Study of Hall Effect Sensor and Variety of Temperature Related Sensitivity

Awadia Ahmed Ali, Guo Yanling* & Chang Zifan

College of Mechanical and Electrical Engineering, Northeast Forestry University, Harbin150040, PR China
*E-mail: guo.yl@hotmail.com

Abstract. Hall effect sensors are used in many applications because they are based on an ideal magnetic field sensing technology. The most important factor that determines their sensitivity is the material of which the sensor is made. Properties of the material such as carrier concentration, carrier mobility and energy band gap all vary with temperature. Thus, sensitivity is also influenced by temperature. In this study, current-related sensitivity and voltage-related sensitivity were calculated in the intrinsic region of temperature for two commonly used materials, i.e. Si and GaAs. The results showed that at the same temperature, GaAs can achieve higher sensitivity than Si and it has a larger band gap as well. Therefore, GaAs is more suitable to be used in applications that are exposed to different temperatures.

Keywords: *carrier concentration; gallium arsenide; Hall effect sensor; materials; sensitivity; silicon.*

1 Introduction

A Hall effect sensor is a semiconductor device that converts a magnetic field to electric voltage. Edwin Hall discovered the Hall effect phenomenon in 1879 [1,2]. However, its application was restricted to laboratory experiments until 1950. The huge developments in the production of semiconductors and electronics made it easy to integrate a Hall effect sensing element with a microsystem in a single integrated circuit. Nowadays, Hall sensors have a wide range of applications in many different devices, from computers to vehicles, airplanes and medical equipment.

For applications where measurement of a weak magnetic field at low temperatures is required, Hall sensors made of materials with high mobility and a small energy band gap are used. This is because materials with a small energy band gap have a high-frequency response. However, such materials possess low operating temperatures. For measurements at high temperature, materials that have moderate mobility and a large energy band gap can be used. The sensitivity of the sensor varies with temperature. This variation may be acceptable for some general applications, but for applications that require a high

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degree of measurement stability, a sensor with high sensitivity under various temperatures must be used. The objective of this study was to present the basic characteristics of the Hall effect sensor and to study the effect of temperature (in the intrinsic region) on the sensitivity of the Hall effect sensor. It further includes a comparison of the results for two materials that are commonly used for Hall effect sensors (Si and GaAs).

2 Theory of Hall Probes

The Hall Effect is a galvanomagnetic phenomenon and is defined as follows: if an electric current flows through a plate of metal or a semiconductor when a magnetic field is applied, a force is experienced which is known as the Lorentz force. This force is perpendicular to both the direction of the current and the direction of the magnetic field. It is the response to this force that produces the Hall voltage [1-6].

The Hall probe consists of a thin plate made of a semiconductor material. The plate has four electrical contacts with ohmic contact. Two out of them are called biasing contacts, through which the biasing current (I) flows. The other two contacts are called sense contacts; their function is to measure the Hall voltage (V_H). The configuration of a Hall effect sensor is depicted in Figure 1[6].

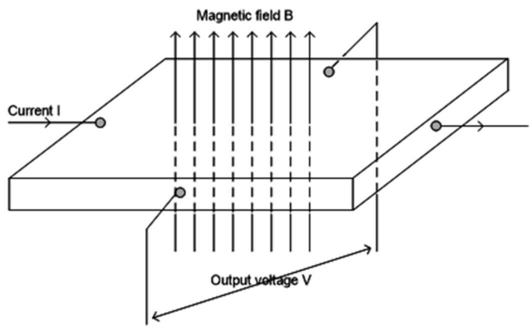

Figure 1 Configuration of a Hall effect sensor.

3 Basic Characteristics of Hall Effect Sensor

3.1 Hall Voltage

The Hall voltage can be characterized in two ways, i.e.:

1. The Hall voltage as a function of the current (I) supplied between the biasing contacts, which can be defined as in Eq. (1) [3,5]:

$$V_H = \frac{r_n}{qnt} GBI \quad (1)$$

where:
I = the biasing current in amperes
q = charge on an electron equal to 1.6×10^{-19}C
n = carrier concentration, carrier/m^3
t = thickness of the plate in meter
r_n = scattering factor
G = geometrical correction factor, ranging from 0 to 1
B = applied magnetic field density, Tesla

2. The Hall voltage as a function of the voltage (V) applied between the biasing contacts, which can be expressed as in Eq. (2) [3, 5]:

$$\mathrm{V_H} = \mathrm{u_H}\frac{\mathrm{w}}{\mathrm{l}}\mathrm{GBV} \quad (2)$$

where:
V = the biasing voltage in volt
u_H = Hall drift mobility, m^2/v.s
w and l = width and length of the Hall plate respectively, in meter

The output voltage of a Hall effect sensor is determined by the material of which the sensor is made, its dimensions, biasing quantities, geometry and magnetic flux density.

