Effect of AlN Layers on The $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ Grown on Sapphire Substrates

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Abstract

The effect of a thin AlN layer inserted between $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ heterostructures grown on sapphire substrates was investigated for possible application in opto-electronic and power electronic devices. The heterostructures with two different Al compositions (0.35 and 0.49) were applied to study. After growing a thin AlN interlayer (~10nm) on the buffer GaN/AlN/sapphire substrate, then a thick $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ heterostructure were grown and investigated the Al mole fractions. Low rocking curves were also achieved with 0.35 and 0.48 for the 0.3 and 0.49 Al compositions, respectively. The experimental results show that with an increasing of Al composition, the crystallinity is also improved with lower surface roughness. The $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ heterostructures with 0.35 and 0.49 Al compositions were also investigated the electrical characteristics to confirm that they are suitable for development in optoelectronic and power electronic devices.

1 Introduction

The alloy of AlN and GaN and their alloy ($\text{Al}_x\text{Ga}_{1-x}\text{N}$) have been intensively studied for decades¹⁻⁶ and they are very important materials for many applications in opto-electronic and power-electronic devices such as visible and ultraviolet light-emitting diodes, high electron mobility, solar cell, high-power electronic devices, field-effect transistor and high-speed electronic devices operating at high temperature and environments, etc.⁷⁻¹⁷ $\text{Al}_x\text{Ga}_{1-x}\text{N}$ epitaxial layers are used for carrier confinement as electron blocking or barrier layers normally in laser and quantum-well ultraviolet light emitting diodes.¹⁸⁻²⁰ But there are a few publications on the properties of the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ alloy and most of these papers are studied on the characteristics of $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ heterostructures having low Al composition values.²¹⁻²² Thus, there is a very few papers studied the growth characterizations of $\text{Al}_x\text{Ga}_{1-x}\text{N}$ epitaxial layers having high Al composition above 0.2.²³⁻²⁴ Lee et al²⁵ studied $\text{Al}_x\text{Ga}_{1-x}\text{N}$ with varying compositions between 0 and 0.7 and found that there was an abrupt decrease in bulk electron concentration and mobility for x in the range of 0.4–0.6, beyond which the

crystal became semi-insulating. Meanwhile,²⁶ observed a rapid decrease in the net ionized donor concentration with increasing Al composition above 0.2. Therefore, the growth of $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ heterostructures having high Al compositions (with x is higher than 20%) which also shows excellent materials crystalline and opto-electronic characteristics is difficult to achieve because of the thermal convection of TMA during the growth at high temperature and the generation of surface cracks due to the large lattice mismatch between $\text{Al}_x\text{Ga}_{1-x}\text{N}$ and GaN.

In this paper, we report the effects of AlN interlayer of about 10 nm thick inserted in between GaN and $\text{Al}_x\text{Ga}_{1-x}\text{N}$ layers on the surface morphology of the top layer. And we also investigated this effect on the opto-electrical characteristics of $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ heterostructures with very high Al compositions (from 35% to 49%).

2 Materials and Method

All the epitaxial layers were grown in a homemade vertical MOCVD reactor system. Trimethylgallium (TMG), trimethylaluminum (TMA) and NH_3 (ammonia) were used as Ga, Al and N sources, respectively. The GaN and AlN layers were grown at the pressures of 300 and 150 Torr, respectively. Ammonia and metal organic sources flow were separated to reduce undesirable parasitic reaction. The reactor was also modified for prevention of pre-reaction, reduction of convection and full mixing of all sources and gases in front of the susceptor. Figure 1 shows a schematic diagram of the $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{AlN}/\text{GaN}$ structure grown on AlN nucleation/sapphire substrate. The 1.5 μm thick GaN layer was grown on sapphire for 60 min at 1040°C after growing a thin AlN nucleation layer. The growth condition of GaN layer was set with the flow rates of NH_3 , TMG and H_2 were 1500 sccm, 60 mmol/min and 6000 sccm, respectively. The AlN interlayer of 10 nm was grown onto that GaN layer at 1070°C and the surface morphology was observed with optical microscope and SEM before the next layer can be grown.

After growing the thin AlN interlayer then 200 nm $\text{Al}_x\text{Ga}_{1-x}\text{N}$ layer was grown on the top at 1060°C and 150 Torr with reducing the flow rate of TMA. During growth of the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ layers, the flow rates of NH_3 , TMG and H_2 were set at 1500 sccm, 40 mmol/min and 6000 sccm. And, the flow rates of TMA were then changed to increase Al content in $\text{Al}_x\text{Ga}_{1-x}\text{N}$. All the samples were characterized by triple crystal diffractometer (TCD), atomic force microscope (AFM), scanning electron microscope (SEM) and 4-points probing system for evaluating the effect of the AlN layer which was inserted in between GaN and $\text{Al}_x\text{Ga}_{1-x}\text{N}$ in individual $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ heterostructure.

3 Results and discussion

Figure 2 shows the surface roughness AFM scan of the 10 nm AlN layer which was grown on GaN/AlN/sapphire before the growth of each $\text{Al}_x\text{Ga}_{1-x}\text{N}$ layer to obtain different Al compositions on each sample. From the figure we can see the surface is very smooth with very low surface roughness (0.11 nm) and free dislocations can be seen.

