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Short Note

Submicron-Scale Photoluminescence of InGaN/GaN Probed by Confocal Scanning Laser Microscopy

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Confocal scanning laser microscopy was used for the first time to obtain the submicron-scale photoluminescence (PL) of InGaN/GaN single quantum wells (SQWs). We found island-shaped spatial inhomogeneities of both PL intensities and spectra as small as 100-200 nm. The spatial resolution of the obtained PL images was much smaller than the diffusion length of carriers in active layers at room temperature. [DOI: 10.1143/JJAP.43.839]

KEYWORDS: confocal scanning laser microscopy, photoluminescence, InGaN/GaN, light emitting diode, quantum well, spatial inhomogeneity

Recently, InGaN/GaN-based light-emitting diodes (LEDs) and laser diodes (LDs) have been developed and used widely. The microscopic inhomogeneities of the optical properties of InGaN active layers are very important for emission efficiency.[1,2] Recently, cathodoluminescence (CL) mapping[3–5] and scanning near-field optical microscopy (SNOM)[6–9] have been used as powerful alternative methods of obtaining optical images of InGaN/GaN on the submicrometer scale. However, the spatial resolutions of such methods are limited by the diffusion lengths of carriers. In this note, we used photoluminescence (PL) spectroscopy with confocal scanning laser microscopy in order to obtain highly spatially resolved PL images and spectra at room temperature. Recently, O'Donnell et al. have published confocal microscopic images of InGaN/GaN,[10,11] but confocal microscopy has not been used thus far to observe the submicron-scale PL of InGaN/GaN.

A sample InGaN/GaN/AlGaN-based single-quantum-well (SQW)-structured LED wafer was grown by the metal-organic chemical vapor deposition (MOCVD) method on a (0001) C-face sapphire substrate. The device structure consisted of a 30 nm GaN buffer layer, a 5 μm-thick layer of n-type GaN:Si, a 3 nm-thick active layer of undoped InGaN, a 60 nm-thick layer of p-type AlGaN:Mg, and a 150 nm-thick layer of p-type GaN:Mg. The indium composition of the InGaN active layer was estimated to be 25–35%. The PL lifetime (τ_{PL}) and the carrier diffusion coefficient (D_{c}) of this sample at room temperature had already been reported as 20 ns and $0.6\,\mathrm{cm^2 s^{-1}}$, respectively.[12] Then, the carrier diffusion length (L) in this sample was estimated to be 1 μm using the relationship of $L = (D_{\mathrm{c}}\tau_{\mathrm{PL}})^{1/2}$.

The confocal scanning laser microscopy system manufactured by Tokyo Instrument (Nanofinder)[13] was used with a X100 objective lens ($N.A. = 0.95$, $\mathrm{F} = 1.8$ mm). The optical arrangement of the confocal scanning laser microscope is shown in Fig. 1. A cw beam from a 488 nm line of an Ar^+ laser at 0.5 mW was used as the excitation beam. The focal size of the laser beam was 300 nm under these conditions. The PL signals emitted from the samples were focused again on a small pinhole (8.5 μm) and the signals that passed through this pinhole were detected using a charge-coupled device (CCD) detector with a monochromator. Such a confocal optical system enables the highly spatial resolution beyond the diffraction limit of a light wave.[14,15] Therefore, the lateral spatial resolution of this system is as small as 200 nm.[13] The measurement was performed at room temperature (23°C). The excitation laser was focused around the upper layer region which includes the InGaN active layer of the LED structure. Photocreated carriers were created within an excitation spot size (300 nm) and diffused within the carrier diffusion length (1 μm at room temperature). PL was emitted by carrier recombination within the carrier diffusion length. Even if the excitation spot sizes of CL and SNOM were on the nanometer scale, the obtained optical images were broadened with increasing carrier diffusion length. Using confocal microscopy, the PL emitted within the spot size can pass the pinhole and be detected (Fig. 1).

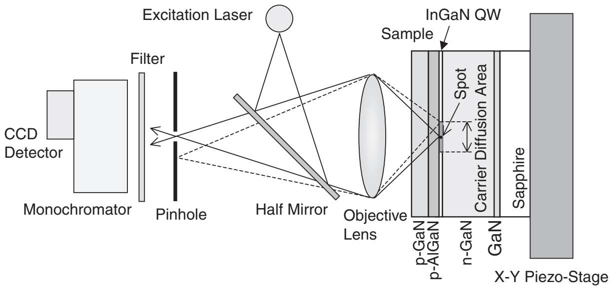

Fig. 1. Optical configuration of the confocal scanning laser microscopy and the sample structure of the InGaN/GaN quantum-well (QW)-based light-emitting diode (LED).

