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Increasing Color-Conversion by Novel Hybrid Micro Light-Emitting Diodes with Non-Radiative Energy Transfer Effect

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Abstract

In this work, the hybrid type light-emitting diodes combined the nano-ring structure and quantum dots was demonstrated. This method promise a high color-conversion efficiency regarding the non-radiative energy transfer effect. The new approach enables a novel manufacturing method of the full-color μ-display.

1. Introduction

The technologies of the micrometer light emitting diodes (μ-LEDs) and the quantum dots (QDs) have been extended rapidly since this few years. The μ-LEDs and the QDs are potentially applied to wearable devices due to their tiny size and high color rendering index (CRI), respectively. Many efforts studied the increase of efficiency for full-color μ-LEDs but the smaller active area limited the output performance of μ-LEDs of late. The tunable wavelength (wavelength range: 535-480 nm) LEDs with the nano-ring structure (NR-LEDs) have been presented by the strain-induced engineering in our previous work [1]. A good method to overcome the low efficiency of μ-LEDs is the NR-LEDs added with red, green, and blue QDs. Furthermore, a smart integration of NR-LEDs with RGB QDs may result in a full-color display without complicating mass transfer process. Thus, the hybrid QDs-correlated NR-LEDs array is essential to be developed for the future μ-display. Figure 1 presents that QDs was sprayed on NR-LEDs for the hybrid QDs μ-LEDs by the aerosol jet printing methodology.

Moreover, it was an important way to improve the color characteristics of hybrid QDs μ-LEDs with the non-radiative energy transfer. The non-radiative energy transfer was an interaction between acceptors and donors where the excitation energy of a donor is transferred to an acceptor. There are three required factors need to be contented with the non-radiative energy transfer: (1) the absorption spectrum of accepter should overlap the fluorescence emission spectrum of donors, (2) the transition of dipole orientation must be parallel, and (3) donors and acceptors must be in close proximity (approximate 10-100 Å) [2]. In this study, NR-LEDs do as a good emitter and emitted high density of photons as donors then recombined with accepters from QDs via non-radiative energy transfer. Hence, the energy-conversion from NR-LEDs to QDs enables a good property and guiding to a great color feature of hybrid QDs μ-LEDs. This structure showed an excellent capability to improve the low efficiency of μ-display.

2. Results and discussion

The NR-LEDs were fabricated by nano-sphere lithography technical and others normal process such as nano-sphere arranging, ICP-RIE to etch the ring structure, and the metal deposited etc. The results of the SEM images of the major steps and the cross-section view of the nano-ring as shown in Figure 2.

The photoluminescence spectrum (PL) of the green NR-LEDs and the photoluminescence excitation (PLE) of QDs were measured, respectively. The line of the PLE spectra means the absorption of the material. The overlap between PL and PLE spectra were able to illustrate the probability to fill a part of the factors to create non-radiative energy transfer, as shown in Figure 3.

The lifetimes of the MQWs were measured by time-resolved photoluminescence (TRPL) system to extract the actual non-radiative energy transfer rate (k_{ET}). The decay rate of MQWs of NR-LEDs with QDs was faster than without QDs have been observed. The results of TRPL measurement confirmed that the lifetime of the QD-NR-LEDs was significant decay than NR-LEDs as shown in Figure 4. The TRPL intensity decay of the MQWs could be approximated to an exponential equation. Through the following equation:

$$I_{MQW}^{H}(t) = Ae^{-k_{MQW}t} + \mathrm{B}e^{-(k_{MQW}+k_{ET})t} \quad (1)$$

The equation (1) provides the method to calculate the parameters of total radiative combination rate and non-radiative combination rate, where A and B are the coefficients of electron-hole pairs that didn't and did undergo non-radiative energy transfer, k_{MQW} is the total decay rate of the bare MQWs, and k_{ET} is the non-radiative decay rate [3]. According to the equation (1), the values of the coefficients could be calculated including A, B, k_{MQW}, $k_{MQW}+k_{ET}$, and lifetime (τ).

From the above results, the lifetime decay which shows the energy transfer of non-radiative recombination and the QDs would be treated as acceptor and the MQWs as a donor. It shows a good benefit to color-conversion efficiency since the energy transfer from MQWs to QDs.

