THE EFFECT OF BIAS CONDITIONS ON ALGAN/GAN 2DEG HALL PLATES

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ABSTRACT

This paper describes the operation of AlGaN/GaN two-dimensional electron gas (2DEG) Hall plates under various supply conditions (0.026 V to 1.27 V). The 100-µm-diameter octagon-shaped devices were microfabricated using metal-organic chemical vapor deposition of AlGaN/GaN on <111> silicon wafers and traditional photolithography techniques. Upon device characterization at various Hall supply voltages, we observed an increase in the residual offset from 0.1 mT to 1.4 mT (from 9% of measured signal to over 60% in a 1 mT magnetic field). In addition, the sensitivity (scaled with bias voltage) was constant at 76 ± 2.5 mV/V/T (stable within 3%) with high linearity ($R^2 > 0.99$) across the tested operating conditions. This work demonstrates improved understanding of AlGaN/GaN sensor elements that may be monolithically integrated with power electronics, as well function within extreme environments.

INTRODUCTION

Hall-effect devices are used in diverse sensing applications such as position and velocity sensors in automobiles and current sensing in power electronics [1]. However, silicon-based Hall-effect sensors have limitations in extreme environments because of the influence of temperature on intrinsic carrier concentration – low-doped materials ($< 10^{16}$ cm^{-3}) become saturated with carriers around 300°C. Recently, two-dimensional electron gas (2DEG) material systems, including AlGaN/GaN, have gained high interest for power electronics monitoring and extreme environment sensing due to their durable nature, wide bandgap, and potential for monolithic integration with electronics [2]. Additionally, piezoelectric and spontaneous polarization create a stable 2DEG carrier concentration across a wide temperature range [3], which enables robust Hall-effect sensing [4], [5]. However, sensing low magnetic field signatures (< 10 mT) under high bias conditions has not been investigated with AlGaN/GaN 2DEG Hall plates.

The Hall-effect can be leveraged for sensing magnetic field signatures through a 4-probe scheme. Constant current is applied across two contacts, and the induced electric potential from the external magnetic field is measured by a Hall voltage reading on the other two contacts. AlGaN/GaN 2DEG plates are promising candidates for Hall-effect sensing because of their high mobility (~2200 cm^2/V·s) [4] and high temperature stability.

In applications with low magnetic field levels, sensors are required to have high signal accuracy to overcome issues with background fields such as Earth's field or from electromagnetic interference. Hall devices generally have high raw offset values (larger than Earth's magnetic field of 50 µT) when no external magnetic field is applied due to inherent material defects or from various steps in microfabrication [6], [7]. This limits the minimum detectable signal to inconvenient ranges and reduces sensor accuracy. To overcome this issue, current spinning [7] and orthogonal layouts [8] have been adopted in practice to remove these "raw" offsets for silicon devices. These techniques can reduce the raw offset to a "residual" offset below 10 µT under various conditions [6], [7], [9], [10], corresponding to an improvement by a factor of up to 4,000.

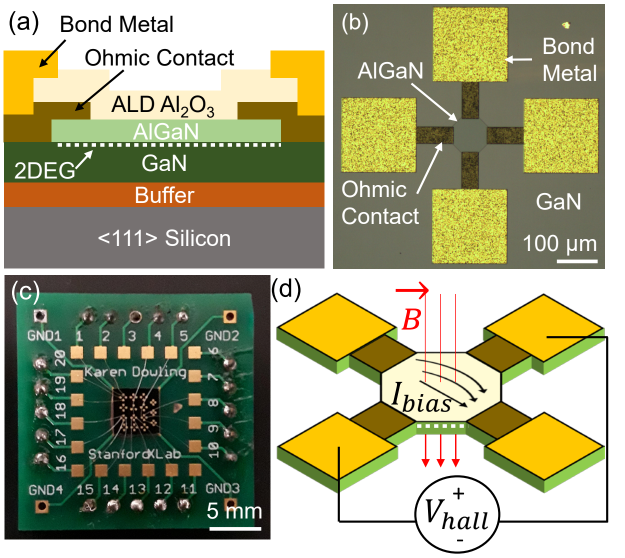

Figure 1: (a) Cross sectional schematic of the AlGaN/GaN 2DEG Hall plate. (b) Optical image of the 2DEG Hall plate with 4 contacts (no top plate). (c) Packaged Sensor #1 for testing with floating substrate. (d) Device operation. Constant current is applied across a 4-contact van der Pauw structure and the Hall voltage is measured across the other two contacts.

