Effect of Stress Due to Plastic Package Moisture Absorption in Hall Sensors

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Commercial magnetic sensors based on the Hall effect are usually encapsulated in non-hermetic plastic packages. These plastic packages are known to swell in high humidity conditions due to moisture absorption. This swelling will modify the stress seen by the Hall sensor, causing the Hall sensitivity to be altered due to the piezo-Hall effect. The sensitivity drift, which is random in nature, may become the long-term stability limiting factor in high-end sensors. The objective of this work is to characterize in depth the sensitivity change due to moisture absorption and to review and implement two Hall sensitivity compensation methods.

Index Terms—**Compensation, Hall effect, moisture absorption, Piezo-Hall, stress.**

I. Introduction

SILICON magnetic sensors based on the Hall effect have proven to be an excellent choice for many applications, such as position sensing, gear-tooth sensing, contact-less switching, and linear sensing [1]. Hall sensors have some key advantages when compared with other magnetic sensors: they can be seamlessly integrated in silicon together with circuits for amplification and control with no added processing steps [2] and their offset can be dynamically compensated [3], [4]. For high-end magnetic sensors, it is very important to asses the long-term stability of the system. As will be shown, the hygroscopic swelling of the plastic package due to moisture absorption may become a limiting factor in certain applications if no stress compensation scheme is implemented in the sensing system.

Moisture absorption is caused by the polymer-water affinity action [5]. Part of the water absorbed by the plastic compound, called "bound" volume, forms hydrogen bonds with the polymer chain while the remaining, called "unbound" volume, occupies voids in the package structure. It is believed that the package swelling is caused only by the "bound" volume [5]. This swelling causes the Hall plate sensitivity to be altered [6], [7] due to the piezo-Hall effect [8].

The piezo-Hall effect describes the change in the Hall coefficient ΔR_{Hi} due to mechanical stress, and it can be defined in terms of the applied stress tensor σ, the piezo-Hall tensor P, and the zero-stress Hall coefficient R_{Ho} [8]

$$\frac{\Delta R_{Hi}}{R_{Ho}} = \sum_j P_{ij}\sigma_j. \tag{1}$$

Because of its symmetry, the stress tensor has been written using the single suffix notation. The crystal symmetry of silicon causes the piezo-Hall tensor P to have only three independent coefficients, P_{11}, P_{12}, and P_{44}. The piezo-Hall coefficients are summarized in Table I, [8] for n-type silicon.

TABLE I
Piezo-Hall Coefficients in Lightly Doped N-Type Silicon at 300 K [8]

	P_{11}	P_{12}	P_{44}
N-Type	-93×10^{-11} Pa^{-1}	45×10^{-11} Pa^{-1}	6×10^{-11} Pa^{-1}

The Hall sensitivity variation due to stress for Hall sensors implemented in the $\{100\}$ plane can be written as [9]

$$\frac{\Delta S}{S} = P_{12}(\sigma_1 + \sigma_2) + P_{11}\sigma_3 \tag{2}$$

with $\sigma_1 = \sigma_x, \sigma_2 = \sigma_y$, and $\sigma_3 = \sigma_z$. It is interesting to note that for this particular plane ($\{100\}$) the piezo-Hall effect is isotropic, meaning that rotating the Hall device in the plane will not modify the relationship between stress and sensitivity change.

The present work is divided into two sections. In the first the transient behavior, reversibility and repeatability of the moisture absorption effect are documented in depth for a commercial Hall sensor. In the second two systems to compensate for the resulting sensitivity variation are designed, implemented in silicon and measured.

II. Effect of Moisture Absorption

Commercial off-the-shelf Hall sensors were used to characterize the effect of moisture absorption. The thickness of the packaging material on top of the die is approximately 0.5 mm. Before each of the tests, the sensor to be measured was placed in a temperature chamber at 150°C for several days, thus effectively removing all moisture from the package.

