

2D In-Plane Sensitive Hall-Effect Sensor [†]

Siya Lozanova, Ivan Kolev, Avgust Ivanov and Chavdar Roumenin *

Institute of Robotics at Bulgarian Academy of Sciences, 1113 Sofia, Bulgaria; lozanovasi@abv.bg (S.L.); ivankolew91@gmail.com (I.K.); avgust.ivanov@abv.bg (A.I.)

* Correspondence: roumenin@bas.bg; Tel.: +359-2-870-3361

[†] Presented at the Eurosensors 2018 Conference, Graz, Austria, 9–12 September 2018.

Published: 30 November 2018

Abstract: A new 2D (two-dimensional) in-plane sensitive Hall-effect sensor comprising two identical n -Si Greek-crosses is presented. Each of the crosses contains one central square contact and, symmetrically to each of their four sides, an outer contact is available. Outer electrode from one configuration is connected with the respective opposite contact from the other configuration, thus forming four parallel three-contact (3C) Hall elements. These original connections provide pairs of opposite supply currents in each of the cross-Hall structure. Also the obligatory load resistors in the outer contacts of 3C Hall elements are replaced by internal resistances of crosses themselves. The samples have been implemented by IC technology, using four masks. The magnetic field is parallel to the structures' plane. The couples of opposite contacts of each Greek-cross are the outputs for the two orthogonal components of the magnetic vector at sensitivities $S \approx 115$ V/AT whereas the cross-talk is very promising, reaching no more than 2.4%. The mean lowest detected magnetic induction B at a supply current $I_s = 3$ mA over the frequency range $f \leq 500$ Hz at a signal to noise ratio equal to unity, is $B_{\min} \approx 14$ μ T.

Keywords: multidimensional magnetic-field microsensors; in-plane sensitive three-contact Hall element; single-chip device for two orthogonal magnetic-field components measurement

1. Introduction

The measurement of more than one orthogonal component of magnetic field vector using single-chip approach is the most advanced problem in the multidimensional microsystems. This method provides advantages as high spatial resolution and minimal operational volume, drastically improved orthogonality between the two or three axes, the position of the device with respect to the magnetic source is not critical, very good electrical, thermal and galvanomagnetic compatibility in individual sensor channels etc. The most advanced 2D and 3D vector configurations use the Hall effect, since their action involves only one simple, well-defined and well-investigated physical principle, [1–8]. These microsensors, irrespective of the pronounced progress, with respect to channel sensitivities, cross-talk, technology compatibility etc. feature some essential drawbacks. They contain too many contacts and numerous electrical connections between them, which seriously complicates fabrication, impedes minimal operational volume and obstructs the required miniaturization degree. Also there are unsatisfactory solutions for overcoming the sensitivity temperature dependence, drift and channel offsets. The relevant technologic realization of these disadvantages exceeds many times the simplicity of the Hall sensor itself. Another problem is the channel cross-talk which reduces the accuracy, [1,6–8]. An original CMOS multidimensional Hall magnetometer strictly measuring B_x and B_y in-plane components is given in [9]. Despite of its merits, the device design is very complicated, containing four 3C in-plane Hall microsensors, similar to described ones in [10,11]. In this paper, a novel single-chip sensing device for measurement of two

orthogonal in-plane magnetic-field components using simple construction, improved cross-talk and satisfactory resolution is presented.

2. Sensor Design and Operation Principle

The multidimensional device consists of two identical *n*-Si Greek-crosses, Figure 1. Each of them contains one central n^+ square contact C_1 , C_2 . Symmetrically to each of their four sides, there is one n^+ outer contact. Each outer terminal from a given configuration is connected to the respective opposite contact from the other arrangement, C_3 – C_9 , C_4 – C_{10} , C_5 – C_7 and C_6 – C_8 , thus forming four parallel 3C Hallelements.

