Modelling of Three-Axis Hall Effect Sensors based on Integrated Magnetic Concentrator

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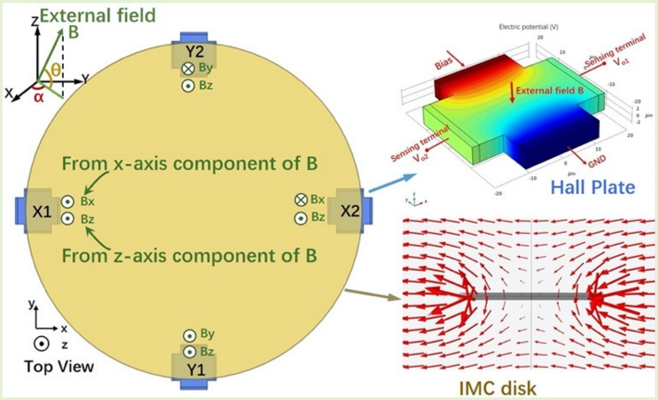
***Abstract*—In this paper, we develop computational model to analyze the magnetic concentrating effect of integrated magnetic concentrator (IMC) on surrounding external magnetic field. We present an IMC-based three-axis Hall sensor model that enables to measure both inclination angles and absolute strength of a random external magnetic field. An IMC changes surrounding parallel magnetic components into perpendicular components, and therefore allows the horizontal Hall plates to measure both the strength and inclination angles of parallel external magnetic fields. We develop a finite element method (FEM) based model in COMSOL Multiphysics for the three-axis Hall sensor. Key factors influencing IMC's magnetic concentrating effect, including material property and sensor structure, are investigated and discussed using the developed model. Comparing to traditional IMC-based three-axis angular sensors, a reference permanent magnet is no longer needed in the sensor. A measurement accuracy of 0.8 and 1.2 degrees are achieved respectively for the angles of α and θ of external magnetic field.**



***Index Terms*—finite element method, Hall effect, integrated magnetic concentrator, magnetic concentrating effect, three-axis sensor**

I. INTRODUCTION

MAGNETIC sensor has been an indispensable element in many systems and instruments, such as automobiles, consumer electronics, and medical devices. So far there have been many types of magnetic sensors that have been popular in the market. Hall sensors maintains the largest market share because of their low cost, high stability, broad measurement range and great compatibility with COMS technology [1]–[4]. The fundamentals and modelling methods of Hall plate has been already discussed in plenty of research works, and Hall plates of different biasing, different materials, and different structure have been presented [5]–[10]. Horizontal Hall plate measures magnetic components perpendicular to Hall plate plane and is widely popular due to the simple structure. However, the main drawback of traditional horizontal Hall plates is that they are not able to sense magnetic components parallel to Hall plate plane. Many efforts have been devoted to make horizontal Hall plates capable of sensing 3-axis magnetic components. One of the most popular solutions is having three Hall plates orthogonally aligned to measure components in each axis respectively. A three axis Hall effect sensors realized by positioning three horizontal Hall plates on three faces of a non-magnetic material cube has been developed [11]. This solution has been improved in the context of accuracy by using three pairs of two Hall plates [12]. Other approaches include combining a horizontal Hall plate and two pairs of vertical Hall sensors to measure z-axis and x,y-axis respectively [13-14]. These typical solutions have the advantage that each axis is measured independently. However, the unique placement of multiple Hall plates sets high requirement for IC manufacturing technology. The utilization of integrated magnetic concentrator

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(IMC) allows the measurement of 3-axis magnetic components with Hall plates in the same plane. Two-axis shifting angle in the IMC plane has been measured by IMC based CMOS Hall angular sensor presented in [15] but shifting angle in z-axis won't be measured [15]. An IMC changes both the directions and strength of a surrounding external magnetic field. At the edge of an IMC, the parallel component of an external magnetic field is changed into the perpendicular direction, hence it becomes possible for horizontal Hall plates to measure magnetic components in all directions. A three-axis CMOS Hall sensor with IMC has been developed that can measure the inclination angles of magnetic field, but the measurement requires a permanent magnet with one end fixed [16]–[18]. Reference [19] mentioned the magnetic saturation effect of the magnetic flux concentrator that may produces nonlinearity error, and presented an analogous three-axis Hall sensor that also measures inclination angles of a fixed permanent magnet [19].

This paper presents an IMC-based three-axis Hall sensor that consists of an IMC and four Horizontal Hall plates. A FEM model is presented to simulate the performance of the three-axis Hall sensor. This paper studies amplification effect of disk-shaped IMC on external magnetic field as the value of IMC's amplification coefficient. Different shapes of IMC could also significantly influence the magnetic concentrating effect and therefore sensitivity of the three-axis Hall sensor. Several unique shapes have been designed, such as a combination five octagonal rings IMC presented in [20]. The main focus of this paper is put on the optimization of disk-shaped IMC's amplification effect, as well as relevant influencing factors. Multiple simulations are conducted to determine the design of specific sensor parameters. An IMC-based three-axis sensor with optimized structure is presented in the end. Unlike the IMC-based three-axis sensors mentioned above, a permanent magnet is no longer needed for the measurement. Both inclination angles and absolute strength of an external magnetic field can be measured by involving IMC's amplification coefficient in the measurement.

