A HORIZONTAL HALL SENSOR 3D COMSOL MODEL

Hua Fan[1], *Sujie Li*[1], *Yuanjun Cen*[2], *Quanyuan Feng*[3], *Hadi Heidari*[4]

[1]School of Electronic Science and Engineering,
University of Electronic Science and Technology of China, Chengdu 610054, China
[2]Chengdu Sino Microelectronics Technology Co., Ltd., Chengdu 610041, China
[3]School of Information Science and Technology, Southwest Jiaotong University, Chengdu 611756, China
[4]University of Glasgow, G12 8QQ, Glasgow, UK

ABSTRACT

This paper presents a three-dimensional finite element method (FEM) model of horizontal Hall sensor in COMSOL Multiphysics. The model aims to simulate the sensors performance in a straightforward way and provides a means to simulate more complex applications with other physics modules. Compared with traditional two-dimensional models, the three-dimensional model is more flexible in designing Hall sensor and shows great significance in verifying the performance of sensors with different materials and geometries. By changing model parameters and comparing simulation results, an optimal design solution can be achieved effectively and economically. The presented Hall sensor achieves a sensitivity of 0.0669 V/(VT). Basic circuit modules of a complete sensor system are also introduced.

***Index Terms*—** COMSOL, finite element method, Hall effect, magnetic sensor

1. INTRODUCTION

Magnetic sensors have been widely used in many areas including automobiles, electronic devices, medical equipment, etc. So far there are many types of magnetic sensors that have been popular in the market, including Hall Effect sensors, anisotropic magnetoresistance (AMR) sensors, tunneling magnetoresistance (TMR) sensors, fluxgate sensors, superconducting quantum interference device (SQUID) sensors and some others [1, 2]. Among all types of magnetic sensors, Hall sensor maintains the largest market share due to its low cost, simple structure, and high stability. Hall sensor works on the principle of Hall effect. Hall effect means, in an electrical conductor with a current flowing through, an external magnetic field perpendicular to the current will cause a voltage difference proportional to the magnetic field. This voltage difference is called Hall voltage, see Fig. 1.

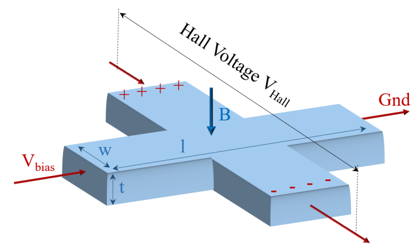

Fig. 1. Hall effect.

The manufacturing and testing process of Hall sensors usually cost a lot of time and money, and many more attempts are needed to explore the actual performance of Hall sensors with different materials and structures. By means of finite element analysis method, Hall sensor is modeled and simulated in COMSOL Multiphysics. This 3D COMSOL model effectively simulates the sensors performance under different sensor structure and material conditions, and therefore being able to find a relatively good design scheme while greatly reducing the cost and time of research and development [3, 4].

This paper presents a 3D FEM model of horizontal Hall sensor in COMSOL Multiphysics. Geometric influence on Hall sensors sensitivity is studied, and an example of designing more complex system with the Hall plate model is demonstrated. The structure of this paper is organized as follows: Section II demonstrates the fundamental of horizontal Hall sensor and its 3D finite element method model, as well as a feasible Hall sensor measurement system design solution. Section III discusses the geometric influence on sensitivity by changing geometric parameters of the sensors structure. Section IV draws the conclusions and mentions some possible future working directions.

The work of Hua Fan was supported by the National Natural Science Foundation of China (NSFC) under Grant 61771111, supported by Sichuan Provincial Science and Technology Important Projects under Grant 19ZDYF2863, as well as supported by China Postdoctoral Science Foundation under grant 2017M612940 & 2019T120834 and Special Foundation of Sichuan Provincial Postdoctoral Science Foundation. The work of Quanyuan Feng was supported in part by the National Natural Science Foundation of China (NSFC) under Grant 61531016, and in part by the Sichuan Provincial Science and Technology Important Projects under Grant 2018GZ0139, Grant 2018ZDZX0148, and Grant 2018GZDZX0001. (Corresponding author: fanhua7531@163.com).

