Uniformity Studies of AlGaN/GaN HEMTs on 200-mm Diameter Si(111) Substrate

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Key Words: GaN-on-Si, 200-mm Si(111), Uniformity, 2DEG mobility, Sheet Resistance, AlGaN/GaN, HEMTs

***Abstract*— AlGaN/GaN high-electron-mobility transistors (HEMTs) with 0.3-µm-gate length were fabricated and the uniformity of its DC properties was studied for the first time on a 200-mm diameter Si(111) substrate. The radial distribution of Hall parameters are >90% over full 200-mm diameter Si(111) substrates. The fabricated transistor DC parameters were exhibited with >90% uniformity over a quarter of a 200-mm Si(111) substrate. More than 90% uniformity in the 2DEG depth and measured threshold voltage of GaN HEMTs are comparable to the grown barrier thickness which is confirmed to be 21 nm by STEM.**

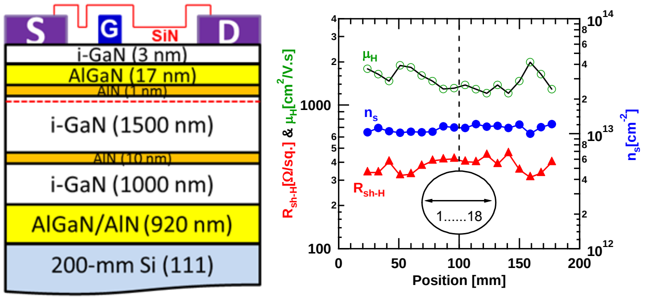
INTRODUCTION

GaN is a promising wide-band-gap semiconductor for next-generation high-frequency and high-power switching devices because of its high saturation velocity at high electric field, high breakdown electric field, and high electron mobility. So far, different groups have demonstrated excellent high-frequency, high microwave power and power switching devices using GaN HEMTs that break the Si limits [1-6]. Growing GaN-on-Si offers the advantages of low-cost and large diameter wafers which make manufacturing costs of GaN-on-Si potentially competitive with existing Si and SiC technologies. To reduce the cost of power-switching and RF electronics, universities/institutes/companies have joined together and are taking significant efforts for the development of GaN HEMTs on 200-mm diameter Si substrates [7-10]. Hence, it is essential to study the uniformity of the fabricated devices on AlGaN/GaN heterostructure grown on 200-mm Si(111) substrates. Recently, we have reported the electrical, structural, optical and device DC & microwave properties of AlGaN/GaN HEMTs on 200-mm Si(111) [9,10]. S. Arulkumaran et. al. had performed similar study on the device uniformity of a full 100-mm wafer by choosing a quarter of 100-mm diameter AlGaN/GaN HEMT wafer [11]. However, to the best of our knowledge, no reports are available on the device uniformity of AlGaN/GaN HEMTs on 200-mm Si substrates.

In this paper, for the first time, we report the uniformity of the electrical performances of AlGaN/GaN HEMTs on a 200-mm diameter Si(111) substrate. In addition, radial distribution of Hall parameters over a full 200-mm wafer were also measured and compared with the fabricated device characteristics.

DEVICE FABRICATION AND MEASUREMENT

AlGaN/GaN HEMT structures were grown by MOCVD on a 200-mm Si(111) substrate. The silicon substrate thickness and resistivity (boron doped) are 1.5 mm and 8×10^{-3} Ω-cm, respectively. Figure 1 (a) shows the schematic cross-section of the grown GaN HEMT structure on the 200-mm Si(111) substrate. The growth details are reported elsewhere [10]. The bowing value of the grown AlGaN/GaN HEMT structure on the 200-mm Si substrate is <20 µm. All the epi-layer thicknesses were confirmed by cross-sectional HAADF-STEM. The structural uniformity of AlGaN/GaN heterostructures were measured across the 200-mm diameter Si substrate and reported elsewhere [10]. To study the radial distribution of electrical properties, about 18 (10 mm×10 mm size) Hall



(a) (b)

Fig. 1. (a) Schematic cross-sectional diagram of AlGaN/GaN HEMTs on 200-mm Si. (b) Radial distribution of Hall parameters (18 Hall samples) in AlGaN/GaN heterostructure on 200-mm diameter Si(111) substrate.

