Simulation of Hall Effect in Semiconductor for Current Sensors Applications

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Abstract

Hall effect simulation program was designed using a numerical direct and iterative method. The validity of this program was checked by comparing it with practical results. This program can be used as the basis for designing electrical current sensors, magnetic sensors, and integrated circuits depending on Hall effect. Moreover, the program support researchers for their practical tests. The designed program was used to study the effect of different parameters on the designing of sensors built on the Hall effect, these parameters are magnetic field, electrical current, type of semiconductor, and the dimension of material. The results showed that the Hall voltage is sensitive to the magnetic field and electric current changes, while the hall voltage is constant with a variation of the sample dimensions. The results showed that the Hall experiment is sensitive to these parameters, especially to the thickness. The simulation software results will enhance the practical applications of the sensors.

1. Introduction

Hall effect was discovered by Edwin Hall in 1879, many years before technology made it possible for integrated circuits (ICs) and devices[1]. Nowadays, Hall sensors and ICs offer a proper way to obtain precise measurements of current that preserve the isolation between the path of the electrical measured current and the measurement circuit[1][2][3][4]. Lorentz force is the origin for the hall effect, which describe the effect of force on charge carriers, i.e. an electron that moves with drift velocity caused by voltage difference and the effect of the external magnetic field lead to the production of the Hall field which is perpendicular to both directions of the current and magnetic field. The galvano-magnetic is the basis for the Hall effect which are physical effects that arise in matter carrying current in the existence of an external magnetic field. Hall field value depends on the concentration and mobility of the charge carriers, which may affect by many parameters that govern the applications of the Hall devices [5][6][7].

The Hall field generated by the effect of electrical current and magnetic field, both are small comparative to the noise, offsets, and the effect of temperature that typically affect the circuit, and thus practical Hall sensors were not popular until changes in the technology of semiconductor allowed for highly integrated circuits that merge Hall devices with an additional circuit to be used in amplifying and conditioning the Hall field. although, Hall sensors are limited in their capability to measure small currents[3][6][7].

Nowadays, the Hall effect is considered an important and thoroughly elaborate topic of condensed matter physics. The Hall effect is relevant to a diversity of sensor applications; devices based on the relation between electrical current, external magnetic field, and generated voltage can be used in different sensors that measure speed, position, and magnetic field intensity[4][6][8][9].
In this study, it will focus on the effect of the main parameters that affect the Hall voltage by using a simulation program, designed according to the mathematical model of Hall voltage. The results are achieved in comparison with available experimental data.

2. Experimental part

Simulation software was performed depending on the mathematical model of the Hall voltage shown in Equation 1 [1][7][10]

\[ U_H = \frac{R_H \times B \times I}{d} \quad \text{... Equation 1.} \]

Where \( U_H \) is the hall voltage, \( R_H \) is the Hall coefficient, \( B \) is the applied magnetic field, \( I \) is the electrical current.

The applied magnetic field is parallel to the z-axis while the current is parallel to the y-axis and the generated Hall voltage is parallel to the x-axis as shown in Figure 1.

The electrical current is calculated using Equation 2 and the conductivity calculated using Equation 3 [1][7][10]

\[ I = \frac{V}{R} = \frac{V \times \sigma \times A}{l} \quad \text{... Equation 2.} \]

\[ \sigma = \frac{l}{R \times A} \quad \text{... Equation 3.} \]

Where \( V \) is the power supply applied voltage in (V), \( R \) is the sample resistance in (Ω), \( \sigma \) is the conductivity of the sample in (Ω⁻¹.m⁻¹), \( A \) is the area of the sample (A=width × thickness) in (m²), \( l \) is the length of the sample in (m). The Hall voltage calculation is done by using LabView code depending on both Eq.1 & Eq.2 as shown in Figure 2, which shows the flowchart used in writing the simulation of the Hall Effect[11].

![Figure 1. Hall effect diagram](image1.png)

![Figure 2. Flowchart](image2.png)
In this study LabView2016 was used to simulate the Hall Effect Model, the written code is shown in Figure 3.

