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Photoluminescence study of InGaN/GaN multiple-quantum-well with Si-doped InGaN electron-emitting Layer

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ABSTRACT

InGaN/GaN multiple-quantum-well (MQW) structure with Si-doped InGaN electron-emitting layer (EEL) was grown by metal–organic chemical vapor deposition and their characteristics were evaluated by photoluminescence (PL) measurements. In a typical structure, a low indium composition and wide potential well was used to be an EEL, and a six-fold MQW was used to be an active layer where the injected carriers recombine. By comparing the PL spectral characteristics of the MQW samples, the PL intensity of MQW with EEL is about 10 times higher than that of typical MQW. Experimental results indicate that the high electron capture rate of the MQW active region can be achieved by employing EEL.

1. Introduction

In the past several years, the most widely researches of wide band-gap semiconductors have been concentrated on the III-nitrides. Among them, GaN and its alloys with InN have attracted much attention as the successful commercialization. Due to advantages of long life, low power consumption, small volume, and high color rendering index of light-emitting diodes (LEDs), extensive efforts are devoted today to the development of high power LEDs for applications on backlight source, the flashlight, and even solid state lighting, etc. However, despite the great success, the origin of the very bright emission characteristics is still controversially discussed [1–5].

In order to further improve the light-emitting efficiency of these LEDs, one should maximize the number of carriers recombining inside the active region while minimizing the number of carriers recombining outside the active region. That is, one should increase the carrier capture rate and carrier confinement effect of the active region. In the case of InGaN/GaN LEDs, single or multiple-quantum-well (MQW) structures are commonly used as the active layer, because the quantum efficiency is higher than the double heterostructure InGaN LEDs. Recently, the authors' group reported the use of the vertical conducting structure, surface texturing, indium–tin oxide current-spreading layer or flip-chip technique to enhance the quantum efficiency of the LEDs [6–9]. Although these methods help to increase LED output power effectively, the results fall short of their expectations.

In this paper, we report the effects of Si-doped InGaN electron-emitting layer (EEL) on the optical properties of InGaN/GaN MQW. The MQW with EEL was grown by metal–organic chemical vapor deposition (MOCVD) and their characteristics were evaluated by photoluminescence (PL) measurements. Temperature-dependences of peak position and emission intensity were also measured to examine the dynamical behavior of radiative recombination processes. These results indicate the importance of the electron capture processes by radiative recombination centers in the MQW.

2. Experiment

Samples used in this study were grown on (0001)-oriented sapphire substrates using a MOCVD system. Fig. 1a shows the schematic structures of the MQW samples. The typical InGaN/GaN MQW structure (MQW1) consists of a 30 nm-thick GaN nucleation layer, a 2 μm-thick undoped GaN layer; a 2 μm-thick Si-doped GaN layer, a six-period InGaN/GaN MQW active region, and a 300 nm-thick Mg-doped GaN cap layer. Each InGaN/GaN pair

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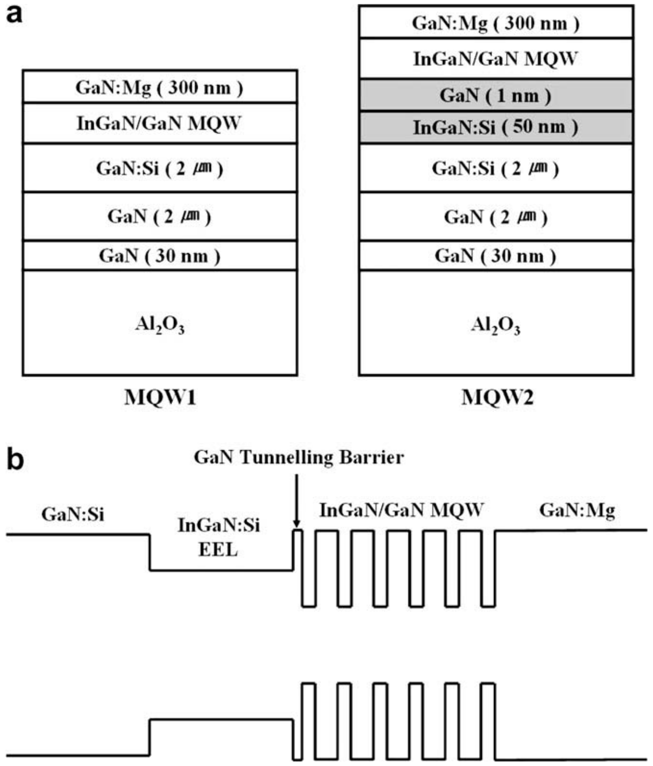

Fig. 1. (a) The schematic structures of the InGaN/GaN MQW samples and (b) the band diagram of the InGaN/GaN MQW with Si-doped InGaN EEL.

