Abstract — This article presents the design and characterization of a direct current (dc) sensor utilizing the Hall effect in AlGaN/GaN 2-D electron gas (2DEG) four-terminal devices and a flux concentrator. The sensor was fabricated from an AlGaN/GaN/Si wafer grown by metal-organic chemical vapor deposition. The sensor exhibited excellent linearity and repeatability with a high Hall voltage under the primary current ranging from −5 to 5 A. The sensitivity of the sensor was measured to be 0.26 (V/A)/A at 20 °C and independent of ambient temperature up to 200 °C. The obtained result is greater than that of other reported Hall effect-based current sensors. The high sensitivity and thermal stability at varying temperatures are attributed to the high electron mobility, wide bandgap, and chemical inertness of GaN, the proposed sensor is promising for current monitoring in a wide range of operation temperatures.

Index Terms—AlGaN/GaN 2-D electron gas (2DEG), current sensor, energy band analysis, Hall effect.

I. INTRODUCTION

CURRENT sensing has been typically employed to monitor electric current, energy consumption, and the energy generated from power plants [1]. One of the conventional current measurement methods relies on measuring the voltage drops across a shunt resistor [2], [3]. However, an overcurrent can permanently damage the shunt resistor, while the high power losses make this method unsuitable for measuring high currents. Other current sensing techniques utilize current transformers and Rogowski coils that are only applicable for alternating current (ac) sensing [4], [5]. Moreover, these techniques yield a low sensitivity at low frequencies and the accuracy depending upon the conductor’s position [6]–[8].

Recently, the successful demonstration of 2-D electron gas (2DEG) formed by AlGaN/GaN heterostructures indicates the potential development of high sensitivity ac/direct current (dc) current sensors based on the Hall effect due to its high electron mobility, wide bandgap, and superior magnetic field sensitivity. The operation of the Hall effect current sensor is based on Ampere’s law that a magnetic field is generated around a current-carrying conductor. This field will be detected by a Hall sensor. There were several researches on coreless Hall current sensor [9]–[14]. However, the magnetic field generated from the conductor is relatively small, consequently creating new challenges for detecting such a small signal. In addition, the magnetic field significantly depends on the distance between the sensors and the conductor.

In this research, we demonstrated a highly sensitive current sensor based on AlGaN/GaN 2DEG. We employ a flux concentrator (magnetic core) to concentrate the magnetic field onto the sensing area. The flux concentrator was proven to eliminate the positional error, which resulted from the position shifting between the conductor and the sensor. It also greatly reduces the interference of ambient magnetic fields.

II. EXPERIMENTS

The Hall device was fabricated by growing a GaN layer with a thickness of 4 μm on a silicon substrate (thickness of 300 μm). The 2DEG layer was then formed by growing an AlGaN layer with a thickness of 10 nm on top of the as-deposited GaN film, as shown in Fig. 1(a). The electrodes were formed by sputtering Ti/Al/Ni (100 nm/300 nm/100 nm) on top of the AlGaN layer, followed by rapid thermal annealing at 800 °C for 30 s in nitrogen-rich ambient. The wafer was then cut into 10 mm × 10 mm square-shaped chips, as shown in Fig. 1(b).

The current–voltage characteristic of the sample was measured using a Keithley 2450 SourceMeter. Fig. 1(c) shows
the linearity of the current–voltage characteristics between terminals A and B, as well as between terminals C and D in the voltage range from −0.5 to +0.5 V, indicating that a good Ohmic contact was formed between the electrodes and AlGaN.

The sensitivity of a Hall effect device with respect to supply current ($S_I$) is defined as follows

$$ S_I = \frac{V_H}{I_s B} $$

where $V_H$ is the Hall voltage, $B$ is the magnetic field applied perpendicular to the plane of the device, and $I_s$ is the supply Hall current. The Hall voltage $V_H$ can be obtained by

$$ V_H = \frac{V_{m,1} - V_{m,2} + V_{m,4} - V_{m,3}}{4} $$

where $V_{m,1}$ is $V_{CD}$ measured at positive field $B$ and positive current $I_{AB}$, $V_{m,2}$ is $V_{CD}$ measured at positive field $B$ and negative current $I_{AB}$, $V_{m,3}$ is $V_{CD}$ measured at negative field $B$ and positive current $I_{AB}$, and $V_{m,4}$ is $V_{CD}$ measured at negative field $B$ and negative current $I_{AB}$. By using this measurement method, the offset voltages from misalignment and thermal electric can be eliminated.

The sensitivity of the AlGaN/GaN 2DEG device was measured to be 77 V A$^{-1}$ T$^{-1}$, which is greater than that of other semiconductor-based devices reported in the literature, Table I. The sensitivity of our device was improved due to several factors, including higher electron mobility and point-like contacts. According to U. Ass Sellner, small contacts make the largest Hall signal but also the largest noise (high impedance) [15].