In addition to low residual offset values, sensors are also required to have high sensitivity in many applications. Sensitivity is defined as a ratio of the change in Hall voltage (V_{Hall}) due to an external magnetic field (B). It is well known that the Hall voltage scales with supply voltage (or current), so most reports show either sensitivity scaled with supply current (S_I) or sensitivity scaled with supply voltage (S_V). However, in most applications, Hall plates are operated with a constant supply voltage to enable ease of integration with interface circuitry.

In this paper, we present the methodology for Hall-effect sensor microfabrication and characterization with a current spinning technique to study offset values in low magnetic fields (<5 mT). We also examine the sensitivity and residual offset in AlGaN/GaN 2DEG Hall plates as influenced by supply voltage. We observed that the sensor exhibited large residual offset values (60% of the signal in a 1 mT field) under high supply voltage conditions, as well as a constant sensitivity of 76 ± 2.5 mV/V/T. A discussion on the leading contributions to residual offset in these high bias schemes is provided. It should be noted that the AlGaN/GaN Hall-effect sensors have higher sensitivity values compared to silicon-based Hall plates and with proper offset calibration can be used over a large temperature range for extreme environments.

METHODOLOGY

Fabrication

To study the effect of bias conditions on AlGaN/GaN 2DEG Hall plate performance, we examined two devices (4-contact van der

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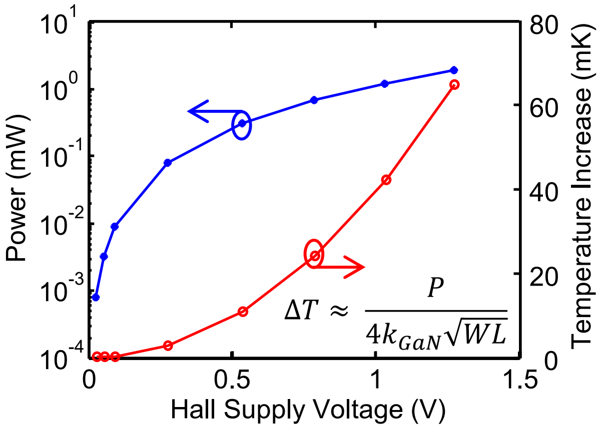

Figure 2. Average operating power of 2DEG Hall plates under various supply voltages, and expected average temperature increase along current path from thermal resistance approximation.

Pauw structures) from different chips. Fig. 1 shows a cross-sectional schematic of the 2DEG Hall plate (Fig. 1a). To microfabricate the device, AlGaN/GaN films were grown on <111> silicon using metal-organic chemical vapor deposition (MOCVD). Then, a 100-μm-diameter octagon mesa with Ti/Al/Pt/Au Ohmic contacts and a 50-nm-thick alumina passivation layer was microfabricated (Fig. 1b) [11]. The Hall plate device was then bonded to a printed circuit board (PCB) with epoxy and electrically connected with aluminum wirebonds. The packaged device is shown in Fig. 1c. The two tested devices have lateral resistances (R) of 867 ± 22 Ω and 896 ± 30 Ω (variation among bias conditions) and the operating power rose from 0.83 μW to as high as 1.91 mW (Fig. 2).

Experimental Set Up

The sensor's principle of operation is shown in Fig. 1d. To characterize the sensitivity of the device, current was applied with a Keithley 2400 current source from 30 μA to 1.5 mA, which correspond to average supply voltages of 0.026 V to 1.2 V. The Hall voltage was then measured with a multimeter (Agilent 34401A). Current spinning was used to suppress offset errors [6] with an Agilent U2715A switching matrix (1 s/measurement).

