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Contactless Mobility, Carrier Density, and Sheet Resistance Measurements on Si, GaN, and AlGaN/GaN High Electron Mobility Transistor (HEMT) Wafers

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14. ABSTRACT

This technical report examines sheet-resistance and Hall-effect results when using a Lehighton Electronics Inc. Model 1605B contactless mobility system. This report gives results on multiple samples including 4-inch, n-type Si; multiple AlGaN/GaN High Electron Mobility Transistor (HEMT) structures grown on SiC substrates; and an unintentionally doped (UID) GaN on sapphire template.

15. SUBJECT TERMS

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1. Introduction

Hall-effect measurements are ubiquitous to the electrical characterization of semiconductor materials. The Hall effect occurs when an electrical conductor is placed in a magnetic field perpendicular to the sample surface, leading to charge separation due to the Lorentz force acting on a charge carrier, thus creating an induced voltage referred to as the Hall voltage. Combined with zero-field resistivity data, the single-field, Hall-effect measurements are used to determine electrical properties of the semiconductor material such as Hall mobility, Hall coefficient, and carrier concentration (electron or hole concentration). The most common method is the Van der Pauw method.[1] Prior to measurement, ohmic contacts are made to the material. The traditional approach to Hall-effect measurements has the disadvantage of the need of fabricating a device structure to make the ohmic contact—thus the measurement is destructive in nature. In a manufacturing environment, such a measurement reduces the overall yield because one or more wafers in a batch would have to be consumed to acquire the Hall data.

An alternative approach to the traditional method of taking Hall-effect measurements is the use of microwaves coupled with waveguide structures. Such a method is contactless in nature and does not require the necessity of fabricating a device or making ohmic contacts.[2] The microwave method works on the basis of low-power microwaves coupled to a series of waveguides. The waveguide network is designed to allow propagation of TE_{10} and TE_{11} modes. The TE_{10} mode is related to the zero-field sheet resistance based on the overall impedance of the waveguide system. The TE_{11} mode is caused by the Hall effect when under an applied magnetic field. This effect rotates the TE_{10} mode 90° where the forward, reflected, and Hall power are detected.[3] Proprietary software then converts the measured powers into reflection coefficients that are used to calculate the conductivity tensors σ_{xx} and σ_{xy}, where σ_{xx} and σ_{xy} are functions of the magnetic field (H). The Hall coefficient (R_H) for a given H is then calculated using Eq. 1:

$$R_H = -\frac{1}{H}\left[\frac{\sigma_{xy}(H)}{\sigma_{xx}^2(H)+\sigma_{xy}^2(H)}\right] \quad . \qquad (1)$$

Subsequently, one determines the resistivity (ρ), Hall mobility (μ) and sheet-carrier density (N_s) shown in Eqs. 2 and 3:

$$\rho(H) = \frac{\sigma_{xx}(H)}{\sigma_{xx}^2(H)+\sigma_{xy}^2(H)} \qquad (2)$$

and

$$\mu = -\frac{R_H}{\rho(H)} \qquad , \tag{3}$$

$$N_s = -\frac{1}{eR_H}$$

where e is the electron charge.

In this technical report, we report Hall data using a Lehighton Electronics Inc. (Lehighton, PA) Model 1605B contactless mobility system located in Room Z2C-33, Building 207 of the US Army Research Laboratory's (ARL's) Adelphi Laboratory Center (Adelphi, MD). We report Hall and sheet-resistance measurements on a series of 5 AlGaN/GaN high electron mobility transistors (HEMTs) grown on SiC substrates, an unintentionally doped (UID) GaN epi layer on a sapphire substrate, and a partial Si wafer. We also report results on a 4-inch Si wafer that will serve as a standard sample for the tool.

2. Experiment

Measurements of the sheet resistance, Hall mobility, carrier concentration, and Hall coefficient on multiple samples were made at room temperature under ambient light with a Lehighton Electronics Inc. (LEI) Model 1605B contactless mobility system (shown in Fig. 1) on multiple samples. The 1605B uses a low-power microwave source (10 GHz) coupled to a wave-guide network in order to direct the power of the surface of the sample being measured. Prior to any set of measurements, a copper short sample was measured in the absence of a magnetic field. The Cu short measurement is used to provide a normalization factor in subsequent measurements. The sample is then placed into the sample holder and held in place by pieces of Kapton tape to ensure the sample does not move between runs (i.e., moving the sample in and out of the magnet for Hall and sheet-resistance measurements, respectively). With no applied magnetic field, the sample is "tuned". The first adjustment is made manually to minimize the reflected power coming from the sample. It is referred to as the "back short" adjustment and is used to position the short to the correct distance behind the sample. The second adjustment is the "Hall Power" adjustment. This turning is automated by the system and is used to balance the bridge circuit to minimize the unwanted TE_{10} mode at zero field. Pickup by the Hall probe is used to detect the rotated TE_{11} Hall power. The measurement itself consists of 2 parts. The first is the zero-field sheet resistance, which is computed from the ratio of the forward to reflected power. The second is under a 2.8-kG magnetic field where the forward, reflected, and Hall power is translated into the conductivity tensor components and subsequently the parameters of interest. (Further explanation is provided in the LEI Model 1605B manual.[3])

