COMSOL Modeling of Hall Sensors Efficiency

Ivelina Nikolaeva Ruskova, Elitsa Emilova Gieva, Ventsislav Mitkov Yantchev, Marin Hristov Hristov
Department of Microelectronics, Faculty of Electronic Engineering and Technologies
Technical University of Sofia
8 Kliment Ohridski blvd., 1000 Sofia, Bulgaria
{ruskova, gieva, mhristov}@ecad.tu-sofia.bg
Dept. Chemistry and Chemical Engineering, Chalmers University of Technology, Goteborg, Sweden
ventsi.yantchev@gmail.com

Abstract – **In this paper we present a finite element analysis routine for modeling of semiconductor Hall sensors. Their efficiency is studied varying the base semiconductor material. More specifically, 2D COMSOL semi-conductor model is initially employed to extract the properties of the conductive channel. Subsequently a 3D COMSOL DC model is used to perform the studies regarding the Hall sensor efficiency. Hall sensors of identical topology and doping levels are studied in a comparative manner.**

Keywords –**Hall sensors, Efficiency, Germanium, Gallium Arsenide, Indium Arsenide, COMSOL**

I. INTRODUCTION

The Hall elements are the most widespread and well technologically developed magnetic sensors. These transducers, which register magnetic fields in an extremely wide range (15-16 orders) are very universal in their applications and are in a constant development process. Their advantages are the miniature size, low price, low supply and very good technical-performance characteristics. The Hall transducers differ in structure, technology and semiconductor materials, package, number of outputs, etc. They can be orthogonal or parallel-field Hall sensors. The variety of applications imposes the development of new solutions in order to increase either the efficiency, or the reliability of such class electronic systems. The requirements to these systems are constantly increasing, regarding their versatility, functionality and compactness, as well as the quality of the magnetic sensors' characteristics and the front end electronics. Despite the enormous progress of the sensor-microelectronics, the there is still need for improvement of the parameters of magnetic sensors. Hence, researchers incessantly try to improve the sensors' topologies, materials and characteristics.

The Hall effect based sensors typically employs the well-known device topology with parallelepiped construction of very thin conducting material with two supply contacts and two output contacts. This is the geometry used by E. Hall in his experiments in 1879. The design flow of Hall sensors includes:

- Geometry optimization;
- Correct choice of materials;
- Fabrication technology

The Hall element acts as good magnetic transducer if it is manufactured from a material with low concentration of doping impurities and high carrier mobility. The only materials that meet these requirements are the semiconductors. The selected materials should respond to the following concerns [1-6]:

- Materials with low concentration of doping impurities are preferred;
- Hall voltage strongly depends on the carrier mobility, which thus need to be as high as possible;
- Carrier concentration and carrier mobility are also important for power dissipation.

Here we develop and demonstrate an analytical scheme employing finite element methods for simulation of semiconductor Hall effect sensors. Sensor performance is simulated as function of both the material properties and the device topology.

II. COMSOL MODEL

In order to perform the studies regarding this paper, a 2D COMSOL semiconductor model was initially employed. The purpose of this model is to extract some specific parameters for the Hall effect sensor stemming from the semiconductor properties. Figure 1 presents cross-section presentation of the studied Hall sensor topology.

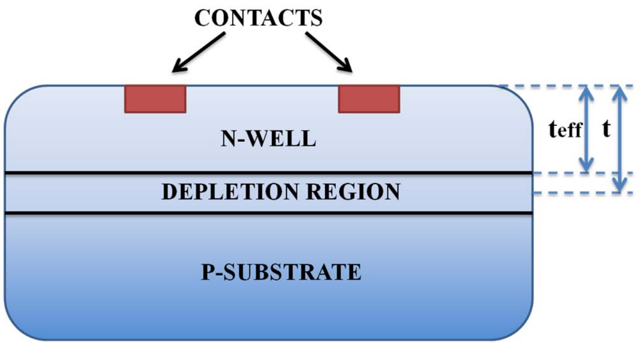


Fig. 1. Cross section view of the Hall sensor. Presented are the effective thickness of sensitive area, the depletion region and the bulk substrate

The Hall sensor is comprised of p-epitaxial layer, n-well, which serves as an active sensor area and n+ contacts. The doping levels used in the COMSOL simulations are practically relevant for the CMOS technology. 2D COMSOL semiconductor model is used to determine the electron concentration values, the conductivity of the n-

978-1-5386-1753-3 /17/$31.00 ©2017 IEEE

well and the Hall coefficient for three base semiconductor materials, respectively. 3.0 V supply voltage is applied on the contacts. Simulation results are shown on Figure 2. Concentration of the electron carriers is shown with color from blue (zero) to red and dark red (maximum). The thickness of the depletion region can be considered constant in the region between the electrodes.

