Electronic Compass Sensor

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Abstract
In this paper, we describe a new two respective three axis integrated IMC Hall-ASIC that can be used as a single chip electronic compass and applied in portable low cost electronic equipment like wrist watches and mobile phones. The electronic compass chip consists of ring shaped integrated ferromagnetic concentrators (IMC), a CMOS integrated circuit and an excitation coil manufactured by direct bonding onto the chip surface. The IMC Hall ASIC measures the two in-plan magnetic field components Bx and By and the vertical component Bz of the earth magnetic field. The IMC Hall sensor exhibits an excellent sensitivity of 8000V/T for the X and Y axis which yields to an in-plane heading accuracy of +/-1 °, whereas the field in the Z-axis is measured with a lower sensitivity of 800V/T. The high sensitivity characteristics are obtained by integrating magnetic flux concentrators directly on Hall-ASIC, which amplifies the earth magnetic field by a factor of 10. Further more the compass sensors provides a low energy method to eliminate the perming effect (remnant field effect after subjecting to strong magnetic fields)

Keywords
Magnetometer, electronic compass, earth magnetic field, Hall sensors, IMC-Hall ASIC, Triaxis-Technology

INTRODUCTION

Magnetic sensors have been in use for direction finding or navigation for centuries. The earth magnetic field is a weak three-dimensional field with an intensity of 50-60µT (0.5-0.6 Gauss) that can be approximated by a dipole model. By definition the X-Y component of the field vector lies parallel to the earth surface and points towards the magnetic north pole. For a latitude not close to the equator the majority of the earth magnetic field lies along the Z-axis and points at the northern hemisphere into the ground. However, the horizontal direction of the earth field is always pointing toward magnetic north and is used to determine the compass direction. Because of this the compass has to be held parallel to the earth's surface or has to be gimbaled in order to be accurate. Hence, a two-axis magnetometer held parallel to the earth surface is the minimum configuration for magnetic compass heading.

For an electronic compass applied in portable low cost equipment, the magnetic field sensor has to have the following features:

- to measure at least two orthogonal axes X and Y of the earth magnetic field with an accuracy of better than 1%.
- to be insensitive to thermal and magnetic shock (perming)
- to be small in size and have low power consumption
- to be mass-manufacturable at low cost.

Today, there are various types of electronic compasses available. The most commonly used magnetic field sensors for compass applications are based on the magneto resistive (AMR) effect, on the fluxgate effect or on magneto-inductive effect. Because of the weakness of the earth magnetic field Hall-effect sensors were hardly applied due to their poor sensitivity.

It is generally believed that Hall sensors are only applicable at magnetic field higher than 0.5mT, and that the measured field must be perpendicular to the sensors surface. On the other hand magneto resistive (AMR) and fluxgate sensors (FG) are considered to be highly sensitive and well adapted for low fields. However, AMR and FG sensors have some drawbacks compared to Hall-sensors. They are either not fully compatible with mass fabrication at low cost or with low power requirements. For example AMR sensors require an integrated set-reset coil for low field DC measurements and are not fully compatible with conventional CMOS technology. Fluxgate sensors were recently fully integrated on single CMOS chip [4] but due to the principle of chopping the magnetic field, the saturation of an open loop core requires a significant current not suitable for low power application.

An effect that arises for magnetic field sensors containing of ferromagnetic material is that the offset of the sensor changes after exposure to a high magnetic field. This effect is known as perming and can be explained by the remnant field effect of the material. Perming is a critical issue for low field measurements and has to be considered for compass applications.

In this paper we present a concept of a high sensitivity Hall-sensor consisting of CMOS-Hall ASIC and IMC. Standard CMOS technology allows for embedding amplification and noise reduction circuit, the A/D conversion, calibration and interfacing on the same chip as well as for low cost mass production. The IMC functions as passive magnetic field amplifier and dramatically improves the sensors performance.

The focus of this paper is not on low power consumption, but rather on demonstrating that IMC-technology can boost the magnetic sensitivity of CMOS-Hall sensors sufficiently for compass applications. An additional key characteristic of the new compass sensor is that it provides for a low-energy method to virtually eliminate the perming effect.

IMC Hall-Sensors

The idea of integrating magnetic flux concentrators directly on Hall-ASICs was first described about 10 years ago [1]. The integrated concentrator converts the external magnetic field parallel with the chip surface locally into a field perpendicular to the plane, which is sensed by conventional planar Hall elements. Figure 1 shows the cross section of a conventional CMOS-Hall chip combined with a planar magnetic concentrator. The combination of IMC and Hall features higher magnetic sensitivity, lower equivalent offset and offset drift compared to conventional Hall sensors, so that the week earth magnetic field can be measured.

