High Resolution Hall Magnetic Sensors

R. S. Popovic

Abstract – The resolution of a magnetic sensor depends on its intrinsic noise, offset instability and the magnetic sensitivity. Both noise and offset can be substantially reduced by the spinning current technique. The effective magnetic sensitivity can be increased by the application of a magnetic flux concentrator. The physical limit of magnetic sensitivity is estimated. Values of sensitivity, noise and offset of various discrete and integrated horizontal and vertical Hall devices, and of sensor systems are given. High resolution integrated Hall sensors are currently mostly used as compass in mobile phones.

I. Introduction

Devices based on the Hall-effect [1] are currently the most used magnetic sensors. This is due to the fact that the material, structure, and dimensions of Hall devices are compatible with microelectronics technology [2]. A Hall device can be implemented as the plate similar to that invented by Hall [1]. A Hall plate can be integrated in-plane with the active surface of an IC dice, as shown in Fig. 1. Such a planar (or "horizontal") Hall sensor "senses" a magnetic field component perpendicular to the IC surface. Alternatively, a Hall device can be implemented as a "vertical" quasi-plate [3], perpendicular to the active surface of an IC dice, as shown in Fig. 2. Such a vertical Hall sensor "senses" a magnetic field component parallel with the IC surface.

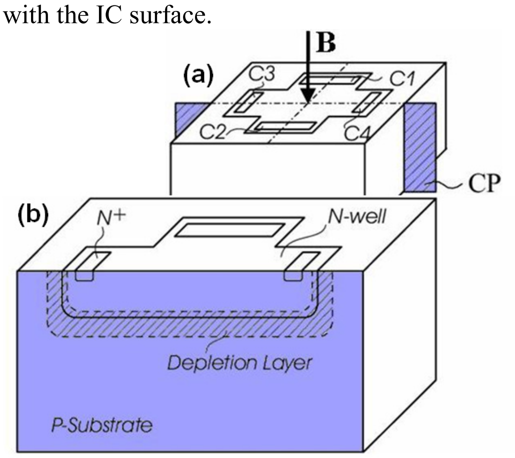

Fig. 1. Integrated planar Hall device in bulk CMOS technology. (a) Layout; CP denotes a crossing plane. (b) View with the cross-section along CP. Metallization and oxide layers are not shown.

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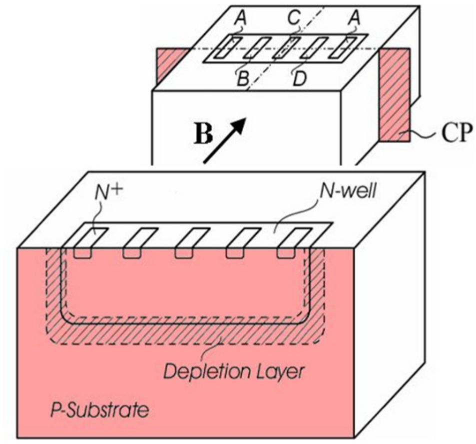

Fig. 2. Integrated vertical Hall device in bulk CMOS technology. (a) Layout; CP denotes a crossing plane. (b) View with the cross-section along CP. Metallization and oxide layers are not shown.

An integrated combination of at least one horizontal and two vertical Hall devices allows for the realization of 3-axis (or "vector") Hall magnetic sensors [4].

In many important applications of Hall magnetic sensors, including compass and position sensing of a small magnet, the key figure of merit of the sensor is its magnetic resolution. The magnetic resolution of a magnetic sensor is the smallest change in the magnetic flux density that can be detected in the output signal of the sensor. The magnetic resolution is usually expressed as an (output-signal-) Artifact-Equivalent Magnetic Field:

$$AEMF = A / S \tag{1}$$

where A denotes a sensor output signal artifact, such as noise voltage or offset drift, and S denotes the absolute magnetic sensitivity of the sensor, see (2).

Resolution of an AC magnetic signal is limited by the intrinsic noise of the sensor in the frequency band of interest. Usually, the intrinsic noise of a sensor is characterized by its noise-equivalent magnetic field (NEMF) spectral density. Then in (1) A denotes the noise voltage spectral density at the sensor output.