Fig. 2. 2D COMSOL semiconductor model of the Hall sensor. Simulation results

In Table 1 the determined parameters are presented for three base semiconductor materials, germanium (Ge), gallium arsenide (GaAs) and indium antimonide (InSb).

TABLE 1. PARAMETERS OBTAINED FROM THE 2D COMSOL MODEL

Param. / Material	N-well conductivity σ [S/m]	Electrons concentration n [1/m^3]	Hall coefficient R_H [m^3/(s.A)]
Ge	3725	5.96E22	1.05E-4
GaAs	8116	6.00E22	1.04E-4
InSb	76180	6.5E22	0.96E-4

These simulations can readily be employed in determination of the basic Hall effect parameters. The Hall voltage depends on both the Hall coefficient and the N-well conductivity. The Hall coefficient R_H is determined using Eq. 1.

$$R_H = \frac{1}{qn}, \quad (1)$$

where, q is the elementary charge and n is the carrier concentration. It is positive if the charge carriers are positive and negative if the carriers are negative. In practice, the polarity of the Hall voltage determines the sign of the main carriers. The N-well conductivity is determined through the current density per unit electric field amplitude, predicted by the model.

The above two parameters are then incorporated into a 3D COMSOL technologically constructive model (Fig. 3) of Hall microsensor, to perform the studies regarding the Hall sensor efficiency with respect to its 3D topology.

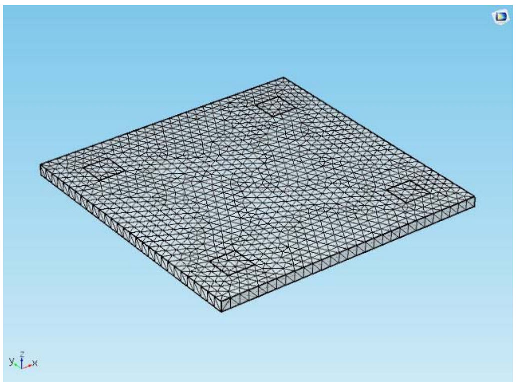


Fig. 3. 3D COMSOL DC Meshed Model of the Hall Sensor

The bias voltage is applied to two of the diagonal contacts, while the Hall voltage (output signal) is measured to the opposite diagonal contacts. The Hall device model is reduced to a square plate (see Fig. 3) with microscopic dimensions (40µmx40µm) corresponding to the N-well surface and thickness determined from the effective thickness of the N-well as determined from the 2D semiconductor model. Contacts are represented by a 6µm x 6µm contact pads ordered in a square with 4µm characteristic side. A 3V bias voltage V_{DD} is applied to the device through two of the diagonal contacts, called the input contacts. The other two diagonal contacts are placed at two equipotential points at the plate boundary and are called the output contacts or the sense contacts. The bias voltage creates an electric field E and forces a current I. If the plate is exposed to a perpendicular magnetic induction $\boldsymbol{B}$, the Hall electric field E_H occurs in the plate. The Hall electric field leads to the generation of the Hall voltage V_H between the two sense contacts.

Current flow obeys the Ohm's law in its general vector – matrix form. More specifically, the current density J and the electric field E are related through the anisotropic conductivity tensor σ represented as a 3x3 matrix.

$$\begin{bmatrix} J_X \\ J_Y \\ J_Z \end{bmatrix} = \begin{pmatrix} \sigma_{XX}\sigma_{XY}\sigma_{XZ} \\ \sigma_{YX}\sigma_{YY}\sigma_{YZ} \\ \sigma_{ZX}\sigma_{ZY}\sigma_{ZZ} \end{pmatrix} \begin{bmatrix} E_X \\ E_Y \\ E_Z \end{bmatrix} \quad (2)$$

