TMR: A New Frontier for Magnetic Sensing

Christophe DURET*  
Shintarou UENO*

We present here a new linear magnetic sensing technology, based on Tunnel Magneto Resistance (TMR). The TMR principle derives from Spintronics, a new branch of Physics which received the 2007 Nobel Prize in Physics. Contrary to “traditional” electronics, a Magnetic Tunnel Junction (MTJ) uses not only the electric charge of the electron, but also its quantum spin value.

During the CAMEL project, we have designed MTJs for sensor applications, i.e. for having, compared to other existing technologies, greater performances, extended working ranges and design capabilities, the robustness needed for harsh mounting and working conditions and of course a cost compatible with a market introduction. The fascinating properties of the TMR sensing elements we have developed open the door to many new possibilities of magnetic sensing.

1. NTN-SNR magnetic sensing technology

1.1 Bearings with active sensor ASB®
NTN-SNR has developed the active sensor bearings, ASB®, the technology for detecting wheel speed used for Antilock Brake System (ABS) and Electronic Stability Program (ESP) for vehicles, as shown in Fig. 1. The ASB®, which helps in reducing the weight and space of vehicles and improves the robustness and zero velocity detection in the severe conditions, is a defacto global standard for detecting wheel velocity in the automobile industry. The following shows the configuration of an ASB®:

- **Target magnet**: Multi-pole ring magnet integrated with the bearing seal. It generates an alternating magnetic field with frequencies proportional to the rotational speed of the wheel.
- **Detection device**: This uses the magnetoresistance effect or Hall effect. It measures the alternating magnetic field that the target magnet generates with no contact and calculates the wheel rotation speed to be used by the ABS and ESP.

1.2 Development and applications of high-resolution rotation sensor MPS40S
After the development of the ASB®, continuing with the research of a low-cost sensor for accurately detecting angles of rotation and for controlling rudder angle of the steering wheel and electric motor, we developed the special-purpose IC MPS40S 1) with a built-in Hall effect device and signal processing circuit. As shown in Fig. 2, MPS40S is applicable for a wide...
range of pole widths, has the capability of outputting high-resolution pulse signals and origin position signals, and satisfies the quality standard AEC-Q100 as the electronic device for automobile use.

MPS40S is also targeted at industry machines such as the rotational control of servo motors. Fig. 3 shows the high-resolution sensor bearing with origin signal output, which integrates MPS40S and bearings for improving ease of assembly with target equipment.

As an application of MPS40S, Fig. 4 shows a high-precision magnetic angle sensor, which detects the absolute angle using the Vernier principle. This sensor is applicable to tubular shafts, where the existing sensors shaft end placements was not applicable. By integrating the multi-pole ring magnet and the bearing rotating ring and placing the detection device with a built-in signal processing circuit to the fixed ring, the axial space adjustment is not required when assembled. The absolute angle can be accurately measured even in high-speed rotation. This is done by setting the dedicated multi-pole ring magnet, which has two rows of concentric magnetic patterns with a different number of magnetic poles inside and outside, and calculating the relative displacement of the patterns from the magnetic sensor signals.

2. Characteristics of various magnetic sensors

In order to apply magnetic sensing technology to a wide range of applications, it is necessary to consider basic performance of magnetic detection sensors (such as output accuracy, frequency bandwidth, and power consumption), as well as operation range against air gap and temperature, size of the sensor, installation allowance, robustness, and cost. Sensors in severe operating environments such as automobile and industrial machine applications typically use the Hall device, anisotropic magnetoresistance (AMR) device, and giant magnetoresistance (GMR) device for magnetic field detection. The following shows their respective characteristics:

- **Hall device**
  It is of very good linearity and is inexpensive. On the other hand, it has limited sensitivity and large power consumption and offset drift.

- **AMR element**
  It has better sensitivity than the Hall device and the hysteresis is small. Linearity, offset-free operation, and high magnetic field detection can be achieved by a barber pole sensor structure, flip driving method, and arranging a stabilizing magnet. However, in a high-temperature environment, slight deterioration of sensitivity and linearity is observed.
• GMR element
It has the highest sensitivity and widest permissible range of input magnetic field strength. However, the performance, such as linearity, significantly deteriorates as soon as the temperature or input magnetic field strength exceeds the operating range.

3. Tunnel Magneto Resistance (TMR) effect
The basic theory of the MTJ element is based on spintronics that uses the quantum spin condition in addition to the electric property of the electron based on the existing electronics theory. When Pr. A. Fert and Pr. P. Grünberg received the Nobel Prize in Physics in 2007, Spintronics attracted immediate attention.

As shown in Fig. 5, the MTJ element generally has the structure of an insulation layer of aluminum oxide (Al₂O₃) or magnesium oxide (MgO) in the middle of two stacked ferromagnetic layers, similar to a GMR element. With the MTJ element, the current flows vertically through these layers while the electrons in a ferromagnetic layer pass through the insulator by quantum-mechanical effect and are injected to the other ferromagnetic layer by the tunneling effect. In this case, the electric resistance to the current changes significantly depends on the relative angular difference of the magnetized direction of two ferromagnetic layers. When the magnetized direction of two layers is antiparallel, it indicates high resistance, and when it is parallel, it indicates low resistance. That is, the resistance changes depending on the relative angle of magnetization direction of two layers. This phenomenon is called the Tunnel Magneto Resistance (TMR) effect. In order to detect an external magnetic field using this effect, the device is configured keeping the magnetized direction of one ferromagnetic material layer (called fixed or pin layer) fixed and allowing the magnetized direction of the other ferromagnetic material layer (called free layer) to change depending on the external magnetic field.

