Effect of Geometry on Sensitivity and Offset of AlGaN/GaN and InAlN/GaN Hall-Effect Sensors

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Abstract—The effect of metal contact lengths on current- and voltage-scaled sensitivities and magnetic field offsets of octagonal AlGaN/GaN and InAlN/GaN Hall-effect sensors were examined in this work. The calculations that take into account the shape of the device show that the devices with point-like contacts have the highest current-scaled sensitivity (68.9 V/A/T), while the devices with contacts of equal length to their non-contact sides have the highest voltage-scaled sensitivity (86.9 mV/V/T). The sensitivities of the two other devices (with “long” and “short” contacts) follow the predicted trends closely. All the devices have offsets less than 20 µT at low supply current operation (<300 µA) and most remain below 35 µT at higher supply current (up to 1.2 mA). The consistent low offsets across the devices imply that the choice of the Hall-effect sensor geometry should mainly depend on the biasing scheme (e.g., current or voltage). Although this work focuses on 2DEG materials, the geometry dependence can be applied to other planar Hall-effect sensors with four-fold symmetry. This work demonstrates that the Hall-effect sensor performance can be improved by adjusting the geometry of the Hall-effect plate specific to its function (e.g., power electronics, navigation, and automotive applications).

Index Terms—Hall effect, gallium nitride, AlGaN/GaN, InAlN/GaN, offset voltage, sensitivity, geometry.

I. INTRODUCTION

MAGNETIC field sensors have a wide array of applications, including position and velocity sensing in vehicles (e.g., valve positions, gear rotation speed, seatbelt buckle clamping, heading determination) and current sensing in power electronics. Devices based on the Hall effect are advantageous over other magnetic field sensing technologies because they are low-cost, easy to integrate, and linear over a wide range of magnetic fields [1].

Hall-effect sensors are typically made of silicon due to its low cost, ease of fabrication, and complimentary metal-oxide-semiconductor (CMOS) compatibility; however, silicon’s narrow bandgap of 1.1 eV limits its functionality to temperatures below 200°C [2], [3]. This temperature limitation can be overcome by using a material with a wide bandgap, such as gallium nitride (GaN). In particular, heterostructures made using GaN have previously shown operation up to 1000°C [4] and radiation hardness beyond that of silicon [5], [6], making it a viable material for space applications. It has additionally become a promising material platform for power electronics due to its high breakdown field and potential for monolithic integration with silicon electronics [7].

GaN heterostructures have a 2-dimensional electron gas (2DEG) that is formed when a nanometers-thick layer of unintentionally doped aluminum or indium gallium nitride (AlGaN or InGaN) is deposited on an underlying GaN layer. The 2DEG, created from differences in the polar-ization fields of the III-nitride layers [8], [9], has a high electron mobility (1500 to 2000 cm²/V · s at room temperature) [2], [5], [10]–[12], which enables high sensitivity devices. Further, 2DEG-based Hall-effect sensors have the potential for lower magnetic field offsets than silicon-based devices [13]–[15]. Junction isolated silicon-based Hall-effect sensors experience electrical nonlinearity due to the dependence of the depletion layer thickness on bias voltage [16], while 2DEG-based Hall-effect plates do not face this limitation.

In this paper, we investigate the effect of Hall plate geometry on its sensitivity and magnetic field offset. We altered the size of the Ohmic contacts to maximize the sensitivity with respect to supply current and supply voltage, and we compare our experimental results to the theoretical performance based on shape factor. While the effect of contact length on sensitivity has been discussed in previous papers [17]–[19], it has never been experimentally verified for octagonal devices. In Section II we report on device fabrication, operation, design, and testing methodology, and in Section III
we evaluate the sensitivity and offset for the four device geometries.

