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Angular position device with 2D low-noise Hall microsensor

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ABSTRACT

A novel position device for full 0–360° contactless wear-free angle measurement has been developed. A CMOS 2D parallel-field Hall microsensor with sensitivity 19 V/AT along the *X*- and *Y*-channels and strongly reduced (at least 60 times) $1/f$ noise has been applied for the first time. This is accomplished by in-plane chip location of the output contacts outside the current-flow zone. An original magnetic actuating system has been used where double flux is achieved by connecting the repulsive poles of two permanent semi-ring shaped magnets. The total angular accuracy of the laboratory setup of this positioning instrument is better than ±2–3° over the range of 360°.

1. Introduction

The angular position devices use various transducing mechanisms, such as resistive, optical, mechanical, inductive, capacitive, magnetic, etc., converting rotation movement into electrical signal. These instruments are required for various consumer, automotive, security control, industrial and other applications, including detection of the rotor position in electric motors and engines, the position of the steering wheels in aircrafts, mining and cars, wireless networks, tilt robot, refrigerators, washing machines position, etc. Currently, the well-known potentiometers with ohmic contact permanently touching a ring-shaped resistive layer are wide-spread [1–3]. The main drawbacks of this type of angular devices are the heavy wear, limited lifetime, poor reliability and great susceptibility to harsh environment. Particularly promising for their high performance, low cost, contactless detection possibility of full 0–360° angle range, repeatability and small size are the angular devices consisting of magnetic actuating systems and magnetic-field sensors. Nevertheless, the use of very sensitive GMR or AMR as transducing element in these setups involves some disadvantages, such as incompatibility with silicon integrated processes and limited measurement angle range resulting from the non-linear output [3,4]. A trade-off approach between the IC compatibility, low price, reliability, accuracy, simplicity and performance is a rotating permanent magnet located over mutually perpendicularly placed silicon microsensors, such as linear Hall plates or lateral bipolar magnetotransistors [1,3,5–7]. These two-dimensional (2D) microsystems detect simultaneously two in-plane x–y magnetic-field components $\boldsymbol{B}_x$ and $\boldsymbol{B}_y$, providing complete information about: (i) the value of the resulting magnetic field $\boldsymbol{B}(\boldsymbol{B}_x,\boldsymbol{B}_y)$ by the sine and cosine output signals as a function of the rotation angle φ, and (ii) the angle value φ of the turning magnet relative to its reference position. In these contactless devices, the integrated 2D Hall magnetometers, which are sufficiently small and enough to perform a "point" measurement of the in-plane magnetic-field vector $\boldsymbol{B}(\boldsymbol{B}_x,\boldsymbol{B}_y)$ are preferred. Most widely applied in these vector transducers are different modifications of Hall microsensors with orthogonal and parallel-field activation. This is due to the fact that their behaviour is well predictable, because the action is controlled by only one clear galvanomagnetic effect. Many different versions of silicon 2D Hall microsensors are available featuring such drawbacks as channels cross-talk, offset, temperature and temporal drift [8–10]. A CMOS 2D parallel-field Hall magnetometer with minimal design complexity is also implemented, containing only 4 contacts [11]. Notwithstanding the achieved good results, the relatively high level of internal $1/f$ noise is not sufficiently well resolved in this 2D vector microsensor. On the other hand, the application of bipolar silicon 2D magnetotransistors encounters certain problems, related to the large channel offsets and temperature drift [8,11,12].

One possibility to enhance the quality and angle measurement accuracy of angular position instruments based on 2D Hall elements described in [11] is the decrease of the internal $1/f$ noise. Also, the efficiency of the magnetic modulating system could be improved. In this paper, an angular position device containing a novel CMOS 2D parallel-field Hall microsensor with strongly reduced internal $1/f$ noise and lacking cross-sensitivity is described. The original

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magnetic modulating system provides for a two-fold increase of the actuating induction flux B value.

2. Low-noise silicon parallel-field 2D Hall microsensor

2.1. Concept of the novel two-axis Hall device

A new design of five-contact parallel-field silicon Hall microsensor is investigated in [13]. Compared to all well-known similar elements, its measuring Hall terminals H_1 and H_2 are located outside the current-flow active region. A three-contact version of this microsensor is presented in Fig. 1 [12]. These Hall elements strongly minimize one 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 most of the supply current in CMOS Hall devices to flow in this area and through the Hall contacts. This short-circuit current reduces the real current in the active Hall region, thus reducing substantially the Hall voltage $V_{H_{1,2}}(\boldsymbol{B})$. Furthermore, the level of the internal $1/f$ noise increases substantially. The five-contact parallel-field Hall microsensors are found out to drastically reduce the internal $1/f$ noise by about three orders of magnitude since the biasing current does not flow through the Hall terminals [14]. Following from the numerous experimental results and the 2D FEM simulations and analysis carried out in [15], the shallower the CMOS parallel-field Hall device, the higher the short-circuit effect, and as a consequence, the magnetosensitivity and the signal-to-noise ratio will be reduced. As proven in [15] again, this microsensor class with two sensing contacts H_1 and H_2 are intrinsically limited in terms of measured transducer efficiency compared to the well-known Hall elements with orthogonal activation at equivalent doping level and thickness. We believe that the major reason for this drawback is that in the classical Hall sensors, the current trajectories are linear with or without magnetic field $\boldsymbol{B}$ and the Hall field is situated between two well-defined sides of rectangular device designs. However, in parallel-field Hall structures the current paths are curvilinear and the kinetic processes are such that in magnetic field $\boldsymbol{B}$ Hall potentials are generated on all boundary surfaces of the chip, inclusive on the rear side. As shown in [15], there is transfer of the Hall voltage from the rear side via the lateral boundaries to the top chip plane while the substrate depth increases. In the general case, the measured Hall voltage $V_{H_{1,2}}(\boldsymbol{B})$ with two Hall terminals H_1 and H_2 located at the top substrate plane is always reduced with respect to the entire Hall voltage $V_{Hall}(\boldsymbol{B})$ generated in the parallel-field Hall microdevice, $V_{H_{1,2}}(\boldsymbol{B}) = KV_{Hall}$, where the coefficient K is substantially <1. Only in case of complete summing up of these Hall voltages could equality of the sensitivities in microsensors with orthogonal and parallel-field activation be achieved. If the parallel-field Hall device is deep enough, by using four separate sensing contacts only, H_1–H_2 and H_3–H_4, located at the top side of the silicon chip, where one of the terminal pairs is located in the zone of the inside supply contacts [6,9,16], and the other terminal pair is located in the zone outside the supply electrodes [6,9,13], it is possible to achieve maximum sensitivity [15]. So far, in parallel-field Hall microsensors, the Hall voltage has been measured experimentally by two contacts, H_1 and H_2, and in the elements with minimal design complexity – by one contact H [6,9,11,12,16].

