Improved characteristics of InGaN multiple-quantum-well light-emitting diode by GaN/AlGaN distributed Bragg reflector grown on sapphire

N. Nakada[a)] and M. Nakaji
Department of Electrical and Computer Engineering, Nagoya Institute of Technology, Gokiso-cho, Showa-ku, Nagoya 466-8555, Japan

H. Ishikawa, T. Egawa, and M. Umeno
Research Center for Micro-Structure Devices, Nagoya Institute of Technology, Gokiso-cho, Showa-ku, Nagoya 466-8555, Japan

T. Jimbo
Department of Environmental Technology and Urban Planning, Nagoya Institute of Technology, Gokiso-cho, Showa-ku, Nagoya 466-8555, Japan

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An InGaN multiple-quantum-well light-emitting diode (LED) containing a GaN/AlGaN distributed Bragg reflector has been grown on a sapphire substrate by metalorganic chemical vapor deposition. Comparing with the conventional LED, the output power has been improved from 79 to 120 μW under 20 mA direct current biasing condition and the external quantum efficiency has been also improved from 0.16% to 0.23% under 10 mA dc current. [S0003-6951(00)03314-3]

GaN, AlN, and their alloys have attracted much attention for optical devices in the blue-ultraviolet region due to their direct transition type band gap structure. GaN-based edge emitting lasers have been extensively studied and have achieved room temperature continuous wave operation.[1] However, to make a flat edge mirror by cleaving from sapphire substrate and polish or dry etching is difficult. Recently, GaN-based vertical cavity surface emitting lasers (VCSELs) with a distributed Bragg reflector (DBR) have attracted much interest for various optical applications due to the fabrication of a smooth mirror without a cleavage technique.[2] Furthermore, the VCSEL can accumulate many devices in a two-dimensional array on the same substrate and its application to parallel light information processing in which the parallelism of light was fully employed efficiently or mass parallel light transmission is expected. The DBR is also effective in improving the output power of a light-emitting diode (LED).[3,4] Since both electrodes are attached to the upper part of sapphire, light is taken out from *p*-side electrode which is translucent for the GaN-based LED. Loss of light from sapphire substrate side is very large because the sapphire is transparent to visible light. If the DBR is introduced before fabrication of the LED, loss of the light in the side of a substrate can be reduced. Moreover, the DBR is useful for simplicity of the fabrication process. Thus, the DBR plays an important role in fabricating high performance optical devices such as a LED and VCSEL. The achievement of high reflectivity double-mirrors is necessary to perform high quality GaN-based VCSELs. Many stacks of periods are required to obtain the high reflectivity in quarter-wave GaN/AlGaN multilayer mirrors, when making such numbers of periods there is a problem referred to as cracks or surface flatness is spoiled. More recently the optical pumping VCSEL at liquid-nitrogen temperature was reported, which used the GaN/AlGaN DBR for the substrate side mirror and the dielectric multilayer mirror for the surface side.[5] The quarter-wave reflectors based on GaN/AlGaN heterostructures have been studied by many authors.[6–11] But the current injection type structure has not been reported yet.

In this study, the 15 periods of a quarter-wave $GaN/Al_{0.27}Ga_{0.73}N$ DBR with reflectivity of 75% on sapphire was used as bottom mirror, then, a LED was fabricated on a DBR as a preparation stage of current injected type VCSELs. We found that the $GaN/Al_{0.27}Ga_{0.73}N$ DBR as a bottom mirror has improved the output power and the external quantum efficiency of the InGaN multiple-quantum-well (MQW) LED on sapphire in comparison with the conventional LED.

A conventional horizontal atmospheric pressure metalorganic chemical vapor deposition technique was employed for the growth of samples on (0001)-oriented, 2 in. diameter sapphire substrates. Trimethylgallium, trimethylalminum, and trimethylindium were used as group III source materials and NH_3 as a group V. SiH_4 diluted in H_2 (10 PPM) and Cp_2Mg were used as the n-type and p-type dopants, respectively. The reflectivity of the DBR was measured by ultraviolet-visible spectrometer as a function of wavelength. Photoluminescence (PL) spectra were measured using a He–Cd laser as an excitation source, which was focused onto the surface of the samples at room temperature. The characteristics of LEDs were measured under direct current biasing condition at room temperature. The Al content in the $Al_{0.27}Ga_{0.73}N$ layer was determined from the double-crystal x-ray diffraction measurement.

