

# Integrated System Based on the Hall Sensors Incorporating Compensation of the Distortions

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This paper addresses the realization of the integrated magnetic field measurement microsystem incorporating regulation electronics for compensation of its non-idealities and environmental influence. The core of the integrated, silicon based, microsystem represents the Hall element sensor which still promises the optimal approach regarding performance versus fabrication cost in a standard 0.35µm CMOS technology. Research is mainly focused on the rejecting the influence of the temperature dependant sensor characteristics with intention of the overall performance improvement. Proposed approach adjust the measured signal with accuracy of 455ppm/°C for all fabrication processes and temperature extending from -40°C up to 130°C and typically up to 32ppm/°C for same process.

## Introduction

A common part of today's sophisticated ASIC (Application Specific Integrated Circuit) incorporate techniques to suppress distortions of the measured signal which are produced as a result of principle of operations, sensor non-idealities or environment in which it operates. The compensation process is especially mandatory in the complex integrated systems where high robustness and reliability is desired. Integration of the electronics in the CMOS (Complementary Metal Oxide Semiconductor) technology has its favorable effects compared to the power consuming and large discrete circuits, but on the contrary it introduces problems mainly related to the fabrication material from which whole ASIC is constituted. As a result, it commonly calls for advance signal processing approaches which mitigate the effects of the sensor noise, offset or sensor sensitivity variability.

Non-idealities originating from the sensor fabrication could be mitigated already during production with one time evaluation and calibration of a small set number of sensors [1], costly approach of sensor laser trimming or calibration at application level [2].

Nevertheless one time calibration is insufficient as devices and its integrated electronics are exposed to unpredictable environmental conditions which affect the sensors performance during operation, so it is crucial to provide compensation on the fly.

In general one of the most problematic environmental condition which degrades the sensor performance is temperature. Compensation of the temperature influence on the sensor could be based on two sensors (sensor within a sensor). One serves for its main function which is measurement of the signal of interest, while the second one

represents temperature sensor which serves as the reference to provide feedback of the sensitivity variability based on the pre-defined temperature characteristics. Another well-known approach is with combination of resistors opposite temperature coefficients which provide biasing current to signal processing stages, nevertheless it suffers from unpredictable behavior through the different fabrication processes and many temperature cycles during aging and packaging stress [3].

The paper concentrates on the implementation of the integrated microsystem based on the Hall element magnetic sensors incorporating compensation of the environmental conditions influences on the sensor and its non-idealities. Employment of the compensation is especially crucial when the sensors are realized with Hall elements as the sensitivity is prone to temperature variations and humidity changes, mechanical stress, packaging and aging drift as well. The material property of the Hall sensor is susceptible to all aforementioned effect and so the piezo-electrically generated voltage comprises distortions and presents deviations from the measured signal proportional to the measured magnetic field. Approach presented in this work is based on the integrated Hall sensors which are used to periodically measure external magnetic field or reference magnetic field as well which eliminates the demand for precision of two sensors layout implementation regarding matching and alignment to each other which could be more evident in some other approaches [4-5]. Characterization promises typically sensitivity variations of around 32 ppm/°C which is comparable to [6] however the proposed compensation approach based on the TSMC 0.35µm models tackles compensation for a wider temperature range. Furthermore, it tackles the technology process variations to some extent as well.

### Magnetic microsystem implementation

The work presents the approach composed of two sub-circuits shown in the block diagram in the Fig. 1, realizing two parallel signal processing paths which attain measured signal form the same sensing device H which is composed of four Hall elements to increase SNR (Signal to Noise Ratio). One signal processing path is responsible for measurement of the external magnetic field of interest  $B_{EX}$  while the other one simultaneously evaluates the system response to the known internally micro-coil generated reference magnetic field  $B_{REF}$  [7] and so determines the Hall element sensitivity.

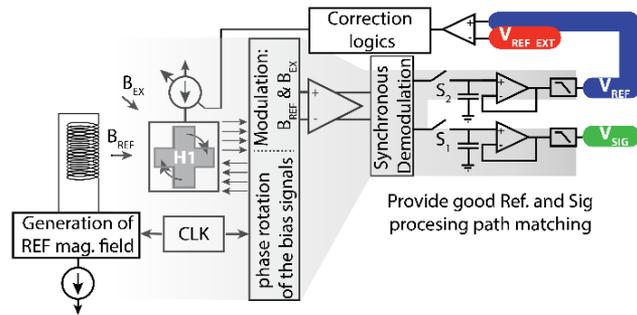


Fig. 1. Block diagram of the compensation concept with signal and reference processing paths.

