Uniformity Studies of AlGaN/GaN HEMTs on 8-in Diameter Si(111) Substrate

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***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 8-in diameter Si(111) substrate. A quarter of 8-in diameter AlGaN/GaN epitaxial wafer was chosen for the uniformity studies of sub-micron gate GaN HEMTs. More than 90% uniformity in the 2 Dimensional Electron Gas (2DEG) depth obtained by capacitance-voltage method are comparable to the grown barrier thickness which is confirmed to be 21 nm by STEM. The average buffer leakage current is ~0.09µA/mm. The fabricated transistor's DC parameters were also exhibited >90% uniformity over a quarter of 8-in Si(111) substrate.**

I. 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 8-in diameter Si substrate [7-10]. Hence, it is essential to study the uniformity of the devices fabricated on AlGaN/GaN HEMTs on 8-in wafers. Recently, we have reported the electrical, structural, optical and device DC & microwave properties of AlGaN/GaN HEMTs on 8-in Si(111) [9,10]. S. Arulkumaran et. al. had performed similar study on the device uniformity of full 4-in wafer using quarter of 4-in 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 8-in Si substrate. In this paper, for the first time, we report the uniformity of the electrical performances of AlGaN/GaN HEMTs on 8-in diameter Si(111) substrate.

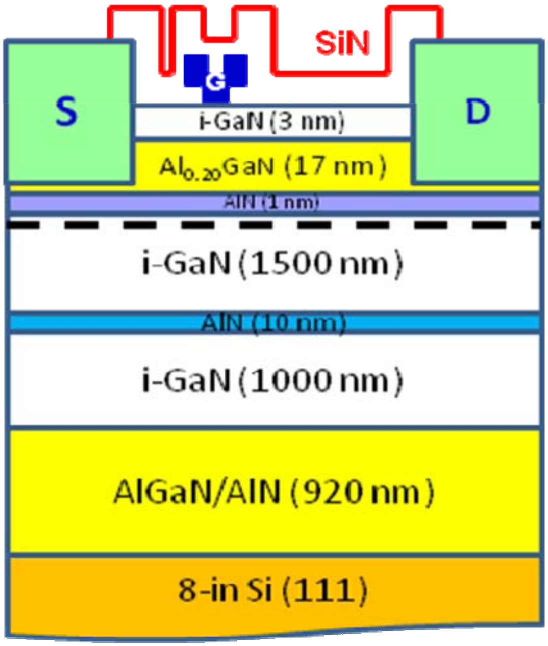

Fig. 1. Schematic cross-sectional diagram of AlGaN/GaN HEMTs on 8-in Si.

II. DEVICE FABRICATION AND MEASUREMENT

AlGaN/GaN HEMT structures were grown by MOCVD on 8-in Si(111) substrate. The silicon substrate thickness and resistivity (boron doped) is 1.5 mm and 8×10^{-3} Ω-cm, respectively. Figure 1 shows the schematic cross-section of the grown GaN HEMT structure on 8-in Si substrate. The growth details are reported elsewhere [10]. The bowing value of the grown AlGaN/GaN HEMT structure on 8-inch Si substrate is <20 μm. All the epi-layer thicknesses were confirmed by cross-sectional HAADF-STEM. To study the wafer uniformity, the full 8-inch wafer was diced into four quarters. One quarter was used to prepare the Hall samples and another quarter was used for device processing. The electrical and structural uniformity of AlGaN/GaN heterostructures were measured across the 8-inch diameter Si substrate and reported elsewhere [10]. The uniformity of the measured parameters reported in this work was calculated using the formula, $Uniformity[\%]=\left(1-\frac{\sigma}{\overline{x}}\right)\times100$, where, σ is the standard deviation of the measured data and $\overline{x}$ is the average of the measured data.

The mesa isolation for HEMT device fabrication was accomplished by dry etching down to GaN

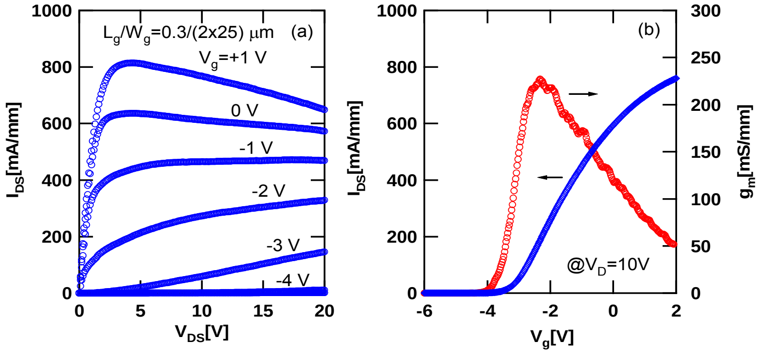

Fig. 2. (a) I_{DS}-V_{DS} and (b) transfer characteristics of AlGaN/GaN HEMTs on a quarter of 8-in. diameter Si(111) wafer.

