Hall Effect Measurements and Analysis for GaN and AlGaN HEMT

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Abstract

The objective of the experiment was to use the Hall effect measurements on Ecopia HMS-3000 system to determine the average Hall voltage V_H and other important parameters such as carrier mobility, sheet carrier density, carrier concentration, the Hall coefficient, resistivity, the sheet resistance, and the conductivity type (N or P). Prepared using Nitrides MOCVD growth system, two samples of GaN were examined at room temperature and two samples of AlGaN HEMT were examined at room and liquid Nitrogen temperatures. The average Hall voltages for GaN I, GaN II and AlGaN HEMT at 300k and 77k samples were -9.75 x 10^{-6}, 1.375 x 10^{-5}, -7.5 x 10^{-6} and -1.9 x 10^{-5} V, indicating the charge carriers to be electrons, holes, electrons and electrons, respectively. The Hall mobility and sheet resistance for GaN I, GaN II and AlGaN HEMT at 300k and 77k samples were determined to 69.1, 1.61, 69.81, and 79.34 cm^2/V-s and 1382.99, 83232.54, 1051.87 and 2348.53 ohm/sq, respectively. The experiment discussed many factors influencing carrier mobility such as the structure of materials, temperature and impurity concentrations. The data showed that mobility increases and sheet concentration decreases as temperature decreases. It was also concluded that electron mobility is larger than hole mobility because electrons have a lower effective mass.

Introduction

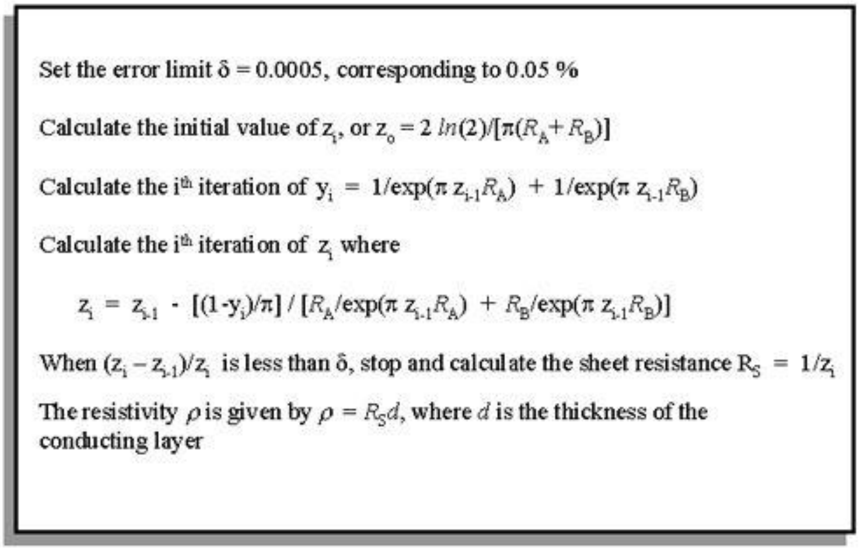
One of the most valuable techniques for material characterization is the Hall effect measurement.[1] In 1879, Edwin Hall discovered the phenomenon of the Hall effect. [2,3] The phenomena can be witnessed when the combination of a magnetic field through a sample and a current along the length of the sample generates an electrical current perpendicular to both the magnetic field and the current. [1,3] This creates a transverse voltage, called the Hall voltage, that is orthogonal to both the magnetic field and the current. The underlying principle is the Lorentz force, which is the force on a charged particle due to electromagnetic fields. [3] The direction of the force on a charge carrier based on its direction of motion and the direction of the applied magnetic field can be determined using the "right hand rule". By measuring the Hall voltage V_H and from the known values of the current and the magnetic field, the sheet density n_s (in units of cm^{-2}) of charge carriers in semiconductors can be determined using the following equation:

$$n_s = 8 \times 10^{-8}\ IB/[qV_H] \tag{1}$$

where V_H is the Hall voltage, I is the current, B is the magnetic field, and q (1.602×10^{-19} C) is the elementary charge. [2] If the Hall voltage is negative, then the carriers are electrons and the material tested belongs to *n*-type semiconductors. If the Hall voltage is positive, then the carriers are holes and the material tested belongs to *p*-type semiconductors. [1,2,3]

