MULTI-AXIS INTEGRATED HALL MAGNETIC SENSORS

by

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Conventional Hall magnetic sensors respond only to the magnetic field component perpendicular to the surface of the sensor die. Multi-axis sensing capability can be provided in the following two ways: (a) by integrating magnetic flux concentrators on the die, and (b) by using vertical Hall devices. Here we review the most important two- and three-axis integrated Hall magnetic sensors based on these concepts. Their applications include mapping of magnetic fields and sensing angular position.

Key words: integrated Hall sensors, multi-axes magnetic sensors, angular position sensing, teslameter

INTRODUCTION

Magnetic field sensors based on the Hall effect [1] are nowadays mostly used in contactless sensors for measuring the position of mechanical parts and electrical currents. They have a big economical impact: any new car has at least a dozen (and some a hundred) Hall magnetic sensors inside it; millions of ventilators and disc drives in personal computers use brushless motors with Hall sensors and, most current sensors in various products are based on Hall magnetic sensors.

Such a big acceptance of Hall magnetic sensors in industry is a consequence of the good performance – price ratio of these products. The good performance – price ratio is due to an almost perfect compatibility of a Hall plate (fig. 1) with microelectronics technology: the optimal Hall plate structure, dimensions and material characteristics are similar to those readily available in integrated circuits. Therefore, the development of Hall magnetic sensors does not require much of an investment. In most cases, the integration of a good Hall plate into an integrated circuit is simply a question of design and does not require any modifications of the fabrication process of the integrated circuit – see fig. 2.

For many years, Hall magnetic sensors have been based on Hall plates similar to those in figs. 1 and 2. Such conventional Hall magnetic sensors respond to the magnetic field component along only one axis – the one perpendicular to the surface of the sensor die.

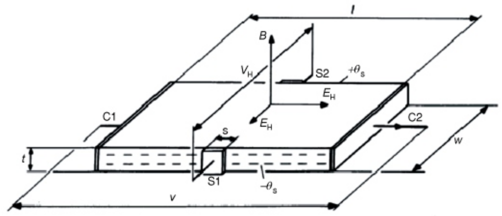

Figure 1. Model of a Hall plate – a moderately-doped semiconductor plate fitted with two pairs of electrical contacts
Modern Hall plates are usually of microscopic dimensions. For example, the thickness might be t = 10 μm, the length 1 = 200 μm and the width w = 100 μm. A bias voltage V is applied to the plate via the two current contacts C1 and C2. The bias voltage creates an electric field E_e and forces a current I. If the plate is exposed to a perpendicular magnetic induction B, the Hall electric field E_H occurs in the plate. The Hall electric field gives rise to the appearance of Hall voltage V_H between the two sense contacts S1 and S2

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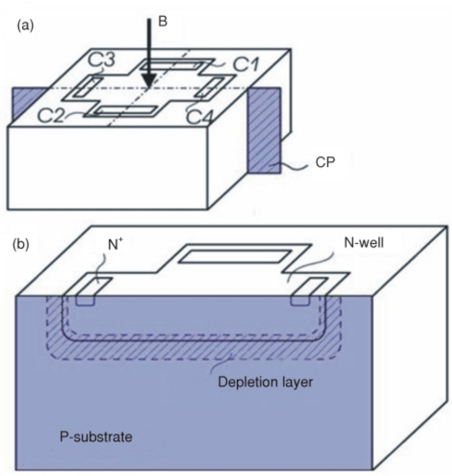


Figure 2. Cross-like Hall device in bulk CMOS technology

(a) general view: compare with fig. 1; CP denotes a crossing plane; (b) view with the cross-section along CP
The Hall plate is realized using the N-well layer which is normally used as a substrate for p-channel MOS transistors. The contact regions of the plate (C1-C4) are heavily doped by the layer N^+ which is normally used for source and drain regions of n-channel transistors. The Hall plate is insulated from the p-type substrate by the depletion layer of the p-n junction well/substrate. For clarity, only the essential semiconductor regions are shown and the Hall device is not biased. When the Hall device is biased, the depletion layer width is not uniform

However, some important applications of magnetic sensors, such as magnetic field mapping and angular position sensing, require multi-axis sensing capability. Traditionally, this capability has been achieved (more or less) by applying two or three orthogonally positioned single-axis sensors, as illustrated in fig. 3. The problems associated with this approach include poor orthogonality of the sensitive axis, insufficient spatial resolution and the handling of many connecting wires.

