Two-axis silicon Hall effect magnetometer

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A novel single-chip sensing device for measurement of two orthogonal magnetic-field components using a common transducer zone and, for the first time, containing four contacts, is presented. On a rectangular n-type silicon substrate, n−-ohmic planar contacts are implemented – two of them are elongated and serve as power supply, and the other two terminals, positioned in the middle of the region between the elongated ones, function as outputs. A proper coupling arrangement is used for obtaining the information about vector components $B_x$ (parallel to the supply contacts) and $B_y$ (perpendicular to the substrate). Actually, the 2D magnetometer integrates an in-plane sensitive Hall element and a device with vertical magnetic-field activation. The sensor operation is determined by the direction of the individual parts of the curvilinear current trajectory and the Lorentz force deflection action on them. The 2D vector sensor interface circuitry in hybrid realization comprises three instrumentation amplifiers and a differential amplifier. Simple fabrication technology is applied, containing four masks. The effective spatial resolution volume is high, constituting about 90 $\times$ 60 $\times$ 40 $\mu$m³. The respective channel-magnetosensitivities without amplification reached: the lateral sensitivity $S_x \approx 17$V/AT and the vertical sensitivity $S_y \approx 23.3$ V/AT.

The channel cross-talk at induction $B \leq 1.0$T is no more than 3% and the lowest detected induction $B_{\text{min}}$ for the two-axis device at supply 3 mA over frequency range $f \leq 100$ Hz is about 11 $\mu$T.

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1. Introduction

The most advanced 2-D and 3-D vector magnetometers are those using the Hall effect principle, since their action involves only one simple, well-defined and well-investigated physical phenomenon [1–6]. These multidimensional devices, irrespective of the pronounced progress in their characteristics, such as channel sensitivities and spatial resolution, feature some essential drawbacks. They contain too many contacts and numerous electrical connections between them; each of the widespread advanced vector microsensor solutions presented in [5–11] requires at least 8 electrodes. This seriously complicates technology fabrication, impedes high spatial resolution and obstructs the achievement of the required miniaturization degree. At the same time, the overview of the available means to overcome some of the most common drawbacks of Hall elements and the vector magnetometers based on them, such as sensitivity temperature dependence, drift, etc., shows that the complexity and the relevant technology realization exceed many times the simplicity of the Hall sensor itself. One of the promising means to overcome these significant problems is the functional multisensor approach, i.e. the combination of more than one sensor function within a common transducer zone of the substrate (chip), the information about which is obtained simultaneously or successively [1]. A silicon magnetic-field vector device was proposed measuring successively the $B_x$, $B_y$, and $B_z$ components [1.12–14]. However, its disadvantage is reduced accuracy due to the large initial channel offset in the individual outputs due to the considerable supply voltage drop on the sensor contacts and greater size of the vector device due to the specific construction which requires too many contacts. Therefore, the resolution is limited. Moreover, the magnetometers presented in [12–14] require complicated conditioning circuit, containing pulse generators, counters, multi-channel analogues multiplexers, sample & hold circuits, etc. The original 2D CMOS Hall magnetometer in [15] measured strictly $B_x$ and $B_y$ in-plane components. Despite its merits, its devise design is very complicated, containing four three-contact in-plane Hall microsensors, similar to described ones in [16,17].

In this paper, a novel single-chip sensing device for measurement of two orthogonal magnetic-field components using one and the same transducer zone, featuring simple construction, high resolution and flexible interface electronics is presented. Moreover, the

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innovation of the presented in our paper solution is the registration of the vertical component $B_z$, which is non-trivial multi-sensing problem.