The structure of this paper is organized as follows: Section II discusses the fundamental of the three-axis Hall sensor and presents a 3D model of sensor in COMSOL Multiphysics. Section III investigates factors that influence the sensor performance and discusses the simulation results. Finally, Conclusions are drawn in Section IV.

II. STRUCTURE AND MODELLING OF THREE-AXIS HALL SENSOR

A. Modelling of Hall plates and IMC

First, a 3D geometry of a single cross-shape horizontal Hall plate has been developed in COMSOL Multiphysics. This model of single Hall plate is used in following simulation of the three-axis sensor. In the model, the Hall plate length is 40 μm with the thickness of 5 μm. A cross-shape is adopted for better sensitivity. The Hall plate model was built under physics "Electric Current" in COMSOL. Finite element analysis divides the model into lots of small elements and computing them respectively. Relevant boundary conditions such as Maxwell's Equations are applied to the model [7][9]. By adding a bias voltage or current on two opposite terminals of Hall plate and applying an external magnetic field, a voltage difference proportional to the strength of perpendicular magnetic components can be seen at the other two terminals. The simulation result of a single horizontal Hall plate is shown in Fig. 1. To maximize the voltage-related sensitivity, we reduced cross-shape Hall plate finger width to 22 μm, with width-to-length ratio of 0.55, based on the simulation results of sweeping Hall plate finger length from 0 to 20 μm, as shown in Fig. 2. Four identical Hall plates are needed for a three-axis sensor.

IMC allows horizontal Hall plate to detect magnetic components which are parallel to its plane. Fig 3 (a) illustrates the influence of an IMC, where the lines surrounding IMC represent external magnetic flux. It can be seen from Fig 3 (a) that, at the edge of the IMC, the magnetic flux of an originally horizontal external magnetic field is transformed into the almost

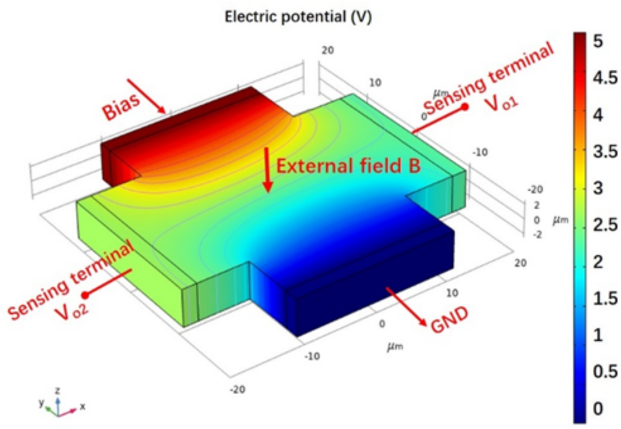


Fig. 1. Cross-shape geometry and 3D model of horizontal Hall plate in COMSOL Multiphysics. A voltage difference on sensing terminals can been clearly seen as sensor biased by 5V voltage.

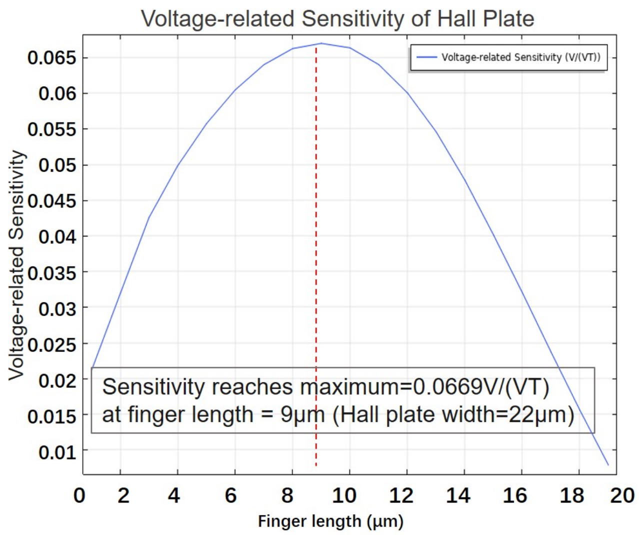


Fig. 2. Voltage-related sensitivity of Hall plate at geometries of different finger length. Best sensitivity of 0.0669V/VT is achieved at a Hall plate width of 22 μm.

