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High mobility AlGaIn/GaN heterostructures grown by gas-source molecular beam epitaxy

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We report on the growth of high electron mobility AlGaIn/GaN heterostructures on sapphire substrates by gas-source molecular beam epitaxy (GSMBE) using ammonia as the nitrogen source. Improvements in structural, electrical, and optical properties of GaN and AlGaIn layers have been made to achieve this goal. For the growth of AlGaIn layers, the reflection high-energy electron diffraction revealed a twofold surface reconstruction, indicative of atomic smoothness of the film surface. High mobility two-dimensional electron gas has been achieved in both unintentionally doped (by piezoelectric effect induced by lattice mismatch strain) and modulation doped AlGaIn/GaN heterostructures. The modulation-doped $n^+ - \text{Al}_{0.2}\text{Ga}_{0.8}\text{N}/i\text{-GaN}$ heterojunction exhibited electron mobilities as high as 750 and 4070 $\text{cm}^2/\text{V s}$ at 300 and 77 K, respectively. Both values are the highest ever reported for the AlGaIn/GaN heterostructures grown by MBE techniques. © 1998 American Vacuum Society. [S0734-211X(98)06603-7]

I. INTRODUCTION

(Al, Ga)N is an ideal material system for both ultraviolet (UV) optical devices and high-power, high-temperature electronic devices due to its wide direct band gap tunable from 3.4 to 6.2 eV and high electron saturation velocities. In particular, with a small lattice mismatch and large band offset between AlGaIn and GaN, the AlGaIn/GaN heterostructure is suitable for developing heterojunction devices with improved performance. There have been numerous studies on growth of AlGaIn/GaN heterostructures by metalorganic chemical vapor deposition (MOCVD)^{1,2} and molecular beam epitaxy (MBE),³ and two-dimensional electron gas (2DEG)^{4,5} and field-effect transistors (HFETs)⁶ were recently demonstrated. However, all of the AlGaIn/GaN heterostructures with highest electron mobilities reported to date were grown by MOCVD and previous efforts on growth of similar structures using MBE were less successful, resulting in much lower 2DEG electron mobilities⁷ compared to those grown by MOCVD.

In this article, we report on the growth of high mobility AlGaIn/GaN heterostructures on sapphire by gas-source MBE (GSMBE) using ammonia as the nitrogen source. The 2DEG in modulation-doped $n^+ - \text{Al}_{0.2}\text{Ga}_{0.8}\text{N}/i\text{-GaN}$ heterojunctions exhibited electron mobilities as high as 750 and 4070 $\text{cm}^2/\text{V s}$ at 300 and 77 K, respectively. Both values are the highest ever reported for the AlGaIn/GaN heterostructures grown by MBE techniques, and are comparable to the results reported for similar structures grown by MOCVD on sapphire substrates.

II. EXPERIMENTAL PROCEDURES AND RESULTS

The growth of the AlGaIn/GaN heterostructures was performed in a Varian GEN-II MBE system equipped with an ammonia gas injector. Detailed system configuration has

been previously reported.^{8,9} In this study, AlGaIn/GaN heterojunctions were grown on highly resistive undoped buffer GaN layers 2–3 μm thick. The film quality of the undoped GaN buffer layers was found to play a key role in achieving high mobility 2DEG. The growth conditions for the GaN buffer layers were optimized: growth temperatures around 800 °C with growth rates around 1 $\mu\text{m}/\text{h}$. High ammonia flow rates of 40–70 sccm were used and found instrumental to reduce the level of unintentional n -type doping generated by nitrogen vacancies. GaN films with significantly improved overall quality in structural, electrical, and optical properties have been achieved. Figure 1 shows the photoluminescence (PL) spectrum at 10 K for a typical high-quality GaN film. The FWHM of the main peak at 3.478 eV, which is attributed to the neutral-donor-bound exciton ($D^0 X$), was as narrow as 3.8 meV, whereas in the higher energy region a free A exciton peak at 3.483 eV was clearly observed; the yellow band emission was also absent in our samples. From van der Pauw Hall measurements, the as-grown undoped GaN films exhibited a resistivity of larger than $10^3 \Omega \text{ cm}$ with an electron mobility of 150 $\text{cm}^2/\text{V s}$ and a doping level of $1 \times 10^{17} \text{ cm}^{-3}$. The FWHM of the x-ray diffraction rocking curve of the as-grown GaN films was as narrow as 101 arcsec for the symmetric (002) and 104 arcsec for the asymmetric (102) directions, respectively, indicative of the high structural quality of the films.

