

Micro-Tesla Offset in Thermally Stable AlGaIn/GaN 2DEG Hall Plates Using Current Spinning

Karen M. Dowling¹, Hannah S. Alpert², Ananth Saran Yalamarthy³,
Peter F. Satterthwaite¹, Sai Kumar², Helmut Köck⁴, Udo Ausserlechner⁴,
and Debbie G. Senesky^{1,2}

¹Department of Electrical Engineering, Stanford University, Stanford, CA 94305 USA

²Department of Aeronautics and Astronautics, Stanford University, Stanford, CA 94305 USA

³Department of Mechanical Engineering, Stanford University, Stanford, CA 94305 USA

⁴Infineon Technologies, Villach 9500, Austria

*Member, IEEE

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Abstract—This article describes the characterization of a low-offset Hall plate using the AlGaIn/GaN 2-D electron gas (2DEG). A four-phase current spinning technique was used to reduce the sensor offset voltage to values in the range of ~ 20 nV, which corresponds to a low residual offset of $\sim 3.4 \pm 2$ μ T when supplied with low voltages (0.25–1 V). These offsets are 30x smaller than the values previously reported for GaN Hall plates, and it is on par with state-of-the-art current-spun silicon (Si) Hall plates. In addition, the offset does not exceed 10 μ T even at a higher supply voltage of 2 V. Current spinning was done with a relay matrix at a switching frequency of 1 Hz to enable an offset reduction. The sensor also shows stable current-scaled sensitivity over a wide temperature range of -100 °C to 200 °C, with a temperature coefficient of 100 ppm/°C. This value is at least 3x better than the state-of-the-art Si Hall plates. Additionally, the sensor's voltage-related sensitivity (~ 57 mV/V/T) is similar to that of the state-of-the-art Si Hall plates. Because of the low offset values enabled by current spinning, the AlGaIn/GaN 2DEG Hall plates are viable candidates for low-field current and magnetic sensing in high-temperature environments.

Index Terms—Magnetic sensors, current spinning, gallium nitride, Hall effect, magnetometer, offset reduction, 2-D electron gas (2DEG).

I. INTRODUCTION

Magnetic field sensing is widely used for both direct purposes such as navigation using the Earth's field and for indirect purposes such as motor position or current monitoring. In most applications, the ideal magnetic field sensor would exhibit a high sensitivity to maximize the output signal, and low offset to accurately detect small fields. While giant magnetoresistance and tunnel magnetoresistance sensors have the highest sensitivities, they suffer from hysteresis, behave nonlinearly, and have large offsets in dc applications [1]. Hall plates have better linearity than such devices and are easily fabricated in integrated circuit (IC) device technology. Current spinning can further mitigate raw offsets in Hall plates without the need for external calibration [2]–[13]. This strategy takes advantage of device symmetry to subtract small nonidealities and create a Hall voltage with a near-zero offset. Current spinning in devices with bulk-film doping was popularized by Munter in 1989 [3], leveraging the complementary metal-oxide-semiconductor analog technology. Recent work shows that this approach can also be used to reduce offsets in 2-D electron gas (2DEG) structures, such as those based on GaAs [14], [15]. This same technique can also benefit GaN devices, enabling low offset, highly sensitive Hall plates that could be monolithically integrated with power devices for *in situ* current monitoring and eventually GaN IC's [16]–[19], as well as a high-temperature operation.

In this article, we close a literature gap in AlGaIn/GaN magnetic sensing devices by examining the offset with current spinning of 2DEG

Table 1. Comparison of GaN and Current-Spun Si Hall Plates

Material	S_I^a (V/A/T)	S_I TC ^b (ppm/°C)	S_V^c (mV/V/T)	Residual Offset ^d (μ T)
Si [6-8, 24, 25, 27]	107	300-800	33-72	2.5
AlGaIn/GaN 2DEG [16, 20-23]	55-113	102	76	100
This Work	89	100	57	3.4 $\pm$ 2

^a Current-scaled sensitivity

^b Temperature coefficient

^c Voltage-scaled sensitivity

^d Supply voltages range from 0.1-2V across literature

Hall plates for the first time. We implemented a 4-phase current spinning technique to significantly reduce sensor offset from millitesla to the order of micro-tesla. Our measured offset values are comparable to the lowest obtained values for Si Hall plates using similar spinning methods [4]–[6] and are much smaller than those previously published for GaN [16], [20], [21]. Our sensor also exhibits sensitivities similar to that of previous GaN and Si Hall plates [16], [22]–[25]. Finally, we characterized the device in a temperature range of -100 °C to 200 °C. This device is, therefore, competitive with silicon (Si) Hall plates on all considered metrics, as shown in Table 1.