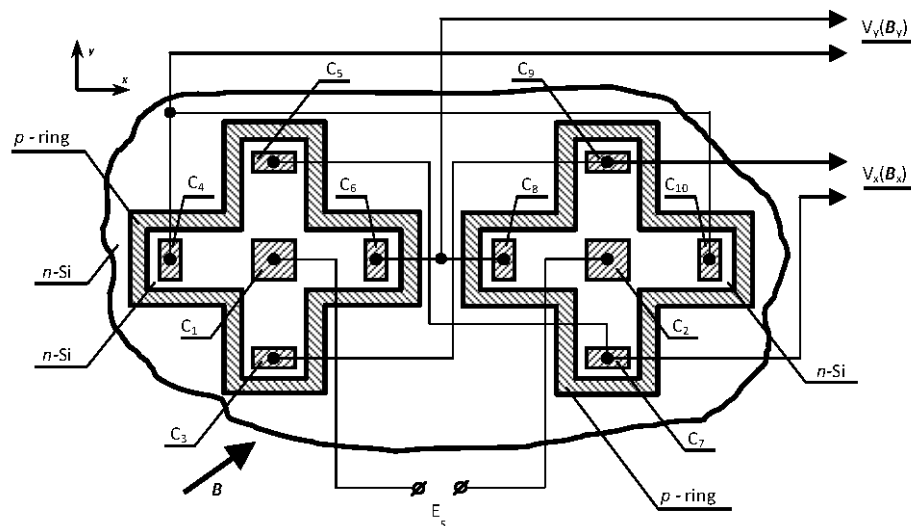


Figure 1. Schematic top-view of 2-D integrated Hall device. The simple design, original connection, inherent symmetry and deep *p*-ring drastically reduce the channels cross-talk and the offset is decreased too.

These original connections provide pairs of opposite in direction supply currents in each of the cross-Hall structure. Also the obligatory load resistors in the outer contacts of 3C Hall elements [10,11] are replaced by internal resistances of cross-configurations themselves. A deep *p*-ring surrounding the Greek-crosses to restrict surface spreading currents and to confine the effective transducer zones within the *n*-Si substrate is formed, too, Figure 1.

The experimental prototype has been implemented using part of the processing steps applied in bipolar IC technology. The low-doped *n*-Si plates are 300 μm thick, with resistivity $\rho \approx 7.5 \Omega\text{-cm}$. The carrier's concentration is $n \sim 4.3 \times 10^{15} \text{ cm}^{-3}$. Similarly to [12], four masks are employed. Mask 1 determines the n^+ -implanted zones for ohmic electrical contacts $C_1 \dots C_{10}$ with the substrate, as the depth of the ohmic n^+ - n junctions is about 1 μm . Mask 2 forms areas for the two deep Greek-crosses *p*-rings. These *p*-rings constrict the effective volume of the device and prevent the surface current spreading. All of this increases the transducer efficiency of novel 2D device. Mask 3 defines the metallization layer and bonding pads. Mask 4 is intended for the contact opening in the surface layer SiO_2 for the electrical contact between metal and the n^+ zones. The dopant donor concentration of the n^+ - n junctions is $n \approx 10^{20} \text{ cm}^{-3}$. The width of the deep surrounding *p*-ring at the surface is about 20 μm (on the mask). The size of the ohmic contacts is $30 \times 30 \mu\text{m}^2$ for C_1 and C_2 , and $30 \times 10 \mu\text{m}^2$ for all the rest $C_3 \dots C_{10}$. The distance between the central contacts and outer ones is 40 μm . The thickness of the effective area is defined in first approximation from the curvilinear trajectory penetration in the *n*-Si substrate with a depth of 30–40 μm . As a result, the effective operational volume of each cross is about $120 \times 120 \times 40 \mu\text{m}^3$, which provides for the satisfying spatial resolution of the device.

