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Magnetic Sensors and Measurement

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Abstract—The global magnetic sensors market is expected to reach about USD 4 billion by 2022. It is driven by technological advancements and an increased awareness regarding vehicle safety in the automotive industry as well as escalating demand for navigation enabled smartphones and other wearable devices. This paper gives an overview of the magnetic sensor technologies and compares the sensors' characteristics critical for use in industrial applications. Measurement applications using magnetic sensors are shown. Finally, this paper introduces the future trends and gives an outlook on magnetic sensors.

Keywords—magnetic sensors, magnetic field measurement

I. INTRODUCTION

According to several market studies, the global magnetic sensors market is expected to reach about USD 4 billion by 2022, more than doubling its size since 2012.[1] It is driven by technological advancements and by the market demand for higher performance devices, including vehicle safety in the automotive industry as well as smart navigation systems in wearable devices. Figure 1 shows the development of the magnetic sensor sales volume on the global market.

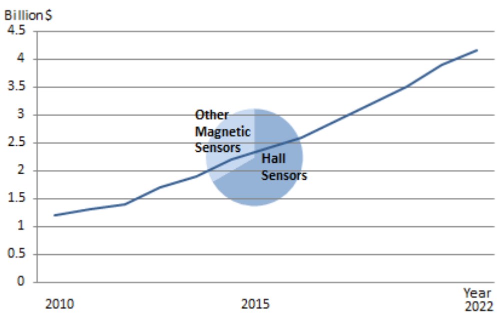

Fig. 1: The development of the global sales volume of magnetic field sensors

The magnetic field sensor market is steadily growing. Today the total sales of magnetic sensors reaches 2.5 billion dollars. The most sold magnetic sensors are based on the Hall-effect. And they make 2/3 of the total world market sale. The other 1/3 of the total sales are particularly magneto resistive sensors (AMR, GMR, TMR), SQUID sensors, Fluxgate sensors, and other magnetic sensors.

Looking back 30 years ago, magnetic sensors were considered outdated. But then, the revolutionary discoveries came.

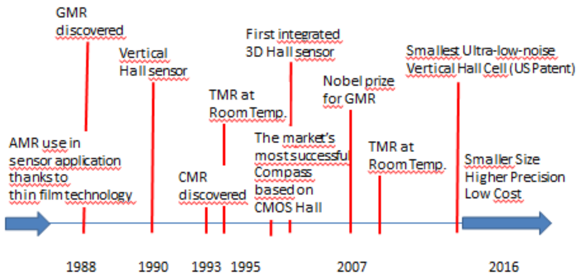

Fig. 2: History of magnetic field sensors that influenced the industrial applications

Figure 2 shows some of the inventions that influenced the evolution of the magnetic sensor applications in industry: Room-temperature AMR (anisotropic magneto resistors) in thin film technology for use in sensor applications were developed. GMR (giant magneto resistors) were discovered and later awarded with the Nobel prize. Vertical Hall sensors were invented that significantly contributed to improve the sensor technology in the automotive industry. The first integrated 3D Hall sensor and miniaturized compasses for use in wristwatches and smartphones were developed.

New sensor technologies and new software design tools allowed to substantially optimize the dimensions and geometry of the magnetic sensors and circuits. The magnetic sensor industry is currently very dynamic and innovative – and the modern applications require smaller size sensors, more precise and particularly with better price/performance ratio.

II. Overview of the Magnetic Sensor Technology

This section gives an overview of the magnetic sensor technologies, shown in Fig. 3.

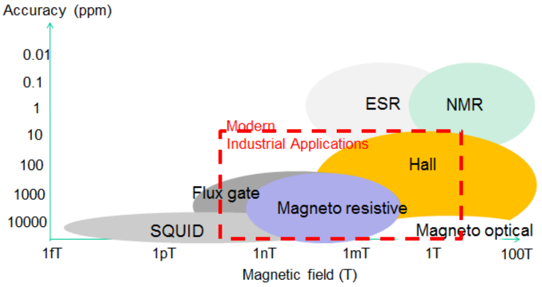

Fig. 3: Magnetic Sensor Technology Overview. The horizontal axis shows the measured magnetic field in Tesla and the perpendicular axis is the accuracy expressed in parts per million.

