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GaN microdisk light emitting diodes

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Microdisk light-emitting diodes (μ-LEDs) with diameter of about 12 μm have been fabricated from InGaN/GaN quantum wells. Photolithographic patterning and inductively coupled plasma dry etching have been employed to fabricate these μ-LED devices. Device characteristics, such as the current–voltage characteristics, light output power, and electroluminescence (EL) spectra have been measured and compared with those of conventional broad-area LEDs. Our results showed that, for an identical area, the quantum efficiencies of μ-LED are enhanced over the conventional broad-area LEDs due to an enhanced current density and possibly microsize effects. The implications of our results on the design of future UV/blue microoptoelectronic devices are discussed. © *2000 American Institute of Physics.* [S0003-6951(00)03805-5]

III–nitride wide band gap semiconductors have recently attracted considerable interest due to their applications for optoelectronic devices, which are active in the blue and ultraviolet wavelength regions and electronic devices capable of operation at high temperatures/high power conditions.[1,2] The recent success of the III–nitride light emitters, including blue light emitting diodes (LEDs) and laser diodes is encouraging for the investigation of microcavity lasers and micro-LEDs. New physical phenomena and properties begin to dominate as device size approaches the wavelength of light, including modified spontaneous emission, enhanced quantum efficiency, and reduced lasing threshold in microcavities, all of which warrant fundamental investigations.[3] We have recently fabricated GaN quantum well (QWs) microdisk cavities, an enhanced quantum efficiency and optical resonant modes have been observed in these microdisk cavities.[4,5] Resonant optical modes in microsize GaN pyramids prepared by lateral epitaxial overgrowth (LEO) have also been observed.[6] Optically pumped lasing actions have also been observed in GaN pyramids prepared by LEO,[7] in GaN microdisks prepared by reactive-ion etching,[8] and in microsize GaN vertical cavity surface emitting-laser structures.[9] However, electrically pumped III–nitride microstructures and microdevices have not been fabricated and studied. The microsize LEDs and lasers offer benefits over edge emitters including the ability to fabricate arrays of individually controllable pixels on a single chip, enhanced quantum efficiency, and reduced lasing threshold.

It this letter, we report the fabrication and characterization of InGaN/GaN QW μ-LEDs, including device fabrication processes, current-voltage ($I-V$) characteristics, light output power, electroluminescence (EL) spectra, and comparisons between the conventional board-area and μ-LEDs. The original InGaN/GaN QW wafers were grown by low-pressure metalorganic chemical vapor deposition on sapphire substrates with a 20 nm GaN buffer layer and consisted of a 2.0 μm thick Si doped ($2\times10^{18}/\mathrm{cm}^3$) GaN epilayer, a 30 Å undoped $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{N}$ ($x\sim0.1$) quantum well, and a 0.5 μm thick Mg doped ($1.0\times10^{19}/\mathrm{cm}^3$) GaN epilayer. Other improvement methods (such as codoping, LEO, etc.) have not yet been employed in our LED structures. The structures were then annealed under a nitrogen ambient at 950 °C for about 5 s in a rapid thermal annealing furnace to activate Mg acceptors. The room temperature carrier concentration and mobility of the Mg-doped (Si-doped) epilayers grown under similar conditions were $p=2\times10^{17}/\mathrm{cm}^3$ and $\mu=12\,\mathrm{cm}^2/\mathrm{V\,s}$ ($n=1.6\times10^{18}/\mathrm{cm}^3$ and $\mu=310\,\mathrm{cm}^2/\mathrm{V\,s}$), respectively.