Resolution of a quasi-DC magnetic signal depends much on the measurement conditions: -
- In some cases, such as laboratory measurements, we can zero the offset of the sensor just before taking a measurement; and subsequently we observe the sensor output signal for about 10 seconds. Since we can perceive the variations of the output signal up to a frequency of about 10Hz, such a measurement involves the frequency bandwidth from about 0.1Hz to 10Hz. For this reason,

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quasi-DC resolution is usually characterized by the fluctuation of the offset-equivalent magnetic field (OEMF) of a sensor in the frequency bandwidth from 0.1Hz to 10Hz. An example is given in [4]. -

- But in typical industrial applications, we can zero offset of a sensor just once, at the beginning of the life-time mission of the sensor. Then the sensor resolution for quasi-DC magnetic signals usually depends much more on the offset drift than on the noise of the sensor; and the resolution is better characterized by the (offset) drift - equivalent magnetic field (DEMF) in the temperature range of interest.

Accordingly, in quasi-DC magnetic measurements, A denotes the relevant offset fluctuations at the sensor output.

In this paper I will briefly describe the phenomena that determine resolution of Hall magnetic sensors, i.e. magnetic sensitivity, noise, offset fluctuation, and offset drift, explain the methods used to boost or suppress these phenomena, and present some successful applications of these methods.

II. Magnetic Sensitivity

The absolute magnetic sensitivity of a Hall magnetic sensor is its transduction ratio:

$$S = V_H / B \tag{2}$$

where V_H denotes the Hall voltage and B is the magnetic signal "seen" by the Hall device. The absolute sensitivity of a Hall device is proportional to its biasing voltage or current. For comparison purposes, it is useful to define also the voltage-related sensitivity:

$$S_V = S / V_b = (1 / V_b)\,(V_H / B) \tag{3}$$

where V_b denotes the biasing voltage of the Hall device. In modern microelectronics, the biasing voltage is strongly limited; therefore, the voltage-related sensitivity of a Hall device is its crucial parameter.

The voltage-related magnetic sensitivity of a Hall device is proportional with the mobility of the majority charge carriers in the device [2]. Accordingly, the most sensitive **planar Hall devices** are those made of high-electron-mobility-materials, such as InSb ($S_V \approx 3T^{-1}$), GaAs ($S_V \approx 0.2T^{-1}$), or low-doped n-type Si ($S_V \approx 0.07T^{-1}$). The low-doped layers in integrated circuits tend to be more doped, so that the voltage-related magnetic sensitivity of modern integrated planar Hall elements are lower. One of the highest values published recently was $S_V = 0.042T^{-1}$ [5].

The published figures on the voltage-related magnetic sensitivities of **vertical Hall devices**, implemented in CMOS technology, range from less than $0.01T^{-1}$ [6], [7] to about 0.04 T^{-1} [8], [9]. Our new vertical Hall devices feature voltage-related magnetic sensitivities as high as 0.049 T^{-1} [27].

III. Noise

The input-referred noise voltage of a Hall magnetic field transducer is the quadratic sum of the noise voltage at the output of the Hall element and the input-referred noise voltage of the Hall signal amplifier. In modern discrete realizations of Hall transducers, the noise voltage of the amplifier may be negligible; but in integrated Hall sensor systems, the noise contributions of the Hall element and that of the amplifier are usually similar. The noise voltage of both the Hall element and the amplifier is the superposition of several noise components, mostly of the thermal noise and the 1/f noise, but, sometimes, also of the shot noise and the generation-recombination noise.

At sufficiently high frequencies (above the 1/f corner frequency, which is usually between 100 Hz and 100 kHz), i.e. in the thermal noise region, at room temperature, and with usual biasing conditions (a few volts and or a few milliamps), the NEMF spectral densities of modern Hall elements are approximately as follows:

- in integrated silicon Hall elements: about 100nT/√Hz;
- in Hall elements made of III-V compound semiconductors, such as epitaxial GaAs or 2DEG Hall elements: about 10nT/√Hz [10];
- in very high-mobility thin-film InSb Hall elements: about 1.5nT/√Hz; however, this is a theoretical value which has never been experimentally demonstrated due to very high 1/f noise in these devices.

