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High-power InGaN single-quantum-well-structure blue and violet light-emitting diodes

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High-power blue and violet light-emitting diodes (LEDs) based on III–V nitrides were grown by metalorganic chemical vapor deposition on sapphire substrates. As an active layer, the InGaN single-quantum-well-structure was used. The violet LEDs produced 5.6 mW at 20 mA, with a sharp peak of light output at 405 nm, and exhibited an external quantum efficiency of 9.2%. The blue LEDs produced 4.8 mW at 20 mA and sharply peaked at 450 nm, corresponding to an external quantum efficiency of 8.7%. These values of the output power and the quantum efficiencies are the highest ever reported for violet and blue LEDs.

Much research has been conducted on high-brightness blue light-emitting diodes (LEDs) and laser diodes (LDs) for use in full-color displays, full-color indicators, and light sources for lamps with the characteristics of high efficiency, high reliability, and high speed. For these purposes, II–VI materials such as ZnSe,[1] SiC,[2] and III–V nitride semiconductors such as GaN[3] have been investigated intensively for a long time. However, it has been impossible to obtain high-brightness blue LEDs with brightness over 1 cd. As II–VI based materials, ZnMgSSe-, ZnSSe-, and ZnCdSe-based materials have been intensively studied for blue and green light-emitting devices, and much progress has been achieved recently on green LEDs and LDs. The recent situation regarding performance of II–VI green LEDs is that the output power is 1.3 mW at 10 mA and that the peak wavelength is 512 nm.[4] When the peak wavelength shortens to the blue region, the output power decreases dramatically to about 0.3 mW at 489 nm.[4] The lifetime of II–VI-based light-emitting devices is still short, which prevents the commercialization of II–VI-based devices at present. SiC is another wise band-gap material for blue LEDs. Current output power of SiC blue LEDs is only between 10 and 20 μW because it is an indirect band-gap material.[2]

On the other hand, there are no suitable substrates for III–V nitride growth without sapphire considering its high growth temperature and the cost of the substrate although the sapphire has a large lattice mismatch between GaN and sapphire. Despite this large lattice mismatch, recent research on III–V nitrides has paved the way for the realization of high-quality crystals of AlGaN and InGaN, and *p*-type conduction in AlGaN.[5–8] Moreover, the hole-compensation mechanism of *p*-type AlGaN has been elucidated.[9] High-power blue and blue-green LEDs with an output power over 1 mW have been achieved by using these techniques and are now commercially available.[10,11] Although these InGaN/AlGaN double-heterostructure (DH) LEDs produce a high-power light output in the blue and blue-green regions, they have a broad emission spectrum [full width at half-maximum (FWHM)=70 nm] with the light output ranging from the violet to the yellow-orange spectral region. This broad spectrum, which results from the intentional introduction of Zn into the InGaN active region of the device to produce a deep-level emission peaking at 450 nm, makes the output appear whitish-blue, when the LED is viewed with the human eye. Therefore, blue LEDs, which produce a sharp blue emission at 450 nm with a narrow FWHM, have been desired for application to full-color LED displays. For this purpose, violet LEDs with a narrow spectrum (FWHM=10 nm) at a peak wavelength of 400 nm originating from the band-to-band emission of InGaN were reported.[12] However, the output power of these violet LEDs was only about 1 mW, probably due to the formation of misfit dislocation in the thick InGaN active layer (about 1000 Å) by the stress introduced into the InGaN active layer due to lattice mismatch, and the difference in thermal expansion coefficients between the InGaN active layer and AlGaN cladding layers. When the thickness of the InGaN active layer becomes small, the elastic strain is not relieved by the formation of misfit dislocation and that the crystal quality of the InGaN active layer improves. We reported the high-quality InGaN multiquantum-well structure (MQW) with the 30 Å well and 30 Å barrier layers.[13] Here, we describe the single quantum-well structure (SQW) blue LEDs which have a thin InGaN active layer (about 20 Å) in order to obtain high-power blue emission with a narrow emission spectrum.

III–V nitride films were grown by the two-flow metalorganic chemical vapor deposition (MOCVD) method. Details of the two-flow MOCVD are described in other papers.[14] The growth was conducted at atmospheric pressure. Sapphire with (0001) orientation (*c* face), which had a 2 in. diameter, was used as a substrate. The growth conditions of each layer are described in other papers.[10,11] In comparison with previous InGaN/AlGaN DH LEDs, the major difference is that the InGaN active layer becomes a thin undoped InGaN layer.

The blue LED device structures (Fig. 1) consists 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 thicklayer of *n*-type $Al_{0.3}Ga_{0.7}N$:Si, a 500 Å thick layer of *n*-type $In_{0.02}Ga_{0.98}N$:Si, a 20 Å thick active layer of undoped $In_{0.2}Ga_{0.8}N$, a 1000 Å thick layer of *p*-type $Al_{0.3}Ga_{0.7}N$:Mg, and a 0.5 μm thick layer of *p*-type GaN:Mg.

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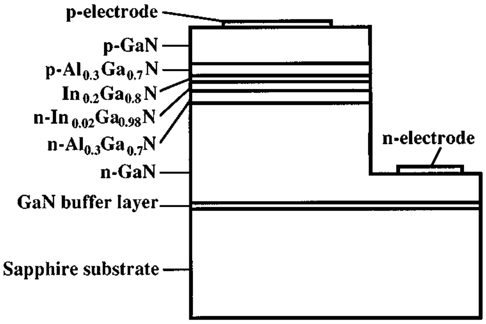

FIG. 1. The structure of SQW blue LED.

