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Normally-off Operation of Non-polar AlGaN/GaN Heterojunction FETs Grown on R-plane Sapphire

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1. Introduction

GaN-based heterojunction field effect transistors (HFETs) have been widely investigated for various applications including high power switching devices [1,2]. High breakdown field and high saturation velocity of the wide bandgap GaN-based material are very attractive features for the future power devices which would require high breakdown voltages together with low on-state resistances. In order to make the GaN-based devices compatible with the currently used Si power MOS (metal-oxide-semiconductor) FETs, they need to be normally-off type which can avoid any circuit troubles at power failures. So far, most of the reported AlGaN/GaN HFETs are rather normally-on type taking advantage of high sheet electron density at the hetero-interface caused by the built-in polarization field along to [0001] direction. High current densities have been achieved with high breakdown voltages where the sheet carrier concentration as high as 1×10^{13} cm^{-2} is formed at the AlGaN/GaN interface without any intentional doping. The sheet charges could be reduced by the epitaxial structure design, however, demonstration of the normally-off type FETs have been very difficult on the c-plane faces because of the extraordinary high inherent charges [3].

In this paper, we report on the nearly normally-off operation of non-polar a-plane AlGaN/GaN HFETs without any influence of the built-in polarization, for the first time. The a-plane epitaxial structures are successfully grown on r-plane sapphire substrate by metal organic chemical vapor deposition (MOCVD). The details of the epitaxial growth and device performance depending on the gate directions are also described.

2. Epitaxial growths of a-plane HFET structures

Non-polar a-plane (11-20) AlGaN/GaN heterostructures are grown on r-plane (10-12) sapphire substrate by MOCVD technique. X-ray diffraction pattern of the grown 1μm-thick GaN film on r-plane sapphire shows a single (11-20) a-plane peak without any inclusion of the other crystallographic planes as shown in Figure 1. According to the X-ray results, schematic epitaxial relationship of GaN on r-plane sapphire can be described as seen in Figure 2 and Figure 3 shows the schematic atomic arrangement indicating the a-plane contains both Ga and N atoms and is not suffered from the built-in polarization parallel to the [0001] direction. The optimization of the growth conditions for the GaN growths results in better crystal quality with the full width half maximum of the X-ray rocking curve of (11-20) plane of 1500 arcsec or less. The value is comparably low as so-far reported values [4]. Although the epitaxial growths are optimized at our best efforts, there still remains the striped surface morphology as shown in Figure 4. Note that the stripe is parallel to [0001] direction. The root mean square of the surface roughness measured by atomic force microscopy (AFM) is around 2.5 nm which is still high compared with the conventional c-plane GaN showing the roughness of 0.5 nm or less.

3. Fabrication of normally-off a-plane HFETs

Figure 5 shows a schematic cross-section of the fabricated a-plane HFET. A Si-doped 25nm-thick $Al_{0.26}Ga_{0.74}N$ layer on undoped 1μm-thick GaN layer is grown on r-plane sapphire. The doping concentration in the AlGaN layer is as high as 4×10^{19} cm^{-3}. The used ohmic contact for source and drain is Ti/Al and the Schottky gate electrode is PdSi. Thermal oxidation is used for the device isolation. The gate length of the fabricated HFETs is 1μm. Gate directions to both [1-100] and [0001] are examined. The measured sheet carrier concentration and the electron Hall mobility are 4.4×10^{13} cm^{-2} and 12 cm^2/Vs at the room temperature, respectively. This is the first report on the electric characteristics of the non-polar heterostructure applicable to the practical HFETs. The resultant DC drain current-voltage characteristics are shown in Figure 6 and Figure 7. The drain current of the HFETs with the gate to [1-100] direction is about twice as high as that to [0001] direction. This implies that the drain current flowing perpendicular to the striped morphology would be affected by more scattering resulting in less drain current for the gate direction of [0001]. The threshold voltages measured are -0.5 V for the HFETs, while that on conventional c-plane HFETs exhibit the value of -4 V with the identical device structure. The maximum drain-source current (I_{max}) and transconductance (g_m) are 19.5 mA/mm and 6.7 mS/mm, respectively. We believe that further optimization of the epitaxial growth conditions to achieve better crystal quality with smoother surfaces would improve the above I_{max} and g_m. Better device structure design including the reduction of the doping concentration and the AlGaN thickness would enable complete normally-off operation, as well.

4. Conclusions

We have demonstrated nearly normally-off operation of non-polar a-plane AlGaN/GaN HFETs, in which no built-in polarization field is formed perpendicular to the epitaxial plane. The non-polar epitaxial layers free from high sheet carrier densities are successfully grown on r-plane sapphire substrate by MOCVD. The fabricated HFETs exhibit threshold voltage of -0.5 V, while the c-plane HFETs exhibit the value of -4 V. Note that the drain current depends on the gate directions. The drain current perpendicular to the typical striped morphology is affected by more scattering than that parallel to the stripe. This is the first report on workable non-polar a-plane GaN-based HFETs.

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References

[1] H. Ishida, Y. Hirose, T. Murata, A. Kanda, Y. Ikeda, T. Matsuno, K. Inoue, T. Tanaka, T. Egawa, D. Ueda, *Technical Digest of 2003 International Electron Devices Meeting* (2003) 583.

