A New Scheme to Enhance the Color Conversion Efficiency of GaN μLEDs

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ABSTRACT

This paper reports our work in the application of localized surface plasmon (LSP) and non-radiative energy transfer (NRET) mechanisms in micro LEDs (μLEDs). μLEDs with the dimension of 40 μm × 60 μm and dry-etched nanoholes (NHs) in the mesas were fabricated. The metal nanoparticles (NPs) and color converting quantum dots (QDs) were filled into the NHs etched through the active region. Through the final optical measurements, the results are quite gratifying. This scheme is expected to promote the development of full-color displays in the future, achieving more efficient display technology based on μLEDs.

1 INTRODUCTION

In the context of information booming society, display equipments have ushered in a generation of opportunities and challenges. In order to meet various new needs, a new generation of display technology must be developed. In recent years, micro light-emitting diodes (μLEDs or micro LEDs) have gained favors from both industry and academia due to its fascinating superiority of efficiency, stability, lifetime and so on [1-4]. However, in order to realize the application of full-color display, a “bottlenack” must be overcome, which is the mass transfer process of three primary color chips (RGB) from one substrate to another. Based on this, a new μLED structure using quantum dots (QDs) as the color converter was proposed [5-7]. In most reports on LED with QDs, the QDs are directly spin-coated onto the surface of LEDs. In this emission-absorption-reemission process, the color conversion efficiency (CCE) is still low, and the process inevitably leads to a waste of energy, reducing the efficiency of LEDs. In order to overcome this drawback, a so-called non-radiative energy transfer (NRET) mechanism has been proposed. This method can avoid the absorption and reemission process, effectively reduce the energy loss, and greatly improve the CCE of LED. At the same time, the luminous efficiency of traditional LED structure is limited due to the existence of uneven quality of the epitaxial layers, non-radiative recombination process, spontaneous polarization and piezoelectric polarization. The localized surface plasmons (LSPs) in metal nanoparticles (NPs) can effectively improve the luminous efficiency of LED by coupling with the luminous center (multiple quantum wells, MQW), which has been widely studied [8-10]. However, the effectiveness of improving the CCE and luminous efficiency by the two methods above is heavily affected by one factor, which is the distance between the coupling parts. The efficiency of NRET increases with the decrease of the distance between the MQW and the QDs, and the intensity of the LSP decreases with the increase of the distance between the MQW and the NPs producing the LSP.

In this paper, therefore, we propose and fabricate a nanohole μLED structure (NH-μLED), which can “access” the MQW region via etching the nanoholes, and then fill the QDs and NPs altogether into the nanoholes by spin-coating, so that they can make close contact with the MQW. This new scheme, we believe, is quite feasible because it can kill two birds with one stone. Through the fabrication and final measurements of the device, we find that the existence of LSP effectively increases the μLEDs’ luminous efficiency, and the NRET process greatly improves the CCE of μLEDs, which plays a certain guidance role in the field of full-color displays in the future.

2 EXPERIMENTS

Three samples were prepared by standard LED manufacturing process. Sample 1 is a μLED coated with red-emitting QDs on the surface. Sample 2 is a NH-μLED filled with QDs. Sample 3 is a NH-μLED filled with Ag NPs. All three samples are shown in Fig. 1. First,

a 300 nm SiO_2 was deposited on the surface of wafer as a etching mask. Then, the patterned area was etched down to the n-type GaN layer to form μLED mesa. By removing the mask, a 500 nm Si_3N_4 was grown as the electrically isolate layer to isolate the p and n electrodes. Finally, Ni/Au with thickness of 100/300 nm was sputtered to serve as p- and n-type electrodes. Afterwards, a nanoimprinted layer with a circular array of NHs with the diameter of about 1 μm was used as the mask to etch the NHs straight into the n-GaN layer to "access" the active region. Finally, by using spin coating method, the QDs and Ag NPs are filled into the NHs, respectively, to form sample 2 and sample 3.

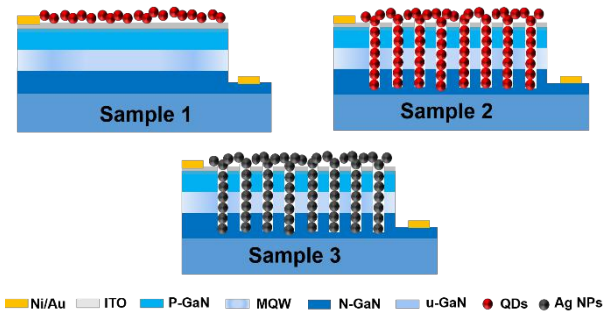

Fig. 1 Schematic diagram of the three samples. MQW stands for multiple quantum well.

3 RESULTS & DISCUSSION

3.1 CCE enhanced by the NRET

Fig. 2 shows the electroluminescence spectra (EL) measured form sample 1 and sample 2 at 20 mA injection current. The spectra consists of two origins: blue light excitation source μLED with luminescence peak of 460 nm and red light QDs with luminescence peak of 640 nm. From Fig. 2, the percentage of red light intensity in the total luminous intensity of sample 2 is much higher than that of sample 1, which benefits from the NRET process. Thus, the CCE of μLED can be effectively enhanced. The illustrations are the optical microscope images of the two samples under 20 mA injection current. As we can see, the luminescence color of sample 2 is more red than that of sample 1, which also confirms that the NRET process does increase the CCE. In addition, in order to prove the existence of NRET process, the time-resolved photoluminescence (PL) spectra of the samples are measured. The results are shown in Fig. 3. Compared with the sample without QDs filling (QD-free NH-μLED), the PL intensity of sample 2 decreases faster. This is because the excitons existing near the QD region directly transmit to the QDs through the NRET process, and then recombination immediately takes place in the QDs to emit red light. In sample 1, however, the situation is quite different. The excitons first recombine in the MQW region and emit blue light which passes through the epitaxial layer. Then, the blue light is absorbed and converted into red light by the QDs. Therefore, the lifetime of the photoluminescence in the QD-free NH-μLED is much longer because the process is slower. A conclusion can thus be reached based on the results above. That is, the existence of the NRET process can greatly improve the energy utilization efficiency, and ultimately increases the CCE of μLED.

