Influence of MOCVD Growth Conditions on the Two-dimensional Electron Gas in AlGaN/GaN Heterostructures

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Abstract

The influence of MOCVD growth conditions (carrier gas, growth temperature, and V/III ratio) on the AlGaN barrier and the corresponding 2DEG for AlGaN/GaN heterostructures grown on 150 mm silicon is investigated. Hall mobility 2200 cm^2/V.s, with sheet carrier concentration 8.7e10^{12} cm^{-2} and sheet resistance 326 Ohm/sq, is obtained for AlGaN grown in N_2 ambient and with high V/III ratios.

INTRODUCTION

AlGaN/GaN based High Electron Mobility Transistors (HEMTs) show superior performance for high-voltage power switching applications due to its large breakdown field strength (3.3 MV/cm) and low specific on-state resistance (R_{ON}) resulting from the high-density and high-mobility carriers in a two-dimensional electron gas channel (2DEG) [1-2]. Adoption of silicon substrates for AlGaN HEMTs is attractive due to the availability of low cost, large size wafers. Despite the large mismatch in lattice constants and thermal expansion coefficient between GaN and silicon, crack-free device-quality GaN has been demonstrated for potential applications of AlGaN HEMT on silicon [3-5].

For switching HEMT structures, reduction of switching conduction losses is related to lowering R_{ON}, which mainly depends on the mobility (μ_n) and sheet carrier concentration (n_s) of the 2DEG formed at the AlGaN/GaN interface. The 2DEG n_s is predominantly determined by the Al composition in the AlGaN layer, which governs the conduction band offset (ΔEc) and the strain in the AlGaN layer [6-8]. Abrupt and smooth AlGaN/GaN interfaces with low alloy disorder and coherently strained AlGaN are critical for 2DEG mobility [9-10]. In this paper, we investigate the influence of MOCVD growth conditions (carrier gas, growth temperature, and V/III ratio) on the AlGaN barrier and the corresponding 2DEG for AlGaN/GaN heterostructures grown on 150 mm silicon substrates.

EXPERIMENTAL RESULTS AND DISCUSSION

The AlGaN/GaN heterostructures in this study are grown on 150 mm (111) silicon substrates using a Veeco Turbodisc K465i production MOCVD system. Crack-free 3μm-thick GaN was grown over ~1μm AlN/AlGaN buffer structure containing one optional strain-relieving AlN interlayer. A barrier layer, 25 nm $Al_xGa_{1-x}N$ (x=0.2-0.25), is deposited with a 1-nm thick AlN spacer layer inserted between the AlGaN/GaN interfaces (as shown in Fig. 1) to improve the performance of the 2DEG [11].

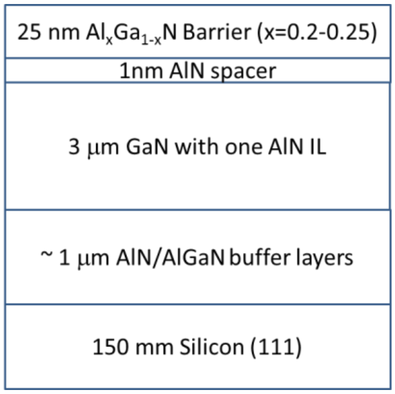


Fig. 1 Schematic of AlGaN/GaN heterostructures on 150 mm (111) Si

The properties of AlGaN barrier and corresponding 2DEG performances are studied with different growth conditions: carrier gas with H_2 or N_2, growth temperature from 920 °C to 1010 °C, and V/III ratio from 2000 to 12000. The reactor pressure is kept at 100 Torr for the AlGaN barrier. Total flow of carrier gas is adjusted to keep the same flow velocity with different carrier gas and NH_3 flow. The Al composition in the AlGaN layer is measured using photoluminescence (PL). The surface morphology of the AlGaN is studied by Atomic Force Microscope (AFM), and the electrical properties of the 2DEG at room temperature are evaluated by Van der Pauw-Hall measurement using indium dots as the Ohmic contact.

AlGaN layers in H_2 ambient are studied at different growth temperatures of 960 °C and 1010 °C. The surface morphology by AFM is shown in Fig. 2 (a) and (b). The TMGa and TMAl gas-phase flows are kept constant resulting in Al compositions of 23.9% and 22.9% for AlGaN layers grown at 960° C and 1010 °C, as measured by PL. Micro-cracks begin to appear on the AlGaN at 1010 °C, indicating partial strain relaxation. The root-mean-square (RMS) roughness is around 0.6-0.8 nm in the 5 μm x 5 μm scanned area.