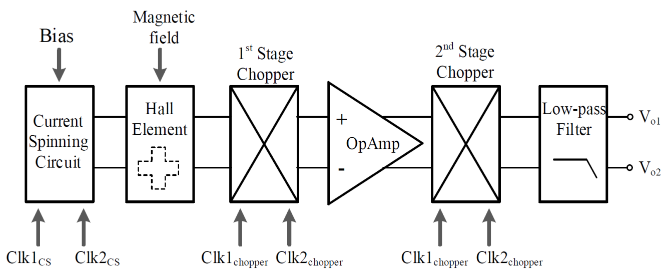

Fig. 2. Hall sensor measurement system.

2. FINITE ELEMENT METHOD MODEL OF HALL SENSOR

Sensitivity is one of the most important performance indexes for sensors, this paper presents a FEM model which can help verify the sensitivities of Hall sensors with different structures. Cross-type Hall sensor structure usually has a higher geometric factor than the rectangular structure [5]. The sensitivity of horizontal hall devices with voltage bias is as follow:

$$S_v = G\frac{W}{L}\mu_H \tag{1}$$

Where μ_H is hall mobility, and the structure factor G is affected by the ratio of width to length $\frac{W}{L}$ of hall device which is given by (2):

$$G = 1 - \frac{16}{\pi^2}e^{-\frac{\pi L}{2W}}\left(1 - \frac{8}{9}e^{-\frac{\pi L}{2W}}\right)\left(1 - \frac{\theta_H^2}{3}\right) \tag{2}$$

Therefore, we get the equation for voltage related sensitivity as in (3):

$$S_v = \left[1 - \frac{16}{\pi^2}e^{-\frac{\pi L}{2W}}\left(1 - \frac{8}{9}e^{-\frac{\pi L}{2W}}\right)\left(1 - \frac{\theta_H^2}{3}\right)\right]\frac{W}{L}\mu_H \tag{3}$$

For a voltage biased cross-shape hall device, there exists an optimal ratio of length to width that enables the Hall elements to reach a relatively high voltage-related sensitivity [5, 6]. This paper compares Hall voltage and voltage-related sensitivity of the Hall element model under different finger lengths ranging from 1 µm to 19 µm, and concludes that the best voltage-related sensitivity of 0.0669 V/ (VT) can be obtained when the finger length is 9 µm for Hall element with a size of 40 µm.

A complete Hall sensor measurement system requires not only a Hall element to convert magnetic signals into electric signals, but also some necessary interface circuit to further process the electric signal [7–10]. This paper presents a Hall sensor measurement system matched with relevant circuit modules including: Hall element, current spinning circuit, two stages of chopper circuits, differential amplifier circuit, and filter circuit. Fig. 2 is the structure diagram of the horizontal Hall sensor measurement system. The current spinning circuit is of great significance in eliminating offset generated in the manufacturing procedure of Hall devices due to process nonideality. Two opposite clock signals control the switching of biasing terminals and sensing terminals, and the output signals at each phase are then combined to eliminate offset. Differential amplifier circuit serves to amplify the Hall voltage as it is usually on the order of microvolts. Chopper circuits can eliminate flicker noise and offset from the differential amplifier circuit by modulate them to high frequency and filter them out with a low pass filter. Hall signals are modulated to high frequency first by 1st stage chopper, and then demodulated back to its original frequency by 2nd stage chopper, so that they remain constant after passing through the low pass filter.

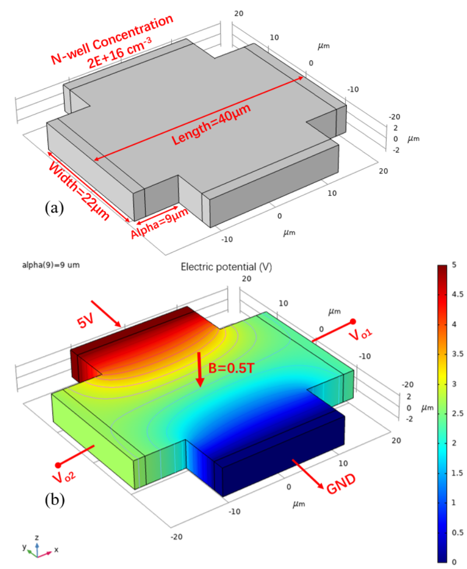

Fig. 3. Simulation of Hall plate in COMSOL.