Corresponding author: Debbie G. Senesky (e-mail: dsenesky@stanford.edu).

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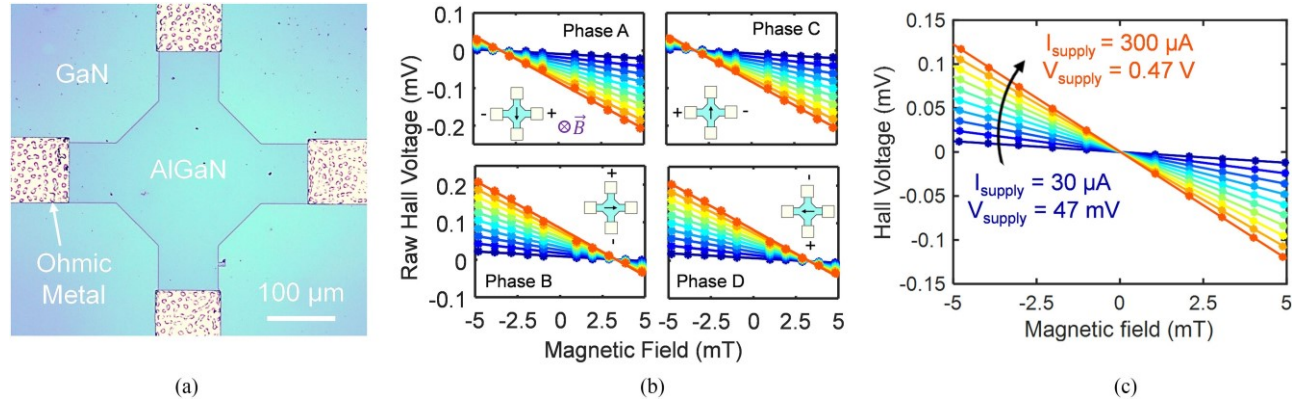


Fig. 1. (a) Optical image of the AlGaIn/GaN 2DEG Hall plate. (b) Raw Hall voltage with respect to a magnetic field under varied supply current (30 to 300 μA) for the four different current spinning phases. Insets show a measurement configuration used for each phase: Arrows indicate supply current, and “+” and “-” indicate Hall voltage measurement terminals. (c) Hall voltage (via current-spinning) with a near-zero offset with respect to the magnetic field under varied supply current (30 to 300 μA).

II. BACKGROUND

The AlGaIn/GaN sensor operates via the Hall-effect [11]; the supply current is applied across the sensor as shown in Fig. 1(a), and in the presence of a magnetic field, a Hall voltage is measured across the other two electrodes. Two metrics of interest for the Hall sensors are sensitivity scaled with supply current and voltage (S_I and S_V). S_I has an inverse relationship to the sheet density of the 2DEG, and S_V is directly proportional to the electron mobility in the 2DEG. S_V and S_I are also related to the geometrical shape of the plate, which is the focus of other recent work [26].

In addition to sensitivity, the offset is a key metric of interest for low-field magnetic sensors. The key sources of measured Hall-effect offset voltages are from resistive asymmetry due to device fabrication and material defects, asymmetric self-heating, and packaging effects [21], [27]. This diverse set of contributions leads to a varied offset voltage in different measurement configurations. In particular, measurements taken with 90° rotated source and sensor electrodes will have offset voltage with opposite polarity, as shown in Fig. 1(b) (Phase A, B, C, and D). An offset reduction with current spinning is possible due to this switching polarity (from static offset sources such as resistance asymmetry), and one can calculate the true Hall voltage from these four unique Hall voltage configurations (V_{A-D}). This can be understood by a simple Wheatstone bridge representation of a Hall plate, described elegantly by Bilotti *et al.* [5]. Static, linear offsets are removed with a 4-phase current spinning using

$$V_H = \frac{V_A + V_B + V_C + V_D}{4} = S * B + V_{0,\text{res.}} \quad (1)$$

When applying this calculation, only the induced voltage from the product of the magnetic field (B) and sensitivity (S), as well as the residual offset voltage ($V_{0,\text{res}}$) from imperfect cancellations between the different measurement phases remain. After (1) is implemented with the raw voltages in Fig. 1(b), the near-zero offsets can be achieved as shown in Fig. 1(c).