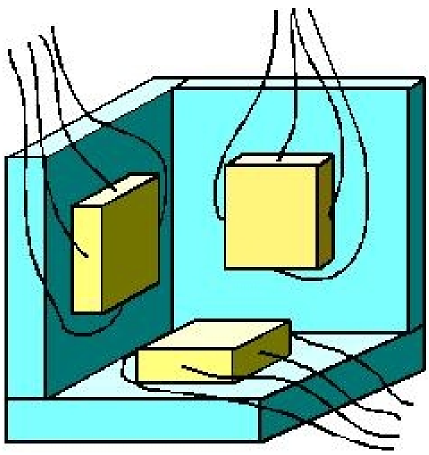


Figure 3. Classical concept of building a 3-axis magnetic field sensor: three Hall plates attached to the three orthogonal faces of a cube

In this paper we shall review the most important concepts used in novel integrated two- and three-axis Hall magnetic sensors. These are the concepts of integrated magnetic concentrators and of a vertical Hall device. We shall illustrate these concepts by devices in which they were implemented, as well as by selected applications.

In the next section we shall first briefly present the state-of-the-art of conventional integrated Hall magnetic sensors for the magnetic field along the perpendicular axis with respect to the sensor chip. This will give us the reference in performance which must be met by the co-integrated sensors for the other two axes. Moreover, we shall see some important concepts developed for conventional Hall magnetic sensors which are also readily applicable in multi-axis Hall sensors.

CONVENTIONAL INTEGRATED HALL MAGNETIC SENSORS

Most modern commercially-available integrated magnetic sensors are realized in conventional bulk CMOS technology. They usually contain four orthogonally-coupled "horizontal" (parallel with the die surface) integrated Hall plates similar to that shown in fig. 2. The orthogonal coupling of several Hall elements is useful for reducing offset, this being one of the most important figures of merit of Hall magnetic sensors.

We can appreciate the importance of offset reduction in a Hall magnetic sensor system by comparing the typical numerical values of Hall voltage and offset voltage. The Hall voltage of a Hall plate is given by:

$$V_{\mathrm{H}} \quad \frac{1}{qnt} IB \qquad (1)$$

where q is the electron charge, n is the average density of free electrons in the Hall plate, t is the plate thickness, I is the supply current, and B is the component of the magnetic flux density perpendicular to the plate. By substituting here the numerical value of q and the typical values for the other parameters ($n = 10^{-16}\mathrm{cm}^{-3}$, $t = 3$ µm, $I = 1$ mA, and $B_{\max} = 10$ mT), we obtain V_{H} 2 mV. The offset voltage is, typically, about 1 mV. Therefore, in order to render our magnetic sensor useful at all, we have to somehow reduce the offset voltage for at least a factor of 100 [2].

In the contemporary integrated Hall magnetic sensor, the most efficient offset reduction is achieved by a variation of the chopper-stabilization technique, known as the spinning current method, see figs. 4-6.

The challenges in the further optimization of the spinning current technique include: decreasing the temperature coefficient of the residual offset

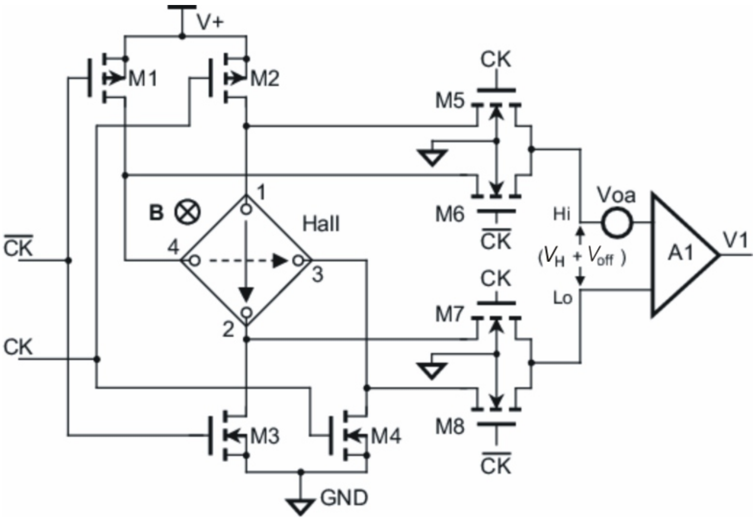


Figure 4. Switched Hall plate
The front-end of a switched Hall plate (or spinning-current) system for the cancellation of the offsets and 1/f noises of both the Hall plate (Hall) and the amplifier (A1). CK and are the clock signals, and M1-M8 are the switches implemented as complementary MOS transistors. When $\overline{CK}$ is "High", the current flows between 1 and 2, and when CK is "High", the current flows between 4 and 3

