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Enhancement of breakdown voltage in AlGaN/GaN HEMTs using AlN buffer layer thickness on 4-inch Silicon

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1. Introduction

Al-though GaN high electron mobility transistors (HEMTs) have demonstrated remarkable performance on sapphire and SiC (7.9 W/mm at 30 GHz) [1], the commercial viability of devices grown on these substrates hampered by cost and high-volume manufacturing issues. However, the use of mature technology like silicon as the substrate material offers a clear commercialization pathway in terms of large-scale wafer fabrication and low-cost manufacturing with reasonably good thermal management. From the mass production point of view, recently, we demonstrated dc characteristics of AlGaN/GaN HEMTs with good uniformity across the 4-in Sapphire [2]. Devices with several hundred volts of breakdown voltage (BV_{gd}) with low on resistance (R_{on}) are of paramount importance in power switching applications such as factory automation, telecommunications and power motor controls [3]. To obtain high output power, devices required high BV_{gd} with free of drain current collapse. Few groups have implemented field plate and passivation to enhance the BV_{gd} of HEMTs on SiC [1]. It is also possible to increase the BV_{gd} by increasing the buffer layer thickness. AlN have been used as a buffer layer for the growth of good quality GaN on Silicon [4-8]. There is no report of AlGaN/GaN HEMTs breakdown characteristics for different buffer layer thickness on 4-in Si substrate. In this work, we present the fabrication and the dc characteristics of AlGaN/GaN HEMTs on 4-inch silicon with different thickness of AlN buffer layers. The influences of AlN buffer layer thickness on the breakdown voltage of HEMTs were also studied.

2. Experimental

The growth of AlGaN/GaN HEMTs on 4-inch p-Si substrate (resistivity=0.001Ω-cm) was carried out in a Nippon Sanso MOCVD system (SR-4000). All the layers were grown at 1130°C. Various thicknesses of AlN nucleation layers (8, 50, 100 and 200 nm) followed by 40 nm thick $Al_{0.26}Ga_{0.74}N$ was grown on Si. The intermediate transition layers of GaN/AlN (20/5 nm) with 20 pairs were grown on the buffer layer [8]. Then 1-μm-thick *i*-GaN layer was grown on the transition layer. To enhance the 2DEG mobility, 1-nm-thick AlN spacer layer was grown on *i*-GaN layer. Finally, the top layer *i*-AlGaN (25nm) was grown on AlN spacer layer. Crack free AlGaN/GaN heterostructures (HSs) were obtained except the HSs on 500 nm buffer layer.

BCl_3 plasma etching was performed for mesa isolation. The source & drain ohmic contacts were formed using Ti/Al/Ni/Au (20/72/12/40 nm) metals followed by lamp annealing at 750 °C for 30 sec. The contact resistance values of 2.33, 192, 1.89 and 1.23 Ω-mm were obtained for the respective AlN buffer thicknesses of 8, 200, 300 and 500 nm, respectively. The gate metal Pd/Ti/Au (40/20/60nm) was formed using conventional

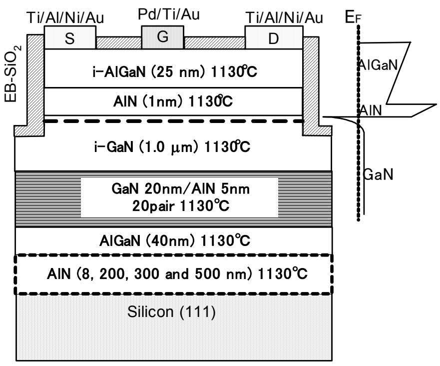

Fig. 1. Schematic diagram of AlGaN/GaN HEMTs on Silicon

photolithography [2,8]. The schematic diagram of AlGaN/GaN HEMTs on silicon is shown Fig 1. The dc and breakdown characteristics of HEMTs were carried out under dark using Agilent 4156c semiconductor parameter analyzer 1MHz capacitance-voltage (C-V) measurements were carried out on the HEMTs to observe the 2DEG carrier profile using HP4845A LCR meter.