To make the electric current sensor, the chip was bonded on a glass film and then attached firmly to the core for the characterization of dc current sensing, as shown in Fig. 2(a) and (b). In this work, the core is formed from two halves of a toroidal core to create a 0.5-mm gap for placing the Hall plate.

### III. RESULTS AND DISCUSSION

The output Hall voltage of a Hall effect device is dependent on the electron density in 2DEG and the intensity of the magnetic field [16]

$$ V_H = G_H \frac{r_H}{qN_{2DEG}} I_s B $$

where $V_H$ is the Hall voltage, $G_H$ is the geometrical correction factor of Hall voltage, $r_H$ is the Hall factor, $I_s$ is the Hall supply current, $B$ is the magnetic field applied perpendicular to the plane of the device, $q$ is the electron charge, and $N_{2DEG}$ is the sheet density.

From (3), a low sheet density would result in a high Hall voltage. At room temperature (RT), electron mobil-
ity \( \mu \) and sheet density \( N_{2\text{DEG}} \) achieved in the AlGaN/GaN heterostructure were measured to be 2500 cm\(^2\)V\(^{-1}\)s\(^{-1}\) and 2.5 \( \times \) 10\(^{13} \) cm\(^{-2}\), respectively. To obtain this result with high accuracy, Hall effect method was used.

An electric current generates a magnetic field surrounding the conductor. The magnetic flux density is determined as [16]

\[
B = \frac{\mu_0 I_p}{2\pi r}
\]

where \( \mu_0 \) is the vacuum permeability (4\(\pi \times 10^{-7} \)Tm/A), \( r \) is the distance from the centerline of the conductor to the sensor (m), and \( I_p \) is the primary current flowing in the conductor. However, the magnetic field that is produced by the electrical-carrying conductor is normally very small. As amplifying the magnetic signal would increase the Hall effect, we utilized a magnetic flux concentrator in the form of a toroidal core, as shown in Fig. 2(a) and (b). The nanocrystalline Vitroperm alloy was selected as core material due to its high permeability 80,000 and low remanence 0.05 mT. The alloy contains 82.8% Fe, 8.8% Si, 1.5% B, 5.6% Nb, and 1.3% Cu.

The magnetic core converges the magnetic flux surrounding the conductor into a magnetic flux perpendicular to the chip surface. The magnetic flux density focused by the core to the sensor can be calculated as [23], [24]

\[
B = \frac{\mu_0 \mu_i I_p}{l_m \mu_0 + l_g \mu_i}
\]

where \( B \) is the magnetic flux density, \( \mu_i \) is the initial permeability of the core, \( l_m \) is the mean length of the core, and the length of the air gap is \( l_g = 0.5 \) mm.

The flux density of the magnetic field is magnified by a factor of 61 compared to the case without the core. The measured results agree well with the simulation result [see Fig. 2(c)].

To investigate the effect of conductor position on the magnetic flux density, we conduct an experiment by using the Magnetometer (Koshava 5) to measure the magnetic flux density at the gap of the magnetic core. The sensing area at the probe’s tip of the magnetometer was 4 \( \times \) 4 mm. The probe’s tip was inserted inside the air gap and aligned carefully so that it was covered completely by the core’s cross section. As shown in the inset Fig. 2(c), the magnetic flux generated in the magnetic core changed less than 4% due to the shifting of the conductor inside the magnetic core.

Fig. 3(a) shows the relationship between the Hall voltage \( V_H \) and the primary current \( I_p \), indicating that the Hall voltage increases/decreases linearly with increasing/decreasing of the primary current.

The sensitivity of the Hall current sensor with respect to primary current can be defined as

\[
S = \frac{V_H}{I_s} \times \frac{1}{I_p}
\]

(6)

The current sensitivity of the fabricated 2DEG Hall effect sensor was found to be as high as 0.26 (V/A)/A. This sensitivity is 13 times higher compared to another report on Hall current sensor using the same material [25] and one order of magnitude higher than other work using Si as Hall plate [10]–[14], [26].

To characterize the reliability of the device, repeatability tests were carried out with a constant Hall supply current \( I_s \) of 0.5 mA. Under the application of a certain primary current \( I_p \) in the range from 1 to 3 A, the Hall voltage was stable without any noticeable signal drift [see Fig. 3(b)]. The Hall voltage also returned to its initial value once the primary current \( I_p \) was completely turned off. When the primary current was OFF, the offset voltage is around 40 nV.

The thermal noise of the device is calculated to be \( V_n = 22.5 \) nV at a measurement bandwidth of 10 Hz.