The TMR effect under low temperature was discovered in 1975; however, it did not attract attention, at that time, as the application was difficult. However, in 1995, when a change of almost 20% of magnetic resistance was achieved (the maximum value at that time) at room temperature in the low magnetic field, the TMR effect was immediately placed under spotlight.

A recent research reports that using crystalline MgO (100) for the insulation layer as an alternative to amorphous Al₂O₃ yields very high magnetoresistance change of about 600% in room temperature. While the TMR effect has been recently used in the hard disk read head, application development for magnetoresistance memory (MRAM) for read/write of quantum information of 0 and 1 and for magnetic sensor has just begun. Also, in order to apply the MTJ element to a magnetic sensor, the resistance needs to be changed depending on the external magnetic field strength and direction, as opposed to the MRAM and hard disk head.

4. CAMEL Project
NTN-SNR has been focusing on the research and development of the TMR effect since 2000, and has filed several patents such as laminated structure of the MTJ element and sensor structure. It also accelerated technology development and application from 2005 to 2010 in the CAMEL (CApteur Magnétique à effet tunnEL) project. Sponsored by the French National Research Agency (ANR), the project was conducted as an academic-industry partnership of NTN-SNR (end-user project leader), Sensitec (making of MTJ element), and two public research institutions.

The project established the MTJ element aimed at sensor applications and linear magnetic sensing technology. It evaluated how they would adapt to the production and high-volume production using the existing production line of AMR/GMR elements owned by Sensitec. An example of the linear magnetic...
sensing using the TMR effect is shown in Fig. 6. As shown in the graph to the right, it was determined that the measured result mostly matched with the linear approximation and the hysteresis was sufficiently small.

In addition, this project received the Yves Rocard prize in 2010 from the French Physics Society for its achievement in advancing the basic technology to practical utilization.

Fig. 6 Example of transfer curve for a MTJ with the following structure

---

5. State-of-the-art magnetic sensing using the TMR effect

The following discusses important properties of the sensor using the TMR effect (hereafter, “TMR Sensor”), which was developed applying this technology. The details of the structure and test results are omitted in this paper. For more information, refer to the references (17) (18) (19).

5.1 Basic performance

1) Low power consumption

The power consumption of the TMR Sensor is 1/100th of the AMR sensors and 1/1000th of the Hall sensors (19), since the internal resistance of the MTJ element is high. Even when the peripheral signal processing circuits are considered, the power consumption is still sufficiently low which enables long operation over the system product life with small batteries or energy harvesting devices. Therefore, it is expected to be used in self-supported wireless sensors. As an example, a comparison image of the number of button cells required for six-month continuous operation is shown in Fig. 7.

Fig. 7 Power and Cost comparison of an AMR and a TMR sensor after 6 months of continuous use
2) High detection accuracy

The sensor detection accuracy is determined by the combination of linearity, hysteresis property, sensitivity, and S/N ratio. The newly developed TMR sensor has the following characteristics compared to the sensors using the existing AMR/GMR/Hall devices.

The linearity of a Hall sensor for detecting high magnetic field and the hysteresis property of an AMR/GMR sensor for detecting low magnetic field are both at a very high level. However, they are not always good across all the properties because they exhibit both advantages and disadvantages. On the other hand, the TMR sensor exhibits a high level of performance across all the properties compared to other sensors, and thus, it can be used for detecting a wide range of magnetic fields. Also, it is possible to verify the position sensing accuracy by the evaluation kit discussed in the next Chapter.

When used for detection of absolute angles, the AMR sensor can only detect a range of 180° of external magnetic field, while the TMR sensor can detect a range of 360° (one full rotation). The TMR sensor can be applied to angle detection placed on the shaft end by using its superior properties of wide-range of input magnetic field strength, good linearity, and low hysteresis.

For magnetic detection sensitivity, although the performance of SQUID⁵ is superior, it is proven that the 1/f noise and thermal noise of MTJ element can be reduced to the $\text{ln}T/\text{Hz}^{1/2}$ level. This implies realization of high spatial resolution and low cost for medical and non-destructive test applications⁶.

5.2 Operating range

1) Wide operating temperature range

In high-temperature life test, it is confirmed that there is no atom diffusion within the MTJ element even in high temperature of over 150°C. Also, different from other sensors, the TMR sensor can be designed to increase sensitivity as the temperature rises to compensate the reduction of magnetic field in high temperature. Therefore, it can detect a magnetic field even in the high temperature range with the same air gap as in room temperature.

2) Wide air gap range⁴

Air gap setting for the AMR sensor for detecting wheel speed in ABS, etc., is usually set at 2 mm or even at 1 mm or less when higher resolution or accuracy is required.