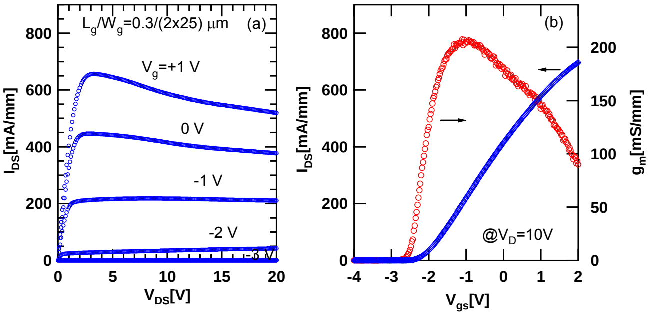


Fig. 2. (a) I_{DS}-V_{DS} and (b) transfer characteristics of AlGaN/GaN HEMTs on a quarter of 200-mm diameter Si(111) substrate.

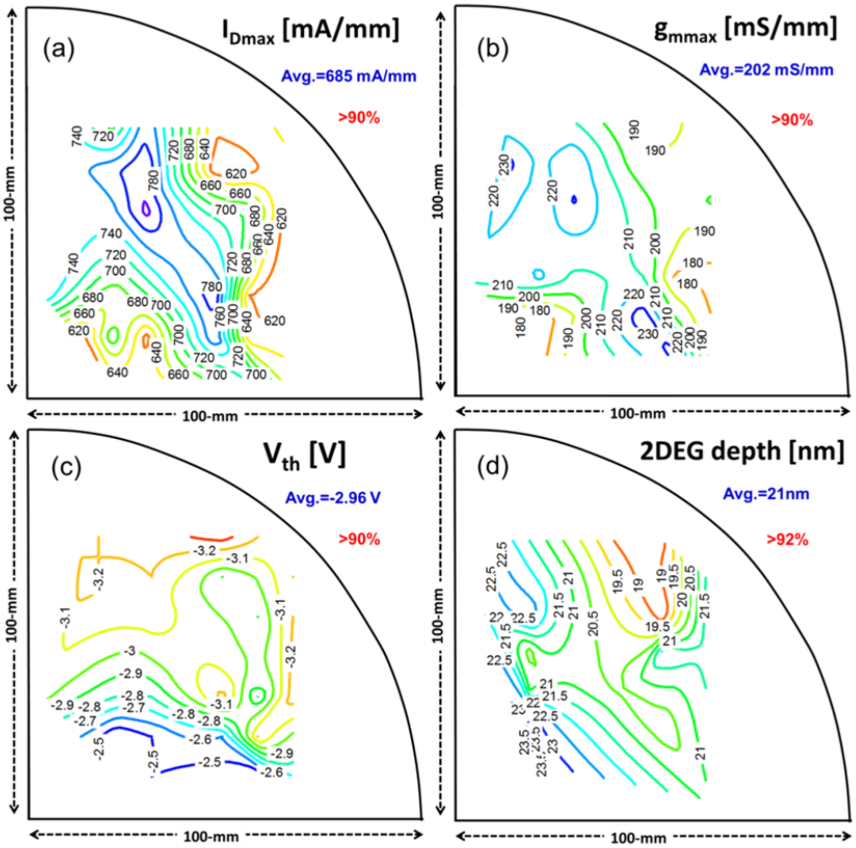


Fig. 3. Contour mapping of (a) I_{Dmax}, (b) g_{mmax}, (c) V_{th} and (d) 2DEG depth for AlGaN/GaN HEMTs on a quarter of 200-mm diameter Si(111).

samples were prepared by dicing a full 200-mm diameter wafer. Figure 1(b) shows the radial distribution of the measured Hall parameters on a full 200-mm wafer. The radial distribution of Hall parameter is symmetrical when we draw a line in the centre of the wafer. Due to the symmetrical nature of Hall parameters, we took quarters of a 200-mm wafer for device fabrication and to evaluate its uniformities. Such an approach -is also similar to the previous publication on a 100-mm diameter substrate [11]. The uniformity of the measured parameters reported in this work was calculated using the formula, $Uniformity[\%]=\left(1-\frac{\sigma}{\bar{x}}\right)\times 100$, where, σ is the standard deviation of the measured data and $\bar{x}$ is the average of the measured data.