III. METHODOLOGY

A. Fabrication

The devices were fabricated with a metal-organic chemical vapor deposited AlGaIn/GaN on <111> Si substrate purchased from DOWA, Tokyo, Japan, using the same process of that of Satterth-

waite *et al.* [28]. The wafer has a manufacturer-specified mobility of 1400 $\text{cm}^2/\text{V}\cdot\text{s}$, and sheet density $>9 \times 10^{12} \text{ cm}^{-2}$. We obtained a sheet resistance of 430 Δ/Q and contact resistance of $\approx 10^{-5} \Delta\cdot\text{cm}^2$ as indicated from transfer length method [29] measurements using dedicated structures fabricated on the same wafer. The device was then wire-bonded with bond pads far from the active sensor to a printed circuit board for testing. An image of the Hall plate is shown in Fig. 1(a). The device is a modified 200- μm -diameter octagon with 70- μm -long legs extending from four sides for an electrical contact. These legs are meant to eliminate the effect of a contact alignment on the active device area [21]. The device can also be thought of as a Greek cross with chamfers to reduce electric field spikes at sharp corners. The longitudinal resistance was $1560 \pm 3 \Delta$, which is only 0.2% asymmetrical.

B. Test Setup

Our test apparatus implements current spinning using the same procedure described previously [21]. The device was tested in a constant-current operation (30 μA to 1.5 mA) using a Keithley 2400 current sourcemeter connected across the plate. An Agilent 34401A voltmeter was used to measure the generated Hall voltage across the other contacts. A switching matrix (Agilent U2715A) was used to alternate the connections across the contacts to create four unique phases [see Fig. 1(b)]. The offset of the voltmeter was cancelled out by reversing its polarity once per voltage measurement and subtracting both values and dividing by two, and thus, eight total configurations (switched at

1 Hz) are used as previously described [14]. These measured voltages are, then, averaged to calculate the low offset signal. Residual offsets were measured in a near-zero magnetic field chamber composed of three concentric canisters made of MuMetal shielding. To determine the background voltage from measurement equipment (thermal EMF and multimeter offset), the measurements were repeated with a Wheatstone bridge of 1-k Δ resistors, which should ideally have zero offset, and showed a maximum average current spun signal of only 20 nV [shaded region in Fig. 2(a)]. The magnetic field was applied via a home-made Helmholtz coil apparatus from 5 to 5 mT, calibrated with a high-sensitivity gaussmeter probe (GM2, AlphaLab, Inc., Salt Lake City, UT, USA). We also examined the influence of temperature on sensitivity from 100 °C to 200 °C in a similar unshielded test apparatus. All measurements were done with a supplied constant current, but we display our results with the averaged measured supply voltage for a simpler comparison between device technologies.

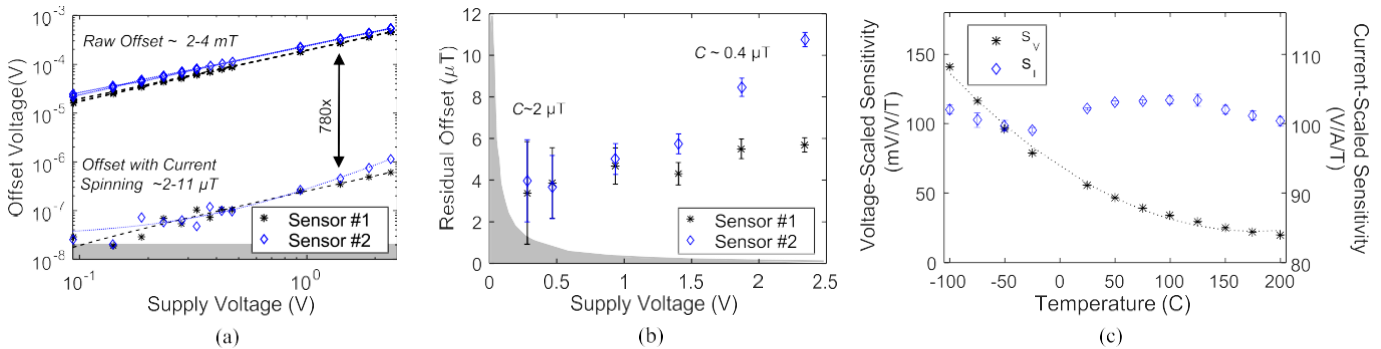


Fig. 2. (a) Magnitude of an average offset voltage (raw and residual) with respect to the measured supply voltage under a constant-current scheme. Residual offset voltage is fit with second-order trendlines. Shaded region refers to the measured electrical measurement limit. (b) Magnetic residual offset with respect to the measured supply voltage under a constant-current scheme, with 1- σ confidence (C) scale bars. Shaded region corresponds to the electrical measurement limit. (c) Hall plate sensitivity scaled with voltage (S_V) and current (S_I) averaged over supply voltages from 0.3 to 1 V across various temperatures. S_V has a second-order trendline fit, and S_I remains fairly constant.