3.2 Sensitivity

Sensitivity is considered the most important characteristic for any sensor. Sensitivity is defined as the responsivity of the output voltage of a Hall device to a magnetic field, which can be characterized in three ways, i.e. absolute sensitivity (S_A), supply current-related sensitivity (S_I), and supply voltage-related sensitivity (S_V).

1. Absolute sensitivity S_A (V/T) can be expressed as in Eq. (3) [3-5]:

$$S_A = \frac{V_H}{B} \quad (3)$$

2. Sensitivity as a function of supply current (S_I) is given in V/T.A as in Eq. (4):

$$S_I = \frac{S_A}{I} = \left|\frac{1}{I}\frac{V_H}{B}\right| = \frac{r_n}{qnt}G \quad (4)$$

3. Sensitivity as a function of supply voltage (S_V) is given in T^{-1} as:

$$S_V = \frac{S_A}{V} = \left|\frac{1}{V}\frac{V_H}{B}\right| = u_H\frac{w}{l}G = \mathrm{r_n u_n}\frac{w}{l}G \quad (5)$$

where (u_n) is the electron drift mobility, which is proportional to the Hall drift mobility (u_H).

3.3 Offset Voltage

The offset voltage (V_{off}) is a quasistatic voltage that appears as output in the Hall device in the absence of an applied magnetic field. Two common sources of this voltage are:

1. The symmetry of a Hall device is never perfect. There are always small errors in geometry and non-uniform doping density, surface conditions, contact resistance, etc. Moreover mechanical stress in the Hall device in combination with the piezo resistance effect can also produce an electrical non-symmetry.
2. Misalignment of the sense contacts. This occurs when two sense contacts are at different levels, as shown in Figure 2 [1].

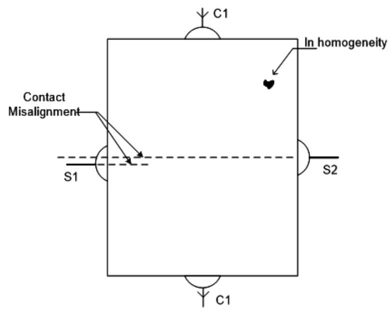

Figure 2 Alignment error of sense contacts and in homogeneities in the plate material.

The result is a parasitic component in the Hall voltage that cannot be distinguished from the real quasistatic part of the Hall voltage. Therefore, the offset severely limits the applicability of a Hall device when low frequency magnetic signals have to be detected.

In a Hall device, the offset voltage is usually described by the offset-equivalent magnetic field (B_{off}) as:

$$B_{off} = \frac{V_{off}}{S_A} \tag{6}$$

The main reasons for the offset being integrated in the Hall device are shortages in the fabrication process and piezo resistive influence. These two effects can be represented using a bridge circuit model of the Hall plate, as shown in Figure 3[5].

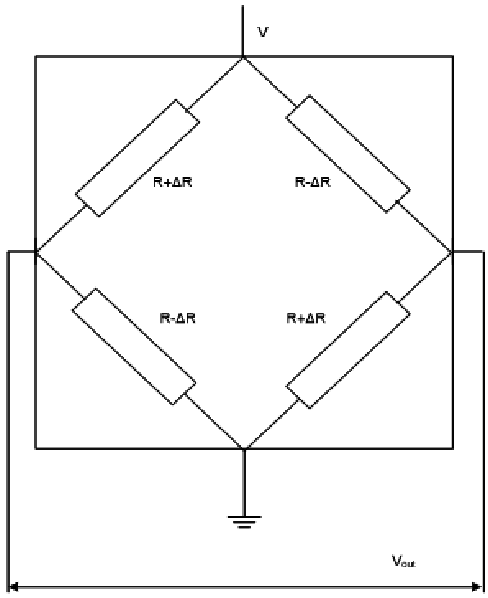

Figure 3 Imbalanced resistive bridge represents Hall plate offsets errors.