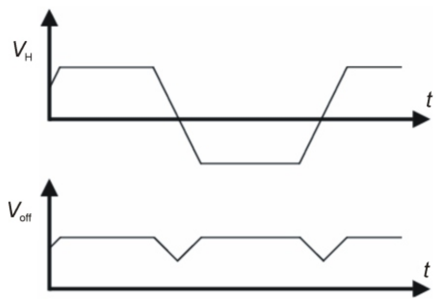


Figure 5. The Hall voltage and the offset signal *vs.* time at the input of the amplifier in fig. 4
The result of the switching is that the Hall voltage is converted into an alternative voltage, whereas the offset stays a quasi-DC voltage

(now about $10^{-4}B_{range}$/K); reducing the noise (now about 1 μT/$Hz^{1/2}$, whereas the physical limit in silicon Hall elements is about 10 nT/$Hz^{1/2}$); improving transduction stability (now 0.02%/K) and increasing the highest frequency of the measured magnetic field. Currently, the highest reported cut-off frequency of a Hall magnetic sensor based on the spinning current is about 100 kHz. This is more than sufficient for all position sensing and for low-frequency current measurement. However, in modern electrically switched power systems, current measurement in a bandwidth from DC to about 1 MHz is needed. An important milestone on the road leading to integrated magnetic sensors suitable for this and other new challenging applications, is adequate modeling of integrated Hall devices [4].

TWO-AXIS HALL MAGNETIC SENSORS BASED ON IMC TECHNOLOGY

The acronym IMC stands for Integrated Magnetic Concentrator. A magnetic concentrator is made of a high-permeability material. So it provides a

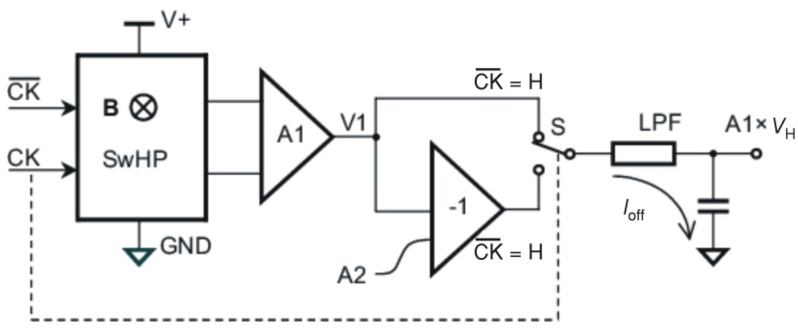


Figure 6. Schematic of the whole switched Hall plate system
The box SwHP represents the front-end of the Switched Hall Plate system shown in fig. 4, without the amplifier A1. The S switch takes the upper position when $\overline{CK}$ is "High", and the lower position when CK is "High". Since the S switch works synchronously with the switches in the box SwHP (M1-M8) in fig. 4, the Hall voltage is demodulated and the offset voltage converted into an AC signal. In the low-pass filter (LPF), the AC offset is cancelled (I_{off}) and the amplified Hall voltage is completely recovered. If the spinning current is performed at a high-enough frequency, then it also reduces the 1/f noise of the Hall-amplifier system, as illustrated in fig. 7. It also reduces the planar Hall effect significantly, fig. 8 [3]

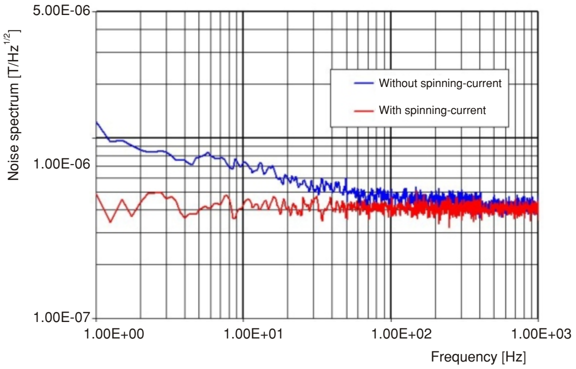


Figure 7. Measured noise voltage spectral density at the output of a Hall magnetic sensor without and with the application of the spinning-current method