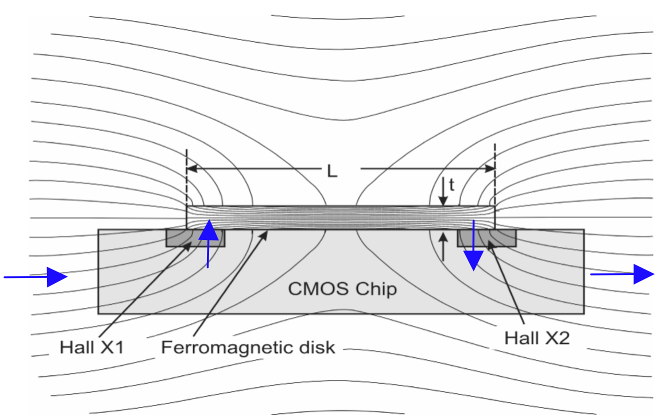

Figure 1: The IMC locally rotates and amplifies the magnetic field so that it can be measured by standard Hall elements X1 and X2.

The basic structure of the compass-sensor consists of a ring shaped IMC and one pair of Hall elements for each measurement axis X and Y. These Hall elements are distributed under the periphery of a ferromagnetic flux concentrator (IMC) where the strongest field concentration appears. Two perpendicular axes X and Y are used to measure two orthogonal magnetic field components in the plane (see fig. 2). The two Hall elements along an axis are exposed to a field component with opposite orientation, so that subtracting the two output voltages yields a output signal proportional to the in-plane magnetic field components X and Y. Designating the in-plane direction by an angle α the output voltage of the X-axis is proportional to $\cos(\alpha)$, whereas the output for the Y-axis is proportional to $\sin(\alpha)$. The vertical component of the field Bz can be measured by adding the output voltages of all Hall elements like for an ordinary Hall sensor without IMC.

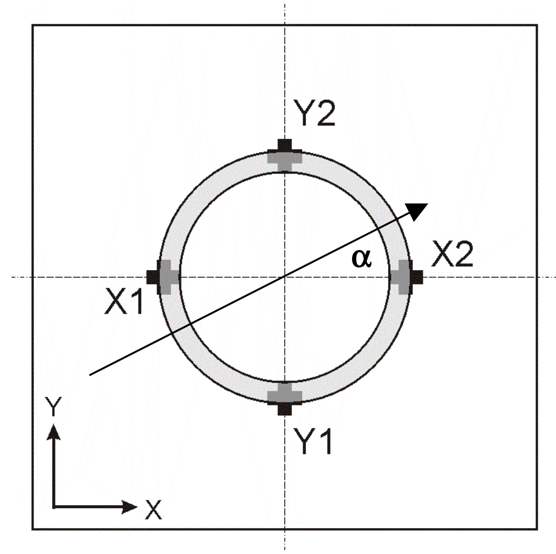

Figure 2: SIN-COS compass structure with two Hall elements per each axis (X1-X2 ,Y1-Y2)

If now the ring-shaped IMC is exposed to a strong (accidentally) magnetic field then the ferromagnetic layer gets magnetized in the X-Y plane. This diametrical remnant magnetization prevails even when the accidental field is not present anymore and leads as consequence to a change of the Hall-output offset voltage.

However, we found an elegant way how to eliminate the remnant diametrical field. The trick is to directly manufacture on the ring shaped IMC layer an excitation coil by wire bonding on the chip surface (see fig. 3). The ring shaped IMC behaves as a closed loop magnetic circuit and can be easily circularly magnetized by applying a short current pulse I. Circular magnetization corresponds to the lowest energy state and as a consequent no magnetic field lines will leave the magnetic layer at the periphery and no change in offset will be experienced.

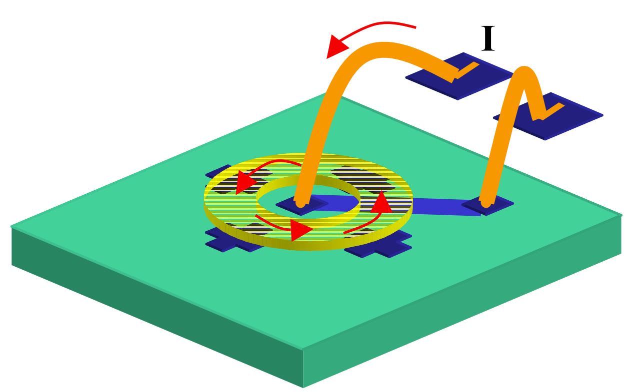

Figure 3: Elimination of perming effects from external fields by circular magnetization of the IMC ring.