The anisotropy in conductivity in this case is due to the Hall effect. The applied magnetic field $\boldsymbol{B}$ produces the Lorentz force on the moving electrons, and the described tensor is in this manner anisotropic. The following matrix elements are produced when B is experienced in the z direction according to Fermi gas theory of free elements [7]:

$$\sigma_{XX} = \sigma_{YY} = \frac{\sigma_0}{1+(\sigma_0 R_H B_Z)^2} \quad (3)$$

$$\sigma_{XY} = -\sigma_{YX} = \frac{\sigma_0}{1+(\sigma_0 R_H B_Z)^2}(\sigma_0 R_H B_Z) \quad (4)$$

$$\sigma_{XZ} = \sigma_{YZ} = \sigma_{ZX} = \sigma_{ZY} = 0 \quad (5)$$

$$\sigma_{ZZ} = \sigma_0 \quad (6)$$

where σ_0 is the n-well conductivity, R_H is the Hall coefficient and $\boldsymbol{B_Z}$ is the magnetic induction.

The effective thickness of the n-well is determined from our 2D semiconductor model. It represents the actual thickness of the sensitive region of the n-well narrowed by the depletion region occurring at the PN-junction (see Fig. 1 and Fig. 2) [8].

The calculated value for the effective depth of the n-well of our structure is 1.49 μm. The depth of the n-well without considering the depletion region is 1.5 μm. The effective thickness of the active area of the sensor is reduced by 0.66% because of the junction effect which is increased by the bias current.

III. HALL SENSOR EFFICIENCY

A. Materials Characteristics

The diversity of Hall sensors is enormous as well as their use. The latter imposes a large variation of specifications for these transducers, depending on the specific application. There is no universal material or topology which can be used for all of the different applications. However, a basic requirement to the Hall sensors is to posses high output voltage at low output resistance, as well as low temperature drift. With regard to these rules, the material should have high values for the Hall coefficient and carrier mobility. Metals do not manifest such properties and that is the reason why Hall effect sensors employ semiconductor materials. $A^{III}B^{V}$ materials are preferred for higher values of the Hall angle, but because of their high temperature sensitivity of the Hall coefficient, they can be used only within small temperature ranges. Another parameter which should be taken into account is bandgap width E_g, and in this respect the silicon (Si) and the gallium arsenide (GaAs) are unique materials [1].

In this paper Hall sensors of identical topology and doping levels are studied in a comparative manner with respect to the chosen semiconductor substrate. Three models with different base substrates but identical topology have been developed. Namely Hall sensors with germanium structure (Ge structure), gallium arsenide structure (GaAs structure) and indium antimonite structure (InSb structure) have been studied. The three materials are chosen in order to achieve higher sensor's efficiency. Some important material parameters are presented in Table 2.

TABLE 2. MATERIAL PARAMETERS OF SELECTED SEMICONDUCTORS FOR GALVANOMAGNETIC SENSORS AT T = 300 K.

Material	E_g (eV)	μ_n ($m^2V^{-1}s^{-1}$)	μ_p ($m^2V^{-1}s^{-1}$)	ρ (Ωcm)
Ge	0.67	0.39	0.19	45
GaAs intrinsic	1.42	0.85	0.045	7.8E7
InSb intrinsic	0.17	7.5	0.075	0.005

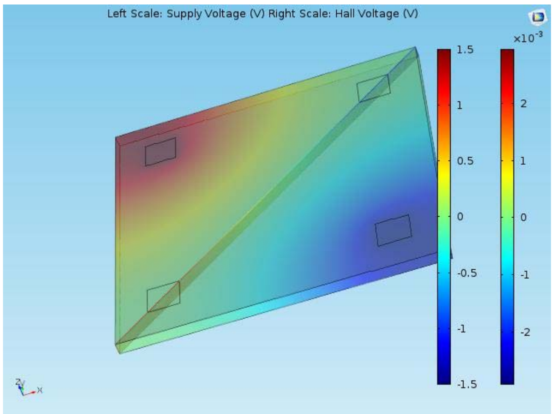
Germanium is an indirect bandgap semiconductor with a room temperature bandgap E_g = 0.67 eV. The germanium Hall element provides increased mobility as compared to its Silicon counterpart, and therefore, a more sensitive Hall effect platform.

Gallium arsenide is a very perspective material. Sensors manufactured from such base material posses linear output characteristics, wide temperature range and higher Hall voltage, because of the higher carriers mobility.