2. Sensor design and operation principle

The novel two-axis magnetometer consists of a rectangular $n$-type silicon substrate with four $n^+$-ohmic planar contacts $C_1$, $C_2$, $C_3$ and $C_4$. Fig. 1. Two of them, $C_1$ and $C_2$, are elongated and serve as power supply. The other two contacts, $C_3$ and $C_4$, are square and function as sensor outputs only. They are positioned in the middle of the region between the elongated ones and near to the edges, Fig. 1. A deep p-ring surrounding the $n^+$-contacts to restrict spreading surface current and delineate restrict the effective transducing zone region within the n-type silicon substrate is formed, too. The $n$-type silicon substrate is floating. This vector multisensor operates in the following way.

Through the elongated contacts $C_1$ and $C_2$ the device is fed with constant supply current, $I_s = I_{C_{1,2}}$, due to the load resistor $R$ (current mode of operation), Fig. 1. The resistance of the load resistor $R$ is about 50 times the inherent resistance of the Hall probe. The carriers’ lines are curvilinear – the current paths start and end on the heavy-doped $n^+$ contacts $C_1$ and $C_2$ on the upper surface of the slab, Fig. 1. Consequently, the primary trajectory is perpendicular to the surface, later shifting to parallel near the chip boundary. The trajectory of current $I_{C_{1,2}}$ in the bulk of the substrate, between the planar contacts $C_1$ and $C_2$, penetrates to a depth of 30–40 μm, Fig. 1. [15]. In magnetic field $B_x > 0$, the Lorentz force $F_l = q v_d x B_x$ controls simultaneously the lateral $v_y$ and the vertical $v_z$ components of the drift velocity $v_d = v_y + i_z$. [1,15]. Therefore, along one direction of the vector $B_x$ the force $F_l$ “shrinks” the trajectory towards the surface of the substrate, where contacts $C_1$, $C_2$, $C_3$ and $C_4$ are located. As a result, the Hall effect appears – on this boundary between the two electrodes $C_1$ and $C_2$, in the region where contacts $C_3$ and $C_4$ are located, an additional (e.g. negative) charge proportional to field $B_x$ and current $I_{C_{1,2}}$ arises. On the other surfaces of the substrate, non-compensated additional (positive) charge remains, $V_{H_{\text{Hall}}} \sim I_{C_{1,2}} B$. In addition, quadratic and even geometrical magnetoresistance effect appears: $V_{MR} \sim B^2$, which increases the internal resistance $R_{C_{1,2}}(B) \sim B^2$ of the element between contacts $C_1$ and $C_2$. Along the opposite direction of magnetic field vector $B_x$, the Lorentz force $F_l$ “expands” the trajectory of the carriers within the bulk of the structure. Thus, the positive charge will be on the surface around contacts $C_3$ and $C_4$. Therefore, the output voltage $V_{H} (B_x)$ across contacts $C_3$ and $C_4$, placed in the middle of the distance $l_{C_{1,2}}$ should be half the sum of the whole Hall voltage $V_{H_{\text{Hall}}} (B_x)$ developed in the substrate. On the terminals $C_3$ and $C_4$ there exist synergistically two signals — the linear Hall voltage and the quadratic magnetoresistance: $V_{H} (B_x) = 0.5(V_{H_{\text{Hall}}} (B_x) + V_{C_{1,2}} (B_x))$. [17,18]. In this expression, the voltage drop in the trimmer $P$ is neglected because we assume that the resistance value of potentiometer $P$ should be very high and hence, the current through trimmer $P$ will be a few microamperes. The presented device is non-symmetric. But, when the device is fed with constant supply current, $I_s = I_{C_{1,2}}$ and exposed to magnetic field $B_x$, the number of the charges formed on the surface zone between the contacts $C_1$ and $C_2$ is equal to the number of the charges (with opposite sign) formed on the rest of the chip surface. That’s why, in magnetic field $B_x$, the generated by the Lorentz force potential $V_{H_{\text{Hall}}} (B_x) = V_{C_{3,4}} (B_x)$ on the middle surface sensor zone comprising the contacts $C_3$ and $C_4$, is equal to half of the whole Hall voltage, which is the potential difference between the top surface (i.e. contact $C_3$ or $C_4$) and the bottom surface, which is floating [17,18]. In order to separate the Hall voltage from the overall signal on contacts $C_3$ and $C_4$, a specific bridge circuit generating reference voltage at the middle point of potentiometer $P$ is proposed, which fully suppresses the quadratic and even magnetoresistance $V_{MR} \sim B^2$, Fig. 1, [17]. The change of the internal resistance in magnetic induction $R$ is proportional to the initial resistance $R_{C_{1,2}} (B = 0)$, $\Delta V_{C_{1,2}} (B) \sim V_{C_{1,2}} (0)$. After preliminary nullification at field $B = 0$ by the trimmer $P$ of the bridge output $V_H$, i.e. the offset, Fig. 1, automatic compensation of the quadratic signal $\Delta V_{C_{1,2}} (B) \sim B^2$ in the Hall voltage on contacts $C_3$ and $C_4$ is achieved. This solution is shown on two circuitries in Fig. 1. Between the middle point of potentiometer $P$ and either of contacts $C_3$ or $C_4$, output signals arise, including Hall voltage $V_{H} (B_x)$, Fig. 1. Two output voltages, containing $V_{H} (B_x)$, may be measured — between the middle point $P$ and $C_3$: $V_{H} (B_x) + V_0$, and between point $P$ and contact $C_4$, respectively: $V_{H} (B_x) − V_0$.

