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Uniformity studies of MOCVD grown AlGaN/GaN HEMTs on 100-mm diameter sapphire

S. Arulkumaran, M. Miyoshi*, T. Egawa, H. Ishikawa and T. Jimbo

Research Center for Nano-Device and System, Nagoya Institute of Technology, Showa-ku, Gokiso-cho, Nagoya 466-8555, Japan. Fax: +81-52-735-5546, E-mail: arul001@yahoo.com

*On Leave from NGK Insulators Ltd., Nagoya, Japan

1. Introduction

AlGaN/GaN high electron mobility transistors (HEMTs) are currently of increased interest for high-power, -frequency and –temperature applications. Al-though very impressive device performance [1] has been achieved, there are still some limitations to get good hetero-epitaxial wafers for the mass production of GaN based HEMTs, because of unavailability of native and suitable low cost substrates. For the mass production of AlGaN/GaN HEMTs, growth of GaN epilayers on substrate larger than 100-mm diameter is now required. However, the growth on larger diameter substrates causes increased bowing of the wafer due to the large thermal expansion coefficient between GaN and sapphire. Recently, our group has been successful in the growth of high quality AlGaN/GaN heterostructures (HSs) using 3-μm GaN buffer layers on 630-μm-thick c-face 100-mm diameter sapphire with a low bowing value of about 35-40 μm [2]. No report is available on the uniformity studies of AlGaN/GaN HEMTs characteristics grown on 100-mm sapphire. In this paper, we report the fabrication and the dc characteristics of AlGaN/GaN HEMTs on 100-mm sapphire substrates. The uniformity of the HEMTs dc properties were also compared with the electrical and structural characteristics of AlGaN/GaN HSs.

2. Experimental

AlGaN/GaN HEMT structures were grown by metal organic chemical vapor deposition (MOCVD) on 100-mm (0001) sapphire substrate (630 μm-thick) using Nippon Sanso SR 4000. The growth details of AlGaN/GaN HSs have already been reported elsewhere [2]. To check the electrical and structural uniformity of AlGaN/GaN HSs, Hall Effect and X-ray diffraction were measured across the 100-mm diameter sapphire. The uniformity of Aluminium content in AlGaN across the 100-mm wafer was estimated to be 25.4 ±0.4% from ω-2θ scanning X-ray diffraction. Good crystalline quality with high homogeneity of GaN has been observed across the 100-mm sapphire [2]. The average thickness (measured by optical reflectivity) GaN and $Al_{0.26}GaN$ was 3.04 ±0.06 μm. and 27.5 ±1.2nm, respectively across the 100-mm diameter sapphire substrate. The bowing value of 60 μm was reported for 2-μm GaN on 430-μm-thick c-face 100-mm sapphire [3]. For our case, the c-face bowing value of the GaN on 100-mm sapphire is in the range of 35 to 40 μm, which was also estimated from optical measurements [2]. This range is suitable for the fabrication of devices using conventional lithographic-process. The HEMTs were fabricated on a quarter of 100-mm diameter AlGaN/GaN HSs to observe the uniformity of HEMTs dc characteristics. Figure 1 shows the schematic diagram of the fabricated HEMTs. The device process details were published elsewhere [4]. To measure the 2DEG carrier density, capacitance-voltage (C-V) measurements were carried out at 1 MHz on 40 identical diameter Schottky diodes at different locations of a quarter of 100-mm wafer using HP4845A LCR meter. The dc characteristics of the devices were measured using Agilent 4156c semiconductor parameter analyser.

