Magnetic Microsensors: Quo Vadis?

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1. Introduction

Magnetic sensors are used for contactless and wearless detection of a wide range of magnetic fields. This includes extremely low fields of a few fT (10^{-15} T) generated by the activity of human brain cells up to hundreds of mT (0.1 T) of modern rare earth magnets. During the last 20 years magnetic sensors have become very popular for detecting different physical properties like electric current, mechanical position, speed, angle, rotational speed or the earth magnetic field for electronic compass applications, because they are extremely reliable, small, cheap and easily integrated within electronics. There are different physical effects which are used to build magnetic sensors. Hall sensors and magneto resistive (MR)-sensors are today's mainstream sensors manufactured in quantities of hundreds of millions devices per year. Current Hall sensors are seamlessly integrated in CMOS logic devices and thus often include the complete signal path, computational logic and digital interfaces. MR sensors, on the other hand, are normally made in a proprietary thin film process and are heterogeneously integrated into sensing systems. The two technologies differentiate mainly in the detectable field range and in the product of resolution and speed. In addition to these mainstream technologies for large volume applications, specific sensing principles are used especially for low field/low noise applications. Currently, fluxgate and SQUID sensors are used especially in medical applications or for magnetic imaging. A fairly new approach is the use of chip scale atomic magnetometers to measure the total field, a technology that is similar to chip scale atomic clocks, which have already proven their high potential.

2. Hall Sensors

A magnetic field acting on charges in a conducting plate normal to the surface leads to a voltage perpendicular to the current direction due to the Lorentz force (Edwin Hall, 1879). The sensitivity depends mainly on the mobility of the charges and is typically 0.2 – 0.25 V/T (@ 5V) in Si based devices. Standard Hall plates are integrated in CMOS devices and detect magnetic fields perpendicular to the die surface. As these plates are also very sensitive to mechanical stress, typically several Hall plates are used in an arrangement to compensate for the stress effect. It is also common practice to use on chip metallic straps to generate fields inside the chip for sensitivity regulation and for test purposes. Hall sensors are available as linear or switching (digital) devices. As no special processes are required they are easily integrated within Si logic and are thus available with digital configuration, signal conditioning and a variety of different digital interfaces. A Hall element requires typically 30 µm x 30 µm of die size making it very attractive to integrate Hall sensing elements in ASICS or other digital devices from a cost point of view.

Unfortunately Hall elements exhibit high offset voltages. These are originated by structure deviations due to the fabrication process and by mechanical stress. There are two common design principles to reduce these offset voltages. One method is static offset cancellation by using four Hall plates located close together. The current bias in the first element is N-S, in the second element E-W, in the third S-N and in the last one W-E. By simply averaging the Hall voltage over all four elements the offset is reduced. Dynamic offset cancellation is possible if the bias current is periodically switched in a single Hall element in the four possible directions mentioned above. This is also known as spinning-current Hall elements [1]. If very low levels of offset are required, both methods can be combined and four Hall plates connected with rotational bias current are simultaneously switched. Besides the voltage offset the temperature coefficient is another limiting factor especially in automotive applications with a large temperature range. New developments using an integrated on chip heater improve the performance by "learning" the temperature coefficient during operation, thus further reducing the overall offset [2].

Recent developments aim to integrate a second or third direction of sensitivity into a Hall sensor. Currently two solutions are commercially relevant. A flux concentrator can be used to redirect the magnetic field into one plane of sensitivity. A disk of soft magnetic material is fixed onto the sensor die in a post processing step. Field components parallel to the chip surface are guided through the ferromagnetic material and generate fringing fields normal to the surface at the edges of the disk. Thus, four conventional Hall plates located at N, E, S and W of the disk are sufficient to measure the x- and y-component of a field parallel to the chip surface as required for an angular sensor. If the third component is also required either a fifth Hall element is used with sufficient distance to the ferromagnetic disk or the z-component is calculated from the data of the four Hall plates [3]. A completely different solution avoiding a heterogeneous process is to integrate vertical Hall plates within the CMOS process. Without special MEMS-type processes there is no access to the buried contact. However, it is possible to show by conformal mapping that an equivalent structure exists consisting of 5 top electrodes. Using the same principles as with planar Hall plates networks of four plates can be arranged with static and dynamic offset cancellation also for these vertical Hall structures [4]. Finally, four vertical networks and a planar Hall array located close together form a „pixel cell“, which is a sensing structure to detect all three components of a magnetic field [5].