The sheet resistance R_S of the semiconductor can be determined by the van der Pauw resistivity measurement technique. The van der Pauw technique states that the resistivity of uniform samples can be determined by inserting them into an arbitrarily shaped thin-plate containing four very small ohmic contacts placed on the margin of the plate.[4] There are two characteristic resistances R_A and R_B, associated with the two different pairs of terminals. As outlined in Figure 1, the sheet resistance R_S can be calculated numerically through the van der Pauw:

$$\exp(-\pi R_A/R_S) + \exp(-\pi R_B/R_S) = 1. \qquad (2)$$



Set the error limit $\delta = 0.0005$, corresponding to 0.05 %

Calculate the initial value of z_i, or $z_o = 2\,ln(2)/[\pi(R_A + R_B)]$

Calculate the i^{th} iteration of $y_i = 1/\exp(\pi z_{i-1}R_A) + 1/\exp(\pi z_{i-1}R_B)$

Calculate the i^{th} iteration of z_i where

$$z_i = z_{i-1} - [(1-y_i)/\pi] / [R_A/\exp(\pi z_{i-1}R_A) + R_B/\exp(\pi z_{i-1}R_B)]$$

When $(z_i - z_{i-1})/z_i$ is less than δ, stop and calculate the sheet resistance $R_S = 1/z_i$

The resistivity ρ is given by $\rho = R_S d$, where d is the thickness of the conducting layer

Figure 1. A numerical method to calculate the sheet resistance R_S.[3]

After determining the sheet resistance R_S, the Hall mobility can be determined from the following equation:

$$\mu = |V_H|/R_S IB = 1/(q n_s R_S). \qquad (3)$$

Hall effect measurements are valuable for characterizing fundamentally every material used in producing semiconductors, such as Gallium nitride and AlGaN HEMT. Gallium nitride (GaN) is a binary direct bandgap semiconductor commonly used in light-emitting diodes since the 1990s.[2] Its wide band gap of 3.4 eV affords it special properties for applications in optoelectronic, high-power and high-frequency devices. AlGaN is used to manufacture light-emitting diodes operating in blue to ultraviolet region. It is also used in AlGaN/AlN/GaN HEMT transistors. HEMT stands for High Electron Mobility Transistors, which is s a field-effect transistor incorporating a junction between two materials with different band gaps as the channel instead of a doped region. AlGaN/GaN HEMT transistors consist of two layers of pure GaN, AlN and AlGaN.[3,4]

The objective of the experiment was to use the Hall effect measurements to determine the average Hall voltage V_H and other important parameters such as carrier mobility, sheet carrier density, carrier concentration, the Hall coefficient, resistivity, the sheet resistance, and the conductivity type (N or P) for GaN and AlGaN HEMT.

Experimental procedure

Two samples of GaN were examined at room temperature and two samples of AlGaN HEMT were examined at room and liquid Nitrogen temperatures. GaN had a thickness of 0.7 µm and AlGaN HEMT had a thinness of approximately 10 nm, which was considered a 0 thickness. The equipment used for the Hall effect measurements was Ecopia HMS-3000. It gives a reliable way to measure microscopic properties such as mobility and carrier concentration.

Metal Organic Chemical Vapor Phase Deposition – MOCVD– is a highly complex process for growing crystalline layers. [5] Nitrides MOCVD growth system was occupied in the experiment. First, circular sections of sapphire were used to grow the materials on top of them. Samples were placed in the furnace and then various gasses were injected. The temperature was elevated. Substances were annealed after growing to reduce unintended impurities such as oxygen molecules. The substances used were Ga, TEG and N with NH_3 and various doping agents were Si with SiH_4, Mg with Cp_2 and Al with TMA. The circular wafers were cut into square pieces. [5] The contact metal used in the experiment was Indium, which is a material that obeys Ohmic law. The Indium wire was linked to the corners of the n-type GaN sample and to the Au/Ni contacts deposited on the corners of the p-type GaN and AlGaN HEMT.

