Gate leakage in AlGaN/GaN HEMTs and its suppression by optimization of MOCVD growth

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Gate-drain current-voltage characteristics in unpassivated AlGaN/GaN high electron mobility transistors (HEMTs) grown by metal-organic chemical vapor deposition (MOCVD) on sapphire substrates were investigated. Under a fixed V/III ratio for AlGaN layer growth, the growth window for getting low gate leakage and good two-dimensional electron gas mobility is narrow. We designed a multi-step growth of the AlGaN for HEMTs, i.e., high-V/III-ratio AlGaN layer starting from the AlGaN/GaN interface, then low-V/III-ratio AlGaN layer, which yielded the best 2DEG mobility and also reduced gate leakage. It was also found that the forward current and reverse current before pinch off can be explained by the thin surface barrier (TSB) model, and the AlGaN layer grown under lower effective V/III ratio shows a larger surface donor density but smaller leaky area.

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1 Introduction AlGaN/GaN high electron-mobility transistors (HEMTs) have attracted lots of attention for their potentially excellent microwave power performances [1]. However, these devices still suffer from large reverse gate leakage currents, which decrease the breakdown voltage, degrade the gate-control characteristics and noise performance, as well as increase the power consumption [2]. In this work, we proposed a multi-step growth of the AlGaN barrier for HEMTs, i.e., high-V/III-ratio AlGaN layer starting from the AlGaN/GaN interface, then low-V/III-ratio AlGaN layer. This multi-step growth technique suppressed the gate leakage across the wafer substantially and enlarged the growth window.

2 Experiments AlGaN/GaN heterostructures were grown on c-plane sapphire substrates in an Aixtron 2000HT system for simultaneous growth of six 2-in wafers. The six satellites, spinning individually, are located center-symmetrically on a rotating circular susceptor for uniform growth. The system has a radial two-flow reactor design, with the upper flow for metalorganic sources, and lower flow for NH3/N2/H2 mixture and SiH4. Both the upper and lower flow were injected from the center of the reaction chamber and spread radially to the edge of the chamber. Trimethylgallium (TMGa), trimethylaluminum (TMAI), and ammonia were used as Ga, Al and N sources respectively. The epitaxial growth began with a 25-nm-thick GaN nucleation layer at a reactor temperature of 550 °C, followed by a 2.5-μm-thick unintentionally doped GaN layer at a reactor temperature of 1185 °C (wafer temperature ~ 1050 °C) as the device buffer. Then, a 2-mm-thick undoped GaN, a 24-mm-thick AlGaN layer were deposited at a susceptor temperature of 1140 °C (wafer temperature ~ 1015 °C). HEMTs fabricated in this work have a source-gate spacing of Lsg = 0.5 μm and a gate-drain spacing of Lgd = 1 μm. The gate width of the devices was 100 μm. Ni/Au was used as the gate metal and the nominal gate length was 1 μm.

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3 Results and discussion  
Sample 1 was grown with the NH$_3$ flowrate of 3000 sccm, corresponding to a V/III ratio of 1772. The Al composition was 30% and the AlGaN thickness was 24 nm. The uniformity of the Al composition and AlGaN thickness across the wafer were less than 2%. Figures 1 (a), (b) and (c) show the AFM images across the wafer of Sample 1. Density of line-shaped defects was high at the center of the wafer and decreased from the center towards the edge of the wafer.

![AFM images across the wafer of Sample 1](image)

The growth temperature across the wafer was very uniform in Aixtron 2000HT system. The surface morphology of the AlGaN/GaN heterostructures is strongly affected by the V/III ratio during growth [3]. The line-shaped defect density decreases with the V/III ratio. Our experiments of growth without satellite disk rotation showed that the V/III ratio increases along the radial direction of the susceptor, due to faster depletion of the III sources. For normal growth with individual satellite rotation, the growth at a certain position in the wafer is an average effect of the growth at the circular positions on the susceptor around the center of the satellite disk. Figure 1 indicates that the effective V/III ratio decreases from the wafer center to the wafer edge after such averaging effect.

