DEFECT AND STRESS CONTROL OF ALGaN AND FABRICATION OF HIGH-EFFICIENCY UV-LED


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ABSTRACT

Defects and stress are the most serious issues for growth of AlGaN. Low-temperature deposited (LT-) AlN interlayer between AlGaN and GaN is found to reduce tensile stress during growth, and at the same time suppress the propagation of dislocations having screw components, by which UV-photodetector showing very-low-dark current has been successfully fabricated. However, additional pure-edge dislocations are generated at the LT-interlayer, which resulted in the poor emission property. In addition to the LT-interlayer, lateral growth at the trenched structure was used, thereby achieving crack-free AlGaN and reduction of the density of all types of dislocations in the AlGaN layer. UV light emitting diodes having AlGaN/GaN multi-quantum well active layer was fabricated on the low dislocation density AlGaN. The LED shows strong and sharp UV-emission from GaN-wells.

INTRODUCTION

The establishment of a high-yield growth technology utilizing a low-temperature-deposited (LT-) buffer layer on a sapphire substrate by metalorganic vapor phase epitaxy and the realization of conductivity control by doping with Si in case of n-type, and Mg followed by a dehydrogenation treatment in case of p-type resulted in the vast expansion of nitride research worldwide.1-4 Products and sales of nitride-based visible-light emitting diodes (LEDs) and violet laser diodes show an extremely high-growth rate in the market. It is expected that they will soon occupy the major portion in the optoelectronics industry.

Detectors and emitters in the vacuum ultraviolet (VUV)/ultraviolet (UV) region are one of the next targets for nitrides, which will have significant impact on the market as visible-LEDs. In order to establish such VUV/UV optoelectronics, high-quality and well-controlled AlGaN is essential. The crystalline quality of AlGaN on a sapphire substrate covered with an LT-AlN buffer layer is far superior to AlGaN directly grown on a sapphire substrate.5 However, it degrades progressively with increasing AlN molar fraction in the AlGaN. Although the quality was significantly improved when an AlGaN was grown on a high-quality GaN,6 at the same time a crack network originating from the lattice mismatch between AlGaN and GaN was generated with a high density if the thickness of AlGaN exceeded a critical value. In-situ stress monitoring revealed that the stiffness of AlGaN is modulated by Si doping or Mg doping; in other words, tensile stress during growth is increased while the strain keeps constant by Si-doping or Mg-doping.7

EFFECT OF LOW TEMPERATURE DEOPSITED ALN INTERLAYER

![Schematic structure of AlGaN growth using LT interlayer.](image)

Fig. 1 (a) Schematic structure of AlGaN growth using LT interlayer. (b) SEM photograph of 1 μm thick AlGaN grown by LT-interlayer technique. (c) SEM photograph of 1 μm thick AlGaN directly grown on GaN.
Table I  Density of threading dislocations of GaN on sapphire, AlGaN grown on sapphire and AlGaN grown on low temperature deposited interlayer (LT-IL) measured by transmission electron microscopy. Low temperature deposited buffer layer (LT-BL) on the sapphire substrate was used in the growth of all the samples.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Dislocation density [cm⁻²]</th>
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<tbody>
<tr>
<td></td>
<td>Pure edge</td>
</tr>
<tr>
<td>GaN/LT-BL/Sap.</td>
<td>1-2×10⁹</td>
</tr>
<tr>
<td>Al₀.₄₃Ga₀.₅₇N/LT-BL/Sap.</td>
<td>&gt;10¹¹</td>
</tr>
<tr>
<td>Al₀.₄₃Ga₀.₅₇N/LT-IL/GaN/LT-BL/Sap.</td>
<td>8-10×10⁹</td>
</tr>
</tbody>
</table>

Fig. 2  (a) Experimental setup for demonstration of p-GaN/i-Al₀.₂₅Ga₀.₇₅N/n-Al₀.₂₅Ga₀.₇₅N pin-type flame sensor. (b) Photocurrent response of the pin-type flame sensor. U₃₃₀ is visible light cut glass filter. Two left hand side figures are the result when the room light is turned off, while the two right hand side figures are the results when room light is turned on.

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We solved the fracture problem in an AlGaN on GaN heterostructure utilizing another LT-AIN layer. Figure 1 (a) schematically shows how to use another LT-AIN layer. The LT-AIN is inserted between the underlying GaN layer and the upper AlGaN layer, and therefore we call it the “LT-interlayer”. One of the major effects of the LT-interlayer is shown in figs. 1 (b) and (c). Thick and crack-free AlGaN is realized as shown in fig. 1 (b), while high-density crack network is formed when an AlGaN is directly grown on GaN as shown in fig. 1 (c). A combination of the (stress)×(thickness) product measured in-situ by a multi-beam optical stress sensor system and the thickness estimated by the interference of the optical beam revealed that tensile stress during the growth of AlGaN on a GaN layer is significantly reduced by the LT-interlayer. Therefore, nearly freestanding AlGaN can be grown on a GaN layer covered with an LT-interlayer.