The 3D finite element method (FEM) model of the horizontal Hall sensor is the focus of this paper. Fig. 3(a) shows the geometric model of the horizontal Hall plate built in COMSOL Multiphysics [11, 12]. This model has a 90° rotationally symmetric cross shape, with a length size of 40 µm and a thickness of 5 µm. The material of the Hall sensor model is silicon with an N-type doping concentration of 2 E+16cm^{-3}. Floating potential condition is used on Hall plate contacts. Necessary corresponding physical conditions were added to simulate the Hall sensor working environment. By changing finger length Alpha from 0 µm to 19 µm, this paper researches the sensitivity influence of different horizontal Hall plate structure. The Hall effect of the Hall device on the COMSOL Multiphysics platform is simulated by adjusting the anisotropic conductivity of the material as follow:

$$\begin{bmatrix} J_x \\ J_y \\ J_z \end{bmatrix} = \begin{pmatrix} \sigma_{xx}\sigma_{xy}\sigma_{xz} \\ \sigma_{yx}\sigma_{yy}\sigma_{yz} \\ \sigma_{zx}\sigma_{zy}\sigma_{zz} \end{pmatrix} \begin{bmatrix} E_x \\ E_y \\ E_z \end{bmatrix} \tag{4}$$

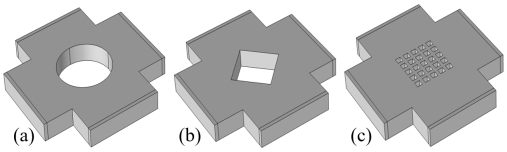

Fig. 4. FEM model of Hall plates with (a) a circular hole, (b) a rectangular hole, or (c) multiple holes in the middle.

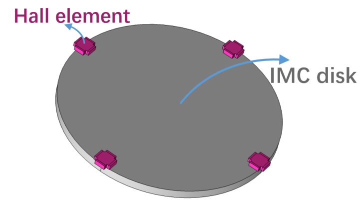

Fig. 5. An IMC-based Hall sensor application.

Where:

$$\sigma_{xx}=\sigma_{yy}=\frac{\sigma_0}{1+(\sigma_0 R_H B_z)^2} \quad (5)$$

$$\sigma_{xy}=-\sigma_{yx}=\frac{\sigma_0}{1+(\sigma_0 R_H B_z)^2}(\sigma_0 R_H B_z) \quad (6)$$

$$\sigma_{xz}=\sigma_{yz}=\sigma_{zx}=\sigma_{zy}=0 \quad (7)$$

$$\sigma_{zz}=\sigma_0 \quad (8)$$

Where σ_0 is the n-well conductivity, R_H is the hall factor, and B_z is the magnetic flux density perpendicular to the Hall plate.

Once finished computing the Simulation Study, the voltage distribution of the Hall device is shown as Fig. 3(b). The Contour line on the Hall device surface represents multiple points with the same voltage value. Fig. 3(b) clearly shows that there exists a voltage difference between Vo1 and Vo2 when 0.5T external magnetic field is applied to the Hall plate.

This model can also be used to verify the performance of Hall sensors of novel structures. This paper presents some new possible design solutions for improving Hall plates performance. For example, unlike traditional designs, Hall plates with a hole or multiple holes in the middle are modeled in COMSOL Multiphysics, as shown in Fig. 4, and the performance of these new designs and the influence of different amounts and shapes of the holes will be further researched in the future. In addition, the influence of different materials of Hall plate can also be simulated in the FEM model by changing the conductivity parameters according to the material characteristics.

