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Characteristics Research of the Three Dimensional Hall Magnetic Field Sensor Based on Packaging Technology

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Abstract: This paper presents a three dimensional (3D) magnetic field sensor composed of three Hall elements with similar characteristics. Through adopting complementary metal oxide semiconductor (CMOS) technology, the chips of Hall element were designed and fabricated on the p-type silicon substrate with high resistivity. Based on the wire bonding technology, the Hall sensors were packaged on printed circuit boards (PCBs), allocating on three faces of a synthetic resin cube (10×10×10 mm^3) to form an orthogonally directional array. When the supply voltage is 5.0 V, the magnetic sensitivities in x axis, y axis and z axis are 137.7 mV/T, 137.2 mV/T and 136.7 mV/T at room temperature, respectively. The experimental results show that the packaging device can achieve the measurement to 3D magnetic field. *Copyright © 2016 IFSA Publishing, S. L.*

Keywords: 3D Hall magnetic field sensor, CMOS technology, Packaging technology, Error analysis.

1. Introduction

Hall Effect was supposed in 1879, and based on that, Hall devices owning many advantages, such as wide measurement range, low power consumption and small size [1-2], are widely used as magnetic sensors. However, there are also many factors which can affect the magnetic characteristics of Hall devices, such as the length-width ratio of magnetic sensitive layer, the position and size of Hall output probe, etc. Based on Hall Effect, some domestic and foreign literatures by studying the Hall devices have reported the 3D magnetic sensor [3-4]. The 3D magnetic sensor is used as geomagnetic measurement, geological examination, special magnetic field measurement, etc. In 2011, Horacio V. Estrada presented a 3D magnetic field sensor fabricated based on MEMS micromachining of SOI wafer, the sensitivity of its each element is about 100 V/AT [5]. In 2013, Hongbing Pan, *et al.* presented a single-chip integrated 3D Hall sensor for high accuracy three-axis magnetic-field measurement, containing horizontal and vertical Hall elements [6]. In recent years, it has be more and more important for developing 3D Hall magnetic sensor, due to special characteristics, such as highly accurate, miniaturized, integration, intelligent and low-cost [7].

A structure of 3D Hall magnetic sensor basing on packaging technology is presented in this paper, and the magnetic sensitivity characteristics and errors for it are also analyzed. The sensitivity of each Hall sensor is about 137.0 mV/T. The integrated sensor without adopting isolation technology exists mutual interference phenomenon, so that it is very important to study the composed 3D magnetic sensor in special circumstance.

2. Basic Structure and Operating Principle

2.1. Basic Structure

Fig. 1 shows the basic structure model of 3D Hall magnetic field sensor. The proposed sensor is composed of three Hall elements with similar characteristics allocated on three faces of a synthetic resin cube (10×10×10 mm^3) to form an orthogonally directional array. The illustration of Hall element gives two current electrodes (I_1 and I_2) and two Hall output probes (V_{H1} and V_{H2}), where both the length (L) and width (W) of magnetic sensitive layer are 80 μm, and width (s) of the Hall output probe is 8 μm. A 3D magnetic sensor is formed by packaging the Hall elements on PCBs by wire bonding technology, using to measure the cube center of three components in magnetic field.

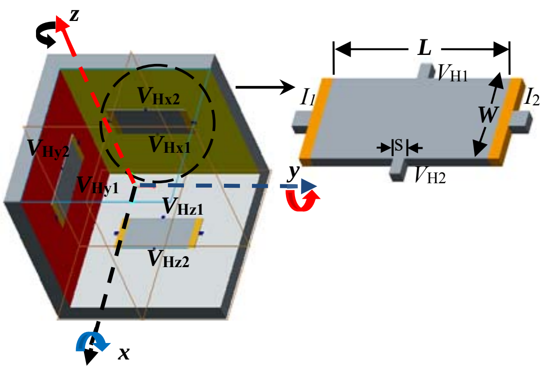


Fig. 1. Basic structure of 3D Hall magnetic field sensor.

3. Operating Principle

Fig. 2 shows the model of three dimensional space magnetic field vectors, where $\vec{B}$ is the magnetic field vector, the α, β and γ are the angles between $\vec{B}$ and x axis, y axis and z axis, respectively.