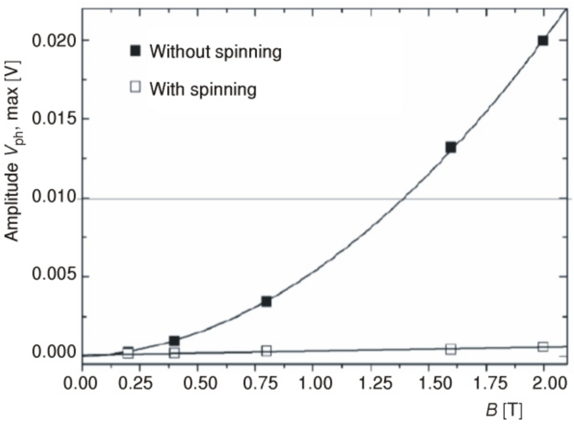


Figure 8. Measured planar Hall voltage of the horizontal Hall plate without and with the application of the spinning-current method; a similar result is also obtained for vertical Hall devices

"low-resistance" path to the magnetic flux and thus concentrates the flux in itself. Moreover, as illustrated in fig. 9, an IMC converts a global magnetic field parallel to the die surface into a locally perpendicular magnetic field which can be sensed by conventional planar Hall elements [5].

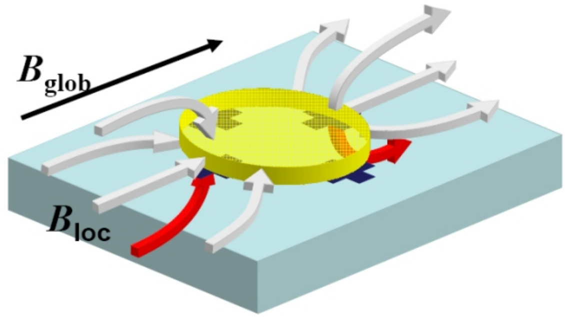
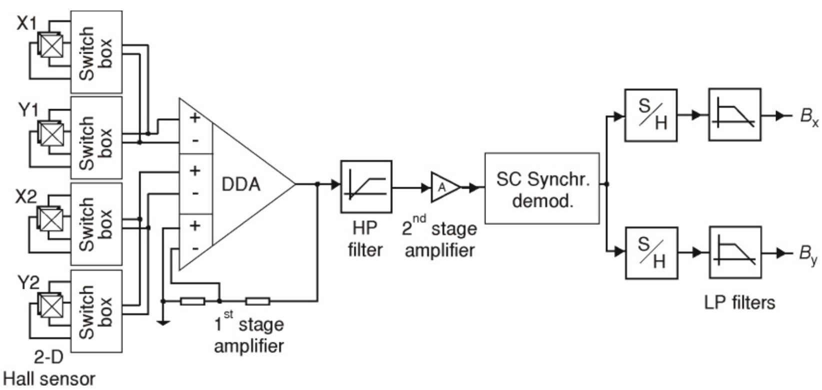


Figure 9. A die with four conventional integrated Hall plates combined with a magnetic flux concentrator
The IMC is a flat disk made of a soft ferromagnetic material. If the general ("global") magnetic field is parallel with the die plane, then the IMC concentrates the magnetic flux in itself. Therefore, the "local" magnetic field has a component perpendicular to the IMC, and so also to the Hall plates. So a horizontal magnetic field is locally converted into a perpendicular magnetic field, which is sensed by the Hall elements

The basis of the IMC technology has been developed at EPFL in collaboration with the start-up company Sentron AG and, later on, with Asulab SA. In brief, an IMC is fabricated by gluing on a finished CMOS wafer, a commercially available ferromagnetic 20 µm thick foil, and by subsequent structuring of the ferromagnetic layer by photolithography. Currently, several products based on the IMC technology are commercially available from companies: Sentron, Melexis, Asahi Kasei, and LEM. A 2-axis integrated magnetic sensor based on the IMC technology is presented in figs. 9-13, while fig. 14 illustrates its applications.

The main advantages of IMC-based magnetic sensors lie in the fact that an IMC provides a magnetic amplification, thus boosting the signal-to-noise (and offset) ratio of the sensor and that the technology of the silicon part of the sensor stays strictly identical to that of conventional single-axis Hall magnetic sensors. The main drawback of this technology is the fact that IMC is made of a non-perfect ferromagnetic material: although the best available material is used, it does have a finite remanent field and eventually goes into

Figure 10. Block diagram of a 2-axis integrated magnetic sensor based on the combination of four Hall plates and IMC, as shown in fig. 9
A major part of the electronics is periodically used for one or the other channel. At the end of the signal processing chain, a de-multiplexer separates the signals to provide analogue output voltages proportional to the two in-plane components of a magnetic field, B_x and B_y