Four centrals were connected to the four ohmic contacts on the sample. These are labeled 1, 2, 3, and 4 counterclockwise. It was important to use the same collection of wire for all four centrals in order to minimize thermoelectric effects. Similarly, all four ohmic contacts consisted of the same material, Ni.

First, the data was checked for internal consistency, for ohmic contact quality, and for sample uniformity. A linear voltage -current relationship was observed. From the linear curve, a constant source of current (1 μA) was determined to be used. The first GaN sample was installed on the test fixture. Measurement was taken to ensure electrical contact. The appropriate polarity for the test fixture relative to the permanent magnet (Ecopia Hall measurement system) was determined. The appropriate magnetic field value was entered (B = .510 Tesla) into the Hall Effect. Then, van der Pauw / Hall Effect measurement was initiated. The measurements as they proceed with no electric field, a forward magnetic field and a reverse magnetic field were observed. The above measurements were repeated for the second GaN sample and AlGaN HEMT samples at room and liquid Nitrogen temperatures.

Results

On the basis of data that was measured, several mesoscopic parameters were determined for the GaN and AlGaN samples. These parameters are the sheet resistance (ohm/sq), resistivity (ohm-cm), average Hall voltage (V), sheet carrier density (carriers/cm^2), carrier concentration (carriers/cm^3), Hall coefficient (cm^3/C), mobility (cm^2/V-s) and carrier type. For each unique calculation, a sample calculation of the first sample of GaN is shown. The sum of the Hall voltages was calculated as following:

$$V_{\mathrm{C}} = V_{24\mathrm{P}} - V_{24\mathrm{N}} = 8.70 \times 10^{-5}\ \mathrm{V}$$

$$V_{\mathrm{D}} = V_{42\mathrm{P}} - V_{42\mathrm{N}} = -1.15 \times 10^{-4}\ \mathrm{V}$$

$$V_{\mathrm{E}} = V_{13\mathrm{P}} - V_{13\mathrm{N}} = -1.11 \times 10^{-4}\ \mathrm{V}$$

$$V_{\mathrm{F}} = V_{31\mathrm{P}} - V_{31\mathrm{N}} = 1.00 \times 10^{-4}\ \mathrm{V}$$

$$\sum \mathrm{V} = V_{\mathrm{C}} + V_{\mathrm{D}} + V_{\mathrm{E}} + V_{\mathrm{F}} = -3.90 \times 10^{-5}\ \mathrm{V}.$$

Consequently, the average Hall voltage equals to $\sum V/4 = -9.75 \times 10^{-6}$ V. The first GaN sample was determined to be (n-type) because the average Hall voltage was negative. Using Equation 1, the sheet carrier concentration was calculated as following:

$$n_s = 8 \times 10^{-8} \times 1 \times 10^{-6} \times 5100 / [1.602 \times 10^{-19} (-3.90 \times 10^{-5})] = -6.54 \times 10^{13}\ \text{cm}^{-2}.$$

The bulk carrier concentration was calculated as following:

$$n = n_s/d = -6.54 \times 10^{13} / 7 \times 10^{-5} = -9.34 \times 10^{17}\ \text{cm}^{-3}.$$

The Hall coefficient was determined as following:

$$\text{The Hall coefficient} = (nq)^{-1} = 1/(-9.34 \times 10^{17} \times 1.602 \times 10^{-19}) = -6.68\ \text{cm}^3/\text{C}.$$

Eight measurements of voltage yielded the following eight values of resistance, all of which were positive:

$$R_{21,34} = V_{34}/I_{21} = 352\ \Omega,\ R_{12,43} = 363\ \Omega,\ R_{32,41} = 282\ \Omega,\ R_{23,14} = 244\ \Omega,$$

$$R_{43,12} = 362\ \Omega,\ R_{34,21} = 346\ \Omega,\ R_{14,23} = 251\ \Omega, \text{ and } R_{41,32} = 262\ \Omega.$$