As per Figure 3, the offset voltage caused by the shown symmetry of the bridge is:

$$V_{off} = \frac{\Delta R}{R} V \quad (7)$$

By combining Eqs. (5), (6) and (7), the equivalent offset field can be expressed as:

$$B_{off} = \frac{\Delta R}{R} \frac{I}{u_n} \frac{l}{wG} \quad (8)$$

Eq. (8) explains that high electron mobility is crucial for achieving a low equivalent offset field. It is important to note that the offset voltage is not stable but rather varies with temperature.

3.4 Noise

Noise is an unwanted signal that appears with output electric voltage, so it is considered to be one of the main limiting factors of sensor efficiency. Noise determines the smallest magnetic field that can be detected. Various sources of inherent noise are generated by the Hall device itself. The noise in a Hall device is due to thermal noise, generation-recombination noise and flicker noise. Total noise can be described as the sum of these three types, as in Eq. (9) [5]:

$$S_{NV}(f) = S_{VT} + S_{V\alpha}(f) + S_{VGR} \tag{9}$$

where S_{VT} is thermal noise, $S_{V\alpha}$ is 1/f noise and S_{VGR} is generation-recombination noise spectral densities.

3.5 Temperature Coefficients

Some surrounding factors can also affect the sensitivity of the Hall device. In this regard, temperature has the largest share due to its influence on carrier concentration and mobility. According to this behavior, materials can be categorized into two groups. The first one is the group of materials with a small band gap, which offer strong temperature dependence (InSb and InAs, for example). The second one is the group of materials with a large band gap, which display a medium temperature dependence (GaAs, for example). The temperature coefficient (T_C) of the sensitivity (S) is given by Eq. (10) [3, 5]:

$$T_c = \frac{1}{S}\frac{dS}{dT} \tag{10}$$

The obtained sensitivity variation over temperature when operating a Hall effect sensor with a constant-voltage bias source is greater than that obtained with a constant-current bias source.

3.6 Power Consumption

The power consumption inside a Hall plate can be expressed as in Eq. (11) [3,5,7]:

$$P = \left(\frac{V_H}{Gr_nB}\right)^2 . \frac{l}{w} . \frac{qnt}{u_n} \tag{11}$$

The Hall voltage as a function of power consumption is one of the most important characteristics that determine the quality of a Hall device. It is given by Eq. (12):

$$V_H = Gr_nB\left(\frac{w}{l}\right)^{1/2}\left(\frac{u_n}{nqt}\right)^{1/2}(P)^{1/2} \tag{12}$$

4 Theoretical Computations

The key parameter that governs the performance of a Hall effect sensor is its sensitivity to the magnetic field. The most important factor that determines the sensitivity is the material of which the sensor is made. Of course, materials with low carrier concentration, high carrier mobility and a large band gap are the preferred materials. The best types of Hall effect sensors are those that are made of n-type semiconductor materials. In practice, silicon (Si) and gallium arsenide (GaAs) are commonly used. Table 1 gives the values of some parameters at temperature 300 K for the mentioned materials [8]. The Hall coefficients and resistivity are also calculated.

Table 1 Parameters values of Silicon and Gallium Arsenide at temperature 300 K.

Properties	Si	GaAs
Carrier concentration (cm^{-3})	1.45×10^{10}	2.1×10^{6}
Energy gap (ev)	1.12	1.42
Electron drift mobility (cm^2/vs)	1500	8500
Hole drift mobility (cm^2/vs)	450	400
Hall coefficient (cm^3/c)	0.49×10^{9}	0.3×10^{13}
Resistivity (Ω.cm)	2.87×10^{5}	3.50×10^{8}

In this study, the variations of current and voltage-related sensitivity with temperature were computed for both Si and GaAs using Eqs. (4) and (5) for temperatures ranging from 300 K to 400 K. Eq. (4) expresses current-related sensitivity as a function of carrier concentration. Eq. (5) expresses voltage-related sensitivity as a function of carrier mobility. The following relationships illustrate that temperature has a direct effect on carrier concentration and carrier mobility. The intrinsic carrier concentration (n) is given by Eq. (13) [5,9]:

$$n = \sqrt{N_C N_V} \exp\left[\frac{-E_g}{2KT}\right] \qquad (13)$$

where:
N_C (cm^{-3}) = effective density of states in the conduction band
N_V (cm^{-3}) = effective density of states in the valance band
E_g = energy bandgap of the semiconductor
K = Boltzmann constant, equal to 1.38×10^{-23} m^2Kg/s^2k
T = temperature in k