SQUID sensors: superconducting quantum interference devices. They are based on superconducting loops containing Josephson junctions. SQUIDs are magnetic sensors with the highest sensitivity, lowest noise, able to detect fT. They have been used to measure the magnetic fields in living organisms, e.g. to analyze magnetic fields resulting from brain activities. SQUIDs allow to measuring changes in magnetic field associated with one flux quantum. However, SQUIDs work only at cryogenic temperatures.

Magneto-optical (MO) sensors: are based on the Faraday-effect. They are particularly used for fast testing of magnetic materials, providing information about the distribution, intensity, and orientation of magnetic fields. MO-sensors have the technical benefit of immediately obtaining measurement data directly above the surface of the magnetic material depending on the sensor size. Thus, real-time investigations of the magnet field distribution can be performed without the need for time-consuming, point-to-point scans, however, MO-sensors are not so precise as e.g. Hall sensors.

The most precise magnetic measurement is performed with NMR: Nuclear Magnetic Resonance is a physical phenomenon in which nuclei in a magnetic field absorb and re-emit electromagnetic radiation. This energy is at a specific resonance frequency which depends directly on the strength of the magnetic field. Many scientific techniques exploit NMR phenomena to study molecular physics, crystals, and non-crystalline materials through nuclear magnetic resonance spectroscopy. NMR is routinely used in advanced medical imaging techniques, e.g. in magnetic resonance imaging (MRI). NMR are also routinely used to calibrate other magnetometers. However, NMR sensors work only at DC magnetic fields, not as Hall sensors that measure both DC and AC magnetic flux densities.

ESR: electron spin resonance are analogous to NMR, but it is electron spins that are excited instead of the spins of atomic nuclei.

The most interesting sensors for modern industrial applications, automotive and consumer markets are flux gate, magneto resistive sensors and Hall effect sensors, described in Section III.

Another overview of magnetic sensors is shown in Fig. 4. By comparing the sensors for use in real applications, we should critically consider the following parameters: sensitivity, accuracy, resolution, frequency bandwidth, magnetic range, temperature range, dimensions and price.

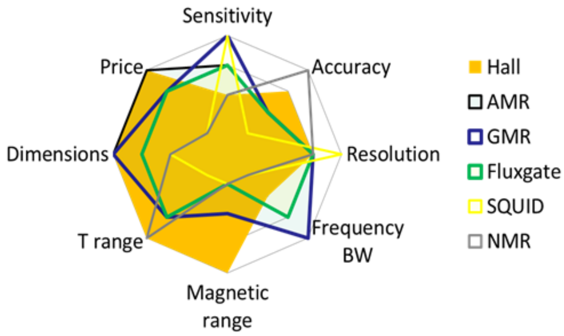

Fig. 4: Comparing Magnetic Sensors' characteristics critical for real use application

For example: GMR sensors have very high sensitivity, but low magnetic range. Fluxgate sensors are very sensitive with high resolution, but the sensor dimensions are large. Hall-effect sensors, shown in orange in Fig. 4, fulfill with a high degree most of the critical parameters. Therefore, they are currently the most popular and the most sold magnetic sensors on the market. However, there future depends in particular on whether means will be found to increase their sensitivity and decrease offset.

III. Magnetic Sensors for Industrial Applications

This section describes the magnetic sensors interesting for modern industrial applications: Fluxgate, Magneto resistors and Hall sensors.

A. *Fluxgate sensors*

A fluxgate sensor consists of a soft-iron core with two coils wrapped around it: a drive coil and a sense coil. An alternating electric current is passed through the drive coil, which magnetizes the core through its complete hysteresis cycle – to the saturation in one direction and back to saturation in the other direction. The sense coil measures the flux changes in the core. In a magnetically neutral background, the voltages induced in the sense coil are equal for both half-periods of the alternating current in the driving coil. However, when the core is exposed to a background field, it is more easily saturated when magnetized in alignment with that field and less easily saturated in the opposite direction. This asymmetry in the magnetization cycle of the core produces a change in the voltage induced in the sense coil. By processing the voltage induced in the sense coil, the magnitude and direction of the component of the environmental magnetic field along the core is deduced.

Fluxgate sensors may have the geometry of a ring, with the drive coil wound toroidally and the sense coil around the entire ring. The direction of the sense coil determines the sensitive direction of the sensor; two orthogonal sense coils on the same ring make an XY sensor; and with two rings one can make an XYZ sensor. Fluxgate sensors are described for example in [2].

