Abstract—Quaternary In\textsubscript{x}Al\textsubscript{y}Ga\textsubscript{1-x-y}N semiconductors have attracted much research interest because of the unique properties these materials offer. These include the great flexibility in tailoring their band gap profile while maintaining their lattice-matching and structural integrity. The structural and optical properties of In\textsubscript{x}Al\textsubscript{y}Ga\textsubscript{1-x-y}N alloys grown by molecular beam epitaxy (MBE) are presented. The structural quality of In\textsubscript{x}Al\textsubscript{y}Ga\textsubscript{1-x-y}N layers was characterized using high-resolution X-ray diffraction (HRXRD). The results confirm that the In\textsubscript{x}Al\textsubscript{y}Ga\textsubscript{1-x-y}N films have wurtzite structure and without phase separation. As the Al composition increases, the Bragg angle of the (0002) In\textsubscript{x}Al\textsubscript{y}Ga\textsubscript{1-x-y}N peak gradually decreases, indicating the increase in the lattice constant c of the alloys. FWHM of (0002) In\textsubscript{x}Al\textsubscript{y}Ga\textsubscript{1-x-y}N decreases with increasing In composition from 0 to 0.04, that could indicate the decrease of quality of the samples due to point defects leading to non-uniformity of the epilayers. UV-VIS spectroscopy has been used to study the energy band gap of In\textsubscript{x}Al\textsubscript{y}Ga\textsubscript{1-x-y}N. As the In composition increases, the energy band gap decreases. However, for In\textsubscript{x}Al\textsubscript{y}Ga\textsubscript{1-x-y}N alloys with In composition of 0.1, the band gap shows a sudden increase in energy. This is probably due to local alloy compositional fluctuations in the epilayer. The bowing parameter which appears also to be very sensitive on In content is investigated and obtained b = 50.08 for quaternary In\textsubscript{x}Al\textsubscript{y}Ga\textsubscript{1-x-y}N alloys. From photoluminescence (PL) measurement, green luminescence (GL) appears at PL spectrum of In\textsubscript{x}Al\textsubscript{y}Ga\textsubscript{1-x-y}N, emitted for all x at ~530 nm and become more pronounced as the In composition (x) increased, which is believed a cause by gallium vacancies and related to isolated native defects.

Keywords—HRXRD, nitrides, PL, quaternary, UV-VIS.

I. INTRODUCTION

Recently, III-nitride materials have been extensively studied because of their many applications for optoelectronic devices operating from blue-green to ultraviolet. Quaternary In\textsubscript{x}Al\textsubscript{y}Ga\textsubscript{1-x-y}N alloys offer increased capabilities for engineering the band gap, lattice constant, strain and polarization of the layers. In\textsubscript{x}Al\textsubscript{y}Ga\textsubscript{1-x-y}N alloys have been regarded as the most promising candidates to replace AlGaN or GaN as barriers due to their band gap and lattice constant that could be independently adjusted by varying the indium (In) and aluminum (Al) compositions [1]. Molecular beam epitaxy (MBE) opens up possibilities for the growth of quaternary alloys in the whole composition range, especially for the effective incorporation of In into high-Al-content In\textsubscript{x}Al\textsubscript{y}Ga\textsubscript{1-x-y}N quaternary alloys [2]. The structural and optical properties of In\textsubscript{x}Al\textsubscript{y}Ga\textsubscript{1-x-y}N alloys with In mole fraction x ranging from 0 to 0.01 and constant Al mole fraction y = 0.06 grown by MBE is presented.

II. EXPERIMENT

The epilayers of In\textsubscript{x}Al\textsubscript{y}Ga\textsubscript{1-x-y}N alloys were grown on sapphire (0001), with AlN buffer layer using MBE technique. The thickness of the epilayers is between 0.11-0.13 μm as measured by Filmetrics F20-VIS. The structure of the layers was studied by high resolution X-Ray diffraction (HRXRD). The HRXRD were carried out on a PANalytical X’pert MRD with a Cu-Kα radiation source to evaluate the crystalline quality of the In\textsubscript{x}Al\textsubscript{y}Ga\textsubscript{1-x-y}N quaternary films. The optical studies were performed in the wavelength range of 300-600 nm by a Hitachi U-2000 Japan double beam spectrophotometer. The absorption coefficient and energy band gap of In\textsubscript{x}Al\textsubscript{y}Ga\textsubscript{1-x-y}N layers were determined from these measurements. The PL measurements were carried out, by using Horiba Jobin-Yvon HR-800 UV PL system. A He-Cd laser with 325 nm was used as an excitation source. The PL spectra were obtained at room temperature from 330-650 nm.

III. RESULTS AND DISCUSSION

The structural properties of the quaternary In\textsubscript{x}Al\textsubscript{y}Ga\textsubscript{1-x-y}N alloys were analysed by HRXRD. Fig. 1 shows the 20 XRD spectra of In\textsubscript{x}Al\textsubscript{y}Ga\textsubscript{1-x-y}N grown by MBE. The XRD measurements confirmed that the heterostructures of quaternary In\textsubscript{x}Al\textsubscript{y}Ga\textsubscript{1-x-y}N were epitaxially grown on sapphire.
The pattern revealed (0002) substrate peaks at 41.65°-41.70° which correspond to sapphire (Al₂O₃). The peaks at 34.41°-34.57° correspond to InₓAlᵧGa₁-x-yN (0002). The peaks in the range of 35.76°-35.93° and 72.53°-72.94° correspond to AlN (0002) and AlN (0004) planes, respectively. These results confirm that the InₓAlᵧGa₁-x-yN films had wurtzite structure and without any phase separation.