The two characteristic resistances were calculated as following:

$$R_A = (R_{21,34} + R_{12,43} + R_{43,12} + R_{34,21})/4 = 355.75\ \Omega$$

$$R_B = (R_{32,41} + R_{23,14} + R_{14,23} + R_{41,32})/4 = 259.75\ \Omega.$$

The sheet resistance R_S was obtained from the two measured characteristic resistances, R_A and R_B, by numerically solving the van der Pauw equation as shown in Equation 2 and Figure 1. The sheet resistance was found to be 1382.99 Ω/sq. The bulk resistivity was calculated as following:

$$\rho = R_S d = 1382.99 \times 7 \times 10^{-5} = 9.68 \times 10^{-2}\ \Omega\text{-cm}.$$

Using Equation 3, the Hall mobility was calculated as following: $\mu = 1/qn_sR_S = 69.0$ cm^2/V-s. Table 1 summarizes the Hall effect measurements for the two GaN samples at room temperature. The average Hall voltages were determined to be -9.75×10^{-6} and 1.375×10^{-5} V for GaN I and

GaN II, respectively. This indicated that GaN I had electrons as the charge carriers (n-type) whereas GaN I had holes as the charge carriers (p-type). Moreover, the n-type GaN was determined to have a larger Hall mobility and a smaller resistivity than the p-type GaN. The bulk carrier concentrations were determined to be -9.34 x 10^{17} and 6.67 x 10^{17} carriers/cm^3 for n-type GaN had p-type GaN, respectively.

Table 1. The Hall effect measurements for GaN I and GaN II at room temperature.

Sample Name	**Average Hall Voltage (V)**	**Sheet Density (carriers/cm^2)**	**Bulk Carrier Concentration (carriers/cm^3)**	**Hall Coefficient (cm^3/C)**
GaN I	-9.75 x 10^{-6}	-6.54 x 10^{13}	-9.34 x 10^{17}	-6.68
GaN II	1.375 x 10^{-5}	4.63 x 10^{13}	6.67 x 10^{17}	9.44
	Carrier Type	**Sheet Resistance (ohm/sq)**	**Resistivity (ohm-cm)**	**Hall Mobility (cm^2/V-s)**
GaN I	n-type	1382.99	9.68 x 10^{-2}	69.0
GaN II	p-type	83232.54	5.85	1.61

As shown in Table 2, both AlGaN samples were found to have a negative average Hall voltage, which indicated that the type of carriers are electrons (n-type). However, the AlGaN HEMT sample measured at room temperature was determined to have a smaller magnitude of mobility and sheet resistance than the AlGaN HEMT sample measured at Nitrogen temperature. Moreover, the sheet densities of the AlGaN HEMT samples measured at 300 and 77 k were -8.5 x 10^{13} and -3.35 x 10^{13} carriers/cm^2, respectively. The sheet density increased with the increase of temperature.

Table 2. The Hall effect measurements for AlGaN HEMT samples at room and liquid Nitrogen temperatures.

Sample Name	**Temperature (k)**	**Average Hall Voltage (V)**	**Sheet Density (carriers/cm^2)**	**Sheet Resistance (ohm/sq)**	**Hall Mobility (cm^2/V-s)**	**Carrier Type**
AlGaN HEMT	300	-7.5 x 10^{-6}	-8.5 x 10^{13}	1051.87	69.81	n-type
AlGaN HEMT	77	-1.9 x 10^{-5}	-3.35 x 10^{13}	2348.53	79.34	n-type

Discussion

Lorentz force is the force generated by the presence of electromagnetic fields that cause the electrons to move. This motion of electrically charged particles causes a flow of an electric current down a conducting wire. The effect of Lorentz force is lessened by a transverse / Hall field. As a result, the Hall effect can be observed.[5] The method used in the experiment was The van der Pauw technique, which uses four point contacts placed around the edges of the sample. This technique provides an average resistivity and a formula the sheet resistance as shown in Equation 2.[4] Ohmic contact are necessary to give accurate results for the resistivity, mobility and Hall voltage.[3,4]

