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# InGaN Light-Emitting Diodes with Quantum Well Structures

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High-power InGaN light-emitting diodes (LEDs) with quantum well structures based on III-V nitrides were grown by metalorganic chemical vapor deposition on sapphire substrates. The typical blue LEDs had a peak wavelength of 450 nm and full width at half-maximum of 20 nm.The output power, the external quantum efficiency and the luminous intensity of blue LEDs at a forward current of 20 mA were 4 mW, 7.3 % and 2 cd, respectively.

## 1. INTRODUCTION

Recent research on III-V nitrides has paved the way for realization of high-quality crystals of AlGaN and InGaN, and p-type conduction in AlGaN.[1-5] The hole-compensation mechanism of p-type AlGaN has also been elucidated.[6,7] High-brightness blue and blue-green light-emitting diodes (LEDs) with a luminous intensity of 2 cd have been fabricated by using these techniques and are now commercially available.[8,9] In order to obtain blue and blue-green emission centers in these InGaN/AlGaN double-heterostructure (DH) LEDs, Zn doping into the InGaN active layer was performed. Although these InGaN/AlGaN DH LEDs produce a high-power light output in the blue and blue-green region with a broad emission spectrum (full width at half-maximum (FWHM)=70nm), green or yellow LEDs which have a peak wavelength longer than 500 nm have not been fabricated.[9] The longest peak wavelength of the electroluminescence (EL) of InGaN/AlGaN DH LEDs achieved thus far is 500 nm (blue-green) because the crystal quality of the InGaN active layer of DH LEDs becomes poor when the indium mole fraction is increased in order to obtain a green band-edge emission.

On the other hand, in conventional green GaP LEDs the external quantum efficiency is only 0.1 % due to the indirect transition band-gap material and the peak wavelength is 555 nm (yellowish green).[10] As another material for green emission devices, AlInGaP has been used. The present performance of green AlInGaP LEDs is an emission wavelength of 570 nm (yellowish green) and maximum external quantum efficiency of 1%.[10] When the emission wavelength is reduced to the green region, the external quantum efficiency drops sharply because the band structure of AlInGaP becomes close to an indirect transition band structure. Therefore, high-brightness pure green LEDs, which have a high efficiency of above 1 % at the peak wavelength between 510-530 nm with a narrow FWHM, have not been commercialized yet.

Among II-VI materials, ZnSSe- and ZnCdSe-based materials have been intensively studied for use in green light-emitting devices, and much progress has been made recently. The recent performance of II-VI green LEDs is an output power of 1.3 mW, external quantum efficiency of 5.3 % at 10 mA and peak wavelength of 512 nm.[11) However, the lifetime of II-VI-based devices is still short, which prevents commercialization of II-VI-based devices at present.

Here, we describe quantum-well structure (QW) LEDs which have a thin InGaN active layer (about 20 Å) in order to obtain high-power emission in the region from blue to yellow with a narrow emission spectrum.

## 2. EXPERIMENTAL

III-V nitride films were grown by the two-flow metalorganic chemical vapor deposition (MOCVD) method. Details of the two-flow MOCVD are described elsewhere.[12] The growth was conducted at atmospheric pressure. Sapphire with (0001) orientation (C face), of a two-inch diameter, was used as a substrate. The growth conditions of each layer are described elsewhere.[8-9]

The green LED device structures (Fig. 1) consist of a 300 Å GaN buffer layer grown at a low temperature (550 °C), a 4-µm-thick layer of n-type GaN:Si, a 1000-Å-thick layer of n-type $Al_{0.1}Ga_{0.9}N$:Si, a 500-Å-thick layer of n-type $In_{0.05}Ga_{0.95}N$:Si, a 20-Å-thick active layer of undoped $In_{0.43}Ga_{0.57}N$, a 1000-Å-thick layer of p-type $Al_{0.1}Ga_{0.9}N$:Mg, and a 0.5-µm-thick layer of p-type GaN:Mg. The active region forms a single-quantum-well structure (SQW) consisting of a 20 Å $In_{0.43}Ga_{0.57}N$ well layer sandwiched by 500 Å n-type $In_{0.05}Ga_{0.95}N$ and 1000 Å p-type $Al_{0.1}Ga_{0.9}N$ barrier layers. The indium mole fraction of the InGaN active layer was varied between 0.2 and 0.7 in order to change a peak wavelength of the InGaN SQW LEDs from blue to yellow.