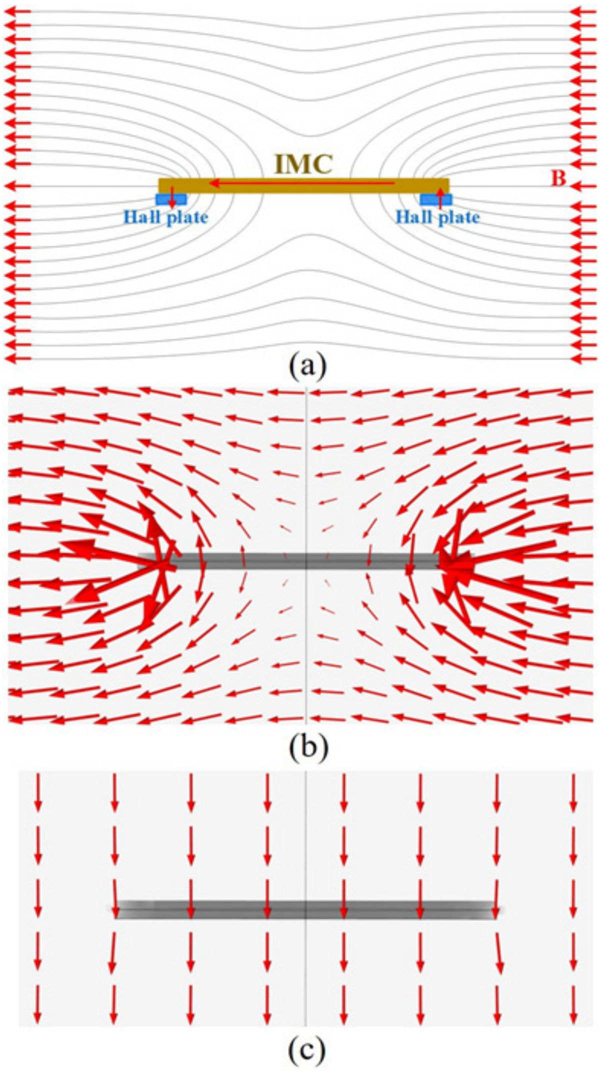


Fig. 3. IMC's influence on surrounding magnetic flux. (a) IMC's magnetic concentrating effect on parallel external magnetic field. (b) Simulation of IMC in a parallel magnetic field in COMSOL. (c) Simulation of IMC in a parallel magnetic field in COMSOL.

vertical direction. Ferromagnetic material is often used to make IMCs because of its high permeability. An ideal IMC is usually expected to be infinite long and extremely thin. Disk shape of IMC has the advantage of keeping its effect uniform for external magnetic field from all directions. Fig. 3 (b) and Fig. 3 (c) show the front view of COMSOL simulation results of putting a thin disk-shaped IMC with a permeability of 10000 into a parallel magnetic field and a perpendicular magnetic field respectively. The rectangular object in the figures is the IMC and the red arrows represent both the strength and directions of the magnetic flux surrounding the IMC. The length of the red arrows is proportional to the magnetic flux density. It can be seen from Fig. 3 (b) that the parallel external magnetic field has been mostly transformed into perpendicular direction and its strength has increased at the edge of IMC. This means the IMC has very strong influence on the horizontal magnetic field, on both strength and direction. However, it has only very limited influence on the vertical magnetic field as shown in Fig. 3 (c). IMC's amplifying effects on parallel external magnetic components can be represented by an amplification coefficient C_{xy}, the value which usually ranges from 1 to 10.

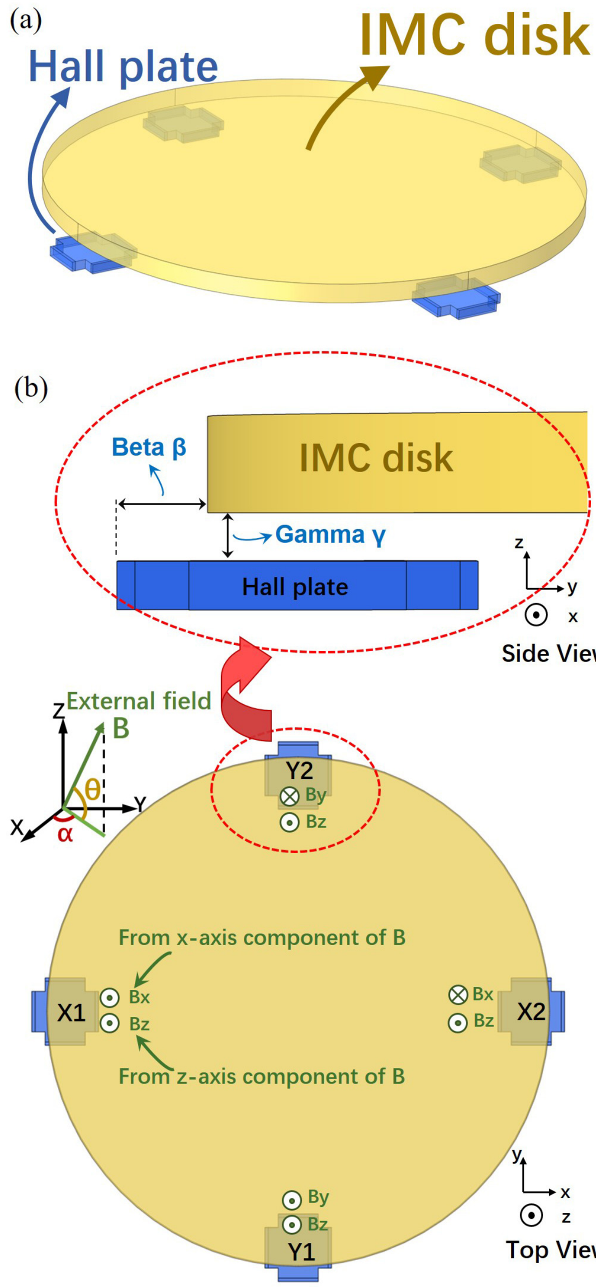


Fig. 4. (a) Structure of the three-axis Hall sensor. (b) Side and top view of the three-axis Hall sensor. An external magnetic field B is applied to the three-axis sensor and sensed by 4 Hall plates with different directions.

IMC's slight influence on perpendicular external magnetic components can be represented by an amplification coefficient C_z, and the value of C_z is usually around 1.