Figure 1 shows the cross-sectional structure of the InGaN MQW LED with 15 periods of a $GaN/Al_{0.27}Ga_{0.73}N$ DBR grown on sapphire substrate. For DBR design, the refractive index of GaN and $Al_{0.27}Ga_{0.73}N$ as a function of wavelength were measured. Although GaN on sapphire is optically anisotropic with two independent refractive index

[a)]Electronic mail: nakada@mothra.elcom.nitech.ac.jp

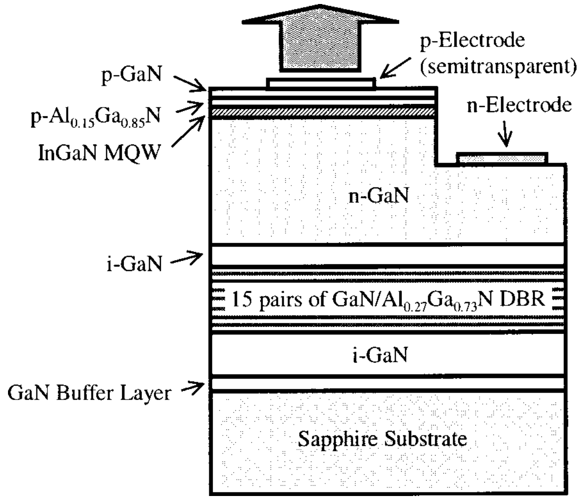

FIG. 1. Schematic structure of the InGaN MQW LED with 15 periods of the $GaN/Al_{0.27}Ga_{0.73}N$ DBR on sapphire.

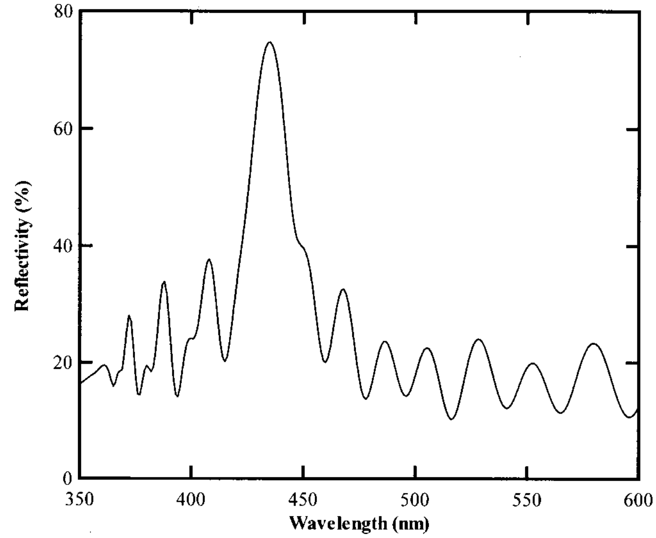

FIG. 2. Reflectance spectra of 15 periods of the $GaN/Al_{0.27}Ga_{0.73}N$ DBR grown on sapphire.

