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Integrated Hall-effect magnetic sensors

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Abstract

Integrated Hall magnetic sensors are used in automotive and computer industry. Their farther penetration into other applications is mainly hampered by the problems of switching noise and of offset and drift related to the packaging stress. The equivalent magnetic noise and offset can be dramatically reduced by integrating magnetic flux concentrators on the sensor chip. A promising way to eliminate the influences of packaging stress and temperature variations is to apply the self-calibration using an integrated coil. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Magnetic field sensors based on the Hall-effect are nowadays probably the most widely used magnetic sensors. Interestingly, they are relatively rarely used to measure just a magnetic field. Much more, Hall sensors are applied as key components in contact-less sensors for linear position, angular position, velocity, rotation, and current. More than 2 billion of Hall magnetic sensors will be soled worldwide in 2000. There is hardly any new car in the world without a dozen of Hall magnetic sensors inside; millions of ventilators and millions of disc drives in personal computers use brush-less motors with Hall magnetic sensors inside; and millions of current sensors in various products depend also on Hall magnetic sensors.

Such a big importance of Hall magnetic sensors is partially due to their almost perfect compatibility with microelectronics technology. The optimal material characteristics, device structures and dimensions, and fabrication processes are similar to those readily available in semiconductor industry. Therefore, the development in Hall magnetic sensors does not require much of specific investments in fabrication processes.

Most of currently applied Hall magnetic sensors are low-cost discrete devices. However, an ever increasing proportion of them comes in the form of integrated circuits. The integration allows the system approach to improve the sensor performance in spite of the mediocre characteristics of the basic Hall cells. In other words, integrated Hall magnetic sensors are "smart": they incorporate means for biasing, offset reduction, temperature compensation, signal amplification, signal level discrimination, and so on.

In this paper, we summarize the characteristics of integrated Hall magnetic sensors decisive for their penetration into new broad application areas; we present the best well-established methods for improving these key characteristics; and we identify and discuss a few emerging concepts for further radical improvement of performance and applicability of integrated Hall magnetic sensors.

2. State of the art

A typical equivalent offset of a Hall element realized in silicon integrated circuit technology is several milliteslas. The offset is supply voltage-, temperature- and stress-dependent, and sets the minimum magnetic field which could be measured. A classical way of reducing offset is to orthogonaly couple two or four identical, but layout-rotated Hall elements. This method, used in integrated Hall sensors realized in bipolar technology, brings an offset of about 1 mT. In Hall circuits realized in CMOS technology, the so-called spinning current method (periodic supply- and output-contact permutations) is widely used. In a commercially available CMOS integrated Hall magnetic sensor this method allowed to reduce offset down to 0.5 mT [1]. But the limits of the method are much farther: an offset as low as 5 μT was recently demonstrated [2]. An equivalent offset of about 5 mT, we find also in some commercially available digitally-trimmed integrated Hall sensors.

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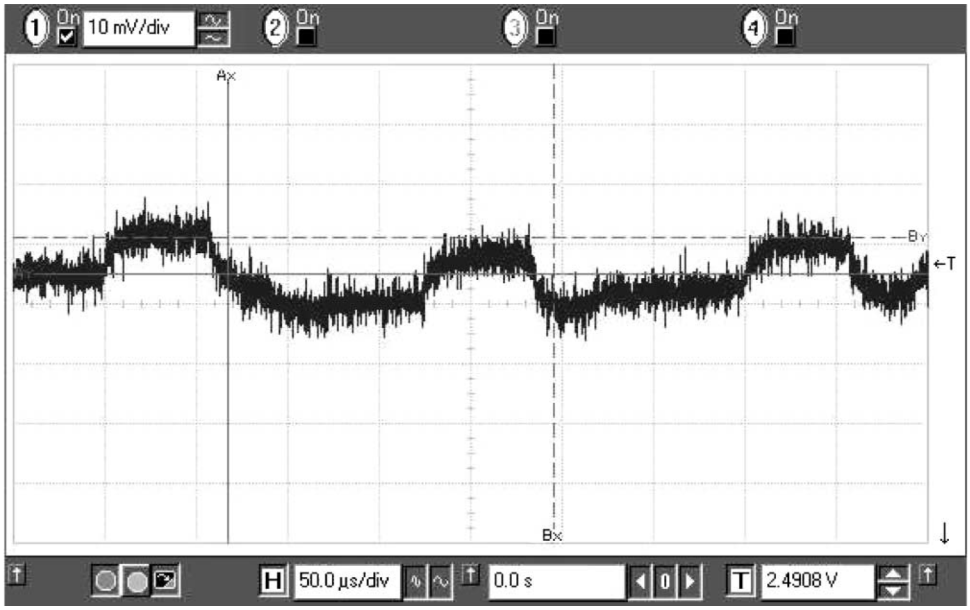


Fig. 1. The output voltage of a commercially available CMOS integrated Hall magnetic field sensor based on the spinning-current and chopping principles. The peak to peak output voltage noise corresponds to an input magnetic field ripple of about 170 µT.