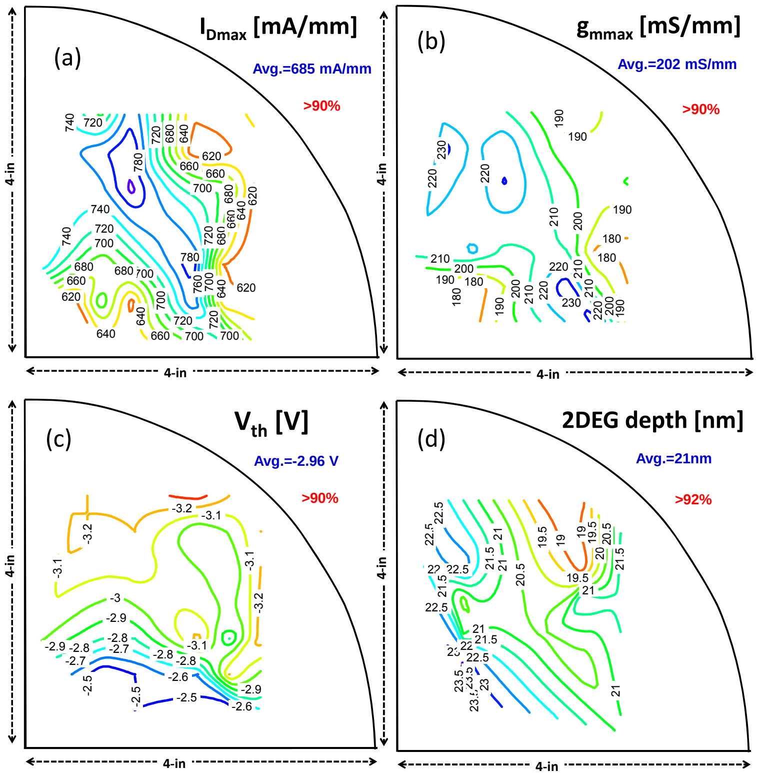

Fig. 3. Contour mapping of a) I_{Dmax}, b) g_{mmax}, c) V_{th} and (d) 2DEG depth of AlGaN/GaN HEMTs on a quarter of 8-in diameter Si(111).

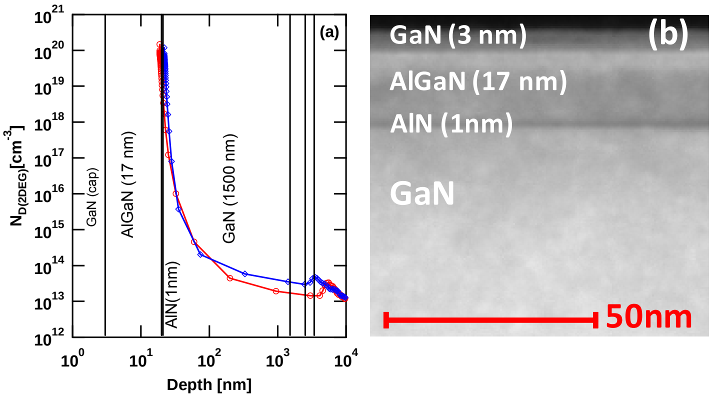

Fig. 4. (a) C-V profiling of AlGaN/GaN HEMTs (b) HAADF-STEM z-contract image of the same sample showing 3 nm-thick GaN cap layer, 17nm-thick AlGaN barrier layer and 1 nm-thick AlN spacer layer.

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 8-in wafer. The isolation current of *i*-GaN varies between 0.01 µA/mm to 0.5 µA/mm. 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, $W_g = (2\times25)$ 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 un-thinned Si substrate using 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].

III. 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 814 mA/mm and extrinsic transconductance (g_{mmax}) of 230 mS/mm has been observed among the 50 devices from a quarter of 8-in wafer. This is the highest g_{mmax} of GaN HEMTs so far reported on 8-in Si substrate. Due to the improved 2DEG mobility by a thin AlN spacer layer in the HEMT structure, an 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 8-in wafer. The average V_{th} value of the devices is –2.96 V with a uniformity of >90%. From the measured device data, we understand that the grown AlGaN/GaN heterostructures have good uniformity across the 8-in diameter wafer. The uniformity of the devices are >90% which is in agreement with the uniformity of the measured Hall mobility (μ_H) and the sheet carrier density (n_{sHall}) of 1832±60 cm^2/Vs and 8.5×10^{12} cm^{-2}[10]. The non-uniformity of the room temperature 2DEG mobility is <5% over a quarter of 8-in Si substrate. The sheet resistance (R_{sh}) of AlGaN/GaN heterostructures were also measured at room temperature using *van der Pauw* patterns on the device processed sample. The average R_{sh} values are 488±33 Ω/sq. with a uniformity >92% which is in good agreement with the R_{sh} values (426±28 Ω/sq) obtained by Hall measurements. This means that the non-uniformity of R_{sh} over a quarter of 8-in wafer is <8 % which is very much comparable to the AlGaN/GaN HEMT structures on 4-in Si substrate [15].