A correlation of gate leakage of HEMTs and the effective V/III ratio during growth was found. At room temperature and $V_{gd} = -20$ V, the gate leakage current for devices from the center, middle and edge area of the wafer were measured to be $1.11 \times 10^{-3}$ A, $9.18 \times 10^{-5}$ A and $1.02 \times 10^{-6}$ A, respectively. The different leakage currents can be correlated to the decreasing line-shaped defects density from the wafer center to the wafer edge.

To reduce the line-shaped defect density in growth, the V/III ratio was decreased by substituting part of the NH$_3$ flow with the same flux of N$_2$/H$_2$ mixture (N$_2$:H$_2 = 1:9$). The Al composition and growth rate of AlGaN across the wafer were invariant when changing the V/III ratio. However, when the defect density was low enough for significantly improvement of surface morphology, the average mobility across the wafer decreased. The degraded mobility was caused by an increase of roughness at the AlGaN/GaN interface. A detailed investigation on the influence of V/III ratio on 2DEG mobility has been reported elsewhere [4]. These results pointed out that the growth window for AlGaN is narrow under a fixed V/III ratio.

As Keller et al. reported, the defects did not form at the interface but appeared in a later growth stage [3]. To combine the advantages of good interfacial 2DEG mobility of AlGaN grown under high V/III ratio and low line-shaped defect density of AlGaN grown under low V/III ratio, we designed a multi-step growth process of the AlGaN layer for HEMTs. A 10.8-nm-thick AlGaN layer was first grown with a constant NH$_3$ flow of 3000 sccm, followed by a 4.8-nm-thick AlGaN layer grown with a decreasing NH$_3$ flow from 3000 sccm to 1000 sccm, and then a 8.4-nm-thick AlGaN layer grown with a constant NH$_3$ flow of 1000 sccm (Sample 2). Figure 1(d) is the AFM image in the center area of Sample 2, which shows that the line-shaped defect density was significantly reduced. Similar to Sample 1, the line-shaped defect density decreased from the wafer center to the wafer edge, and no line-shaped defects were observed in the edge area. The average sheet charge density of 2DEG was $1.70 \times 10^{13}$ cm$^{-2}$ and the average mobility was 1040 cm$^2$/Vs across the wafer of Sample 2, with an uniformity of <5%. These results indi-
cate that the multi-step grown AlGaN can effectively improve the surface morphology without degrading the transport properties of 2DEG.

The reverse gate leakage current was largely reduced for devices from Sample 2 compared with those from Sample 1. At room temperature and Vgs = -20 V, the gate leakage currents were 6.36 x 10^-4 A, 2.47 x 10^-5 A and 5.05 x 10^-7 A for devices in the center, middle and edge area of Sample 2, respectively.

Igs-Vgs-T of HEMTs was measured to investigate the mechanism of the gate leakage current. To compare the samples with high-V/III-ratio AlGaN and multi-step AlGaN, two devices, denoted as Device A and Device B, were selected. Device A was from Sample 1 as well as device B was from Sample 2, and both devices were located 15 mm from the wafer center. The gate leakage current of devices A was slightly larger than that of devices located in the center area of Sample 2, where the leakage is the largest across the wafer of Sample 2. Figure 2 shows the Igs-Vgs characteristics of the two devices measured at temperature from 180 K to 500 K. For ln|Igs|-V curves of both devices measured at different temperatures, there is a turning point at Vgs ~ -4.5 V, corresponding to the pinch-off of the 2DEG channel under the gate, suggesting different mechanism for the increasing of the reverse leakage current before and after pinch-off. The mechanism of the forward current and the reverse leakage before pinch-off is related to properties of the AlGaN barrier and is discussed below.