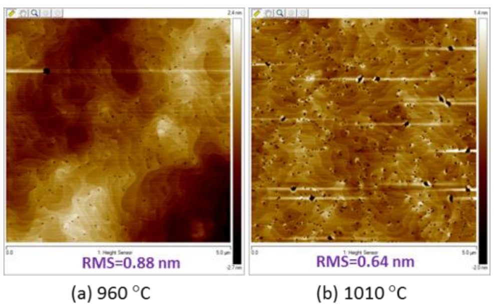


Fig. 2 5 μm x 5 μm AFM images of AlGaN/GaN hetrerostructures in H_2 ambient, (a) 960 °C, (b) 1010 °C.

The electrical properties of the 2DEG in H_2 ambient at 960 °C and 1010 °C are shown in Fig. 3 (a)-(c). The decrease in n_s at 1010 °C could be related to the lower Al composition and reduction of strain in the partially relaxed AlGaN layer. Increasing Al composition will increase the n_s due to the increase of ΔEc, the strain and thus the piezoelectric field. As n_s increases, the electrons are pushed more closely to the AlGaN/GaN interface and more easily affected by the interface roughness scattering, which leads to a decrease of μ_n [6-8]. Therefore, the low mobility observed for AlGaN at 960 °C might be explained by the increase of n_s from high Al composition. In addition, the decrease in μ_n at 960 °C might be explained by an increase in AlGaN surface roughness (Fig. 2), since the electron transport is affected by the roughness in the AlGaN/GaN interface [9-10].

The surfaces of AlGaN in N_2 ambient show smoother surfaces compared with AlGaN grown in an H_2 ambient. AFM images of AlGaN show a step flow feature comparable to the surface of underlying GaN layer, indicating pseudomorphic growth with less strain relaxation for the growth temperature from 920°C to 1010 °C, as shown in Fig. 4 (a)-(c). The root-mean-square (RMS) roughness is around 0.3-0.4 nm in the 5 μm x 5 μm scanned area. The TMGa and TMAl flows were kept constant for these experiments. The Al composition is 24.7%, 23.4%, and 21.0% for AlGaN grown at 920 °C, 960 °C, and 1010 °C, respectively.

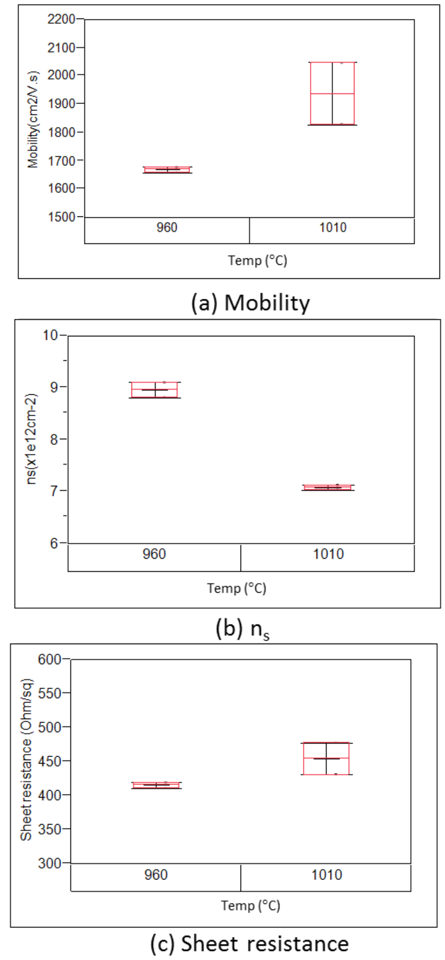


Fig. 3 Electrical properties of the AlGaN/GaN hetrerostructures in H_2 ambient at 960 °C and 1010 °C, (a) Mobility, (b) Sheet carrier concentration n_s, (c) Sheet resistance.

