Phosphor-free white-light light-emitting diode of weakly carrier-density-dependent spectrum with prestrained growth of InGaN/GaN quantum wells

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The authors grew a white-light InGaN/GaN quantum-well (QW) light-emitting diode epitaxial structure with its electroluminescence spectrum close to the ideal condition in the Commission International de l'Eclairage chromaticity based on the prestrained metal-organic chemical vapor deposition technique. The prestrained growth leads to the efficient yellow emission from three InGaN/GaN QWs of increased indium incorporation. The color mixing for white light is implemented by adding a blue-emitting QW at the top of the yellow-emitting QWs. The blueshifts of the blue and yellow spectral peaks of the generated electroluminescence spectra are only 1.67 and 8 nm, respectively, when the injection current increases from 10 to 70 mA. Such small blueshifts imply that the piezoelectric fields in their QWs are significantly weaker than those previously reported. © 2007 American Institute of Physics. [DOI: 10.1063/1.2723197]

The development of phosphor-free white-light light-emitting diodes (LEDs) has become an important trend because of the disadvantages of using phosphors for converting light colors, including lower efficiency, shorter lifetime, and patent control. Various device schemes have been proposed for such development. Since the band gap of InGaN can cover up to the near-infrared range, using InGaN/GaN quantum wells (QWs) of different parameters for emitting lights of various colors to mix into white light has been attempted. By controlling the QW width, different levels of piezoelectric field can lead to different emission wavelengths.¹ In this case, however, the strong quantum-confined Stark effect (QCSE) in a QW of a large well width will result in a significant blueshift when plenty of carriers are injected to produce the screening effect. Although white-light LEDs of simultaneously emitting two or three colors by growing InGaN/GaN QWs of different indium contents have been reported,^{2,3} the internal quantum efficiencies of the long-wavelength components were quite low and the QCSE screening effect was still a major problem. In implementing a multicolor LED for white-light generation, the major problem is the inefficient yellow-red emission. CdSe/ZnS nanocrystals have been used for converting blue photons into red light. The combination of a blue/green two-color LED with such nanocrystals led to white-light generation of three primary colors.⁴⁻⁷ Therefore, although the idea of using various InGaN/GaN QWs to mix multiple colors for white light has been proposed, the implementation of such a white-light LED of good chromaticity was never reported.

In this letter, we report the growth of a blue/yellow dual-wavelength white-light InGaN/GaN QW LED epitaxial structure based on the prestrained growth technique.^{8,9} The prestrain technique implies the growth of a fully strained (normally with low-indium content) InGaN/GaN QW to generate a tensile strain in the barriers above it for reducing the lattice mismatch between the well and barrier layers of

the QWs grown subsequently. Therefore, this technique can be used for enhancing indium incorporation such that a long-wavelength visible-emitting QW can be grown at a relatively higher temperature and hence can have higher emission efficiency. The electroluminescence (EL) spectra correspond to a white-light source of the coordinates in the Commission International de l'Eclairage (CIE) chromaticity diagram close to (1/3, 1/3) and a color temperature around 5600 K. The QCSE screening effect in the implemented white-light LED is quite small.

To demonstrate the contribution of the prestrained growth technique to the implementation of such a white-light source, we compare the optical properties of two InGaN/GaN QW samples. The samples were grown with metal-organic chemical vapor deposition (MOCVD). The general growth structure is as follows: First, a 30 nm GaN nucleation layer was grown on (0001) *c*-plane sapphire substrate at 530 °C. Then, after the growth of a 2 μm *n*-GaN at 1080 °C, InGaN/GaN QWs of different compositions were deposited for the two samples. In growing the QWs in each sample, after the growth of a 3 nm InGaN QW layer at 670 °C, the growth temperature was ramped to 870 °C within 1 min for depositing GaN barrier of 15 nm in thick-

FIG. 1. XRD patterns of the two samples. The zero level of the XRD pattern of sample A is upshifted by 20 dB for demonstration clarity.