A magnetic field was applied using a home-built and calibrated Helmholtz coil (up to ±5 mT) inside a zero-field Mu-metal® chamber. Finite element modeling (FEM) with COMSOL® was leveraged to design a compact Helmholtz coil system to apply magnetic fields from -5 to 5 mT within 1 A of supply current (Fig. 3a). Once the design was selected, a 3D-printed scaffold was made to support the hand-wound coils. Each coil pictured in Fig. 3b is 250 turns of copper wire in a 1x1 cm cross-section. The Hall sensor is placed in the center of the coils through the top of the scaffold with a custom sample holder (not pictured). Since the fields being measured are relatively small, the entire setup was placed within three concentric magnetic shielding canisters made of MuMetal®. This shielding reduced the background field to ~6 μT, checked with a gaussmeter (1 nT resolution) from AlphaLab, Inc. The vertical coil pair, which was used in this study, was calibrated with another gaussmeter (1 μT resolution, ±80 mT range) from AlphaLab, Inc. Once assembled, the entire set up was controlled using LabView (National Instruments) to control the current spinning, measurements, and magnetic field (Fig. 3c).

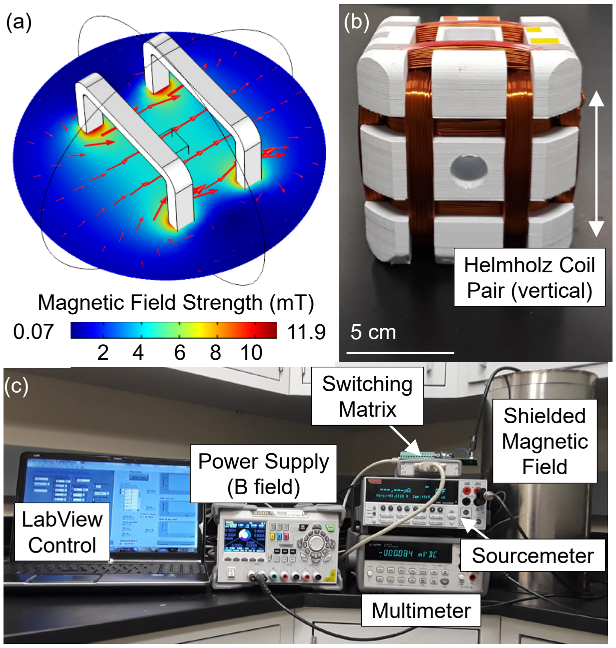

Figure 3. (a) Finite element model of the magnetic field profile from a Helmholtz coil with 250 turns of 9 x 9 cm of copper wire powered at 1 A. (b) Home-made Helmholtz coil pair using a 3D printed scaffold. (c) Complete test setup, the Helmholtz coil scaffold sits inside the shielding canisters.

RESULTS

Hall Voltage

The net Hall voltage after current spinning is plotted with respect to magnetic field in Fig. 4a and the residual offset was calculated from the x-intercept of the linear fit of these curves. Ideally, the x-intercept should be near zero, which would indicate a high accuracy sensor. However, the increased supply power seems to cause an additional offset that cannot be canceled with current spinning. Visualizing the data from another perspective (Fig. 4b), the Hall voltage is compared to the supply voltage directly. It can be clearly seen that the data is skewed with a positive Hall voltage, especially at higher supply voltages as indicated in Fig. 4b. When this offset voltage is removed from the measured data, the resulting calibrated data show Hall voltages linear with supply voltage. This further confirms the need for Hall calibration at high supply bias on the devices.

Sensitivity

Voltage-scaled sensitivity (S_V) for the two devices is shown in Fig. 5. S_V was constant at 76 ± 2.5 mV/V/T, which is within 3% and has high linearity with respect to magnetic field. The small variations are subject to the power supply variation and slightly non-Ohmic nature of some sensor contacts, which would affect the average supply voltage. Current-scaled sensitivity (S_I), similarly measured, is around 68 V/A/T ± 1.3 V/A/T. From these values, the sheet density was calculated to be 9.3 x10^{12} cm^{-2} and the mobility was calculated to be around 1635 cm^2/V·s. These values agree with similar 2DEG characteristics from previously reported values for AlGaN/GaN Hall plates [4], [5], [12]. Since the sensor shows relatively stable sensitivity, the residual offset must be addressed to enable AlGaN/GaN 2DEG Hall plates for extreme environment sensing.