Fluxgate sensors may reach very high magnetic resolution – of the order of 1pT; but then they are quite large in their dimensions – several centimeters.

It has been demonstrated that fluxgate sensors can be miniaturized. As an example, a two-axis miniature fluxgate sensor in CMOS technology is described in [3]. The size of this 2-axis fluxgate sensor was 2.5 mm including electronics. However, the small dimension compromises the magnetic resolution.

Standard fluxgate sensors are affordable, sensitive, with high resolution and they are robust. Fluxgate sensors are particularly used in military applications, but also in geology and archeology. Typical products include fluxgate compasses and gradiometers.

B. *Magnetoresistors*

Magneto resistors are the second most commonly used magnetic sensors after Hall sensors. In their basic form, they are very simple: they change the value of their electrical resistance in an externally-applied magnetic field.

There are three types of magneto resistors, called AMRs, GMRs, and TMRs.

AMRs, the magneto resistors based on the Anisotropic Magneto Resistance effect, contain a single ferromagnetic layer. The resistance of a pre-magnetized ferromagnetic layer changes with the direction of the applied magnetic field. The resistance change is in the order of a few percent and this effect can be used even for very weak magnetic fields.

GMRs, the magneto resistors based on the Giant Magneto Resistance effect, contain at least two ferromagnetic layers and a non-magnetic spacer. If the magnetization in these layers is non-parallel, the resistance is larger than if the magnetization is parallel. The change in resistance may reach up to 50 per cent, thus the name “giant”.

TMRs, the magneto resistors based on the Tunnel Magneto Resistance effect, which occurs in layer systems consisting of at least two ferromagnetic layers and a very thin isolation layer. The tunnel resistance between the two ferromagnetic layers depends on the angle between the two magnetization directions. TMRs have high-sensitivity but also high flicker noise. They are good for high temperature applications.

More on magneto resistors can be found in [4].

MR sensors are applied in Automotive, Industry, consumer and medicine. GMRs are used i.e. to read data in hard disk drives, incremental encoders, etc. MR sensors are low cost, miniature, have high resolution and sensitivity and high frequency bandwidth. Their disadvantage is the possibility of demagnetization by high magnetic fields. Methods for re-magnetization are used, though they increase the sensor’s complexity.

C. *Hall sensors*

Hall sensors are magnetic sensors based on the Hall effect. The Hall sensors are currently the mostly used magnetic sensors on the market.

The Hall sensor is a thin plate of conducting (preferably semi-conducting) material, fitted with four electrical contacts. A bias current is supplied via two non-neighboring contacts. If a perpendicular magnetic field is applied to the device, a voltage appears between the other two contacts, the so-called Hall voltage. An excellent book on Hall sensors is [5].

Hall sensors find wide applications in industry, automotive and consumer markets. They are used not only to continuously measure magnetic fields but also widely used as linear and angular position sensors or as current sensors [6].

The well-known week points of Hall sensors is their low sensitivity, offset, its temperature dependence and some parasitic effects, e.g. the planar Hall effect. These week points can be reduced with signal processing methods. Therefore, a magnetic sensor rarely comes alone. It is usually combined with some integrated electronics forming an IC (integrated circuit).

Most of commonly used integrated Hall sensors are made of silicon. Some other semiconducting materials, such as GaAs, InAs, InSb, have higher electron mobility and therefore, they have a stronger Hall effect than that of silicon. But silicon Hall sensors have much smaller low frequency noise, and they can be easily integrated in CMOS integrated circuits.

IV. HALL SENSORS: PAST AND PRESENT ACHIEVEMENTS

The market is steadily asking for magnetic sensors of higher performance, smaller size, and lower cost. Achieving these criteria makes the sensor more attractive for modern applications e.g. in automotive, consumer and industry. Sensors help improving vehicle safety and reducing energy consumption.

A. *Increasing Hall sensor’s sensitivity*

About fifteen years ago, the Hall sensor’s sensitivity was increased for a factor of 10 due to the invention of the IMC-Hall® Technology. The planar IMCs (integrated magnetic concentrators) were integrated on standard CMOS Hall sensors. The IMC converts the magnetic field components parallel to the device surface into the component perpendicular to the device surface. The IMC also functions as a magnetic flux concentrator, which provides the magnification of the local magnetic field without amplifying the device noise.