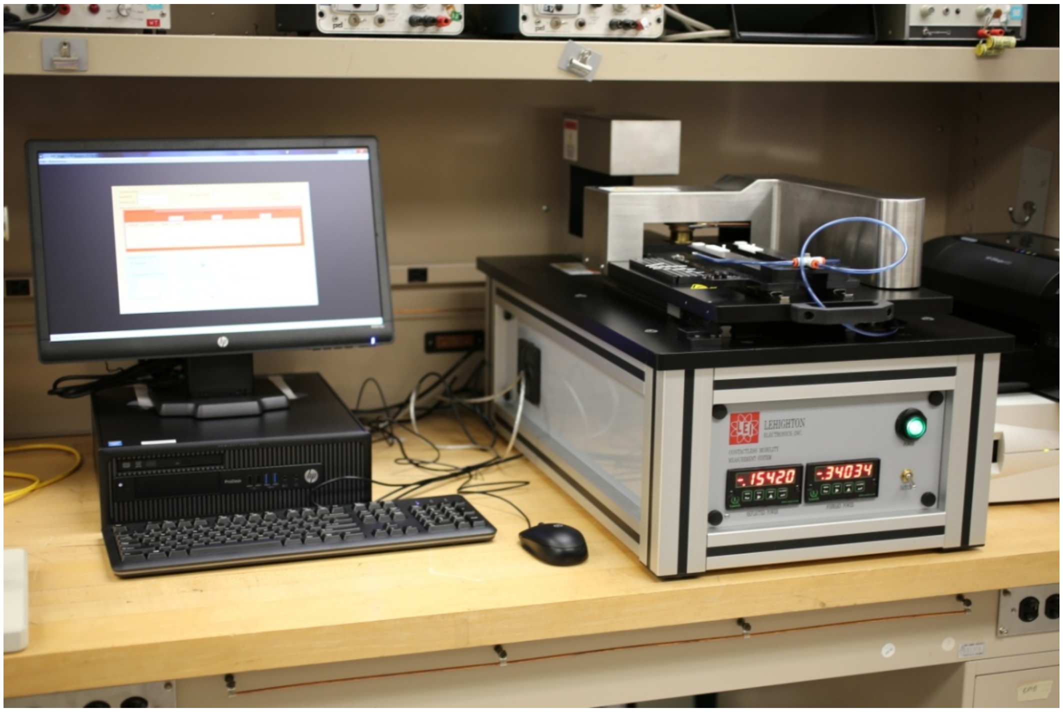

Fig. 1 LEI Model 1605B contactless mobility system at the Adelphi Laboratory Center (Building 207, Room Z2C-33)

Initially, Lehighton measured a 4-inch, n-type Si wafer as a standard to qualify the tool. A single measurement in the center of the wafer was made for the sheet resistance. Subsequently, 10 consecutive measurements were made for the Hall mobility and carrier concentration.

We also tested five 3-inch AlGaN/GaN HEMT samples on insulating SiC substrates as well as a ¼ of a 2-inch wafer of UID GaN sample and a ¼ of a 4-inch wafer of n-type Si. Table 1 outlines the different layer structures of each sample tested.

Table Details of samples

Sample ID	Structure Detail	Total Epi Thickness (µm)
1	SiC substrate/AlN nucleation/GaN buffer/19.5 nm 24.4% AlGaN barrier/3 nm GaN cap	1.84
2	SiC substrate/AlN nucleation/GaN buffer/19.5 nm 24.4% AlGaN barrier/3 nm GaN cap	1.83
3	SiC substrate/AlN nucleation/GaN buffer/19.5 nm 24.4% AlGaN barrier/3 nm GaN cap	1.81
4	SiC substrate/AlN nucleation/GaN buffer/17.4 nm 25.3% AlGaN barrier/3 nm GaN cap	1.94
5	SiC substrate/AlN nucleation/GaN buffer/17.4 nm 25.3% AlGaN barrier/3 nm GaN cap	1.94
6	N-type Bulk Si substrate	620
7	Sapphire substrate/8 um UID GaN	8.0

For 3-inch wafers, we took a single measurement of both sheet resistance and Hall effect at 5 different locations shown in Fig. 2. We repeated this process 5 times for each of the five 3-inch AlGaN/GaN HEMT structures grown on SiC substrates. Thus a total of 25 measurements were taken for each sample, 5 at each location identified in Fig. 2. Because of the smaller size of both the UID gallium nitride on sapphire sample and the partial Si sample, we took measurements the center of the sample. We captured 10 measurements of both the zero-field sheet resistance and the Hall mobility to investigate the repeatability of the measurement. We repeated this process 5 times, for a total of 50 measurements on each sample. We then used JMP 11 software to analyze all of the data in this report.