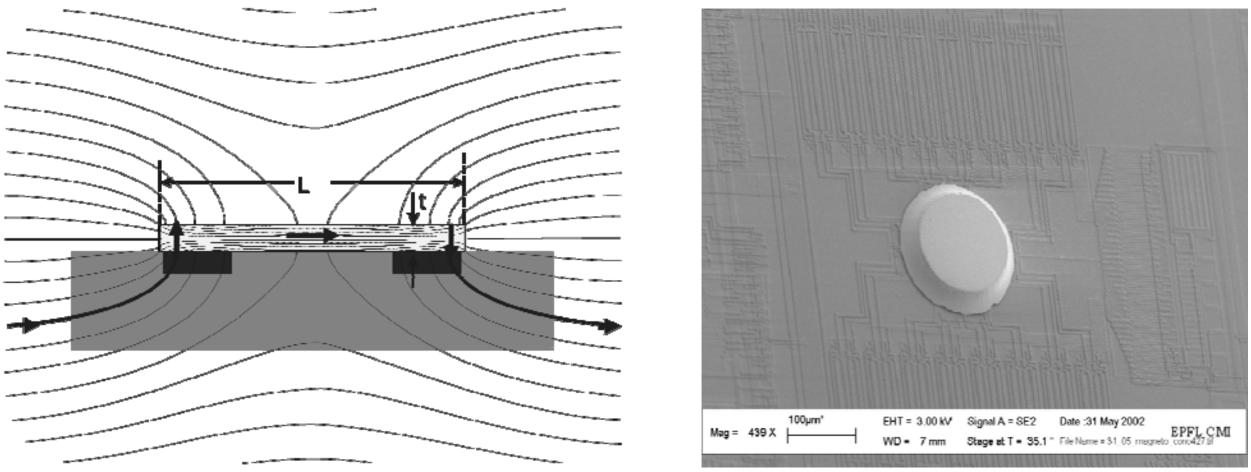


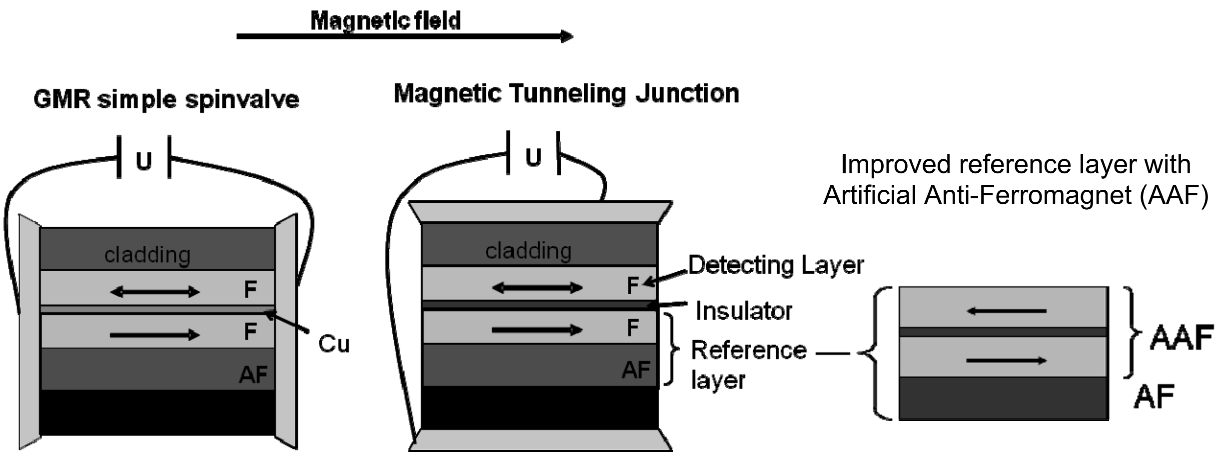
Fig. 1: Hall sensor with integrated magnetic concentrator (IMC) for the measurement of two magnetic field components in the plane of the chip. Function principle (left): magnetic flux is redirected by the IMC leading to vertical local field at the sensor surface, where the Hall plates are positioned. Realization (right) of the IMC on a CMOS Hall sensor device. Taken from [3].

