CMOS HALL SENSOR FOR SUBSEQUENT MAGNETIC-FIELD COMPONENTS MEASUREMENT

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A novel CMOS Hall sensor for subsequent measurement of the three orthogonal magnetic-field components utilising unique transducer zone is suggested and experimentally tested. Five n^+ *planar contacts on n-Si epilayer are implemented both as supply, as well as to obtain information about the vector components. The microdevice is manufactured through standard CMOS process. The effective sensor volume is* $120\ \mu m \times 120\ \mu m \times 10\ \mu m$*, the respective channel-magnetosensitivities consists of* $S_x = 74$ *V/AT,* $S_y = 83$ *V/AT and* $S_z = 37$ *V/AT, the nonlinearity and channel cross-sensitivities at* $B \leq 1$ *reach no more than 0.4 % and 3 % respectively, and the frequency response to a.c. magnetic field is greater than 40 kHz.*

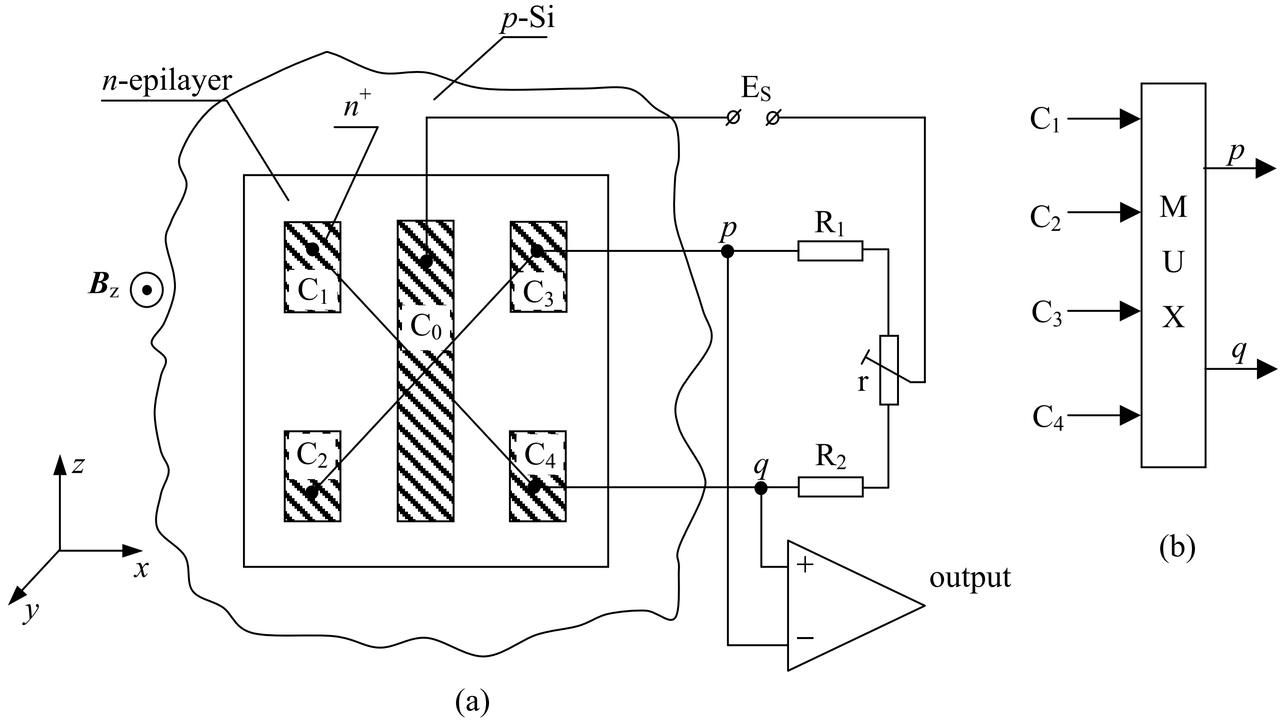
Keywords: 3-D Hall sensing, subsequent measurement approach, magnetic-field instrumentation