It is an important benefit that the ring shaped IMC features high magnetic amplification and allows for easy magnetization by an integrated coil with low energy pulse.

Applied Technology - IMC Process

The integrated magnetic flux concentrators consist of a high-permeability and very low-coercive-field (very soft) amorphous ferromagnetic layer, which is first glued in form of ribbons onto the wafer containing electronic circuitry and Hall elements and then structured by photolithography and wet-chemical etching. Finally the wafer is cleaned from glue residues. The IMC process used for the compass prototypes (fig. 4) has already been applied on over 300 wafers at Sentron. IMC can be considered as a simple post process applied on completely manufactured CMOS wafers.

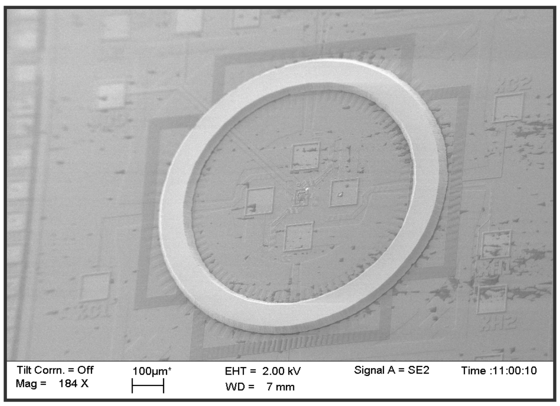

Figure 4: SEM Photograph of a ring shaped Integrated Magnetic Concentrator (IMC)

Results

We have realized for the first time a compass sensor entirely based on standard 0.8um CMOS technology, and additional low-cost IMC post process (see fig. 5). The circuit contains the magnetic sensor front-end and other state of the art electronic circuitry for amplification, offset compensation, filtering etc. The CMOS circuit features an electronic gain of 2500 and a power consumption of 16mA @5V.

Figure 5: Layout of the CMOS IMC-Hall compass sensor

The integrated IMC structure consists of five rings. A central ring with a diameter of 1mm is surrounded by 4 symmetrically arranged smaller rings with the diameter of 0.5mm (see fig. 6). Such an arrangement allows achieving a high magnetic gain through a long metallic structure, which at the same time features minimum distance to the bonding wires. In this 5-ring IMC structure again each two Hall elements per axis are placed under the center ring concentrator extremities shown as yellow dots. But in addition we add for each axis two Hall-elements below the surrounding IMC just beneath the air gap shown as white dots. Bonding pads are placed in the center of the IMC rings in order to build an integrated coil for the circular magnetization.

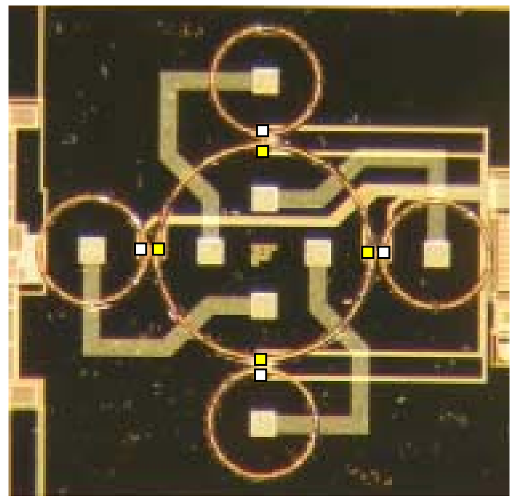

Figure 6: Closed up photograph of the 5-ring IMC structure.

The sensors output characteristic was measured in a Helmholtz coil by performing a sweep of the magnetic field in the range of +/- 400µT. The voltage output is plotted in fig. 7. The magnetic field sensitivity in X and Y is 8000 V/T which includes a passive magnetic gain contribution from the IMC of a factor 10. The Z-axis doesn't feature magnetic gain from the IMC. The linearity error is 1% for the field range of +/- 150µT.

