A 342-nm ultraviolet AlGaN multiple-quantum-well laser diode

HARUMASA YOSHIDA*, YOJI YAMASHITA, MASAKAZU KUWABARA 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**

The realization of semiconductor laser diodes and light-emitting diodes that emit short-wavelength ultraviolet light is of considerable interest for a number of applications including chemical/biochemical analysis, high-density data storage and material processing. Group III nitride materials are one of the most promising candidates for fabricating such devices. Here we describe an AlGaN multiple-quantum-well laser diode that emits light at 342 nm, the shortest wavelength ever reported for an electrically driven laser diode. To fabricate the laser, a low-dislocation-density AlGaN layer with an AlN mole fraction of 0.3 was grown on a sapphire substrate using a hetero facet-controlled epitaxial lateral overgrowth (hetero-FACELO) method[1–3]. An AlGaN multiple-quantum-well structure was then grown on the high-quality AlGaN layer. Lasing at a wavelength of 342.3 nm was observed under pulsed current mode at room temperature.

Ultraviolet laser diodes (UV-LDs) and light-emitting diodes (LEDs) with GaN, AlGaN or AlGaInN active layers can emit light at a wavelength shorter than 365 nm due to GaN having a large bandgap energy of 3.4 eV. Operation of such nitride-based UV-LEDs has already been demonstrated in the deep UV at wavelengths as short as 210 nm (ref. 4). However, progress in developing short-wavelength electrically driven UV-LDs has been limited in recent years despite demonstrations of lasing and stimulated emission in the deep UV region from AlGaN and AlN layer under optically pumping[5,6]. Several groups have reported UV-LDs with AlGaInN/AlGaN (well/barrier), AlGaN/AlGaInN, AlGaInN/AlGaInN or GaN/AlGaN quantum wells grown on sapphire, GaN and SiC substrates[3,7–10]. However, the laser emission wavelengths reported span only from 343 to 365 nm, and detailed characteristics have only been reported for LDs operating at wavelengths of 350.9 nm or longer[3,7–9].

For LDs it is difficult to shift the lasing wavelength towards the shorter UV region, because they require a more complex structure, thicker layers and lower dislocation density than LEDs in order to achieve suitable optical and electrical confinement for lasing as well as high emission efficiency. The growth of AlGaN layers with high AlN mole fractions, which are typically used as cladding layers to achieve optical and electrical confinement, is very difficult because of issues with poor crystalline quality[11]. As a result of tensile strain, epitaxial AlGaN layers grown on substrates such as sapphire, SiC and GaN suffer from dislocations and crack formation, in particular at higher AlN mole fractions or for thicker layers. AlGaN materials with high AlN mole fractions and having high crystalline quality (low dislocation density and crack-free) are necessary for the fabrication of high-performance devices.

For blue-violet LDs and LEDs based on GaInN active layers, emission efficiency is improved by the presence of indium-rich clusters, which allows the capture of electrons and holes in localized centres[12,13]. Previously reported UV-LDs include small amounts of indium in all the active layers, with the exception of the GaN/AlGaN active layer. Indium-free AlGaN active layers have never been used in any previous UV-LD. However, the inclusion of indium in the active layers inhibits emission at shorter UV wavelengths because of the very small bandgap of the InN and its sensitive growth condition. We believe that it is possible to further shift the emission wavelength to shorter UV wavelengths by increasing the AlN mole fraction in the active layers. The lack of indium in the AlGaN active layers increases the probability of non-radiative recombination in the active layers[14,15]. From this point of view, it is important to grow the AlGaN layer with a reduced number of dislocations acting as non-radiative centres and demonstrate operation of UV-LDs in which the multiple quantum wells (MQWs) consist of AlGaN wells and barriers without the assistance of indium.