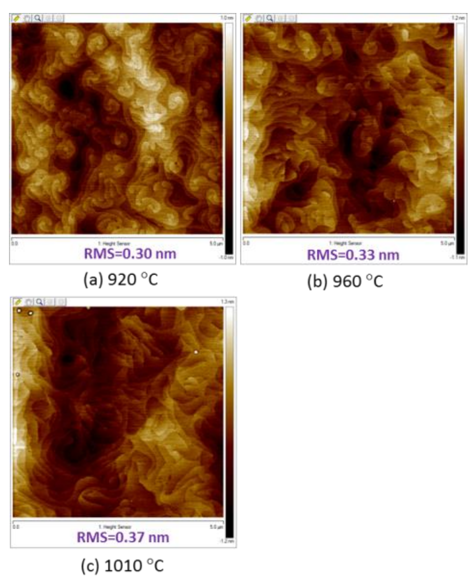
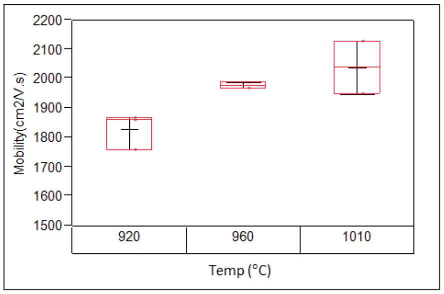
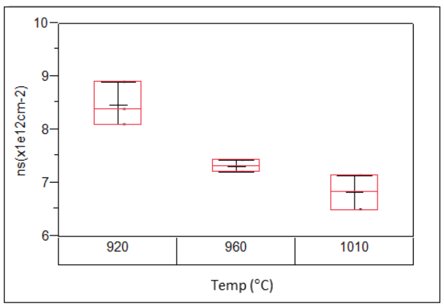


Fig. 4 5 μm x 5 μm AFM images of AlGaN/GaN hetrerostructures in N_2 ambient, (a) 920 °C, (b) 960 °C, (c) 1010 °C.

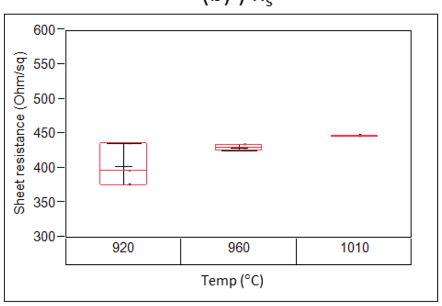
The electrical properties of the 2DEG in N_2 ambient from 920 °C to 1010 °C are shown in Fig. 5 (a)-(c). The difference in n_s is likely related to the difference in Al composition, similar to the case of AlGaN in an H_2 ambient. Since the surface roughness is very similar for growth at different temperatures, the difference in mobility μ_n might be explained by the difference in n_s correlating to varying Al composition.



(a) Mobility



(b)) n_s

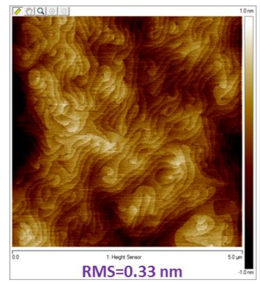


(c) Sheet resistance

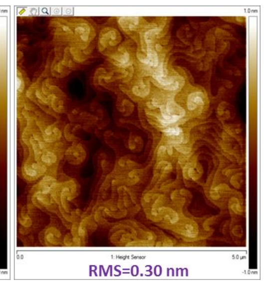
Fig. 5 Electrical properties of the AlGaN/GaN hetrerostructures in N_2 ambient at 920 °C, 960 °C and 1010 °C, (a) Mobility, (b) Sheet carrier concentration n_s, (c) Sheet resistance.

The Al composition (and growth rate) decreases as growth temperature increases for AlGaN layers in both H_2 and N_2 ambient from 920 °C to 1010 °C, which is likely caused by enhanced Al parasitic reactions with an increase of temperature [12]. No significant dependence of n_s and μ_n on growth temperature is observed for AlGaN layers grown at different temperatures, but having the same Al composition. However, the uniformity of Al composition improves at the lower growth temperature.