B. THREE-AXIS HALL SENSOR

The IMC-based three-axis Hall sensor, shown in Fig. 4, consists of an IMC disk and four horizontal Hall plates. Fig. 4 (a) is the essential parts of the COMSOL model geometry of the IMC-based three-axis Hall sensor. The models of Hall plates and IMC disk are already respectively built in COMSOL. Four Hall plates are evenly distributed under the edge of IMC, so that both the x-axis and y-axis components of an external magnetic field will be transformed to z-axis direction by IMC and will therefore be detected by the horizontal Hall plates, as illustrated in Fig. 3 (a). Four Hall plates are used in the sensor and this enable to distinguish contribution from x-axis, y-axis and z-axis magnetic components. Fig. 4 (b) shows the side and top views of the three-axis Hall sensor. Because of IMC's magnetic concentrating effect, as shown in Fig. 3 (b), Hall plates X1 and X2 sense upward and downward perpendicular magnetic flux contributed by x-axis external magnetic components, respectively. As illustrated in Fig. 4 (b), for such an external magnetic field B, Hall plates X1 and X2 detect a sum of z-axis magnetic component and x-axis magnetic component, while the measurement results of X1 and X2 are not affected by y-axis magnetic component. In addition, the x-axis magnetic components detected by X1 and X2 are in opposite directions. Also, Hall plates Y1 and Y2 detect a sum of z-axis magnetic component and y-axis magnetic component (in opposite directions). In addition, the sensed x-axis and y-axis components are strengthened by IMC with an amplification coefficient of C_{xy}, the influencing factor of which will be discussed here. In a three-axis Hall sensor, the Hall voltages of four voltage-biased horizontal Hall plates are expressed by:

$$V_{HallX1} = S_v V_{bias}(B_z C_z + B_x C_{xy}) \tag{1}$$

$$V_{HallX2} = S_v V_{bias}(B_z C_z - B_x C_{xy}) \tag{2}$$

$$V_{HallY1} = S_v V_{bias}(B_z C_z + B_y C_{xy}) \tag{3}$$

$$V_{HallY2} = S_v V_{bias}(B_z C_z - B_y C_{xy}) \tag{4}$$

where S_v is the voltage-related sensitivity of the Hall plates. V_{bias} is biasing voltage on Hall plates. B_x, B_y, B_z represents the x, y, and z axis components of the external magnetic field respectively. C_z is the IMC amplification coefficient for vertical magnetic field components. C_{xy} is the IMC amplification coefficient for parallel magnetic field components.

The sensitivity of the three-axis sensor is primarily de- pendent on Hall plates' sensitivity and the IMC amplification coefficient. The sensitivity for the three axis components is:

$$S_x = \frac{V_{HallX1} - V_{HallX2}}{V_{bias} B_x} = 2 S_v C_{xy} \tag{5}$$

$$S_y = \frac{V_{HallY1} - V_{HallY2}}{V_{bias} B_y} = 2 S_v C_{xy} \tag{6}$$

$$S_z = \frac{V_{HallX1} + V_{HallX2}}{V_{bias} B_x} = \frac{V_{HallY1} + V_{HallY2}}{V_{bias} B_y} = 2 S_v C_z \tag{7}$$

For an external magnetic field, the direction of which is shown as the green arrow in Fig. 4, both the angle θ between the direction of magnetic field B and the position of x-y plane, and the angle α between the x-axis line and the projection of magnetic field B on the x-y plane can be measured by the three-axis Hall sensor. The x, y, and z axis components of external magnetic field B are respectively described as:

$$B_x = B\cos\theta\cos\alpha \tag{8}$$

$$B_y = B\cos\theta\sin\alpha \tag{9}$$

$$B_z = B\sin\theta \tag{10}$$

Therefore, the specific value of angle α and angle θ can then be obtained from IMC amplification coefficient C_z, C_{xy} and measured Hall voltages of four Hall plates:

$$\frac{V_{HallY1} - V_{HallY2}}{V_{HallX1} - V_{HallX2}} = \frac{B_y}{B_x} = \tan\alpha \tag{11}$$

$$\frac{C_{xy}}{C_z} \frac{V_{HallX1} + V_{HallX2}}{\sqrt{(V_{HallX1} - V_{HallX2})^2 + (V_{HallY1} - V_{HallY2})^2}} = \frac{B_z}{\sqrt{B_x^2 + B_y^2}} = \tan\theta \tag{12}$$

The measurement of inclination angle α only depends on the output voltages of the four Hall plates. The measurement of inclination angle θ involves not only the Hall voltages, but also the value of amplification coefficients C_{xy} and C_z. For a settled structure of three-axis sensor, the value of C_{xy} and C_z are invariant during measuring process and can be measured in advance.

Apart from inclination angle of external magnetic field, the three-axis Hall sensor is also capable of measuring the absolute strength of external magnetic field B:

$$B = \frac{B_z}{\sin\theta} = \frac{V_{HallX1} + V_{HallX2}}{2 S_v V_{bias} C_z \sin\theta} \tag{13}$$

The measurement accuracy of external magnetic field strength depends on the accuracy of the measured inclination angles as well as the accuracy of adopted Hall plates..