3. Results and Discussions

Fig.1 a) shows the good pinch-off I_{DS}-V_{DS} characteristics of AlGaN/GaN HEMTs grown on 300 nm thick AlN buffer layer. The maximum extrinsic transconductance (g_{mmax}) and maximum drain current density (I_{Dmax}) values increases up to the buffer layer thickness of 300nm. I_{Dmax} of 632 mA/mm and g_{mmax} of 186 mS/mm were observed on HEMTs with 300 nm AlN buffer layer. However, HEMTs with 500 nm thick buffer layer showed rather reduced I_{Dmax}. This is possibly due to the occurrence of cracks. The product of 2DEG mobility (μ_H) and sheet carrier density (n_{sHall}) of grown AlGaN/GaN HEMT structure as a function of buffer layer thickness is shown in Fig. 2a). No change in the product ($\mu_H.n_{sHall}$) values for the buffer layer thickness of 8 and 200 nm. However, HEMTs with 300 nm-thick buffer layer showed rather small product values. The low temperature (77 K) measured 2DEG mobility increases with the increase of AlN buffer thickness. This is an indication of recombination center reduction with the increase of buffer layer thickness. Due to the occurrence of crack, Hall parameters were not successfully obtained from the HEMTs

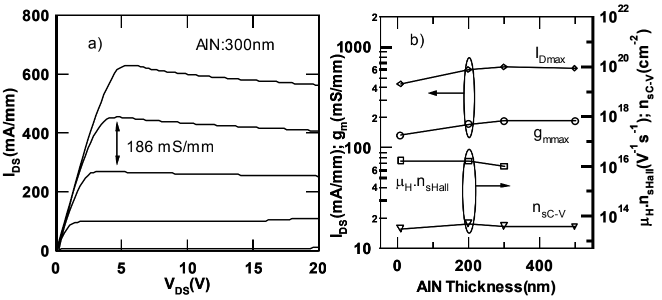

Fig. 2 a) I_{DS}-V_{DS} characteristics of AlGaN/GaN HEMTs on 4-inch Si: top V_g=+1.5V, ΔV_g=-1.0V, b) I_{Dmax}, g_{mmax}, $\mu_H.n_{sHall}$ and n_{sC-V} of AlGaN/GaN HEMTs as a function of AlN thickness with buffer layer thickness of 500 nm. The C-V profile was carried out on all buffer layer grown HEMTs, it reveals the sheet carried density ($n_{sC\text{-}V}$) values in the range of 3.11to 4.92 x10^{13} cm^{-2} (see Fig. 2b)). These values are in agreement with the values of Hall measurements.

Many devices with an identical dimension ($L_{sd}/L_g/L_{gd}/W_g$=11/2/5.5/200μm and $L_{sd}/L_g/L_{gd}/W_g$= 9.5/2/4/400μm) were destroyed to obtain BV_{gd} characteristics. Fig. 3 a) and b) shows the OFF-state and ON-state BV_{gd} characteristics of 400-μm-wide and 200-μm-wide gate AlGaN/GaN HEMTs for different thicknesses of AlN buffer layers, respectively. The device BV_{gd}:ON and BV_{gd}:OFF were measured at the gate voltage of +1.5V and -4.5V, respectively. The maximum BV_{gd}:ON was observed on the devices with the buffer layer thickness of 200 nm. Not much change has been observed in BV_{gd}:ON values except the devices with 500 nm thick buffer layer. This is due to the occurrence of cracks. After a complete device breakdown, the devices were investigated to check the burn-marks by optical microscope.

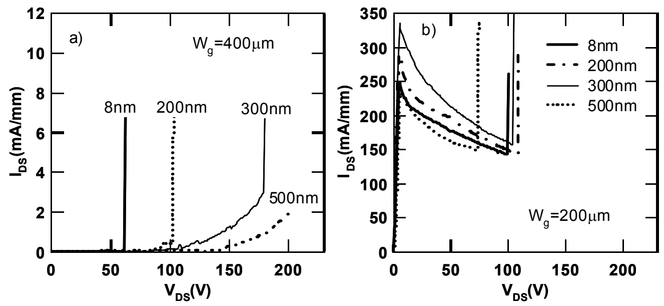

Fig. 3 a) BV_{gd}:OFF and b) BV_{gd}:ON of AlGaN/GaN HEMTs for different AlN thickness

No burn-marks were observed except a burned dot on the drain metal. There is no burn-mark in the drain-source gap.