Acquisition of the signal by the same Hall element provides the same conditions for both, external magnetic field and reference magnetic field measurement. These two signals are alternately modulated in four clock cycles into one signal at spinning frequency which is substantially above signal bandwidth as shown in the timing diagram in the Fig 2. Measured external magnetic field  $B_{EX}$  could be DC (Direct Current) or AC (Alternating Current) but for simplified explanation of the timing diagram it is represented as DC component. After signal conditioning synchronous demodulation take place and separates measured signal  $V_{SIG}$  and  $V_{REF}$  proportional to the external magnetic field  $B_{EX}$  and the reference magnetic field  $B_{REF}$  respectively. Offset added in the signal processing stage and noisy interferences, sneaked through the substrate material are successfully eliminated by the differential output stage which presents summation and subtraction node for acquisition of  $B_{EX}$  and  $B_{REF}$ . Based on the acquired reference signal  $V_{REF}$  which corresponds to the Hall element sensitivity which changes with the environment conditions, the negative feedback corrects it to desired externally driven  $V_{REF\_EXT}$  and ensures stable and constant response mitigating aforementioned effects. It takes minimum four clock cycles to successfully distinguish two signals  $V_{SIG}$  and  $V_{REF}$ , however more periods it takes, higher yield of compensation precision is acquired which is convenient for a slowly changing interfering conditions as the environmental temperature. The compensation is effective as long as both paths, signal and reference one, express comparable susceptibility to the exposed magnetic field, otherwise compensation malfunction to correctly

adjust the Hall element sensitivity. To preserve the constant reference magnetic field during calibration over the temperature range from  $-40^{\circ}\text{C}$  to  $130^{\circ}\text{C}$  the microsystem should be capable of providing adjustable current through micro-coil, as the resistivity of the inductor is changing with the temperature and change of the reference magnetic field would yield poor calibration performance.