Fabrication of LED chips was accomplished as follows. The surface of the p-type GaN layer was partially etched until the n-type GaN layer was exposed. Next, Ni/Au contact was evaporated onto the p-type GaN layer and a Ti/Al contact onto the n-type GaN layer. The wafer was cut into a rectangular shape (350 µm x 350 µm). These chips were set on a lead frame, and were then molded. The characteristics of LEDs were measured under direct current (DC)-biased conditions at room temperature.

## 3. RESULTS AND DISCUSSION

Figure 2 shows the typical EL of the blue, green and yellow SQW LEDs with different indium mole fractions of the InGaN well layer at forward current of 20 mA. The longest emission wavelength is 590 nm (yellow). The peak wavelength and the FWHM of the typical blue SQW LEDs are 450 nm and 20 nm, respectively, of green SQW LEDs 525 nm and 40 nm, respectively, and of yellow SQW LEDs 590 nm and 90 nm, respectively. Figure 3 shows the FWHM of the EL spectra as a function of the peak wavelength. When the peak wavelength becomes longer, the value of the FWHM of the EL spectra increases, probably due to the strain between well and barrier layers of the SQW which is caused by the mismatch of the lattice and the thermal expansion coefficients between well and barrier layers.

The output power of the SQW LEDs is shown as a function of the forward current in Fig. 4. The output power of the blue SQW LEDs slightly increases sublinearly up to 40 mA as a function of the forward current. Above 60 mA, the output power almost saturates, probably due to the generation of heat. At 20 mA, the output power and the external quantum efficiency of blue SQW LEDs are 4 mW and 7.3 %, respectively, which are much higher than those of InGaN/AlGaN DH LEDs (1.5 mW and 2.7 %).[8] Those of the green SQW LEDs are 1 mW and 2.1 %, respectively, and those of yellow SQW LEDs are 0.5 mW and 1.2 %, respectively. The output power of green and yellow SQW LEDs is relatively small in comparison with that of blue SQW LEDs, probably due to poor crystal quality of the InGaN well layer which has large lattice mismatch and difference in thermal expansion coefficients between well and barrier layers. A typical on-axis luminous intensity of green SQW LEDs with 10° cone viewing angle is 4 cd at 20 mA. This luminous intensity is the highest ever reported for green LEDs based on III-V nitride.

The output power decreases when the peak wavelength becomes longer, probably due to the large strain between well and barrier layers. The output power of green and yellow LEDs is 1 mW (at 525 nm) and 0.5 mW (at 590 nm), respectively. The conventional green GaP LED with a peak wavelength of 555 nm has an output power of 0.04 mW. Also, the output power of green AlInGaP LEDs with a peak wavelength of 570 nm is 0.4 mW.[10] Therefore, the output power of green InGaN SQW LEDs is much higher than that of conventional yellowish green LEDs. Also, the luminous intensity of InGaN green SQW LEDs (4 cd) is about 40 times higher than that of conventional green GaP LEDs (0.1 cd), and the color of InGaN SQW LEDs is greener than those of conventional GaP and AlInGaP LEDs. A typical example of the I-V characteristics of the green SQW LEDs shows that the forward voltage is 3.0 V at 20 mA.