The spinning current method not only reduces the offset but also can completely remove the 1/*f* noise of a Hall element [2]. If the integrated amplifier is also chopped, which is usually the case in a modern integrated CMOS Hall sensor, the sensor becomes virtually free from the 1/*f* noise. However, the offset and the 1/*f* noise reappear at the internal switching frequency, see Fig. 1. Such a "switching noise" in an integrated CMOS Hall sensor is usually equivalent to an input magnetic ripple of several 100 µT. This corresponds usually to an equivalent magnetic noise density of up to $1\,\mu T/\sqrt{Hz}$. One solution of the problem is to use an array of several Hall elements; then a noise density as low as $50\,nT/\sqrt{Hz}$ is achievable [3].

Another major problem with the state-of-the-art Hall magnetic sensors integrated in silicon is drift in their characteristics. The instability is the consequence of a variable stress in the sensor chip created by the package. A variable stress in the sensor chip transforms itself, via the piezo-resistance and the piezo-Hall-effects, into a drift in the sensor parameters. Whereas the disastrous influence of these effects on the offset is virtually eliminated by the current spinning and the chopping, the influence on the sensitivity and its temperature dependence stays. The effect is particularly serious in plastic-encapsulated integrated Hall magnetic sensors. Figs. 2 and 3 illustrate the problem.

Briefly, we found that the encapsulation of an integrated Hall device in a plastic package may drastically change the temperature coefficient of its magnetic sensitivity [4,5]. This makes difficult the thermal compensation. We also found that a thermal shock may produce a non-permanent change in sensitivity of an integrated Hall sensor as high as 2% [5,6]. The importance of these problems becomes particularly clear in view of the current need of the automotive industry for magnetic sensors working well in the temperature domain between −40 and 150°C (and perhaps up to 175°C).

In Table 1, we compare some characteristics of a few representative commercially-available integrated Hall magnetic field sensors. Note the information on noise and drift, which are usually not given in the data sheets of vendors.

3. New concepts

One way to cope with the purely electrical parasitic signals, such as electronic offset and noise, is to amplify in situ the useful magnetic signal seeing by the Hall element.

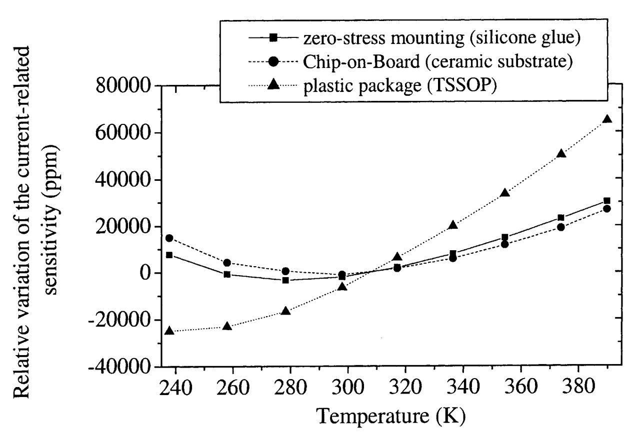


Fig. 2. Measured variation of the current-related sensitivity of a CMOS Hall element as a function of temperature for three assembling and encapsulation cases. The variation is expressed in percent relative to the value at 308 K [4,5].

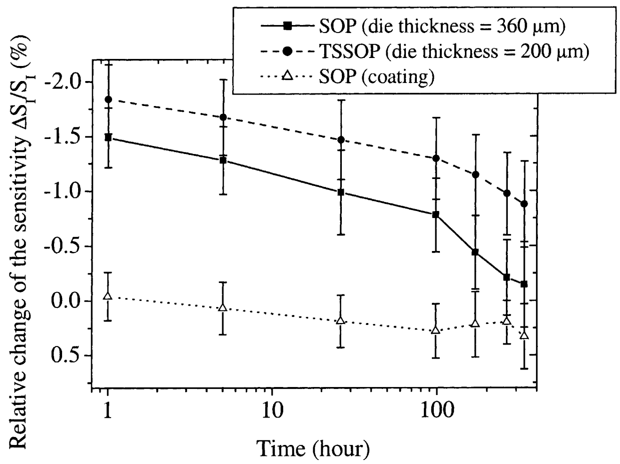


Fig. 3. Mean drift of the magnetic sensitivity after a reflow soldering cycle for conventional SOP and TSSOP plastic packages. The drift is related to the initial sensitivity value (value before the reflow soldering). The error bars give the standard deviation on 30 samples [5,6].