IMC-Halll® sensors are used in various applications, such as compass function in the wrist watch T-Touch of the Swatch Group [7]; in LEM current sensors; in Melexis Hall sensors for automotive applications; and also the Japanese company ASAHI (KLM) uses a version of the IMC technology for the compass in iPhones. SENIS is the successor of the company SENTRON that invented the IMC technology [8]. The history of IMC-Hall is illustrated in Fig. 5.

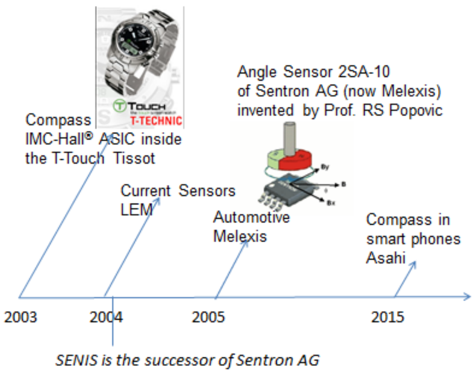

Fig. 5: History of IMC-Hall®

B. *First integrated 3-axis Hall sensor*

The conventional Hall sensors measure the magnetic field that is perpendicular to the sensor chip. The development of the vertical Hall devices allowed measuring the parallel components of the magnetic flux densities. By integrating vertical and horizontal Hall devices it was possible to build a very small 3D Hall sensor. On the same CMOS silicon chip both, horizontal and vertical Hall devices are integrated on a very small sensitive volume. The horizontal Hall device measures the perpendicular magnetic field component and the vertical Hall measures the two in-plane magnetic field components [9].

C. *World's smallest ultra-low noise vertical Hall cells*

Recently the world's smallest and most sensitive vertical CMOS Hall cells were invented [10]. The Hall cells feature impressively low flicker noise. Fig. 6 shows the noise voltage spectral density of the SENIS vertical Hall cells combined with the external electronics [11].

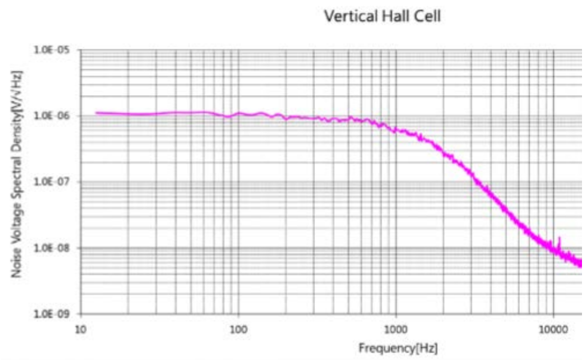

Fig. 6: Noise voltage spectral density of the SENIS vertical Hall cells combined with external electronics, with the bandwidth limited to about 1kHz. The corresponding noise-equivalent magnetic field spectral density is 80nT/√Hz [11].

V. Measurement Applications of Hall Sensors

Hall sensors are applied in large quantities as position sensors, angle sensors, or current sensors, as mentioned in Section III-C. They also find application in test and measurement industry. This section describes two measurement systems based on Hall sensors and shows their applications.

Hall-effect-based teslameters / gaussmeters are currently the mostly applied instruments for measuring DC and AC magnetic flux densities in the range from 1µT to 30T. The SENIS new digital teslameter system, as shown in Fig. 7, incorporates 1-, 2- or 3-axis Hall probe based on a single silicon chip with monolithically integrated horizontal and vertical Hall magnetic sensors and a temperature sensor. The Hall sensor chip is encapsulated in a robust ceramic package, a version of which is only 250µm thick. The teslameter features high spatial resolution 100 µm, magnetic resolution ±2ppm of the range, the accuracy ±0.0001% of reading + 0.001% of range, temperature coefficient less than 5ppm/°C, and angular errors less than 0.1°. In addition to desktop teslamters, the handhald 3D USB teslameters are available with a very favourable price/performance ratio.