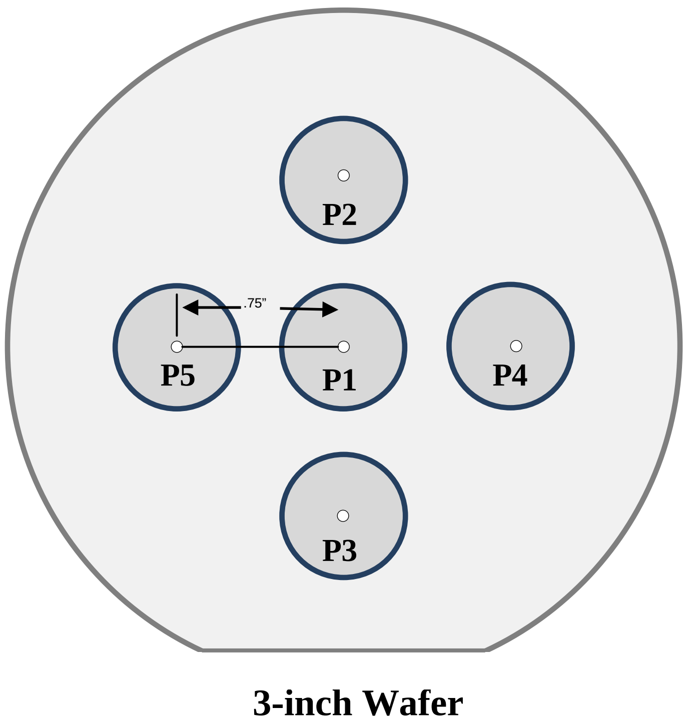

Fig. 2 Test locations on a 3-inch HEMT sample

3. Results

3.1 Standard n-type Si Sample

The wafer manufacturer reports a sheet resistance of 226.170 ohms/sq. for sample LEI Si-17, which we will refer to as the standard sample. Prior to shipment of the tool, Lehighton measured a sheet resistance of 220.93 ohms/sq. using the ARL contactless mobility tool. Thus, the measured value of sheet resistance is within 2% of the manufacturer's measured value.

Figure 3 reports Hall results for a total of 10 runs to investigate the repeatability of the tool. The mean values of mobility and sheet concentration were 1591.5 ± 3.38 cm^2/V-s and 1.77 × 10^{13} ± 5.27 × 10^{10} cm^{-2} respectively, where the uncertainty is quoted as one standard deviation.

	Mobility	Sheet Concentration
N	10	10
Mean	1591.506	1.775e+13
Std Dev	3.38518078	5.2705e+10
Max	1595.67	1.78e+13
Min	1585.33	1.77e+13
Range	10.34	1e+11
Variance	11.4594489	2.7778e+21
Std Err	1.07048815	1.6667e+10
Median	1592.17	1.775e+13

Fig. 3 Summary of results for sample LEI Si-17, which also is referred to as the standard sample. (Note: Units of mobility are *cm^2/V-s* and units of sheet concentration are *cm^{-2}*.)

In the future, sample LEI Si-17 will serve as the standard sample for the contactless mobility tool. The sample should be measured prior to use of the system as outlined in the experimental section; that is, one measurement in the center of the 4-inch wafer of both the sheet resistance as well as a contactless Hall measurement. Users will record the data in an Excel spreadsheet titled "standard_sample.xlsx". An electronic copy of the Excel file is located on the desktop of the computer connected to the LEI contactless mobility system. Within that Excel file are process control charts for sheet resistance, mobility, and sheet concentration that will be continuously updated by the individual users after they input their data. Users should be aware of process control charts and data that potentially would indicate a problem with the system. (For further information on process-control charts, consult a book on statistical quality control such as the one named in Reference 4.)

3.2 AlGaN/GaN HEMTs on SiC Sample Series

Hall results are presented for the series of 5 AlGaN/GaN HEMTs on SiC samples in Figs. 4–8. Five measurements of both sheet resistance and Hall effect were taken at each position on the wafer, as outlined in Fig. 2. Each figure provides a bar chart for both the mean and one standard deviation of each measured quantity (sheet resistance, Hall mobility, and electron concentration) for each of the 5 locations. Thus the standard deviation represents the variation or repeatability of the 5 measurements at a single location, while the chart itself is representative of the variation of each of the 3 quantities across the wafer positions P1–P5.

Samples 2 and 4 had the largest variation at any one location as well as across the wafer. Samples 1, 3, and 5 had lower variation run to run in a given location as well as lower variation across the wafer. With a few exceptions, the variation across the wafer and run to run was within 5% or less for samples 1, 3, and 5. It is not clear why samples 2 and 4 had larger variation. Identifying the reason is beyond the scope of this report, but may be related to material and/or surface-quality issues.