Hall sensor developments in the next years will mainly benefit from integration advances and cost reduction in CMOS technology. More Pixel cells, more computing power and thus more local intelligence and resulting flexibility will be available at further reduced cost. One example for this trend is the presentation by Hackner and Hohe in this session [6].

3. MR Sensors

MR-Sensors are built in a proprietary thin film process utilizing a family of physical effects in thin metallic resistors. The anisotropic magneto resistive effect was found in 1857 by Lord Kelvin, while the tunnel magneto resistive effect (TMR) and the giant magneto resistive effect (GMR) are more recent developments [7, 8]. P. Grünberg and A. Fert were awarded the Nobel Prize in 2007 for the discovery of the GMR effect. In all three cases networks of thin stripes of magneto resistive material are structured to form half- or full Wheatstone bridges. The nature of all MR-effects is a change of resistivity of the material under the effect of an external magnetic field. A bridge voltage is generated if the individual branches of the bridge are exited differently.

By layouting a variety of different sensing structures sensors for different application profiles can be constructed [9]. The most simple structure utilizes a single Wheatstone bridge to sense the magnetic field strength. This principle is used for speed measurements at active scales or in back-biased configurations with ferromagnetic gears. To measure magnetic fields down to 1 nT (10^{-9} T) an integrated coil is used for offset cancellation. As a magnetic stripe is bi-stable, the magnetization direction of all MR stripes in the



	GMR Spinvalve	Magnetic Tunneling Junction (MTJ)
MR-ratio	Up to 14%	Al_2O_3: 70% ; MgO: 800 % @ RT
Anneal temperature	220°C	300°C - 450°C
Resistance	low	high (~ kΩ(µm)² - MΩ(µm)²)
Geometry	lines	„point“ ➔ high spatial resolution

Fig. 2: Comparison of a GMR-Spin-Valve and a Magnetic Tunneling Junction (MTJ) based on the TMR effect. The basic layer stack is similar in both cases, the only difference being spacer layer separating the two ferro-magnetic sensor layers: for GMR a non-magnetic metallic spacer (typically Cu) is used, for TMR a thin insulating layer (the best material currently is MgO). Both are sensitive to magnetic fields in the layer plane, but while the GMR resistance is also measured in the plane, the tunneling resistance across the insulating layer perpendicular to the plane is evaluated in an MTJ. This leads to a much higher resistance allowing smaller sensor elements and, thus, higher spatial resolution. Additionally, the higher anneal temperature extends the temperature range.

bridge can be switched by a short magnetic field pulse generated by the integrated coil (“flipping”). As a result, the sensor transfer curve changes its sign, thus the sensor offset vanishes if two subsequent measurements are subtracted before and after flipping. These sensors are well suited to detect the earth magnetic field. Combining two bridges on one sensor with one bridge rotated by 45° to the other enables angular sensing independent of the magnetic field strength, allowing a good stability without requiring very exact positioning of sensor vs. magnet. Modern AMR sensors achieve an angular resolution of better than 0.1°. The inherent measurement range of 180° for AMR sensors (meaning the sensor cannot differentiate between North and South) can be extended to 360° by using an integrated coil to create a small offset, where the sign of the offset defines the overall orientation [10]. To avoid perturbations of the signal by shape anisotropy effects special design patterns have been developed which act to suppress higher harmonics in the output signal improving the performance especially for low fields of the magnetic scale, which reduces the overall system cost. Furthermore, it is possible to design sensors which match exactly to the pole length of a magnetic scale. These sensors provide very high signal quality compared to non-matched sensors enabling very high accuracy for angular or linear length measurement. However, for each different magnetic scale a separate sensor layout is required. Using multiple magnetic tracks, absolute measurements over a range of several 10 cm can be achieved. But even a single track with varying scale period can be used for absolute measurements by using two sensors and evaluating the position dependent phase difference between both sensors [11]. For current sensing or non destructive testing (NDT) gradiometric bridge configurations are used. In a gradiometric measurement all homo-geneous stray fields are effectively suppressed by the sensing element itself. Using improved layout designs, offset effects caused by slight variations in film thickness or material properties (i.e. MR and temperature coefficient) can be effectively suppressed.