The current $I_s \equiv IC_{1,2}$ is constant in the 2D sensor, due to the high internal resistances as result from a few kilo ohms of the cross-configurations. The current paths start and end on the heavy-doped n^+ contacts on the upper surface of the slab, thus the carriers' trajectories are

curvilinear. In magnetic field $B(B_x, B_y) > 0$, the Lorentz forces $F_L(F_{Lx}, F_{Ly})$ influences the respective trajectories in the y - z and x - z planes. As a result forces $F_L(F_{Lx}, F_{Ly})$ simultaneously shrink and expand the opposite paths in the two Greek-crosses towards the surfaces and to the bulks forming 3C in-plane sensitive Hall devices. Thus, opposite-sign Hall potentials are generated on the respective contacts. Through the circuitry connections, the potentials with the same sign are linked in parallel, forming the respective differential Hall outputs $V_x(B_x)$ and $V_y(B_y)$, Figure 1.

3. Results

The output characteristics for the $V_x(B_x)$ channel of the new 2D magnetometer are shown in Figure 2, the dependence of the channel $V_y(B_y)$ is the same. Inevitable offsets are fully compensated in advance. The obtained channel-magnetosensitivities are equal and reach $S_{RI} \approx 115$ V/AT at temperature $T = 20$ °C.

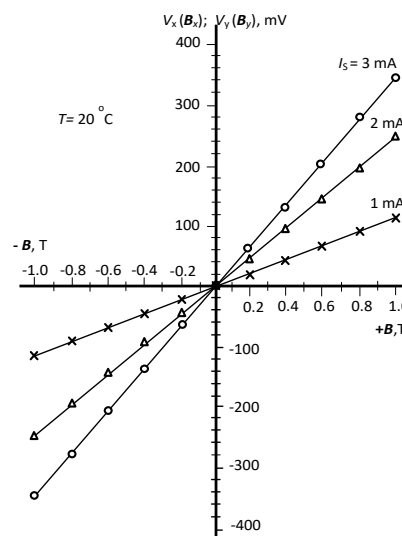


Figure 2. Output characteristics for the $V_x(B)$ channel of the new 2D device. The obtained magnetosensitivities are equal.

The non-linearity NL reaches no more 0.5% in the range $0 \div \pm 0.6$ T and $NL \approx 1\%$ at ± 0.6 T $\div \pm 1.0$ T. The main sensor characteristic in the vector magnetometry is the cross-sensitivity C.S. This important parameter determines the parasitic output signal in a given channel, when the field B is applied in the other orthogonal sensor direction. In Figure 3 the cross-talk i.e., the characteristic C.S. of 2D in-plane sensitive Hall sensor is presented as a function of induction B at temperature $T = 20$ °C. The experimental results are very promising, parameter C.S. reaches no more than 2.4%. The power spectral density of internal noise for the channel $V_y(0)$ at $T = 20$ °C is demonstrated in Figure 4, the supply current I_s is as a parameter. For the channel $V_x(0)$ the noise density is the same. The dependencies are $1/f$, if the supply I_s increase, the noise $1/f$ augment too. The mean lowest detected magnetic induction B at a supply current $I_s = 3$ mA over the frequency range $f \leq 500$ Hz at a signal to noise ratio equal to unity, is $B_{min} \approx 14$ μ T.

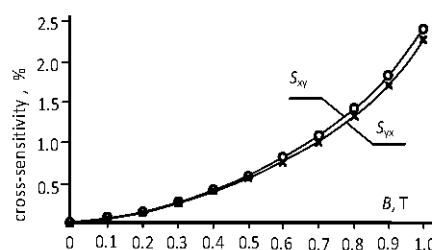


Figure 3. Channel cross-talk of 2D in-plane sensitive Hall sensor as a function of induction B at temperature $T = 20$ °C.