II. EXPERIMENTAL METHODS

A. Device Operation

The Hall voltage \( V_H \), measured perpendicular to both the applied current \( I \) and the external magnetic field \( B \), is defined as

\[
V_H = \frac{IBr_n G_H}{qn_s} \tag{1}
\]

where \( r_n \) is the scattering factor of the material (~1.1 for GaN) [20], \( G_H \) is the shape factor, \( q \) is the electronic charge, and \( n_s \) is the sheet electron density. The shape factor, \( G_H \), accounts for the reduction in Hall voltage and change in linearity due to the short-circuiting effect of having finite contacts [17], [21], [22]. For Hall-effect plates with four-fold rotational symmetry at low magnetic fields, \( G_H \) depends only on the geometry of the Hall-effect plate and the contacts. The magnetic field may be considered low if its magnitude is the Hall mobility of the electrons. Equations (4) and (5) show that high Hall mobility is necessary for high voltage-related sensitivity, motivating the use of the 2DEG as the sensing platform, and low sheet density is needed for a high current-related sensitivity.

In addition to high sensitivity, another desirable parameter in a Hall-effect device is low offset. The offset voltage is defined as

\[
G_H \approx \frac{(L/W)_{eff}^2}{\sqrt{(L/W)_{eff}^4 + \frac{2}{\pi} \frac{\pi}{4} + 4}} \tag{2}
\]

This approximation is exact when \((L/W)_{eff} = \sqrt{2}\), and has an error of up to 2% for the geometries studied here [23]. The error can be reduced by over two orders of magnitude by multiplying the previously calculated \( G_H \) by the following factor:

\[
1 + \Lambda \ast e^{(-2.279 - (1.394 + \Lambda)2 + (0.6699 + \Lambda)(4 - (0.4543 + \Lambda)^2}} \tag{3}
\]

where \( \Lambda = \ln \left( \frac{L/W}{\sqrt{2}} \right) \), further described in [23].

The sensitivity of a Hall-effect device with respect to supply current \( S_i \) is proportional to \( G_H \):

\[
S_i = \frac{V_H}{IB} = \frac{r_n}{qn_s} \frac{G_H}{I} \tag{4}
\]

In addition, the sensitivity with respect to supply voltage \( S_v \) is proportional to \( G_H/(L/W)_{eff} \):

\[
S_v = \frac{V_H}{V_sB} = \frac{r_n G_H}{Rqn_s} = \mu H r_n \frac{G_H}{(L/W)_{eff}} \tag{5}
\]

where \( V_s \) is the supply voltage, \( R \) is device resistance, and \( \mu H \) is the Hall mobility of the electrons. Equations (4) and (5) show that high Hall mobility is necessary for high voltage-related sensitivity, motivating the use of the 2DEG as the sensing platform, and low sheet density is needed for a high current-related sensitivity.

In addition to high sensitivity, another desirable parameter in a Hall-effect device is low offset. The offset voltage is defined as the Hall voltage measured in the absence of a magnetic field. Offset voltages are usually caused by mechanical stress, thermal gradients, geometrical errors, defects, and other irregularities within the device [25], [26]. Implementing current-spinning has been shown to reduce the offset voltage by a factor of over 1000 [27], [28]. In this method, the direction and polarity of the sourcing and sensing contacts are swapped, resulting in eight total configurations (phases) in which the Hall voltage is measured. The first four phases are identical to the first four phases, but the polarity of the voltage measurement is swapped in order to cancel out multimeter error. Due to the measurement configurations (shown in Table I, where the four contacts are labeled N, W, S, E corresponding to their location on the Hall plate), four of the Hall voltages are positive and four are negative. When these Hall voltages are added together a large portion of the raw offset is canceled out, as shown in Fig. 1. The magnetic field offset \( B_{off} \) is calculated, using the Hall voltage after current-spinning, as

\[
B_{off} = \frac{V_H}{V_s \ast S_v} \tag{6}
\]
Fig. 2. \((L/W)_{eff}\) values that maximize Hall-effect sensitivities with respect to supply current (left) and supply voltage (right) in Equations (4) and (5).

Fig. 3. Images of 100-μm-diameter Hall plates with various geometries, where \(b\) is the length of the contacts and \(a\) is the length of the sides without the contacts. The device with point-like contacts is optimized for \(S_i\) and the device with equal sides is optimized for \(S_v\).