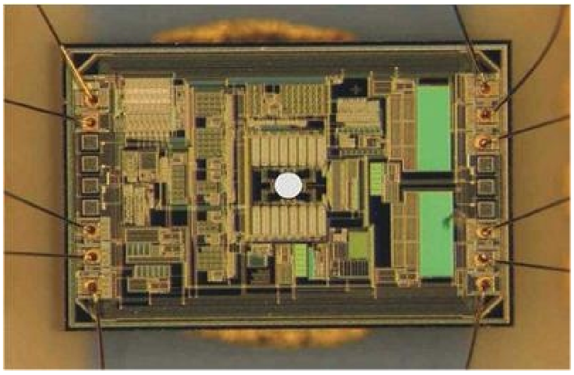


Figure 11. Photograph of the two-axis IMC Hall sensor
The dimensions of the silicon chip are 2.7 mm × 1.9 mm. The white circle in the center of the chip is the disk-shaped IMC of 200 μm in diameter (Courtesy of SENTRON, Zug, Switzerland)

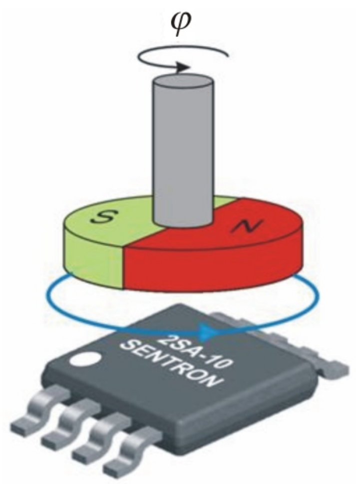


Figure 12. A small rotating magnet and the two-axis Hall sensor, shown in fig. 11, form a very accurate angular position sensor – see also fig. 13

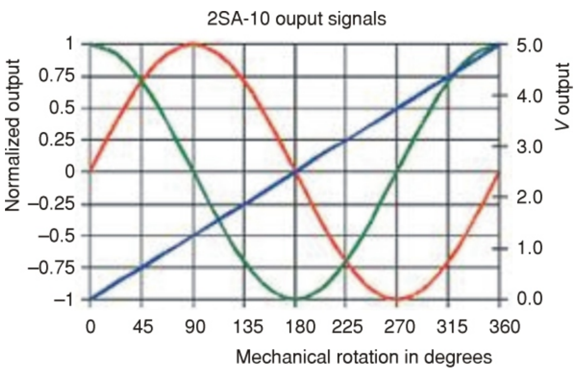


Figure 13. Output voltages
As the permanent magnet in fig. 12 rotates, the output voltages of the 2-axis magnetic sensor vary as sine and cosine of the rotation angle φ. The output voltages can be further processed to retrieve the angle φ (the straight line)

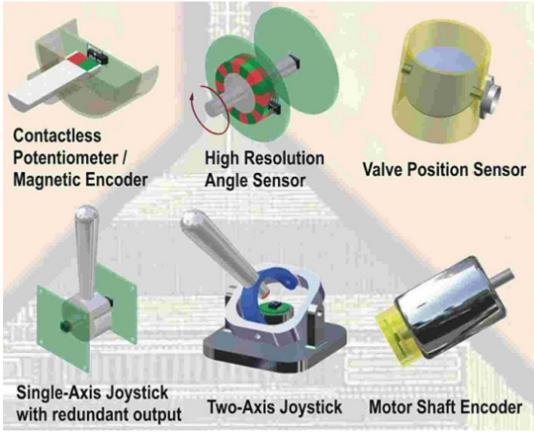


Figure 14. Typical applications of a 2-axis magnetic sensor

magnetic saturation. The consequences are the appearance of a magnetic hysteresis in offset and a limited linear magnetic operating range of the IMC Hall magnetic sensor.

MULTI-AXIS HALL MAGNETIC SENSORS BASED ON VERTICAL HALL DEVICES

In principle, the sensing capability parallel to the die surface could be achieved by placing a conventional Hall plate perpendicularly with respect to the die surface. The problem is that the structure of such a device is not compatible with the conventional integrated circuit technologies. Back in 1984, one of us found a solution to this problem [6]. The idea of the vertical Hall device is illustrated in fig. 15. Interestingly, the Hall voltage of the transformed device, obtained by integrating the Hall electric field $E_{\rm H}$ over the dashed line connecting sense contacts S1 and S2 in fig.15 (right), *i. e.*,

$$V_{\rm H} = \int_{S_1}^{S_2} E_{\rm H} \, {\rm d}S \qquad (2)$$

reduces to eq. (1). This is precisely the same result as in the case of the classical long conventional Hall plate shown in fig. 1. Therefore, a vertical Hall device is, in principle, equivalent to a conventional rectangular Hall plate.