Here we report the first detailed characterization of an indium-free AlGaN MQW UV-LD fabricated on a sapphire substrate. First, a low-dislocation-density AlGaN layer was fabricated by metalorganic vapour phase epitaxy (MOVPE). $Al_{0.3}Ga_{0.7}N$ layers, even with relatively high AlN mole fractions of 0.3, were successfully grown by the hetero-FACELO method[1–3]. In order to evaluate the quality of the AlGaN layer, photoluminescence (PL) measurements from MQWs on the $Al_{0.3}Ga_{0.7}N$ layer (sample A) and an $Al_{0.2}Ga_{0.8}N$ layer (sample B) were performed. Sample B consists of the layers that have been used to previously fabricate 355-nm UV-LDs[3] and a low dislocation density with an average dark spot density of $3.9 \times 10^8\ cm^{-2}$ has already been determined by cathodoluminescence measurements. The PL intensity of sample A was 16% lower than that of sample B. This result indicates that the crystalline quality of sample A is almost equivalent to that of sample B, and that the $Al_{0.3}Ga_{0.7}N$ layer has a low dislocation density and is suitable for producing a UV laser structure.

Next, we fabricated UV-LDs on the $Al_{0.3}Ga_{0.7}N$ layer. The device structure is illustrated in Fig. 1. The design provides suitable optical confinement with a theoretically calculated factor of 0.8 in the waveguide as a result of the low refractive index of the $Al_{0.3}Ga_{0.7}N$ cladding layers. Figure 2a,b shows a series of room-temperature spontaneous and lasing spectra of a UV-LD

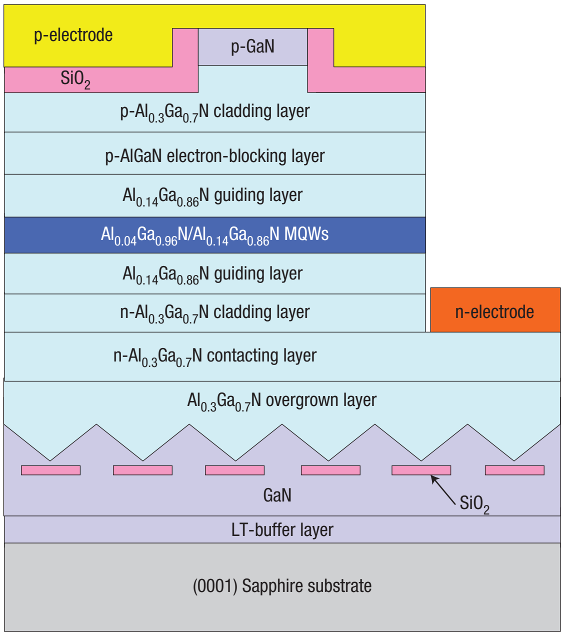

Figure 1 AlGaN MQW UV laser diode. The schematic shows a layer structure of an AlGaN MQW UV-LD on a sapphire substrate.