1. INTRODUCTION

Obtaining of metrological data about the orthogonal components $\boldsymbol{B}_x$, $\boldsymbol{B}_y$ and $\boldsymbol{B}_z$ of the magnetic field $\boldsymbol{B}$ sensor problem is a current sensor challenge. The typical solution consists of integration of three individual mutually orthogonal magnetosensitive microdevices such as magnetotransistors, magnetodiodes or Hall elements onto common silicon substrate [1-4]. Adopting this approach, however, it is difficult to fulfill the main requirement for high spatial resolution capability (measurement at a "spot"), typical for that class of transducers. Satisfactory results are achieved by the application of the principle of *functional integration* - the same active sensor zone is used for measurement of all three magnetic components utilising the physical effects in solids [1,2,5-9]. In both cases, the information about $\boldsymbol{B}_x$, $\boldsymbol{B}_y$ and $\boldsymbol{B}_z$ components is obtained simultaneously. However, the measurement of the magnetic field variations in geomagnetism, volcanology, spatial positions of objects, traffic detection, contactless automation etc., is not fast enough regarding the registering instruments and can be considered quasi-static in first approximation. Thus, for previously discussed processes it is an expedient approach to extend in time the sensing of the magnetic field vector, this way allowing for the information about $\boldsymbol{B}_x$, $\boldsymbol{B}_y$ and $\boldsymbol{B}_z$ fields be obtained subsequently within the same zone. This technique is suggested for the first time in [10] using four collectors bipolar silicon p^+-n-p^+ magnetotransistor. The subsequent measurement method is also experimentaly tested with silicon Hall microstructure [11]. In this paper the solution from [11] is developed further using CMOS realization, and the measurement of all magnetic-field components is characterized by a very high-resolution. Therefore the novelty in this investigation is to use CMOS technology process for the solution from [11] enhancing the spatial resolution and the magnetosensitivities of the three output channels. Its performance is based on three subsequent in time coupling combinations of two parallel-field and one orthogonal Hall elements, functionally integrated onto *n*-Si epilayer.

2. 3-D HALL DEVICE AND OPERATON

The novel 3-D Hall мagnetometer is shown in Fig. 1. On one of the sides of an *n*-Si epilayer are formed middle strip n^+ contact C_o and four n^+ contacts C_1, C_2, C_3 and C_4 symmetrically to it [11]. The *n*-epilayer defines the boundaries of the transducer and confines perfectly the active sensor zone in the *p*-Si substrate.



(a)

(b)

Fig.1. Top-view of the novel CMOS 3-D Hall magnetometer with the onset circuit. The shown cross-coupling of contacts C_1-C_4 and C_2-C_3 realizes the $\boldsymbol{B}_z$- field sensing. The multiplexer (MUX) in Fig. 1(b) realize the subsequent in time measurement process with frequency f = 18 kHz.

The measurement of the three components $\boldsymbol{B}_x$, $\boldsymbol{B}_y$ and $\boldsymbol{B}_z$ of the magnetic-field vector $\boldsymbol{B}$ is accomplished through three subsequent in time coupling combinations of the four contacts C_1, C_2, C_3 and C_4, shown in Fig. 1(b) and Fig. 2. These combinations are realized continuously throug multiplexing unit, Fig. 1(b). The terminals *p* and *q* of each of the combinations from Fig. 2(a), 2(b) and 2(c) are fed through multiplexer, two resistors R_1 and R_2, trimmer r and energy supply E_S from the middle terminal C_o. As a result from the transducer symmetry within the active region, four equal in value bias currents flow.

