Paper

Internal Quantum Efficiency of Nitride-based Light-Emitting Diodes

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ABSTRACT

The internal quantum efficiency (IQE) of InGaN-based light-emitting diodes has been studied by means of excitation-power-density- and temperature-dependent photoluminescence spectroscopy. The IQE was evaluated at various excitation photon energies using a wavelength-tunable dye laser system. The IQE obtained under selective excitation of InGaN active layers was higher than that obtained under band-to-band excitation of GaN and AlGaN cladding layers. The enhanced value of IQE under selective excitation reflected the intrinsic optical quality of the InGaN active layer itself.

KEYWORDS: internal quantum efficiency, InGaN-based light-emitting diode, selective excitation

1. Introduction

External quantum efficiency (EQE) is one of the most useful parameters to evaluate the device performance of light-emitting diodes (LEDs). Recently, the EQE of more than 60 % has been demonstrated for highly efficient InGaN-based blue LEDs[1]. The EQE of nitride-based LEDs operating in the UV to deep-UV and green spectral range is also expected to be improved in the near future[2].

It is well known that the EQE is approximately given by the product of internal quantum efficiency (IQE) and light extraction efficiency (LEE). In order to improve the EQE of LEDs, it is necessary to evaluate separately the two components, IQE and LEE, and to improve both components individually. However, there is no direct way to measure IQE experimentally. The best estimate of IQE is needed to evaluate and improve the device performance.

One usually measures temperature-dependent photoluminescence (PL) at a certain excitation condition in order to estimate IQE experimentally. Assuming that the PL efficiency at low temperature is equal to 100 %, one describes the ratio of the PL intensity at RT relative to that at low temperature as the IQE. This is one of the most simple and conventional method to estimate IQE. However, it is known that the IQE of nitride-based LEDs is strongly dependent on the carrier density injected into active layers of LEDs. In other words, the PL efficiency is strongly dependent on the excitation-power density even at low temperature. This is because nitride-based LEDs have a large number of defects which act as nonradiative recombination centers. Therefore, it is quite important to measure the PL efficiency as a function of excitation-power density, and to discuss the IQE which depends on the injected carrier density.

We have proposed so far the experimental procedure to estimate the IQE of InGaN-based LEDs by means of excitation-power-density- and temperature-dependent PL spectroscopy[3]. For example, the IQE of 64 % was obtained for a highly efficient LED sample with the EQE of 43 % at 406 nm. As a result, the LEE was estimated to be about 70 %. The IQE of 35 % was also obtained for another LED sample with the EQE of 24 % at 380 nm. In this case, the LEE was also estimated to be about 70 %. This coincidence of the LEE was consistent with the fact that both the two LED samples mentioned above were fabricated similarly on patterned sapphire substrates by lateral epitaxial growth technique[4]. On the other hand, in the above experiments, a Xe-Cl excimer laser (λexc = 308 nm) was used as an excitation source, which performed the band-to-band excitation of GaN and AlGaN cladding layers. Then, most of the photo-excited carriers were created into GaN and AlGaN cladding layers.

In the present work, we measure the PL
efficiency of nitride-based LEDs at various excitation photon energies using a wavelength-tunable dye laser system. This enables us to evaluate the IQE of LEDs under selective excitation of InGaN active layers as well as under band-to-band excitation of GaN and AlGaN cladding layers.

2. Experimental procedure

The samples used mainly in the present work were two kinds of InGaN-based LEDs with their PL peak wavelength of 400 nm. Both LEDs were grown by lateral epitaxy on patterned sapphire substrates. The LED structure consisted of a 27-nm-thick GaN buffer layer, 6-μm-thick n-GaN:Si, a multiple-quantum-well structure with 6 periods of 3-nm-thick InGaN wells separated by 12-nm-thick GaN barriers, 50-nm-thick p-AlGaN:Mg, and 100-nm-thick p-GaN:Mg. The details of the growth condition and the LED structure have been described elsewhere. The two LEDs, samples A and B, had the same structure except for the growth temperature of InGaN active layers, which resulted in the difference in their device performance. The growth temperature of the active layers for the samples A and B were 700 and 750 °C, respectively. It is found from our separate experiments that the electroluminescence (EL) output of the sample B is 1.2 times as high as that of the sample A.

