AlGaN-based laser diodes for the short-wavelength ultraviolet region

Harumasa Yoshida¹, Masakazu Kuwabara, Yoji Yamashita, Yasufumi Takagi, Kazuya Uchiyama and Hirofumi Kan

Central Research Laboratories, Hamamatsu Photonics K.K., 5000 Hirakuchi, Hamakita-ku, Hamamatsu 434-8601, Japan
E-mail: harumasa@crl.hpk.co.jp

New Journal of Physics 11 (2009) 125013 (14pp)
Received 30 April 2009
Published 17 December 2009
Online at http://www.njp.org/
doi:10.1088/1367-2630/11/12/125013

Abstract. We have demonstrated the room-temperature operation of GaN/AlGaN and indium-free AlGaN multiple-quantum-well (MQW) laser diodes under the pulsed-current mode. We have successfully grown low-dislocation-density AlGaN films with AlN mole fractions of 20 and 30% on sapphire substrates using the hetero-facet-controlled epitaxial lateral overgrowth (hetero-FACELO) method. GaN/AlGaN and AlGaN MQW laser diodes have been fabricated on the low-dislocation-density Al₀.₂Ga₀.₈N and Al₀.₃Ga₀.₇N films, respectively. The GaN/AlGaN MQW laser diodes lased at a peak wavelength ranging between 359.6 and 354.4 nm. A threshold current density of 8 kA cm⁻², an output power as high as 80 mW and a differential external quantum efficiency (DEQE) of 17.4% have been achieved. The AlGaN MQW laser diodes lased at a peak wavelength down to 336.0 nm far beyond the GaN band gap. For the GaN/AlGaN MQW laser diodes, the modal gain coefficient and the optical internal loss are estimated to be 4.7 ± 0.6 cm kA⁻¹ and 10.6 ± 2.7 cm⁻¹, respectively. We have observed that the characteristic temperature $T₀$ ranges from 132 to 89 K and DEQE shows an almost stable tendency with increase of temperature. A temperature coefficient of 0.049 nm K⁻¹ is also found for the GaN/AlGaN MQW laser diode. The results for the AlGaN-based laser diodes grown on high-quality AlGaN films presented here will be essential for the future development of laser diodes emitting much shorter wavelengths.

¹ Author to whom any correspondence should be addressed.
1. Introduction

Ultraviolet photonic devices such as laser diodes, light-emitting diodes (LEDs) and photodetectors have attracted considerable interest recently for a number of potential applications including chemical analysis, medical devices and material processing. Most of the currently used ultraviolet light sources are large, inefficient and expensive to run and only cover a discrete range of wavelengths. Switching to ultraviolet laser diodes and LEDs could address all of these issues.

Group III nitride materials are one of the most promising candidates for producing such devices. Ultraviolet laser diodes and LEDs with GaN, AlGaN or AlGaInN active layer can provide light emission at a wavelength shorter than 365 nm corresponding to the GaN band gap of 3.4 eV. The emission wavelengths of nitride-based LEDs have already covered the spectrum region down to a deep ultraviolet wavelength of 210 nm [1]. Despite the achievement of optically pumped stimulated emissions at the deep ultraviolet region from AlGaN and AlN materials [2, 3], only limited progress has been made in research on ultraviolet laser diodes. Several groups reported on ultraviolet laser diodes with various types of active layers such as AlGaInN/AlGaN (well/barrier), AlGaN/AlGaN, AlGaN/AlGaN or GaN/AlGaN quantum wells grown on sapphire, GaN and SiC substrates [4]–[9]. The reported emission wavelength region spanned only from 343 to 365 nm. Ultraviolet laser diode emission is shifting toward shorter wavelengths beyond these records. More recently, there have been a couple of reports on laser diodes with indium-free AlGaN active layer emitting in the shorter wavelength ultraviolet spectral region [10, 11].

Laser diodes require a more complex structure, thicker layers and lower dislocation density than LEDs to satisfy all the requirements of suitable optical and electrical confinements as well as high emission efficiency. Furthermore, in order to shift in the lasing wavelength toward the shorter ultraviolet wavelength region, AlGaN layers with high AlN mole fractions are necessary in the layer structure of laser diodes. The growth of AlGaN layers with high AlN mole fractions has serious problems due to the poor crystalline quality under the condition of a lack of suitably lattice-matched substrates [12]. At higher AlN mole fractions or layer thicknesses, the growth AlGaN layers on foreign and/or lattice-mismatched substrates such as sapphire, SiC and GaN substrates results in dislocations and eventually crack formation in
the epitaxial layers because of tensile strain. High-crystalline-quality (low-dislocation-density and crack-free) AlGaN materials with high AlN mole fractions are necessary for meeting the requirements of laser operation. However, bulk AlN and AlGaN substrates are not yet readily accessible as lattice-matched substrates for ultraviolet laser diodes [13].