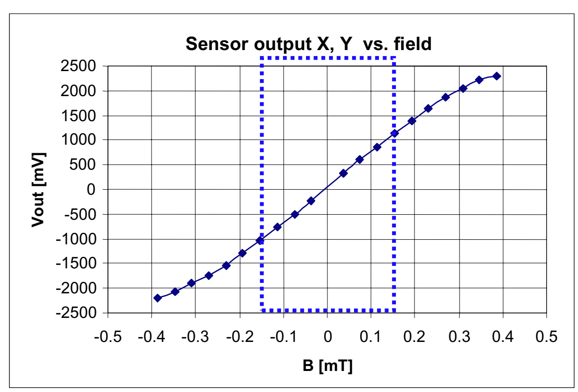

Figure 7: Response of the compass-sensor to external magnetic field

The horizontal component of the earth magnetic field can be considered to be 20μT. To be able to estimate the achievable resolution we have measured the field equivalent noise versus the integration time. Fig. 8 shows that an integration time of 10ms is required in order to achieve a signal resolution of about 1% of the earth magnetic field.

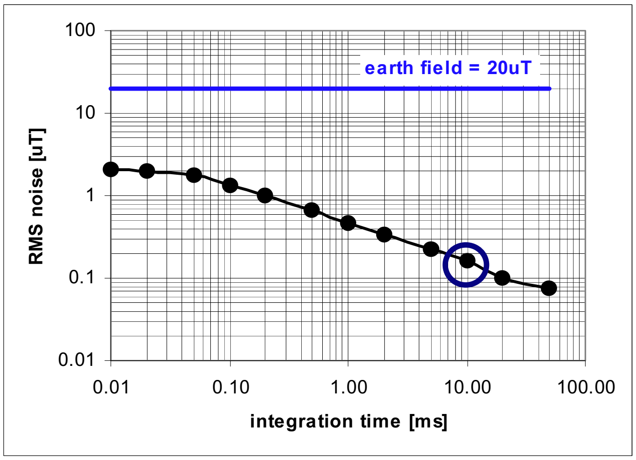

Figure 8: Field equivalent noise vs. integration time

In order to quantify the effect of magnetic perming, the compass sensor was subjected to a strong magnetic field of > 20mT. The corresponding field error from perming is about 5-6 uT (see fig. 9). After applying a short current pulse (25μs) with the amplitude of 20mA, the perming was reduced to 0.2 μT, which corresponds to 1% of the earth magnetic field. The wire-bonded prototype of this coil consists of 4 loops. By applying flip chip technology the number of loops can be increased and so the current amplitude will proportionally decrease.

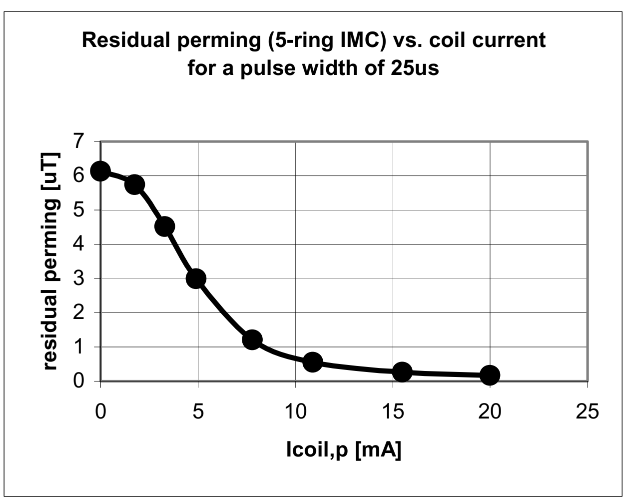

Figure 9: Field equivalent perming effect vs. circular magnetization current.

Conclusions and outlook

We have presented the first time that a single chip CMOS-Hall ASIC in combination with ring shaped integrated magnetic concentrator (IMC) can be used to measure the in plane components of the earth magnetic field with an accuracy of 1%.

The compass sensor consists of ring shaped integrated ferromagnetic concentrators; a CMOS integrated circuit and an excitation coil manufactured by direct bonding onto the chip surface and feature a low cost, small size, single chip solution.

The IMC structure amplifies the in plane magnetic field components Bx and By by a factor of 10 and yields a output sensitivity Sx and Sy of 8000V/T. Although the compass sensor measures the 3 axes of the earth magnetic field, the field component Bz doesn't benefit from the IMC and exhibits a sensitivity of 800 V/T.

Perming is virtually eliminated by applying a low energy pulse on excitation coil so that the ring shaped IMC is circularly magnetized.

Next steps will be to increase the signal quality of the z-axis in order to make the performances similar to X and Y, and to adapt the circuit for low power consumption.

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