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Effect of Buffer Thickness on Degradation of AlGaN/ GaN HEMTs on Si

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Abstract

In this work, we have evaluated the electrical reliability for AlGaN/ GaN HEMTs on Si with varying buffer thickness to identify the critical buffer thickness. We have performed step-stress measurement under OFF-state condition. Raman techniques were studied to investigate the strain relaxation process on 1μm thick GaN grown on different buffer thickness ($T_{\rm Buf}$) on Si (111). We observed the device degradation was minimized with the negligible threshold shift ($V_{\rm th}$) before and after step-stress test for $T_{\rm Buf}$ = 2.5 μm. Also the calculated residual stress of GaN on Si was found very close to the unstrained GaN for $T_{\rm Buf}$ = 2.5 μm.

Introduction

AlGaN/ GaN HEMTs are currently considered to be promising candidates in application for power device application because of the high breakdown voltage and low on-resistance [1]. Though different substrates are available for the GaN epi-growth, Si substrate is the most suitable one because of its low cost and large scale availability. However, reliability becomes a bigger concern because of its large lattice mismatch and thermal coefficient between Si and GaN [2]. Recently, fewer studies were reported on the electrical reliability for AlGaN/GaN HEMTs on Si substrate but still it needs better understanding of the device failure mechanism. The electric field drives the device degradation and it is commonly attributed to inverse piezoelectric field [3]. Also hot carrier-induced defect creation at the AlGaN barrier and GaN buffer have been considered as reasons for the increased gate leakage current or carrier trapping [4]. It is believed that GaN epitaxial layers grown uniformly on Si substrate suffer from distributed thermal cracks hence the growth of GaN on superlattice buffer and on prepatterned Si substrate have been demonstrated as efficient ways to control the geometrical distribution of the thermal crack [5]. Besides the strong voltage dependence of the degradation, a buffer thickness dependent has also been found.

Experimental

AlGaN/GaN HEMTs structure with different buffer thickness were grown on a 4” p-Si (111) substrate by Taiyo Nippon Sanso (SR4000) horizontal metal-organic chemical vapor deposition (MOCVD) system. The growth started with the nucleation layer of 100 nm AlN, followed by the 40 nm of AlGaN. In order to understand the contribution of the buffer thickness towards reliability of the device degradation, wafers with different buffer thickness ($T_{\rm Buf}$ = 1.25, 2.5, 4.0 and 5.0μm) were grown. In order to study the step-stress reliability the un-intentionally doped GaN of thickness 1.0 μm and final 25 nm $Al_{0.26}Ga_{0.74}N$ top layers were fixed. All these layers were grown at a high temperature of 1130^{o}C and these samples are free from cracks. The schematic diagram of the MOCVD grown HEMT structure used in the current study is shown in Fig. 1.

The AlGaN/ GaN HEMTs on Si substrate with device dimension of gate width (W_g) = 200 μm, the gate-drain distance ($L_{\rm gd}$) = 4.0μm, the source-drain distance ($L_{\rm sd}$) = 9.5μm and the gate length (L_g) = 1.5μm were studied. We have performed the step-stress test under OFF-state and $V_{\rm DS}$ = 0 state condition for many devices. In a typical experiment, at OFF-state, $V_{\rm DS}$ is stepped from 5V to 40V with 5V step keeping $V_{\rm GS}$ = -10V, well below threshold voltage. The device is stressed for 600sec in each step voltage.

Results and Discussion

Fig. 2 compares the results of an OFF-state step-stress test for different buffer thickness for AlGaN/ GaN HEMTs on Si. This experiments stops at $V_{\rm DS}$ = 40V. Although the device undergo various pattern of degradation from the beginning the $T_{\rm Buf}$ = 2.5 μm shows a less degradation when compared to the other buffer thickness. Fig. 3. shows a change in the $V_{\rm th}$ shift before and after stress. The transfer characteristics measured before and after stress shows a negligible difference in the threshold voltage for $T_{\rm Buf}$ = 2.5 μm. The positive $V_{\rm th}$ shift for $T_{\rm Buf}$ = 1.25 μm observed due to the high dislocations which act as a trapping centers for electrons in the two-dimensional electron gas (2DEG) channel [6]. $T_{\rm Buf}$ = 4.0 and 5.0 μm resulted in negative $V_{\rm th}$ shift, this is because at high electric field, electrons can be injected from the AlGaN layer to the buffer. For sufficiently high voltage levels, electrons may achieve enough energy to ionize the deep acceptor in the buffer or to promote the transfer of an electron from the valence band to the deep acceptor, thus leading to the generation of a free hole. Generated holes may accumulate at the AlGaN/GaN interface which in turn resulted in a negative $V_{\rm th}$ shift [7]. Using visible Raman technique E_2 phonon frequency (Strain) and phonon stress relationship was calculated to identify the nature of stress (tensile/compressive) as shown in Fig. 4. It is believed that, the E_2 high mode originated from the GaN buffer. As the E_2 high mode frequency for unstrained GaN at 300 k is 567.5 cm^{-1}, the E_2 high mode for grown GaN on $T_{\rm Buf}$ = 2.5 μm was 567.22 cm^{-1}which almost very close to the relaxed GaN. As the E_2 high mode is related to the biaxial stress, the residual stress based on the peak shift can be calculated from the Eq.1.