A five-contact vertical Hall device according to this concept has been successfully realized as a discrete device [7]. A two-axis version of this device allowed the development of precise magnetic position sensors [8].

Integrating a vertical device into an integrated circuit proved difficult. The reason is in the following: the device must use an n-well as an active region, as illustrated in fig. 16; however, modern integrated circuit technologies have very shallow doped layers which are not compatible with the depth needed for a vertical Hall device. The solution was found by using a high-voltage CMOS technology which includes a relatively deep n-well and by a very careful optimization of the design of

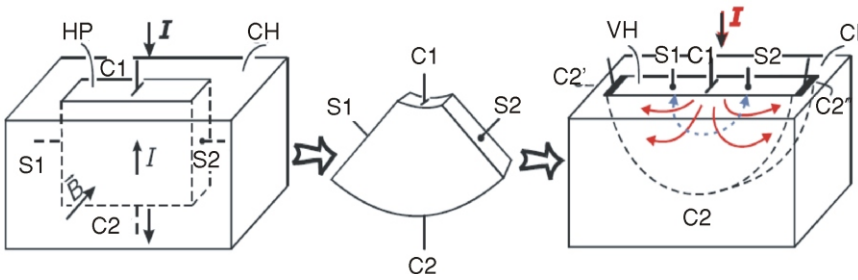


Figure 15. Vertical Hall device
Imaginary conformal transformation of a conventional Hall plate HP embedded vertically into a chip CH (left), via an elastic stage (middle), into an integrated vertical Hall device V_H *(right). The vertical Hall device has all terminals (C1, C2', C2'', S1 and S2) accessible at the chip surface. In the right-hand structure, the solid arrows represent the current lines, while the dashed line between the terminals S1 and S2 is the integration path for determining the Hall voltage by eq. (2)*

the vertical Hall device. This has made possible the development of the first fully integrated 3-axis magnetic field sensor in a standard CMOS technology, without any alteration and/or post-processing, as shown in fig. 17 [9].

Examples of application of integrated 3-axis Hall magnetic field sensors

The optimized version of the integrated 3-axis Hall, fig. 17, is now used as a 3-axis probe for measuring magnetic fields [3]. This is the only 3-axis Hall probe in the world featuring a spatial resolution under a few millimeters (*de facto*, only about 0.1 mm), a hardly measurable error in the mutual perpendicularity of the three axes and a negligible cross-talk. Two versions of the probe are shown in figs. 18 and 19. This probe is the enabling component in advanced 3-axis analogue and digital teslameters (fig. 20), now commercially available [10].

Figures 21 and 22 illustrate two further aspects of the performance of this unique instrument [3]. The standard accuracy of the teslameter is 0.1% of the measurement range which may be from 20 mT to 20 T. The major part of the error budget are the residual non-linearity errors (up to 0.05% for 2 T range – see fig. 21) and sensitivity errors (up to 0.02%). These two types of errors can be much reduced by using a calibration table.

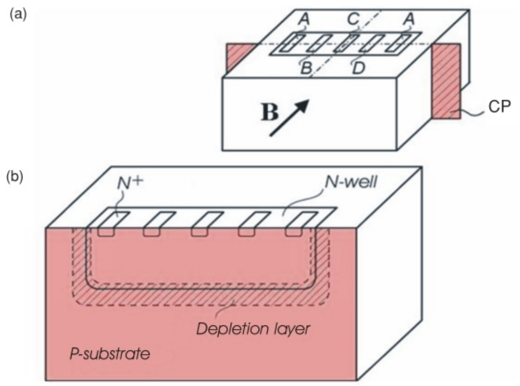


Figure 16. An implementation of the 5-terminal Hall device of fig. 14 in bulk CMOS technology
(a) general view; CP denotes a crossing plane; (b) view with the cross-section along CP
The vertical Hall device is realized using a deep N-well layer, which is available in high-voltage CMOS technology. The contacts and the pn-junction isolation are similar to those of the conventional Hall element shown in fig. 2