In magnetic field $B_z$, perpendicular to the upper surface of the substrate, the well-known Lorentz force $F_l (B_z) \approx 0$, where $\pm F_l (B_z) \approx \pm q v_y B_z$, Fig. 1 [1–3]. The force $F_l (B_z)$ deflects the current lines to the front or back side of the substrate, depending on the directions of the supply current $I_{C_{1,2}}$ and field $B_z$. (Both the front and the back side of the structure are perpendicular to the short edges, Fig. 1). Under outer contacts $C_1$ and $C_2$, the current paths are perpendicular to the surface; therefore the field $B_z$ do not perturb them. The component of the field $B_z$, i.e. the respective Lorentz force acts on the middle part of the current trajectory $I_{C_{1,2}}$. The enlarged active region in our case leads to increase of the sensitivity mainly for the x channel. Furthermore, through the structure greater supply current may be fed. For the z channel, the sensitivity depends mainly on the distance between the corresponding opposite sides of the p-ring, Fig. 1. As is known [1,4,19], for such kind of microsensors, the galvanomagnetic processes develop in volume with depth about 30 μm. That’s why, the structure is implemented in such a way as to obtain a tradeoff of appropriately high values for the sensitivities for both x and z channels. The difference between the solution for $B_z$ measurement component in Fig. 1 and the presented in [16,17] three-contacts in-plane microsensor, is related to the Lorentz force deflection – for $B_z$ channel (Fig. 1), the force $F_l$ operates in the x-y plane. The middle contacts $C_3$ and $C_4$ are differential z-channel output. For $B_z$, channel, the force $F_l$ acts in the y-z plane. For the presented in [16,17] device, the force $F_l$ influences in
the y-z plane for \( B_z \) registration only. Thus, the concentration of the current charges in the vicinity of contact \( C_3 \) increases or decreases, and respectively the concentration of the charges around contact \( C_4 \) decreases or increases. Non-compensated electrical charges appear simultaneously in the vicinity of both terminals, \( C_3 \) and \( C_4 \), and between terminals \( C_3 \) and \( C_4 \), hence Hall voltage \( V_{HI}(B_z) \) appears. The additional voltage \( V_0 \) is proportional to \( V_{HI}(B_z) \) as follows: \( V_0 = \pm G_{HI} V_{HI}(B_z) \), where \( G_{HI} \) is the geometrical correction factor for Hall voltage. The Hall geometrical factor is within the range \( 0 < G_{HI} < 1 \), [1–3].