It is well known, for blue–violet nitride-based laser diodes and LEDs, that emission efficiency is remarkably improved owing to indium-rich clusters, allowing the capture of electrons and holes in localized centers [14, 15]. The previously reported ultraviolet lasers have the benefit of indium in the active layers (excluding the GaN/AlGaN active layer). AlN, GaN and InN have band gap energies of 6.2, 3.4 and 0.7 eV at room temperature, respectively. Accordingly, adding indium to the AlGaN active layer inhibits extending the emission toward the deep ultraviolet region. The lack of indium in the AlGaN active layer increases the probability of non-radiative recombination [16, 17]. The growth of AlGaN layers with reduced numbers of dislocations acting as non-radiative centers is a key to improve the emission efficiency without the assistance of indium.

In this paper, we report the successful growth of low-dislocation-density AlGaN layers with high AlN mole fractions of 20 and 30% on sapphire substrates using the hetero-facet-controlled epitaxial lateral overgrowth (hetero-FACELO) method [9, 18, 19]. Next, we describe the detailed characterization of GaN/AlGaN multiple-quantum-well (MQW) ultraviolet laser diodes with binary GaN wells and ternary AlGaN barriers fabricated on the AlGaN films. So far, there have been few studies on optical gain and temperature characteristics in nitride-based ultraviolet laser diodes. In order to improve the performances of laser diodes emitting in the shorter wavelength ultraviolet spectral region, more detailed studies are necessary on these characteristics. We present and discuss the optical and temperature characteristics here. Furthermore, we demonstrate indium-free AlGaN MQW laser diodes, in which the active region consists of ternary AlGaN wells and barriers, lasing in the shorter wavelength ultraviolet spectral region far beyond the GaN band gap without the assistance of indium.

2. High-quality AlGaN growth

High-quality AlGaN crystal films were prepared by the hetero-FACELO method on sapphire substrates [9]–[11]. Figure 1 shows a schematic illustration of the layer structure. Two kinds of Al_,Ga_(1−x)N films, one with nominal x = 20% and the other with x = 30%, were grown for the fabrication of GaN/AlGaN and AlGaN MQW laser diodes, respectively. The material growth for crack-free and low-dislocation-density AlGaN layers was carried out by metalorganic vapor-phase epitaxy (MOVPE). Trimethylgallium (TMG), trimethylaluminum (TMA) and ammonia (NH₃) were used as the source materials. The c-plane (0001) sapphire was used as the substrate. After the deposition of a buffer layer with a thickness of 25 nm at 500 °C on the sapphire substrate, a 2.5-µm-thick GaN layer was grown at 1050 °C. Following the deposition of SiO₂ striped masks along the ⟨1100⟩ axis on the GaN layer, inclined-facet GaN seed crystals were selectively grown at 900 °C through the masks by the facet-controlled epitaxy [20]. Both the width and the spacing of the stripe masks are 2–3 µm.

Then, for the GaN/AlGaN MQW laser diodes, a subsequent Al₀.2Ga₀.8N layer was laterally overgrown at 1150 °C on the inclined facets of the GaN seeds. A successful coalescence of each overgrown Al₀.2Ga₀.8N layer from opposite facets of the GaN seeds was achieved. There was no crack over the entire area of the 2 inch diameter wafer. Figure 2(a) shows half of the wafer on which the laser structure has already been grown. As a reference, similar layers were grown
Buffer layer

AlGaN overgrown layer

GaN

Sapphire substrate

\begin{align*}
\langle 0001 \rangle_{\text{GaN}} & , \\
\langle 1 \bar{1} 00 \rangle_{\text{GaN}} & \rightarrow \langle 11 \bar{2} 0 \rangle_{\text{GaN}}
\end{align*}

Figure 1. Illustration of an AlGaN crystal film grown on a sapphire substrate using the hetero-FACELO method.

