Proceedings of the Euroensors XXIII conference

A Novel 2D Magnetometer Based on a Parallel-Field Silicon Hall Sensor

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Abstract

A CMOS 2D Hall magnetometer for in-plane vector measurements using an original design is tested. Its unique advantages are very low internal 1/f noise, minimal device complexity containing four contacts only, one and the same supply current generating the channel sensitivities, and non-observed cross-talk between the channels at induction \( B \leq 0.25 \text{T} \). The high effective circuitry fully compensates the offsets and the geometrical magnetoresistance of the outputs. The experimentally obtained sensitivities along the \( X \)- and \( Y \)- outputs are equal, reaching \( S_{Rx} = S_{Ry} \approx 19 \text{ V/AT} \), and the noise is reduced at least 60 times.

Keywords: 2D magnetic-field vector sensor; parallel-field Hall-effect principle; 1/f noise; offset; cross-sensitivity

1. Introduction

Integrating more than one measurement function in the transducer zone of the substrate is one of the most topical trends in microsystems’ development. This method is the basis of the multidimensional 2D and 3D magnetic-field sensors detecting simultaneously or subsequently the individual vector components \( B_x, B_y \) and \( B_z \) in plane (2D) and in space (3D) with the same fixed microstructure. Integrated silicon technologies, such as CMOS, BiCMOS, micromachining etc. are used for the fabrication of such devices. Their main advantages compared to discrete one-component galvanomagnetic sensors as Hall plates, bipolar magnetotransistors, magnetodiodes etc. mounted upon two or three walls of a quartz cube are: an exclusively small transducer region with remarkable resolution which makes them suitable to measure highly divergent field \( \bigtriangledown B \); improved orthogonality because of the precision of planar process steps; perfect electrical, thermal, technological and electromagnetical compatibility of the \( B_x, B_y \) and \( B_z \) channels etc. Most widely applied in these vector magnetometers are different modifications of Hall microsensors with orthogonal and parallel-field activation. This is due to the fact that their behaviour is very well predictable, because only one and clear sensor effect controls the action. Many different versions of silicon 2D Hall microdevices are available, in which such drawbacks as channels cross-sensitivity, offset, temperature and temporal drift are successfully overcome [1-3]. A CMOS 2D parallel-field Hall magnetometer is also implemented, with minimal design complexity and original structure, containing only 4 contacts, which is very suitable for MEMS applications [4]. The problems associated with the number of contacts and connection leads and the channels cross-

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talk are removed, too. Notwithstanding the achieved good results, the high level of internal 1/f noise is not sufficiently well resolved in this 2D vector microsensor. The paper presents a new CMOS 2D magnetometer using an original parallel-field Hall microsensor in which this disadvantage is overcome.

2. Concept of the novel two axis Hall device

A new device design of 1D 5-contact parallel-field silicon Hall microsensor is investigated in [5]. In comparison to all well-known similar elements, its measuring Hall terminals $H_1$ and $H_2$ are located outside the sensor active region. Three supply contacts $C_1$, $C_2$, and $C_3$ are positioned inside the sensor active region with respect to Hall electrodes $H_1$ and $H_2$. A three-contact version of this microsensor is presented in Fig. 1 [6].

These Hall elements strongly minimized an essential problem, related to the CMOS technology – the existence of a surface conductive $n$-layer of the silicon substrate. This enhanced electrical conductivity at the top of the silicon chip causes the most of the supply current in CMOS Hall devices to flows in this area and through the Hall contacts. This short-circuit current reduces the real current in the active Hall-area, thus reducing substantially the Hall voltage $V_{\text{Hall}}(B)$. The novel device designs eliminate this drawback. It is found out that these parallel-field Hall microsensors reduce drastically the internal 1/f noise by about three orders of magnitude since the biasing current does not flow through the Hall terminals [7]. Therefore, the innovative task is reduced to designing a two-axes Hall magnetometer, which combines simultaneous measurement of the in-plane magnetic-field components $B_x$ and $B_y$, the advantages of the 2D microsensor from [4], so as to reduce sufficiently the level of the 1/f noise.