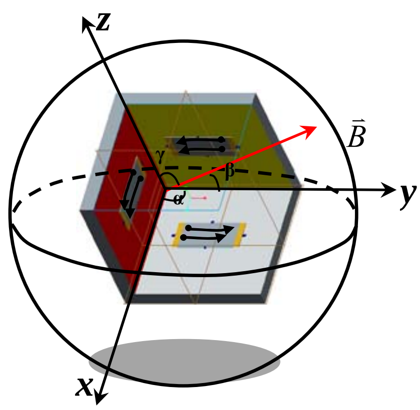


Fig. 2. Three dimensional space magnetic vector.

Based on the spherical harmonic model of space magnetic field, the spherical harmonic expressions of space magnetic field are given:

$$\begin{pmatrix} \bar{B}_x \\ \bar{B}_y \\ \bar{B}_z \end{pmatrix} = \bar{B} \begin{pmatrix} \cos\alpha \\ \cos\beta \\ \cos\gamma \end{pmatrix} \tag{1}$$

Based on Hall Effect, the carriers in sensitive layer of Hall element are deflected under the action of external magnetic field, and the expressions of V_{Hx}, V_{Hy} and V_{Hz} can be driven:

$$V_{Hx} = f'_{Hx}\left(\frac{L}{W},\theta\right)\cdot\mu_n\cdot\frac{W}{L}\cdot B\cdot\cos\alpha\cdot V_{DD}, \tag{2a}$$

$$V_{Hy} = f'_{Hy}\left(\frac{L}{W},\theta\right)\cdot\mu_n\cdot\frac{W}{L}\cdot B\cdot\cos\beta\cdot V_{DD}, \tag{2b}$$

$$V_{Hz} = f'_{Hz}\left(\frac{L}{W},\theta\right)\cdot\mu_n\cdot\frac{W}{L}\cdot B\cdot\cos\gamma\cdot V_{DD} \tag{2c}$$

According to Eq. (2), the output voltage V_H of 3D magnetic sensor is:

$$V_H = \sqrt{V_{Hx}^2+V_{Hy}^2+V_{Hz}^2} = \begin{bmatrix} f_{Hx}^2\left(\frac{L}{W},\theta\right)\cos^2\alpha + \\ f_{Hy}^2\left(\frac{L}{W},\theta\right)\cos^2\beta + \\ f_{Hz}^2\left(\frac{L}{W},\theta\right)\cos^2\gamma \end{bmatrix}^{\frac{1}{2}} \cdot\mu_n\cdot\frac{W}{L}\cdot B\cdot V_{DD} \tag{3}$$

From above Eq. (3), it gives that the V_H is proportional to μ_n and W/L, respectively. In the ideal case, the geometric structure factors of Hall magnetic field sensor are:

$$f_{Hx}\left(\frac{L}{W},\theta\right) = f_{Hy}\left(\frac{L}{W},\theta\right) = f_{Hz}\left(\frac{L}{W},\theta\right) = f_H\left(\frac{L}{W},\theta\right) \tag{4}$$

So, the Eq. (3) is:

$$V_H = \sqrt{V_{Hx}^2+V_{Hy}^2+V_{Hz}^2} = \left[\cos^2\alpha+\cos^2\beta+\cos^2\gamma\right]^{\frac{1}{2}}, \quad f_H\left(\frac{L}{W},\theta\right)\cdot\mu_n\cdot\frac{W}{L}\cdot B\cdot V_{DD} \tag{5}$$

where θ is the Hall angle, μ_n is carrier mobility in magnetic sensitive layer, B is external magnetic field, and V_{DD} is the supply voltage, $f_{Hx}\left(\frac{L}{W},\theta\right)$, $f_{Hy}\left(\frac{L}{W},\theta\right)$, $f_{Hz}\left(\frac{L}{W},\theta\right)$ are geometric structure factors of x axis, y axis and z axis, respectively.

From the above expressions, the measured V_H is proportional to V_{DD} and B, respectively, and increases with them. It gives that the packaging structure can realize measurement of 3D magnetic field according to theoretical analysis.

4. Fabrication Technology

The Hall element is designed and fabricated on p-type silicon substrate with <100> orientation by CMOS technology [8-9]. Fig. 3 shows the main fabrication technology process:

a) Cleaning silicon wafer with high resistance (ρ>1000 Ω·cm);

b) Growing SiO_2 thin films with thickness of 550 nm on the surface of silicon wafer by thermal oxidation;

c) The first photolithography to form magnetic sensitive region;

d) Growing thin oxygen with 50 nm and phosphorus injection, the injection energy is 60 keV and the injection dose is 2E13 cm^{-2};

e) The second photolithography and phosphorus injection, the injection energy is 60 keV and the injection dose is 3E15 cm^{-2}, the subsequent annealing treatment;

f) Growing SiO_2 thin films with the thickness of 450 nm by plasma enhanced chemical vapor deposition (PECVD);

g) The third photolithography to form contact holes;

h) Sputtering Al on the top by magnetron sputtering, patterning Al layer to create electrode, and metalizing at 420 ºC for 25 minutes to achieve ohmic contacts.