The innovative task in this research is to design a two-axis Hall magnetometer, which combines the simultaneous measurement of the in-plane magnetic-field components $\boldsymbol{B}_x$ and $\boldsymbol{B}_y$ and the advantages of the 2D microsensor from [11,14] to reduce sufficiently the $1/f$ noise level.

2.2. CMOS 2D Hall microsensor description and operation

The 2D Hall microtransducer 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's active region $I_{C_{1,2}}$ are formed. The structure is bent at right angle [17]. This solution uses only one supply current $I_{C_{1,2}}$ for $\boldsymbol{B}_x$ and $\boldsymbol{B}_y$ sensing. The magnetometer operates in the following way. The current $I_{C_{1,2}}$ 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 $\boldsymbol{B}(\boldsymbol{B}_x,\boldsymbol{B}_y)$ deflect laterally the vertical currents I_{C_1} and I_{C_2}, producing Hall voltages: $V_{H_1}(\boldsymbol{B}_y) = K_0V_{Hall}(\boldsymbol{B}_y)$, and $V_{H_2}(\boldsymbol{B}_x) = K_0V_{Hall}(\boldsymbol{B}_x)$, where V_{Hall} are the total Hall voltages developed in the respective ram C_1-m and C_2-m, and K_0 is a coefficient, $K_0 < 0.5$. There is a longitudinal electrical component $V_{C_{1,2}}(\boldsymbol{B})$. In magnetic field $\boldsymbol{B}$ it generates quadratic geometrical magnetoresistance $V_{C_{1,2}} \equiv V_{MR} \sim B^2$. Therefore, on the electrodes H_1 and H_2, linear and odd Hall voltages and quadratic even magnetoresistance co-exist. An original circuitry fully compensates the inevitable offsets and the corresponding parts of the magnetoresistance voltages $V_{MR} \sim B^2$ developed on contacts H_1 and H_2 (Fig. 3). When the offsets are tuned to zero by trimmers r_1 and

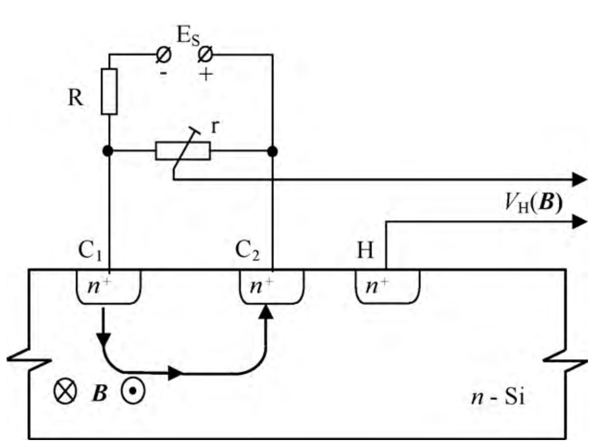

Fig. 1. Cross-section and circuitry of parallel-field Hall microsensor with minimal design complexity and outside Hall contact H.

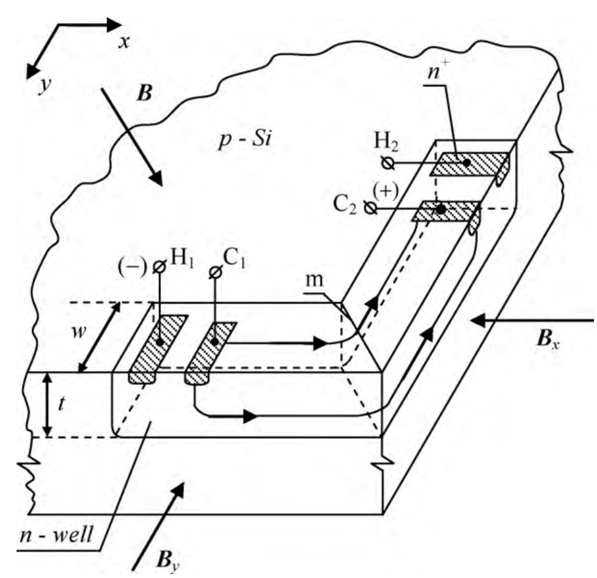

Fig. 2. The new 2D CMOS vector magnetometer, containing only four contacts. The current components I_{C_1} and I_{C_2} generate Hall voltages on contacts H_1 and H_2. The C_1-m and C_2-m parts are equal.