Another promising feature is that the 3D COMSOL model can be incorporated into complex applications. 3-axis IMC-based Hall sensor is a good example of complex system design and simulation in COMSOL. As shown in Fig.5, the previously designed Hall plate model is applied to comprise a more complex measuring system. The thin disk in Fig.5 is an integrated magnetic concentrator (IMC) which changes parallel magnetic flux into perpendicular direction [13, 14]. As presented in [14], by placing 4 horizontal Hall plates on the edges of IMC disk and process output signals, the strength of magnetic field in 3 axis can be measured respectively. This measuring system can be simulated based on the 3D Hall plate model. Influence of some key factors, such as the dimension of IMC disk and the distance between Hall elements and IMC, can therefore be well simulated to optimize the design. This case is just the epitome of great potential of Hall plate 3D COMSOL model. Design of Hall sensors' application with some other physics modules, such as heat module and force module, are also available for the 3D COMSOL model.

3. ANALYSIS OF SIMULATION RESULTS

The 3D FEM model of horizontal Hall sensor presented in this paper is very helpful in simulating sensors performance while saving a lot of cost and time. By using Parameter Sweep function and sweeping finger length Alpha, the geometric influence of different ratio of width to length on sensitivity is discussed, while other sensor characteristics stay constant in the mean time [12]. A cross-shaped silicon Hall plate with a doping concentration of 2E+16cm^{-3} is designed and simulated in the case. Silicon Hall plate has been popular due to factors such as its cheap price and compatibility to standard CMOS technology. The size of Hall plate is chosen as 40 µm. Generally a smaller size of Hall plate would result in decrease of sensitivity and offset performance, while a larger size would cause increase of chip size, so a Hall plate size of 40 µm is chosen as a trade-off. The thickness of Hall plate is 5 µm. A bias voltage of 5 V is added to one sensor terminal, as it is a proper value and accessable in 0.18 µm CMOS technology, and the output voltage on sensing terminals would be around 2.5 V. The opposite terminal is connected to the ground.

The resulted Hall voltage and voltage-related sensitivity are given in Fig. 6 as finger length Alpha varying from 0 µm to 19 µm. The Hall voltage is directly measured by subtracting the two sensing terminal voltages Vo1 and Vo2. Voltage-related sensitivity of the model is calculated by (9) :

$$S_v=\frac{V_{Hall}}{V_{bias}B_z} \quad (9)$$

Where, as mentioned above, bias voltage V_{bias} is 5 V, and applied perpendicular testing magnetic field B_z is 0.5 T.

Fig. 6 shows the graphical results of output voltages Vo1 and Vo2 on Hall plates sensing terminals. When finger length Alpha is 9 µm, which means the width of Hall plate is 22 µm and the ratio of width to length is 0.55, the voltage difference between output voltages Vo1 and Vo2 reaches a maximum value of 0.3348V, which means the sensitivity also reaches a maximum value of 0.0669 V/(VT).

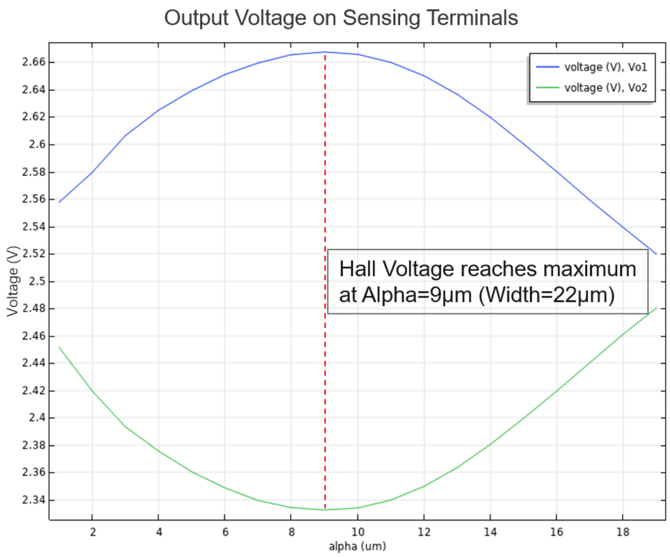

Fig. 6. The output voltage of Hall plates under different finger length.