The thermal noise can be described as [27]

\[
V^2_{1/f (rms)} = \frac{4k_B T R}{N} \ln \left( \frac{f_{\text{max}}}{f_{\text{min}}} \right)
\]

(8)

where \( k_B \) is Boltzmann’s constant, \( R \) is the resistance, \( \Delta f \) is the measurement bandwidth, and \( T \) is the absolute temperature. The impedance of our device is 3125 \( \Omega \). The thermal noise of the device is calculated to be \( V_n = 22.5 \) nV at a measurement bandwidth of 10 Hz.

The \( 1/f \) noise can be described as [27]

\[
V^2_{1/f (rms)} = \frac{\alpha V_0^2}{N} \ln \left( \frac{f_{\text{max}}}{f_{\text{min}}} \right)
\]

(9)

where \( \alpha \) is the Hooge parameter. For AlGaN/GaN, \( \alpha \) was reported to be 10\(^{-4} \) [28]. \( V_0 \) is the supply voltage to the sensor, and \( f_{\text{max}} \) and \( f_{\text{min}} \) are upper and lower limits of measurement frequency, respectively. The total number of carriers \( N \) is proportional to the area of the 2DEG (\( N = \) sheet density \( \times \) width \( \times \) length = 2.3 \( \times \) 10\(^{13} \) electrons). With \( V_0 = 1.56 \) V, \( f_{\text{min}} = 2 \) Hz to \( f_{\text{max}} = 12 \) Hz, and the \( 1/f \) noise voltage can be calculated to be \( V_{1/f} = 5.97 \) nV. The total noise voltage caused by thermal noise is \( V_{\text{noise,cal}} = \sqrt{V_n^2 + V_{1/f}^2} = 23.2 \) nV.

The voltage spectral density \( V(f) \) was also measured at different supply currents \( I_s \) in the frequency range from 1 Hz to 1 kHz by using the spectrum analyzer (USB-SA44B, Signal Hound), as shown in Fig. 4. \( V(f) \) in the low-frequency region is dominated by the \( 1/f \) noise, which decreases with
increasing frequency, whereas $V(f)$ in the high-frequency region is mainly thermal noise, and it is independent on the frequency. The measured noise voltage with supply current $I_i = 0.5 \, \text{mA}$ in the frequency range 2–12 Hz can be obtained by $V_{\text{noise, } m} = \sqrt{S} V(f)\, df = 23.7 \, \text{nV}$. The difference between the calculation and measurement results may arise from other noise sources (e.g., measurement equipment and electromagnetic noise) rather than just thermal noise and $1/f$ noise from the sensor.

The voltage noise can be converted to current noise by using the following formula:

$$I_{\text{noise}} = \frac{V_{\text{noise, } m}}{S}$$

where the sensitivity of the device $S = 0.26 \, \text{V/\text{A}}$. With the typical measurement frequency range 2–12 Hz and the measurement bandwidth of 10 Hz, the actual noise voltage $V_{\text{noise}} = 23.7 \times 10^{-9} \, \text{V}$. Accordingly, the current noise was calculated to be $I_{\text{noise}} = 9.11 \times 10^{-8} \, \text{A} \cdot \text{A}$. This current noise is also considered as the measurement resolution of this current sensor, i.e., the sensor cannot measure the current smaller than $9.11 \times 10^{-8} \, \text{A} \cdot \text{A}$.

We characterized the operation of the sensor at elevated temperatures. The permeability of the magnetic core Vitroperm typically changes by less than 5% in the temperature range from 20 °C to 200 °C [29]. The Hall voltage versus primary current characteristics in temperature ranges from 20 °C to 200 °C were measured, as shown in Fig. 5. A sensitivity of 0.26 V/\text{A} was monitored at 20 °C then slightly increased to 0.27 V/\text{A} at 200 °C, (see the inset in Fig. 5). This increase in sensitivity with increasing temperature can be explained by the following equation:

$$S = G_H \frac{r_H}{q N_{\text{2DEG}}} \frac{\mu_o \mu_i}{l_m \mu_o + l_g \mu_i}.$$  

(10)

The sensitivity of the device $S$ depends on the geometrical correction factor $G_H$, the Hall factor $r_H$, and the sheet density $N_{\text{2DEG}}$. According to the layout of the Hall plate, as shown in Fig. 1(b), the contact size is significantly small compared to the device size, so it can be considered as point-like contact, and therefore, $G_H = 1$ [16]. However, for nonperipheral contacts of the Hall plate, $G_H$ may be smaller than 1. The Hall factor $r_H$ was proven to be very weak dependence on temperature [30]. Thus, the sheet density is the dominant temperature-dependent parameter, and it will be analyzed in more detail in the following.