The BV_{gd}:OFF of HEMTs at a fixed drain current density (of 1.5 mA/mm for W_g=400 μm and 5 mA/mm for W_g=200 μm) as a function of AlN thickness is shown in figure 4 a). From the figures 3a) and 4a), it is clear that the BV_{gd}:OFF increases with the increase of AlN buffer layer thickness. From the Fig 4 b), we understand that the increase of BV_{gd}:OFF is independent of gate-leakage current. Two junctions involved for the possibility of device breakdown such as, AlGaN/GaN junction and GaN/AlN/Si junction. To locate the broken junction, breakdown characteristics were carried out on two ohmic metals (e.g. drain contact of one device and the source contact of an adjacent device) of two

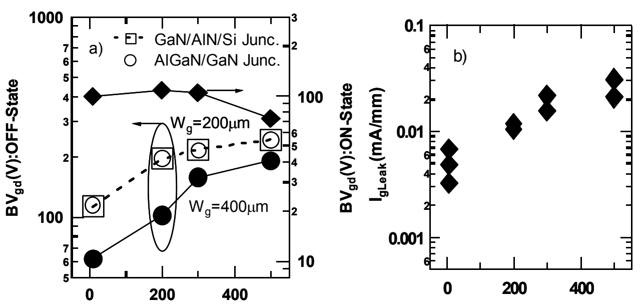

Fig. 4 a) BV_{gd}:OFF and BV_{gd}:ON of HEMTs as a function of AlN thickness b) Device gate leakage current as a function of AlN thickness

isolated adjacent 200-μm-wide gate devices with the gap of 50 μm (See Fig. 5). The junction breakdown voltage values of two adjacent devices are same as the breakdown voltage of a single device. From this, it is confirmed that the breakdown did not occur at AlGaN/GaN junction (region 1 of Fig.5). The actual breakdown occurred at GaN/AlN/Si junction (region 2 of Fig. 5). The GaN/AlN/Si interface is weaker than the interface of AlGaN/GaN. Maximum BV_{gd}:OFF and BV_{gd}:ON values of 215 and 104 V, respectively were observed on HEMTs with 300 nm AlN buffer layer. It is possible to increase the BV_{gd}:OFF values by changing the p-Si with

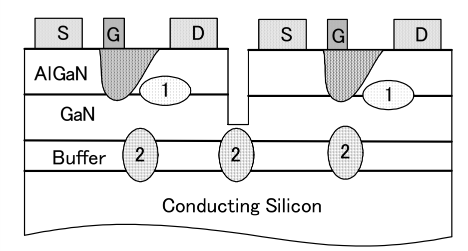

Fig. 5. Breakdown junctions in AlGaN/GaN HEMTs on Silicon

high-resistive-Si substrate. The device output power can be estimated from the static characteristics as in P_{out}~ (I_{DS}/2)x(V_{DS}-V_{knee})/2. Where I_{DS}, V_{DS} and V_{knee} are drain current, drain voltage and knee voltage of the devices, respectively. The estimated values of P_{out} for HEMTs with 300 nm-thick buffer layer are 2.3 and 5.11 W/mm at drain voltages of 20 and 50 V, respectively.

4. Conclusion

We have achieved the fabrication and the dc characteristics of AlGaN/GaN HEMTs from films grown by MOCVD on 4-in silicon. The g_{mmax} and I_{Dmax} increases up to the buffer layer thickness of 300nm. The I_{Dmax} of 632 mA/mm and g_{mmax} of 186 mS/mm were observed on HEMTs with 300 nm AlN buffer layer. Not much change has been observed in BV_{gd}:ON values except the devices with 500 nm thick buffer layer. This is due to the occurrence of cracks. The increase of BV_{gd}:OFF with the increase of AlN buffer layer has been observed. The junction breakdown has been identified as GaN/AlN/Si. Maximum BV_{gd}:OFF and BV_{gd}:ON values of 215 and 104 V, respectively were observed on HEMTs with 300 nm AlN buffer layer. The estimated values of P_{out} for HEMTs with 300 nm-thick buffer layer are 2.3 and 5.11 W/mm at drain voltages of 20 and 50 V, respectively. The AlGaN/GaN HEMTs on 4-in Si with thicker AlN buffer layers are suitable to get high breakdown voltage for high power applications.

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