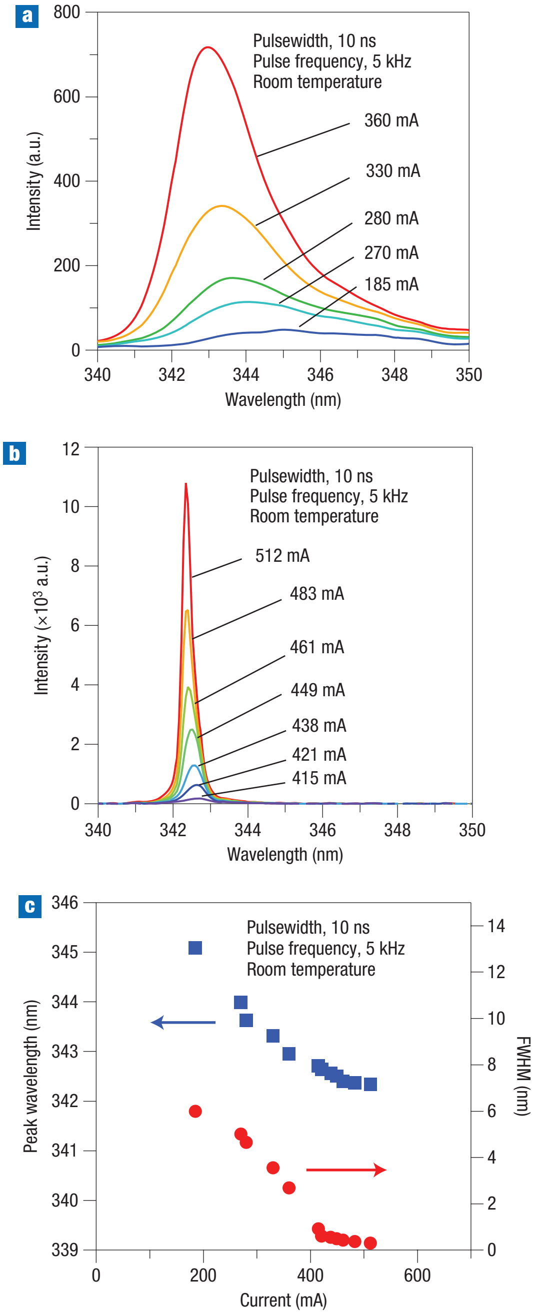

Figure 2 Room-temperature emission spectra. a,**b**, Emission spectra of the AlGaN MQW UV-LD for different injection currents below threshold (**a**) and above threshold (**b**). **c**, Peak wavelength and FWHM of emission spectra dependence on injection current.

with a 900 μm-long cavity operating below and above threshold, respectively. These spectra were measured using a calibrated spectrometer with a resolution of 0.3 nm and the LD was driven in pulsed-current mode with a pulse duration of 10 ns and a repetition frequency of 5 kHz. Spontaneous emission can be observed at a peak wavelength of approximately 345 nm with a full-width at half-maximum (FWHM) of only 6 nm at a current of 185 mA. This very narrow spectrum of the spontaneous emission can be interpreted in terms of a low fluctuation of the well width and a homogeneous composition in the AlGaN MQWs. The peak of the spontaneous emission shifts to a shorter wavelength and the width becomes narrower by increasing the injection current. The relatively broad lasing emission with a peak wavelength of 342.7 nm and a FWHM of 0.9 nm can be observed at a current of 415 mA, as shown in Fig. 2b. On increasing the injection current the peak of the emission slightly shifts to a shorter wavelength and the width becomes narrower. Finally, sharp lasing emission at a wavelength of 342.3 nm with a FWHM of 0.3 nm, which is very close to the resolution limit of the spectrometer, was obtained with a current of 512 mA. The multimode spectrum could not be resolved because of the narrow spacing (0.25 Å) of the longitudinal modes of the LD. Figure 2c shows the peak wavelength and the FWHM of spectra as a function of the injection current. Peak wavelength decreases almost linearly with increased injection current below threshold, accompanied by a linear narrowing of the FWHM. In contrast, nonlinear behaviour of the peak wavelength shift can be observed around the threshold current. Thermal bandgap narrowing is negligible, because the pulse duration of the injection current is as short as 10 ns. We attribute this shift of the emission wavelength mostly to the effects of screening the internal electric field and countering the quantum confined Stark effect[12,13,16,17]. The internal electric field is induced along the ⟨0001⟩ axis of the AlGaN MQWs by spontaneous and piezoelectric polarization. Although the reduced shift of the peak wavelength around the threshold is generally attributed to a clamping of the carrier density in the MQWs, a relatively strong screening of the internal electric field by free carriers can also be anticipated. Increasing electron–hole wavefunction overlap by this screening effect allows efficient electron–hole recombination in the MQWs, which could provide high optical gain for lasing.

The transverse electric (TE) and transverse magnetic (TM) emission spectra from the LD operating at a current of 450 mA are shown in Fig. 3 and were measured using a high-sensitivity spectrometer (Hamamatsu C7460). A very strong polarization of the laser output was observed above the threshold. The emission

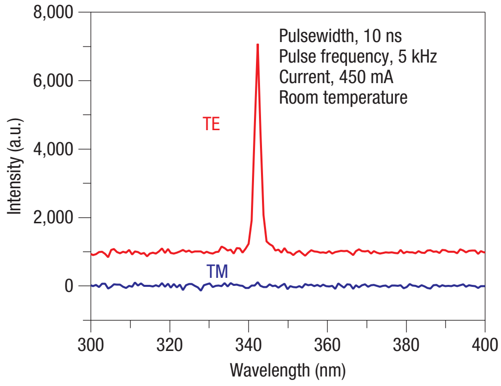

Figure 3 Polarized emission spectra. TE($E_{\perp}\langle 0001\rangle$) and TM ($E_{\parallel}\langle 0001\rangle$) polarized emission spectra of the AlGaN MQW UV-LD operating above threshold.