IV. RESULTS AND DISCUSSION

A. Residual Offset

Fig. 2(a) compares the magnitude of the raw offset voltage of the four unique phases measured to the residual offset voltage after applying current spinning. The average residual offset voltage varied from 36 nV to 1.12 μ V as the supply voltage increased from 92 mV to 2.34 V (60 μ A to 1.5 mA supply current). Across this bias range, the overall attenuation of raw to residual offset voltage is 780: a significant improvement in a minimum resolvable signal.

Typically, offset voltages between different sensor technologies, are translated to magnetic offset values for a comparison. A magnetic offset is then calculated by dividing the average offset voltage with the sensitivity. In Fig. 2(b), the residual magnetic field offset for two different sensors is shown. The magnetic field offsets are as low as 3.4 μ T and increase to only 11 μ T at a measured supply voltage of 2.34 V. Differences in offset between sensors are likely due to varied wire bond placement from the assembly process and resulting magnetic field induced from the wire.

Due to the limitations in the measurement equipment, the standard deviation of the residual offset voltage was 0.63 μ V, regardless of supply conditions, which implies larger errors at lower supply voltages. We repeated offset voltage measurements 300 times at each supply condition and averaged the final offset value to reduce the stochastic noise. We then calculate the confidence of the offset measurement by taking the standard deviation of the magnetic offset divided by the square root of repeated measurements. When the measured supply voltage was 0.28 V, the confidence value was 2 μ T and then decreased at higher supply conditions to 0.4 μ T. One could operate the device at these higher voltages (1 to 2 V) to have lower noise in a practical measurement application.

Magnetic field offset values in current-spun Si Hall plates have been reported as low as 2.5 μ T with similar improvements in a ratio with a raw offset [3], [5], [6], [10], [12]. The lowest offsets resolved here were comparable (3.4 $\pm$ 2 μ T). Thus, GaN Hall plates benefit from current spinning methods in a similar fashion to that of Si Hall plates.

B. Sensitivity

At 25 $^{\circ}$ C, the voltage and current-scaled sensitivities measured for the AlGaIn/GaN 2DEG Hall-effect plate are 57 mV/V/T and 89 V/A/T, respectively. These values are, respectively, slightly lower and higher than previously reported GaN 2DEG Hall plate sensitivity values [16],

[21]–[23]. This discrepancy is due to the device geometry. This design has additional resistance from the contact legs. This lowers S_V by reducing the voltage drop across the active region and increases S_I with the higher resistance. The sensitivities have since been increased in AlGaIn/GaN 2DEG Hall Plates through an optimized design of the Hall-effect plate geometry [26].

The voltage and current-scaled sensitivities measured from 100 $^{\circ}$ C to 200 $^{\circ}$ C are shown in Fig. 2(c). S_V increases by 180% from 25 $^{\circ}$ C to $\sim$ 100 $^{\circ}$ C and decreases by 60% from 25 $^{\circ}$ C to 200 $^{\circ}$ C, because it is directly related to electron mobility. The sheet resistance, inversely proportional to mobility, increases by 130% from 430 Δ /Q at 25 $^{\circ}$ C to 1 k Δ /Q at 150 $^{\circ}$ C. S_I , however, remains fairly stable with measurement drift within 1.8% of its room temperature value. The measured temperature coefficient (TC) of the average S_I of this 2DEG Hall-effect plate is approximately 100 ppm/ $^{\circ}$ C, consistent with previous reports [22], [23]. This is an advantage of AlGaIn/GaN in extreme environments: The 2DEG sheet density formed by the crystals' spontaneous and piezoelectric polarizations is invariant in this temperature range [30], [31]. However, the sheet density in Si-based devices is from external ionizing dopants, so its S_I TC is larger (336 to 800 ppm/ $^{\circ}$ C) [25], [32]. There is at least 3x stability improvement for the AlGaIn/GaN Hall-effect plate due to the lack of thermally induced intrinsic carriers. Thus, when temperature stability is required in an extreme environment, the 2DEG Hall plates should be implemented with a constant-current interface circuit.

V. CONCLUSION

In this article, we presented a 2DEG GaN Hall plate with record low offset of 3.4 μ T ($\sim$ 7% of the Earth's magnetic field), which is on par with the best reported Si Hall plate offsets. We accomplished this by using a 4-phase current spinning technique to reduce the raw offset in AlGaIn/GaN 2DEG Hall plates by three orders of magnitude. We also confirmed a robust sensor operation at extreme temperatures from 100 $^{\circ}$ C to 200 $^{\circ}$ C. Since current spinning enables quality low-offset GaN Hall plates on par to those of Si, it is ready for the next steps towards system level integration. Future research should create the proper on-chip AlGaIn/GaN amplification and current spinning circuits to enable a low offset, monolithically integrated solution for magnetic field sensing in harsh environments. Once achieved, GaN magnetic-field sensors may be a competitive sensor solution for power systems, autonomous position sensing, and novel space exploration applications.

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