values, $n_\perp$ (perpendicular to the c axis) and $n_\parallel$ (parallel to the c axis), in our case we assumed GaN and AlGaN are optically isotropic because of small deviation of $n_\perp$ and $n_\parallel$. We used the refractive index values of 2.1 and 2.2 for GaN and $Al_{0.27}Ga_{0.73}N$ at a wavelength of 440 nm, respectively. Using these measured refractive index values, we designed a quarter-wave $GaN/Al_{0.27}Ga_{0.73}N$ multilayer with peak reflectivity centered at 440 nm. A thermal cleaning process was carried out at 1100 °C for 10 min in a stream of hydrogen ambient before growth. After depositing a low-temperature 100-nm-thick GaN layer, a 1-μm-thick GaN, and 15 periods of a quarter-wave $GaN/Al_{0.27}Ga_{0.73}N$ multilayer mirror were grown. Desired thickness of GaN and $Al_{0.27}Ga_{0.73}N$ were 50 and 52 nm, respectively. A 0.5-μm-thick undoped GaN layer and a 4-μm-thick n-type GaN layer with Si-doped to $\sim 1 \times 10^{19}\ cm^{-3}$ were grown on the DBR. Then three periods of quantum well consisting of a 5-nm-thick $In_{0.01}Ga_{0.99}N$ barrier and a 3-nm-thick $In_{0.13}Ga_{0.87}N$ well, a 20-nm-thick p-type $Al_{0.15}Ga_{0.85}N$ layer and a 0.2-μm-thick p-type GaN layer with Mg-doped to $\sim 1 \times 10^{18} cm^{-3}$ were grown. The growth rates of the GaN and $Al_{0.27}Ga_{0.73}N$ layers were 3.1 and 0.25 μm/h, respectively. The surface of the p-type GaN layer was partly etched till the n-type GaN layer by reactive ion etching in a BCl_3 plasma by using photoresist as the etch mask. The n- and p-side ohmic contacts were obtained with Ti/Al annealed at 900 °C for 30 s and Ni/Au at 600 °C for 3 min in N_2 ambient, respectively. The p-electrode was semitransparent and the diameter was 400 μm. For comparison, the LED without a DBR was also grown on sapphire.

Figure 2 shows the reflectivity spectra of 15 periods of the $GaN/Al_{0.27}Ga_{0.73}N$ DBR measured at room temperature. The DBR structure was designed to have the peak reflectivity at the wavelength of 440 nm, which coincides with the electroluminescence (EL) peak of the InGaN MQW LED without a DBR. A peak reflectivity of 75% was obtained at 435 nm. We confirmed that the $GaN/Al_{0.27}Ga_{0.73}N$ DBR exhibited the reflectivity of 93% for 30 periods of multilayer. However, the 30 periods of the DBR showed some cracks in the surface morphology by optical microscopy. Therefore, the 15 periods of the DBR was applied to the improvement of the LED. Figure 3 shows the PL spectra of the MQW structures with and without the DBR. As shown in Fig. 3, the PL spectra were modulated strongly for the MQW structure with the 15 periods of the $GaN/Al_{0.27}GaN_{0.73}N$ DBR. The mode space, for example 6.6 nm between 436.9 and 443.5 nm, was caused by the vertical cavity formed between the surface and the DBR. The mode spacing $\Delta\lambda$ is expressed as

$$\Delta\lambda = \frac{\lambda_0^2}{2n_{\text{eff}}L}, \tag{1}$$

where L is the cavity length and n_{eff} is the effective refractive index, which is defined as

$$n_{\text{eff}} = n\left(1 - \frac{\lambda_0}{n}\frac{\partial n}{\partial\lambda}\bigg|_{\lambda=\lambda_0}\right). \tag{2}$$

Inserting the following values, $\lambda_0 = 443.5$ nm, $n_{\text{eff}} = 3.1$, $L = 4.5\ \mu$m (from crosssectional scanning electron microscopy), we obtained $\Delta\lambda = 7.0$ nm. The mode spacing was in good agreement with the calculation.

The characteristics of light output power of the LEDs are shown in Fig. 4 as a function of injected current. The optical