As MR stripes are both sensor as well as non-volatile storage elements (for the magnetization direction of the MR layer) they can be used also for quite unique applications like true power on multiturn sensors without any mechanical gears. A spiral racetrack pattern with N turns combined with a domain wall generator to switch the magnetization direction in the stripes allows a discrete measurement of N turns even if the system turns while the sensor is not powered [12, 13], which is required for example for automotive steering angle applications.

Compared to Hall sensors MR sensor are beneficial mainly for three reasons. Due to the much higher sensitivity significantly lower fields can be measured. This makes MR sensors ideal for electronic compass, magnetic monitoring or other applications, where large air-gaps or small magnets are used. Secondly, the signal to noise ratio and thus the product of resolution and time is orders of magnitudes higher than for Hall Sensors. This enables the construction of highly dynamic measurement applications. MR based current sensors for example provide a response faster than 1 µs (10^{-6} s), MR based position measurement systems are able to operate in high speed spindle motors. However, typically it is required to add separate signal conditioning electronics at PCB or package level as MR sensors itself are passive elements. Finally, as the resistance change is not proportional to the driving current MR sensors can be designed with high internal bridge resistance values, which are well suited for low power applications.

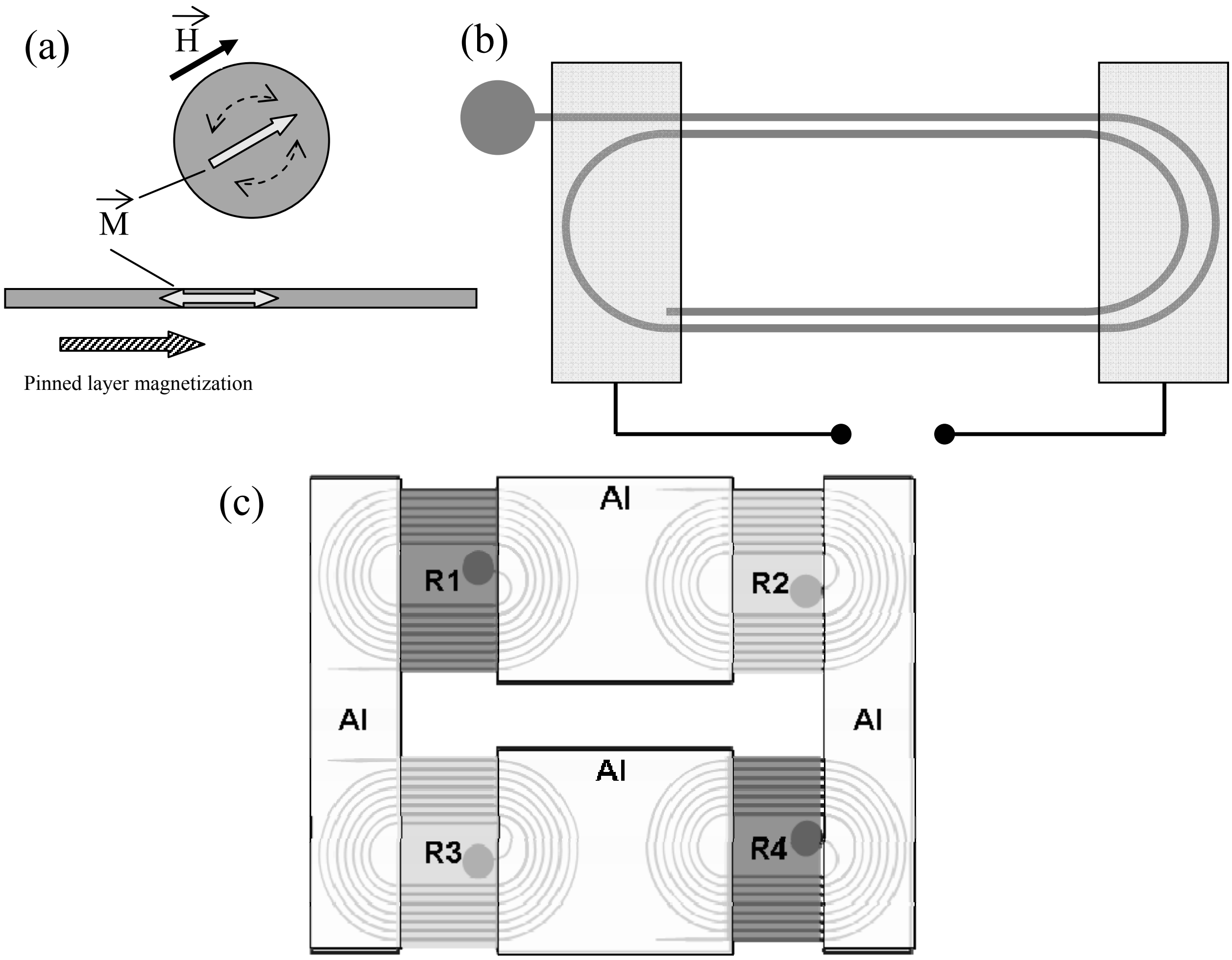


Fig. 3: Function principle of a non-contact multiturn sensor based on a GMR-Spin-Valve-stack [12, 13].

(a) In a round GMR structure, the magnetization M of the free layer follows the direction of the external field H, in a long thin stripe, the magnetization is pinned along the stripe axis due to its form anisotropy. The resistance of the stripe is low for M parallel to the pinned layer magnetization and high for the anti-parallel configuration.