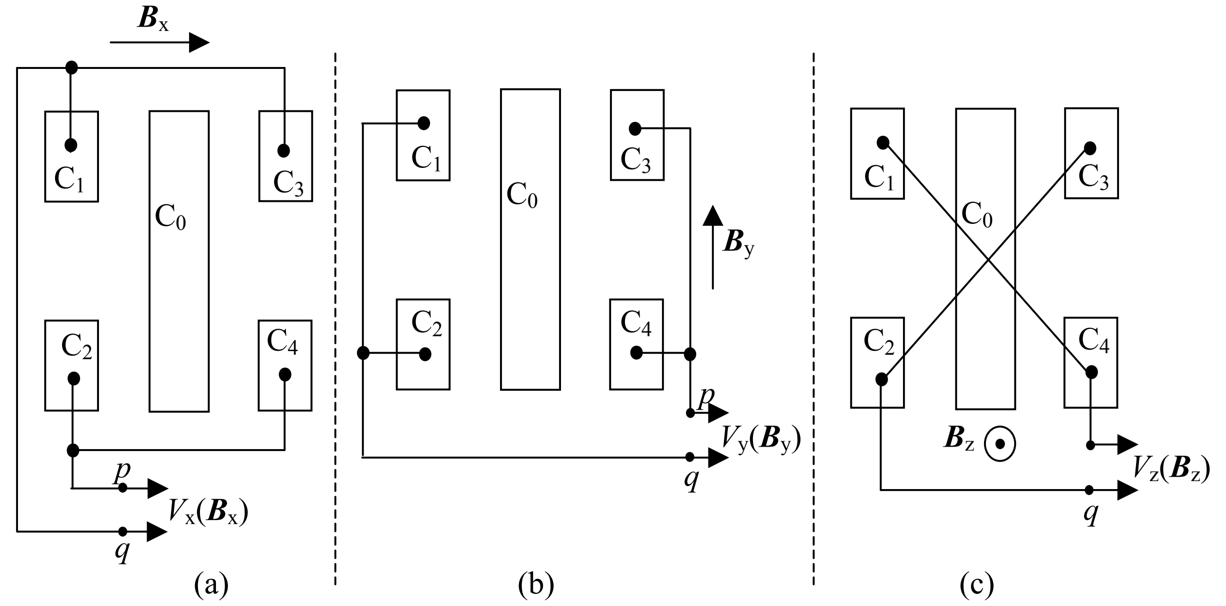


Fig.2. The three coupling combinations for subsequent measurement of magnetic vector components, (a), (b) and (c) corresponds to $\boldsymbol{B}_x$, $\boldsymbol{B}_y$ and $\boldsymbol{B}_z$ sensing respectively.

The latter are two by two opposite in direction, i.e. $I_{Co,C1} = |- I_{Co,C3}|$ and $I_{Co,C2} = |- I_{Co,C4}|$. The sum of these components is equal to the current I_{Co} via the contact C_o. The coupling combinations 2(a) and 2(b) together with the onset circuitry constitute parallel-field triple Hall microsensors, sensitive respectively to the $\boldsymbol{B}_x$- and $\boldsymbol{B}_y$-components, similarly to [1,2,8,9]. The conversion of the magnetic field $\boldsymbol{B}_x$ or $\boldsymbol{B}_y$ into electrical signal is described as follows. In devices of the type shown in Fig. 1 the effective path of the majority of the carriers in the substrate is nonlinear - it begins and ends on the side with the contacts [1,2,5-9]. The equi-potentiality of the heavily doped n^+ regions C_o, C_1...C_4 ensures an orthogonally of the current lines with respect to the upper surface at $B = 0$. As a result, the effective trajectory can be regarded as curvilinear in the n-Si epilayer. Consequently, the carrier velocity $\boldsymbol{v}$ is characterised by components $\boldsymbol{v}_x$ and $\boldsymbol{v}_z$, $\boldsymbol{v} = \boldsymbol{v}_x + \boldsymbol{v}_z$, Fig. 1. When an external magnetic field is applied, $\boldsymbol{B}_x$ for instance, depending on its direction, the Lorentz force $\boldsymbol{F}_L = q\boldsymbol{v}_z x\boldsymbol{B}$ deflects the carriers laterally with velocity $\boldsymbol{v}_z$ under contacts C_1,...C_4 to a Hall angle $\Theta_H = \mu_n B_x$ in the y-z plane, where μ_n is the carrier mobility. Thus, on the contacts C_1 and C_3, and respectively on contacts C_2 and C_4, charges with opposite signs are generated. The direct coupling of leads C_1-C_3 and C_2-C_4, Fig. 2(a), ensure summation of Hall potentials with the same sign. Therefore, by the Hall voltage $V_x(\boldsymbol{B}_x) \equiv V_{C1,2}(\boldsymbol{B}_x)$ of the parallel-field Hall device C_1-C_3-C_o-C_2-C_4 the strength and polarity of the field $\boldsymbol{B}_x$ is measured. Through the contacts coupling C_1-C_2 and C_3-C_4, Fig. 2(b), the component $\boldsymbol{B}_y$ is sensed. In this case, the Lorentz force $\boldsymbol{F}_L$ modulate respectively in left and in right from the contact C_o the carrier trajectories in x-z plane. As a result, from the Hall voltage $V_y(\boldsymbol{B}_y) \equiv V_{C2,4}(\boldsymbol{B}_y)$ of the parallel-field Hall element C_1-C_2-C_o-C_3-C_4 the value and direction of the magnetic field $\boldsymbol{B}_y$ measurement is performed. Component $\boldsymbol{B}_z$ interacts with the carrier velocity $\boldsymbol{v}_x$ and - $\boldsymbol{v}_x$ so that the Lorentz force