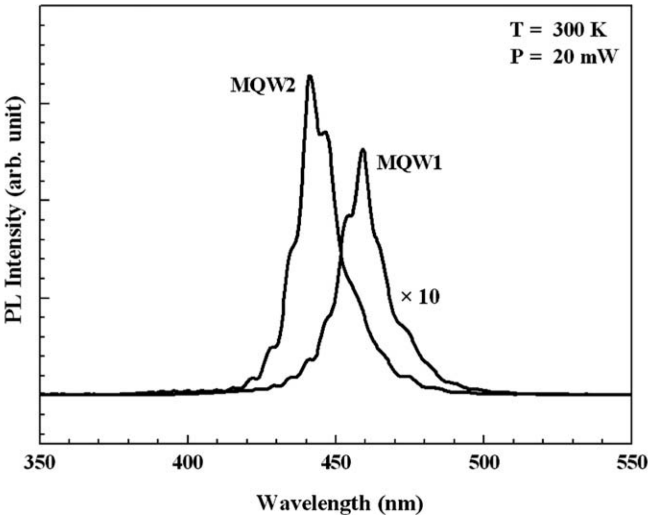

Fig. 2. PL spectra of the InGaN/GaN MQW samples measured at room-temperature.

consists of a 3 nm-thick InGaN well layer and a 10 nm-thick GaN barrier layer. The InGaN/GaN MQW with EEL structure (MQW2) consists of a 50 nm-thick Si-doped InGaN EEL between the n-GaN layer and the six-period InGaN/GaN MQW layer, and the first GaN barrier of MQW is thinner than others (1 nm). Fig. 1b shows the band diagram of the MQW2 structure.

For PL measurements, a He–Cd laser with a wavelength of 325 nm was used as an excitation source to generate electron–hole pairs. The luminescence light from the samples was focused with collection lenses, dispersed using a 1-m monochromator and detected by a photomultiplier tube. For the temperature-dependent PL, the samples were mounted on the cold finger of a closed-cycle helium cryostat. The PL spectra were taken in the nominal output power range of 1–20 mW and the temperature range of 16–300 K.

3. Results and discussion

Fig. 2 shows typical PL spectra from InGaN/GaN MQW samples. The PL was measured at room-temperature and an excitation power of 20 mW. The main PL peaks of MQWs were located at 459 (MQW1) and 441 nm (MQW2), respectively. It can be seen that the PL intensity of MQW2 is about 10 times higher than that of MQW1. In this study, we designed our MQW2 structure so that the electrons can tunnel from a wide potential well, through the tunneling-barrier layer, into the MQW active region. As shown in Fig. 1; MQW2 consists of the EEL formed by a 50 nm-thick Si-doped InGaN layer and a thin GaN tunneling-barrier is different

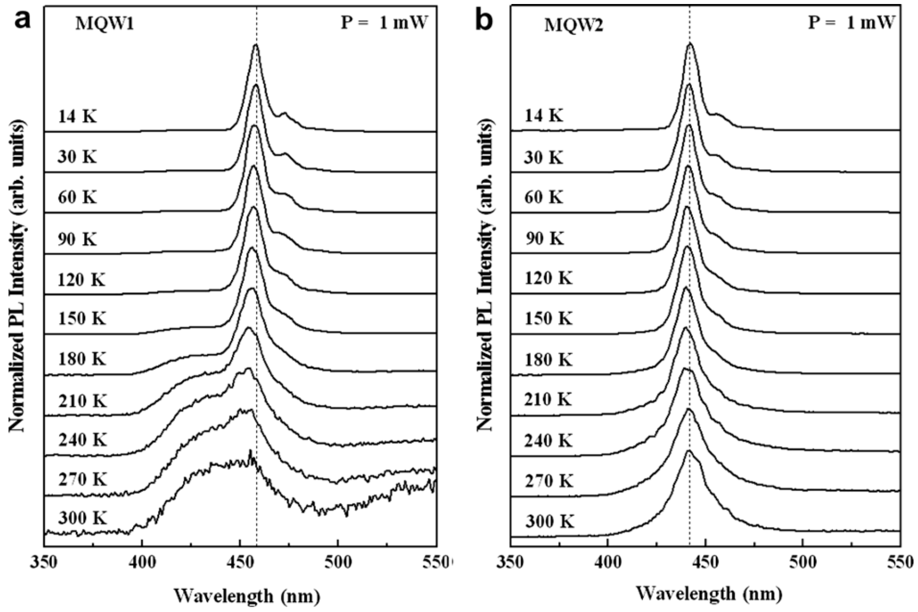

Fig. 3. Temperature-dependent PL spectra from: (a) the typical InGaN/GaN MQW and (b) the InGaN/GaN MQW with Si-doped InGaN EEL samples measured at an excitation power of 1 mW.