3. Interface circuitry

The 2D magnetometer interface circuitry shown in Fig. 2 is very simple. It comprises three instrumentation amplifiers and one differential amplifier. The channel for obtaining voltage \( V_{HI}(B_z) \), proportional to the induction \( B_z \), includes two instrumentation amplifiers, \( A_1 \) and \( A_2 \), with gains \( G_1 = G_2 = 1 \). The inputs of in-amp \( A_1 \) are connected between the middle point of potentiometer \( P \) and terminal \( C_4 \) in such a way that the output of in-amp \( A_1 \) provides voltage \( V_{HI}(B_z) + V_0 \). The inputs of in-amp \( A_2 \) are connected between point \( P \) and contact \( C_3 \) in such a way that the output of in-amp \( A_2 \) provides voltage \(-V_{HI}(B_z) + V_0 \). The differential amplifier \( A_3 \) has gain \( G_3 \) > 1. It subtracts the output voltages of in-amp \( A_1 \) and in-amp \( A_2 \), providing output signal \( V_{out}(B_z) = 2G_3 V_{HI}(B_z) \) which is proportional to \( V_{HI}(B_z) \), as follows: \( V_{out}(B_z) = V_0 - (V_{HI}(B_z) + V_0) = 2G_3 V_{HI}(B_z) \). The parasitic signal \( V_0 \) is completely compensated. The channel for obtaining voltage \( V_{HI}(B_z) \) contains only one instrumentation amplifier in-amp \( A_4 \) with gain \( G_4 \) > 1. It provides output voltage \( V_{out}(B_z) = G_4 V_{HI}(B_z) \) which is proportional to \( V_{HI}(B_z) \).

4. Realization

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 \( \mu \)m thick, with resistivity \( \rho \approx 7.5 \) \( \Omega \) cm. The current carrier’s concentration is \( n \approx 4.3 \times 10^{15} \) cm\(^{-3} \). Similarly to [19], four masks are used employed. Mask 1 determines the \( n^+ \)-implanted zones for ohmic electrical contacts \( C_1 \) – \( C_4 \) with the substrate, as the depth of the ohmic \( n^+ - n \) junctions is about 1 \( \mu \)m. Mask 2 forms areas for the deep \( p \)-ring with rectangular shape. This \( p \)-ring constrains the effective volume of the device and prevents the surface current spreading. All of this increases the transducer efficiency of our 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 \( n \approx 10^{20} \) cm\(^{-3} \). The width of the deep surrounding \( p \)-ring at the surface is about 20 \( \mu \)m (on the mask). The size of the ohmic contacts is \( 10 \times 60 \) \( \mu \)m\(^2 \) for \( C_1 \) and \( C_2 \), and \( 10 \times 10 \) \( \mu \)m\(^2 \) for \( C_3 \) and \( C_4 \). The effective operational volume is about 90 \( \times \) 60 \( \times \) 40 \( \mu \)m\(^3 \), which provides for the high spatial resolution of the 2D device. 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 \( \mu \)m. The microphotography of the 2D multisensor is shown in Fig. 3. The whole microsystem has been achieved by hybrid realization, using three instrumentation amplifiers and one differential amplifier. The instrumentation amplifiers should be precise enough, with low input bias current and high CMRR. For example, the low-cost in-amp AD623, with its single supply operation ability, high accuracy of 50 ppm maximum nonlinearity, low input bias current of 25.0 nA max, 84 dB Min CMRR, and low noise, is ideal for use in precision data acquisition systems like this application.

