Molecular Beam Epitaxy of AlGaPN Alloys for Optical Confinement Structure of Monolithic Optoelectronic Integrated Circuits on Si Substrate

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1. Introduction

Monolithic integration of III-V-based photonic devices and Si-based LSIs is one of the most promising approaches for fabricating optoelectronic integrated circuits (OEICs) [1]. III-V-N alloy semiconductors such as GaPN[2] and InGaPN[3] have been investigated as materials for light emitting device on Si. Recently, strained quantum well structure composed of a direct-transition semiconductor having well layer on Si has been intensively studied [4]. In order to realize a practical laser structure such as separate confinement heterostructure (SCH), a cladding layer, which can be lattice-matched to Si, is required.

An AlP-based III-V-N alloy is one of the candidates for the cladding layer, since the lattice constant of AlP has low refractive index and wide bandgap compared to GaP. For instance, AlP has 12.6 % lower refractive index than GaP at a wavelength of 850 nm. Lattice constants of AlP are decreased as increasing the nitrogen (N) contents and can be matched to Si by taking 3.3% N content. However, there are few studies on AlGaPN[6]. In this work, growth properties of AlGaPN, especially growth temperature and Al content dependence of N incorporation and the crystalline quality, were investigated. Then optical constants also investigated to design the optical confinement structure.

2. Experiments

Epitaxial growth of AlGaPN was carried out using a solid source molecular beam epitaxy (MBE) with rf-plasma cell for N source. A 50-nm-thick undoped GaP buffer layer was grown on undoped semi-insulating GaP (100) substrate. Then a 250-nm-thick AlGaPN layer was grown. Growth rate, rf-power and N₂ flow rate were set to be 0.66 µm/h, 150 W and 0.10 sccm, respectively. To see the effect of Al contents on the N incorporation, the Al contents in AlGaPN layer were varied by changing beam-equivalent flux ratio BEP(Al)/BEP(Ga) of 0, 0.80, 1.00 at the growth temperature of 550-700 °C. The N content was estimated from free-standing lattice constants of the epitaxial layer determined from (400) symmetrical and (511) asymmetrical x-ray diffractions, assuming the elastic constants of AlGaPN. The crystalline quality and refractive index were evaluated by using transmission electron microscopy (TEM) and ultraviolet/visible-near infrared spectrophotometer, respectively.

3. Results and discussion

The solid phase content of Al was not dependent on the growth temperature and equal to two beam flux ratio. Figure 1 shows the N composition in AlGaPN as a function of the growth temperature. It is clearly seen that N composition in AlGaPN is independent on the growth temperature. Figure 2 shows cross-sectional TEM images of AlGaPN layer grown at 550 °C and 600 °C. Both images show that the samples have high quality. Figure 3 shows the N composition in the AlGaPN layer as a function of Al content. The N composition dramatically increased in the low Al content range. Then it saturated in high Al content range. This enhancement of N incorporation efficiency at low Al contents could be expressed by the high cohesive energy of Al-N bond compared with Ga-N [8]. Also higher cohesive energy leads to low desorption rate of III element. At the grown surface, N-adatoms would create more stable bonds with Al than Ga, meaning that enhancement of N-incorporation efficiency by existing Al-atom at the surface. Therefore, experimentally observed phenomena can be explained by the difference of cohesive energy.

In order to design an optical confinement structure, knowing the optical constants of AlGaPN is necessary. The reflective index of AlGaPN was evaluated from the interference obtained in reflection spectra from AlGaPN grown on the GaP substrate. The results are summarized in Table I. In the case of GaPN with the N-contents about 2 %, clear interference was not observed, and thus, the reflective indexes of GaPN is almost the same as the GaP. Using the values in Table I, optical confinement coefficient was estimated by assuming conventional slab waveguide composed
Fig. 1. The N composition dependence on growth temperature of AlGaPN. RF-power and N$_2$ flow rate GaPN: 350W, 0.3sccm, AlGaPN: 150W, 0.1sccm.

Fig. 2. Cross-sectional TEM images of the AlGaPN/GaP.

Fig. 3. The N composition dependence on Al composition of AlGaPN.

Table I. Refractive index of evaluated AlGaPN and GaP to wavelength 850 nm.

<table>
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<tr>
<th>Sample</th>
<th>Refractive index n</th>
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<tbody>
<tr>
<td>Al$<em>{0.4}$Ga$</em>{0.6}$P$<em>{0.983}$N$</em>{0.017}$</td>
<td>2.98</td>
</tr>
<tr>
<td>Al$<em>{0.8}$Ga$</em>{0.2}$P$<em>{0.981}$N$</em>{0.019}$</td>
<td>2.85</td>
</tr>
<tr>
<td>GaP [5]</td>
<td>3.18</td>
</tr>
</tbody>
</table>

4. Conclusion

AlGaPN have been grown on GaP substrate by using a means of solid source MBE. The N content in AlGaPN was independent on the growth temperature.

Al$_{0.8}$Ga$_{0.2}$PN grown at 550 °C includes stacking faults. But stacking fault could be eliminated by increasing growth temperature at 600 °C. The N composition dramatically increased in the low Al content range, then saturated at the Al content above 0.4. The reflective index of AlGaPN was evaluated. These result shows that AlGaPN is useful as a low reflective index material of laser structure on Si.

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References