Reference [4] presented a 2D COMSOL model of a current-mode hall sensor. This paper developed a 3D COMSOL model that allows the design and simulation of a more complex sensor structure, and provides a means to simulate not just Hall plate but also some of its applications with other physics modules. The rectangular Hall plate model mentioned in [3]] shows a sensitivity of 0.058 V/(VT), while the Hall plate model presented in this paper reaches a maximum sensitivity of 0.0669 V/(VT) when the ratio of width to length is 0.55.

4. CONCLUSION

A three-dimensional finite element method (FEM) model of horizontal Hall sensor in COMSOL Multiphysics is presented in this paper. This model provides an inside look at Hall sensors working condition and shows great significance in designing Hall sensors and studying the influence of relevant factors. By analyzing the simulation results as finger length varying from 0 μm to 19 μm, an optimal width to length ratio of 0.55 is achieved, and the corresponding sensitivity is 0.0669 V/(VT).

5. REFERENCES

[1] P. Ripka and M. Janosek, "Advances in magnetic field sensors," *IEEE Sensors Journal*, vol. 10, no. 6, pp. 1108–1116, 2010.

[2] P. Ripka and A. Tipek, *Modern Sensors Handbook*, January 2010.

[3] M. Sen, I. Balabozov, I. Yatchev, and R. Ivanov, "Mod-elling of current sensor based on hall effect," in *2017 15th International Conference on Electrical Machines, Drives and Power Systems (ELMA)*, 2017.

[4] H. Heidari, U. Gatti, E. Bonizzoni, and F. Maloberti, "Low-noise low-offset current-mode hall sensors," in *Proceedings of the 2013 9th Conference on Ph.D. Research in Microelectronics and Electronics (PRIME)*, June 2013, pp. 325–328.

[5] R. S. Popovic, "Hall-effect devices," *Sensors and Actuators*, vol. 17, no. 1-2, pp. 39–53.

[6] C. Marco, Biondi M., Romani A., Tartagni M., and Sangiorgi E., "Optimum design rules for cmos hall sensors," *Sensors*, vol. 17, no. 4, pp. 765–.

[7] H. Heidari, E. Bonizzoni, U. Gatti, and F. Maloberti, "A current-mode cmos integrated microsystem for current spinning magnetic hall sensors," in *2014 IEEE International Symposium on Circuits and Systems (ISCAS)*, 2014.

[8] X. Hu, Y. Xu, and J. Xu, "A low-offset current-mode cmos vertical hall sensor microsystem with four-phase spinning current technique," in *2018 China Semiconductor Technology International Conference (CSTIC)*, March 2018, pp. 1–3.

[9] H. Heidari, E. Bonizzoni, U. Gatti, and F. Maloberti, "A 0.18-m cmos current-mode hall magnetic sensor with very low bias current and high sensitive front-end," *Sensors*, vol. 2014, November 2014.

[10] V. Mosser, N. Matringe, and Y. Haddab, "A spinning current circuit for hall measurements down to the nanotesla range," *IEEE Transactions on Instrumentation and Measurement*, vol. 66, pp. 637–650, April 2017.

[11] I. Ruskova, E. Gieva, V. Yantchev, and M. Hristov, "Comsol modeling of hall sensors efficiency," in *IEEE International Scientific Conference*, September 2017, pp. 1–4.

[12] H. Heidari, N. Wacker, S. Roy and R. Dahiya, "Towards bendable CMOS magnetic sensors," 2015 11th Conference on Ph.D. Research in Microelectronics and Electronics (PRIME), Glasgow, 2015, pp. 314-317, doi: 10.1109/PRIME.2015.7251398.

[13] H. Fan, S. Li, V. Nabaei, Q. Feng and H. Heidari, "Modelling of Three-Axis Hall Effect Sensors based on Integrated Magnetic Concentrator," in IEEE Sensors Journal, doi: 10.1109/JSEN.2020.2989325.

[14] H. Heidari, and V. Nabaei. Magnetic Sensors for Biomedical Applications. John Wiley & Sons, 2019.