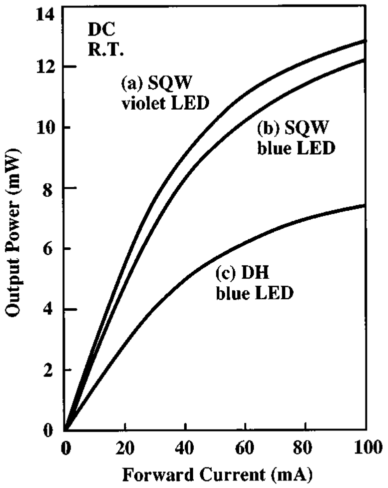

FIG. 3. The output power of (a) SQW violet LED, (b) SQW blue LED, and (c) DH blue LED as a function of the forward current.

The active region forms a SQW structure consisting of a 20 Å $In_{0.2}Ga_{0.8}N$ well layer sandwiched by 500 Å *n*-type $In_{0.02}Ga_{0.98}N$ and 1000 Å *p*-type $Al_{0.3}Ga_{0.7}N$ barrier layers. In violet LEDs, the active layer is $In_{0.09}Ga_{0.9}N$.

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, a 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×350 μm). These chips were set on the lead frame, and were then molded. The characteristics of LEDs were measured under direct current (dc)-biased conditions at room temperature.

Figure 2 shows the electroluminescences (EL) of the SQW blue LEDs in comparison with the previous Zn-doped InGaN/AlGaN DH blue LEDs at forward current of 20 mA. The peak wavelengths of both LEDs are 450 nm. The FWHM of the EL spectrum of the SQW blue LEDs is about 25 nm, while that of DH LEDs is about 70 nm. The peak wavelength and the FWHM of SQW LEDs are almost constant when the forward current is increased to 100 mA. On the other hand, the peak wavelength of DH LEDs becomes shorter with increasing forward current and a band-to-band emission (around 385 nm) appears under a high-current injection condition.[10,11] In the SQW blue LEDs, the active layer is an $In_{0.2}Ga_{0.8}N$ whose band-edge emission wavelength is 420 nm under the stress-free.[12] On the other hand, the emission peak wavelength of SQW blue LEDs is 450 nm. The energy difference between the peak wavelength of the EL and the stress-free band-gap energy is approximately 190 meV. In order to explain this band-gap narrowing of the $In_{0.2}Ga_{0.8}N$ active layer, the quantum size effects, the exciton effects (Coulomb effects correlated to the electron-hole pair) of the active layer, and the strained effects by the mismatch of the lattice and the difference in thermal expansion coefficients between well layer and barrier layers must be considered. Among these effects, the tensile stress in the active layer caused by the thermal expansion coefficient difference between well layer and barrier layers is probably responsible for the band-gap narrowing of the InGaN SQW structure.

The output power of the SQW LEDs and the DH blue LEDs is shown as a function of the forward current under dc in Fig. 3. The output power of the SQW LEDs and that of the DH 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. The output power of the SQW violet LEDs is 2.8 mW at 10 mA, and 5.6 mW at 20 mA, which is about twice as high as that of the DH blue LEDs. The external quantum efficiency is 9.2% at 20 mA. The output power of SQW blue LEDs with a peak wavelength of 450 nm is 4.8 mW at 20 mA and the external quantum efficiency is 8.7%.

A typical example of the $I-V$ characteristics of the SQW blue LEDs is shown in Fig. 4. The forward voltage is 3.1 V

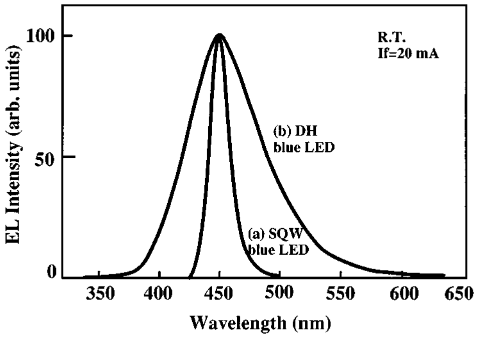

FIG. 2. Electroluminescence spectra of (a) SQW blue LED and (b) DH blue LED at a forward current of 20 mA.

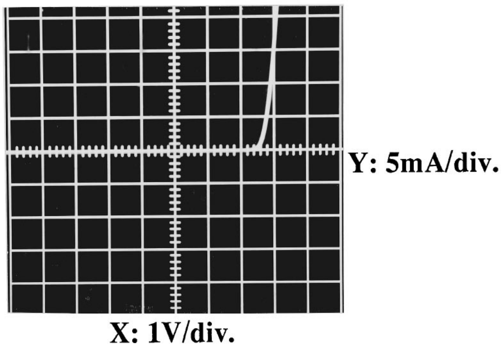

FIG. 4. Typical $I-V$ characteristics of SQW blue LED.

at 20 mA. This forward voltage is the lowest value ever reported for III–V nitride LEDs.

In summary, high-power InGaN SQW blue and violet LEDs were fabricated. The output power of the violet LEDs was 5.8 mW and the external quantum efficiency was as high as 9.2% at a forward current of 20 mA at room temperature. The peak wavelength and the FWHM were 405 and 20 nm, respectively, and those of blue LEDs were 450 and 25 nm, respectively. Such LED performances of quantum well structures will pave the way for the realization of blue LDs based on III–V nitride materials in the near future.

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