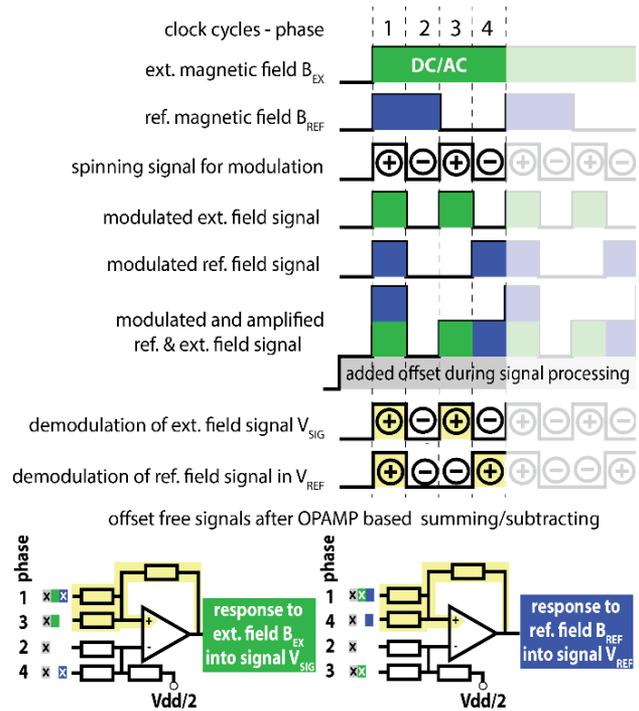


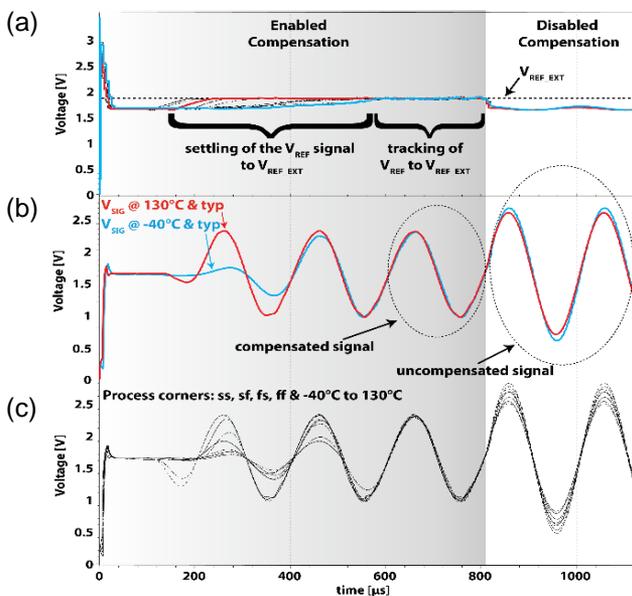
Fig. 2. Timing diagram of processed signals.

Beside the Hall sensor sensitivity correction, the proposed approach with negative feedback compensates variations of the overall system sensitivity as well. Additionally, in contrary to numerous conventional digitally adjustable solutions presented system tackles this issue in the mixed signal design approach and ensures precision by continuous calibration. Furthermore continuous calibration of the linear system successfully mitigate the effect of nonlinear distortions as a result of external interferences in a harsh environment conditions, while discrete nature of digital compensation cannot accurately cope with it. Non-idealities as a sensor offset as a result of asymmetry and  $1/f$  noise are cancelled out by the spinning technique at high enough frequency, in our case 250 kHz. Hall element residual offset is additionally reduced by a factor of two as four sensing devices are used to measure magnetic field.

### Evaluation of the microsystem

The circuitry is designed in TSMC  $0.35\mu\text{m}$  CMOS technology and characterized using HSPICE models. It is analyzed in terms of temperature and fabrication process parameters as well. Temperature range is extending from  $-40^{\circ}\text{C}$  up to  $130^{\circ}\text{C}$ ; for process corners: typ, slow-slow (ss),

slow-fast (sf), fast-slow (fs) and fast-fast (ff) and supply voltage of 3.3V. **Fig. 3** shows response of the microsystem after start-up including all above listed conditions. For the combination of the slow-slow process corner and  $-40^{\circ}\text{C}$  it takes longest time of  $600\mu\text{s}$  for  $V_{\text{REF}}$  calibration signal to settle to the desired value of  $V_{\text{REF\_EXT}}$  (**Fig. 3a**), which is expected as a result of longer time constants. In the time slot from  $600\mu\text{s}$  to  $800\mu\text{s}$  calibration takes place and adjust the signals with typical variations of  $32\text{ppm}/^{\circ}\text{C}$  (**Fig. 3b**), while signal amplitudes deviations from each other dramatically deteriorate out of the calibration range after  $800\mu\text{s}$  which is more evident for all process corners (**Fig. 3c**). Accuracy over all process corners and temperature are summarized in the **Table 1**. Lowest row of the table represents worst signal deviation conditions, combination of all fabrication process corners and temperatures.



**Fig. 3.** Calibration of 5kHz sine-wave  $V_{\text{SIG}}$  occur in time slot from  $600\mu\text{s}$  to  $800\mu\text{s}$  when  $V_{\text{REF}}$  settles to the desired value of  $V_{\text{REF\_EXT}}$  (a); response for (b) typical and (c) all process corners over temperature range from  $-40^{\circ}\text{C}$  up to  $130^{\circ}\text{C}$ .