In the first experiment, the sample was placed in a 90% relative humidity (RH) environment at 25°C for ten days, with measurements taken every 30 min under a constant magnetic field. Afterwards, the relative humidity was set to 45% for another 10 days. Finally, the humidity was changed back to 90% RH. As shown in Fig. 1, the Hall sensor sensitivity increased while the environment was set at 90% RH. Once the humidity was

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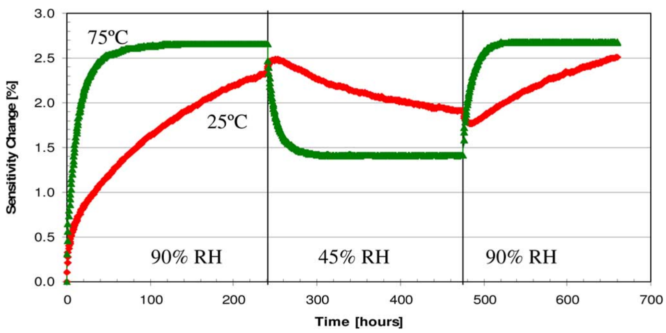

Fig. 1. Sensitivity change of an initially "dry" sensor exposed sequentially to 90% RH, 45% RH, and 90% RH, at 25°C and 75°C.

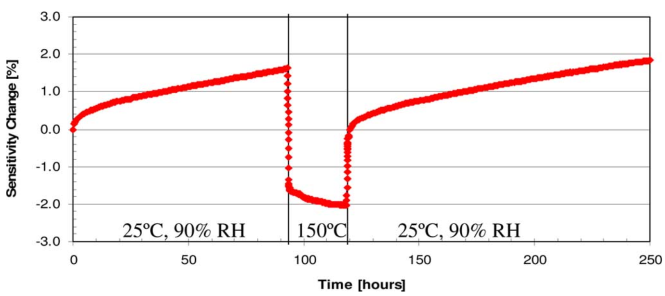

Fig. 2. Sensitivity change of an initially "dry" sensor exposed sequentially to 90% RH 25°C, 150°C, and 90% RH 25°C. The absolute sensitivity values are within 0.1% at the beginning of both 90% RH cycles.

reduced to 45% RH, the sensitivity decreased. Finally, the sensitivity increased again once the ambient humidity was changed back to 90%. The same experiment was repeated with the environmental chamber temperature set to 75°C.

Several conclusions can be drawn from this experiment. The positive sensitivity drift in both measurements proves that the package is effectively swelling. The compressive stress created by the plastic compound is reduced as the package swells (a positive stress change) which is translated into a positive sensitivity change. Moreover, the moisture absorption by the plastic package is a reversible effect, while the operating temperature greatly affects the rate of sensitivity change in the Hall sensor.

For the second experiment the sensor was placed in a high humidity environment (90% RH) at 25°C. After approximately four days, the temperature was raised to 150°C for two days to drive the moisture out of the package. Finally, the temperature was reduced back to 25°C, and the humidity set to 90% RH. The resulting drift in the sensitivity is shown in Fig. 2. The sensitivity of the Hall sensor has a small temperature dependence, which explains the drop in sensitivity when going from 25°C to 150°C.

Fig. 3 compares the change in sensitivity over time for the initial part of this experiment at 25°C, the sensitivity drift after staying at 150°C and a third series, which corresponds to a new measurement performed with the same device two months later (also at 25°C, 90% RH). Two important conclusions can be obtained from this test. The rate of sensitivity change and thus the rate of moisture absorption by the plastic package for a given

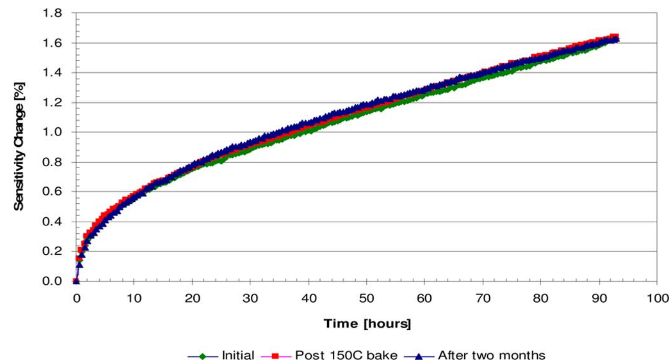

Fig. 3. Repeatability of the sensitivity drift at 90% RH, 25°C.

part is a deterministic and repeatable effect. A time period of two days at 150°C is sufficient to drive all the moisture out of the package used in this sensor.