**Figure 2.** Flowchart algorithm for Hall Effect simulation

In this study LabView2016 was used to simulate the Hall Effect Model, the written code is shown in Figure 3.
Figure 3. Program code for Hall Effect Simulation

The Experimental data were performed using P-doped germanium on circuit board 1009810 from 3B scientific and Hall-effect p-Ge carrier board 11805-01 for P-type Ge semiconductor with high purity Ge crystal of dimension (20mm × 10mm × 1mm). Also N-doped germanium on circuit board 1009760 from 3B scientific and Hall-effect n-Ge carrier board 11802-01 for N-type Ge semiconductor with high purity Ge crystal of dimension (20mm × 10mm × 1mm).

3. Results and discussion

The Resulted value of Hall voltage depends on the mobility of the charge carrier (or the drift velocity of the carrier) and the value of the applied Magnetic field. The simulation software was designed to describe and study the effect of these two parameters mainly, and also to study the effect of the sample dimensions on the resulted \( U_{H} \), the latter will decide the measurement instrument (for measuring current and voltage). The graphical user interface for the simulation program is shown in Figure 4.
3.1. Practical and Simulation.

Before using the simulation, it is important to compare and check the validity of the results of the simulation with datasheets or experiments. The experimental work for N-Type Ge semiconductor was performed under two lines, the first was with a constant value of the current and variable magnetic field and the second was performed under constant magnetic field and variable current. Also, different conditions were used for the experiments i.e. Experiments were conducted on more than a case to verify the response of the simulation program and the compatibility of the practical and simulation results. Figure 5. shows the experimental and simulation results for N-Type Ge of both Hall voltage vs. Magnetic field and Hall Voltage vs. Current.

**Figure 5.a.** N-type Ge Experiential and simulation results for Hall voltage vs. magnetic field at different current.

**Figure 5.b.** N-type Ge Experiential and simulation results for Hall voltage vs. current at different Magnetic field.
The experimental work for P-Type Ge semiconductor was performed under the same condition for N-type, but with different current and field value. **Figure 6.** shows the experimental and simulation results for P-Type Ge of both Hall voltage vs. Magnetic field and Hall Voltage vs. Current.

**Figure 6.a.** P-type Ge Experiential and simulation results for Hall voltage vs. magnetic field at different current.

**Figure 6.b.** P-type Ge Experiential and simulation results for Hall voltage vs. current at different Magnetic field.

### 3.2. Effect of current on Hall voltage

Simulation differs from an experiment by its ability to apply a wide range of conditions easily. To obtain various results. Firstly, by testing the simulation at different currents to see the effect of current on the resulted Hall voltage at a constant dimension (20mm × 10mm × 1mm). The current is changed by adjusting the power supply voltage that causes voltage difference at the edge of the sample with resistance (R) i.e. adjusting the power supply lead to an adjustment of the electrical current that drift through the sample. Different values for electrical current were used 10mA, 20mA, 30mA, 40mA, 50mA, and 60mA as shown in **Figure 7.** for both N-type and P-type Germanium.

**Figure 7.a.** N-type Ge simulation results at different current value 10mA, 20mA, 30Ma, 40mA, 50mA, and 60mA

**Figure 7.b.** P-type Ge simulation results at different current value 10mA, 20mA, 30Ma, 40mA, 50mA, and 60mA.

The outcomes show that an increase in current lead to raising in Hall voltage value, i.e. experimenting with the same conditions used in the simulation, it is necessary to use an Ammeter with milliamp
sensitive range as well as a voltmeter with millivolt sensitive range. The second impression of our outcomes, it is the difference between the curve of N-type and P-type shown in Figure 7.a and Figure 7.b respectively, the slope for all curves in Figure 7.a of N-Type is negative due to the negative value of the Hall coefficient while for P-type shown in Figure 7.b slopes are positive due to the positive value of the Hall coefficient.

3.3. Effect of Magnetic field on Hall voltage

The second application of simulation is to study the effect of the magnetic field on the Hall voltage on the types of semiconductors for the same samples with dimension (20mm × 10mm × 1mm). Practically, the adjustment of the external magnetic field is done by adjusting the external power supply used to supply the coil to generate a magnetic field, so the adjustment of the external power supply lead to adjust the value of the applied magnetic field. In the simulation, a numeric Knob was used for adjustment of the magnetic field. The first simulation was done at constant magnetic field B=100mT the second was 200mT then 300mT, 400mT, 500mT, and 600mT respectively for both N-type and P-type Ge samples as shown in Figure 8. The results showed that increments of the magnetic field lead to an increase in the value of Hall voltage, that’s means for more sensitivity it’s important to use a huge magnetic field i.e. the increments of magnetic field lead to enhance the sensitivity of the Hall voltage. This result should be taken into Figure 8.a when designing the sensors and devices of magnetic sensors built on hall phenomena.