PL measurement was carried out by employing a Xe-Cl excimer laser (308 nm) as an excitation source. The pulse width and the repetition rate were 2.5 ns and 100 Hz, respectively. A wavelength-tunable dye laser pumped by a Xe-Cl excimer laser was also used as an excitation source in order to perform selective excitation of InGaN active layers. The pulse width and the repetition rate were 20 ns and 100 Hz, respectively. PL signals were detected by a liquid-nitrogen-cooled charge-coupled-devices camera in conjunction with a 50-cm single grating monochromator.

3. Results and discussion

3.1 IQE under Band-to-Band Excitation

Figure 1 shows the PL spectra at RT taken from the sample A in (a) and the sample B in (b) under excitation-power densities of 12, 61, 200, 1.7×10^3, 8.2×10^3, and 2.4×10^4 kW/cm^2. In this case, a Xe-Cl excimer laser (λ_{exc} = 308 nm) was used as an excitation source, which performed band-to-band excitation of p-GaN and p-AlGaN cladding layers. At the lowest excitation-power density shown in Fig. 1, the PL linewidth of the sample A is broader than that of the sample B. With increasing excitation-power density, the PL peak position shifts toward the shorter-wavelength side (blueshift) for both samples. The blueshift of the sample A is also larger than that of the sample B. Both the broader PL linewidth and the larger PL blueshift indicate the larger optical inhomogeneity of the sample A as compared with that of the sample B.

In order to obtain the IQE of the two LEDs, we
first define the PL efficiency. Dividing the integrated PL intensity by the corresponding excitation-power density, we evaluated the PL efficiency as the PL intensity per unit excitation-power density. The PL efficiency was obtained as a function of excitation-power density both at low temperature and RT. Then, the PL efficiency was normalized by the maximum value at low temperature. This procedure means that the maximum value of the PL efficiency at low temperature under a certain excitation condition is equal to 100%. This assumption enables us to discuss the IQE of LED samples as a function of excitation-power density both at low temperature and RT.

Figure 2 shows the IQE curves at 6 K and RT taken from samples A and B as a function of excitation-power density. In each sample, the IQE curves are normalized by the maximum value of the IQE at 6 K. Then, the maximum value of the IQE at RT is estimated to be 46 and 50 % for the samples A and B, respectively. It is found from this figure that the IQE is strongly dependent on the excitation-power density even at low temperature. This observation indicates that nonradiative recombination processes are active even at low temperature. The IQE increases with increasing excitation-power density at the lower-excitation condition. This increase in IQE results from the saturation of nonradiative recombination centers by the photo-generated carriers. On the other hand, the IQE decreases with further increasing excitation-power density at the higher-excitation condition. This decrease in IQE reflects the saturation of states which are responsible for radiative recombination by the photo-generated excess carriers.

Under the band-to-band excitation using a Xe-Cl excimer laser ($\lambda_{\text{exc}} = 308$ nm), most of the photo-excited carriers are generated into $p$-GaN and $p$-AlGaN cladding layers. Then, the observed IQE is strongly influenced by the optical quality of the cladding layers. In this case, the difference in IQE between the two samples is small as shown in Fig. 2. This result is consistent with the fact that the two samples have the same structure except for the growth temperature of the InGaN active layers.