Figure 2(a) shows the PL image of InGaN/GaN with a 50 μm × 50 μm area using a conventional fluorescence microscope with a mercury lamp and color CCD camera. We obtained PL inhomogeneity on the micrometer scale in this figure. The spatial resolution was estimated as approximately 1 μm, which was similar to the carrier diffusion length in InGaN. Figure 2(b) shows the microscopic PL spectrum of this sample. The peak wavelength is 525 nm and the line width is about 100 nm. Using this setup, it was very difficult to observe the spatial dependence of the PL intensities or spectra.

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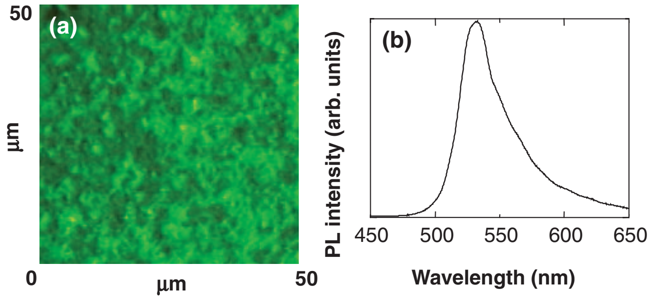

Fig. 2. Microscopic image (a) and microscopic photoluminescence (PL) spectrum (b) of InGaN/GaN LED excited by mercury lamp.

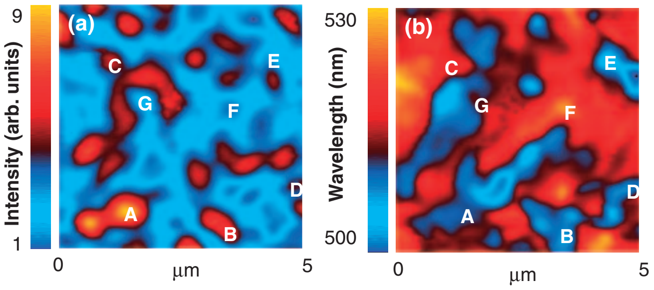

Fig. 3. Peak intensity mapping (a) and peak wavelength mapping (b) of the photoluminescence (PL) measured by scanning confocal laser microscopy of InGaN/GaN LED at room temperature.

Figure 3 shows the PL intensity mapping (a) and the PL peak wavelength mapping (b) of InGaN/GaN by scanning a 5 µm × 5 µm area using a confocal scanning laser microscope. We found clear and fine structures of both PL intensities and spectra smaller than the micrometer scale. The relative PL intensity fluctuated from 1 to 9 and the peak wavelength fluctuated from 500 to 530 nm. From the fine structures shown clearly in this image, the spatial resolution was estimated as approximately 200 nm, which was much smaller than the carrier diffusion length at room temperature (∼1 µm). We found that the correlation between PL intensity and peak wavelength is not clear in Figs. 3(a) and 3(b). We already reported similar behavior with NSOM measurement.[8] For the InGaN-based LED with blue emission (470 nm), a clear correlation has been reported between PL intensity and wavelength, where the areas of strong PL intensity correspond to those at a long wavelength.[9] However, such a correlation was not found for this InGaN-based LED with green emission. This finding suggests that the observed submicron-scale inland structure of inhomogeneities, which is mainly caused by the fluctuation of the indium component, does not act as the localized center of carriers and/or excitons in the active layer. Such microscopic optical properties are very important factors for the emission efficiency, though they have been very difficult to observe.

The submicron-scale PL spectra at positions A to G marked in Fig. 3 are depicted in Fig. 4. We obtained the PL spectra with various PL intensities and peak wavelengths. Such spatially resolved spectra were very difficult to obtain by conventional microscopy (Fig. 2). Quite recently, our group succeeded in obtaining high-resolution PL images by SNOM in the illumination-collection mode.[8,9] In this method, both excitation and detection were operated through the same optical fiber tip with 30 to 200 nm apertures, and we succeeded in obtaining higher spatially resolved inhomogeneities of both PL intensities and spectra.[8,9] In this note, we found that a similar highly resolved PL image was obtainable by confocal microscopy. The experimental setup and operation of confocal scanning laser microscopy are much easier and simpler than that of NSOM or CL mapping. To the best of our knowledge, this is the first report of confocal scanning laser microscopy and spectroscopy measurement for the submicron-scale inhomogeneity of the PL of InGaN/GaN-based LEDs. We conclude that confocal scanning laser microscopy is a very powerful and convenient technique for observing the submicron-scale optical properties of InGaN/GaN-based LEDs or other optical devices.

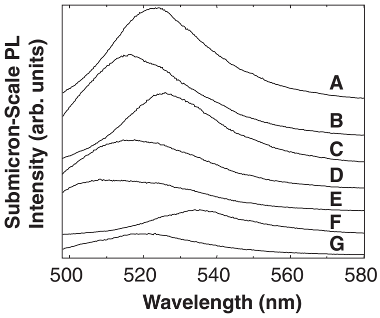

Fig. 4. Spatially resolved PL spectra of InGaN/GaN LED at positions A to G marked in Fig. 3.

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