At low enough frequencies, 1/f noise dominates in NEMF spectral density. In this low frequency region, the differences in NEMF spectral density among above mentioned Hall elements are not so pronounced; and if they do exist, they are more related to the device size and processing details, rather than to the used basic material.

IV. Offset

Similarly to the case of noise, offset of a Hall magnetic transducer is the sum of the offsets of the Hall element and the offset of the amplifier. In discrete Hall transducers the offset contribution of the amplifier may be negligible; but in integrated Hall transducers, the offset contributions of the Hall element and that of the amplifier are similar.

The offset of a Hall element is due to lithographic errors, gradients in physical characteristics of the material used for the Hall device, the junction-field effect, the self-magnetic field, piezo-resistance effect caused by mechanical and/or thermal stress, and the thermoelectric effects. The typical OEMF of a Hall element realized in the silicon integrated technology is 5mT - 50mT, while the OEMF of the high mobility quantum well Hall sensors is about 1mT.

Albeit with a stochastic initial value, a good portion of the offset voltage of a Hall element is deterministic and behaves as a voltage at the output of a Wheatstone bridge: it is proportional to the voltage applied at the input terminals of the Hall element. But there are always non-deterministic changes in the offset voltage: the fluctuations caused by 1/f and other low-frequency noise, the fluctuations related to packaging stress, ageing, and other causes. This unpredictable change of offset is referred to as the offset drift. The offset drift may severely limit the quasi-DC resolution of Hall magnetic transducers in most industrial applications.

V. OFFSET REDUCTION TECHNIQUES

Canceling deterministic offset is usually a relatively easy task. We will concentrate here on the techniques which may, at least partially, reduce the offset fluctuations and drift of a Hall magnetic transducer.

- Orthogonal coupling of Hall cells is based on the pairing of an even number of integrated Hall cells and biasing them orthogonally [11]. Due to the non-reciprocity of the Hall cell for the Hall voltage and reciprocity for the offset voltage, the outputs of the cells can be connected in such a way that the respective Hall voltages of the cells are averaged and the offset voltages cancelled.
- Spinning-current method, also known as the connection-commutation and switched Hall plate [12], illustrated in Figs. 3 and 4. The direction of the biasing current is made to spin around the axes of symmetry of the Hall cell, whereas the output voltage is taken from the pair of contacts with transverse position with respect to the direction of the biasing current. The Hall voltage is, to the first approximation, invariant with respect to the symmetry axis, while the offset voltage changes its sign, but remains (almost) constant in magnitude. This technique reduces the offset, but due to the averaging over time, it also reduces the bandwidth of the Hall sensor.

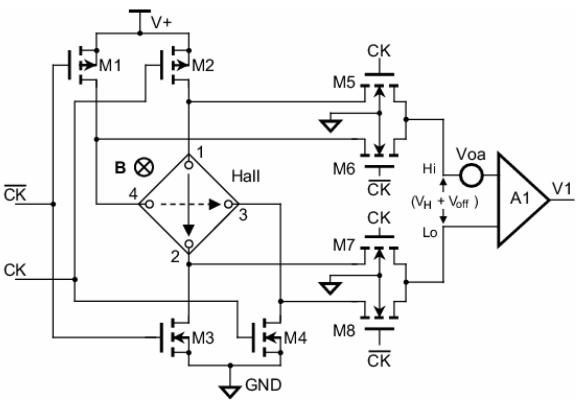

Fig. 3. A simple implementation of the Hall spinning-current biasing circuit. The whole system is shown in Fig. 4.

- Combination of orthogonal coupling and spinning-current method in an array of Hall cells, as demonstrated, for example, in [13].

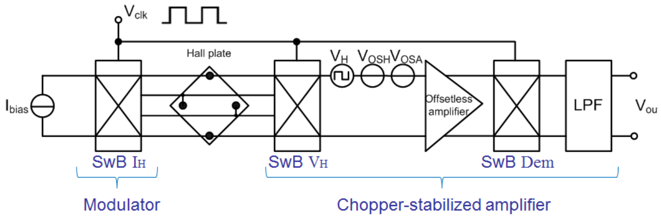

Fig. 4. Block diagram of the Hall spinning current biasing and signal conditioning system. Notation: SwB: Switching Box; I_H: Hall biasing current; V_H: Hall voltage; Dem: Demodulator.