III. Stress Compensation

Two schemes have been implemented in silicon to compensate for the sensitivity drift. The first one uses integrated piezoresistors of the same material as the Hall sensor to measure changes in the stress conditions and use these results to compensate the sensitivity [10], [11]. The second method employs an integrated coil to generate a reference magnetic field that measures the sensitivity of the Hall sensor and can be used to implement a feedback system that dynamically compensates the variations in the system gain [12], [13].

A. Compensation by Mechanical Stress Feedback

The stress on the die surface can typically be considered to be homogeneous over small distances [14], so that resistors placed close to the Hall plate can be employed to measure the stress change via the piezoresistive effect. This information can then be used to compensate the Hall sensitivity drift [10], [11]. In the following, the effect of the normal stress will be neglected ($\sigma_z = 0$). As a result, the sensitivity change due to stress in a Hall device implemented in the $\{100\}$ plane can be considered as

$$\frac{\Delta S}{S} = P_{12}(\sigma_x + \sigma_y). \tag{3}$$

The Hall sensor sensitivity depends on the sum of the in-plane normal stresses $\sigma_x + \sigma_y$; thus, the stress sensor should be designed to respond to the sum of in-plane normal stresses as well. A group of two series resistors of the same value placed in orthogonal directions (L shape) [15] fulfill this requisite, regardless of the group orientation in the $\{100\}$ plane. The resistors are made of the same material as the Hall sensor in order to have the best possible stress tracking. Their change in resistance is given by

$$\frac{\Delta R}{R} = (\sigma_x + \sigma_y)\frac{\pi_{11} + \pi_{12}}{2} \tag{4}$$

TABLE II
PIEZORESISTANCE COEFFICIENTS IN LIGHTLY DOPED N-TYPE SILICON AT 300 K [16]

	π_{11}	π_{12}	π_{44}
N-Type	$-102.2\text{x}10^{-11}$ Pa^{-1}	$53.4\text{x}10^{-11}$ Pa^{-1}	$-13.6\text{x}10^{-11}$ Pa^{-1}

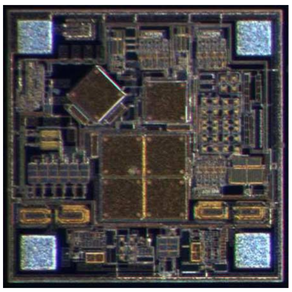

Fig. 4. Microphotograph of the silicon die with implemented Hall plates and L-shaped piezoresistor pairs for stress measurement.

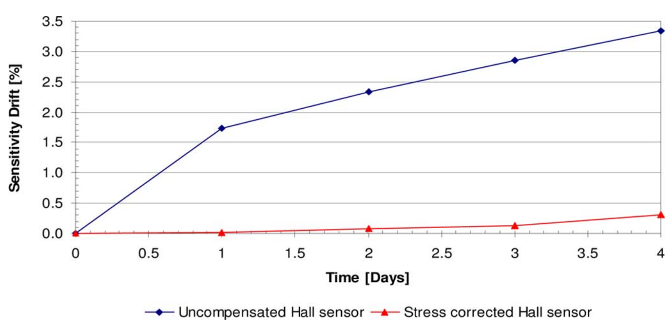

Fig. 5. Uncompensated and compensated sensitivity drift of an initially dry sensor with ambient conditions set to 90% RH, 25°C.

where π_{11} and π_{12} are the piezoresistance coefficients of the material from which the resistors are made (Table II, [16]).