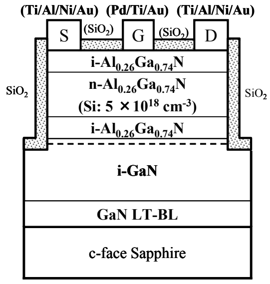

Fig. 1. Schematic diagram of fabricated AlGaN/GaN HEMTs

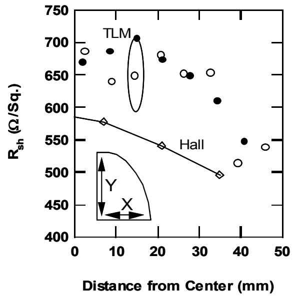

Fig.2. Line scan distribution of R_{sh} measured from Hall and TLM method

3. Results and Discussions

The sheet resistance (R_{sh}) measurements of AlGaN/GaN HSs were carried out at room temperature using Transfer Length Method (TLM) and Hall Effect measurements. The average contact resistance (R_c) values were 2.07 ±0.26 Ω-mm. Both Hall and TLM measured R_{sh} values decrease from the center to periphery of the wafer [see Fig. 2]. The average R_{sh} values measured from TLM and Hall were 621 and 575 Ω/Sq. with a total variation of 16.98 and 13.16%, respectively. These R_{sh} values are in agreement with the values of non-contact measured R_{sh} of 558 Ω/□ with a total variation of 14.5% [3].

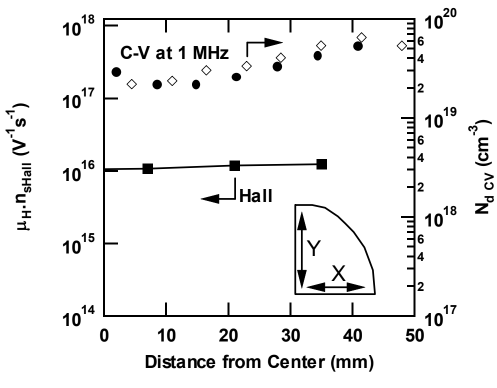

Fig. 3. Line scan distribution of the product of $\mu_H.n_{sHall}$ and N_{dCV} for AlGaN/GaN HEMTs

From this, we understand that the grown AlGaN/GaN HSs were in good uniformity across the 100-mm diameter wafer. The average 2DEG carrier density measured from C-V measurements (see Fig. 3) are 3.69×10^{19} cm^{-3} at a depth of 22.51 ±1.78 nm. The carrier density at a depth above 2 μm was as low as 5×10^{12} cm^{-3}. Except the periphery of the wafer, the isolation current of *i*-GaN varies between 0.17 nA to 0.5 μA. The combination of low leakage current of *i*-GaN and the

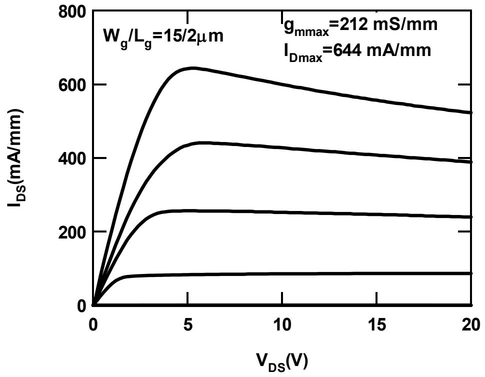

Fig. 4. Typical I_{DS}-V_{DS} characteristics of AlGaN/GaN HEMTs V_G=+1.5V, ΔV_G=-1.0V

observation of minimum carrier density at a depth of 2 μm indicate that the grown AlGaN/GaN HSs were of good quality with highly insulating GaN layer across the 100-mm sapphire. Normally, the 2DEG carrier density depends on both the AlGaN doping concentration and AlGaN thickness. In this case, we believe that the AlGaN thickness (27.5 ±1.2nm) is a more dominant cause for the variation of 2DEG carrier density when compared with the AlGaN doping concentration.