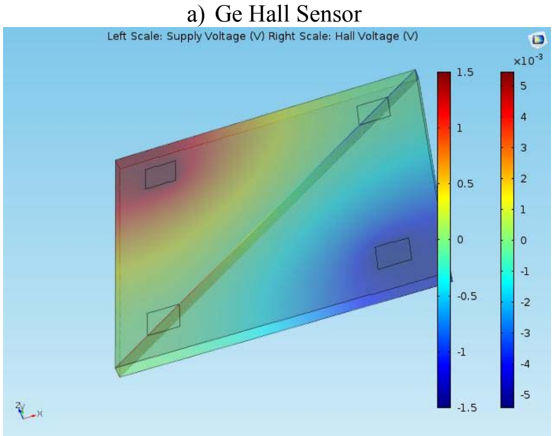
Indium antimonite gives highest output voltage because of the increased carrier mobility compared to the other materials. This material is appropriate for applications which require high sensitivity at low magnetic fields. The disadvantages of InSb element are the higher temperature dependency of its parameters and the nonlinearity of the output characteristics due to the resistivity variations as a function of the magnetic field.

B. Sensors Efficiency

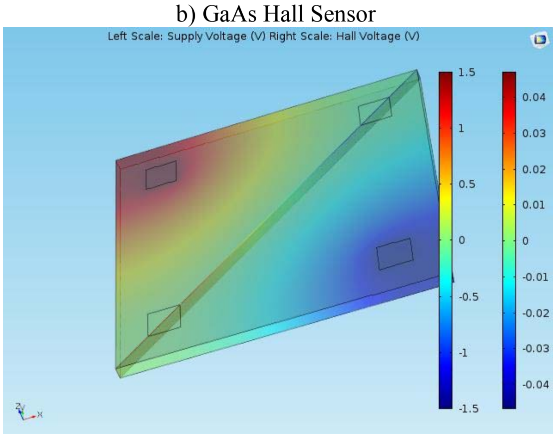
For the vast majority of applications, the key characteristics that need to be analyzed are the output signal (Hall voltage) and the magnetic sensitivity of the element. The Hall voltage is examined at supply voltage V_{DD} = 3.00 V and at magnetic field $\boldsymbol{B}$ = 8 mT. Fig. 4 illustrates the output signal as a function of V_{DD} and $\boldsymbol{B}$ for the examined materials.