Lengths for two of the devices maximized \(S_i\) and \(S_v\). Optimal \((L/W)_{eff}\) values were calculated by maximizing (4) and (5), shown in Fig. 2. These \((L/W)_{eff}\) values (infinity for maximum \(S_i\) and 1.41 for maximum \(S_v\)) were fed back into (2) and (3) to compute the corresponding \(G_H\). The ratio \(\lambda\) is defined as the length of the sides with contacts \((b)\) divided by the sum of the sides with contacts and those without \((a + b)\), where \(a\) is the length of the sides without contacts). From [19] and [22], \(\lambda\) was calculated for octagonal devices:

\[ G_H \approx 1 - 1.940 \left( \frac{\lambda}{1 + 0.414\lambda} \right)^2. \]  

The shapes of the fabricated Hall-effect plates are shown in Fig. 3 and the geometrical parameters of the four devices fabricated are summarized in Table II. The first and third columns correspond to devices optimized for \(S_i\) and \(S_v\) respectively. The other two devices were fabricated to have “short” contacts and “long” contacts, respectively corresponding to \(\lambda\) of 0.3 and 0.7, for a more complete study of how the current- and voltage-related sensitivities depend on contact length. Because true point-like contacts are impossible to realize, the fabricated “point-like” device had a \(\lambda\) of 0.150, which resulted in a \(G_H\) of 0.981 and a \((L/W)_{eff}\) of 3.26, corresponding to \(a = 5.66b\). The predicted percent of the sensitivity relative to the optimized shape is listed in Table III, where the values for the point-like device are based on the dimensions of the fabricated device. For \(S_i\), this percentage is equivalent to the \(G_H\) ratio between the given Hall plate and that with point-like contacts, as per (4). For \(S_v\), this percentage was calculated as the ratio of \(G_H/(L/W)_{eff}\) between the Hall plate and that with equal sides, as per (5).

### Table II

| Name                  | Point-like | Short Contacts | Equal Sides | Long Contacts |
|-----------------------|------------|----------------|-------------|---------------|
| \((L/W)_{eff}\)       | 3.26       | 2              | \(\sqrt{2}\) | 1             |
| \(G_H\)               | 0.981      | 0.861          | 0.667       | 0.431         |
| \(\lambda\)           | 0.15       | 0.3            | 0.5         | 0.7           |

| Side Lengths (b = contact length) | \(a = 5.66b\) | \(2.33b = a\) | \(a = b\) | \(b = 2.33a\) |

### Table III

| Geometry | \(S_i\) | \(S_v\) |
|----------|---------|---------|
| Point-like | 100%   | 63.8%  |
| Short Contacts | 87.8%  | 91.3%  |
| Equal Sides | 68.0%  | 100%   |
| Long Contacts | 43.9%  | 91.3%  |

### C. Fabrication

Two sets of devices were fabricated: one on an AlGaN/GaN-on-Si wafer grown by metal-organic chemical vapor deposition (MOCVD) in an Aixtron close-coupled showerhead (CCS) reactor in the Stanford Nanofabrication Facility, and the second on an InAlN/GaN-on-Si wafer purchased from NTT Advanced Technology Corporation. The AlGaN/GaN stack consists of a 1.5 μm buffer structure, a 1.2 μm GaN layer, a 1 nm AlN spacer, a 30 nm Al0.25Ga0.75N barrier layer, and a 2 nm GaN cap. The InAlN stack consists of a 300 nm buffer structure, a 1 μm GaN layer, a 0.8 nm AlN spacer, and a 10 nm In0.17Al0.83N barrier layer. For the AlGaN/GaN and InAlN/GaN stacks respectively, the sheet resistances at room temperature were 361 Ω/□ and 248 Ω/□, the carrier mobilities were 1811 cm²/V · s and 1143 cm²/V · s, and the sheet electron densities were \(9.2 \times 10^{12}\) cm⁻² and \(2.1 \times 10^{13}\) cm⁻², measured with van der Pauw and Hall-effect measurements. The subsequent fabrication process was followed for both sets of devices: a mesa etch was performed on the III-nitride layer,
a Ti (20 nm)/Al (200 nm)/Mo (40 nm)/Au (80 nm) metal stack was deposited and annealed for 35 seconds at 850°C to form Ohmic contacts, a 7-nm-thick Al2O3 passivation layer was atomic layer deposited (ALD) to prevent oxidation, vias were etched to allow for electrical connection to the contacts, and bond metal (Ti/Au) was deposited on top. The devices were then diced and wirebonded to a printed circuit board (PCB) for testing.