III. ANALYSIS OF KEY FACTORS AND SENSOR PERFORMANCE

A. Factors influencing IMC Amplification Coefficient

IMC structure and positions of Hall plates are key factors that influence IMC's magnetic concentrating effect. Amplification coefficient of perpendicular field C_z does not vary too much and usually floats around 1, however, amplification coefficient of parallel field C_{xy} is largely influenced by the variation of these factors. A larger value of IMC amplification coefficient results in a greater sensitivity of the sensor. We focus in this paper on the improvement of IMC amplification coefficient, and therefore to find an optimized sensor structure.

A desired three-axis sensor model is already finally determined. So in the following simulations, one key factor is designed as variable each time while other parameters are chosen to be proper values and remain constant. In the final sensor model, the bar length and thickness of single Hall plates are 40 μm and 5 μm, respectively. The permeability of IMC material is 20000 and the IMC length and thickness are 300 μm and 5 μm, respectively. The vertical distance between IMC and Hall plates, i.e. Gamma γ in Fig. 4 (b), is 5 μm. The horizontal distance between IMC and Hall plates, i.e. Beta β in Fig. 4 (b), is 10 μm. The magnetic concentrating effect of IMC is highly dependent on its material. Ferromagnetic material is a commonly adopted IMC material because of it high permeability. However, materials' permeability cannot be infinite. To determine a proper relative permeability value for IMC's magnetic concentrating effect, we calculated amplification coefficients of parallel magnetic components C_{xy} for different material relative permeability and simulation results shown in Fig. 5 verify the theory that the higher the IMC material permeability is, the better the magnetic concentrating effect is. The amplification coefficient C_{xy} increases rapidly while the permeability is low, and tends to converge to a maximum value. As shown in the results, the amplification coefficient is almost saturated with the fixed structure when the relative permeability of IMC material increased to 20000, and the corresponding amplification coefficient is 2.335. Thus, a relative permeability value over 20000 is optimal for IMC material.

The shape of IMC, which also strongly influences IMC's magnetic concentrating effect, would need to be determined. Disk shape is popular in IMC design, as it provides a uniform concentrating effect on external magnetic field from all directions. IMC's effective length in the direction of parallel external magnetic components largely affects the magnetic concentrating effect. Simulations are conducted to find the IMC amplification coefficient of parallel field C_{xy} under different IMC length. Fig. 6 shows the simulation results of sweeping IMC length. It can be seen from the results that the x, y-axis amplification coefficient C_{xy} increases as the IMC length increases, which means a larger IMC length enhances the magnetic concentrating effect. However, increasing IMC length leads to an increase of chip area. According to the simulation results, an IMC length value of 300 μm is chosen to be the design parameter as the trade-off in the case.

The influence of IMC thickness is then simulated, and the results are shown in Fig. 7. Smaller IMC heights can lead to stronger magnetic concentrating effect. In addition, when the IMC thickness decreased to a very small value, which means the IMC disk is thin enough, decreasing IMC thickness no longer significantly improves magnetic concentrating effect. Thus, an IMC thickness of 5 μm is determined in the final sensor design. Once material and geometry of IMC disk are determined, the Hall cross position with respect to IMC should be optimized. An initial idea is that the position Hall cross should be close to the edges of IMC disk, where vertical components of external magnetic field achieve a maximum value, see Fig. 3 (b). Two key parameters, the vertical distance

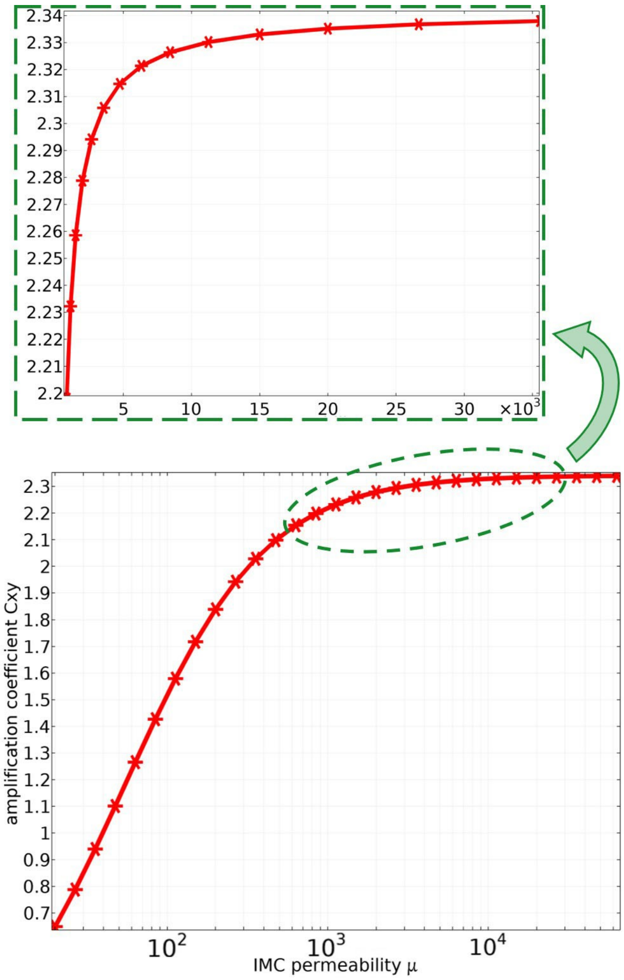


Fig. 5. (a) Influence of material permeability on amplification coefficient. Amplification coefficient Cxy increases as permeability increases, and tends to be stable after IMC permeability reaches 20000.