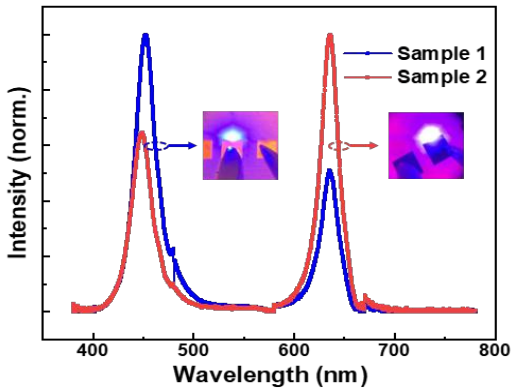

Fig. 2 The EL intensity of samples 1 and 2. The inserts show the optical microscope images of the two samples at 20 mA injection current.

3.2 Luminous efficiency increase by the LSP coupling

The localized surface plasmon is a kind of electron oscillation behavior typically existing at the interfaces of metals and semiconductors. The field generated by the LSP can couple with the emission center, increase the density of states and thus improve the emission efficiency. Moreover, the closer the metal NPs are to the luminescent center, the stronger the coupling. In this paper, the NH-μLED structure we used can effectively ensure that the metal NPs have nominally zero distance contact with the MQW. It can ensure the effective coupling between the LSP and the MQW.

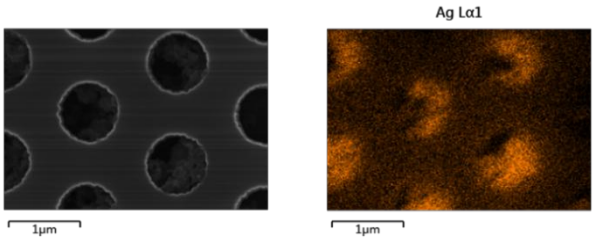

Fig. 3 SEM image and EDS image of the NH-μLED, where the filled Ag NPs can be clearly seen in the hole region.

The scanning electron microscope (SEM) and energy dispersive spectroscopy (EDS) images of the NH-μLED filled with Ag NPs are shown in Fig. 4. We can clearly see that the Ag NPs are successfully filled into the holes, and the size of the holes is about 1 μm. In order to verify

the coupling between the MQW and the LSPs, we have further measured the time-resolved PL spectra of the samples. The results are shown in Fig. 3. The PL lifetime of sample 3 is shorter than that of the NP-free NH-μLED, which strongly indicates that the coupling between the LSPs and the MQW is effectively achieved. The PL spectra of the samples with and without the Ag NP filling are measured at both 300 K and 10 K temperature. Fig. 5 shows the luminous intensity ratio (I_w stands for intensity with Ag NPs, $I_{w/o}$ stands for intensity without Ag NPs) of the two devices. At 300 K temperature, the PL intensity of the sample filled with Ag NPs is greatly enhanced, and the maximum increase is about 1.7 times at 468 nm. However, at 10 K temperature, the non-radiative recombination is not obvious, so there is no significant enhancement of PL intensity. It can be inferred form the results that the coupling between the MQW and LSP can effectively increase the luminous efficiency of μLED.

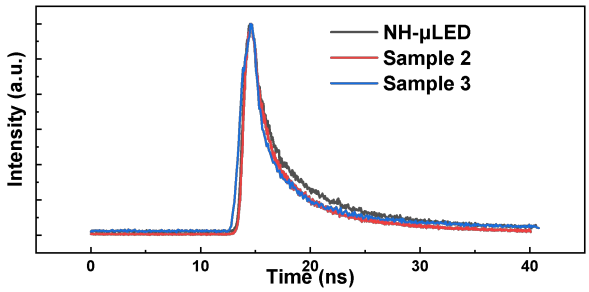

Fig. 4 The time-resolved PL spectra of the three samples: QD and NP free NH-μLED, sample 2 and sample 3.

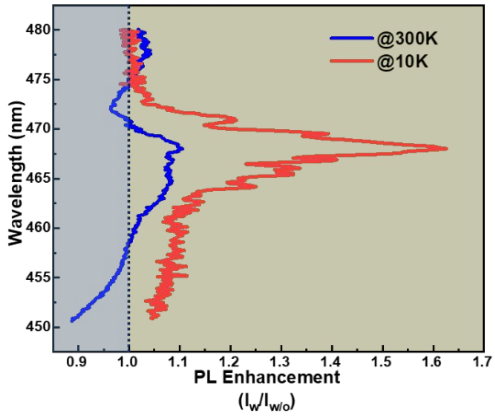

Fig. 5 Enhancement factor of two different samples at 10 K and 300 K temperature. I_w stands for I with Ag NPs, and $I_{w/o}$ stands for I without Ag NPs.

4 CONCLUSIONS

In this paper, we show some progress in the application of the NRET and the LSP effects in μLEDs. The CCE and the luminous efficiency are greatly enhanced by the NRET process and the LSP coupling. Moreover, the above two methods can be combined together with further optimized mixing ratio of the QDs and metal NPs. They can be simultaneously filled into the nanoholes to achieve even better device performance. This provides a reference and a new idea for the application of the LSPs and the NRET in high efficiency μLED full-color display.

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