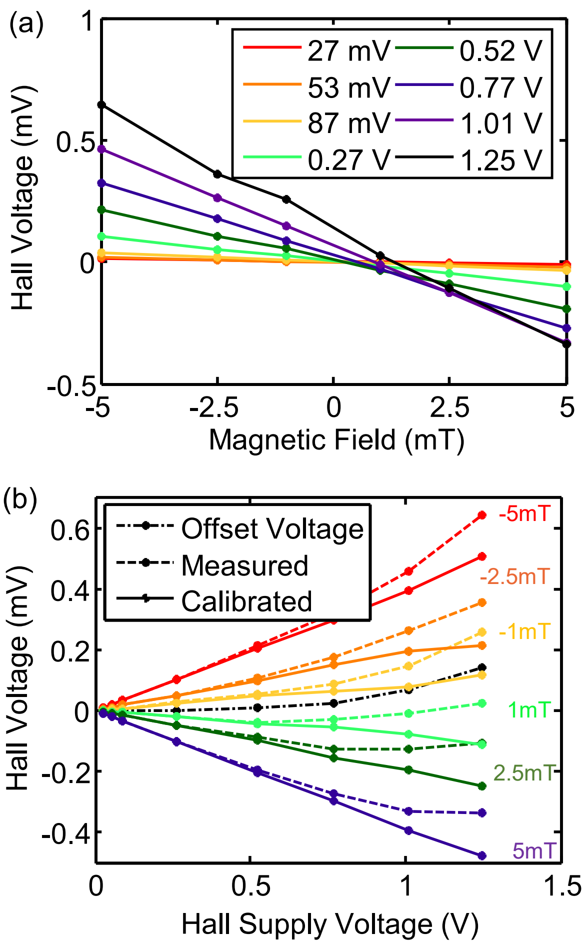

Figure 4. (a) Hall output voltages under varied magnetic fields and Hall supply current of sensor #1. (b) Hall output voltages before and after calibration by removal of residual offset voltage at each magnetic field condition.

Residual Offset

The residual offset is defined as the magnitude of magnetic field that is read in a zero-field. The x-intercepts from Fig. 4a are shown in Fig. 5. Here, the 2DEG Hall plates have residual magnetic offset values that are quadratically proportional to the supply voltage. Fig. 5 shows that a residual offset as high as 1.4 mT is present at 1.25 V, which is over 60% of the measured signal at $B = 1$ mT. These results will be further examined in the discussion section below.

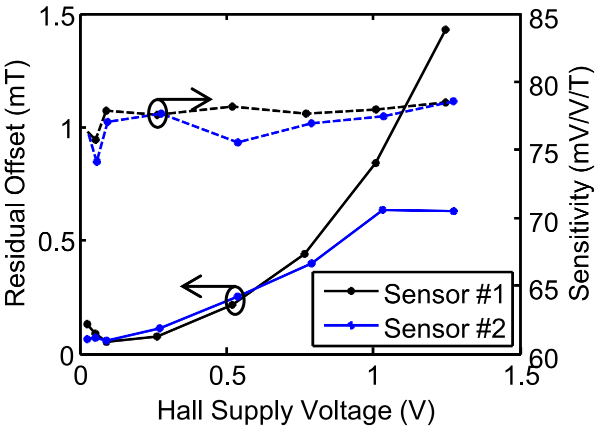

Figure 5. Residual magnetic offset of two AlGaN/GaN 2DEG Hall plates under varied bias voltages. Sensitivity (scaled with Hall supply voltage) under various supply voltages on the secondary axis.

Table 1. Possible contributions to increase in residual offset with high bias conditions.