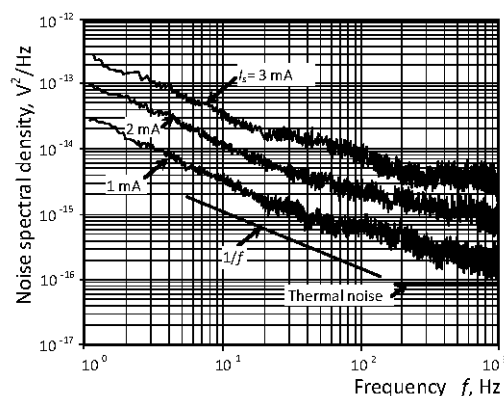


Figure 4. Power spectral density of internal noise in channel $V_y(0)$, the supply current I_s is as a parameter, $T = 20^\circ\text{C}$.

4. Conclusions

In summary the obtained performance of the novel 2D in-plane sensitive Hall device is very promising. This important result is achieved through simple in design innovative structure, original connections between contacts, possibility of simultaneous extraction of two independent channel voltages with drastically suppressed cross-talk between them, high inherent symmetry of the channels and simplified technology realization. The applications of the 2D sensor are wide—robotics, mechatronics, low-field magnetometry, position devices, multirotor systems, contactless automation etc.

Acknowledgments. This work was supported by Sci. Res. Fund under project No. DN 07/18-15.12.2016

References

1. Roumenin, C. Solid State Magnetic Sensors, Elsevier, 1994; Microsensors for magnetic field. In *MEMS—A Practical Guide to Design, Analysis and Application*; Korvink, J.G., Paul, O., Eds.; William Andrew Publisher: Norwich, NY, USA, 2006; pp. 453–521.
2. Ramsden, E. *Hall Effect Sensors—Theory and Application*, 2nd ed.; Elsevier: Amsterdam, Netherland, 2006.
3. Kaufmann, T. *On the Offset and Sensitivity of CMOS-Based Five-Contact Vertical Hall Devices*; Der Andere Verlag: Tönnig, Germany, 2013; Volume 21, p. 147.
4. Demierre, M.; Schurig, E.; Schott, C.; Besse, P.-A.; Popovic, R. Contactless 360° absolute angular CMOS microsystem based on vertical Hall sensors. *Sens. Actuators A* **2004**, *116*, 39–44.
5. Pascal, J.; Hebrard, L.; Frick, V.; Blonde, J.P. 3D Hall probe integrated in 0.35 μm CMOS technology for magnetic field pulses measurements. In Proceedings of the 6th International IEEE Northeast Workshop on Circuits and Systems and TAISA 2008, 22–25 June, Montreal, Quebec, Canada, 2008; pp. 97–100.
6. Yu, C.-P. *The Study and Application of a 2D Folded Hall Sensor Chip*; National Taipei University of Technology: Taipei, Taiwan, 2012; p. 88.
7. Yu, C.-P.; Sung, G.-M. Two-dimensional folded CMOS Hall device with interacting lateral magnetotransistor and magnetoresistor. *Sens. Actuators A* **2012**, *182*, 6–15.
8. Wouters, C.; Vranković, V.; Rössler, C.; Sidorov, S.; Ensslin, K.; Wegscheider, W.; Hierold, C. Design and fabrication of an innovative three-axis Hall sensor. *Sens. Actuators A* **2016**, *237*, 62–71.
9. Sander, C.; Leube, C.; Paul, O. Three-dimensional magnetometer based on subsequent measurement principle. *Sens. Actuators A* **2015**, *222*, 329–334.
10. Roumenin, C.; Kostov, P. Planar Hall-Effect Device. Bulg. Patent No. 37208/26.12.1983, 26 December 1983.
11. Lozanova, S.V.; Roumenin, C.S. Parallel-field silicon Hall effect microsensors with minimal design complexity. *IEEE Sens. J.* **2009**, *9*, 761–766.
12. Schott, C.; Popovic, R. Integrated 3-D Hall magnetic field sensor. In Proceedings of the Transducers '99, Sendai, Japan, 7–10 June 1999; Volume 1, pp. 168–171.