The spinning-current method is a variation of the chopping technique – see Fig. 4. Similarly to the chopping, the spinning current method also reduces the 1/f noise of the switched Hall device. This can be understood by imagining the 1/f noise voltage at the output terminals of a Hall device as a slowly fluctuating offset voltage. If the biasing current of the Hall device spins fast enough, then there will be no difference between the static and the fluctuating offset, and the system will cancel both of them. An essential condition for good operation of the spinning current method is that the spinning frequency is significantly higher than both the highest frequency of the measured magnetic field and of the corner frequency of the 1/f noise. This allows efficient filtering of the offset voltage and the parasitic spikes that are added by the switches, without deteriorating the spectrum of the measured magnetic signal.

The modulation-demodulation loop of a Hall element usually includes the first amplifier, in such a way that the offset and low-frequency noise of the amplifier are also reduced.

In the reference [14] are estimated the limits of the offset reduction in silicon integrated Hall sensors. The residual OEMF can be 1μT for a Hall plate biased by constant voltage; but if the Hall plate is biased by the constant current the residual offset can be reduced to 100 nT, provided that the voltage at the supply terminals of the Hall plate is less than 1.75 V.

A serious challenge in the design of a Hall sensor based on the spinning current technique is how to cope with the switching spikes. In many practical designs, the switching spikes result in additional noise and/or residual offset, offset drift, and 1/f noise. For this reason, in practical realizations of Hall magnetic sensors, it is difficult to approach the physical limit of the magnetic resolution estimated below in Section VII.

VI. MAGNETIC FLUX CONCENTRATORS

The effective resolution of a magnetic sensor can be increased by increasing the local magnetic field "seen" by the sensor. This could be achieved by combining a magnetic sensor with the suitable ferromagnetic parts, which reduce the reluctance of a magnetic circuit, and/or concentrate the magnetic flux on the relevant part of the magnetic sensor. The resulting increase of the magnetic field perceived by the sensor is equivalent with an increase in its magnetic sensitivity – see (2).

We will consider particularly the planar integrated magnetic concentrators (IMC) [15], Fig. 5. A planar IMC is a flat ferromagnetic part integrated on the surface of a magnetic sensor in a wafer post-processing step. The magnetic flux density "seen" by a Hall element placed near an edge of an IMC can be up to 10 times higher than the flux density far away from the IMC. Since such magnetic field amplification ads no noticeable noise, the effective magnetic resolution of a combination IMC-Hall element can be 10 times higher than that of the Hall element alone.

Moreover, an IMC modifies locally the direction of an in-plane external magnetic field. This enables the realization of 2- and 3-axis integrated magnetic sensors by using only conventional planar Hall plates.

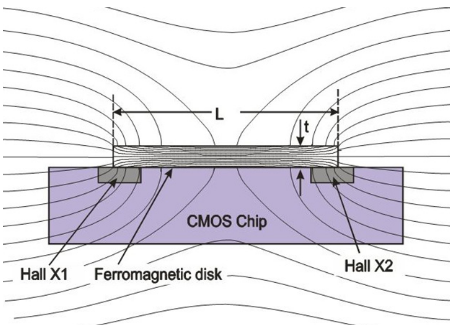

Fig. 5. IMC-Hall: Integrated combination of a planar magnetic flux concentrator and horizontal Hall devices.

VII. PHYSICAL LIMIT OF RESOLUTION

Let us estimate the physical limit of the magnetic resolution of a Hall magnetic sensor under the following conditions:

- The Hall device is operated under perfect spinning-current conditions, so that its offset and 1/f noise are completely eliminated, and the residual thermal noise is not increased;
- The Hall device is combined with a magnetic flux concentrator, which acts as a noiseless magnetic field amplifier.