Offset Source	Explanation
Seebeck Voltage	Increase in residual offset directly proportional to input power, combined with inhomogenous current density around defects and contacts causes localized heating [11], [13], [14]
Buffer effect	Underlying GaN substrate induces Hall voltage prominent at higher bias conditions. [6]
Packaging	Thermal and mechanical stress in substrate and packaging from high bias operation[7]Also induced magnetic fields from bond wires [15]
Asymmetry	Linear imbalance due to geometrical asymmetries is removed with current spinning, Nonlinear effects remain [7]

DISCUSSION

The residual offset increases with supply voltage as a function of V^2. There are many possible physical mechanisms that contribute to the increase in residual offset with supply voltage. The potential contributions to the nonlinear offset are summarized in Table 1 [6], [7], [11], [13]–[15] and are discussed in this section in detail.

The first contribution is due to thermoelectric effects from self-heating. The increase in supply voltage (and supply current) corresponding to an increase in operating power of the Hall plate. Power (P) increases with V^2/R (and I^2R), which causes the device to increase in temperature (ΔT). The device is an octagonal Hall plate, but the highest current concentration is across the supply contacts, so the majority of heating occurs across the octagon length (L) and contact width (W). Using Eq. (1),

$$\Delta T = \frac{P}{4k_{GaN}\sqrt{WL}}, \tag{1}$$

an estimated average temperature rise of at least 65 mK in the current path is expected, assuming an in-plane thermal conductivity (k_{GaN}) of 115 W/m·K [11]. AlGaN/GaN 2DEG devices have been recently reported to have a lateral Seebeck coefficient of 120 µV/K [11] at room temperature. Thus, the thermal gradients generated in the Hall plate from high supply voltages could be generating an additional voltage measured on the Hall contacts, regardless of measurement orientation or external magnetic field direction.

The second potential contribution to residual offset could be due to underlying material buffers. Larger supply voltages (and currents) could start to cause a portion of the current to flow through underlying buffer structures (Fig. 1a). When the current values get large enough, this buffer could be causing an additional contribution of Hall voltage to the sensor. However, the Hall plate still has constant S_V at high supply voltage, and a buffer component would alter the sensitivity, which is not seen here.

A third potential source of the residual offset could be from packaging. Strain has been reported to cause an increase in residual offset in silicon devices, due to the directional change in resistance from its asymmetric piezo-resistive components. Analogously, the

AlGaN/GaN 2DEG forms from a combination of spontaneous and piezoelectric polarization, so any strain from packaging could cause local changes in the 2DEG concentration, and thus would contribute to resistance asymmetry. In addition to packaging stress, these sensors were electrically connected using wirebonding with different wire layouts. At higher supply power, the induced magnetic field of the wirebonds could interfere with the device measurement. However, simple finite element modeling predicts this additional external field to be around 12 μT when supplied with 1 V, much smaller than the measured conditions.

The final contribution mechanism considered here is the linear imbalance from fabrication. Current spinning successfully removes linear offsets in contact resistance from lithography misalignment. However, nonlinear differences in contact resistance from misalignment remain (ΔR is not constant between measurement phases). Our sensors had up to 60 Ω difference between the orthogonal current paths in the sensor, which is around 7% change between lateral and longitudinal directions of current spinning. This could contribute to a nonlinear offset in V_{Hall} that scales with increased current. This could be improved with tighter fabrication tolerances in future work.

CONCLUSION

Here, we presented work on AlGaN/GaN 2DEG Hall plates with high, stable sensitivity values, which match results of Si-based Hall plates found in the literature and even slightly better sensitivity due to higher electron mobility. Current spinning was used to reduce the offset voltages, but there were large residual offsets when biased with a large supply voltage. This is particularly problematic when operating to sense small magnetic fields (<5 mT). While AlGaN/GaN sensors are of interest for extreme environment applications, these electrical operation conditions need to be further understood for proper calibration and use. We discussed some key factors that cause residual offsets, including self-heating and nonlinear contact resistance asymmetry. Future work should focus on reducing the causes of large signal offset to enable improved sensing capability. Regardless, this work confirms that AlGaN/GaN 2DEG Hall plates could be used as magnetic field sensors and offers a monolithically integrated sensing solution for GaN power electronics, as well as harsh environment operation.

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