Undoped ternary AlGaIn layers of typically 2000 Å thick were also studied. C -plane sapphire substrates were used for the growth, and the standard two-step deposition method was followed.¹⁰ A thin AlN nucleation layer of 200–300 Å was first deposited at 500 °C and then the substrate temperature was increased to high temperatures for the growth of the main layers. AlGaIn was either directly deposited on the low-temperature-grown AlN buffer or on a 1 μm thick GaN layer. The AlGaIn was grown at 800 °C at a growth rate of

FIG. 1. Photoluminescence of a 2 μm thick undoped GaN buffer layer. The FWHM of the D^0X peak is as narrow as 3.8 meV, and free excitons are also observed.

0.7 μm per hour. An NH_3 flow rate of 50 sccm was used, ensuring a N-rich condition. The Al beam flux was varied between 8×10^{-8} and 2×10^{-7} Torr for various Al compositions. The RHEED showed a very streaky (1×1) pattern during the growth of AlGaIn, indicating a smooth layer-by-layer two-dimensional growth mode. As the substrate temperature was lowered to below 500 $^\circ\text{C}$ after the growth, a sharp 2×2 RHEED reconstruction pattern was clearly observed along the (1120) azimuth, as shown in Fig. 2. We believe it was a result of the changed surface structure corresponding to increased group V coverage.¹¹ This is the first observation of twofold surface reconstruction for AlGaIn growth. The morphology of as-grown AlGaIn films was examined by Nomarski microscopy and scanning electron mi-

FIG. 2. Twofold RHEED reconstruction pattern observed along the (1120) azimuth for AlGaIn growth, indicating an atomically smooth surface.

FIG. 3. X-ray rocking curve of the $\text{Al}_{0.22}\text{Ga}_{0.78}\text{N}/\text{GaN}$ heterostructure. The FWHMs for the 2000 $\text{\AA}$ AlGaIn layer and the underlying 2 μm GaN buffer layer are as narrow as 120 and 95 arcsec, respectively.

croscopy (SEM). The films exhibited a mirror-like featureless morphology without cracks or textured patterns. The structural properties of the AlGaIn films were characterized by x-ray diffraction. Figure 3 shows the (0002) plane x-ray rocking curve of an AlGaIn/GaN heterostructure with 2000 $\text{\AA}$ AlGaIn grown on a 2 μm GaN layer. It can be seen that the diffraction peaks for both AlGaIn and GaN are well resolved, and the FWHMs of the peaks are as narrow as 95 and 120 arcsec for GaN and AlGaIn, respectively, indicating the high structural quality of the AlGaIn/GaN heterostructure.