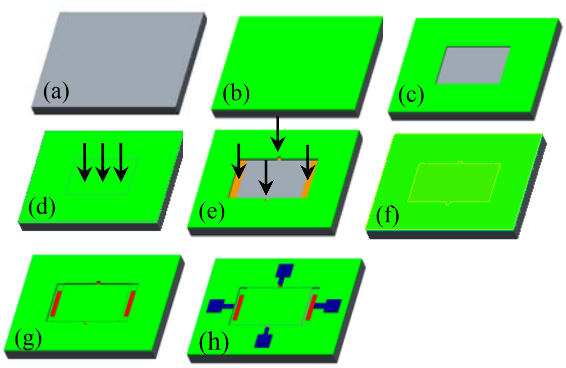


Fig. 3. Main fabrication technology process of the Hall magnetic field sensor.

The photograph of 3D magnetic field sensor is shown in Fig. 4, the photograph of chip (1500×750 μm²) in illustration.

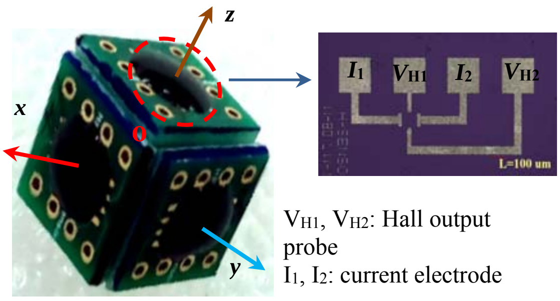


Fig. 4. Photograph of a 3D magnetic field sensor.

5. Experimental Results and Discussion

Fig. 5 shows the testing system principle diagram of 3D magnetic field sensor [10], including magnetic field generator (CH-100), multi-meter (Agilent 34401A), power source (RIGOL DP832A) and rotating platform. The sensor was fixed on the rotating platform with rotation angle θ from 0° to 360° with a step of 5° at room temperature, which can been controlled by computer under a constant external magnetic field, so that the measurement of 3D magnetic field can be realized.

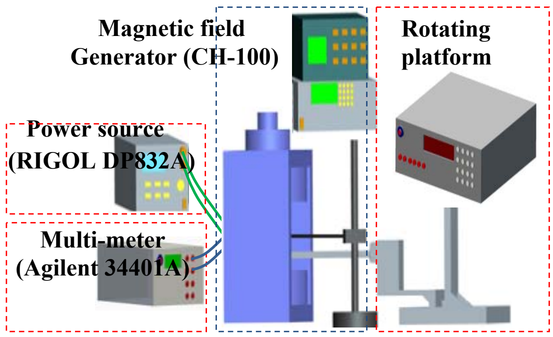
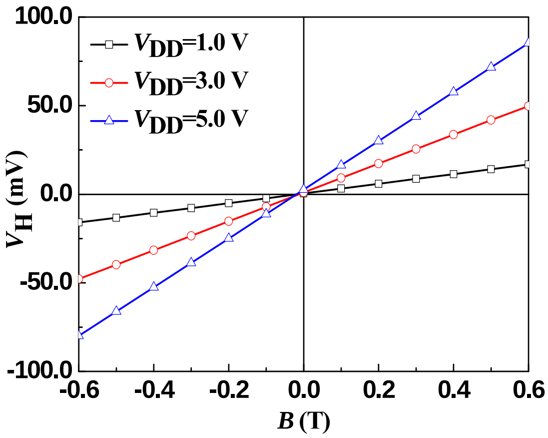


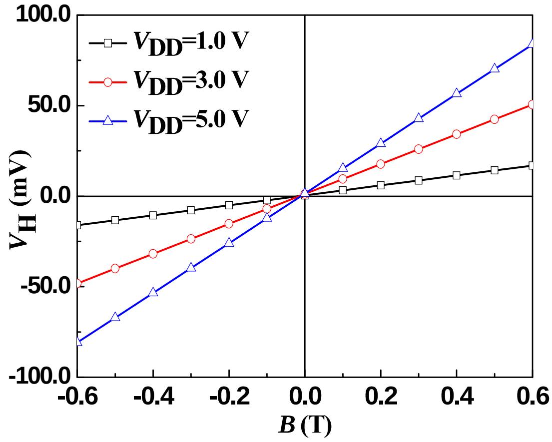
Fig. 5. Testing system of the 3D magnetic field sensor.