3. 2D silicon Hall microsensor description and operation

The 2D microdevice uses an original parallel-field Hall device, Fig. 2, containing $n$-Si resistive layer with rectangular shape. Two supply $n^+$ - contacts $C_1$ and $C_2$ and Hall electrodes $H_1$ and $H_2$ positioned outside the transducer active region $l_{C1,2}$ are formed. The structure is bent at right angle. This solution uses only one supply current $I_{C1,2}$ for $B_x$ and $B_y$ sensing. The magnetometer operates in the following way. The current $I_{C1,2}$ under the equipotential $n^+$-regions $C_1$ and $C_2$ at field $B = 0$ is orthogonal to the upper surface, after which the current becomes parallel to the respective rams $C_1$-m and $C_2$-m. The Lorentz forces in the field $B(B_x,B_y)$ deflect laterally the vertical currents $I_{C1}$ and - $I_{C2}$, resulting in Hall voltages: $V_{\text{Hall}}(B_x) = 0.5$, $V_{\text{Hall}}(B_y)$, and $V_{\text{Hall}}(B_x) = 0.5 V_{\text{Hall}}(B_y)$, where $V_{\text{Hall}}$ are the total Hall voltages developed in the respective ram. There is a longitudinal electrical component $V_{\text{TM}}(B) = V_{\text{MR}} \sim B^2$, associated with the geometrical magnetoresistance. Therefore, on the electrodes $H_1$ and $H_2$ linear odd Hall voltages and quadratic even magnetoresistance co-exist. An original circuitry fully compensates the inevitable offsets and the corresponding parts of the voltages $V_{\text{MR}} \sim B^2$ on contacts $H_1$ and $H_2$, Fig. 3. When the offsets are tuned to zero by trimmers $r_1$ and $r_2$, the values of voltages $V_{\text{r1}}(B_x)$ and $V_{\text{r2}}(B_y)$ on the middle points of two trimmers are just equal to the potentials on contacts $H_1$ and $H_2$ generated by the magnetoresistance. The 2D microdevice is fabricated using standard CMOS process. The silicon $n$-epi-layer with doping concentration of $n_0 = N_D \approx 10^{15}$ cm$^{-3}$ is $t = 10$ μm thick. The length $l_{C1,2}$ and width $w$ of the layer are 40 μm and 10 μm, respectively. Since the contacts $H_1$ and $H_2$ are outside the active sensor region $l_{C1,2}$, their shunting role on the biasing current which generates the Hall...
voltages should be strongly reduced and also the noise compared to the conventional case with electrodes H₁ and H₂ located inside the zone $I_{C1,2}$ [4].

4. Experimental results

The output characteristics of one of the sensor channels are shown in Fig. 4. The non-linearity is no more than 0.3 % at induction $0 \leq B \leq 0.3$ T. The temperature coefficient of magnetosensitivity in the range $0 \leq T \leq 80$ °C is about $T_C \sim 0.1$ %/°C. The sensitivities along the $X$- and $Y$- outputs reach $S_{Rx} = S_{Ry} \approx 19$ V/AT, Fig. 4.

In order to evaluate the behaviour of the 2D device to the in-plane magnetic-field vector $\mathbf{B}(B_x, B_y)$, experiments are performed with a rotatable pair of coils generating $dc$ homogeneous magnetic induction with the probe centred...
on the axis of rotation. The output dependences $V_{H1}(\phi)$ and $V_{H2}(\phi)$ as a function of the rotational angle $\phi$ at induction $B = \text{const}$ are presented in Fig. 5. The offset of each channel is cancelled in advance. The signals follow $X = B\cos\phi$ and $Y = B\sin\phi$ and agree with the theory. The conversion of the two voltages $V_{H1}$ and $V_{H2}$ for $X$ and $Y$ into absolute value and the angle $\phi$ are obtained by the relations $|B| = (X^2 + Y^2)^{1/2}$ and $\phi = \tan^{-1}(X/Y)$. The cross-sensitivity between the channels at field $B \leq 0.25$ T is not observed experimentally. Measurements to evaluate the channels magnetosensitivities to ac magnetic fields are carried out. Because of the prototype character of the 2D microsensor, the conditioning electronics has not yet been integrated on the same silicon chip and hence, the connecting wires introduce significant inductive pick-up in the outputs. The obtained bandwidth of the detected ac magnetic fields in which the output characteristics are frequency-independent is about 40 kHz for the two channels. The noise spectral density in the range $f \leq 1$ kHz is of $1/f$ type, Fig. 6. As a result of the new sensor topology, Fig. 2, for the first time, the internal noise is reduced at least 60 times.

5. Conclusion

The new 2-D magnetometer with unique device topology resulting in extremely low $1/f$ noise contains only 4 contacts for measuring in-plane vector components, a cross-sensitivity is not observed and has very high spatial resolution. The main applications of the 2D microsensor are contactless positioning systems, wear-free potentiometers, joy sticks, electronic compasses etc.

Acknowledgements

The work was supported in part by Bulg.M.E.S under projects TN-1501/2005 and MI-1509/2005.

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