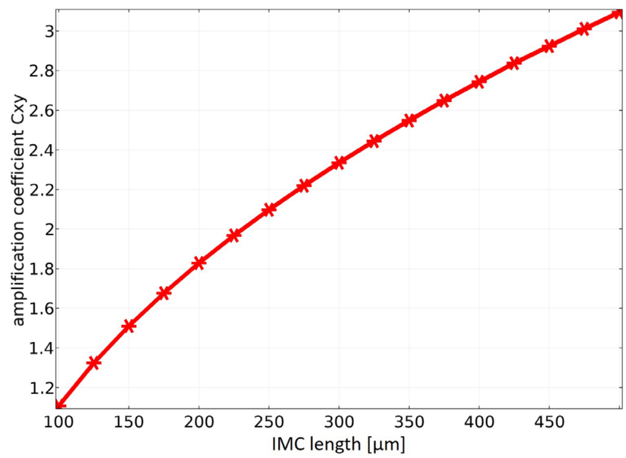


Fig. 6. Influence of IMC length on amplification coefficient. Increasing IMC length leads to larger amplification coefficient Cxy, but at a cost of larger chip area.

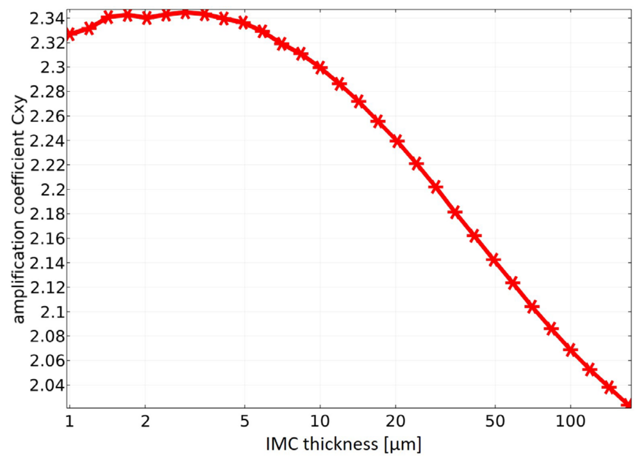
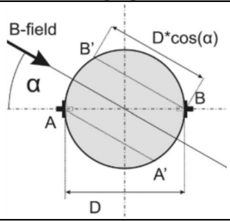
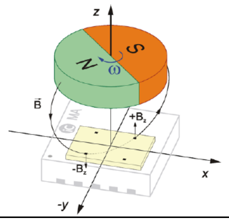
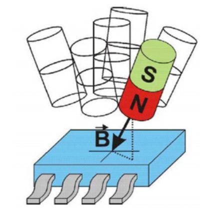
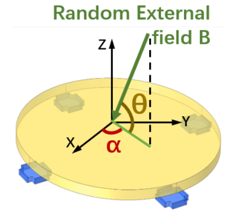


Fig. 7. Influence of IMC thickness on amplification coefficient. An ideal IMC is expected to be thinner than 5 μm. Thicker IMC tend to have weaker magnetic concentrating effect.

TABLE I
COMPARISON OF IMC-BASED THREE-AXIS SENSOR

Reference	Popovic *et al.*		Schott *et al.* [16]	This work
	[15]	[19]		
Structure				
Measurement range	2D (x-y axis)	3D (x-y-z axis)	3D (x-y-z axis)	3D (x-y-z axis)
components	IMC + 4 Hall plates	IMC + 4 Hall plates +permanent magnet	IMC + 4 Hall plates +permanent magnet	IMC + 4 Hall plates
Amplification factor Cxy	Not involved	Not involved	2.0 (according to results)	2.335
Amplification factor Cz	Not involved (z-axis not measured)	Not involved	Neglected	1.035

Gamma γ and horizontal distance Beta β between IMC and Hall cross, are used to fix the position of IMC and Hall plates. The simulation results of the influence of vertical distance Gamma γ are shown in Fig. 8. Just like the initial estimate, as the vertical distance Gamma γ becomes larger the transformed perpendicular components sensed by Hall plates become weaker. To improve the sensitivity of the three-axis sensor, the four Hall plates are designed to be 5 μm under IMC edges.

Horizontal distance between IMC and Hall crosses, as the horizontal distance β indicated in Fig. 4 (b), is a key factor that significantly influence both the amplification coefficient of parallel magnetic components C_{xy} and the amplification coefficient of perpendicular magnetic components C_z. Fig. 9 shows the relations between C_{xy} and β. It can be seen that the amplification coefficient C_{xy} tends to be 0 when the Hall plates are placed horizontally far from the IMC. C_{xy} also reduces when Hall plates are placed closely under the IMC center, and this can be explained by the presented results in Fig. 3 (b) that the external magnetic field is weakest around IMC center. In addition, we obtain maximum C_{xy} when β is 10 μm, which represents the position for highest sensitivity. However, according to the obtained simulation results for relation between C_z and β in Fig. 10, the C_z also can be increased when β is 10 μm. At the point of $\beta = 27$ μm, the value of C_z is 0 and the IMC's influence on vertical magnetic components can be ignored to further reduce deviation. As a trade-off between sensitivity and accuracy, β = 10 μm and γ = 5 μ is the final design, which results in amplification coefficient C_{xy} = 2.335 and $C_z = 1.035$.