The sensitivity of the TMR sensor is 10 times that of the AMR sensor and 3 times that of the GMR sensor. Its internal noise is so small that it can also be used for magnetic field measurement of geomagnetism in $\mu$T scale. Therefore, as shown in Fig 8, detection with maximum of 5 mm of air gap is possible, which significantly expands the freedom of design. For example, a wall of non-magnetic material such as stainless steel, aluminum, or plastic can be installed between the sensor and the ring magnet for improving dust-, oil-, or heat-resistant properties.

![Fig. 8 Magnetic field generated by an elastoferrite pole ring as a function of the air gap](image)

5.3 Freedom of design

1) Small size

Different from the AMR element and GMR element, the MTJ element uses electric current that flows vertically through the layers that compose the device. Therefore, it is possible to significantly reduce the area of the sensor by improving the manufacturing process such as the etching machining performance and side-etching performance. MRAM, where the recording density is the most critical parameter, can be configured with 1 $\mu$m² or less of area per MTJ element. On the other hand, for sensor application, it is necessary to ensure the operation by securing the minimum dimension in the bonding pad. That is also possible with about 30% less space than the AMR sensor.

2) Larger installation tolerance

Magnetic sensors for speed and position detection are susceptible to inaccuracy of sensor and magnet installation. When they are not properly installed, signals may not be detected or the detection accuracy may be deteriorated.
The TMR sensor operates from a low magnetic field of -0.5 to 0.5 kA/m to a high magnetic field of -15 to 15 kA/m, as shown in Fig.6. It is possible to apply the most appropriate design for the application and the installation tolerance can be larger.

5.4 Robustness

1) Electrostatic discharge (ESD) capability

The MTJ element can be regarded as a capacitor with a very thin insulator of nanometer scale susceptible to high insulation breakdown risk. However, the risk is reduced as follows:
- To increase dielectric strength voltage by improving the quality of the insulation layer
- To distribute ESD voltage per MTJ element by serially connecting multiple MTJ elements
- To reduce the risk of ESD by controlling the process of connecting the TMR sensor and signal processing circuit for quick handling, as the ESD is mostly found in the sensor packaging process.

After introducing the above measures, the testing based on the machine model after installation onto the printed wiring board revealed improvement in insulation breakdown risk.

2) Tolerance against high magnetic field

As shown in Fig.6, the resistance of the TMR has reversed property against the external magnetic field; therefore, the TMR sensor does not break down even when it is exposed to a strong magnetic field produced by a rare-earth magnet.

5.5 Cost

1) Facility investment cost

As previously noted, the MTJ element is made by the same manufacturing facility as the AMR/GMR elements that Sensitec owns. In other words, the TMR sensors can be manufactured by using similar process and materials as the manufacturing for the GMR elements, and any special facility investment for the volume production is not required.

2) Cost reduction effect by TMR sensor

The following shows the cost reduction effects:
- Sensor chips can be made smaller so that more chips can be manufactured from one wafer.
- Inexpensive ferrite magnets can be deployed instead of expensive rare-earth magnets since a very low magnetic field can be detected.
- Low power consumption drive is possible due to simplified signal processing circuit, as the resistance of the device itself is high and amplifying circuitry is not required.

3) Cost reduction of the entire system

In applications such as electric motors and ABS, consideration for assembly and installation of the entire system configuration including peripheral components is required, not only the sensing functionality.

When the air gap and installation tolerance is broader, such as the case of the TMR sensor, the requirement for assembly/installation can be reduced and overall reduction of manufacturing cost is achieved from a simplified assembly process.

6. TMR sensor evaluation kit

NTN-SNR and Sensitec created three types of evaluation kits for detection of rotation and position and are providing them to potential users for the broader use of the TMR sensor technology (Fig. 9 and 10). The configuration of the evaluation kits is shown as follows:
7. Summary

The TMR sensor has the following significantly superior properties and high potential as a next-generation magnetic sensor for automobile and industrial machine applications:

- Basic performance (low power consumption/high output accuracy/high sensitivity)
- Operating range (high temperature/wide air gap/360° angle detection/detection of extremely low magnetic field)
- Freedom of design (smaller sensor size/larger installation tolerance)
- Robustness (ESD capability/high magnetic field tolerance)
- Low cost

Taking advantage the TMR sensor and its use in many broader applications is expected, such as electronic compass, switches, non-destructive testing, current sensors, speed sensors and position sensors, image processing equipment, and the medical field.

NTN group including NTN-SNR will actively pursue further improvement and new market development of the TMR sensors.

Reference

5) C.P.O. Treutler: Magnetic sensors for automotive applications, Sensors and Actuators A91, 2-6 (2001)
12) B. N. Engel and al.: A4-Mb Toggle MRAM Based on a Novel Bit and Switching Method, IEEE Transactions on Magnetics, VOL. 41, NO. 1, p132-136, JANUARY 2005

---

* Active sensing: A detection method with multi-pole magnet as the detection target
* Passive sensing: A method, with a magnet placed behind the sensor, to detect change of magnetoresistance as a magnetic body passes through.