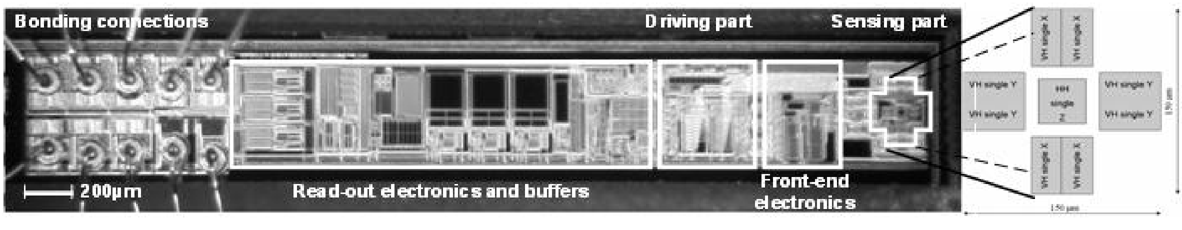


Figure 17. Photograph of a fully integrated 3-axis Hall magnetic sensor
This is a CMOS integrated circuit which consists of: the magnetic sensing part, the signal processing part, and the connecting part. The magnetic sensing part, is shown on the right-hand side. A single horizontal Hall plate (HH) measures the magnetic field component perpendicular to the die plane and two pairs of vertical Hall devices (VH) measure each of the two in-plane components of a magnetic field. All of these Hall elements are integrated on an area of about 150 μ*m 150* μ*m and have a depth of less than 10* μ*m. The die dimensions are 4300* μ*m × 640* μ*m × 550* μ*m (thickness)*

Figure 18. The encapsulated 3-axis Hall probe
The magnetic-sensitive region of the integrated Hall sensor is visible trough the window, allowing the precise positioning of the probe. The dimensions of the probe are 4 mm × 2 mm × 16 mm (Courtesy of SENIS, Zurich, Switzerland), [10]

Figure 19. The world's smallest 3-axis Hall probe
The thin tip of the probe is a part of the silicon integrated Hall sensor chip which is not encapsulated. The dimensions of the naked silicon tip are 0.5 mm × 0.55 mm × 3 mm. The magnetic sensitive point is only 0.15 mm away from the tip end (Courtesy of SENIS, Zurich, Switzerland), [10]

Figure 20. A three-axis analog teslameter (magnetic flux density to voltage transducer)
The transducer consists of a single-chip 3-axis Hall magnetic sensor described above, electronic box and a long cable connecting the probe to the box. The front end of the cable is very thin and flexible so as to allow easy positioning of the probe. The electronic box contains analogue electronics for additional amplification of the signals and for cancelling residual offsets, thermal drifts, and non-linearity (Courtesy of SENIS, Zurich, Switzerland), [10]

These teslameters are used in scientific laboratories all over the word for the precise mapping of magnetic fields, notably in particle accelerators. They are also used in industry, mostly for monitoring electrical machines and for characterizing permanent magnets.

Let us briefly consider this last application. Most vendors of permanent magnets quote the tolerances in

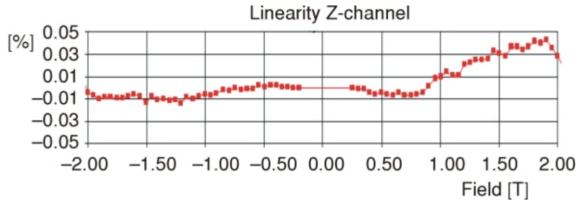


Figure 21. The transducer non-linearity error as a function of the measured magnetic flux density in the range 2 T

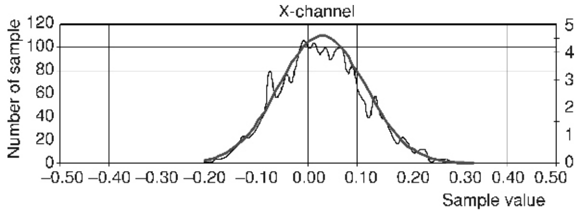


Figure 22. The histogram of the transducer offset voltage fluctuations during a period of 100 s, in the frequency bandwidth from 0.01 Hz to 10 Hz, and the corresponding approximation by a Gaussian distribution; the standard deviation is about 83 μV, which corresponds to 17 μT

the remanent flux density 5% and magnetization orientation tolerances 5°. For some applications of permanent magnets, notably those in magnetic position sensors and free electron radiation sources, these tolerances are too big. We recently developed an apparatus for fast testing and sorting of permanent magnets [11]. The said apparatus is displayed in fig. 23. It consists of four 3-axis teslameters described above, A/D converters, a computer, and LabVIEW-based software. The Hall probes of the teslameters are arranged near the