on a sapphire substrate without the inclined-facet GaN seed crystals. A number of cracks were obviously generated in the wafer, as shown in figure 2(b). In order to evaluate dislocation densities by cathodoluminescence (CL), GaN/AlGaN MQWs were grown on the Al$_{0.2}$Ga$_{0.8}$N film (sample A). The CL observation revealed the low dislocation density of the Al$_{0.2}$Ga$_{0.8}$N film of sample A with an average dark spot density of 4 $\times$ 10$^8$ cm$^{-2}$ [9]. The reduction rate of the dislocation density of this Al$_{0.2}$Ga$_{0.8}$N film grown by the hetero-FACELO method is almost two orders of magnitude higher compared with the reported one ($>3 \times 10^{10}$ cm$^{-2}$ for $x = 22\%$) of an Al$_x$Ga$_{1-x}$N film directly grown on a sapphire substrate with a low-temperature AlN buffer layer [16].

Next, an Al$_{0.3}$Ga$_{0.7}$N film for the AlGaN MQW laser diodes was also grown in accordance with a similar procedure to that mentioned above. An Al$_{0.3}$Ga$_{0.7}$N layer was laterally overgrown at 1175 $\degree$C on inclined facets of the GaN seeds on another sapphire substrate. GaN/AlGaN MQWs were also grown on the Al$_{0.3}$Ga$_{0.7}$N film (sample B). Photoluminescence (PL) measurements for samples A and B were performed at room temperature using a 325 nm continuous-wave He-Cd laser, respectively. The PL intensity of sample B was 16\% lower than that of sample A. This result indicates that the crystalline quality of each sample is almost equivalent.

3. GaN/AlGaN MQW laser diodes

3.1. Fabrication of GaN/AlGaN MQW laser diodes

We fabricated GaN/AlGaN MQW laser diodes, in which the active region consists of GaN wells and AlGaN barriers, on the Al$_{0.2}$Ga$_{0.8}$N film. The layer structure on the Al$_{0.2}$Ga$_{0.8}$N film was composed of an n-Al$_{0.2}$Ga$_{0.8}$N contacting layer, an n-Al$_{0.2}$Ga$_{0.8}$N cladding layer, an Al$_{0.2}$Ga$_{0.8}$N guiding layer, GaN/AlGaN MQWs, an Al$_{0.2}$Ga$_{0.8}$N guiding layer, a p-Al$_{0.2}$Ga$_{0.8}$N cladding layer and a p-GaN contacting layer. A p-AlGaN electron-blocking layer with higher Al content than that of the cladding layer was incorporated into the waveguide on the MQWs. After the formation of 5 $\mu$m laser stripes and after exposing the n-Al$_{0.2}$Ga$_{0.8}$N contacting layer
by the conventional dry etching technique, a Ti/Al contacting pad was deposited on the exposed n-Al$_{0.2}$Ga$_{0.8}$N contacting layer. The Ni/Au contacting pad was deposited on the p-GaN contacting layer. Facets of the laser cavities were formed by dry etching. Finally, we successfully fabricated the GaN/AlGaN MQW laser diodes on the high-quality Al$_{0.2}$Ga$_{0.8}$N film without any cracks. High reflective coating was not employed for the cavity facets.

### 3.2. Optical characteristics of GaN/AlGaN MQW laser diodes

The optical characteristics of the GaN/AlGaN MQW laser diodes have been investigated. Figure 3 shows a series of room-temperature lasing spectra of a 500-µm-long cavity laser diode for different injection currents. These spectra were measured under the pulsed-current mode with a pulse duration of 100 ns and a repetition frequency of 5 kHz. The very weak spontaneous emissions can be observed below the threshold current. The full-width at half-maximum (FWHM) of the spectrum is approximately 5 nm at a current of 187 mA. The narrow spectrum of the spontaneous emission can be interpreted in terms of a homogeneous composition and a low fluctuation of the well width in the MQWs. The spectrum width becomes narrower with increasing the injection current of the laser diode. Above the threshold current, sharp lasing emissions at a wavelength of 359.6 nm with a FWHM of 0.3 nm, which was very close to the resolution limit of the spectrometer, were obtained at a current of 247 mA.