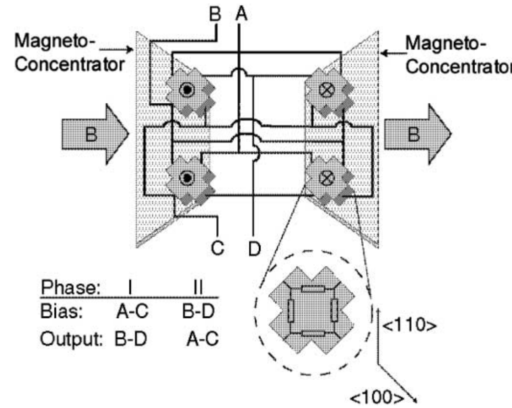


Fig. 5. A combination of four Hall plates with two magnetic concentrators. The concentrators change the direction of the magnetic field and focus magnetic flux on the Hall elements. The Hall plates below the different concentrators see a magnetic field in the opposite direction. The Hall plates are connected in parallel so that their offset voltages partially cancel out.

To this end, we developed the concept of integrated magnetic flux concentrators [7] (Fig. 4). The integrated magnetic flux concentrators convert locally a magnetic field parallel with the chip surface into a magnetic field perpendicular to the chip surface. Moreover, the local perpendicular component of the magnetic field may be for a factor 5 or more stronger than the original field.

By placing a pair or a quad of conventional Hall elements below the flux concentrators and close to the gap (Fig. 5), we obtained a magnetic sensor system with the following

Table 1
Characteristics of some commercially available integrated Hall magnetic field sensors

Vendor	A	B	C	Units
Technology	CMOS: spinning current; programmable offset; gain; temperature coefficient	Bipolar: quad Hall sensing element; laser trimmed thin film resistors	BiCMOS	
Bandwidth	1.3	NA	23	kHz
Sensitivity (S)	52	31.25	13	V/T
$\Delta S/S$[a]	−1.2[b]	−1.66	−0.4	%
Offset (B_{offset})	−1.26[b]	−0.73	−3.1	mT
$\Delta B_{\mathrm{offset}}$[c]	0.01[b]	0.13	0.72	mT
White noise	1540	64	30.15	$\mathrm{nT}/\sqrt{\mathrm{Hz}}$
Ripple noise	0.460	1.29	1.0	$\mathrm{mT_{pp}}$

[a] Thermal hysteresis: the relative change in sensitivity at room temperature, after performing a slow temperature cycle up to 125°C and down to room temperature.
[b] At sensitivity set by programming to 10 V/T.
[c] Change in equivalent offset at room temperature, after performing a slow temperature cycle up to 125°C and down to room temperature.

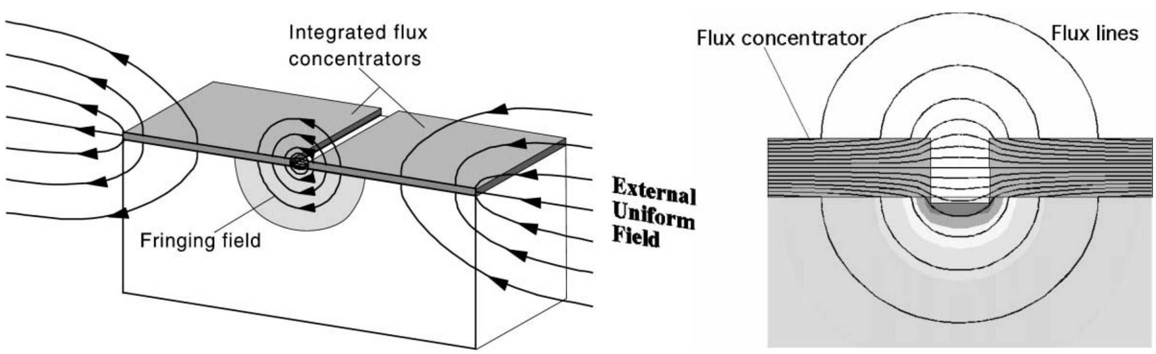
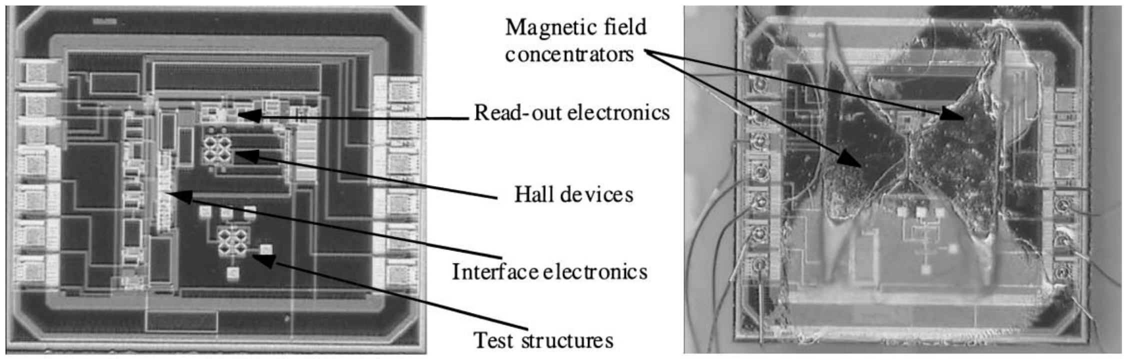