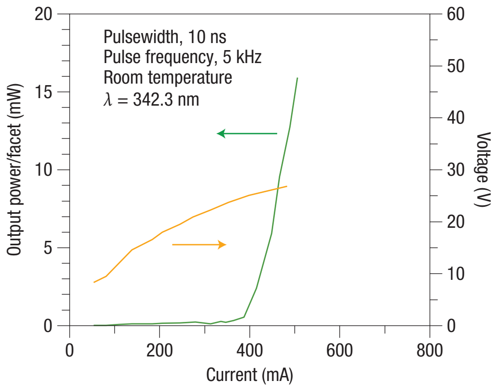

Figure 4 Light output power and electrical characteristics. Light output/current and voltage/current characteristic for the AlGaN MQW UV-LD lasing at a wavelength of 342.3 nm.

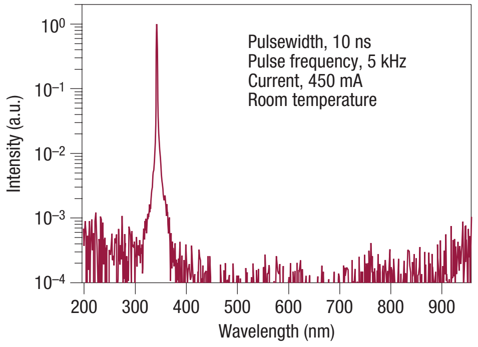

Figure 5 Wide band spectrum. Single sharp spectrum of the emission from the AlGaN MQW UV-LD measured by a wide band spectrometer.

is believed to be $E_{\perp}\langle 0001\rangle$ polarized due to the 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[6,18,19], as well as the high reflectivity of the TE mode as a result of the cavity facets.

Figure 4 shows the light output/current and the voltage/current (V–I) characteristics of the same device. The device exhibits clear nonlinear behaviour in the light output/current characteristic. 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 is close to 16 mW, as measured by a silicon photodiode (Hamamatsu S1337-1010BQ). The differential external quantum efficiency (DEQE) for the output from both facets was estimated to be 8.2%. These output characteristics are comparable with previous reports on UV-LDs lasing at longer wavelengths[3,7,8]. From the V–I characteristics, it can be seen that the operation voltage is 25 V at the threshold. The differential series resistance around the threshold is estimated to be ~32 Ω from the slope of the V–I curve. The device exhibits rather high resistive characteristics compared to previously reported UV-LDs[3,8,9]. Conductivity tends to decrease with increasing AlN mole fraction due to an increase in donor and acceptor ionization energies, which lowers the carrier concentration, and also as a result of the degradation in crystalline quality, which decreases carrier mobility[20–22]. It would appear that the high resistivity of this device is mainly attributable 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. A next step towards developing a higher-performance device for continuous-wave operation would be achieved through having a smaller device resistance.

It should be noted that the design and fabrication of UV-LDs is much more complex than that for LEDs, and it also requires the use of higher-quality materials. To confine a sufficient number of carriers in the MQWs so as to invert the electron population, we used AlGaN cladding layers with a sufficiently high AlN mole fraction. The low refractive index of the cladding layer also leads to substantial optical confinement in the waveguide. Non-radiative recombination results in an increase of lasing threshold or even failure of the population inversion. In all previous successful demonstrations of UV-LDs, several growth techniques were performed to reduce dislocation density in the layers[3,7–10]. The effects of using an AlGaN layer with a high AlN mole fraction of 0.3 and a low dislocation density brought about by the hetero-FACELO method appear to be critical for achievement of laser operation.