The light output–current ($L$–$I$) characteristic of the same device is shown in figure 4. The $L$–$I$ characteristic was also measured under the same pulsed-current mode (100 ns pulse width and 5 kHz repetition frequency) at room temperature. The device exhibits a clear nonlinear behavior in the $L$–$I$ characteristic with pulse output powers of more than 80 mW from one
Figure 3. Room-temperature emission spectra of the GaN/AlGaN MQW laser diode below and above the threshold. The laser was operated under the pulsed-current mode.

side of the cavity facets. The threshold current of 200 mA corresponds to a current density of 8 kA cm\(^{-2}\). The differential external quantum efficiency (DEQE) for the output from both cavity facets is estimated to be 17.4%. This DEQE is remarkably high compared with the previous reports on ultraviolet laser diodes [4, 5]. The operating voltage of the laser diodes was approximately 18 V at the threshold current. The high resistive characteristic of the device is considered to be due to the low carrier concentration and mobility of each AlGaN cladding and guiding layer, as well as the low conductivities of the p- and n-contacts that have not yet been optimized.

Next, we carried out gain spectroscopic analysis to estimate the modal gain of the GaN/AlGaN MQWs by means of the variable stripe length (VSL) method [21, 22]. A series of GaN/AlGaN MQW laser diodes with different cavity lengths was investigated by the electrically pumped VSL method. Figure 5 shows the modal gain \(G\) as a function of the injection current densities for the peak emission wavelength from the MQWs. \(G\) is related to the material gain \(g\) and the optical internal loss \(\alpha_i\) by

\[
G = \Gamma g - \alpha_i, \tag{1}
\]

where \(\Gamma\) is the optical confinement factor. Assuming that \(g\) is directly proportional to the current density \(J\), \(\alpha_i\) is estimated to be 10.6 ± 2.7 cm\(^{-1}\). A modal gain coefficient of 4.7 ± 0.6 cm kA\(^{-1}\) is found from the slope of the fitted line. The threshold condition is expressed by the following
Figure 4. $L$–$I$ characteristic of the GaN/AlGaN MQW laser diode lasing at a wavelength of 359.6 nm. The laser was operated under the pulsed-current mode at room temperature. DEQE is estimated to be 17.4% from the slope.

equation:

$$G = \frac{1}{L} \ln \frac{1}{\sqrt{R_1 R_2}},$$  \hspace{1cm} (2)

where $L$ is the cavity length and $R_1$ and $R_2$ are the reflectivities of each cavity facet. Assuming $R_1 = R_2 = 0.2$ as a reflectivity of the non-coated cavity facet with a typical refractive index of $\sim 2.6$ for the AlGaN wave guide and applying $L = 500 \mu m$ to equation (2), we can obtain $G = 32 \text{ cm}^{-1}$ for a threshold. The corresponding threshold current density is found to be $9 \text{ kA cm}^{-2}$ for $G = 32 \text{ cm}^{-1}$. The actual threshold current density of $8 \text{ kA cm}^{-2}$ is almost in agreement with the estimated one. Even lower threshold currents are expected by employing a highly reflective coating on the cavity facets.

3.3. Temperature characteristics of GaN/AlGaN MQW laser diodes

We have investigated the temperature characteristics of the GaN/AlGaN MQW laser diodes. The temperature dependence of the threshold current density $J_{th}$ and DEQE of another 500-$\mu m$-long cavity laser diode was investigated, as shown in figure 6. Lasing characteristics of the device were observed in the temperature range from $-5$ to $95 \degree C$ under the pulsed-current mode with a pulse duration of 10 ns and a repetition frequency of 5 kHz. Figure 6 shows relative threshold current densities and relative DEQEs normalized to unity at 25 $\degree C$. The characteristic temperature $T_0$ is derived by fitting an exponential dependence of $J_{th}$ on temperature to the experimental data. $T_0$ in the low-temperature range between $-5$ and $35 \degree C$ is estimated to be 132 K. Meanwhile, in the high-temperature range between 45 and
Figure 5. Modal gain $G$ as a function of current densities for peak emission (open squares) from the GaN/AlGaN MQW laser diodes. Measurement was performed under the pulsed-current mode (100 ns pulse width and 5 kHz repetition frequency) at room temperature. The solid line is a linear fit of the measured modal gains.

95 °C, $T_0$ drops down to the value of 89 K. This is mostly due to the increase of non-radiative recombination as well as the increase of electron current overflow from the active region to the p-cladding layer at a higher temperature.