Fig. 4. The integrated magnetic flux concentrators consists of a high-permeability ferromagnetic layer deposited on the chip surface. The layer is structured so that a narrow air gap is created in the middle of the chip. Around the air gap, the fringing field has a strong component perpendicular to the chip surface. The inset at the right-hand side shows a simulation result (adapted from [8]).



(a) (b)

Fig. 6. The test chip of an integrated Hall magnetic sensor based on the concept shown in Fig. 5: (a) the basic CMOS chip; (b) the chip combined with the magnetic flux concentrators [9].

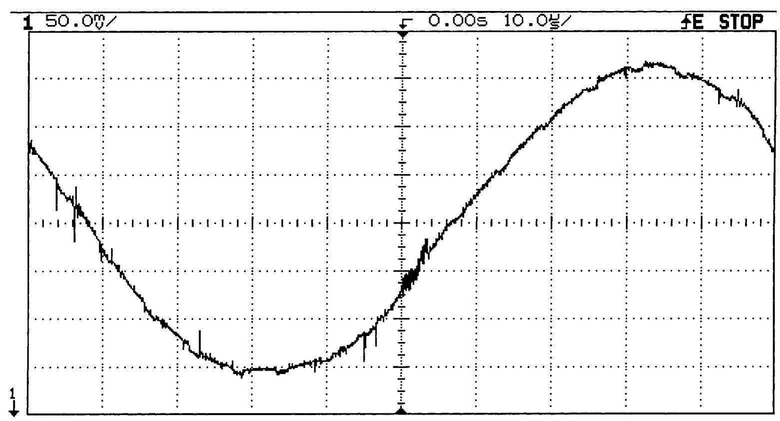


Fig. 7. An example of the output signal of the integrated Hall sensor shown in Fig. 5. The excitation magnetic field has the amplitude 0.85 mT and the frequency 10 kHz. Horizontal scale: 10 ms per division; vertical scale: 50 mV per division.

combination of features: existence of a magnetic gain, which brings a higher magnetic sensitivity, lower equivalent magnetic offset, and lower equivalent magnetic noise than those in conventional integrated Hall sensors; and sensitivity to a magnetic field parallel with the chip surface, much as in the case of magneto-resistance sensors. The four Hall elements may be first orthogonally coupled, and then spin-biased, as indicated in Fig. 5; or the four Hall elements may be treated as the units of an array, as suggested in [3].

Fig. 6 shows the test chip of an integrated CMOS Hall magnetic sensor based on the above concept [9]. Fig. 7 illustrates the performances of the test chip. We obtained the following main characteristics: equivalent magnetic offset = 0.15 mT; magnetic sensitivity = 125 V/T; bandwidth limited by the filter 30 kHz, otherwise 200 kHz.

In our opinion, the most promising way to cope with the problem of the sensitivity dependence on stress, temperature, and aging is the self-calibration using an integrated coil. Proposed already many years ago, this concept is becoming feasible only nowadays, with the advent of the sub-micrometer IC technology. A three-turn integrated coil can provide a calibrating magnetic induction of 0.15 mT per 1 mA of the coil current [3]. Recently, by applying the auto-calibration concept, a virtually zero temperature cross sensitivity Hall magnetic sensor was demonstrated [10].

4. Conclusion

Silicon integrated Hall magnetic sensors can be further improved. Using more than one Hall element on a chip helps decreasing offset and noise. By integrating magnetic flux concentrators with the sensor chip, we can increase their resolution at least for a factor of 5. A promising way to eliminate the drift due to the packaging stresses is to apply the self-calibration using an integrated coil. Scaling down the dimensions of the Hall element and of the coil renders the self-calibration easier.

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