magnetoresistance (AMR) sensors, discovered in 1856 but first used commercially in 1971, offered improvements over Hall sensors. Magnetoresistance (MR) is the change in electrical resistance of a conductor caused by a magnetic field. AMR sensors utilize the change in electrical resistance due to the angle between the direction of electric current and magnetization in a thin magnetic film. However, the magnetoresistance ratio is typically below 5%, and they often require additional circuits or permanent magnets to reset the magnetization of the thin film after usage, which complicates packaging and raises the cost.

GMR (giant magnetoresistance) sensors, on the other hand, use layered structures where electron spin influences conductivity. While GMR sensors improved the MR ratio to about 10%, their performance is still hindered by material and structural limitations. These sensors are more sensitive than AMR, but they consume more power and are less thermally stable than desired in modern applications.

Despite these improvements over Hall sensors, both AMR and GMR technologies are ultimately constrained by limited MR effects and are inadequate for applications requiring ultra-low noise, higher accuracy, and minimal energy consumption.

Enter TMR: a new benchmark for magnetic sensing

Today, the magnetometer market is evolving, due to TMR magnetic sensor technology which is more accurate, and has lower noise and current consumption than the previous magnetometer technologies. Originally discovered in 1975, the TMR effect is based on an arrangement that is comparable to the GMR effect.

In contrast to GMR with a non-magnetic layer, for TMR a non-conductive intermediate layer is sandwiched between two magnetic layers. It occurs in a magnetic tunnel junction (MTJ), which is a component comprising of two ferromagnets separated by a thin insulator.

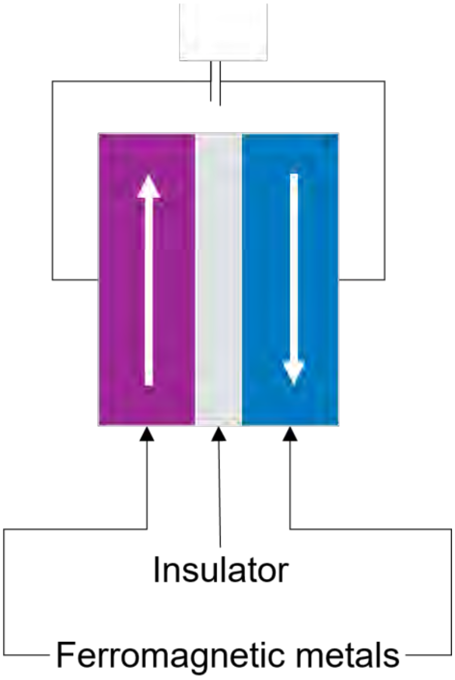

Figure 1: Schematic TMR arrangement of ferromagnetic layers with insulating intermediate layer (Image: Bosch Sensortec)

If the insulating layer is thin enough (typically a few nanometers), electrons can tunnel from one ferromagnet layer into the other one through the tunnel barrier. The tunneling probability is also spin-dependent, which leads to high MR values for parallel vs. antiparallel magnetization of the spins in the magnetic tunnel junction layers. Materials with fully spin-polarized electrons should show the greatest effects.

The direction of the two magnetizations of the ferromagnetic films can be switched individually by an external magnetic field. If the magnetizations are in a parallel orientation it is more likely that electrons will tunnel through the insulating film than if they are in the oppositional (antiparallel) orientation. Consequently, such a junction can be switched between two states of electrical resistance, one with low and one with very high resistance.