Another conclusion that can be drawn from the results by comparing Figure 8.a and Figure 8.b represented by the difference in the behavior of N-type and P-type, the slope for N-type is negative while for P-type the slope is positive as a result for the negative Hall coefficient (RH) associated with N-Type, and positive (RH) for P-Type. This result should be considered while designing the magnetic sensors.

3.4. Effect of sample thickness.

Dimension is an important parameter that should be taken into consideration in designing sensors and actuators. The design of sensors like electric current sensors must be subject to several factors, the most important factors are dimensions of the sensor [2][10][12]. Moreover, dimension is an important factor in the designing of semiconductor devices i.e. devices are limited by dimensions[10][13][14]. In
nanotechnology, the dimensions are less than 100nm, so it’s important to study the effect of dimensions on the sensitivity and current limits at the small dimensions especially the effect of material thickness since the thickness is very important in semiconductor devices and integrated circuit due to the technology used in the manufacturing and building of integrated circuits [15][16][17]. In this study, a simulation was performed at different thicknesses, d=1mm, 100μm, 10μm, 1μm, 100nm, and 10nm as shown in Figure 9. The results showed that the dimension effect on the resistance and current passing through the sample as shown in Figure 9.a and Figure 9.b, while the Hall voltage did not affect by the dimension. In Figure 9.c and Figure 9.d, it’s clear to notice the effect of thickness on the electrical current, these results are important for the practical designing of current sensors [4][15][18][19].

Figure 9.a. N-type Ge simulation Hall voltage vs. Magnetic field at different thickness 1mm, 100μm, 10μm, 1μm, 100nm, and 10nm.

Figure 9.b. P-type Ge simulation Hall voltage vs. Magnetic field at different thickness 1mm, 100μm, 10μm, 1μm, 100nm, and 10nm.

Figure 9.c. N-type Ge simulation Hall voltage vs. Current at different thickness 1mm, 100μm, 10μm, 1μm, 100nm, and 10nm.

Figure 9.d. P- N-type Ge simulation Hall voltage vs. Current at different thickness 1mm, 100μm, 10μm, 1μm, 100nm, and 10nm.
In Figure 9.e. and Figure 9.f. explores the effect of dimensions on the value of resistance of the sample, since, decreasing the thickness leads to an increase in the resistance and reduce the current while the dimension or thickness did not affect the Hall voltage results. The last result is very important in practical applications to be considered in designing sensors and integrated circuits [20][21][22].

In general, this simulation program can be used as the basis for designing current sensors, magnetic sensors, and integrated circuits depending on the Hall effect or Hall ICs. Moreover, this simulation program opens a new superiority for researchers Who perform their experiments using the Hall experiment to study the Hall coefficient and charge carrier concentration practically, because it will determine the sensitivity of the instruments that the researcher should use in the measurements. In addition to the aforementioned precedent, the use of this simulation program will enhance the researcher's ability to understand some practical variables of the experiment.

4. Conclusion

This study focus on the effect of some variables or parameters of the experiment built on the Hall effect to be used in some practical and technological applications such as sensors and Hall ICs, for this purpose simulation program was Designed to cover the mentioned elements. The results showed that the generated Hall voltage changes with the magnetic field, Electrical current, and dimension. Hall experiment proved its sensitivity to these parameters, especially to the thickness. The simulation software results will enhance the practical applications of the sensors; we strongly recommend to exam more material under different variable parameters.

References.

[1] C. Chien, *The Hall Effect and Its Applications*. Springer US, 1980.

[2] A. Ali and D. K. Potter, “A new contactless trackball design using Hall effect sensors,” *Sensors Actuators, A Phys.*, vol. 147, no. 1, pp. 110–114, Sep. 2008, doi: 10.1016/j.sna.2008.04.010.

[3] E. Ramsden, *Hall-effect sensors : theory and applications*. Amsterdam; Boston: Elsevier/Newnes, 2006.