Then, based on Equations (1) - (3), we can write for the minimum NEMF spectral density

$$\text{NEMFsd,min} \geq \sqrt{(4\,k\,T\,R_H)} / (G_{MC}\,S_V\,V_b) \qquad (4)$$

with the following notation:
k – Boltzmann constant; T – absolute temperature; R_H – the resistance of the Hall device; G_{MC} – the magnetic flux density gain of the magnetic concentrator; S_V - the voltage-related sensitivity of the Hall device; and V_b - the biasing voltage of the Hall device.

Equation (4) can be transformed into the following form:

$$\text{NEMFsd,min} \geq \sqrt{(4\,k\,T)} \;/\; (G_{MC}\,S_V\,\sqrt{P_b}) \qquad (5)$$

where P_b denotes the biasing power of the Hall device,

$$P_b = V_b\,I_b \qquad (6)$$

For example, at the conditions typical for an integrated magnetic sensor, namely
V_b = 1V, I_b = 1mA, T = 300K, S_V = 0.05 (contemporary limit for silicon Hall), equation (5) gives

$$\text{NEMFsd,min} \geq 82\text{nT}/\sqrt{\text{Hz}} \;/\; G_{MC} \qquad (6)$$

Even with G_{MC} = 1 (no magnetic concentrator), such a magnetic resolution is compatible with some compass applications: for the sensor bandwidth DC to 10Hz, (6) corresponds to the magnetic resolution of 0.26µT(rms).

By combining the output signals of N equal Hall devices, the magnetic resolution can be improved by a factor of $\sqrt{N}$.

VIII. EXAMPLES OF HIGH RESOLUTION HALL MAGNETIC SENSORS

The residual offset of silicon integrated Hall sensors was 5µT [16] when the nested-chopper technique was applied; and 2µT [17], when four eight-contact Hall cells were orthogonally coupled and the eightfold spinning current method applied simultaneously.

One of the best results reported so far for the temperature drift of offset of an integrated Hall sensor is 0.3µT/C (typical) and 1µT/C (maximum) [18].

A silicon integrated magnetic sensor based on the combination IMC-Hall elements has the NEMF spectral density less than 125nT/√Hz at frequencies above 10Hz [19].

The three-axis magnetic sensor based on the combination IMC-Hall, similar to that shown in Fig. 5, is currently the dominant technology used for electronic compass in mobile phones [20] – Figs. 6, 7. The latest versions of such compass chips operate at very low power level (supply voltage 2.4V, average current 350µA at repetition rate 8Hz, resolution 0.3µT) [21].

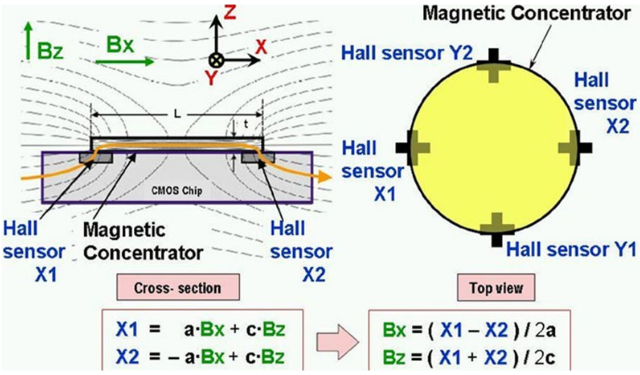

Fig. 6. Illustration of the 3-axis magnetic field sensor based on IMC-Hall technology (Courtesy of AKM, Japan.)

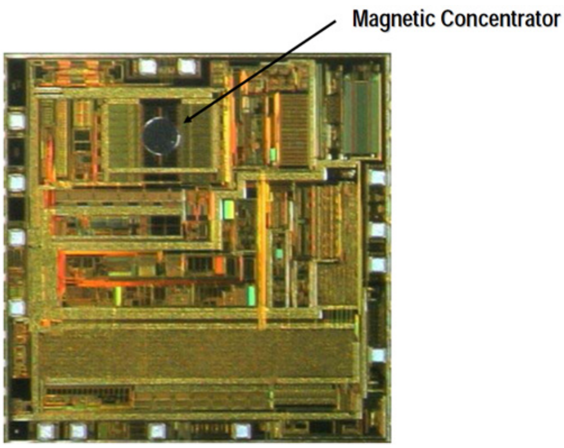

Fig. 7. Photograph of the 3-axis integrated compass chip based on the IMC-Hall technology, as illustrated in Fig. 6. This chip is applied as electronic compass in mobile phones.