The mesa isolation for HEMT device fabrication was accomplished by dry etching down to GaN buffer layer using Cl_2/BCl_3 plasma-based inductive coupled plasma (ICP) system. The isolation current was measured at 60 different locations on a quarter of 200-mm wafer. To have low R_c values from the GaN HEMTs with AlN spacer layer, the HEMT wafer went through the optimized ohmic-recess process [12]. The ohmic contacts were realized with an average contact resistance of R_c = 0.31 ±0.05Ω-mm using a four-layer metallization scheme (Ti/Al/Ni/Au) followed by rapid thermal annealing at 825 °C for 30 s. Following the ohmic contacts formation, the bilayer Ni/Au (100/400 nm) Schottky gate was formed with 0.3 µm gate-length. The device processing details can be found elsewhere [13]. The dimensions of the devices used in this study are as follows: source-gate distance, L_{sg} =0.8 µm; gate width, W_g = (2×25) µm; gate length, L_g = 0.3 µm; gate-drain distance, L_{gd} = 1.25 µm and gate-gate distance, L_{gg}=12 µm. On-wafer DC characteristics were performed to characterize the fabricated devices on the un-thinned Si substrate using an Agilent B1500 semiconductor parameter analyzer. To measure the 2DEG density as a function of channel depth, capacitance-voltage (C-V) measurements were carried out at 1 MHz on the Schottky diodes fabricated on the same sample [14].

RESULTS AND DISCUSSION

Figure 2 shows the typical (a) I_{DS}-V_{DS} and (b) transfer characteristics of HEMTs with good pinch-off . Maximum drain current density (I_{Dmax}) of 806 mA/mm and extrinsic transconductance (g_{mmax}) of 230 mS/mm was observed among the 50 identical devices (W_g=2×25 µm) from a quarter of the 200-mm wafer. This is the highest g_{mmax} of GaN HEMTs so far reported on a 200-mm Si substrate. Due to the improved 2DEG mobility (maximum=1990 cm^2/V.s) by a thin AlN spacer layer in the HEMT structure, improved g_{mmax} values were observed when compared to our previous report [9].

Figure 3 shows the contour mapping of (a) I_{Dmax}, (b) g_{mmax} and (c) threshold voltage (V_{th}) of AlGaN/GaN HEMTs. The average I_{Dmax} and g_{mmax} values of 685 mA/mm and 202 mS/mm with uniformities of >90% were observed on a quarter of the 200-mm wafer. The uniformity of the device parameters are

>90% which is consistent with the uniformity of the material properties such as 2DEG Hall mobility (μ_H) (Avg.: 1600 cm^2/V.s), sheet carrier density (n_s) (Avg.: 1.11×10^{13} cm^{-2}) and sheet resistance ($R_{sh\text{-}H}$) (Avg.: 387 Ω/sq). From the measured Hall parameters, we understand that the grown AlGaN/GaN heterostructures have good uniformity across the 200-mm diameter substrate. The non-uniformity of μ_H, n_s and $R_{sh\text{-}H}$ are <10% over a full 200-mm Si substrate (See Figure 1(b)). The average V_{th} value of the devices is –2.96 V with a uniformity of >90% which is consistent with the uniformity of 2DEG depth measured by capacitance-voltage (C-V) measurements.