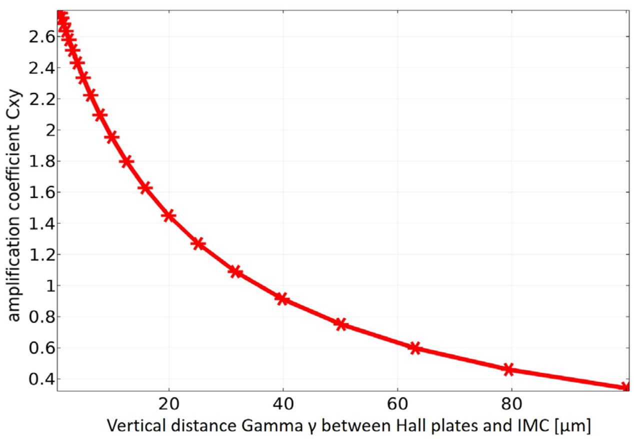


Fig. 8. Influence of vertical distance γ. The closer the Hall plates are placed under the IMC, the stronger the magnetic components sensed by Hall plates are.

B. Design and Simulation of Three-axis Hall Sensor

For the determined material and structure of three-axis sensor, the amplification coefficient $C_{xy} = 2.335$ and $C_z = 1.035$

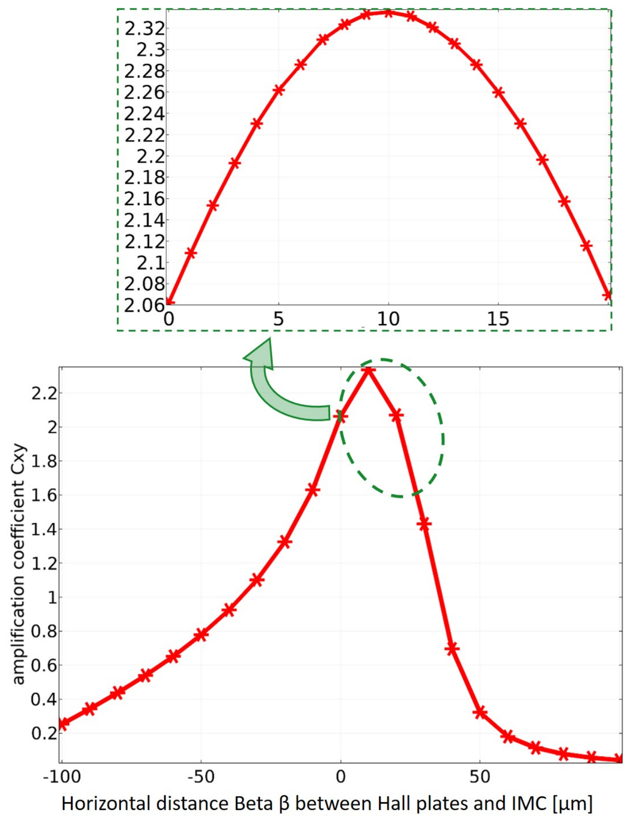


Fig. 9. Influence of horizontal distance β on Cxy. The magnetic concentrating effect is weak both in centre of or far away from the IMC. A maximum amplification coefficient Cxy is achieved when β is 10 μm.

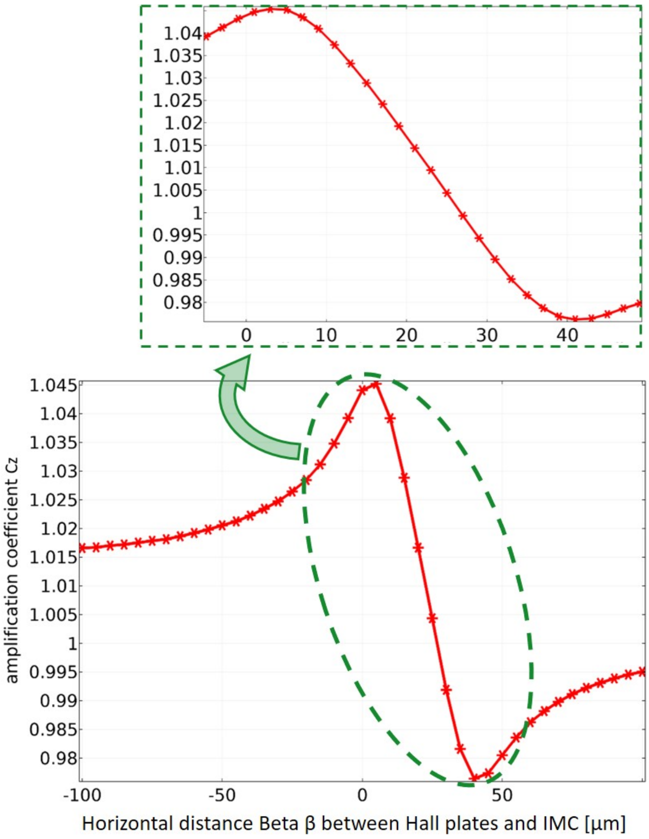


Fig. 10. Influence of horizontal distance β on Cz. The amplification coefficient Cz is 1.035 when β is 10 μm. IMC's effect on perpendicular magnetic field can be neglected when β is 27 μm.

can be used to realize the measurement of inclination angle and magnetic field strength. An external magnetic field B is applied on the three-axis sensor model in COMSOL. The direction of external magnetic field changes in the form of varying angles α and θ (see Fig. 4). Plugging the values of amplification coefficient C_{xy} = 2.335, C_z = 1.035, and the measured Hall voltages from 4 Hall plates into (11) and (12), both accurate angles and absolute strength of the external magnetic field can therefore be measured.