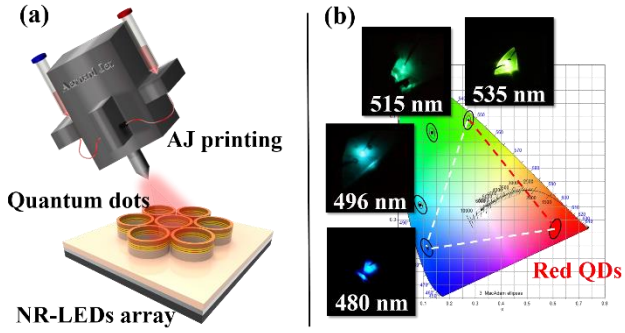

Fig. 1. (a) The red QDs were sprayed onto the NR-LEDs by the aerosol jet printing evenly with pulse. Consequently, the QDs would adhere on MQWs of the NR-LEDs. (b) The insets present the color of the emitting light after nano-ring process. Controlling the ring wall width could modulate the emission peaks on one epitaxy wafer which are 480 nm, 496 nm, 515 nm, and 535 nm, respectively.

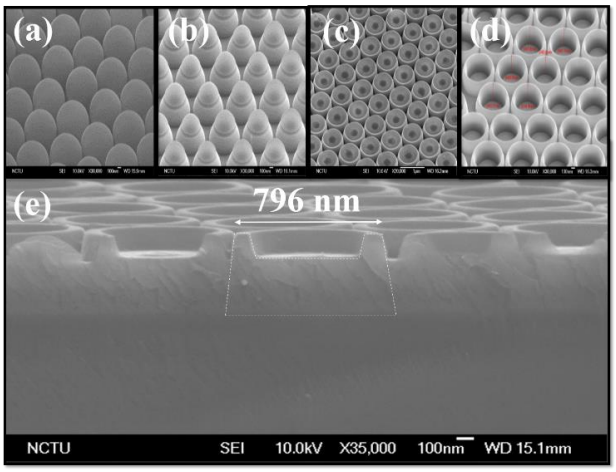

Fig. 2. The SEM images of the results of the critical steps, (a) nanosphere array, (b) nano-rod structure, (c) nano-rod structure with the hard mask, (d) nano-ring light-emitting diodes, (e) cross-section view of the nano-ring.

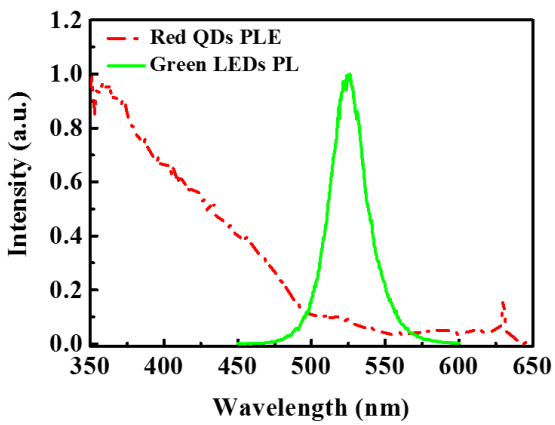

Fig. 3. The spectral overlap of the MQWs emission peak is at 535 nm (green solid line) and the red QDs absorption (red dash line).

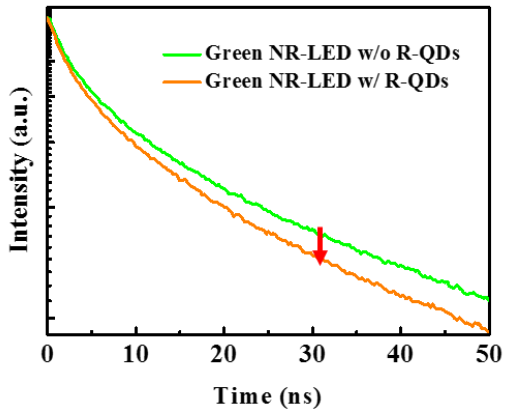

Fig. 4. The TRPL intensity decay of the green NR-LEDs without QDs (green solid line) and with (orange solid line) red QDs, it showed the lifetime of the MQWs of the NR-LEDs with QDs is shorter than without QDs.

3. Conclusions

A novel hybrid QD-NR-LEDs were demonstrated in this work. The non-radiative transfer between the multiple quantum wells and the quantum dots have been observed. Based on the PL and PLE analysis, the overlap region of PL and PLE spectra explained that the quantum dots directly attached to the exposed multiple quantum wells to make the energy non-radiative transfer happened. As a result of the TRPL analysis, it illustrates that the lifetime was significant decay and the value of lifetime was calculated. Afterward, it could combine our previous experimental results of the wavelength tunable NR-LEDs, each ring could be considered as a sub-pixel in micrometer level when separately added RGB QDs into the ring. A new idea to produce full color μ-LEDs array without mass transfer technology come up with the hybrid QD-NR-LEDs.

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