### 3.2 IQE under Selective Excitation

We have also measured the PL efficiency of the two samples under selective excitation of InGaN active layers. Figure 3 shows the PL spectra at RT taken from the sample A in (a) and the sample B in (b) under excitation-power densities of 0.14, 0.43, 1.1, 3.0, 8.6, and 26 kW/cm². In this case, a 375 nm line from a dye laser pumped by a Xe-Cl excimer laser was used as an excitation source, which performed selective excitation of InGaN active layers. The spectral features such as linewidth broadening and blueshift under the selective excitation are similar to that observed under the band-to-band excitation. Using the same procedure mentioned above, we evaluated the IQE of the two samples under the selective excitation of the InGaN active layers. Figure 4 shows the IQE curves at 6 K and RT taken from the samples A and B under the selective excitation of the InGaN active layers. The difference in IQE between the two samples is clearly observed as compared with the case of the band-to-band excitation shown in Fig. 2. The maximum value of the IQE at RT is estimated to be 49 and 68 % for the samples A and B, respectively. In the case of the selective excitation, the photo-excited carriers are directly generated into the InGaN active layers.

Then, the IQE under the selective excitation mainly reflects the optical quality of the InGaN active layers. Therefore, the large difference in IQE between the two samples under the selective excitation results from the optical quality of the InGaN active layer itself. It is noted here that the difference in IQE between the two samples is very small under the band-to-band excitation of the
Figure 3  PL spectra at RT taken from two kinds of LEDs, sample A in (a) and sample B in (b), under excitation-power densities of 1.3, 5.5, 15, 42, 130, and 640 kW/cm². The excitation wavelength is 375 nm, which corresponds to the selective excitation of InGaN active layers.

Figure 4  PL efficiency at 6 K and RT taken from LED samples A and B under selective excitation of InGaN active layers (λexc=375 nm) as a function of excitation-power density.

Figure 5  PL efficiency at RT taken from LED samples A and B under selective excitation of InGaN active layers from λexc=375 to 380 nm.

p-GaN and p-AlGaN cladding layers. Such a result under the selective excitation is supported by the fact that only the growth temperature of the InGaN active layers is different between the two samples, and is also consistent with the fact that the EL output of the sample B is higher than that of the sample A.

Furthermore, we measured the IQE of the two LED samples under the selective excitation of the InGaN active layers as a function of excitation wavelength. Figure 5 shows the IQE at RT taken from the samples A and B as a function of excitation wavelength. The excitation wavelength from the dye laser was varied from 375 to 380 nm by a step of 1 nm. The IQE of both samples increases gradually as the excitation wavelength is moved to the...
longer-wavelength side. The IQE at 380 nm is estimated to be 72 and 78 % for the samples A and B, respectively. The increase rate of the IQE for the sample A is larger than that for the sample B. Then, the difference in IQE between the two samples becomes smaller as the excitation wavelength is moved to the longer-wavelength side. Such an excitation-wavelength-dependent change of the IQE under the selective excitation reflects the inhomogeneity of the optical quality of the InGaN active layer itself, mainly due to compositional fluctuation in the ternary alloys and interface fluctuation between well and barrier layers. The larger change of the IQE, which is significantly observed in the sample A, indicates the larger inhomogeneity of the optical quality of the InGaN active layer. In fact, as shown in Figs. 1 and 3, the PL linewidth of the sample A was broader than that of the sample B, and the blueshift of the sample A was also larger than that of the sample B. It is obvious that the inhomogeneity in the active layer results in the lowering of the IQE.

4. Conclusions

We have measured the PL efficiency of nitride-based LEDs by means of excitation-power-density- and temperature-dependent PL spectroscopy. We evaluated the IQE of LEDs both under the band-to-band excitation of GaN and AlGaN cladding layers and under the selective excitation of the InGaN active layers. The IQE under the selective excitation was higher than that under the band-to-band excitation. The enhanced IQE under the selective excitation reflected the intrinsic optical quality of the InGaN active layer itself because the selective excitation of the InGaN active layer effectively created the photo-excited carriers into the InGaN active layer without the influence of the GaN and AlGaN cladding layers. Furthermore, the IQE under the selective excitation was sensitive to the variation of the excitation wavelength when the LED sample had the large inhomogeneity of the optical quality in the active layer.

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References


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