(b) By combining a round structure with a long thin stripe the direction of M in the stripe can be flipped by turning the magnetization in the round structure (called domain wall generator) by inserting a 180°domain wall in the stripe. The stripe stores the domain walls and therefore counts the revolutions of the external field. To read out the desired information (i.e. the number of turns) the stripe is patterned in an oval spiral shape (termed “racetrack configuration”). With the first 180° turn of the external field, a domain wall is generated which will wander to the right end of the spiral. With each subsequent half turn this wall will wander further into the spiral by another half turn and at the same time a new domain wall is injected into the spiral. At the same time, the resistance R of the stripes along the racetrack length changes, which can be measured by contacts covering the racetrack ends. If the external field rotates in the opposite direction the domain walls will also wander in the opposite direction, i.e. out of the spiral. The resistance therefore reflects the number of turns of the external field as long as they do not exceed the spirals number of turns.

(c) By combining four spirals (two with cw rotation and two ccw) a bridge is created which changes its output with each half turn of the external field allowing easy measurement. Note that the information is stored also when the device is not powered leading to a true non contact multiturn sensor.

MR based sensing is still a fairly new technology and currently a couple of new developments appear on the market. New design concepts allow setting the device sensitivity to zero enabling very simple electronics to store the current offset value for electronic compensation. Another approach for new devices is the integration of micro structured flux-guides, which allow manipulation of the field within the chip. Using these types of integrated flux-guides a 2D field sensor can be designed on 0.25 mm² die size. Technological improvements include better GMR layer stacks with application tuned parameters, the utilization of the TMR effect for sensing applications and the integration of superconducting structures for flux concentration with GMR sensing layers to construct sensors for ultra low field applications. Finally, some manufacturers are starting to offer monolithically integrated MR sensors. These sensors are built on the basis of standard CMOS wafers, on top of which the MR structures are manufactured in a back-end of line add on process.