N_C and N_V = are temperature dependent and given by Eqs. (14) and (15) [9,10]:

$$N_C = 2\left[\frac{2\pi m_n KT}{h^2}\right]^{3/2} \qquad (14)$$

$$N_V = 2\left[\frac{2\pi m_P KT}{h^2}\right]^{3/2} \qquad (15)$$

where:
m_n = mass of the electronics, m_p = the mass of the holes
h = Planck's constant, equal to 6.626×10^{-34} m^2Kg/s

The band gap of the semiconductor is also temperature dependent. The variation of the energy band gap with temperature is given by Eq. (16) [8,11]:

$$E_g(T) = E_g(0) - \frac{\alpha T^2}{T+\beta} \tag{16}$$

The electron drift mobility (u_n) is given by the following equation [3,11,12]:

$$u_n = \frac{qD}{KT} \tag{17}$$

where D = the electron diffusion constant (m^2/s).

The values of the Hall effect device (with a classical Greek cross shape) are assumed as in reference [7]. The values of E_g, α and β are given in [11] and the value for D is given in [13]. Table (2) explains all values of the variables related to the Hall effect device. In order to obtain the variations of the current-related sensitivity and the voltage-related sensitivity in the intrinsic region of temperature for Si and GaAs, a MATLAB program was developed. The results are presented graphically in the next section.

Table 2 Values of variables related to Hall Effect device.

Material	Si	GaAs
$E_g(0)$ ev	1.17	1.519
β (K)	636	204
α (10^{-4}ev/k)	4.73	5.41
D (cm^2/s)	36	219
r_n	1.15	1.028
G	0.913	0.913
t (μm)	3.5	3.5
w/l	0.54	0.54

5 Result and Analysis

5.1 Current-Related Sensitivity

The variations of current-related sensitivity with temperature for Hall effect sensors made of GaAs and Si were computed. The results are depicted in Figures 4 and 5 respectively.

As can be seen in Figures 4 and 5, current-related sensitivity decreases with temperature. This is due to the fact that in the intrinsic region of temperature (temperature range of about 290 K to 400 K), the carrier concentration increases with temperature. Hall effect sensors are commonly used for measurements in the intrinsic region of temperature. Using Eqs. (13)-(16), the variations of carrier concentration (cm^{-3}) with temperature in the intrinsic region for GaAs and Si were calculated. The results are depicted in Figures 6 and 7 respectively.

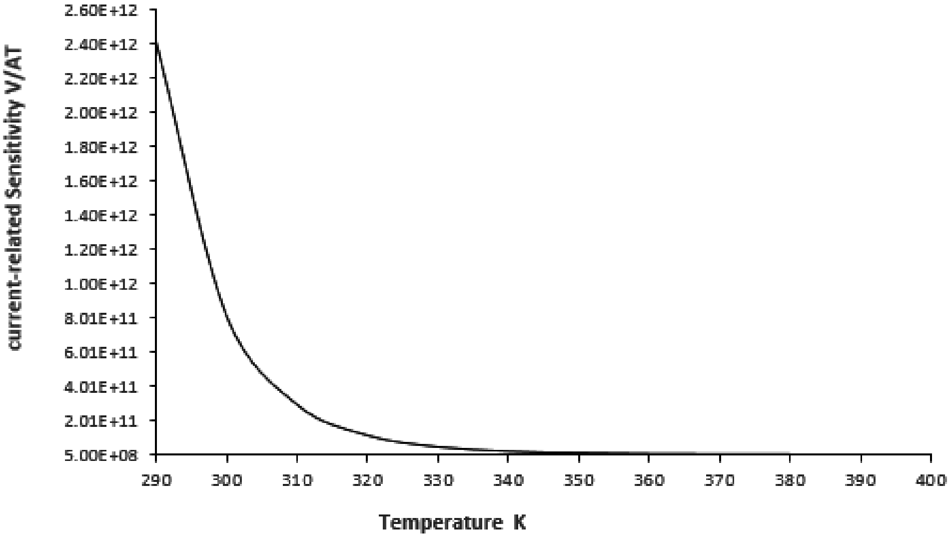

Figure 4 Variation of current-related sensitivity for GaAs.