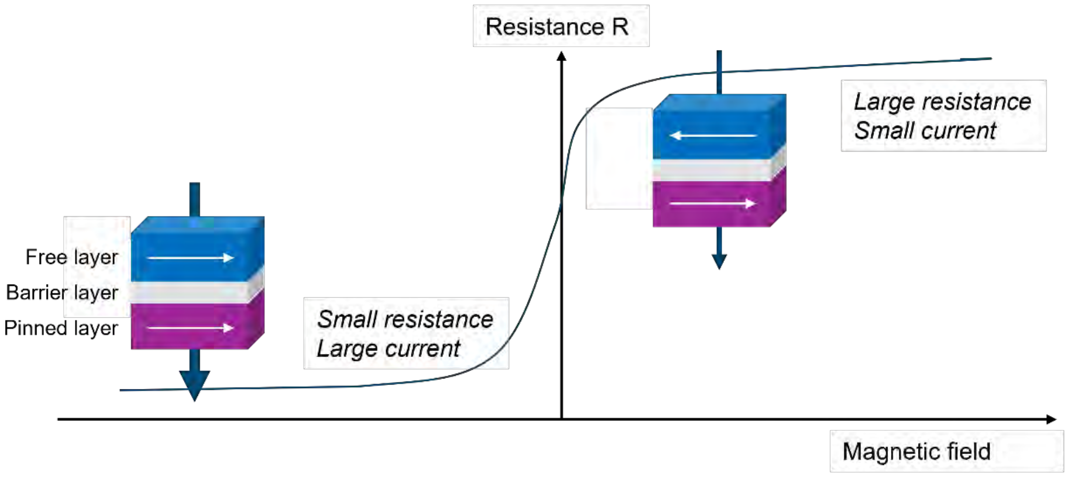

Figure 2: Principle of TMR effect (Image: Bosch Sensortec)
Left: when the magnetization directions of the free layer and pin layer are parallel, the resistance becomes small and a large current flows. Right: when the magnetization directions of the free layer and pin layer are antiparallel, the resistance becomes large and only a weak current flows.

This MTJ configuration allows TMR sensors to achieve extremely high MR ratios—often exceeding 100%. This is significantly higher than GMR (~8–10%) and AMR (~2–5%). Moreover, because TMR relies on spin-dependent tunneling rather than metallic conduction, the signal output is more binary-like (i.e., distinct high and low states, such as “1” or “0”), enhancing reliability in digital applications.

TMR sensors exhibit unmatched performance across key metrics. Below is a comparison highlighting the significant advantages of TMR over older technologies:

	TMR	**GMR**	**AMR**
Magnetoresistance effect *(%)*	> 100	8	2
Sensitivity	Ultra-high	Very high	High
Current consumption at 100Hz (µA)	200	280	3400

Why TMR matters: core advantages

TMR sensors bring several key advantages that position them as the leading technology for modern magnetic sensing requirements. These benefits are particularly valuable for applications that demand precision, efficiency, and reliability in compact, energy-constrained environments.

1. High Sensitivity and Accuracy: With MR ratios greater than 100%, TMR sensors can detect even the smallest magnetic field changes, and they also offer excellent linearity over a wide magnetic field range. This allows for highly accurate position, current, and motion measurements in both static and dynamic environments.

2. Ultra-Low Power Consumption: TMR sensors are optimized for energy efficiency, with typical current consumption as low as 200 µA at 100 Hz—making them ideal for always-on battery-powered applications like wearables, AR/VR, and IoT devices.

3. Temperature Stability: TMR elements maintain performance over a wide temperature range, often from sub-zero conditions to 125°C. This is crucial for automotive and industrial deployments where environmental variability is the norm.

4. Noise Immunity: Compared to Hall, AMR, and GMR sensors, TMR sensors demonstrate significantly lower noise levels, enabling clearer signal detection and improved performance in low-frequency applications. This can be critical for applications measuring ultra-weak magnetic fields, such as biomagnetism (e.g., magnetocardiography - MCG), and high-resolution linear position sensing.

5. Robustness and Reliability: Bosch Sensortec's TMR sensors include features like field shock recovery, making them resilient to magnetic field disturbances and enhancing measurement stability.

6. True 360° Sensing Capability: Like GMR, TMR technology can inherently sense magnetic fields in a 360° range, which is an advantage over AMR that typically has a more limited sensing angle. This facilitates the design of absolute angle sensors, as used in rotary encoders for motors and robotics.

7. Integration and Miniaturization: The compact nature of TMR components allows seamless integration into devices where space is limited, without sacrificing sensing capability.

Real-world applications of TMR sensors

Magnetic sensors are used in a wide variety of applications, ranging from industry and automotive technology to consumer electronics. In wearables, hearables, and smartphones, TMR magnetometers enable advanced functionalities like head tracking and orientation detection. When fused with inertial measurement units (IMUs), they compensate for gyroscope drift, essential for 3D audio experiences. In AR/VR systems, TMR sensors help reduce pixel latency, improve immersion, and reduce user discomfort by providing accurate and stable orientation data.

TMR sensors are well-suited for electric bicycles and vehicle systems, where they serve as wheel speed sensors using a back-bias magnet or encoder wheel. They also excel in current measurement for power electronics and battery systems, offering better linearity and sensitivity than Hall or AMR sensors, while operating with lower power and greater stability.
In industrial automation and robotics, TMR sensors provide highly accurate position and angle measurements. Their low power operation is critical in remote sensing applications such as smart meters, building automation, and predictive maintenance systems. Their immunity to electromagnetic interference also enhances reliability in harsh industrial environments.