5.1. Magnetic Characteristics of Hall Magnetic Sensor

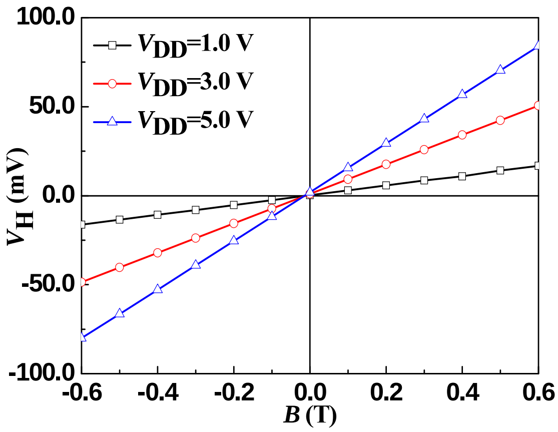
Fig. 6 (a), (b) and (c) show the relation curves between Hall output voltages (V_{Hx}, V_{Hy} and V_{Hz}) and B, the magnetic field range of -0.6 T to 0.6 T with a step of 0.05 T, and tests for three times. Experiment results show that the measured V_H increases with V_{DD} under a constant external magnetic field, and also increases with B under a constant operating voltage. The Hall sensor has positive and negative magnetic characteristics. When the V_{DD} is 5.0 V, the sensitivities of x axis, y axis and z axis are 137.7 mV/T, 137.2 mV/T and 136.7 mV/T, respectively. The linearity is 0.10 %F.S., 0.09 %F.S. and 0.11 %F.S., respectively. So, the magnetic sensitivities for them are relatively consistent.



(a)



(b)

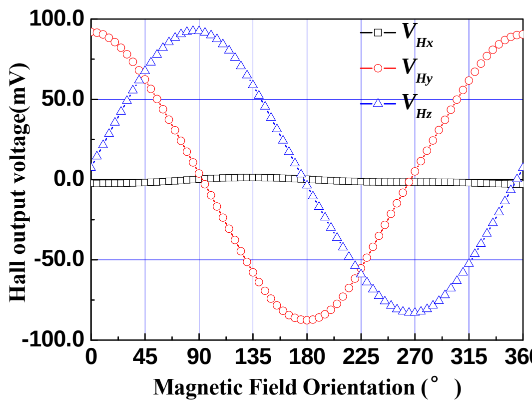


(c)

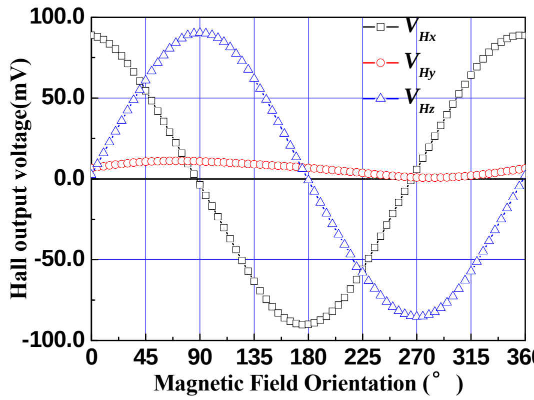
Fig. 6. The magnetic characteristic curves of Hall sensor (a) x direction; (b) y direction; (c) z direction.

5.2. Magnetic Characteristics of 3D Magnetic Field Sensor

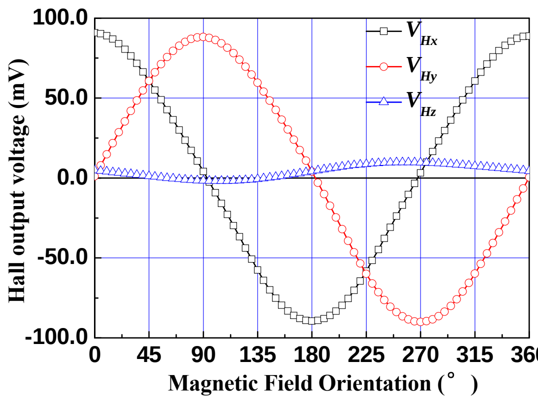
When B= 0.6 T and V_{DD}= 5.0 V. Fig. 7(a), (b) and (c) show the measured V_H (V_{Hx}, V_{Hy} and V_{Hz}) of rotated along x axis, y axis and z axis, respectively. In Fig. 7(a), it gives that the maximum of V_{Hy} occurring along x axis when β is 0°, corresponding to Fig. 7 (a) for either the y- or z-oriented sensor, observed at 180°, 360° and 90°, 270°, respectively. The measured V_{Hx} is closed to zero over the 360°, although a voltage with a sinusoidal or cosine behavior is observed. The Fig. 7 (b) and (c) show both of the measured Hall output voltages of rotated along y axis and along z axis are the same as the one along x axis.