From the figure 3, we can see each curve shows one high and one low peak, where the first one is related to the GaN layer and the other is that of $\text{Al}_x\text{Ga}_{1-x}\text{N}$. The Al composition of the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ was easily determined by calculating the distance between two peaks of $\text{Al}_x\text{Ga}_{1-x}\text{N}$ and GaN and applied the Vegard's law. The TCD FWHMs of the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ layers for (0002) diffraction grown on AlN interlayer/GaN/sapphire substrate were also determined. The FWHMs of $\text{Al}_{0.35}\text{Ga}_{0.65}\text{N}$ and $\text{Al}_{0.49}\text{Ga}_{0.51}\text{N}$ are 91 and 35 arcsec, respectively. As we can see, the incorporation of Al in $\text{Al}_x\text{Ga}_{1-x}\text{N}$ increases from 0.35 to 0.49, the crystallinity also increase. However, we do not know are there any variations between them or not since we are limited by the research conditions as well as the number of samples can be grown. However, as compared with a previous reported paper, the crystallinity of $\text{Al}_x\text{Ga}_{1-x}\text{N}$ layer which was grown directly on GaN without AlN interlayer showed a worse result than our work as the values of Al composition increases above 0.2.²⁵ The problem can be explained by the increase of the lattice mismatch between $\text{Al}_x\text{Ga}_{1-x}\text{N}$ and GaN, which occurs by raising the Al composition. Therefore, it is obvious that AlN interlayer between $\text{Al}_x\text{Ga}_{1-x}\text{N}$ and GaN plays a significantly important role in advancing the crystallinity of $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ heteroepitaxy by reducing the lattice mismatch, surface cracks, so on.

Figure 4 shows the surface morphologies observed by SEM with large scanned size of $\text{Al}_{0.35}\text{Ga}_{0.65}\text{N}$ (Figure 4-left) and $\text{Al}_{0.49}\text{Ga}_{0.51}\text{N}$ layers (Figure 4-right) grown on the thin AlN interlayer with no any cracks can be seen on both samples. However, there are some hills can be observed on the surface of the $\text{Al}_{0.35}\text{Ga}_{0.65}\text{N}$ and it is likely no any particles and very smooth on the surface of $\text{Al}_{0.49}\text{Ga}_{0.51}\text{N}$ layer.

Figure 5 shows the AFM images of $\text{Al}_{0.35}\text{Ga}_{0.65}\text{N}$ (Figure 5-left) and $\text{Al}_{0.49}\text{Ga}_{0.51}\text{N}$ (Figure 5-right) layers grown on the thin AlN interlayer. As we can see the cylindrical islands related to the Al composition. Thus, the surface roughness RMS values of $\text{Al}_{0.35}\text{Ga}_{0.65}\text{N}$ and $\text{Al}_{0.49}\text{Ga}_{0.51}\text{N}$ layers are 1.2 and 0.5 nm, respectively. This change of surface roughness agrees with the variation of crystalline measured by TCD and showed in Figure 3. Therefore, we can conclude that the tendency for two-dimensional lateral growth has become stronger than that for three-dimensional growth with the increasing of Al composition in $\text{Al}_x\text{Ga}_{1-x}\text{N}$ layer. So that, the thin AlN interlayer is really significant factor for the two-dimensional growth with lower defects.

We also measured the electrical resistivity of two samples which grown on GaN/AlN nucleation/sapphire substrates with AlN interlayer by four point probing method. The measured resistivities of the samples are 13.42 $\Omega\cdot\text{cm}$ for $\text{Al}_{0.35}\text{Ga}_{0.65}\text{N}$ and 36.50 $\Omega\cdot\text{cm}$ for $\text{Al}_{0.49}\text{Ga}_{0.51}\text{N}$. As the Al compositions in $\text{Al}_x\text{Ga}_{1-x}\text{N}$ increases from 0.35 to 0.49, the electrical resistivity also increases. It may result from the increment of the intrinsic $\text{Al}_x\text{Ga}_{1-x}\text{N}$ resistance related to their Al composition. Therefore, the Al composition can be considered as an important dominant factor independent of their other characteristics for the electrical resistivity of $\text{Al}_x\text{Ga}_{1-x}\text{N}$ with different Al compositions.

4 Conclusions

We have successfully investigated the effects of about 10 nm thick AlN interlayer

inserted between GaN and $\text{Al}_x\text{Ga}_{1-x}\text{N}$ on the characteristics of $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ heterostructures with different Al compositions from 0.35 to 0.49 with very low surface roughness and high TCD FWHMs have been obtained. From the results, we can conclude that It is possible to reduce the lattice mismatch by inserting a thin AlN interlayer. The electrical resistivity of $\text{Al}_x\text{Ga}_{1-x}\text{N}$ aslso increase consistently with the increase of Al composition due to the increase of the intrinsic $\text{Al}_x\text{Ga}_{1-x}\text{N}$ resistivity related to the higher Al composition.

Acknowledgements

We would like to thank the University of Cambodia for all financial support to carry out this research as well as the assistant of many people at the University of Cambodia.

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Figure 1. Schematic diagram of the $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ heterostructure grown with 10 nm AlN interlayer on the sapphire substrate

Figure 2. Shows TCD results of $\text{Al}_x\text{Ga}_{1-x}\text{N}$ layer at the (0002) diffraction direction which was grown on the thin AlN interlayer and GaN/sapphire substrate.

Figure 3. The diffraction patterns for the (0002) diffraction of $\text{Al}_x\text{Ga}_{1-x}\text{N}$ layers grown on the thin AlN interlayer and GaN/AlN/sapphire substrate

Figure 4. The surface morphology SEM images observed by of $\text{Al}_{0.35}\text{Ga}_{0.65}\text{N}$ (left) and $\text{Al}_{0.49}\text{Ga}_{0.51}\text{N}$ layer grown on the thin AlN/interlayer/GaN/AlN/sapphire substrates

Figure 5. AFM images of $\text{Al}_{0.35}\text{Ga}_{0.65}\text{N}$ (left) and $\text{Al}_{0.49}\text{Ga}_{0.51}\text{N}$ layer grown on the thin AlN/interlayer/GaN/AlN/sapphire substrates