4. Low field sensors

The measurement of low fields has important applications, however the number of sensors manufactured per year is much smaller and the system cost is much higher. For the measurement of magnetic fields below 1 µT (10^{-6} T) typically flux-gate („Förster-Sonde“) magnetometers are used. These devices are inductive transformers built around a soft magnetic core. Flux-gate magnetometers exhibit an extremely low offset drift rate, however, the sensitivity is proportional to the volume of the device and thus a three axis sensor typically has a weight of a couple hundred grams. Flux-gate sensors have also been realized using micromachining technology to integrate the coil and core on a chip but for mainstream applications they cannot compete with Hall and MR technology. Finally, the highest field sensitivity today can be achieved with SQUID (superconducting quantum interference device) sensors. However, SQUID sensors have to be operated at liquid nitrogen (77 K) or liquid helium (4.2 K) temperatures which limits their use to research and medical applications. A new approach for very sensitive magnetic field measurements is currently under study based on a new technology for chip scale atomic clocks. Both use optical resonances to sensitively measure the energy differences between states in alkali metal atoms. While for atomic clocks, energy levels are selected that are independent of the magnetic field, choosing magnetic field dependent levels will result in a sensitive magnetometer, which can be either a total field or a vector magnetometer. In chip scale atomic clocks a resolution of 10 ps/day or better than 10^{-16} has already been

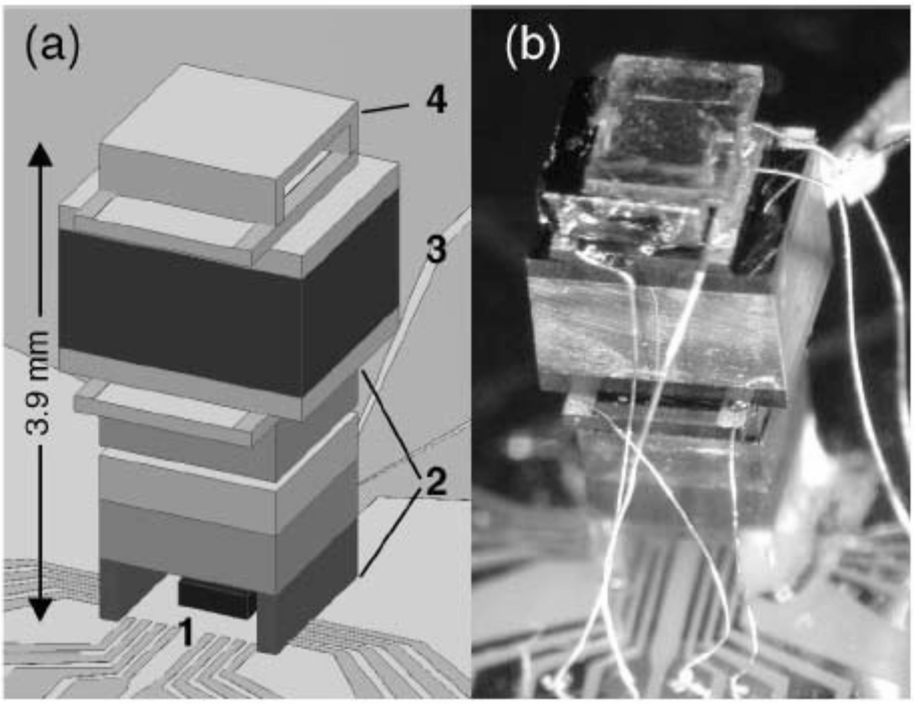


Fig. 4: Chip-scale atomic magnetometer (CSAM). (a) Schematic of the magnetic sensor. The components are: 1 VCSEL, 2 optics package including (from bottom to top) a glass spacer, a neutral-density filter, a refractive microlens surrounded by an SU-8 spacer, a quartz λ/4 waveplate, and a neutral-density filter, 3 87Rb vapor cell with transparent ITO heaters above and below it 4 photodiode assembly. (b) Photograph of the magnetic sensor. Taken from Ref. [14]

shown, and for chip scale atomic magnetometers (CSAM) a sensitivity of 10 $fT/Hz^{½}$ (10^{-14} $T/Hz^{½}$) has been demonstrated [14, 15, 16]. As the volume for an optically pumped CSAM is in the order of 10 mm³ and the manufacturing process is mainly based on fairly well controlled micromachining and micro optical technologies, this approach might result in a highly competitive sensor technology in a few years.