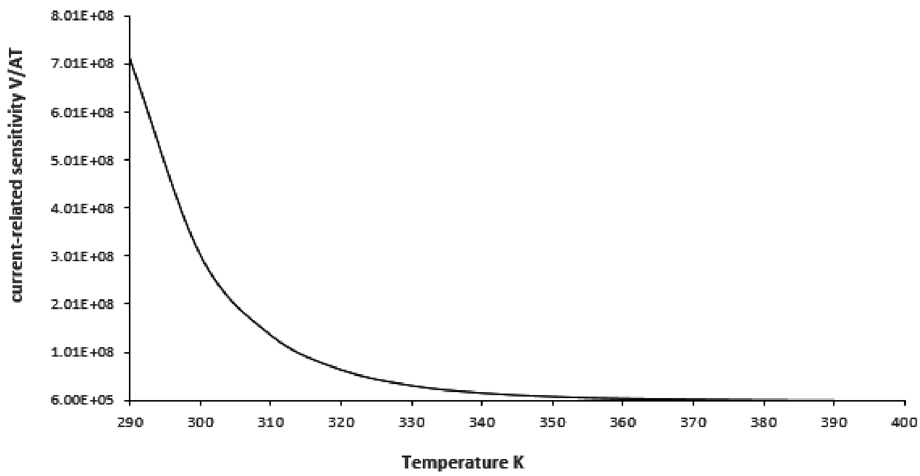

Figure 5 Variation of current-related sensitivity for Si.

From Figures 6 and 7 it is clear that the carrier concentration increases with temperature. Therefore, current-related sensitivity decreases with temperature.

Si has a much higher carrier concentration than GaAs (2990 times higher at the same temperature), thus the achieved sensitivity is much lower than for GaAs (2674 times lower at the same temperature).

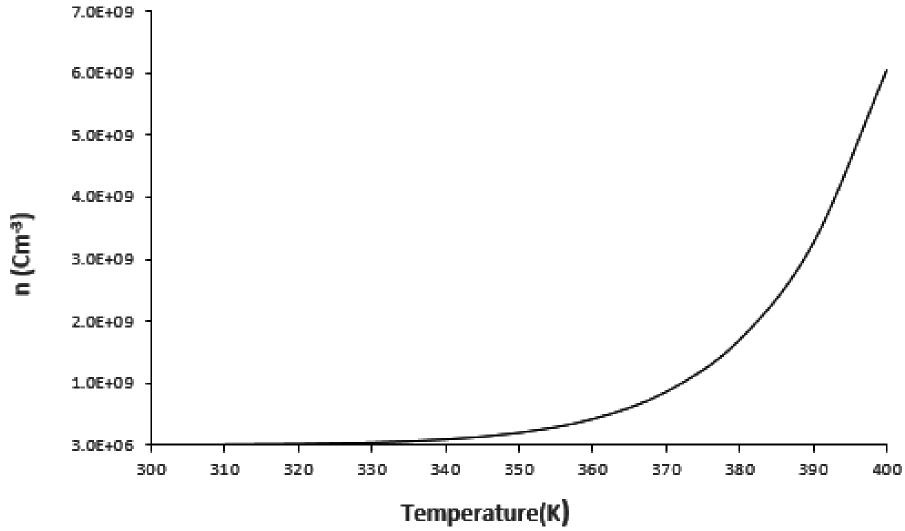

Figure 6 Variation of carrier concentration with temperature for GaAs.

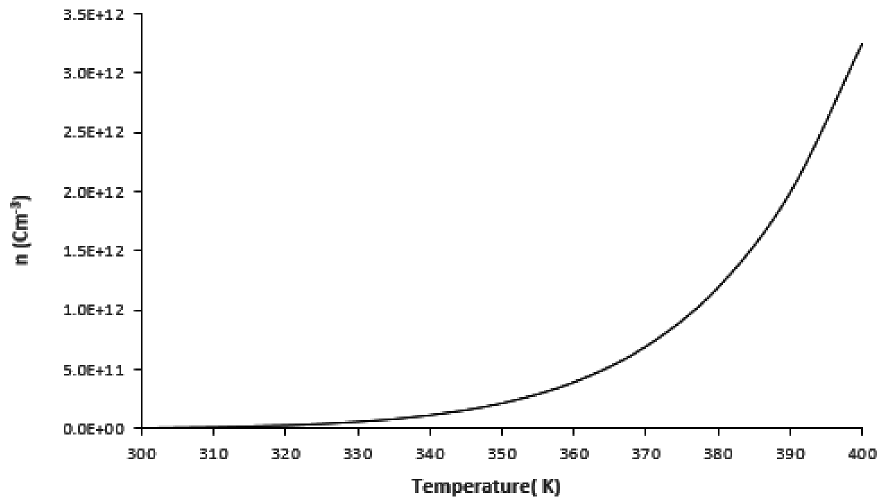

Figure 7 Variation of carrier concentration with temperature for Si.