[4] Y. Sharon, B. Khachatryan, and D. Cheskis, “Towards a low current Hall effect sensor,”
Sensors Actuators, A Phys., vol. 279, pp. 278–283, Aug. 2018, doi: 10.1016/j.sna.2018.06.027.

[5] R. S. Popović, “Hall-effect devices,” Sensors and Actuators, vol. 17, no. 1–2, pp. 39–53, May 1989, doi: 10.1016/0250-6874(89)80063-0.

[6] R. S. Popovic, Hall effect devices, second edition. CRC Press, 2003.

[7] C. M. Hurd, The Hall Effect in Metals and Alloys. Springer US, 1972.

[8] H. Wei, H. H. Wieder, W. F. Striedieck, H. Wei, and H. Weiss, Structure and Application of Galvanomagnetic Devices, 1st Edito. 1969.

[9] S. Dimitrijev, Principles of Semiconductor Devices - [Book Review], vol. 22, no. 5. New York: Oxford University Press, 2008.

[10] C. Wouters et al., “Design and fabrication of an innovative three-axis Hall sensor,” Sensors Actuators, A Phys., vol. 237, pp. 62–71, Jan. 2016, doi: 10.1016/j.sna.2015.11.022.

[11] N. B. Mahmood and E. K. Al-Shakarchi, “Simulation and Experimental Data of PE Hysteresis Loop in BNT and BKT,” J. Mod. Phys., vol. 8, no. 05, p. 844, 2017.

[12] N. Kuze and I. Shibasaki, “MBE research and production of Hall sensors,” III-Vs Review, vol. 10, no. 1. Elsevier Ltd, pp. 28–32, Mar. 01, 1997, doi: 10.1016/S0961-1290(99)80054-4.

[13] B. Cao et al., “Development of magnetic sensor technologies for point-of-care testing: Fundamentals, methodologies and applications,” Sensors and Actuators, A: Physical, 2020. https://www.sciencedirect.com/science/article/abs/pii/S0924424719318539 (accessed Sep. 22, 2020).

[14] I. Drujba, Solid State Magnetic Sensors, 1st Edito. Elsevier Science Ltd, 1994.

[15] A. Roy, P. Sampathkumar, and P. S. Anil Kumar, “Development of a very high sensitivity magnetic field sensor based on planar Hall effect,” Meas. J. Int. Meas. Confed., vol. 156, p. 107590, May 2020, doi: 10.1016/j.measurement.2020.107590.

[16] M. A. Reed, Nanostructured systems, vol. 53, no. 9. Academic Press, 1992.

[17] S. G. Tan and M. B. A. Jalil, Introduction to the physics of nanoelectronics: A volume in woodhead publishing series in electronic and optical materials. 2012.

[18] X. Duan, S. Li, A. Medellin, C. Ma, and J. Zou, “A two-axis water-immersible micro scanning mirror using hybrid polymer and elastomer hinges,” Sensors Actuators, A Phys., vol. 312, Sep. 2020, doi: 10.1016/j.sna.2020.112108.

[19] A. Hamodi, T. Hökelek, Y. I. Hamodi, N. B. Mahmood, and N. Nakamori, “Restorations of fresh surfaces for topological materials by de-capping Te,” Appl. Surf. Sci., vol. 530, p. 147225, Nov. 2020, doi: 10.1016/j.apsusc.2020.147225.

[20] A. Persson et al., “Modelling and design of planar Hall effect bridge sensors for low-frequency applications,” Sensors Actuators, A Phys., vol. 189, pp. 459–465, Jan. 2013, doi: 10.1016/j.sna.2012.10.037.

[21] P. Le Kim, N. P. Thuy, P. LeMinh, and D. H. Manh, “Narrow-range angle sensor based on wiggles in angular dependence of pseudo-Hall effect,” in Sensors and Actuators, A: Physical, Apr. 2002, vol. 97–98, pp. 308–317, doi: 10.1016/S0924-4247(01)00844-5.

[22] A. Girgin and T. C. Karalar, “Output offset in silicon Hall effect based magnetic field sensors,” Sensors Actuators, A Phys., vol. 288, pp. 177–181, Apr. 2019, doi: 10.1016/j.sna.2019.01.020.