In contrast to the change in $J_{th}$, DEQE did not decrease with an increase in temperature. It showed an almost stable or even slightly increasing tendency with an increase of temperature. Similar temperature dependences of DEQE were reported in GaInN laser diodes with longer emission wavelength [23, 24]. For indium-free GaN/AlGaN MQW laser diodes, this is the first observation of improved DEQE characteristic with rise in temperature. Generally, the increase of free carrier absorption due to the increase of $J_{th}$ results in a drop of DEQE at elevated temperature. However, a temperature rise leads to a drastic increase of free hole concentration in Mg-doped AlGaN [25]. The temperature-induced increase of the hole concentration is believed to improve the quantum efficiency for stimulated emission above the threshold.

Furthermore, temperature dependence in the emission spectra was measured for the device under the pulsed-current mode (10 ns pulse width and 5 kHz repetition frequency). Figure 7 shows the temperature dependence of peak lasing wavelength in the temperature range between -5 and 95 °C. The peak wavelengths were shifted to longer wavelengths with increasing temperature. A temperature coefficient of 0.049 nm K$^{-1}$ is derived from the slope of the fitted line. This result is in good agreement with the empirical Varshni equation for the temperature dependence of the band gap $E_g(T)$:

$$E_g(T) = E_0 - \frac{\alpha T^2}{T + \beta},$$

(3)
where $T$ is the temperature, $E_0 = 3.561$ eV, $\alpha = 9.39 \times 10^{-4}$ eV K$^{-1}$ and $\beta = 772$ K \cite{26}. Using equation (3), a temperature coefficient of $0.048$ nm K$^{-1}$ is calculated for the change in temperature from $-5$ to $95$ °C. The temperature coefficient of the GaN/AlGaN MQW laser diode is slightly smaller than that reported for a GaInN laser diode ($0.052$ nm K$^{-1}$) \cite{27}.

4. Indium-free AlGaN MQW laser diodes

The GaN/AlGaN MQW laser diodes can emit light only in a limited wavelength region due to the intrinsic band gap of binary GaN wells even without indium in the active layer. In contrast, AlGaN MQW laser diodes, in which the active region consists of AlGaN wells and barriers, offer the potential to access shorter wavelengths by adding AlN to the active layers being free from the influence of the very low band-gap energy of InN because of the indium-free design. In order to open the path for semiconductor laser diodes lasing at ultraviolet wavelengths deeper than that corresponding to the band gap of GaN ($\sim 365$ nm), we have fabricated and investigated indium-free AlGaN MQW laser diodes \cite{10,11}.

AlGaN MQW laser diodes were fabricated on the Al$_{0.3}$Ga$_{0.7}$N film. The layer structure on the Al$_{0.3}$Ga$_{0.7}$N film was composed of a 2.8-$\mu$m-thick n-Al$_{0.3}$Ga$_{0.7}$N contacting layer, a 600-nm-thick n-Al$_{0.3}$Ga$_{0.7}$N cladding layer, a 90-nm-thick AlGaN guiding layer, AlGaN MQWs, a 120-nm-thick AlGaN guiding layer, a 20-nm-thick p-AlGaN electron-blocking layer, a 500-nm-thick p-Al$_{0.3}$Ga$_{0.7}$N cladding layer and a 25-nm-thick p-GaN contacting layer. Devices were processed as ridge waveguide lasers in accordance with the same procedure as for the GaN/AlGaN MQW laser diodes. Three types of AlGaN MQW laser diodes have been fabricated with different combinations of AlN mole fraction in the well/barrier/guiding layers ranging from 4/14/14% to 6/16/16%. A highly reflective coating was not employed for the cavity facets of each device.

Figure 6. Temperature dependence of threshold current densities $J_{th}$ (solid circles) and DEQEs (open squares) of the GaN/AlGaN laser diode. $J_{th}$ and DEQE are normalized to unity at 25 °C. The solid lines indicate the best fits for the measured data.
Figure 7. Temperature dependence of peak emission wavelengths (solid circles) for the GaN/AlGaN laser diode. The laser was operated under the pulsed-current mode (10 ns pulse width and 5 kHz repetition frequency) at room temperature. The temperature coefficient is estimated to be 0.049 nm K$^{-1}$ from the slope of the fitted solid line.

Figure 8 shows a series of lasing spectra for the AlGaN MQW laser diodes with the AlN mole fraction in the AlGaN wells being 4, 5 and 6%. These spectra were measured under the pulsed-current mode with a pulse duration of 10 ns and a repetition frequency of 5 kHz. The laser operation has been successfully achieved for all the AlGaN MQW laser diodes with emission wavelengths at 342.3, 339.5 and 336.0 nm depending on the MQWs composition. By stepping up the AlN mole fraction in the AlGaN MQWs, we have pushed the lasing emission to the wavelength of 336 nm, which is the shortest wavelength ever achieved for a semiconductor laser diode. This emission wavelength of 336 nm is nearly identical to that of conventional nitrogen gas lasers (337 nm).