5. Experimental results

Some of the 2D magnetometer characteristics are shown. Output characteristics of the 2D Hall device are presented in Fig. 4. The respective channel magnetosensitivities consist of \( S_x \approx 17 \) V/AT and \( S_y \approx 23.3 \) V/AT, without amplification. The offset in the x-channel is compensated by means of the trimmer P. The offset in the z-channel is generated by the mask misalignment ant technological imperfection. The possible reason for the relatively low sensitivities is due to the open bottom part of the device and around 10–12 \( \mu \)m deepness of the \( p \)-ring wall in the \( n \)-silicon substrate. The static non-linearity constitutes no more than NL \( \leq 0.1 \% \) at \( T \leq \pm 0.4 \) T; NL \( \leq 0.5 \% \) at \( \pm 0.4 \leq B \leq \pm 0.7 \) T, and the NL \( \leq 1.3 \% \) at \( \pm 0.7 \leq B \leq \pm 1.0 \) T, respectively. The methodology for obtaining of the NL parameter is given in detail in [1]. The determined temperature coefficient of the magnetosensitivity in the interval \( -10 \leq T \leq 80 \) °C is \( T_{C_S} = 0.1 \% / \) °C and the offset temperature drift is about 0.02%/°C. The experimental measurements of the sensor characteristics of the presented 2D magnetometer are performed in full compliance with the compre-
transducer zone is very promising. The interface electronics is simple and reliable. The obtained results and performance are appropriate for many contactless applications, such as: robotics, mechatronics and industrial controls – tactile systems, space orientation, measuring angular and linear displacements, speed sensors, end-of-travel sensors, encoders, magnetic compass and robotized unmanned flight vehicles; automobiles – ignition timing, antilock braking (ABS) systems; various electronic equipment – commutation for brushless fans, disk drive index sensors etc. The future objective is to develop a three-axis magnetometer for both 3D magnetic field sensing and contactless in-plane 360° absolute angle encoding based on the simple-design device presented in this paper.

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References

Biographies

Siya Lozanova received her M.Sc. degree in automation and electronics from Sofia Technical University, Bulgaria, and the Ph.D. degree from the Institute of Robotics (IR) at Bulgarian Academy of Sciences (BAS) for her work on three-contact in-plane sensitive silicon Hall devices with minimal design complexity. She is currently working as a full Professor at ISER-BAS. Her research interests are in the field of sensor systems, magnetic-field micro- and nanodevices as magnetotransistors, magnetodiodes, Hall elements, MEMS, etc. Prof. Lozanova has published over 100 papers and over 50 patents on magnetic and temperature sensors and microsystems. In 2009 she received the prestigious National Award for outstanding young scientist “Professor Marin Drinov”. Currently Dr. Lozanova is Deputy Director of IR-BAS and head of laboratory “Magnetic measurements”. Since 2013 she is a member of Executive Council of the Bulgarian Academy of Sciences and expert at the Bulgarian Ministry of Education and Science.

Svetoslav Noykov received the M.Sc. degree in Electromechanical Engineering from Tula State University, Russia, in 1992. He developed a Ph.D. thesis in the Institute of Control and System Research — Bulgarian Academy of Sciences, and received the Ph.D. degree in Elements and Devices of the Automation and the Computer Technique, in 2004. He is currently working as a Professor at the Institute of Robotics (IR) at Bulgarian Academy of Sciences. His current research interests include sensors devices and sensor interface electronics.

Chavdar Roumenin received the B.Sc. and M.Sc., PhD and Dr.Sci. degrees in engineering physics, semiconductor electronics and sensors from Moscow State University, Russia, Sofia University and Sofia Technical University, Bulgaria, respectively. He is currently a professor of sensorics and MEMS at the Institute of Robotics (IR) at Bulgarian Academy of Sciences (BAS). Since 1999, he is Director of the IR. In 2004, C. Roumenin is elected as Corresponding Member of BAS and in 2012 as Academician of BAS. He has published over 400 papers, three books and over 120 patents on magnetic and temperature sensors and microsystems, robotics etc. His citations are over 6000. His research interests are multiple varieties of micro- and nano-sensors based on novel principles of operation. Prof. Roumenin is a member of the Eurosensors International Steering Committee and the Editorial Board of Sensors and Actuators Journal. The title Emeritus Inventor of Bulgaria is assigned to him and his name has been entered in the Golden Book of Bulgarian Inventors. In 2008C. Roumenin has been awarded from the Bulgarian Government with honored Diploma for exceptionally special merits in invention, Bulgarian development and prosperity.