Figures 4–8 are bar charts showing measurements of mean sheet resistance, mean Hall mobility, and mean sheet concentration for samples 1–5 from the 5 positions on the 3-inch wafer. The error bars represent 1 standard deviation.

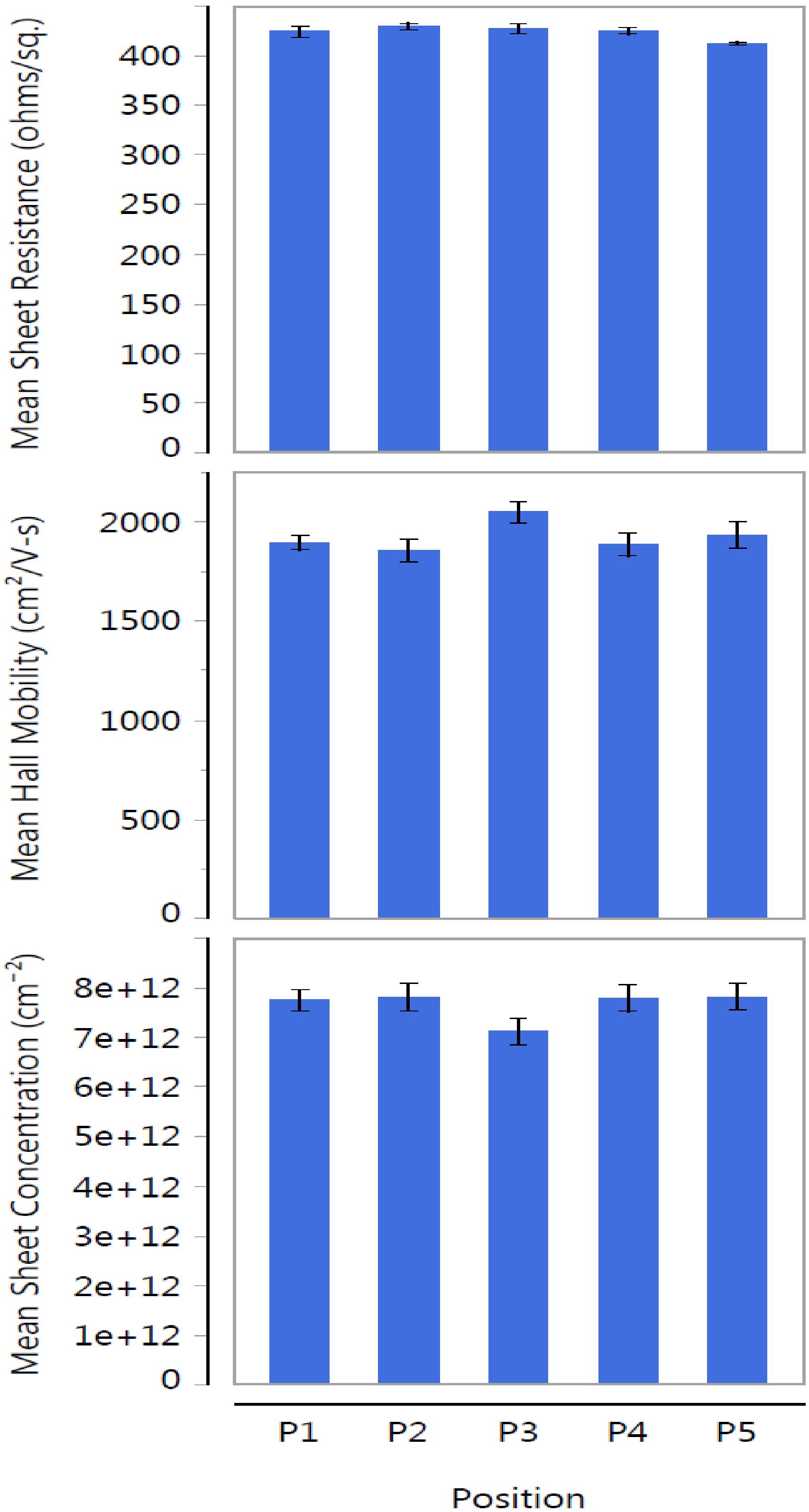

Fig. 4 Sample 1 data for each of the 5 positions on the 3-inch wafer

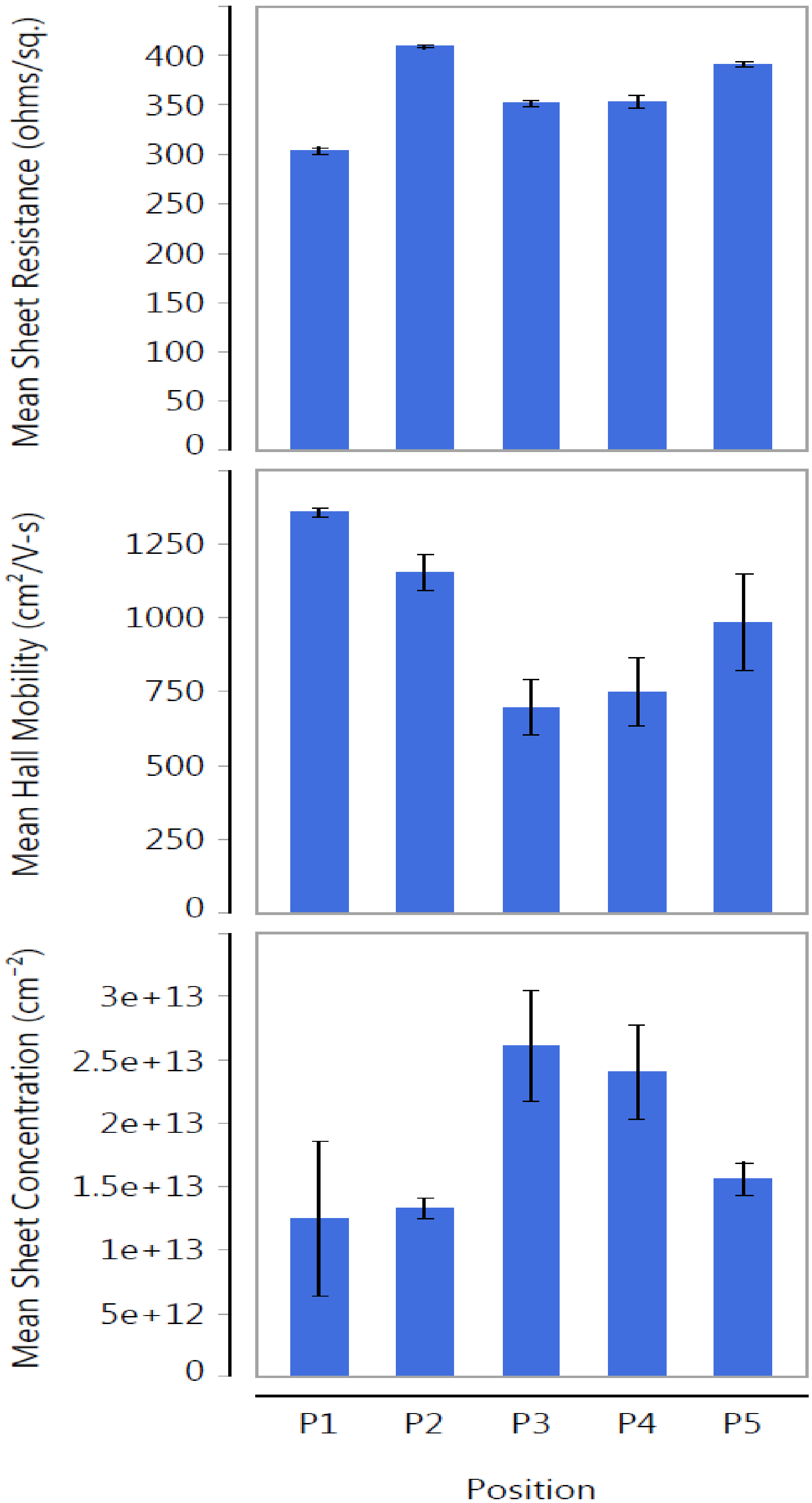

Fig. 5 Sample 2 data for each of the 5 positions on the 3-inch wafer

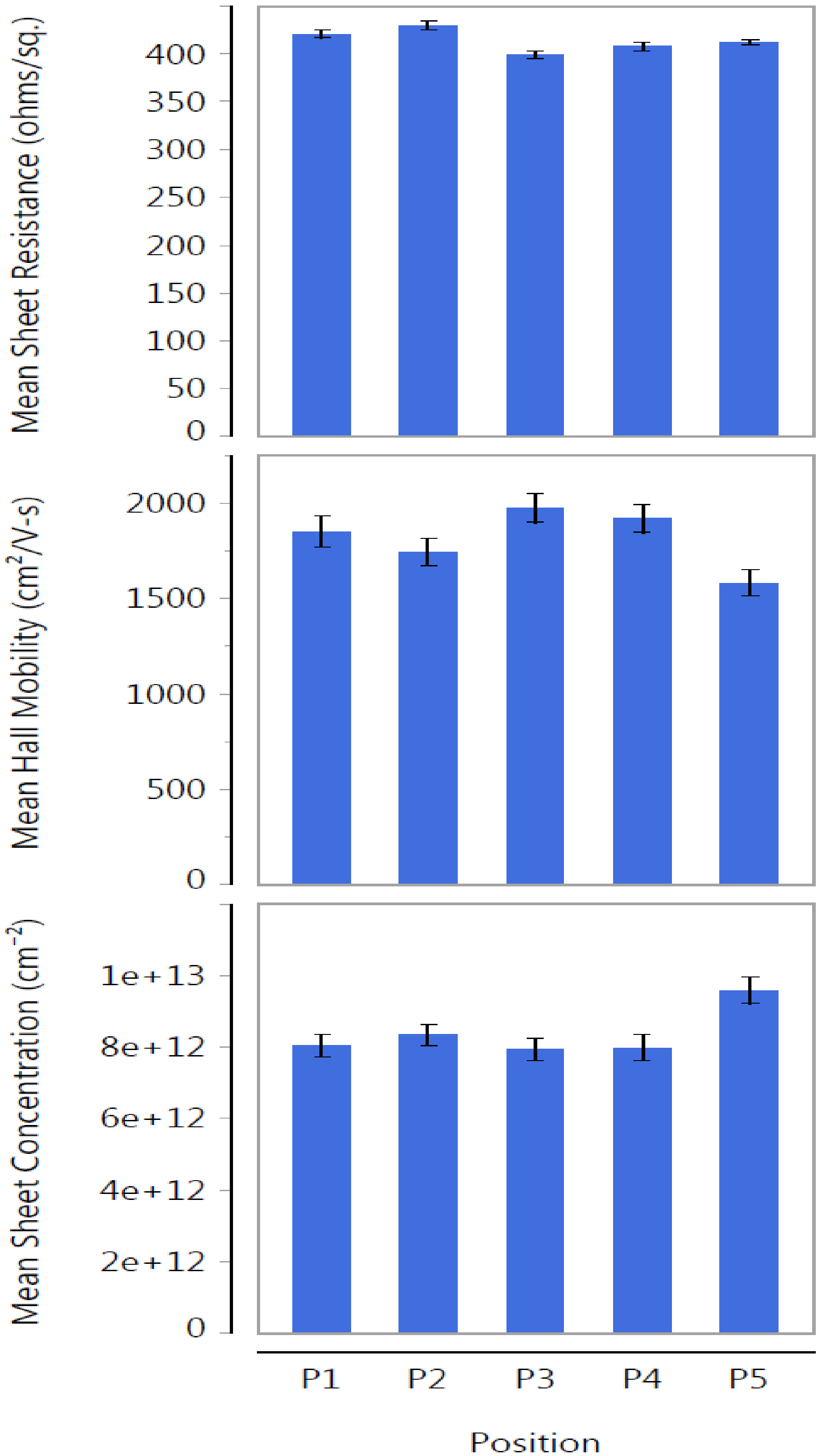

Fig. 6 Sample 3 data for each of the 5 positions on the 3-inch wafer

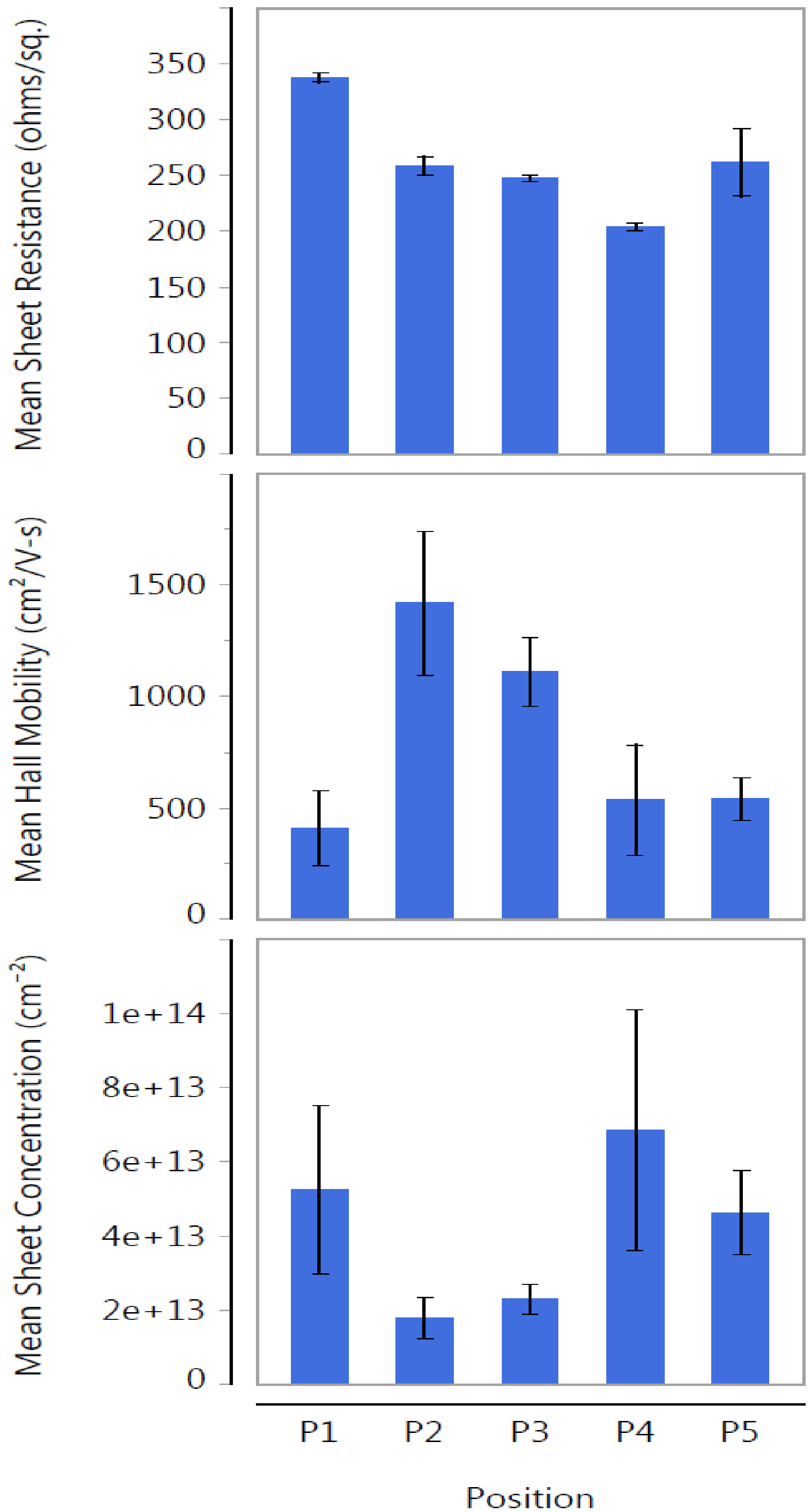

Fig. 7 Sample 4 data for each of the 5 positions on the 3-inch wafer

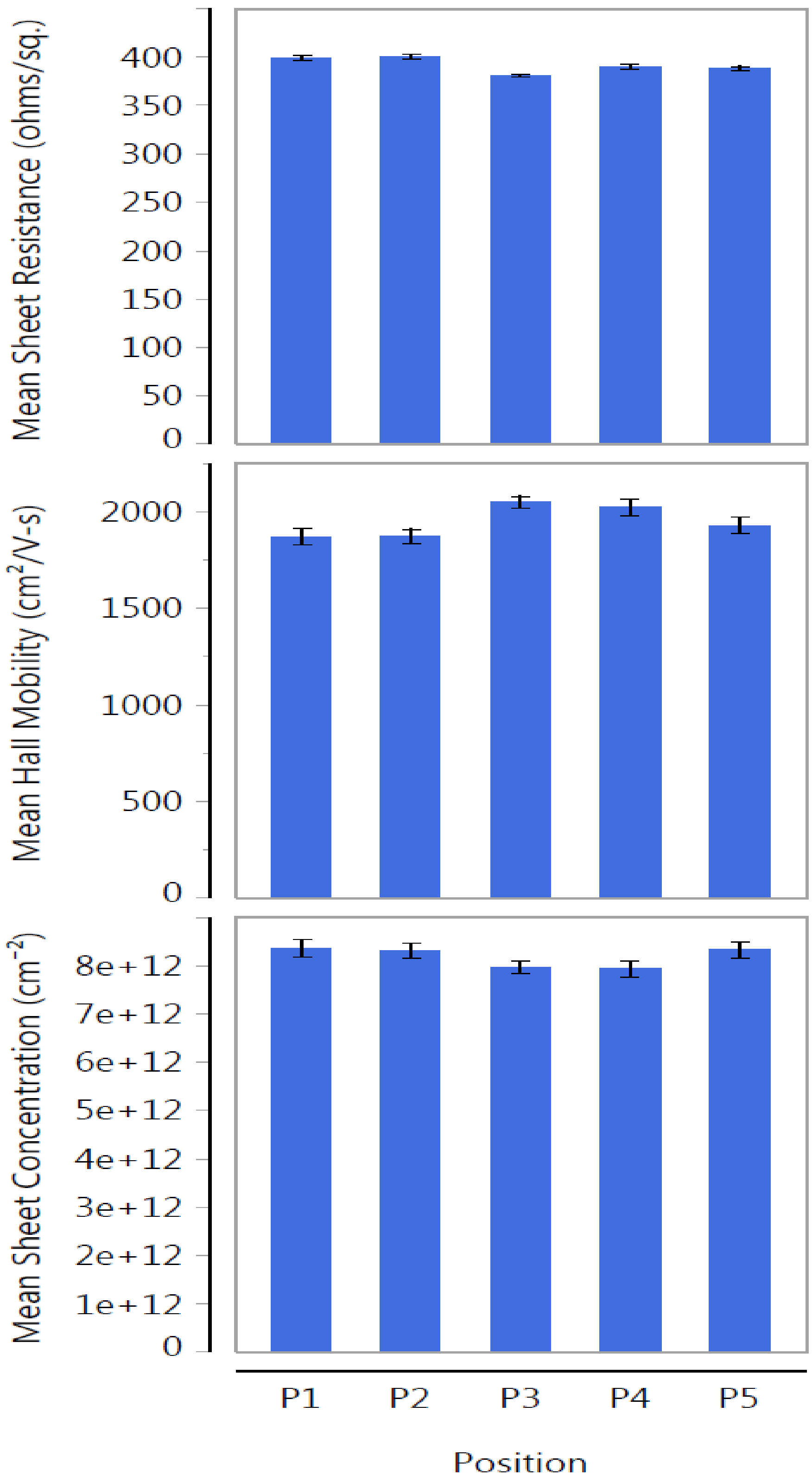

Fig. 8 Sample 5 data for each of the 5 positions on the 3-inch wafer

3.3 Si and UID GaN on Sapphire Pieces