More than 40 identical device dimensions (W_g=15 μm, L_g=2.0 μm, L_{sg}=2.0 μm, L_{sd}=9.0 μm) were chosen for the uniformity studies across the wafer. Figure 4 shows the HEMTs typical I_{DS}-V_{DS} characteristics with good pinch-off. Maximum drain current density (I_{Dmax}) of 644 mA/mm and extrinsic transconductance (g_{mmax}) of 212 mS/mm has been observed among the HEMTs from a quarter of 100-mm wafer. Figure 5 a), b) and c) show the contour mapping of I_{Dmax} and g_{mmax} and threshold voltage (V_{th}) of AlGaN/GaN HEMTs on a quarter of 100-mm sapphire substrate. The average g_{mmax} and I_{Dmax} values of 197 mS/mm and 515 mA/mm with standard deviations of 4.82% and 9.34% respectively were observed on a quarter of 100-mm wafer. The uniformity of the device parameters were in agreement with the uniformity of Hall mobility (μ_H) and sheet carrier density (n_{sHall}) of 1322 cm^2/Vs and 8.36x10^{12} cm^{-2} with standard deviations of 4.27% and 6.75%, respectively. Figure 3 show the line scan distribution of g_{mmax}, I_{Dmax}, product $\mu_H.n_{sHall}$ and 2DEG sheet carrier density (n_{sCV}) measured from C-V measurements as a function of distance from the center of wafer. The g_{mmax} and I_{Dmax} values increase towards the periphery of the wafer, which is consistent with the product values of μ_H and n_{sHall} (see figure 3). It is also clear that, both n_{sCV} and n_{sHall} values increase towards the periphery of the wafer. From these, we understand that the uniformity of HEMTs dc properties were in agreement with the uniformity of Hall mobility and the sheet carrier density across the 100-mm wafer. The average values of source (R_s) and drain (R_d) resistance of the devices were 2.64 ±0.20 Ω-mm and 5.80 ±0.37 Ω-mm, respectively. It is clear that both the R_s and R_d distributions are less than 7.5%. The average V_{th} values of the devices are –2.30 V with a standard deviation of 6.52%. The C-V measured average V_{th} values (-2.45 V with a standard deviation of 4.88%) from Schottky diodes were in agreement with the values from $\sqrt{I_D} - V_G$ plot of HEMTs [see Fig. 5c) and d)]. From this, it is clear that, the AlGaN/GaN HEMTs on 100-mm sapphire substrates were in good homogeneity across the wafer.

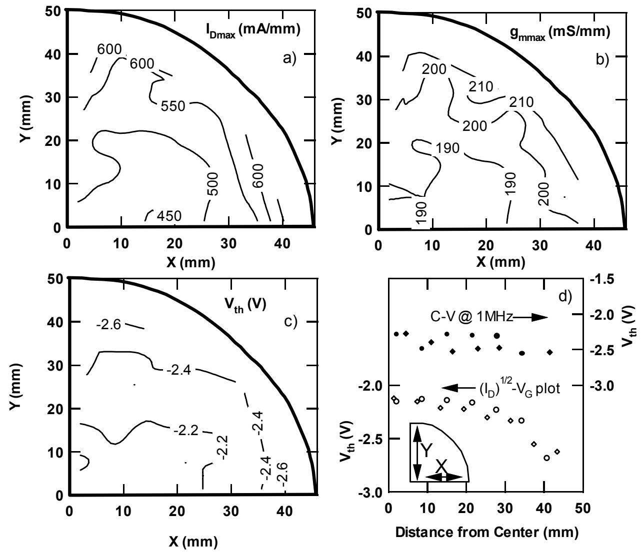

Fig. 5. Contour mapping of a) I_{Dmax}, b) g_{mmax} and c) V_{th} of AlGaN/GaN HEMTs on a quarter of 100-mm diameter sapphire. d) Line scan distribution of V_{th} measured from C-V and $(I_D)^{1/2}$-V_G plot.

4. Conclusion

We have achieved the fabrication and the dc characteristics of AlGaN/GaN HEMTs from films grown by MOCVD on 100-mm sapphire. The average values of I_{Dmax}, g_{mmax} and V_{th} for HEMTs were 515 mA/mm, 197 mS/mm, and -2.30 V with standard deviations 9.34%, 4.82% and 6.52%, respectively. The standard deviation of g_{mmax} is in good agreement with the uniformity of μ_H across the 100-mm wafer. The g_{mmax} and I_{Dmax} values increase towards the periphery of the wafer, which is consistent with the product of $\mu_H.n_{sHall}$. The Hall and TLM measured sheet resistance of the AlGaN/GaN HSs were in good uniformity with the standard deviations of 9.01 and 9.43%, respectively. The V_{th} uniformity of HEMTs on 100-mm sapphire is as low as 6.65%. The uniformity of HEMTs dc properties were in good correlation with the electrical characteristics of AlGaN/GaN HSs, which was obtained from the Hall Effect and Capacitance-Voltage measurements. In conclusion, the fabricated AlGaN/GaN HEMTs on 100-mm sapphire by MOCVD are suitable for the mass production of high-power, high-temperature, high-frequency microwave device applications.

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