To measure the 2DEG carrier density, C-V measurements were carried out at 1 MHz on 30 Schottky diodes at different locations of a quarter of 8-in wafer. Figure 4 shows (a) C-V profiling of

AlGaN/GaN HEMTs on 8-in Si substrate. The average 2DEG carrier density measured from C-V measurements are 3.69×10^{19} cm^{-3} 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 is <8% for a quarter of 8-in wafer. The background carrier concentration at a depth of above 3 μm is as low as 1×10^{13} cm^{-3}. The combination of low leakage current of *i*-GaN and the observation of minimum carrier density at a depth of 3 μm indicate that the grown HEMT structure were of highly insulating GaN buffer layer over a quarter of 8-in Si substrate. The measured carrier concentration profile is comparable to the published reports [14]. The buffer leakage current at 20 V is in the range between 0.01 μA/mm to 0.6 μA/mm. The lateral buffer breakdown voltage (BV_{buff}) has also been measured in 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 8-in diameter Si substrate. The BV_{buff} with an average value of 170 V has been obtained over a quarter of 8-in diameter Si substrate with > 88% uniformity. Figure 6 shows the contour map of buffer leakage current measured at the bias voltage of 20 V. A close correlation has been observed between the buffer breakdown and buffer leakage current.

IV. CONCLUSION

We have carried out the device uniformity studies of AlGaN/GaN HEMTs fabricated for the first time on a quarter of 8-in diameter Si substrate. The 2DEG depth of AlGaN/GaN HEMT is confirmed to be 21nm by STEM which has 92% uniformity over a quarter of 8-in Si substrate. The BV_{buff} of GaN-on-Si has also exhibited an average value of 170 V with >88% uniformity over a quarter of 8-in diameter Si substrate which is in good agreement with the measured buffer leakage current (~0.09μA/mm). The observed average I_{Dmax}, g_{mmax} and V_{th} values for HEMTs were 685 mA/mm, 202 mS/mm and -2.96V with uniformities of >90%. The uniformity of sheet resistance for AlGaN/GaN HEMT on 8-inch Si substrate is also >90%. Our demonstrated result shows that the feasibility of achieving good uniformity AlGaN/GaN HEMTs on 8-in diameter Si for low-cost high-power switching device applications.

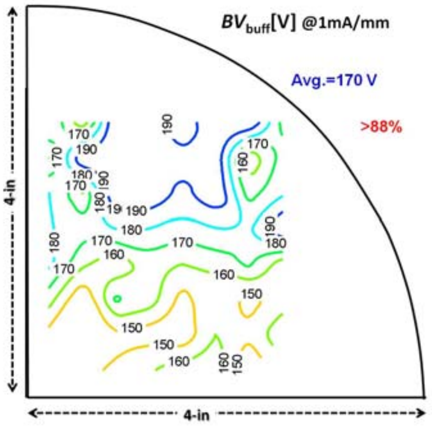

Fig. 5. Contour mapping of Buffer breakdown measured by fixing a current compliance of 1 mA/mm.

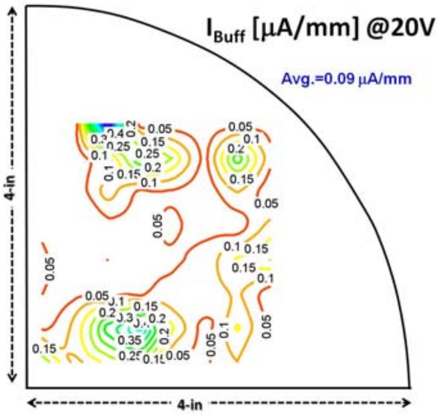

Fig. 6. Contour mapping of the measured buffer leakage current at the bias voltage of 20V.

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ACRONYMS

Si(111): Silicon (111)
AlGaN: Aluminium Gallium Nitride
GaN: Gallium Nitride
MOCVD: Metal Organic Chemical Vapour Deposition
HEMT: High Electron Mobility Transistor
C-V: Capacitance-Voltage
I_{DS}-V_{DS}: Drain Current-Voltage
2DEG: 2 Dimensional Electron Gas
DC: Direct Current
HAADF-STEM: High Angle Annular Dark-Field Scanning Transmission Electron Microscopy