$\boldsymbol{F}_L$ deflects currents $I_{Co,1}$, $I_{Co,2}$, $I_{Co,3}$, and $I_{Co,4}$ to a Hall angle $\Theta_H = \mu_n B_z$ in *x-y* plane. The cross-coupling of C_1-C_4 and C_2-C_3, shown in Fig. 1(a) as well as in Fig. 2(c), realize a summation of current changes with the same sign. The combination on Fig. 2(c) together with the onset circuit represents a Hall microsensor C_1-C_4-C_o-C_2-C_3 with orthogonal activation, which output voltage $V_z(\boldsymbol{B}_z) \equiv V_{C1,3}(\boldsymbol{B}_z)$ can be utilised for a measurement of the field $\boldsymbol{B}_z$. The *CMOS realization* used confines very well the supply currents I_{C1}, I_{C2}, I_{C3} and I_{C4}. This increases the magnetosensitivity of the three output channels in comparison to [11] with about 7 %. The absolute value of vector $\boldsymbol{B}$ is given by the well-known operation $|\boldsymbol{B}| = \left(B_x^2 + B_y^2 + B_z^2\right)^{1/2}$.

The use of unique transducer region guarantees obtaining of metrological information about all three magnetic components under identical electrical, thermal and technological conditions. This provides us with optimal sensor characteristics, including high spatial resolution, which is especially important for the measurement of strongly non-uniform magnetic fields.

3. REALIZATION AND EXPERIMENTAL RESULTS

The new three-axis Hall microdevice based on subsequent measurement approach is manufactured by standard CMOS technology process, using low doped *p*-Si substrate.

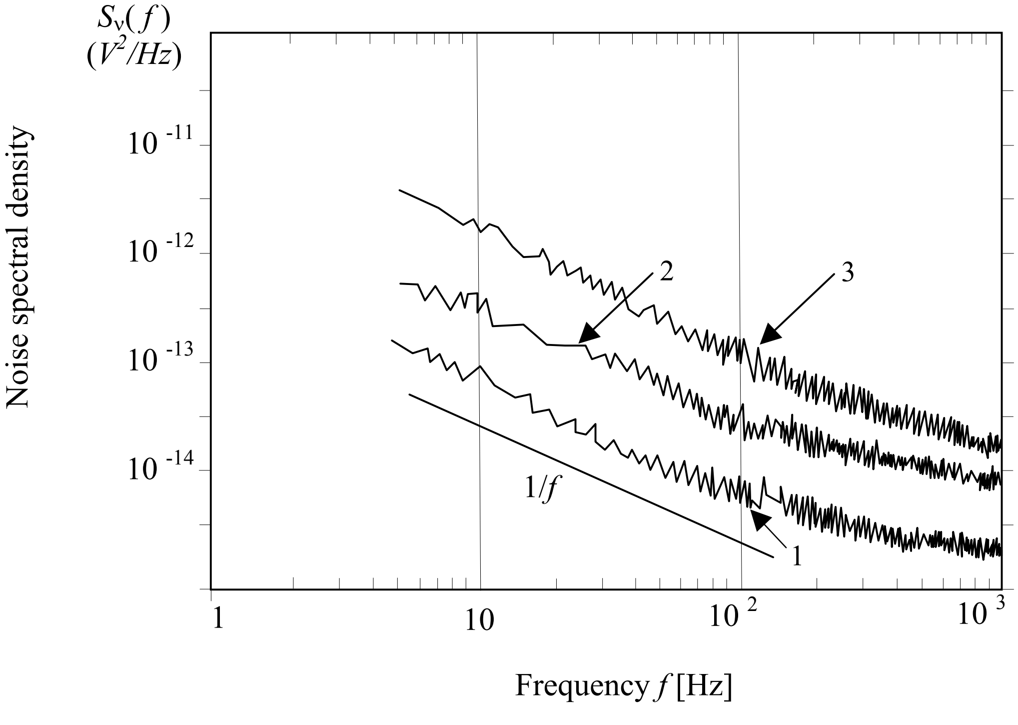


Fig.3. Measured power spectral density of noise fluctuations for the $\boldsymbol{B}_x$- channel, the supply current I_{Co} is as a parameter; 1- 0.5 mA, 2 – 1.0 mA, 3 – 1.5 mA, $T = 20$ °C.