Figure 8 also shows two lasing spectra of the GaN/AlGaN MQW laser diodes with the emission wavelengths of 359.6 and 354.4 nm depending on the GaN well widths. The transition energy state can be shifted by varying the well width. However, only by the well width control, there is a limit for the GaN/AlGaN MQW laser diodes to shift the lasing wavelength toward the deeper ultraviolet region, because higher material gain for lasing should be required as a compensation for a low optical confinement factor at very narrow well thickness, as indicated in equation (1). The well thickness is, theoretically, estimated to be as low as $\sim$5 Å for achieving emission wavelengths around 340 nm based on a finite one-dimensional square well model. The calculated optical confinement factor $\Gamma$ is less than 1% for the GaN/AlGaN MQW laser diodes with such a narrow well thickness. Consequently, it is not practically possible for the GaN/AlGaN MQWs to access shorter wavelengths far beyond the GaN band gap. By contrast, AlGaN MQWs would provide the possibility of lasing emission at an even shorter ultraviolet wavelength.
Figure 8. A series of emission spectra of AlGaN and GaN/AlGaN MQW laser diodes. The lasers were operated under the pulsed-current mode at room temperature. The emission wavelengths are 336.0, 339.5 and 342.3 nm for AlGaN MQW laser diodes and 354.4 and 359.6 nm for GaN/AlGaN MQW laser diodes.

Figure 9 shows the $L-I$ characteristics of AlGaN MQW laser diodes with emission wavelengths of 342 and 336 nm. Both the devices exhibit a clear nonlinear behavior in the $L-I$ characteristics. For a 342 nm laser diode with a 900-$\mu$m-long cavity, the threshold current of 390 mA corresponds to a threshold current density of 8.7 kA cm$^{-2}$. The measured pulse output power from one side of the facets approaches a value as high as 16 mW. The DEQE for the output from both facets is estimated to be 8.2%. For a 336 nm laser diode with a 500-$\mu$m-long cavity, the threshold current density is around 17.6 kA cm$^{-2}$ with an output power of more than 3 mW and a DEQE of 1.1%. These are output characteristics comparable with previous reports on the ultraviolet laser diodes lasing at even longer wavelengths [4, 5]. Highly reflective coating on the cavity facets as well as optimized laser structures is required for achieving lower threshold current density. At the threshold current, the operating voltage of 25 V for the 342 nm laser diode was higher than that of the GaN/AlGaN MQW laser diode. A slightly increasing tendency of the operating voltage at the same current density with increase of AlN mole fraction in both the MQWs and guiding layers was observed. The high resistivities of these devices seem to be dominated mainly by those of the thick cladding layers with high AlN mole fraction.

There is a great difference in the performances of AlGaN MQW and GaN/AlGaN MQW laser diodes depending on the emission wavelength. In order to increase the emission efficiency, it is important to reduce the number of defects acting as non-radiative centers and improve doping in AlGaN layers for sufficient carrier concentration even with a high AlN mole fraction. Conductivity tends to decrease with increasing AlN mole fraction due to increases in donor and acceptor ionization energies, which lower the carrier concentrations, and also due to the degradation of crystalline quality, which decreases the carrier mobility [25, 28, 29].

New Journal of Physics 11 (2009) 125013 (http://www.njp.org/)
It would appear that the high resistivity of these devices is mainly attributable to the low carrier concentration and mobility of each AlGaN cladding and guiding layer. A typical solution might be to use superlattice and/or Mg-δ-doped layers [30, 31]. It is also important to optimize both the p- and n-contacts. These points are further problems to be solved to improve the conductivity of the devices.

Due to the large negative crystal-field splitting in AlN compared with the positive value in GaN, an unusual valence band structure of AlN gives rise to unique optical polarization properties in AlGaN materials. The optical emission is dominantly transverse electric (TE) polarized ($E \perp c$) for GaN. In contrast, the emission is predominantly transverse magnetic (TM) polarized ($E || c$) for AlN, because a crystal-field split-off hole state lies quite lower than each heavy and light hole state. The introduction of Al significantly changes the polarized optical gain property in the MQW [3], [32]–[36]. Based on these research results, the decrease in TE optical gain with increasing AlN mole fraction in the MQWs is considered to be the second reason for the increase in the threshold current density and the decrease in the DEQE [11]. In order to clarify this, further investigations are required.