(a)



(b)



(c)

Fig. 7. Relation curves between V_{Hx}, V_{Hy}, V_{Hz} and rotation angle: (a) along x axis; (b) along y axis; (c) along z axis.

Fig. 8 shows the relation curves between output voltage (V_{Hx}, V_{Hy} and V_{Hz}) and rotated along body diagonal of the three dimensional magnetic field sensor. A precise periodic response for three elements is shown in Fig. 8. When the magnetic field orientation is 60°, the output voltage of *z* axis achieves a maximum, and the *x* axis and *y* axis are the same; when the magnetic field orientation is 120°, the output voltage of *y* axis is maximum, and the *z* and *x* axis are the same; when the magnetic field orientation is 180°, the output voltage of *x* axis is maximum, and the *y* and *z* axis are the same.

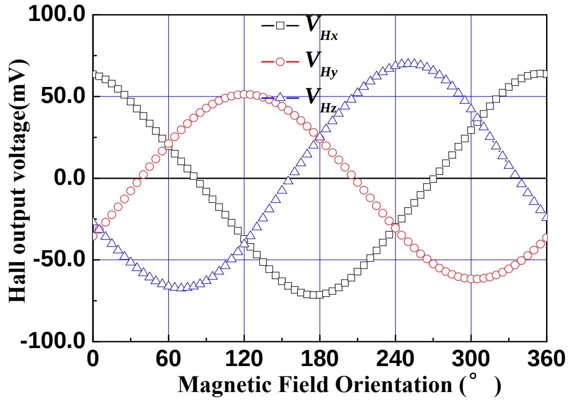


Fig. 8. Relation curves between three elements output voltage and rotated around body diagonal of the three dimensional magnetic field sensor.

5.3. Error Analysis of 3D Magnetic Field Sensor

Fig. 9 shows the error analysis of output voltage with the whole cycle (2π), the measured max and min voltages are 79.4 mV and 69.4 mV, respectively.

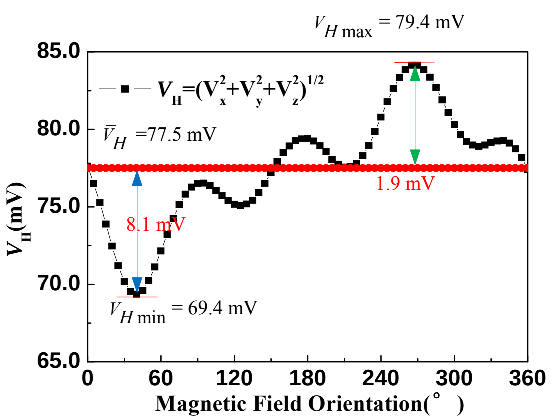


Fig. 9. Error analysis of the output voltage with the whole cycle.

Eq. (6) is the average value expression of Hall output voltage in the whole period.

$$\overline{V}_H = \frac{1}{n}\sum_{i=1}^{n} V_{Hi} = \frac{1}{n}\sum_{i=1}^{n}\sqrt{V_{xi}^2 + V_{yi}^2 + V_{zi}^2} \quad (i = 1, 2, 3 \ldots 73) \tag{6}$$

From the Eq. (6), the obtained average value of V_H is 77.5 mV. The difference between maximum and the average value of V_H is 1.9 mV, and the difference between average and minimum is 8.1 mV. The range of error is 1.9 mV to 8.1 mV. The experimental results show that the sensor can reach the detection for the strength and direction of 3D magnetic field.

6. Conclusions

This paper presents a packaging structure of 3D magnetic sensor based on Hall Effect. Based on the CMOS and wire bonding technology, a 3D magnetic sensor was designed and fabricated. Through experiment research, the magnetic sensitivities of three Hall magnetic sensors when V_{DD} is 5.0 V, can reach about 137.0 mV/T, and the coherence is very well from experimental results. Through the error analysis, the average of V_H is 77.5 mV and the range of error is from 1.9 mV to 8.1 mV. The research results show that it is possible to detect the 3D magnetic field by the sensor, which also lays a foundation for the further study of 3D magnetic sensor integration.

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