Fig. 7: SENIS Teslameter with 3-axis Hall probes of various forms and miniaturized dimensions

At the last International Measurement Confederation World Congress, an overview of the commercially available teslameters was published [12]. The publication gives an overview of the available teslameters at the high-end performance market. The teslameters have been evaluated by following characteristics that are published by suppliers: probe dimensions, magnetic field sensitive volume, accuracy, magnetic resolution, measurement range, frequency bandwidth, temperature coefficient sensitivity, and price/performance ratio. The comparison is shown in Fig. 8. [13], [14]

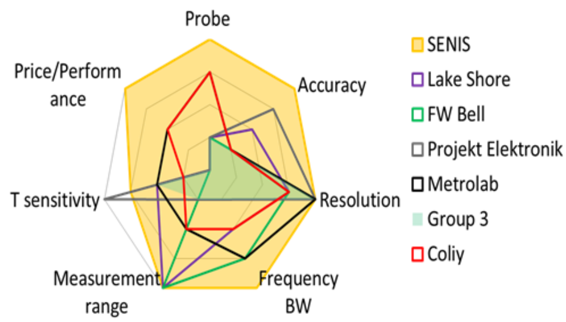

Fig. 8: A comparison of commercially available teslameters. The teslameters' comparison was published at the International Measurement Confederation World Congress. [12]

Teslameters are typically applied for quality control and monitoring of permanent magnets and magnet systems (generators, motors); for the development of magnet systems and process control; for magnetic field mapping and in general for magnetic field measurement applications in production lines and in laboratories.

An example of teslameter application is presented in Fig. 9: the magnetic field measurement in undulators of the electron light sources. The photo shows the Swiss FEL undulator at Paul Scherrer Institute in Switzerland. A flat 3D Hall probe is required that enters in the very small gap of the undulator and accurately maps the magnetic flux density [15].

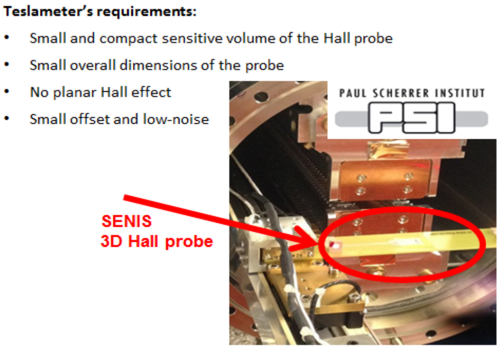

Fig. 9: Teslameter application: magnetic field measurement in undulators of electron light sources

Another application of Hall sensors in measurement is the control of permanent magnets for use in automotive applications [16]. This is done with a magnetic field mapper system incorporating a 3D Hall probe. The state-of-the-art mapper system, shown in Fig. 11, applies a calibration process for reducing the error of the sensitivity vectors of the 3-axis Hall probe to less than 0.1°. The Hall probe is easily exchangeable in the mapper system with an eddy-current probe, a touch stylus and other specialized probes, shown in Fig. 12. This allows a complete quality control of permanent magnets applied in modern industrial applications by providing accurate mapping of the magnetic field around the magnet under test or motor under test, combined with crack detection.

Fig. 11: The new Magnetic Field Mapper consists of four main parts: (a) the mechanical part, (b) the Hall Probe (or any other probe – as shown in Fig. 12), (c) an electronic box with digital signal processing, motor drives, encoder control, and power supply; (d) and a PC and Software for measured data acquisition, visualization, and analysis.

Fig. 12: Measuring different characteristics of permanent magnets is possible due to an easy way to interchange different measurement probes in the mapper. The photo shows some of the available probe options: Hall probe for rotor tests (special holder that allows the scanning of larger rotors); Standard Hall probe; Stylus; Eddy-current probe; Sliding probe; very long and thin probe for rotor air-gaps.

VI. Outlook and Conclusions

Unless radically novel inventions or discoveries happen in the next years, the evolution of the magnetic sensors in the next 20 years can be envisaged as follows:

Hall devices will continue to profit from the developments in IC technology and they will continue to dominate in industrial low-cost applications.

AMR and GMR will keep the niche of low-field high resolution applications.

TMR will probably find larger application in the area of higher magnetic fields and high-temperatures.

Fluxgate sensors will dominate the niche of high-resolution military and geology market.

In general, magnetic sensor microsystems [17], which are magnetic sensors combined with other small-size devices, will feature higher performance/price ratio and they will dominate high-requirement applications.

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