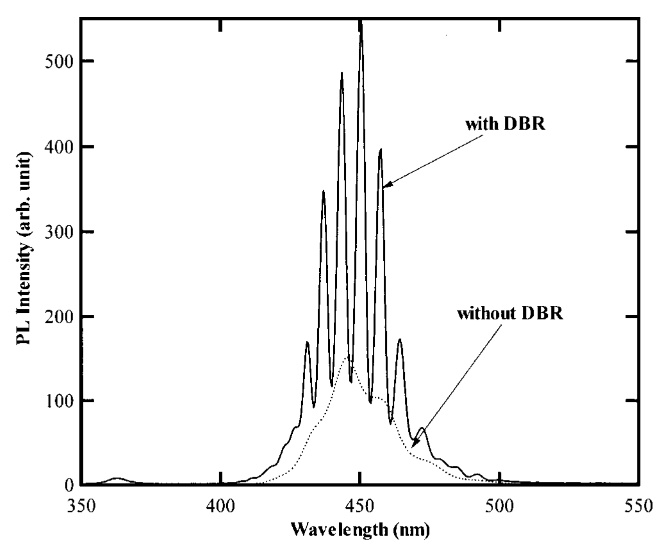

FIG. 3. PL spectra of MQW structures with and without 15 periods of the $GaN/Al_{0.27}Ga_{0.73}N$ DBR.

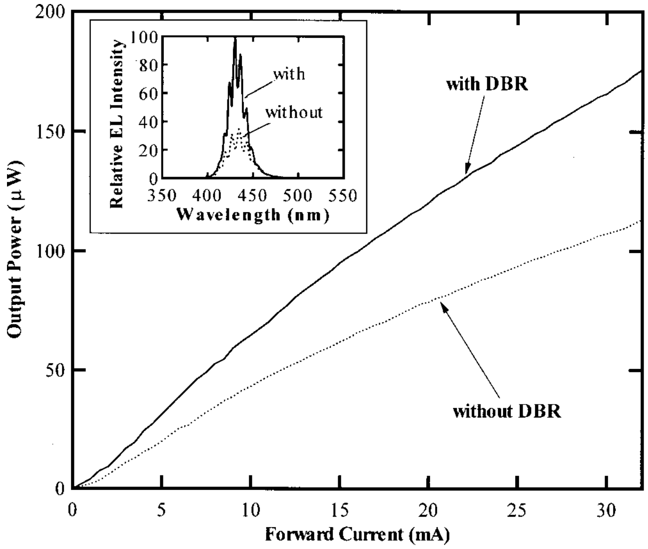

FIG. 4. The light output power of the MQW LEDs with and without 15 periods of the $GaN/Al_{0.27}Ga_{0.73}N$ DBR on sapphire as a function of the injected current. The inset shows the EL spectra for the InGaN MQW LEDs at 20 mA.

detector was set above the surface of samples to detect the surface emission. The light was not detected totally except the vertical light because the LEDs were not mounted and the light was not integrated. Six devices were successfully tested from each group of LEDs. We have shown the typical results obtained. The forward voltage was 4.5 V at an injected current of 20 mA and the series resistance was 60 Ω for the LED with the DBR, which were comparable to those of the LED without the DBR. The output powers of the LEDs with and without the DBR were 120 and 79 μW at 20 mA, respectively. The output power of the LED grown on the DBR is about 1.5 times larger than that of the LED without the DBR. It is also noticeable that the external quantum efficiency at 10 mA has been improved from 0.16% to 0.23% by use of the DBR. The enhancement of optical output and external quantum efficiency were contributed by the introduction of the DBR. This result suggested that a large fraction of the light propagated toward the emitting surface by the DBR. As shown in Fig. 4, a saturation of output power at a high-injected current was seen, that was probably due to the heating effect. The inset of Fig. 4 shows the EL spectra of the LEDs with and without the DBR at the injected current of 20 mA. The peak wavelengths of the LEDs with and without the DBR were 430 and 434 nm, respectively, and the full width at half maximum of the peak emission was 22 nm for both the LEDs. The peak wavelength of the EL spectra agreed well with the peak wavelength in the reflectivity spectra of the DBR.

In conclusion, the characteristics of the InGaN MQW LED on sapphire have been improved by use of the GaN/AlGaN DBR. For the InGaN MQW LED consisting of 15 periods of the GaN/AlGaN DBR with a reflectivity of 75%, the output power of 120 μW, and the external quantum efficiency of 0.23% were obtained which are about 1.5 times as large as those of the conventional LED. Thus, the DBR is very promising for the fabrication of high performance GaN-based LED as well as a VCSEL on sapphire.

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