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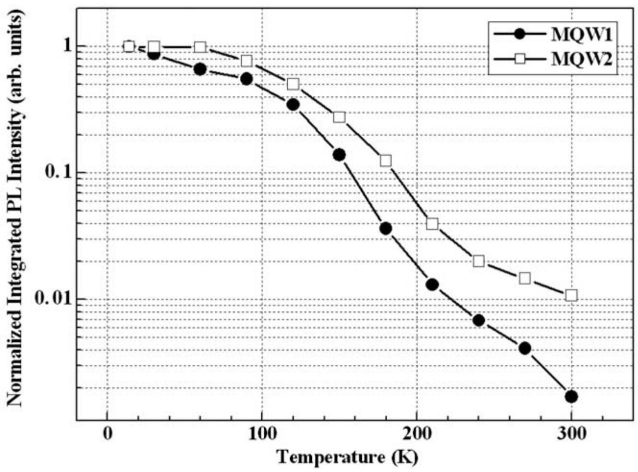

Fig. 4. Temperature-dependence of the normalized integrated PL intensity for InGaN/GaN MQW samples.

from the typical structure with a symmetric layer structure. When the electron energy level positions in the InGaN EEL layer are leveled at the electron energy level positions in the MQW layer, the electrons may directly tunnel through the thin barrier into the well [10]. Therefore, such a barrier design allows electrons to tunnel freely and thereby increase the capture efficiency of the electrons. On the other hand, the Mg-doped GaN cap layer can also serve as the hole-emitter which supplies holes into the active region. At the same time, the 1 nm-thick GaN tunneling-barrier layer can still effectively confine holes inside the active region. Due to the significant difference of the effective mass between electrons and holes, the tunneling probability of holes is much smaller. Thus, we can increase the number of carrier recombination inside the MQW active region. As a result, we can significantly increase the radiative recombination efficiency.

Fig. 3 shows the temperature-dependence of PL spectra for InGaN/GaN MQW samples. The PL spectra were taken in the nominal output power of 1 mW and the temperature range of 14–300 K. For the MQW1, the blue-shift ($\Delta E = 24$ meV) from 14 K to 210 K and the red-shift ($\Delta E = 12$ meV) from 210 K to RT were observed as shown in Fig. 3a. On the other hand, In the case of the MQW2, a small blue-shift from 14 to 210 K and a red-shift from 210 to 300 K were 9 and 8 meV, respectively (Fig. 3b). The temperature-dependence of PL spectra of the InGaN based MQWs is affected by the carrier localization, as discussed in some reports [11,12]. It is indicated that the blue-shift with increase of temperature at lower temperatures is due to the photo-excited carrier activation from localized states into extended states, while the red-shift at higher temperature is due to the band gap reduction. Therefore, the relatively small energy shift for MQW2 implies that the carrier localization inside the MQW2 would be much larger than MQW1, indicating a high quantum efficiency and good device performance.

The temperature-dependence of the normalized integrated PL intensity for InGaN/GaN MQW samples is shown in Fig. 4. When the temperature is increased, the PL intensity of both MQWs significantly decreases due to an enhancement of non-radiative recombination processes, i.e., a reduction of the radiative recombination rates. This reduction of the radiative recombination efficiency is commonly observed, which is similar to the one usually seen at higher temperatures. However, the difference in the PL intensity between the two samples persists, i.e., the PL intensity of MQW2 is always stronger than the one for MQW1. Increasing the temperature, we find an enhanced difference in the PL intensity for the two cases. The reduction of the PL efficiency of MQW1 is much larger than for MQW2. The improvement of the PL efficiency for MQW2 with EEL is in fact remarkable, indicating the importance of the electron capture processes by radiative recombination centers in the MQW layer.

4. Conclusion

We have experimentally demonstrated the effects of Si-doped InGaN EEL in a InGaN/GaN MQW using PL measurements. By comparing the optical properties of the MQW samples, the PL intensity of MQW with EEL at room-temperature is about 10 times higher than that of typical MQW. In addition, temperature-dependences of peak position and emission intensity were also measured. These experimental results show that the high electron capture rate of the MQW active region can be achieved by employing EEL, indicating a high quantum efficiency and good device performance.

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