a) Ge Hall Sensor



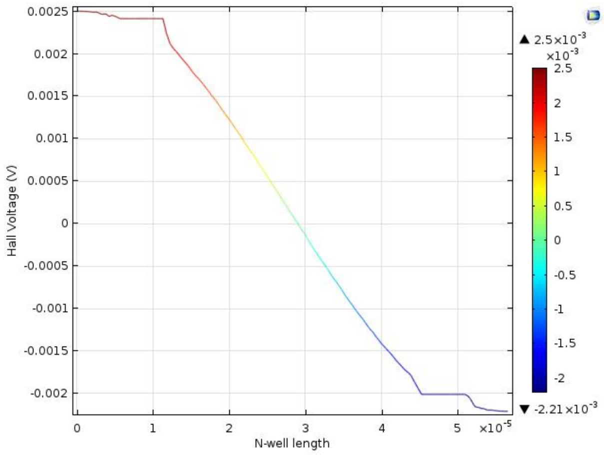
b) GaAs Hall Sensor



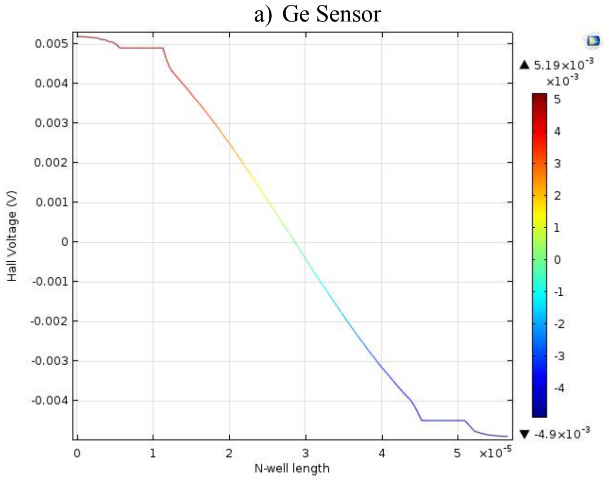
c) InSb Hall Sensor

Fig. 4. Hall Voltage for the three structures

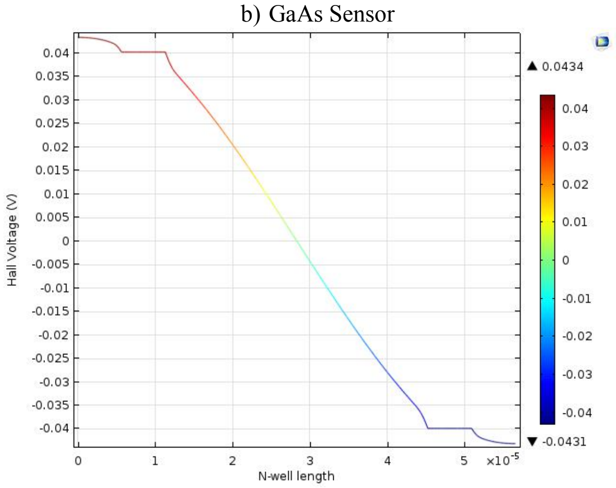
Graphical results for the Hall voltage as a function of the bias voltage and magnetic field are presented in Fig. 5.



a) Ge Sensor



b) GaAs Sensor



c) InSb Sensor

Fig. 5. Output potential for the three structures

Then, the sensitivity is calculated using (8):

$$S_V = \frac{V_H}{V_{DD} B}, T^{-1} \quad (8)$$

S_V is the voltage related sensitivity, V_H is the Hall voltage, V_{DD} is the supply voltage and B is the applied magnetic field. The sensitivity or the transduction efficiency is the most important figure of merit of solid-state magnetosensitive devices and other types of sensors. This parameter can be defined as a ratio of the output signal variation to the variation of the external magnetic field at constant environment. The calculated sensitivity (using Eq. 8) is given in Table 3.

TABLE 3. VOLTAGE RELATED SENSITIVITY FOR THE THREE BASE MATERIALS.

Material	V_{HALL} (mV)	S_V (T^{-1})
Ge	4.43	0.185
GaAs intrinsic	9.39	0.391
InSb intrinsic	80.08	3.336

The obtained results are in good agreement with data from literature. The ratio between the input parameters and the achieved output signals is proven and the developed models are adequate to the real behavior of the Hall effect transducers.

IV. CONCLUSION

In this work, a 2D COMSOL Semiconductor model and a 3D COMSOL DC model are developed and subsequently employed in a complementary manner towards the analysis of Hall micro sensors. The results for three different base semiconductor materials (germanium, galium arsenide and indium antimonide) prove that the analytical scheme proposed here is efficient and can be successfully implemented for the analysis of wide variety of Hall sensors.

ACKNOWLEDGEMENT

This research was supported by Project No. 171ПР0002-03, Scientific and research sector of Technical University of Sofia.

REFERENCES

[1] C. Roumenin. *Handbook of Sensors and Actuators*, Vol. 2, Elsevier Science B.V., ISBN: 0 444 89401 2, 1994

[2] E. Ramsden, *Hall-Effect Sensors: Theory and Application*, Elsevier Inc., ISBN-13: 978-0-7506-7934-3, ISBN-10: 0-7506-7934-4, USA, 2011.

[3] V. Matveev, V. Levashov, O. Konenko, V. Volkov. *Hall effect sensors on the basis of carbon material*, Materials Letters 158 (2015)384–387, 2015.

[4] A. Gradoboev and G Karlova. *Stability of the GaAs based Hall sensors irradiated by gamma quanta*, IOP Conference Series: Materials Science, 2015

[5] Y. Shiomia and E. Saitoh. *Dispersion-type Hall resistance in InSb|Pt hybrid systems*, Sci Rep. 2016

[6] John Braurer. *Magnetic Actuators and Sensors*, IEEE Press, A JOHN WILEY & SONS, INC., PUBLICATION, ISBN-13 978-0-471-73169-6, ISBN-10 0-471-73169-2, USA, 2016

[7] D. Tong. *The Quantum Hall Effect*, TIFR Infosys Lectures, Cambridge, CB3 OBA, UK, January 2016.

[8] M. Crescentini M., Biondi M., Romani A., Tartagni M., Sangiorgi E., *Optimum Design Rules for CMOS Hall Sensors, Sensors (Basel)*, 2017 Apr; 17(4): 765.