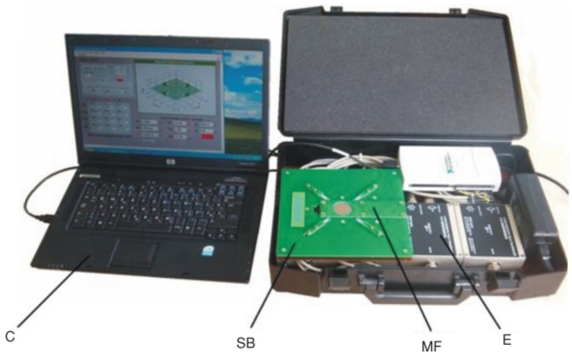


Figure 23. A system for fast testing of permanent magnets
The system consists of: SB – a sensor board to which four 3-axis Hall probes (S1-S4) are attached; MF – a magnet fixture which places the magnet under test into a suitable position on the sensor board; E – an electronic module for the conditioning of the signals of the Hall probes, and C – a computer with a software which calculates, displays, and memorizes the test results (Courtesy of SENIS, Zurich, Switzerland), [12]

magnet under test, so as to allow an easy positioning of the magnet. Each probe measures the three components of the field produced by the magnet at its respective position. The measured values are then inserted into appropriate equations derived from the dipole approximation of the magnet and the so-called global parameters of the magnets are calculated. The said global parameters include the magnetic moment of a magnet (its magnitude, position coordinates and inclination angles), and its remanent flux density. In the local mode of operation, the system determines the magnitude, orientation and gradient of the magnetic field in a small volume of interest. The measurements can be done "on the fly", *i. e.* by moving the magnet very fast via the testing position.

FURTHER RESEARCH IN MULTI-AXIS HALL MAGNETIC SENSORS

Apart from curiosity and intellectual pleasure, research in any field is driven by as yet unsolved problems and eventual new important applications. In the present case, multi-axis Hall magnetic sensors could, for example, have an economically very important application as 3-axis compasses in mobile phones (1); if they had a better magnetic resolution then that of the contemporary 3-axis sensors; they could, also, replace optical encoders in many industrial products (2); if they had a lover offset drift and a higher magnetic range than that of the existing products, they could be used in many more different products (3) if the whole system, including the magnet, the 2-axis sensor, signal-processing electronics, and packaging, could be produced at a lower cost.

Some of these objectives may be reachable thanks to the expected continuous evolutionary improvement of the characteristics of known integrated Hall magnetic sensors, as mentioned in section *Conventional integrated Hall magnetic sensors*. Some of them, however, may require revolutionary new ideas. Such an idea might be the new circular structure of a two-axis integrated magnetic sensor which we have recently presented at two specialized conferences [13, 14].

CONCLUSIONS

For some important applications of magnetic sensors, such as magnetic field mapping and angular position sensing, conventional Hall magnetic field sensors are not adequate, since such applications require multi-axis sensing capability.

Most important two- and three-axis integrated Hall magnetic sensors are based on the following two concepts: (a) integrated magnetic flux concentrators (IMC) and (b) vertical Hall devices.

The IMC-technology is used in two-axis integrated Hall magnetic sensors. An IMC converts a global magnetic field parallel to the die surface into a locally perpendicular magnetic field which can be sensed by conventional planar Hall elements. Moreover, an IMC provides a magnetic amplification and so improves the signal-to-noise ratio of the sensor. Typical industrial applications of two-axis magnetic sensors are contactless potentiometers, position sensors, joysticks, *etc*.

The development of the first fully integrated 3-axis magnetic field sensor in a standard CMOS technology, without any post-processing, was made possible by applying vertical Hall devices. Such a 3-axis magnetic sensor is used as a Hall probe. It is the only 3-axis magnetic field probe in the world featuring a spatial resolution well under a millimeter, virtually no error in the mutual perpendicularity and negligible cross-talk of the three axes. This 3-axis Hall probe is the enabling component in commercially available advanced analog and digital teslameters. These teslameters are used in scientific laboratories for the precise mapping of magnetic fields, notably in particle accelerators. They are also used in industry for monitoring electrical machines and for characterizing permanent magnets.

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ИНТЕГРИСАНИ ХОЛОВИ МАГНЕТСКИ СЕНЗОРИ СА ВИШЕ ПРАВАЦА ОСЕТЉИВОСТИ

Конвенционални магнетски сензори на бази Холовог ефекта мере само компоненту магнетског поља која је управна на површину сензора. Мерење магнетског поља дуж више оса може да се оствари на следећа два начина: (а) интеграцијом концентратора магнетског флукса и (б) коришћењем вертикалних Холових елемената. У овом раду приказујемо најважније Холове магнетске сензоре са два и три правца осетљивости који базирају на овим концептима. Њихове најважније примене су мерење магнетских поља и бесконтактно мерење угла.

Кључне речи: интегрисани Холови сензори, мерења магнетских поља у више правца, бесконтактно мерење угла, тесламетар