5.2 Voltage-Related Sensitivity

The variation of voltage-related sensitivities with temperature for Hall effect sensors made of GaAs and Si were computed using Eqs. (5) and (17). The results are depicted in Figured 8 and 9 respectively.

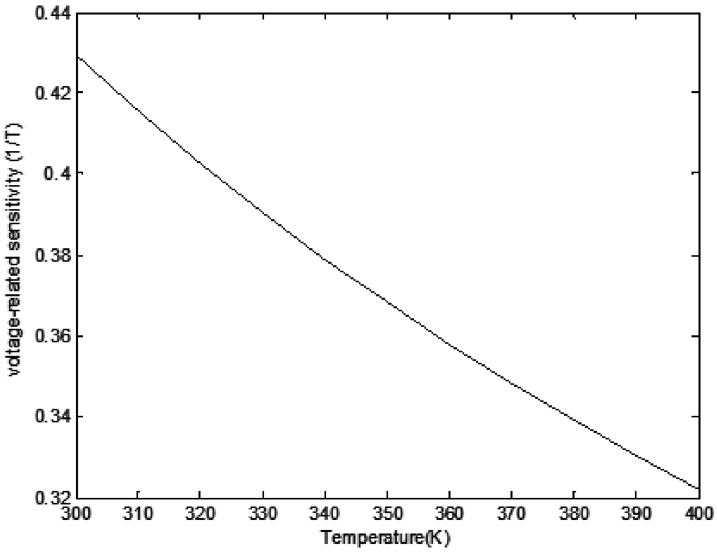

Figure 8 Variation of voltage-related sensitivity for GaAs.

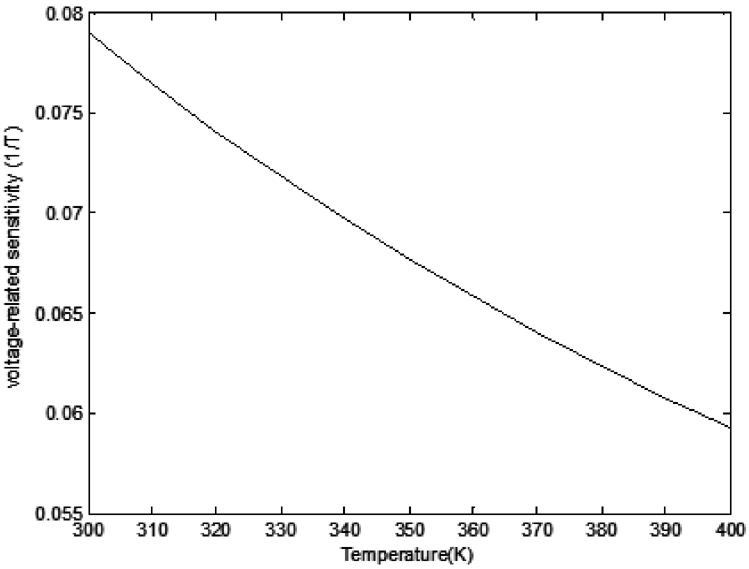

Figure 9 Variation of voltage-related sensitivity for Si.

Voltage-related sensitivity decreases with increasing temperature because the mobility of carrier decreases with temperature, as explained by Figures 10 and 11.

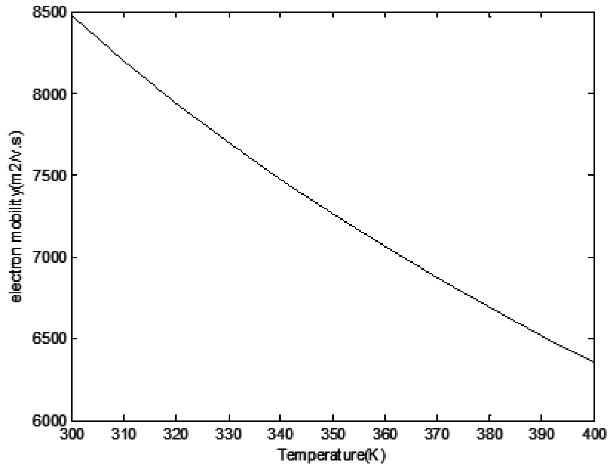

Figure 10 Variation of electron mobility with temperature for GaAs.