To investigate the crystalline quality of the epilayers, the XRD rocking curve was also carried out in this study. Fig. 2 represents the full width at half maximum (FWHM) intensity of quaternary InₓAlᵧGa₁-x-yN alloys (0002) peaks as a function of the In mole fraction using XRD rocking curve. FWHM of (0002) InₓAlᵧGa₁-x-yN decreases with increasing In composition from 0 to 0.04, that could indicate the increase of quality of the samples. However, for InₓAlᵧGa₁-x-yN with In composition of 0.06 and 0.10, the figure shows a sudden increase in FWHM. This is probably due to local alloy compositional fluctuations (ACF) in the epilayer contributed by incomplete substitutions of Ga atoms that introduced point defects leading to non-uniformity of the quaternary alloys.

The optical properties were investigated in the spectral region of 300-600 nm using UV-VIS spectroscopy. Using these data, the absorption coefficient, \( \alpha \), can be calculated by applying the relation:

\[
\alpha = \frac{2.303}{d} \ln \left( \frac{1}{T} \right)
\]

where \( d \) and \( T \) are, respectively the film thickness and the transmittance.

The composition of the quaternary alloys covered the band gap range from 3.72 eV down to 1.86 eV. The band gap decreases with increasing In composition from 0.01 to 0.08. This trend is expected since the incorporation of In lowers the energy band gap of InₓAlᵧGa₁-x-yN [6]. However, for InₓAlᵧGa₁-x-yN with In composition of 0.10, the band gap shows a sudden increase in energy. This is probably due to a more significant effect of the local alloy compositional (ACF) in the epilayer contributed by incomplete substitutions of Ga atoms that introduced point defects leading to non-uniformity of the quaternary alloys.

The explanation for the \( b \) sensitivity on In-content in quaternary alloys could be the strong volume deformation in alloys varying In-content, due to large In atomic number and much larger In-N bonds compared to the Ga-N and Al-N bonds [7]. It should be noted here that the data of In = 0.10 is not taken into account for the determination of the bowing parameter because its energy band gap is placed outside the trend line of the other data.

![Fig. 4 shows the room temperature photoluminescence spectra of the quaternary samples InₓAlᵧGa₁-x-yN with the](image-url)
constant Al content ($y = 0.06$) and different In composition ($x$ varies from 0 to 0.1). The spectra for $x = 0$ and $x = 0.01$, there is one dominant peak with narrow FWHM at ~342 nm with energy band gap of 3.63 eV [8]. The presence of several peaks at $x = 0.02$ and 0.04 indicated point defects which originated from transition of defects energy levels in the band gap. At this point, their dominance interchanges with different value of $x$. As In composition ($x$) increased from 0.06 to 0.10, the first peak became broader and decreased in intensity. Moreover, it is slightly shifted to the higher wavelength (redshifts) indicating a decrease in the energy band gap, $E_g$ from 3.63 eV down to 3.09 eV (~402 nm) [9]. This trend is expected since the incorporation of In lowers the energy band gap of In$_{x}$Al$_{1-x}$N [6].

From Fig. 4, a secondary broad emission is also observed at ~530 nm. This peak corresponds to the green luminescence (GL) in In$_{x}$Al$_{1-x}$N and most likely cause by gallium vacancies and related to isolated native defect [10]. This GL peak appears at very low intensity for low In mole fractions, but it becomes more pronounces as the In content increased. In principle, this green luminescence actually attributed to the formation of indium-rich cluster. Somehow, the presences of GL at $x = 0$ is most probably due to the non-uniformity of ternary epilayers [10].

IV. CONCLUSION

In conclusion, the structural and optical properties of In$_{x}$Al$_{y}$Ga$_{1-x-y}$N quaternary alloys grown on sapphire by MBE with Al composition of 0.06 and different In mole fraction ranging from 0 to 0.10 has been investigated. The experimental results showed that the In$_{x}$Al$_{y}$Ga$_{1-x-y}$N epilayers were epitaxially grown on sapphire substrate. XRD rocking curve was used to investigate the FWHM of the (0002) peaks of In$_{x}$Al$_{y}$Ga$_{1-x-y}$N samples. The band gap of In$_{x}$Al$_{y}$Ga$_{1-x-y}$N alloys decrease with increasing In composition. However, for In composition of 0.1, the band gap shows a sudden increase in energy. A bowing parameter, $b$ of 50.08 has been obtained through this study. The secondary broad emission is observed through PL measurement, which corresponds to the green luminescence (GL) in In$_{x}$Al$_{y}$Ga$_{1-x-y}$N. These GLs are believed to be related to an isolated native defects (isolated gallium vacancies ($V_{Ga}$) or isolated complex involving $V_{Ga}$ and $V_{G}$) in the quaternary alloys.

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REFERENCES