The bandgap of GaN was calculated using the Varshni equation [31]

$$E_g - \text{GaN} = E_g(0) - \frac{T^2 \alpha_H}{\beta + T}$$

where $E_g(0)$ is energy bandgap of GaN at $T = 0 \, \text{K}$, and $\alpha_H$ and $\beta$ are constants.

The bandgap of AlGaN is deduced from the commonly known compositional dependence [32]

$$E_g - \text{AlGaN} = (1 - x)E_g - \text{GaN}(T) + x(E_g - \text{GaN}(T) - bx(1 - x))$$

where $b$ is the bowing parameter and $x$ is the aluminum concentration. Through solving the Schrodinger and Poisson equations by using the Silvaco Atlas software [33], the temperature-dependent energy band diagram of AlGaN/GaN heterostructure can be simulated, as shown in Figs. 6 and 7.

Fig. 6 shows the calculated temperature dependence of the bandgap of GaN and AlGaN and the conduction band offset of AlGaN/GaN heterostructure. The bandgaps of GaN and AlGaN are found to decrease with increasing temperature. Besides the energy bandgaps, the conduction band offset of AlGaN/GaN heterostructure also drops with the temperature.

According to Fig. 7(a), the conduction and valence band energies of both GaN and AlGaN layers increase with increasing temperature, especially in the GaN layer. Compared with the conduction band, the valence band shows a larger shift with varying temperatures. Thus, the energy bandgaps of GaN and AlGaN layers decrease with increasing temperature. As a consequence, the depth of the quantum well at the AlGaN/GaN
interface becomes shallower and the confinement of electrons in the well reduces [see Fig. 7(b)]. Therefore, the sheet density of 2DEG falls off with the rising of temperatures, as shown in Fig. 7(c).

In addition, the 2DEG concentration in AlGaN/GaN heterostructures shows a direct proportional relationship to the conduction band offset, according to the following equation [34]:

\[
\frac{n_s}{e} = \sigma \left( \frac{\varepsilon_0}{d_{\text{AlGaN}}} \right) [e\phi_b + E_F - \Delta E_c] \\
\]  

(13)

where \( \sigma \) is the total bound sheet charge, \( \varepsilon \) is the relative dielectric constant of AlGaN, \( d_{\text{AlGaN}} \) is the thickness of the AlGaN layer, \( e\phi_b \) is the Schottky barriers of the gate contact on top of the AlGaN layer, \( E_F \) is the Fermi level with respect to the GaN conduction band-edge energy, and \( \Delta E_c \) is the conduction band offset at the AlGaN/GaN interface. Thus, the sheet density of 2DEG decreases with increasing temperature due to the reduction of conduction band offset \( \Delta E_c \). To characterize 2DEG sheet density of the chip at different temperatures, we put the chip and permanent magnet in a furnace. The Hall voltage \( V_H \) was recorded at a temperature range from 20 °C to 200 °C. Hall supply current \( I_S \) was supplied and kept constant at 0.5 mA throughout the experiment. The magnetic flux density \( B \) was measured at room temperature using Magnetometer Koshava 5. For higher temperature, \( B \) was calculated using the performance loss per degree rise in temperature factor \%/°C. Based on the recorded data of \( V_H, I_S, \) and \( B \) at specific temperature points, we obtained the 2DEG sheet density \( N \) at temperature range 20 °C to 200 °C. The simulation result of temperature-dependent sheet density agreed well with the experimental result shown in Fig. 8. According to (10), the reduction in sheet density leading to a slight increment of device sensitivity.

Koide et al. [18] and Alpert et al. [35] already reported that AlGaN/GaN Hall effect sensors can operate from 0 °C up to 570 °C without dropping its current-scale sensitivity [13]. Therefore, the temperature range of the AlGaN/GaN 2DEG current sensing system can be expected to be 0 °C–570 °C. However, the system also consists of other components, such as a magnetic core. The characterization of the system above
200 °C will be conducted in the future work for confirmation of the predicted value.

IV. CONCLUSION

We successfully demonstrated an AlGaN/GaN heterostructure 2DEG Hall device for highly sensitive dc current sensing. High linearity of the Hall voltage versus primary current was observed at different temperatures between 20 °C and 200 °C. The device exhibited a high sensitivity of 0.26 (V/A)/A with good repeatability, showing its feasibility for current sensing applications. The magnetic core was used to concentrate the magnetic field generated from the electric current in the conductor. By using the magnetic field concentrator, the sensitivity of the Hall effect sensor increased significantly compared to the case without the magnetic core. The device showed a slight increase in sensitivity with increasing temperature due to the conduction band offset lowering. Combining these factors, the AlGaN/GaN 2DEG Hall sensor is promising for current monitoring in a wide range of temperatures.

REFERENCES