The results for the ¼ of a 4-inch wafer Si piece are given in Fig. 9. Because of the irregular shape of the Si piece, the sample was tested in the center 50 times to determine system repeatability. Figure 5 shows a statistical analysis for the sheet resistance, Hall mobility, and electron concentration. The mean of the sheet resistance, mobility, and sheet concentration was 175.72 ± 0.082 Ω/sq, 1481.1 ± 5.44 cm^2/V-s, and $2.39 \times 10^{13} \pm 8.45 \times 10^{10}$ cm^{-2} respectively, where the uncertainty in the measurement is quoted as 1 standard deviation. These numbers correspond to a variation of 0.05%, 0.36%, and 0.35% for the sheet resistance, mobility, and sheet concentration over the 50 measurements.

	Sheet resistance	Mobility	Sheet concentration
N	50	50	50
Mean	175.7288	1481.1662	2.39828e+13
Std Dev	0.0822797617	5.4476375295	84540534898
Min	175.56	1469.98	2.383e+13
Max	176.1	1491.23	2.416e+13
Range	0.54	21.25	330000000000
Variance	0.0067699592	29.676754653	7.147102e+21
Std Err	0.0116361155	0.7704122877	11955837102
Median	175.72	1482.25	2.396e+13

Fig. 9 Summary of results for the ¼ of a 4-inch wafer Si; units of sheet resistance, mobility, and sheet concentration are *ohms/sq.*, *cm^2/V-s*, and *cm^{-2}*, respectively.

The same data set was taken on a UID GaN piece. The results are presented in Fig. 10. The mean of the sheet resistance, mobility, and sheet concentration was 64.69 ± .015 Ω/sq, 371.99 ± 12.67 cm^2/V-s, and $3.285 \times 10^{17} \pm 1.17 \times 10^{16}$ cm^{-3}, respectively, where the uncertainty in the measurement is quoted as one standard deviation. These numbers correspond to a variation of 0.23%, 3.6%, and 3.6% for the sheet resistance, mobility and carrier concentration respectively over the 50 measurements.

It should be noted that while the UID GaN piece was used to test system repeatability, the actual number for mobility does fall outside the system specifications for the LEI 1605B contactless mobility tool. Another group measured a