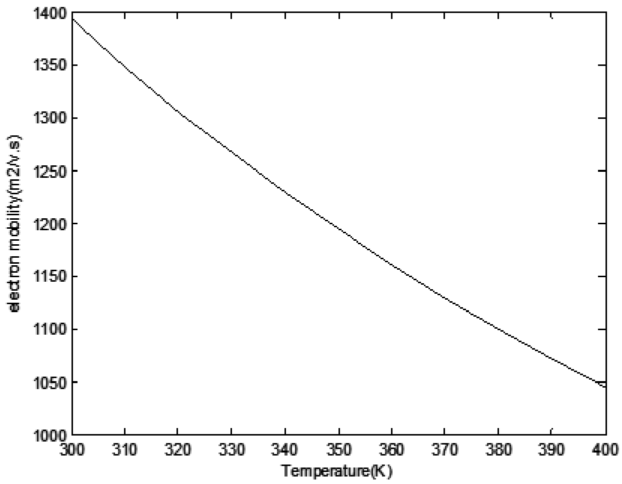

Figure 11 Variation of electron mobility with temperature for Si.

Furthermore, GaAs achieves voltage-related sensitivity higher than Si (5 times higher at the same temperature) because it has a higher mobility of carrier than Si (6 times higher at the same temperature).

At high temperature, GaAs and Si achieve a high carrier concentration and low mobility of carrier and narrow energy gap. All these variations decrease the sensitivity of the sensor.

Using Eq. (16), the variation of the energy gap with temperature was calculated for both GaAs and Si. The results are depicted in Figures 12 and 13.

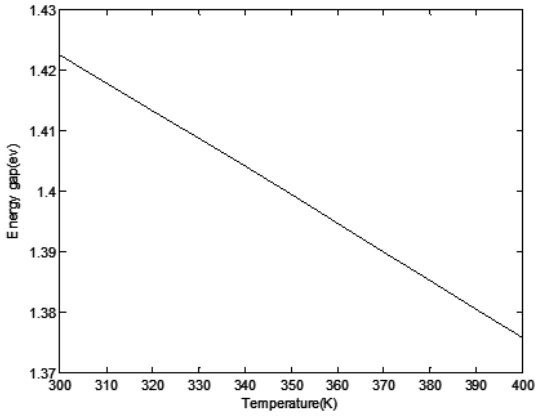

Figure 12 Variation of energy gap with temperature for GaAs.

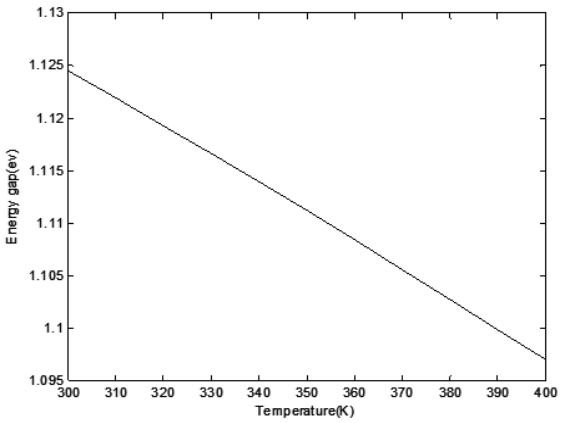

Figure 13 Variation of energy gap with temperature for Si.

GaAs has an energy gap that is 1.3 times higher than the energy gap for Si. Therefore, Si can be used up to 150 °C only, while GaAs can be used even up to 250 °C.

6 Conclusion

The efficiency of a Hall effect sensor is strongly dependent on sensitivity. Based on the results of theoretical computation it is evident that current- and voltage-related sensitivity are inversely proportional to temperature. At the same temperatures, GaAs achieves higher sensitivity than Si. This is because the carrier concentration of GaAs is lower than that of Si and the carrier mobility of GaAs is higher than that of Si. Moreover, GaAs has the additional advantage of having a large energy band gap compared to Si. However, GaAs faces the drawback of having high resistivity.

It is pertinent to mention here that sensitivity, at the same time, is not the only characteristic that varies with temperature. Other attributes of Hall devices like equivalent offset field and noise are also influenced by temperature. This can be discussed in a future work.

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