Another effect of the LT-interlayer is summarized in Table I. LT-interlayer acts as a filter against threading dislocations which have screw components. A flame sensor which is not only solar-blind but also fluorescent-light-blind has been fabricated using the LT-interlayer. The result is shown in fig. 2.

One of the disadvantages of the LT-interlayer technique is also shown in Table I. Although threading dislocations which have screw components are significantly reduced, additional pure edge dislocations are generated with a density as high as 10^{10} cm^{-2} or more, which is found to act as a non-radiative recombination center. Therefore, the fabrication of highly luminescent AlGaN remains one of the most critical and difficult issues.

LOW TEMPERATURE INTERLAYER AND SLANTING GROWTH

Several epitaxial lateral overgrowth (ELO) techniques have been performed to grow partially low-dislocation-density GaN. The process of ELO involves initial selective growth on the window area and subsequent lateral growth on the mask area, the basic idea of which originated from the microchannel epitaxy in the growth of GaAs on Si. In the case of Al-containing alloys, however, polycrystals tend to deposit on the mask. Therefore, it is difficult to apply the conventional-ELO technique to the growth of Al-containing alloys.

\[ \text{Fig. 3 Schematic structure (figs. 3(a) and (b)) and the SEM images of each samples (figs. 3 (c) and (d)).} \]

\[ \text{BL: Low temperature deposited AlN buffer layer} \]
\[ \text{IL: Low temperature deposited AlN interlayer} \]
We applied a maskless dislocation density reduction growth technique for the growth of Al-containing alloys. Figures 3 (a) and (b) schematically depicts the structure. Trenches were formed on the thick and high-quality GaN. Threading dislocations were bent during the slanting growth of AlGaN on the trench area. The mechanism for dislocation bending during slanting growth is well known \(^{15}\) and has been already reported in the GaN growth. \(^{16}\) In case of pure screw type or mixed type dislocations, they induce stress field around them, by which they propagate keeping the relationship between the surface to be normal. \(^{15}\) In case of pure edge type dislocations, another mechanism was proposed. \(^{16}\) Therefore, a low-dislocation-density region is obtained above the trench area. Due to the lattice mismatch between AlGaN and GaN, however, many cracks were formed, as shown in fig. 3 (d). In order to achieve both crack-free and low-dislocation-density layer, we combined the LT-interlayer and the maskless slanting growth technique on the rugged structure. Initially, trenches were formed on the surface of GaN. Then, an LT-interlayer was deposited on the GaN with a trench. Finally, AlGaN was grown on the rugged GaN covered with the LT-interlayer. As shown in fig. 3 (c), no cracks were formed. Figure 4 shows the cross-sectional transmission electron microscopic image of the newly developed AlGaN. A low-dislocation-density region was formed above the trench area. As shown in fig. 5, the dislocation density of AlGaN above trench is \(2 \times 10^8\) cm\(^{-2}\) at most. Thus, dislocation is reduced by more than two orders of magnitude and simultaneously fracture is avoided.

Fig. 4 Cross sectional transmission electron microscopic image of Al\(_{0.19}\)Ga\(_{0.81}\)N on GaN covered with LT-interlayer. Low dislocation density region is achieved on the 5 \(\mu\)m wide trench area.

LT-IL: Low temperature deposited interlayer

DD: Dislocation density

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The luminescent properties of the $\text{Al}_{0.08}\text{Ga}_{0.92}\text{N}:\text{Si}/\text{GaN}$ multi-quantum wells (MQWs) grown on the newly developed $\text{AlGaN}$ were characterized by microscopic-photoluminescence (PL) mapping measurement at room temperature. The PL efficiency of the MQWs above the trench area is approximately one order of magnitude higher than that of MQWs grown on the terrace area, and is almost comparable to that of the $\text{GaInN}$-based MQWs used as the active layer in the violet-LD. This result clearly shows that reduction of density of all types of dislocations is essential to achieve highly luminescent $\text{AlGaN}$-based MQWs having GaN wells. UV-LEDs having such $\text{Al}_{0.08}\text{Ga}_{0.92}\text{N}:\text{Si}/\text{GaN}$ MQW active layer was fabricated. It shows intense UV emission with a peak wavelength of 352 nm emitted from the GaN wells. FWHM is as narrow as 6 nm, which is much narrower than that of GaInN based visible LEDs by a factor of two or more. Microscopic EL pattern clearly shows again the importance of reduction of all types of threading dislocations. Figure 6 shows the example of the demonstration of newly developed UV-LED. Blue, green and red phosphors are excited with the UV light from the UV-LED through U-330 visible light cut filter.
CONCLUSIONS

In summary, stress and defect control by LT-interlayer and slanting growth was studied. High performance UV-PD and high efficiency UV-LED was demonstrated. We can expect UV-LD based on a low-dislocation density AlGaN very soon.

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REFERENCES