A silicon chip containing several Hall sensors and L-shaped piezoresistor pairs was designed, fabricated, and encapsulated using the same type of plastic package as commercial sensors. Additional circuitry had to be designed and integrated on the chip in order to output the Hall sensor and piezoresistor signals through a four-pin package. A microphotograph of the silicon die is presented in Fig. 4.

To test the compensation method, the packaged part was placed in an environmental chamber with ambient conditions set to 25°C, 90% RH, after performing a dehydration bake. The Hall sensor sensitivity change and stress sensor resistance change were measured in these conditions every 24 h for four days. From the resistance variation in the stress sensor the change in stress was inferred [see (4)]. This value was then used to estimate the sensitivity variation (3). A stress-corrected sensitivity change was finally obtained by subtracting the measured sensitivity change from the estimated change. The two sensitivity drifts are presented in Fig. 5.

As it can be readily seen, the compensation method reduces the sensitivity drift by an order of magnitude. The experiment was repeated with the environmental chamber set to 75°C,

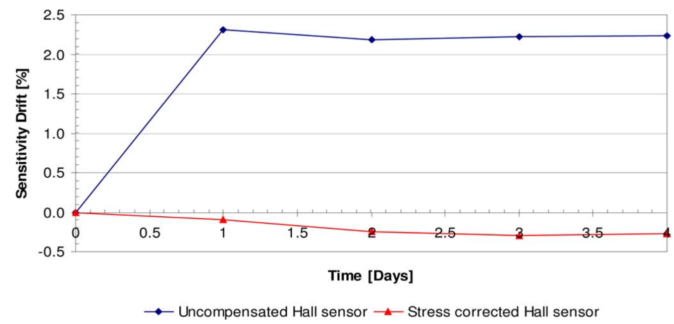

Fig. 6. Uncompensated and compensated sensitivity drift of an initially dry sensor with ambient conditions set to 90% RH, 75°C.

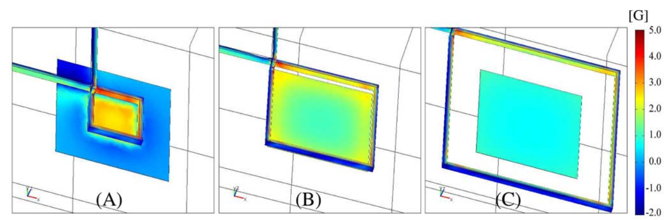

Fig. 7. Magnetic field normal to the Hall plate surface for different coil sizes. Hall plate size: 50 μm side length. Bias current: 5 mA. Distance from Hall plate edge to coil: (A) -15 μm, (B) 0 μm, (C) 15 μm.

90% RH, with the results shown in Fig. 6. The piezo-Hall and piezoresistance coefficients had to be adjusted to the new operating temperature using their respective temperature coefficients [9], [16].

B. Compensation by Magnetic Feedback

An integrated coil can be used to generate a reference magnetic signal to calibrate the Hall sensor [12], [13]. In this section the design, implementation, and measurement results of an integrated coil are shown, and a complete system featuring magnetic feedback is proposed.

The integrated coil was optimized to achieve maximum magnetic field strength on the Hall plate surface using coupled electrostatic-magnetostatic finite element simulations. Single turn-coils were simulated first. Fig. 7 shows the magnetic field distribution on the surface of a 50 μm Hall plate for three different coil sizes. In all cases, a current of 5 mA is flowing through the coil.

Fig. 8 shows a plot of the magnetic field averaged over the surface area of a 50 μm Hall plate generated by a single turn coil as a function of the distance between coil and Hall plate edge. It can be clearly seen that the average magnetic field is largest for coils with geometry similar to that of the Hall plate. It is also interesting to see that for coils with dimensions smaller than the Hall plate size [as in Fig. 7(A)] the average magnetic field contribution is still positive.