To measure the 2DEG carrier density ($N_{D(2DEG)}$), C-V measurements were carried out at 1 MHz on 30 Schottky diodes at different locations of a quarter of the 200-mm wafer. Figure 4 shows (a) C-V profiling of AlGaN/GaN HEMTs on a 200-mm Si substrate. The average $N_{D(2DEG)}=3.69\times10^{19}$ cm^{-3} is peaking at a depth of 21.2 ±1.6 nm. The obtained 2DEG depth by C-V profiling is in good agreement with the thicknesses of the GaN cap layer, AlGaN barrier layer and AlN spacer layer which were measured by STEM [see Figure 4(b)]. The uniformity of 2DEG-depth profile is >92%. This means that the non-uniformity of V_{th} and 2DEG depth is <8% for a quarter of a 200-mm wafer. The background carrier concentration at a depth of above 3 μm is as low as 1×10^{13} cm^{-3}. The lateral buffer leakage current at 20 V is in the range of 0.01 μA/mm to 0.5 μA/mm. The combination of low leakage current of *i*-GaN and the observation of minimum carrier density ($N_{D(2DEG)}$ at a depth of 3 μm indicate that the HEMT structure was grown on a highly insulating GaN buffer layer over a quarter of a 200-mm Si substrate. The measured carrier concentration profile is comparable to the published reports [4,14].

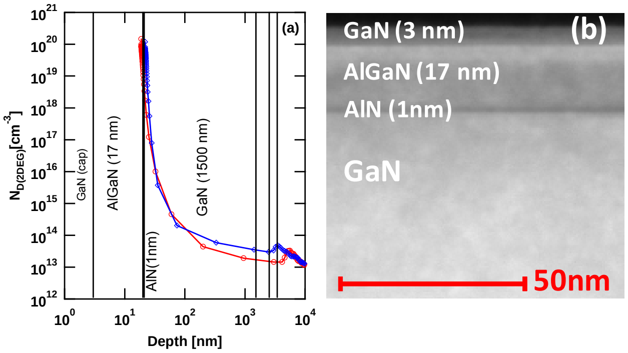


Fig. 4. (a) C-V profiling of AlGaN/GaN HEMTs on 200-mm Si(111) (b) HAADF-STEM z-contract image of the same sample showing 3 nm-thick GaN cap layer, 17nm-thick AlGaN barrier layer and 1 nm-thick AlN spacer layer.

The lateral buffer breakdown voltage (BV_{buff}) has been measured between the two isolated ohmic contacts (50μm×50μm) with a gap of 10 μm by fixing the current compliance of 1 mA/mm. Figure 5 shows the contour map of BV_{buff} over a quarter of a 200-mm diameter Si substrate. The BV_{buff} with an average value of 170 V has been obtained over a quarter of the 200-mm diameter Si substrate with > 88% uniformity. The highest BV_{buff} on this HEMT structure is 200 V. This can be further improved by optimizing the growth of the GaN buffer on Si substrates.

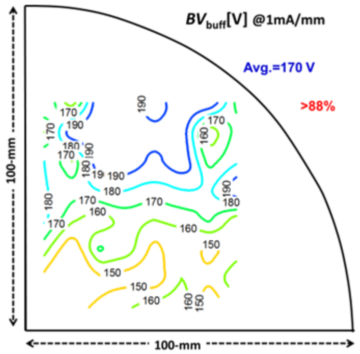


Fig. 5. Contour mapping for buffer breakdown voltage of GaN HEMT on a quarter of 200-mm wafer by fixing a current compliance of 1 mA/mm.

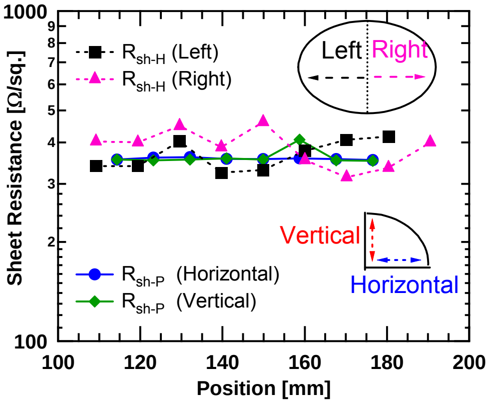


Fig. 6. Sheet Resistance measured using *van der Pauw* Hall samples taken from full 200-mm GaN HEMTs on Si and *van der Pauw* patterns on the processed quarter of 200-mm HEMT wafer.