For both samples, the forward ln|Igs|-V plots show the presence of straight line portions. The reverse ln|Igs|-V plots before pinch off of both samples also show a straight line, and the slope of the line changes with temperature. The linear characteristics of lnII-V is generally interpreted as an indication of thermal emission (TE), or thermionic-field emission (TFE) tunneling, or field emission (FE) tunneling, depending on how the slope changes with temperature.

Calculations indicate that the ideality factors of forward I-V change much slower than what TE model offers, indicating TFE or FE is the applicable model for interpreting the I-V characteristics. Padovani and Stratton theoretically analyzed the forward and reverse bias currents for TFE/FE tunneling process [5]. The ideality factor for forward currents, nF, is given by

\[
n_F = \frac{E_0}{kT} \coth \left( \frac{E_0}{kT} \right)
\]  

(1)

\[E_0 = \frac{\hbar}{2} \sqrt{\frac{N_D}{m^*e}}.
\]

(2)

where \(N_D\) is the donor density, and the definition of other parameters is the same as those in ref [6]. Figure 3 shows the \(n_F\) vs. T for both devices and the fitting of \(E_0\) from \(n_F\). Excellent fitting were obtained for \(E_0 = 39.5\) meV, and 65 meV for the three devices, respectively. From equation (3), \(N_D\) was determined to be 1.1x10^{20} cm^-3, and 3.0x10^{20} cm^-3 for Device A and Device B respectively.
Hasegawa and Oyama investigated the gate leakage mechanism of AlGaN/GaN HEMTs and explained the large gate leakage by the thin surface barrier (TSB) model [6, 7]. According to the TSB model, TSB regions in addition to normal barrier regions exist in Schottky contacts. The TSB region is formed by high density of unintentionally surface donors. Due to high nonuniformity of the GaN(AlGaN) surface involving many dislocation, it is highly likely that TSB regions are distributed spatially nonuniformly rather than being one uniform region [6]. The high $N_D$ of the two devices can be explained by high concentration of the surface donor. Calculations with TSB model also show good agreements of the ideality of reverse current-voltage characteristics before pinch-off at different temperatures for these two devices. Therefore, the forward and reverse current before pinch-off in this work can be explained by TFE with TSB model.

The surface donor concentration ($N_{DS}$) determines $E_{00}$ and the temperature dependence of the current. The barrier height and the (TSB area [leaky area]/total contact area) ratio determines the current density. Analysis of the I-V characteristics show that all these parameters are correlated with V/III ratio during growth of AlGaN layer. From the calculated results shown in Fig. 3, Device A has a much higher surface donor concentration than Device B. As described above, the effective V/III ratio for the growth of the top AlGaN layer of Device B is lower than Device A, which is likely to cause a higher density of nitrogen vacancy in Device B. The nitrogen vacancy was thought to be the origin of unintentional surface donors ($N_{DS}$) [6]. Therefore, as compared with Device A, a lower effective V/III ratio in Device B resulted in a higher $N_{DS}$ and a higher $E_{00}$. In addition, the surface defect (e.g., the line-shaped defects) density is much higher in Device A than in Device B, which means that the (TSB area/total contact area) ratio is much higher in Device A than in Device B, also resulted in much higher leakage current density.

Comparison of the leakage characteristics of Device A and B also show that this multiple-step AlGaN decreases the gate leakage and also enlarges the usable area on the wafer and the growth window.

### 4 Summary

In summary, we designed a multi-step growth of the AlGaN for HEMTs, i.e., high-V/III-ratio AlGaN layer starting from the AlGaN/GaN interface, then low-V/III-ratio AlGaN layer, which yielded the best 2DEG mobility and also reduced gate leakage. The forward current and reverse current before pinch off can be explained by the thin surface barrier (TSB) model. The AlGaN layer grown under lower effective V/III ratio shows a larger surface donor density. The multi-step growth of AlGaN layer shows a lower surface defect density, resulted in a lower total area of the TSB regions, and/or a higher effective Schottky barrier, leading to a lower leakage. All these results showed that the gate leakage was effectively suppressed and the growth window was enlarged using this multi-step AlGaN.

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