The information obtained from these simulations was used to set the coil design variables, including the number of turns, cross-sectional area, and inner radius. The optimized coil was implemented in silicon (Fig. 9). Measurements show that the normalized Hall plate output due to the magnetic field generated

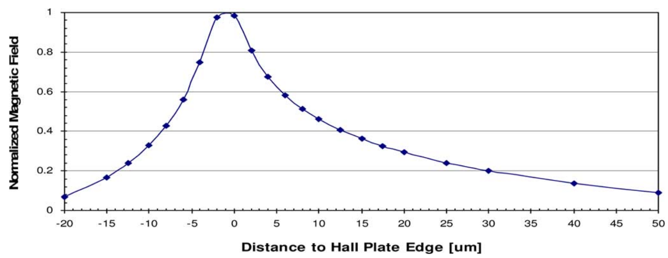

Fig. 8. Average magnetic field on a 50 μm Hall plate for single-turn coils as a function of the distance to the Hall plate edge, normalized with respect to the maximum magnetic field.

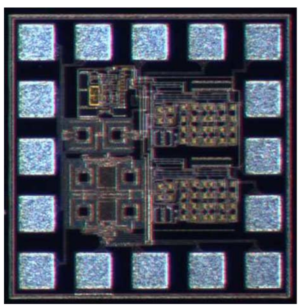

Fig. 9. Microphotograph of the silicon die with implemented Hall plates and integrated coils.

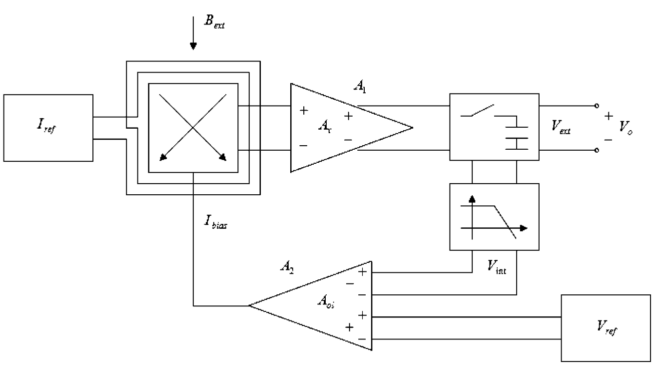

Fig. 10. Schematic diagram of the proposed system for Hall sensor sensitivity compensation based in magnetic feedback.

by the coil is 70.6 V/A^2, a 67% improvement with respect to previous results [12].

Based on these results, a magnetic field sensing system that automatically compensates the sensitivity changes via magnetic feedback is proposed (Fig. 10). The signal path consists of a Hall device with an integrated coil surrounding it, an amplifier A_1 (with a closed-loop gain A_v) and a subsystem to discriminate the external magnetic field, the internal magnetic field and the Hall-plate-plus-amplifier offset. The feedback loop consists of a low-pass filter and an amplifier A_2 (with open-loop gain A_{ol}), which controls the Hall sensor bias current I_{bias}. A reference voltage V_{ref} is used in the feedback loop, and a current I_{ref} (derived from V_{ref}) biases the integrated coil.

An advantage of the system presented in Fig. 10 is that it not only compensates for stress variations but also temperature changes. It can be shown that the system gain precision is solely defined by the $V_{\mathrm{ref}}/I_{\mathrm{ref}}$ ratio (a resistor that can be implemented off-chip) [17]. In the future this system should be implemented in silicon to verify these claims.

IV. Conclusion

The measurements performed confirm the important role that moisture absorption has on the stability of Hall-based magnetic sensors. It was demonstrated that the sensitivity drift due to moisture absorption was reversible when the moisture was driven out of the package. To guarantee a higher degree of system stability the implementation of sub-systems to compensate the effect of hygroscopic package swelling in particular, and other stress related effects in general, is recommended for high-end sensors.

An open-loop compensation method with integrated stress measurement showed an order of magnitude reduction in moisture induced drift when compared to an uncompensated device. However, this compensation scheme must also account for the temperature dependence of the piezoresistors, e.g., using an integrated temperature sensor. The magnetic feedback compensation method, on the other hand, is a closed loop system which has the additional advantage of correcting sensor drift due to not only moisture, but thermal effects.

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