On the basis of the results presented earlier, the first GaN sample and the two AlGaN HEMT samples were determined to belong to n-type semiconductors because they showed negative values for the Hall voltage and the sheet concentration. In n-type-semiconductors, the majority charge carriers are electrons, which are caused to move closer to the conduction band by the existence of donor impurities.[1,2] On the other hand, the second GaN sample was determined to belong to p-type semiconductors as its Hall voltage extent and sheet concentration showed positive values, indicating that holes were the majority charge carriers. P-type semiconductors are synthesized by doping intrinsic semiconductors with acceptor impurities, which create holes in the valance band.[1,2]

With regard of Hall mobility of n-type GaN and p-type GaN samples, electron mobility was observed to be significantly higher than hole mobility because the effective mass of electrons is smaller than the effective mass of holes. The effective mass of charge carrier is inversely proportional to mobility.[2] Furthermore, the measurements of AlGaN samples showed that mobility increased with the decrease of temperature. The experimental results also suggested that as temperature increases, the magnitude of sheet concentration increases. This phenomenon can be explained by the fact that there is less ionized impurity scattering at lower temperature. The most influential factor at high temperature is lattice vibration scattering whereas the most influential factor at low temperature is the ionized impurity scattering. [1,2]

For the AlGaN HEMT structure, the mobility was greater than the mobility for the uniformly doped samples because a two-dimensional electron gas with induced polarization was molded at the interface of the layers, which created a lattice mismatch between AlGaN and GaN. The junction between semiconductor materials with different band gaps produces electrons that move faster than in typical semiconductors. As a result, AlGaN HEMT had higher mobility than GaN semiconductors. [2,5]

In the literature, the sheet concentration of n-type GaN has a value of 1.1 x 10^{17} cm^{-3}, having the same order of magnitude to the measured sample. [6] However, the mobility of AlGaN and n-type GaN are reported to be 1240 and 440 cm^2/V-s, respectively. [2,6] These values are much larger than the calculated values for mobility. Source of errors may include improper contact to the sample, light interruption and the difference in thickness and doping levels. However, the measured values for GaN and AlGaN HEMT overall agree with the trends observed in the literature.

Conclusion

The objective of the experiment was to use the Hall effect measurements to determine the average Hall voltage V_H , carrier mobility, sheet carrier density, carrier concentration, the Hall coefficient, resistivity, the sheet resistance, and the conductivity type (N or P) for GaN and AlGaN HEMT at room and liquid nitrogen temperatures.

Overall, the experiment was successful in determining the type of carriers and the trends of the parameters in the Hall effect measurements. The average Hall voltages for GaN I, GaN II and AlGaN HEMT at 300k and 77k samples were -9.75 x 10^{-6}, 1.375 x 10^{-5}, -7.5 x 10^{-6} and -1.9 x 10^{-5} V, indicating the charge carriers to be electrons, holes, electrons and electrons, respectively. The Hall mobility and sheet resistance for GaN I, GaN II and AlGaN HEMT at 300k and 77k samples were determined to 69.1, 1.61, 69.81, and 79.34 cm^2/V-s and 1382.99, 83232.54, 1051.87 and 2348.53 ohm/sq. The experiment confirmed that electron mobility is larger than hole mobility because of the difference in the effective mass. In addition, AlGaN HEMT has better mobility than GaN because of the induced polarized electric gas between its layers. Moreover, mobility decreases and sheet concentration increases with the increase of temperature. The experiment results also imply that the existence of more impurities yields lower electron mobility. [1,2]

Source of errors in the Hall effect measurement can be minimized by preforming the experiment in the dark to prevent light interruption. Additionally, obtaining samples with clean surfaces to evade scattering and assuring equivalent resistances in the contacts can greatly reduce errors.

References

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