D. Experimental Testing

The devices were tested in a tunable 3D Helmholtz coil, detailed in [29]. A sourcemeter (Keithley 2400) generated a current between two contacts across the Hall-effect plate, and a multimeter (Agilent 34410A) measured the Hall voltage generated across the other two contacts. A switching matrix (U2715A) was used to alternate between the eight phases to implement current spinning [29]. During testing, the devices were placed in MuMetal® shielding cannisters to block extraneous magnetic fields; the magnetic field inside the cannisters was below 6 μT. The devices were tested with supply current ranging from 60 μA to 1.2 mA, and for sensitivity testing the applied magnetic field was ±2 mT. This applied magnetic field is well within the range for which the Hall voltage of the device is linear with respect to magnetic field. Fig. 4 shows the output voltage Hall voltage with respect to magnetic fields ranging from −4 mT to 4 mT, with a supply current of 300 μA, showing linearity of the response in the range of −4 mT to 4 mT. All devices showed similarly linear behavior.

Fig. 4. Output Hall voltage (after current spinning) versus magnetic field for one of the AlGaN/GaN devices and one of the InAlN/GaN devices with a supply voltage of 300 μA, showing linearity of the response in the range of −4 mT to 4 mT. All devices showed similarly linear behavior.

D. Experimental Testing

The devices were tested in a tunable 3D Helmholtz coil, detailed in [29]. A sourcemeter (Keithley 2400) generated a current between two contacts across the Hall-effect plate, and a multimeter (Agilent 34410A) measured the Hall voltage generated across the other two contacts. A switching matrix (U2715A) was used to alternate between the eight phases to implement current spinning [29]. During testing, the devices were placed in MuMetal® shielding cannisters to block extraneous magnetic fields; the magnetic field inside the cannisters was below 6 μT. The devices were tested with supply current ranging from 60 μA to 1.2 mA, and for sensitivity testing the applied magnetic field was ±2 mT. This applied magnetic field is well within the range for which the Hall voltage of the device is linear with respect to magnetic field. Fig. 4 shows the output voltage Hall voltage with respect to magnetic fields ranging from −4 mT to 4 mT, with a supply current of 300 μA, showing linearity of the response in the range of −4 mT to 4 mT. All devices showed similarly linear behavior.

Fig. 5. Voltage-scaled and current-scaled magnetic sensitivity for various octagonal AlGaN/GaN and InAlN/GaN Hall plates. Both sets of devices follow the predicted trend: the devices with equal sides have the highest $S_v$ and the devices with point-like contacts have the highest $S_i$. The colored line shows the theoretical values based on sweeping $\lambda$ between 0 and 1 and calculating $G_H$ and $(L/W)_{eff}$. $S_v$ varies directly with $G_H$, while $S_i$ varies with $G_H/(L/W)_{eff}$. The error bars depict the standard deviation of the sensitivity values over multiple supply currents from 60 μA to 1.2 mA.

### TABLE IV

| AlGaN/GaN | $S_i$ (mV μA⁻¹ T⁻¹) | Value | % Max | $S_v$ (VA⁻¹ T⁻¹) | Value | % Max |
|-----------|----------------------|-------|-------|------------------|-------|-------|
| Point-like | 68.85                | 100%  | 51.36 | 59.1%            |
| Short Contacts | 61.77           | 89.7% | 72.92 | 84.0%            |
| Equal Sides | 50.82             | 73.8% | 86.85 | 100%             |
| Long Contacts | 33.82            | 49.1% | 80.23 | 92.4%            |
| InAlN/GaN | $S_i$ (mV μA⁻¹ T⁻¹) | Value | % Max | $S_v$ (VA⁻¹ T⁻¹) | Value | % Max |
|-----------|----------------------|-------|-------|------------------|-------|-------|
| Point-like | 32.18                | 100%  | 35.77 | 63.7%            |
| Short Contacts | 28.00           | 87.0% | 45.15 | 80.4%            |
| Equal Sides | 24.20             | 75.2% | 56.13 | 100%             |
| Long Contacts | 15.45            | 48.0% | 50.31 | 89.6%            |