mobility of 120 cm^2/V-s and sheet resistance of 62 ohms/sq. with a 9 T magnet system. We conclude that the system could measure the UID GaN sample, although with a large offset.

	Sheet resistance	Mobility	Carrier Concentration
N	50	50	50
Mean	64.6942	371.9994	3.28508e+17
Std Dev	0.1512949545	12.674739849	1.172583e+16
Min	64.34	346.71	3.087e+17
Max	64.97	396.12	3.532e+17
Range	0.63	49.41	4.45e+16
Variance	0.0228901633	160.64903024	1.37495e+32
Std Err	0.0213963377	1.7924788994	1.658282e+15
Median	64.71	373.835	3.2625e+17

Fig. 10 Summary of results for the ¼ of a 2-inch wafer UID GaN sample; units of sheet resistance, mobility, and carrier concentration are *ohms/sq.*, *cm^2/V-s*, and *cm^{-3}*, respectively.

4. Conclusions

In this technical report we presented Hall and sheet-resistance results using a contactless method on a standard Si sample, a series of AlGaN/GaN HEMTs on SiC substrates, and piece samples of both Si and UID GaN. We measured all samples using a new (as of October 2014) Lehighton Electronics Model 1605B contactless mobility system at the Army Research Laboratory. We measured the sheet resistance of the Si sample to within 2% of the manufacturer's quoted value. Si and UID GaN samples showed repeatability (as determined by the standard deviation of 10 or 50 consecutive measurements depending on the sample) of 3.6% or less for sheet resistance, sheet concentration, and the Hall mobility. However, under most circumstances the standard deviation was less than 1%. The contactless mobility method has the advantage of being a nondestructive, efficient, and quick way to take Hall data. We anticipate the contactless mobility tool to span multiple research groups and material systems at ARL, as the tool could be used as a filter/gatekeeper after material growth and prior to any device processing.

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