The typical TE and TM emission spectra from the AlGaN MQW laser diode are shown in figure 10. Above the threshold, a very strong polarized emission was observed at the wavelength of 342 nm. The emission is TE polarized due to the continued dominance of TE optical gain in the Al$_{0.04}$Ga$_{0.96}$N/Al$_{0.14}$Ga$_{0.86}$N MQWs with relatively low AlN mole fraction as well as the high reflectivity for the TE mode as a result of the cavity facets. For AlGaN MQWs with rather high AlN mole fraction, the TM emission is expected to be the dominant laser emission due to the polarization properties of AlGaN materials for the reason described above.
Figure 10. Polarized emission spectra of the AlGaN MQW laser diode operating above the threshold. The emission is strongly TE polarized.

5. Conclusion

We have grown low-dislocation-density AlGaN films with AlN mole fractions of 20 and 30% on sapphire substrates using the hetero-FACELO method. GaN/AlGaN and AlGaN MQW laser diodes have been successfully fabricated on the Al$_{0.2}$Ga$_{0.8}$N and Al$_{0.3}$Ga$_{0.7}$N films, respectively.

The room-temperature operation of the GaN/AlGaN laser diodes with emission wavelengths between 359.6 and 354.4 nm has been demonstrated under the pulsed-current mode. A pulsed threshold current density of 8 kA cm$^{-2}$ has been achieved. The peak output power was as high as 80 mW with a DEQE of 17.4%. We have investigated the gain and temperature characteristics of the GaN/AlGaN MQW laser diodes. Using the VSL method, the modal gain coefficient and the optical internal loss are estimated to be 4.7 ± 0.6 cm kA$^{-1}$ and 10.6 ± 2.7 cm$^{-1}$, respectively. We have observed that $T_0$ ranges from 132 to 89 K and DEQE shows an almost stable tendency with an increase in temperature. A temperature coefficient of 0.049 nm K$^{-1}$ is also found for the device.

The AlGaN MQW laser diodes lased at peak wavelengths of 342.3, 339.5 and 336.0 nm depending on the AlN mole fractions in the MQWs. The emission wavelength of 336 nm is the shortest wavelength achieved so far for a semiconductor laser diode.

The GaN/AlGaN and AlGaN MQW laser diodes are useful sources of ultraviolet coherent light that can be used to access any ultraviolet wavelengths by designing the MQW configuration, unlike the currently used bulky ultraviolet lasers that cover only a discrete range of wavelengths. Indium-free AlGaN MQW laser diodes grown on low-dislocation-density AlGaN material should continue to provide opportunities for lasing emission into an even deeper ultraviolet region.

Acknowledgment

We acknowledge Professor Hiroshi Amano for valuable discussions.