The average dopant concentration in the *n*-epilayer reach about $n \sim 10^{15}$ cm^{-3} and its depth is 10 μm. The active sensor volume of the 3-D magnetometer prototype is approximately 120 μm × 120 μm × 10 μm. The chip is mounted and bonded on a ceramic plate. The experimentally obtained magnetosensitivities of the three output channels of the 3-D device are: $S_x = 74$ V/AT; $S_y = 83$ V/AT and $S_z = 37$ V/AT. The nonlinearity of the channels at induction $B \leq 1$ T does not exceed NL ≤ 0.5 %. The offsets are nullified easily by the trimmer r, or by the op-amp, Fig. 1(a). The temperature coefficient of magnetosensitivity T.C. in the range 10 °C ≤ T ≤ 80 °C is T.C. = 0.1 %/°C. The measured noise power spectral density of the vector sensor for one of the channels is shown in Fig. 3. For the other two output channels the dependencies are similar. As it can be seen, in the range from 1 Hz to 1000 Hz the internal noise is of $1/f$ kind, as with the increase of the supply current I_{Co} the noise increases too. The cross-sensitivities C.S. between the three axes are measured according to the method described in [9] and results are presented in Fig. 4.

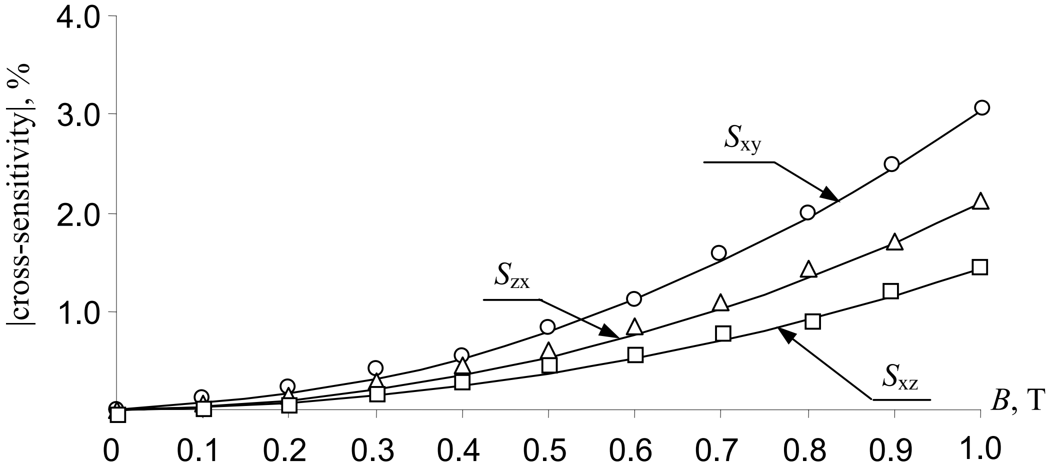


Fig.4. The cross-channel sensitivities at $B \leq 1$ T, $T = 20$ °C

A completely satisfactory application result with C.S. ≤ 3 % at $B \leq 1$ T, are obtained which correlates well with the data about other vector sensors [5-7]. The dynamic behavior of the CMOS Hall magnetometer is also experimentally investigated. The frequency response is measured as the dependence of the amplitude ratio of the respective channel output signal to the AC sine wave magnetic field. In the range $0 \leq f \leq 40$ kHz parasitic effects are not expected (3-D transducer with read-out circuitry) [1].

4. CONCLUSION

The obtained sensor characteristics of the CMOS 3-D Hall microdevice are very promising for a wide range of practical applications, when high-resolution and high accuracy are needed [12,13 and references herein]. The method of subsequent measurement of $\boldsymbol{B}_x$-, $\boldsymbol{B}_y$- and $\boldsymbol{B}_z$- fields with unique sensor region is an important advantage. Only five contacts are enough for the supply and obtaining of full information regarding all three components of the magnetic field $\boldsymbol{B}$. The received experimental results in comparison with these from [11] prove the successful CMOS process solution for high-resolution and enhanced sensitivity. The very well performance of the CMOS 3-D Hall microsensor contributes to a large scale of applications.

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5. REFERENCES

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