Figure 6 shows the measured sheet resistance ($R_{sh\text{-}P}$) of AlGaN/GaN heterostructures using *van der Pauw* patterns on the device processed sample and the $R_{sh\text{-}H}$ values measured in the *van der Pauw* Hall samples. The processed quarter of the 200-mm GaN HEMT sample's average $R_{sh\text{-}P}$ values are 380±14 Ω/sq. with a uniformity >90% which is consistent with the $R_{sh\text{-}H}$ values (387±44 Ω/sq) obtained from Hall samples prepared from a full 200-mm GaN HEMT wafer [see also figure 1(b)]. From this experimental data, we can infer that the remaining three quarters of the 200-mm wafer can have similar uniformity to the selected quarter of the 200-mm GaN HEMT wafer. Overall, the radial distribution of $R_{sh\text{-}H}$ over a full 200-mm GaN HEMT wafer and $R_{sh\text{-}P}$ over a quarter of the 200-mm GaN HEMT wafer is >90 % which is very much comparable to the AlGaN/GaN HEMT structures on a 100-mm Si substrate [15].

CONCLUSION

We have carried out the device uniformity studies of AlGaN/GaN HEMTs fabricated for the first time on a quarter of a 200-mm diameter Si(111) substrate. The radial distribution of Hall parameters were >90% over a full 200-mm diameter Si(111) substrate. The uniformity of I_{Dmax}, g_{mmax} and V_{th} values for HEMTs on a quarter of the 200-mm diameter Si substrate were also >90%. The uniformity of 2DEG depth is >90% in the AlGaN/GaN HEMT structure which is consistent with the uniformity of the measured barrier thickness by STEM and V_{th} of AlGaN/GaN HEMTs. The BV_{buff} of GaN-on-Si has also exhibited an average value of 170 V with >88% uniformity over a quarter of the 200-mm diameter Si(111) substrate. The uniformity of $R_{\text{sh-P}}$ (>90%) in AlGaN/GaN HEMT structures over a quarter of the 200-mm diameter Si is in agreement with the radial distribution of $R_{\text{sh-H}}$ over a full 200-mm diameter Si substrate. Our demonstrated result shows the feasibility of achieving good uniformity AlGaN/GaN HEMTs on 200-mmdiameter Si(111) substrate for low-cost high-power switching device applications [2,6].

ACKNOWLEDGMENT

The authors would like to acknowledge the support from SERC-A*STAR under the TSRP program grants for "GaN-on-Si and GaN-based Devices on Si for mm-wave Applications" with grant Nos. 102-169-0126 and 102-169-030.

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ACRONYMS

AlGaN: Aluminium Gallium Nitride
GaN: Gallium Nitride
Si(111): Silicon (111)
MOCVD: Metal Organic Chemical Vapour Deposition
HAADF-STEM: High Angle Annular Dark-Field Scanning Transmission Electron Microscopy
2DEG: 2 Dimensional Electron Gas
HEMT: High-Electron-Mobility Transistor
μ_H: 2DEG Hall mobility
n_s: Sheet Carrier Density
$R_{\text{sh-H}}$: Sheet Resistance from *van der Pauw* Hall sample
C-V: Capacitance-Voltage
$N_{D(2DEG)}$: 2DEG carrier density by C-V method
DC: Direct Current
I_{DS}-V_{DS}: Drain Current-Voltage
I_{Dmax}: maximum drain current density
g_{mmax}: maximum extrinsic transconductance
BV_{Buff}: Buffer Breakdown Voltage
$R_{\text{sh-P}}$: Sheet Resistance from *van der Pauw* pattern in the device processed sample