With the capability of growing high-quality GaN and AlGaIn, undoped and modulation-doped AlGaIn/GaN heterostructures were grown on a high-quality highly resistive undoped GaN layers. First, thin AlGaIn layers of 300 $\text{\AA}$ were deposited on GaN buffer layers of different thickness, from 0.5 to 3 μm , to investigate the effects of the underlying GaN buffer layers. It was revealed that the undoped GaN buffer layers had to be above a certain thickness to obtain high mobility 2DEG in AlGaIn/GaN heterostructures. This observation can be explained by the reduced threading dislocation density near the AlGaIn-GaN interface with increased thickness of the GaN buffer layers. In the present work, a GaN thickness of at least 2 μm was found to be necessary. The Al composition of AlGaIn was calibrated by Vegard's law from x-ray diffraction data. In the 2DEG study described below, an Al composition of $x=0.2$ was chosen for all AlGaIn layers. The AlGaIn/GaN heterostructures consisted of an undoped i -GaN layer of 2–3 μm , followed by a 250 $\text{\AA}$ AlGaIn layer, either undoped or doped with Si to a level of 2×10^{18} to $6 \times 10^{18} \text{ cm}^{-3}$. An undoped AlGaIn spacer layer of 30–80 $\text{\AA}$ was inserted between the i -GaN and the n^+ -AlGaIn for the latter case. Van der Pauw Hall measurements were performed at 300 and 77 K to characterize the electrical properties of the as-grown samples. We have studied ohmic contacts to both n - and p -type GaN. Indium makes excellent practical ohmic contacts to both n -type and p -type GaN with linear I – V characteristics and thus apparently without significant barriers to carrier transport. The detail mechanisms are not completely understood yet. This indicates that for routine sample characterizations using van

FIG. 4. Temperature-dependent electron mobility and sheet carrier density for a modulation-doped AlGaIn/GaN heterostructure.

der Pauw Hall measurements, the complicated procedures of evaporating Al on *n*-type and Au on *p*-type GaN as ohmic contacts are not necessary. In this study, In dots were soldered to the surface of the as-grown samples to make ohmic contacts for measurements. For the undoped AlGaIn/GaN sample, an electron mobility of $583 \text{ cm}^2/\text{V s}$ was found at room temperature, and $2070 \text{ cm}^2/\text{V s}$ at 77 K. These enhanced mobilities, compared to those for bulk GaN, were clear indications of 2DEG. We have previously reported an observation of the 2DEG generated by the strain-induced piezoelectric field in a similar AlGaAs/GaAs/InGaAs system.¹² With a piezoelectric constant two to four times larger than that of GaAs, the strain-induced piezoelectric effect is expected to play a more important role in the formation of 2DEG in the AlGaIn/GaN system,¹³ with which our experiments exhibit good agreement. For modulation-doped samples, the 2DEG mobility was $753 \text{ cm}^2/\text{V s}$ at room temperature and $4070 \text{ cm}^2/\text{V s}$ at 77 K. Figure 4 shows the temperature-dependent Hall mobility and sheet carrier density for the modulation-doped sample. Electron mobilities reach $4070 \text{ cm}^2/\text{V s}$ and became constant at temperatures below 100 K, clearly indicating the existence of a 2DEG. Our results represent the highest reported 2DEG mobilities for AlGaIn/GaN heterostructures grown by MBE techniques. These mobility values are comparable to the best published data for the 2DEG in AlGaIn/GaN grown on sapphire by MOCVD.^{4,5} The sheet carrier density of these samples was in the range $1 \times 10^{13} - 4 \times 10^{13} \text{ cm}^{-2}$, depending on such

structure parameters as the doping level of the AlGaIn barrier and the thickness of spacer layer.

III. SUMMARY

High electron mobility AlGaIn/GaN heterostructures have been grown on sapphire substrates by GSMBE using ammonia as the nitrogen source. Significant improvements in structural, electrical, and optical properties for GaN and AlGaIn layers have been made to achieve this goal. For the AlGaIn growth, a $2 \times$ RHEED reconstruction pattern was observed for the first time, indicative of an atomically smooth surface of the layer. A 2DEG has been observed in both unintentionally doped and modulation-doped AlGaIn/GaN heterostructures. The modulation-doped $n + \text{-Al}_{0.2}\text{Ga}_{0.8}\text{N}/i\text{-GaN}$ heterojunctions exhibited electron mobilities as high as 750 and $4070 \text{ cm}^2/\text{V s}$ at 300 and 77 K, respectively. Both values are the highest ever reported for AlGaIn/GaN heterostructures grown by MBE techniques.

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