5. Conclusion

A great variety of magnetic sensing principles are available today allowing users to tailor their sensors to the application. As with other sensor areas miniaturization and integration with powerful electronics are the main drivers for reduced size and cost as well as improved performance. In this context, miniaturized force sensors based on MEMS cantilevers could also be used for magnetic field sensing using magnetic or magnetostrictive materials. Due to their specific advantages and disadvantages resulting from the physical sensor principle, there is no universally “best” magnetic sensor technology. Depending on the application requirements and the allowable cost different sensor principles and technologies will provide the best solution. And, with the availability of new sensors and magnetic sensing principles, new applications can be addressed in the future further expanding the impact and importance of magnetic sensors. One example is the detection of single biomolecules like DNA or proteins marked with magnetic beads for medical applications of pharma screening. Due to the close proximity of sensor and bead and the high sensitivity of i.e. TMR sensors, a better overall sensitivity can be achieved than with established optical methods like fluorescence marking. The challenge for the sensor engineer will be to understand the basic principles of the different techniques as well as their potential and limitations when combined with i.e. magnetic scales, electronics and signal processing for a specific application in order to select and develop the most suitable sensor system.

6. References

[1] A.A. Bellekom, P.J.A. Munter: Offset Reduction in Spinning Current Hall Plates, Sensors and Materials 5, 253 (1994).
[2] M. Stahl-Offergeld et al.: Offset Tracing in Hall Sensors by Integrated Temperature Coefficient Determination, Proceedings SENSOR 2009, paper A7.4.
[3] C. Schott, R. Racz, S. Huber: CMOS Three Axis Hall Sensor and Joystick Application, Proceedings IEEE Sensors Conference 2004, Wien, Österreich, 25.-27.10.2004.
[4] R.S. Popovic: Hall effect Devices, Adam Hilger, Bristol, Philadelphia and New York, 1991.
[5] P. Kejik, E. Schurig, F. Bergsma, R.S. Popovic: First Fully CMOS-integrated 3D Hall Probe, Proceedings Transducers 2005, Seoul.
[6] M. Hackner, H.-P. Hohe: An integrated Nine-dimensional Hall-Gradient-Sensor, Proceedings SENSOR 2009, paper A6.2.
[7] P. Grünberg, R. Schreiber, Y. Pang, M.B. Brodsky, and H. Sowers, Phys. Rev. Lett. 57 (1986)
[8] J.S. Moodera, L.R. Kinder, T.M. Wong, and R. Meservey, Phys. Rev. Lett. 74 (1995)
[9] A. Schütze: MR-Sensoranwendungen in der Automatisierungstechnik: Prinzipien und Herausforderungen, Proceedings 8. MR-Symposium Wetzlar, 08.-09.03.2005.
[10] A. Bartos, A. Meisenberg, D. Schmitz: A Novel Magnetoresistive Angle Sensor for 360° Detection, Proceedings SENSOR 2003, Nürnberg.
[11] A. Voß, A. Meisenberg, R. Pieper, A. Bartos: Absolute Positionsbestimmung mit Magnetoresistiven Sensoren, Proceedings zur Konferenz Sensoren und Messsysteme 2008, Ludwigsburg.
[12] M. Diegel, R. Mattheis, E. Halder: Multiturn Counter Using Movement and Storage of 180 Magnetic Domain Walls, Sensor Letters, Vol. 5, No. 1 (2007).
[13] R. Mattheis, Quad16: The New Generation of Multiturn Counters, 10th Symposium Magnetoresistive Sensors and Magnetic Systems, Wetzlar, 31.03.-01.04.2009.
[14] P.D.D. Schwindt et al.: Chip-scale atomic magnetometer, Appl. Phys. Lett., Vol. 85, No. 26 (2004).
[15] A. Edelstein: Advances in magnetometry, J. Phys.: Condens. Matter 19 (2007) 165217.
[16] D. Budker and M. Romalis: Optical magnetometry, Nature Physics, Vol. 3, April 2007.