[2] M. Hikita, M. Yanagihara, K. Nakazawa, H. Ueno, Y. Hirose, T. Ueda, Y. Uemoto, T. Tanaka, D. Ueda, T. Egawa, *Technical Digest of 2004 International Electron Devices Meeting* (2004) 803.

[3] O. Ambacher, J. Smart, J. R. Shealy, N. G. Weimann, K. Chu, M. Murphy, R. Dimitrov, L. Wittmer, M. Stutzmann, W. Rieger, J. Hilsenbeck, J. Appl. Phys. **85** (1999) 3222.

[4] M. D. Craven, S. H. Lim, F. Wu, J. S. Speck, S. P. DenBaars, Appl. Phys. Lett. **81** (2002) 469.

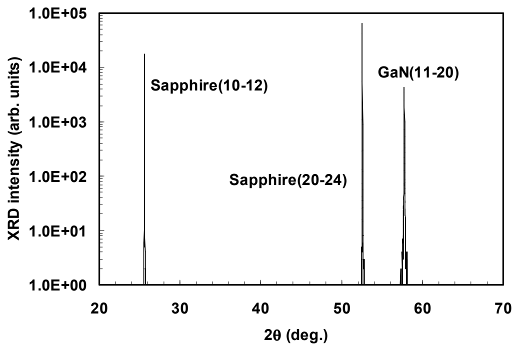

Figure.1 X-ray diffraction 2θ–ω scan of the 1-μm-thick a-plane GaN

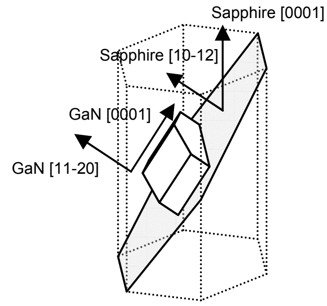

Figure.2 Schematic diagram of the epitaxial relationship of a-plane GaN on r-plane sapphire.

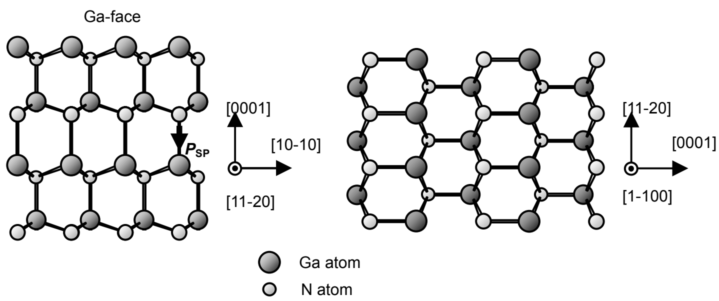

Figure.3 Schematic atomic arrangement on c-plane GaN (left) and a-plane GaN (right)

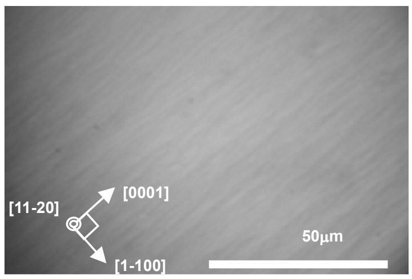

Figure.4 Surface morphology of the a-plane GaN/AlGaN HFET

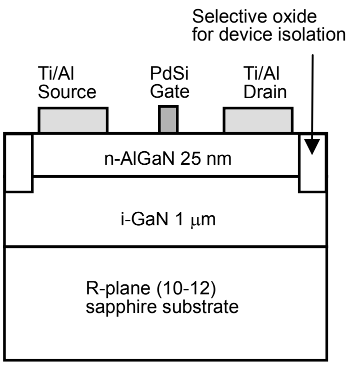

Figure.5 A cross section of the a-plane GaN/AlGaN HFET.

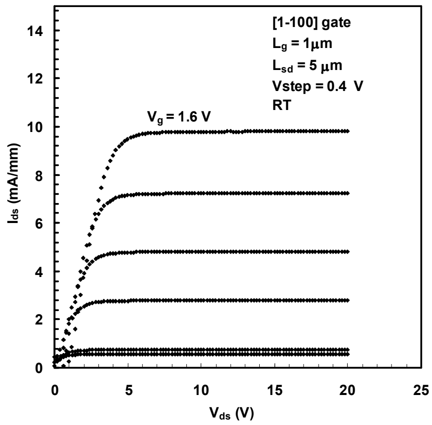

Figure.6 Drain characteristics of the a-plane GaN/AlGaN HFET along [0001] direction

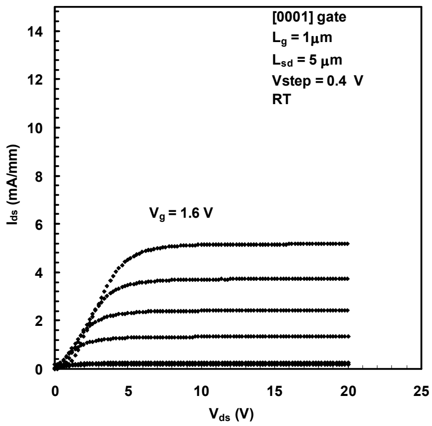

Figure.7 Drain characteristics of the a-plane GaN/AlGaN HFET along [1-100] direction