*New Journal of Physics* **11** (2009) 125013 (http://www.njp.org/)
References

[1] Taniyasu Y, Kasu M and Makimoto T 2006 Nature \textbf{441} 325
[2] Takano T, Narita Y, Horiuchi A and Kawanishi H 2004 Appl. Phys. Lett. \textbf{84} 3567
[3] Shatalov M, Gaevski M, Adivarahan V and Khan A 2006 Japan. J. Appl. Phys. \textbf{45} L1286
[4] Kneissl M, Treat D W, Teepe M, Miyashita N and Johnson N M 2003 Appl. Phys. Lett. \textbf{82} 4441
[5] Kneissl M, Treat D W, Teepe M, Miyashita N and Johnson N M 2003 Phys. Status Solidi a \textbf{200} 118
[6] Masui S, Matsuyama Y, Yanamoto T, Kozaki T, Nagahama S and Mukai T 2003 Japan. J. Appl. Phys. \textbf{42} L1318
[7] Iida K et al 2004 Japan. J. Appl. Phys. \textbf{43} L499
[8] Edmond J et al 2004 J. Cryst. Growth \textbf{272} 242
[9] Yoshida H, Takagi Y, Kuwabara M, Amano H and Kan H 2007 Japan. J. Appl. Phys. \textbf{46} 5782
[10] Yoshida H, Yamashita Y, Kuwabara M and Kan H 2008 Nat. Photon. \textbf{2} 551
[11] Yoshida H, Yamashita Y, Kuwabara M and Kan H 2008 Appl. Phys. Lett. \textbf{93} 241106
[12] Ito K, Kawamoto T, Amano H, Hiramatsu K and Akasaki I 1991 Japan. J. Appl. Phys. \textbf{30} 1924
[13] Kneissl M, Yang Z, Teepe M, Knollenberg C, Schmidt O, Kiesel P and Johnson N M 2007 J. Appl. Phys. \textbf{101} 123103
[14] Chichibu S, Azuhata T, Sota T and Nakamura S 1996 Appl. Phys. Lett. \textbf{69} 4188
[15] Chichibu S F et al 2006 Nat. Mater. \textbf{5} 810
[16] Iwaya M, Nakamura R, Terao S, Ukai T, Kamiyama S, Amano H and Akasaki I 2000 Proc. Int. Workshop on \textit{Nitrde Semiconductors} (IPAP, Nagoya, 2000) (IPAP Conf. Ser. 1) p 833
[17] Hirayama H, Kinoshita A, Yamabi T, Enomoto Y, Hirata A, Araki T, Nanishi Y and Aoyagi Y 2002 Appl. Phys. Lett. \textbf{80} 207
[18] Kamiyama S, Iwaya M, Takanami S, Terao S, Miyazaki A, Amano H and Akasaki I 2002 Phys. Status Solidi a \textbf{192} 296
[19] Liu R, Bell A, Ponce F A, Amano H, Akasaki I and Chems D 2003 Phys. Status Solidi c \textbf{0} 2136
[20] Hiramatsu K, Nishiyama K, Onishi M, Mizutani H, Narukawa M, Motogaito A, Miyake H, Iyechiya Y and Maeda T 2000 J. Cryst. Growth \textbf{221} 316
[21] Kim S T, Amano H and Akasaki I 1994 Appl. Phys. Lett. \textbf{64} 1535
[22] Kimura Y, Ito A, Miyachi M, Takahashi H, Watanabe A, Ota H, Ito N, Tanabe T, Sonobe M and Chikuma K 2001 Japan. J. Appl. Phys. \textbf{40} L1103
[23] Świetlik T et al 2006 Appl. Phys. Lett. \textbf{88} 071121
[24] Ryu H Y et al 2006 Appl. Phys. Lett. \textbf{89} 031122
[25] Li J, Oder T N, Nakarmi M L, Lin J Y and Jiang H X 2002 Appl. Phys. Lett. \textbf{80} 1210
[26] Leroux M and Gil B 1999 \textit{Gallium Nitride and Related Semiconductors} ed J H Edgar, S Strite, I Akasaki, H Amano and C Wetzel (London: INSPEC) p 45
[27] Masui S, Tsukayama K, Yanamoto T, Kozaki T, Nagahama S and Mukai T 2008 Proc. SPIE \textbf{6909} 69090G
[28] Bremser M D 1999 \textit{Gallium Nitride and Related Semiconductors} ed J H Edgar, S Strite, I Akasaki, H Amano and C Wetzel (London: INSPEC) p 147
[29] Pophristic M, Guo S P and Peres B 2003 Appl. Phys. Lett. \textbf{82} 4289
[30] Kauser M Z, Osinsky A, Dabiran A M and Chow P P 2004 Appl. Phys. Lett. \textbf{85} 5275
[31] Nakarmi M L, Kim K H, Li J, Lin J Y and Jiang H X 2003 Appl. Phys. Lett. \textbf{82} 3041
[32] Suzuki M, U and enomiya T 1999 \textit{Gallium Nitride and Related Semiconductors} ed J H Edgar, S Strite, I Akasaki, H Amano and C Wetzel (London: INSPEC) p 159
[33] Nam K B, Li J, Nakarmi M L, Lin J Y and Jiang H X 2004 Appl. Phys. Lett. \textbf{84} 5264
[34] Shakya J, Knabe K, Kim K H, Li J, Lin J Y and Jiang H X 2005 Appl. Phys. Lett. \textbf{86} 91107
[35] Kawanishi H, Senuma M and Nukui T 2006 Appl. Phys. Lett. \textbf{89} 041126
[36] Chow W W, Kneissl M, Northrup J E and Johnson N M 2007 Appl. Phys. Lett. \textbf{90} 101116

\textit{New Journal of Physics} \textbf{11} (2009) 125013 (http://www.njp.org/)