$$\Delta\omega = 4.3\ \sigma_{xx}\ \mathrm{cm^{-1}Gpa^{-1}} \qquad (1)$$

The residual stress of the GaN buffer calculated shows from tensile to compressive stress The calculated stress in the GaN buffer shows very minimum of +0.05 GPa for $T_{\rm Buf}$ = 2.5 μm which believe to be the critical thickness for the i-GaN = 1.0 μm.

Conclusion:

We have evaluated the reliability of AlGaN/ GaN HEMTs on Si with various buffer thicknesses. We find that $T_{\rm Buf}$ = 2.5 μm shows a better reliability performance. The residual stress calculated using Raman spectroscopy showed a very close value to the typical unstrained GaN and the transfer characteristics shows negligible threshold shift before and after stress which ensures that T_{Buf} = 2.5 µm is the ideal thickness for i-GaN of 1 µm.

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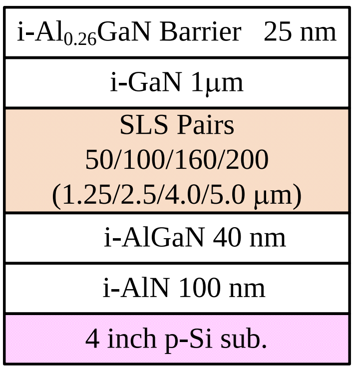

Fig. 1. Device Structure of AlGaN/GaN HEMTs on p-Si.

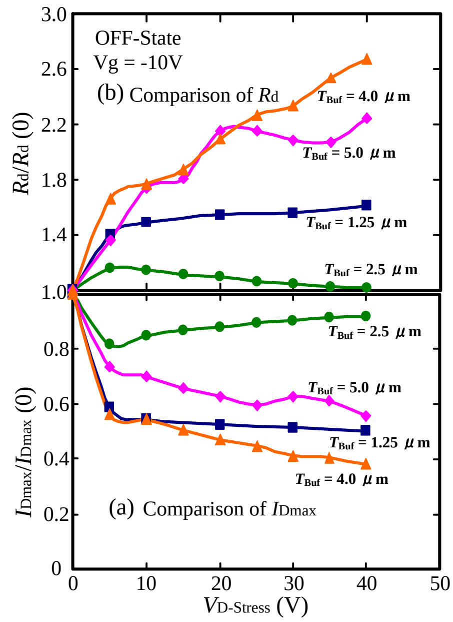

Fig. 2. Change in (a) I_{Dmax} (b) R_d at OFF-State condition. i.e. V_G = -10 V, $V_{D\text{-}stress}$ = 0V to 40V; step of 5V; time 600sec.

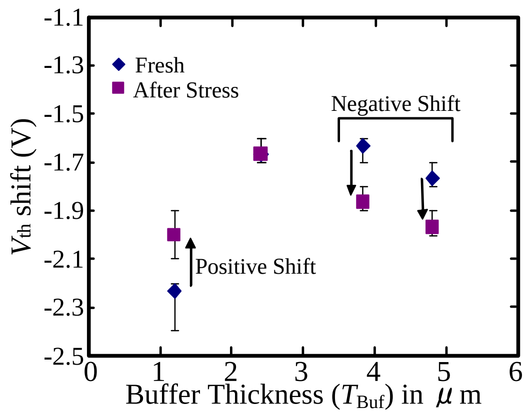

Fig. 3. Threshold voltage shift V_{th} measured before and after stress shows the positive shift for T_{Buf} = 1.25 µm, negative shift for T_{Buf} = 4.0 and 5.0 µm and negligible shift for T_{Buf} = 2.5 µm.

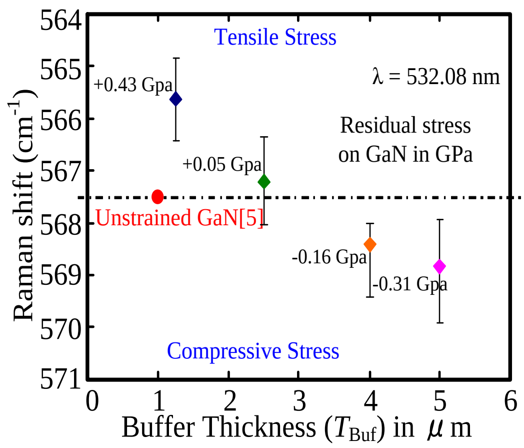

Fig. 4. The Raman shift observed for different T_{Buf} and their residual stresses are calculated and it shows that the T_{Buf} = 2.5 µm is very close to the unstrained GaN.