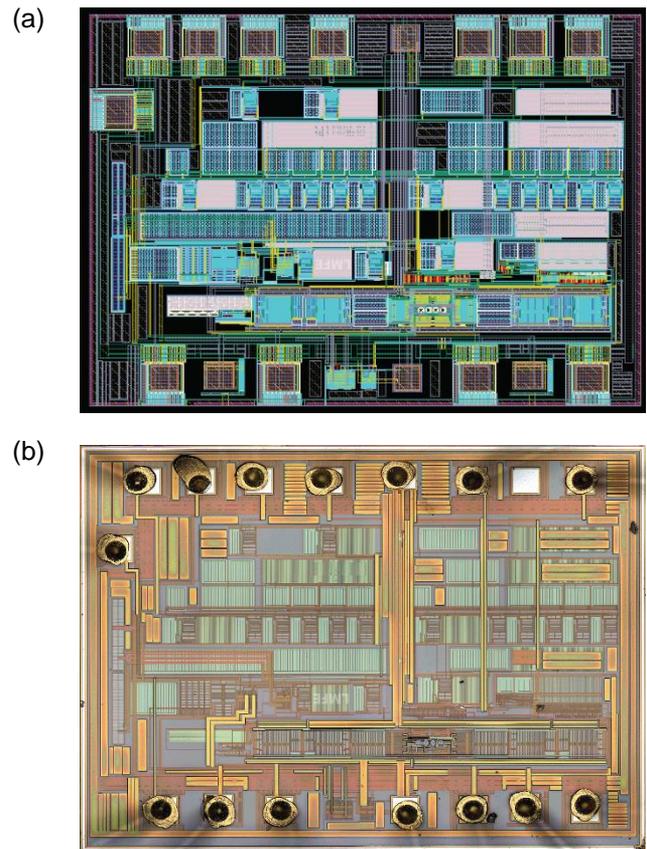
**Table 1.** Accuracy of calibration over whole temperature range and for all 5 fabrication process corners.

$IV_{\text{SIG}}$ deviation [ppm/ $^{\circ}\text{C}$ ]	
Uncompensated @ typ	Compensated @ typ
540	32
Uncompensated @ typ, ss, sf, fs, ff	Compensated @ typ, ss, sf, fs, ff
2180	455

### Realized microsystem

As mentioned, implementation of microsystem should be taken with care especially two symmetrical signal paths. Caution should be taken to correctly position 4 Hall elements to mitigate sensor temperature dependent offset as a result of the Seebeck effect as well. Area of the designed layout of the whole design including bonding pads is approximately  $2\text{mm}^2$ . Designed layout and a

photomicrograph of the die bonded inside ceramic package are presented in the **Fig. 4**.



**Fig. 4.** Realized microsystem (a) layout and (b) photomicrograph.

### Summarized conclusions

Integrated CMOS microsystem based on sensing magnetic field with realized on-chip compensation is analyzed. Compensation is based on mixed signal solution which mitigate effects of the temperature dependent variability of Hall sensing device material parameters and further reduce measured signal amplitude deviation as a result of microsystem non-idealities in the temperature range from  $-40^{\circ}\text{C}$  to  $130^{\circ}\text{C}$ . Circuitry incorporate signal processing approaches which mitigate effects of measured signal distortion as a result of sensor residual offset and noise as well. Furthermore, presented approach promise reduction of the fabrication process influence on the microsystem performance in terms of temperature variations which is demonstrated, nevertheless not in such extent as typically for one process corner. This calls for further work regarding the ratio-metric approaches which are immune to absolute variability of integrated devices parameters over fabrication processes.

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#### Keywords

Hall element sensitivity, magnetic field, calibration.

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#### References

1. Racz, R.; Schott, C.; Huber, S.; Electronic compass sensor, Proceedings of IEEE Sensors, Vienna, Austria, **2004**, pp. 1446-1449.
2. Motz, M.; Draxelmayr, D.; Werth, T.; Forster, B.; *IEEE Journal of Solid-State Circuits*; **2005**, *40*, 1533.
3. Manic, D.; Petr, J.; Popovic, R. S.; Short and long-term stability problems of Hall plates in plastic packages, 2000 IEEE International Reliability Physics Symposium Proceedings, 38th Annual (Cat. No. 00CH37059), San Jose, CA, USA, **2000**, pp. 225-230.
4. Huber, S.; Leten, W.; Ackermann, M.; Schott, C.; Paul, O.; *IEEE Sensors Journal*; **2015**, *15*, 2924.
5. Lindenberger, S. Huber; Active stabilization of the magnetic sensitivity in CMOS hall sensors, Albert-Ludwigs-Universität Freiburg, **2017**.
6. Pastre, M.; Kayal, M.; Blanchard, H.; *IEEE Sensors Journal*; **2007**, *7*, 860.
7. Trontelj, J.; Trontelj, L.; Opara, R.; Pletersek, A.; CMOS integrated magnetic field source used as a reference in magnetic field sensors on common substrate, Conference Proceedings 10th Anniversary. IMTC/94 Advanced Technologies in I & M. 1994 IEEE Instrumentation and Measurement Technology Conference (Cat. No.94CH3424-9), Hamamatsu, Japan, **1994**, pp. 461-463.