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FIG. 2. Room-temperature normalized PL spectra of the two samples.

ness. Abrupt interfaces between the wells and barriers can be achieved using this method of fast growth-temperature ramp. Such an abrupt interface can enhance the quantum confinement of carriers resulting in higher efficiency. After the growth of the QWs, a 30 nm p -Al_{0.2}Ga_{0.8}N layer, followed by a 120 nm p -GaN layer (both grown at 945 °C), was deposited. In the two samples, sample A includes five high-indium QWs with the growth conditions described above. In sample B, before the growth of the three high-indium QWs with the same growth conditions as those of sample A, a low-indium InGaN/GaN QW with the well layer grown at 750 °C was deposited to generate the prestrain effect.⁸ Also, a blue-emitting QW with the well layer grown at 740 °C was added at the top of the QW sequence.

Figure 1 shows the x-ray diffraction (XRD) patterns of the two samples. One can see a typical XRD pattern of a set of high-indium InGaN/GaN QWs in sample A. However, the XRD pattern of sample B becomes rather irregular, indicating the significant differences among the five QWs in sample B (one low-indium, three high-indium, and one blue-emitting QWs). In our previous study of prestrained growth,⁸ the insertion of the low-indium QW normally led to a large variety of QW indium content among the high-indium QWs above and hence quite an irregular XRD pattern.

Figure 2 shows the room-temperature, normalized photoluminescence (PL) spectra of the two samples. Here, one can see that the green-yellow PL emission of sample A is centered around 550 nm. After the addition of the low-indium QW for the prestrain effect and the blue-emitting QW in sample B, a strong peak around 400 nm appears. Also, the prestrain effect leads to an emission redshift of the high-indium QWs from 550 to around 560 nm. Meanwhile, one more major peak around 460 nm can be seen due to the growth of the blue-emitting QW at the top in sample B. Note

FIG. 3. Normalized EL spectra of the two samples with the injection current at 20 mA.

FIG. 4. EL spectra of sample B at various injection current levels.

that the broad spectral peaks around 550–560 nm in both samples imply that the high-indium QW compositions in these two samples are quite nonuniform within one QW or among different QWs.

Figure 3 shows the normalized EL spectra of the two samples with the injection current at 20 mA. Here, one can see that the EL peak wavelength of the blue component is about the same as that of its PL counterpart. However, those of the green-yellow components in both samples are longer than their counterparts of PL. The prestrain growth has redshifted the EL emission of the high-indium QWs from 555 nm in sample A to 576 nm in sample B. Hence, with the prestrained growth, we can obtain a purely yellow component for color mixing into white light.

Figure 4 shows the EL spectra of sample B at various injection current levels. Here, as the injection current increases from 10 to 70 mA, the blue and yellow spectral peaks blueshift only by 1.67 nm (from 469.80 to 468.13 nm) and 8 nm (from 581 to 573 nm), respectively, due to the QCSE screening effect. The spectral peaks were calibrated by first filtering out the Fabry-Pérot oscillations in the spectra. These blueshifts are quite small when compared with those of the related devices previously reported. The smaller blueshifts in our sample can be attributed to the weaker piezoelectric fields in the QWs. Figure 5 shows the EL spectra of sample A at several injection current levels. The blueshift of the spectral peak in this sample is 11 nm (from 558 to 547 nm) when the injection current increases from 10 to 70 mA. Considering the longer central wavelength (normally leading to a larger blueshift) and the smaller blueshift of the yellow peak shown in Fig. 4 for sample B, we may speculate that the weaker piezoelectric fields in the QWs of sample B are related to the prestrained growth. Here, the prestrain effect may reduce the strain levels in the QWs above the low-indium one such that their induced piezoelectric fields are weakened. However, this speculation requires

FIG. 5. EL spectra of sample A at various injection current levels.

FIG. 6. (Color online) Picture of a 2 in. epitaxial wafer of sample B with a portion excited with 20 mA injection current.

further confirmation. The CIE chromaticity coordinates of the EL spectrum at 50 mA of sample B are (0.334, 0.338), which are very close to the ideal white-light source of (1/3, 1/3). The corresponding color temperature at this injection current level is 5600 K. Figure 6 shows the picture of a 2 in. epitaxial wafer of sample B with a portion excited with 20 mA injection current. One can see the bright white light generated in the excited region through the contacts of indium balls. This picture means to demonstrate the high quality white light without using any phosphor.

In summary, we have grown a white-light InGaN/GaN QW LED epitaxial structure with its EL spectrum close to

the ideal condition in CIE chromaticity based on the prestrained MOCVD growth technique. The prestrained growth led to efficient yellow emission. The QCSE screening effects of the QWs in this LED structure were quite weak.

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