## 4. SUMMARY

In summary, high-brightness InGaN green SQW LEDs were fabricated for the first time. The luminous intensity was 4 cd and the external quantum efficiency was as high as 2.1 % at a forward current of 20 mA at room temperature. The peak wavelength and the FWHM of the green LEDs were 525 nm and 40 nm, respectively, and those of blue LEDs were 450 nm and 20 nm, respectively. The color of green InGaN SQW LEDs was greener than those of conventional GaP and AlInGaP LEDs. Fabrication of practical visible LEDs in the range from

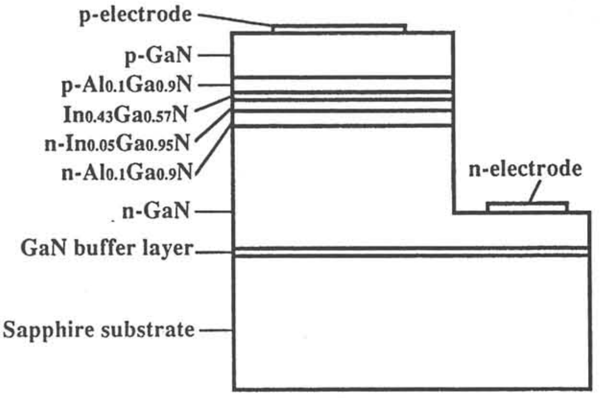


Fig. 1. The structure of green SQW LED.

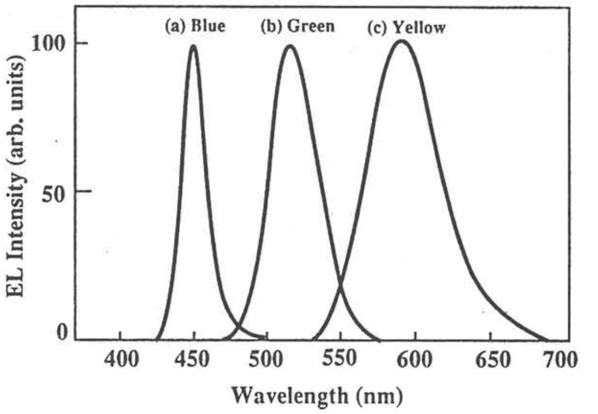


Fig. 2. Electroluminescence of (a) blue, (b) green and (c) yellow SQW LEDs at a forward current of 20 mA.

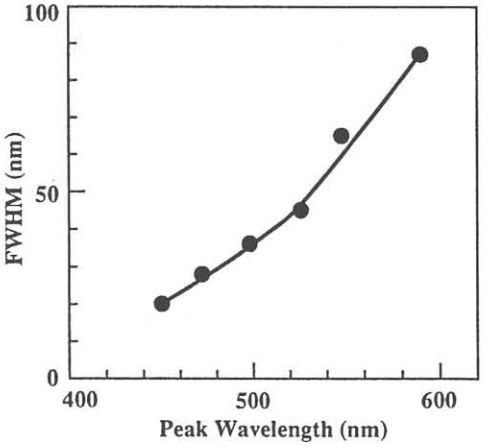


Fig. 3. FWHM of the EL spectra of SQW LEDs as a function of the peak wavelength.

blue to yellow is possible using III-V nitride materials at present.

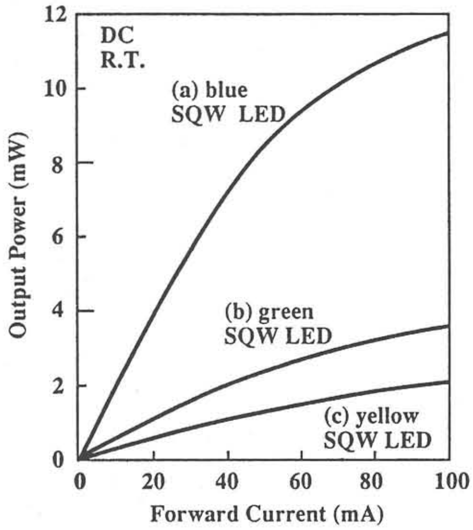


Fig. 4. The output power of (a) blue, (b) green and (c) yellow SQW LEDs as a function of the forward current.

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