The simulation of three-axis angular sensor is conducted in COMSOL and the results of inclination angle α and θ are shown in Figs. 11 (a) and (b), respectively. It can be seen, the measurement accuracy of angles of α and θ are 0.8 and 1.2 degree, respectively. The absolute strength of external magnetic field B can also be obtained through (13). The accuracy of absolute strength is significantly influenced by performance of the four Hall plates. Hall plates with high accuracy being adopted in the design could lead to high accuracy of the measurement of magnetic field strength. Therefore, by taking into consideration the specific value of magnetic amplification coefficients C_{xy} and C_z, both the strength and inclination angles of 3-axis external magnetic fields can be measured with only horizontal Hall plates.

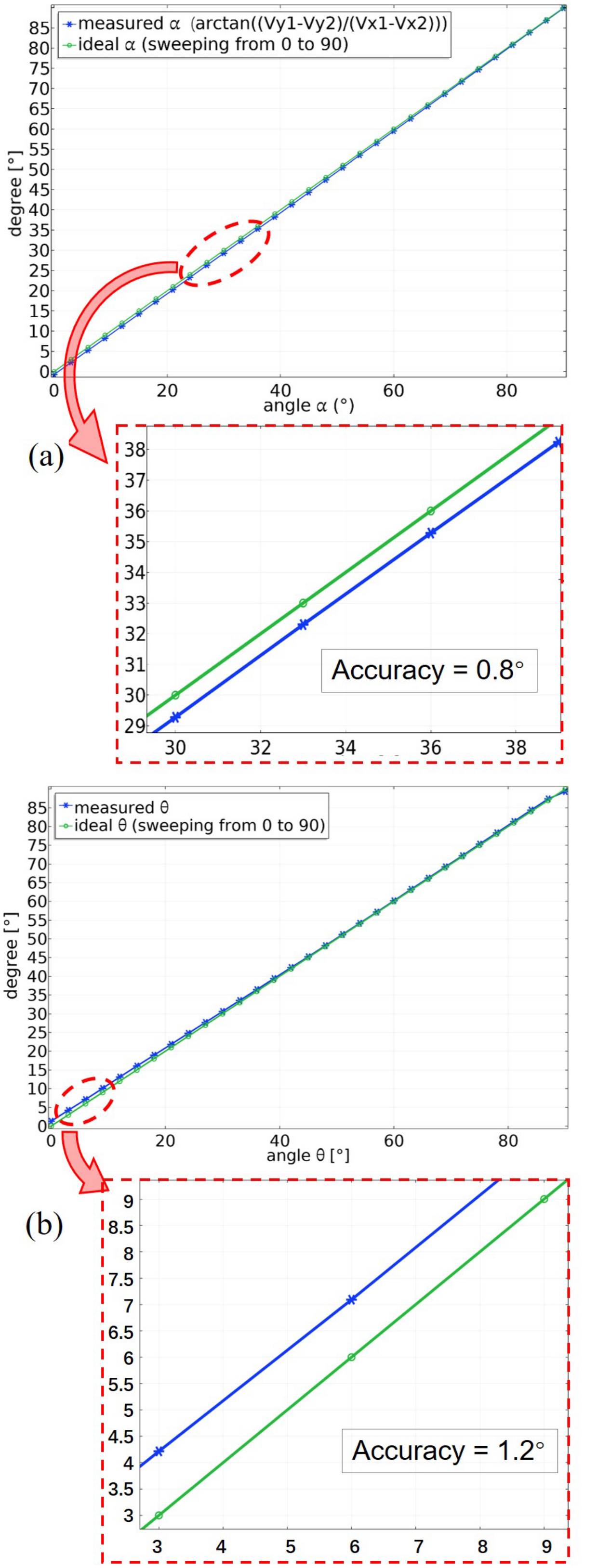


Fig. 11. (a) Accuracy of 0.8 degree can be achieved for the measurement of angle α. (b) Accuracy of 1.2 degree can be achieved for the measurement of angle θ.

IV. CONCLUSION

This paper aims to study IMC's magnetic concentrating effect in an IMC-based three-axis Hall sensor. Influence of geometric factors and IMC permeability on the IMC's magnetic concentrating effect are firstly investigated and compared to find optimal parameters for sensor design. TABLE I shows the comparison with state-of-the-arts. An improvement in amplification factor is achieved by optimizing sensor structure. The amplification factor of parallel magnetic components has achieved a value of 2.335. The effect of IMC's magnetic concentrating effect on perpendicular component has been taken into consideration to improve the measurement accuracy. In addition, through the usage of IMC's magnetic amplification coefficient C_{xy} and C_z, the three-axis Hall sensor no longer need a reference external magnet and shows great significance comparing to traditional IMC-based magnetic sensors. A three-axis Hall sensor 3D model in COMSOL Multiphysics is also presented in this paper. An accuracy of 1.2 degree has been achieved for the three-axis angular sensor in the case. In addition, more customized sensor design can be investigated and applied to the proposed FEM model in the future, such as novel shapes of IMC and different arrangement of Hall plates. With this being said, this paper aims to provide a new perspective as well as a general method for researchers to optimize relevant designs.

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