The AlGaN/GaN devices consistently have higher current- and voltage-related sensitivities than the InAlN/GaN devices. Since the AlGaN/GaN device has lower sheet concentration and higher mobility than the InAlN/GaN device, these trends hold with (4) and (5) respectively. The InAlN/GaN Hall plate voltage-related sensitivities are an average of 64.7% of the values for the AlGaN/GaN Hall plates, which closely

III. RESULTS AND DISCUSSION

A. Sensitivity

For both material platforms, the devices with the point-like contacts had the highest current-related sensitivity and the devices with equal sides had the highest voltage-related sensitivity. The measured $S_i$ and $S_v$ closely follow the predicted trends in Table III. The device sensitivities for both samples are shown in Fig. 5 and they are listed in Table IV along with the percentage of the maximum value, for comparison. The AlGaN/GaN devices consistently have higher current- and voltage-related sensitivities than the InAlN/GaN devices. Since the AlGaN/GaN device has lower sheet concentration and higher mobility than the InAlN/GaN device, these trends hold with (4) and (5) respectively. The InAlN/GaN Hall plate voltage-related sensitivities are an average of 64.7% of the values for the AlGaN/GaN Hall plates, which closely
TABLE V
MEAN OFFSETS AlGaN/GaN HALL PLATES AT LOW BIAS (<300 μA)

| Geometry     | Offset Voltage (nV) | Magnetic Field Offset (μT) |
|--------------|---------------------|---------------------------|
| Point-like   | 66.8                | 6.84                      |
| Short Contacts| 45.4                | 4.72                      |
| Equal Sides  | 37.3                | 4.17                      |
| Long Contacts| 37.1                | 11.0                      |

TABLE VI
MEAN OFFSETS InAlN/GaN HALL PLATES AT LOW BIAS (<300 μA)

| Geometry     | Offset Voltage (nV) | Magnetic Field Offset (μT) |
|--------------|---------------------|---------------------------|
| Point-like   | 70.7                | 14.6                      |
| Short Contacts| 13.8                | 2.98                      |
| Equal Sides  | 25.4                | 1.03                      |
| Long Contacts| 13.4                | 7.56                      |

Fig. 6. Measured magnetic field offsets of the AlGaN/GaN and InAlN/GaN devices with equal sides. Offsets tend to be <20 μT at low bias currents (<300 μA) and greater at higher bias currents (up to 1.2 mA).

B. Magnetic Field Offset
At low bias currents (<300 μA), the offset voltages of all the AlGaN/GaN and InAlN/GaN devices were consistently in the nanovolt range, corresponding to a magnetic field offset below 20 μT, detailed in Table V and Table VI. For both material platforms the point-like devices showed higher offset voltages than the other geometries; however, their higher internal resistances lead to larger bias voltages for the same supply current, resulting in magnetic field offsets that are similar in magnitude to that of the other devices. At high biases (up to 1.2 mA), the magnetic field offsets for some of the devices remained constant below 20 μT, while some showed larger increases, up to 80 μT. The magnetic field offsets of the AlGaN/GaN and InAlN/GaN devices with equal sides are shown in Fig. 6, and similar trends were seen for the other geometries. There is no strong correlation between Hall-effect plate geometry and offset; the variation may be due to minor flaws during fabrication or slight differences in packaging.

IV. Conclusion
We designed octagonal Hall plates to examine current- and voltage-scaled sensitivities and experimentally verified how device sensitivity depends on the metal contact lengths of the Hall-effect sensor. Both the AlGaN/GaN and InAlN/GaN devices follow similar trends, confirming the validity of the shape factors over multiple material platforms. Additionally, the voltage-scaled sensitivities are an average of 46.3% of the AlGaN/GaN values, and similar in magnitude to that of the other devices. At high biases (up to 1.2 mA), the magnetic field offsets for some of the devices remained constant below 20 μT, while some showed larger increases, up to 80 μT. The magnetic field offsets of the AlGaN/GaN and InAlN/GaN devices with equal sides are shown in Fig. 6, and similar trends were seen for the other geometries. There is no strong correlation between Hall-effect plate geometry and offset; the variation may be due to minor flaws during fabrication or slight differences in packaging.

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