Figure 5 shows a wide band spectrum of the UV-LD (measured using a Hamamatsu C7460 spectrometer). No parasitic emission is observed at wavelengths from 200 to 950 nm. These results suggest that AlGaN MQW LDs offer an alternative to the currently used UV lasers.

In conclusion, we have demonstrated the operation of an electrically driven AlGaN MQW LD. We have successfully grown a low-dislocation-density AlGaN layer with an AlN mole fraction of 0.3 on a sapphire substrate using the hetero-FACELO method, and have fabricated AlGaN MQW UV-LDs on the AlGaN layer grown by MOVPE. The device lased at a peak wavelength of 342.3 nm, which is the shortest wavelength ever reported for a semiconductor LD operating in pulsed-current mode at room temperature. We have also reported, for the first time, detailed characteristics of an indium-free AlGaN MQW UV-LD. The laser emission is strongly TE polarized with a peak output power of 16 mW and a DEQE of 8.2%. AlGaN MQWs grown on a low-dislocation-density AlGaN layer would provide for the possibility of lasing emission at an even shorter UV wavelength.

METHODS

GROWTH OF THE LOW-DISLOCATION-DENSITY AlGaN LAYER

A low-dislocation-density AlGaN layer was grown by MOVPE. Following the deposition of a low-temperature (LT) buffer layer with a thickness of 25 nm at

500 °C on a (0001) sapphire substrate, a 2.5 μm-thick GaN underlayer was grown at 1,050 °C. Inclined-facet GaN seed crystals with a height of ∼2.5 μm were selectively grown at 900 °C by facet-controlled epitaxy[23] on the GaN underlayer, which was periodically masked by SiO_2 stripes. The SiO_2-striped masks with a width of 2 μm and a spacing of 2 μm were deposited along the $\langle 1\bar{1}00 \rangle$ axis on the GaN underlayer. An $Al_{0.3}Ga_{0.7}N$ layer was then laterally overgrown at 1,175 °C on the inclined facets of the GaN seeds. Finally, coalescence of each overgrown $Al_{0.3}Ga_{0.7}N$ layer from opposed facets of the GaN seeds was successfully achieved even with the relatively high AlN mole fractions of 0.3.

MEASUREMENTS

PL measurements were performed at room temperature using a 325 nm continuous-wave He-Cd laser. Conditions for each measurement were kept consistent by using a standard specimen of GaN.

DEVICE FABRICATION

The layer structure on the overgrown $Al_{0.3}Ga_{0.7}N$ layer was composed of a 2.8 μm-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 $Al_{0.14}Ga_{0.86}N$ guiding layer, $Al_{0.04}Ga_{0.96}N$/$Al_{0.14}Ga_{0.86}N$ MQWs, a 120-nm-thick $Al_{0.14}Ga_{0.86}N$ guiding layer, a 20-nm-thick p-AlGaN electron-blocking layer (EBL), a 500-nm-thick p-$Al_{0.3}Ga_{0.7}N$ cladding layer and a 25-nm-thick p-GaN contacting layer. The EBL is a commonly used thin layer with a higher AlN mole fraction than that of the cladding layers. After forming 5 μm ridge stripes and exposing the n-$Al_{0.3}Ga_{0.7}N$ contacting layer by conventional dry etching, Ni/Au and Ti/Al contact pads were deposited on the p-GaN and the exposed n-$Al_{0.3}Ga_{0.7}N$ contacting layer, respectively. The mirror facets of the laser cavities were formed by dry etching. No highly reflective coatings were used for the mirror facets.

SPECTROMETER CALIBRATION

The spectrometer used for measuring the series of spectra (Fig. 2) was calibrated by using the two mercury strong lines at 334.148 and 365.015 nm. The resolution of the spectrometer was defined by FWHM of the mercury lines.

The sensitivity of the spectrometer Hamamatsu C7460 was calibrated for a uniform spectral response over the entire range of wavelengths using calibrated standard light sources.

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Author information

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