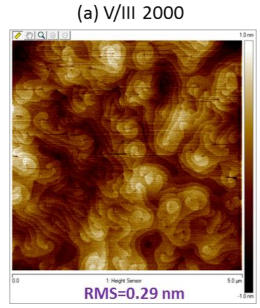
The effect of V/III ratios is investigated for AlGaN in N_2 ambient at 920 °C. V/III ratios are varied from 2000 to 12000 based on the NH_3 to the TMGa ratio. AFM images of AlGaN with different V/III ratios are shown in Fig. 6 (a)-(c). Similar to previous experiments, the TMGa and TMAl flows were kept constant. The Al composition in AlGaN layers does not decrease with the increase of V/III ratio (24.6%, 24.7%, 25.0% for V/III ratios at 2000, 4000, and 12000 respectively), indicating no significant increase of Al parasitic reactions with the increase of NH_3.



(a) V/III 2000



(b) V/III 4000



(c) V/III 12000

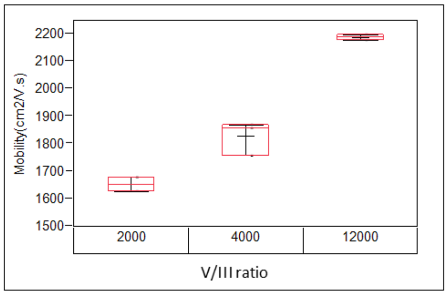
Fig. 6 5 μm x 5 μm AFM images of AlGaN/GaN hetrerostructures with different V/III ratio, (a) V/III = 2000, (b) V/III =4000, and (c) V/IIII = 12000 at 920 °C in N_2 ambient.

The 2DEG mobility increases with the increase of V/III ratio from 2000 to 12000, as shown in Fig. 7 (a)-(c). Since the electron transport is limited by the scattering of dislocations/ionized impurities, interface roughness, and alloy disorders [6-10], the enhanced 2DEG mobility could be attributed to the improved crystalline quality of AlGaN layers grown with high V/III ratio by suppression of nitrogen vacancies, improvement of smoothness and coherence of lattice/strain. With a V/III ratio of 12000, a Hall mobility 2200 cm^2/V.s with sheet carrier concentration 8.7e10^{12} cm^{-2} and sheet resistance 326 Ohm/sq is obtained.

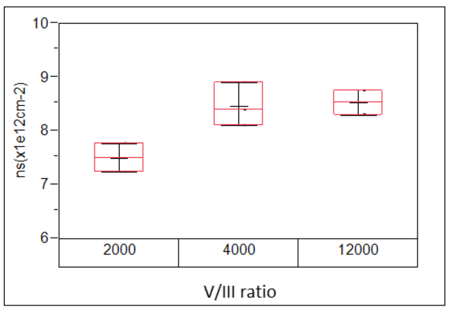
SUMMARY

The influence of MOCVD growth conditions (carrier gas, growth temperature, and V/III ratio) on the AlGaN barrier and the corresponding 2DEG for AlGaN/GaN heterostructures grown on 150 mm silicon was investigated. AlGaN layers in N_2 ambient show smoother surface

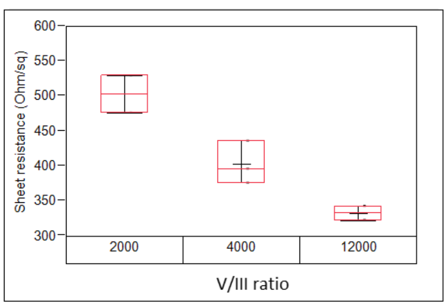
compared with those grown in H_2 ambient. Hall mobility 2200 $cm^2/V.s$, with sheet carrier concentration 8.7e10^{12} cm^{-2} and sheet resistance 326 Ohm/sq, was obtained for AlGaN grown at 920 ^oC in N_2 ambient and with high V/III ratios.



(a) Mobility



(b) n_s



(c) Sheet resistance

Fig. 7 Electrical properties of the AlGaN/GaN hetrerostructures grown at 920 ^oC with different V/III ratios (2,000, 4,000, and 12,000), (a) Mobility, (b) Sheet carrier concentration n_s, (c) Sheet resistance.

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Acronyms

MOCVD: Metal-Organic Chemical Vapor Deposition
HEMT: High Electron Mobility Transistors
2DEG: Two-Dimensional Electron Gas
R_{ON}: Specific on-state resistance
μ_n: 2DEG Hall Mobility
n_s: Sheet Carrier Concentration
ΔEc: Conduction Band Offset
PL: Photoluminescence
AFM: Atomic Force Microscope
RMS: Root-Mean-Square