For quantum well Hall elements, the measured DC OEMF was 1μT [10], and with the current spinning, the residual fluctuations were 100nT [10] and 30nT [22]. In [23] for Sn-doped InSb single crystal thin film the DC resolution of 480nT for DC Hall biasing was reported, as well as the DC resolution of 42nT for AC Hall biasing, including the spinning current offset cancellation in both cases.

The best reported quasi-DC resolution for a Hall sensor system is the OEMF fluctuation in the frequency bandwidth from 0.1Hz to 10Hz of 10nT(rms) [24]. The application of this technology enabled the development of the Hall probes and teslameters with unprecedentedly high resolution and accuracy, approaching those of NMR teslameters [25], [26].

We have recently developed CMOS integrated horizontal and vertical Hall devices with remarkably low NEMF (Fig. 8) [27]. With appropriate biasing power and application of an efficient spinning current technique, the magnetic resolutions of magnetic sensors with such horizontal and vertical Hall devices are about equal and approach the level that was estimated in Section VII.

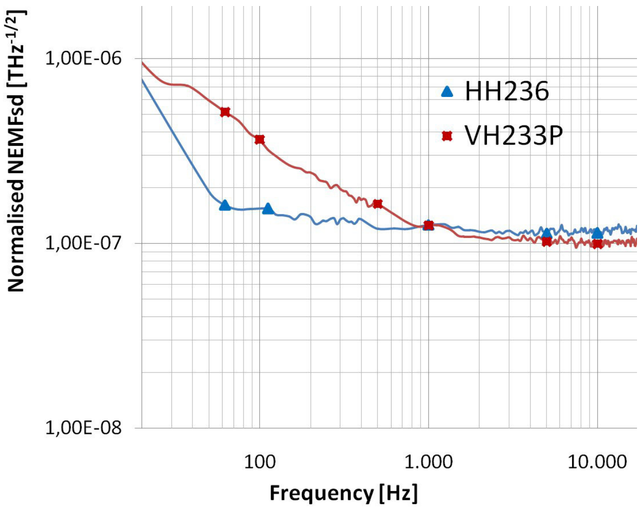

Fig. 8. Measured noise-equivalent magnetic field spectral density of the SENIS' Hall devices implemented in 0.35μm CMOS technology, normalized to biasing power of 1mW. HH236: horizontal Hall device ($S_V = 0.038T^{-1}$, R = 3kΩ); VH233P: vertical Hall device ($S_V = 0.043T^{-1}$, R = 1.9kΩ); Bias voltage (both): 1V.

The results shown in Fig. 8 disprove the claims in the literature that a vertical Hall device has to be substantially worse than a planar Hall element.

IX. Conclusion

For a given power dissipation and with the application of the spinning current technique, the magnetic resolution of a Hall magnetic sensor is determined by the voltage-related magnetic sensitivity (S_V) of the employed Hall-effect device. S_V is proportional to the electron mobility of the device material. Due to the doping level found in silicon integrated circuits and certain design constrains, S_V of Hall devices integrated in contemporary silicon ICs is limited to about $0.05T^{-1}$. The limit in S_V is about the same for both horizontal and vertical integrated Hall devices. For a Hall device biasing power of 1mW, this results in the theoretical limit of the noise-equivalent magnetic field spectral density NEMFsd ≥ 82nT/√Hz. The limit in NEMF is much lower for high-electron-mobility materials.

Higher resolution Hall magnetic sensors can be built by increasing the biasing power P_b of the Hall device (resolution improvement proportional with $\sqrt{P_b}$), by using several (N) equally biased Hall devices (improvement proportional with $\sqrt{N}$), and by combining the Hall device(s) with a magnetic flux concentrator (resolution improvement proportional with magnetic gain of the flux concentrator, which is typically between 3 and 10).

ACKNOWLEDGEMENT

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