Here are some specific use cases benefiting from TMR:

- High-Precision Current Sensing: Measuring small currents accurately in power supplies, motor controls, and battery management systems. TMR can also be combined with Hall sensors for extended range current sensing (TMR for low currents, Hall for high currents).

- Precise Linear and Angular Position Sensing: Applications in automotive (steering, pedal position), industrial robotics (joint angle, end-effector position), and machine tools requiring high accuracy and repeatability.

- Low-Power Magnetometers for Portable Devices: Compass functionality in smartphones and tablets, Hall-effect replacements in flip covers, and other battery-operated sensors. The low power of TMR sensors enables ‘always on’ sensing, for example to provide location information for smartphones to avoid delays when making an emergency call.
- High-Sensitivity Magnetometers for Weak Field Detection: Biomagnetic measurements (MCG) to enable highly accurate sensing and location of problems, geological surveys, and detection of subtle magnetic anomalies.
- Advanced Driver Assistance Systems (ADAS): Highly accurate steering angle sensors and wheel speed sensors for enhanced safety features like ESP.
- Industrial IoT and Smart Sensors: Low-power, high-accuracy magnetic sensors for various monitoring and control applications.
- Virtual and Augmented Reality (VR/AR): Precise head orientation tracking for improved immersion and reduced motion sickness.
- 3D Audio: Head orientation detection for spatial audio experiences.
- E-bikes and Vehicle Positioning/Speed Detection: Accurate and reliable speed and position sensing.

While TMR technology offers these significant advantages, it's important to note that the "best" magnetometer technology depends on the specific application requirements, including cost, bandwidth, magnetic field range, and environmental conditions.

Hall effect sensors, for example, may still be preferred for high dynamic range current sensing at a lower cost, while fluxgate magnetometers might be chosen for extremely low field measurements where size and power are less critical. However, TMR is increasingly becoming the technology of choice for applications demanding high sensitivity, low power, and accuracy in compact form factors.

Proof point: Bosch Sensortec’s BMM350

Bosch Sensortec’s BMM350 exemplifies the high-performance potential of TMR technology. As a 16-bit 3-axis magnetometer, it leverages the core benefits of TMR to deliver ultra-low power consumption, exceptional sensitivity, and robust magnetic field resilience. The BMM350 is housed in a wafer-level chip-scale package (WLCSP) measuring just 1.28 × 1.28 × 0.5 mm. Despite its size, it consumes only 200 µA at a 100 Hz data rate, which is 94% lower than typical AMR sensors and 80% lower than standard Hall sensors.

Its superior noise performance—over 70% lower than Hall sensors on the x/y axis—and 100x better sensitivity compared to AMR or Hall sensors make the BMM350 suitable for a wide range of next-generation applications. Moreover, it includes a patented ‘field shock recovery feature’, ensuring high measurement accuracy even in the presence of transient, external magnetic fields – which are all around us, such as from the magnets in in a smartphone’s loudspeaker. This feature is a reset function: by sending current through the sensor, it enables calibration back to a known reference point.

Applications for the BMM350 span wearable and hearable devices, smartphones, AR/VR headsets, and mobility solutions like e-bikes. It provides improved head orientation tracking, indoor positioning, speed measurement, and even precise current sensing in compact, power-sensitive designs.

Future outlook: TMR as an enabling technology

As digital devices continue to integrate more sensing capabilities, the demands on sensor precision, stability, and energy efficiency will only grow. TMR stands out not merely as an evolutionary step, but as a foundational leap. It enables more accurate, low-noise, and energy-efficient data acquisition—powering smarter, context-aware applications at the edge. TMR technology's compatibility with modern semiconductor manufacturing and its potential for further miniaturization make it a key enabler for future applications in AIoT, smart health devices, connected mobility, and beyond. With continued innovation in materials and integration techniques, TMR will likely outpace legacy magnetic sensing technologies across nearly every performance vector.

Bosch Sensortec’s BMM350 demonstrates the real-world viability of TMR, combining cutting-edge performance with the reliability required by OEMs and developers. As demands for smarter, smaller, and more efficient devices continue to rise, TMR will play an increasingly central role in enabling high-performance sensing across a wide range of markets.

Bosch Sensortec GmbH
Headquarters

Gerhard-Kindler-Strasse 9
72770 Reutlingen, Germany
Telephone +49 (0) 7121 3535-900