An array of μ-disk cavity GaN LEDs with a diameter of 12 μm and a spacing of 50 μm was fabricated by photolithographic patterning and inductively coupled plasma (ICP) dry etching. A layer of about 0.9 μm thick was removed by ICP etching (with an etching rate of 0.65 μm/min) before depositing metal contacts. Bilayers of Al (400 nm)/Ti (30 nm) and Au (300 nm)/Ni (30 nm) were deposited by sputtering as *n*- and *p*-type ohmic contacts and followed by a thermal annealing in a nitrogen ambient at 500 °C for 4 min. A schematic diagram of our GaN μ-LEDs is shown in Fig. 1(a). A scanning electron microscopy (SEM) image of our fabricated GaN μ-LEDs is shown in Fig. 1(b). ICP etching produced very smooth top and edge surfaces. The inner (outer) circle with a diameter of about 8 (12) μm is the image of *p*-type contacts (μ-LEDs). Conventional broad-area LEDs with size of $240\times240\,\mu\mathrm{m}^2$ (*p*-type contacts $80\times80\,\mu$m) were also fabricated from the same wafers for comparison studies.

A bonding scheme for a μ-LED array contact connection has not yet been employed. A probe station was utilized to inject current for the subsequent measurements of the $I-V$, EL spectra, and the output powers of the μ-LEDs. A large number of LEDs were tested and the results were similar to within a 10% variation. The $I-V$ characteristics for one of our InGaN/GaN QW μ-LEDs is plotted as solid squares in Fig. 2(a). The $I-V$ characteristics of a conventional broad-area InGaN/GaN QW LED fabricated from the same wafer is also plotted as open circles in Fig. 2(a). The current saturation occurs around 13 V in μ-LEDs. As expected, the current in μ-LEDs is smaller than that in the broad-area LEDs due to the reduced area of μ-LEDs. However, the current density of the broad-area LEDs, j_{LED}, is actually much smaller than

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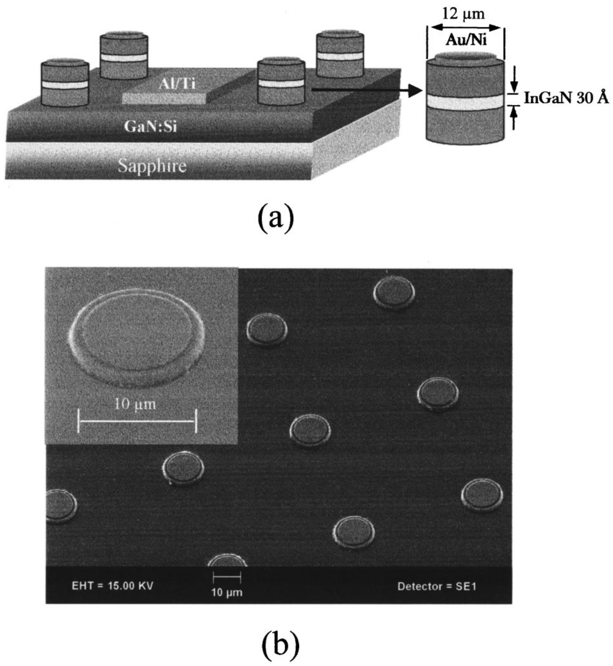

FIG. 1. (a) Schematic diagram and (b) SEM image of InGaN/GaN QW microsize LEDs (μ-LEDs).

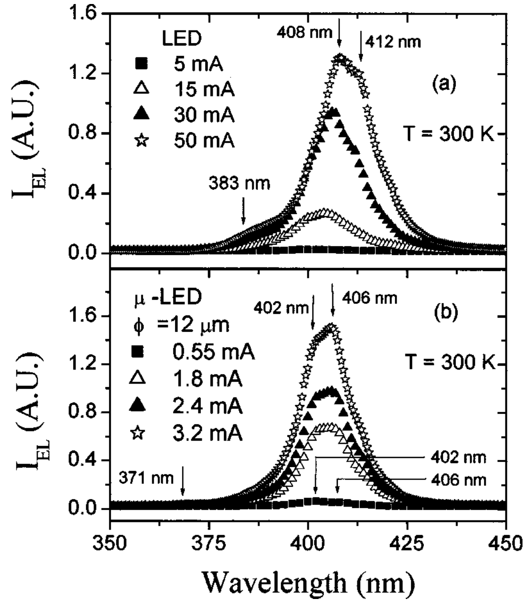

FIG. 3. 300 K electroluminescence (EL) spectra of an unpackaged (a) InGaN/GaN QW conventional broad-area LED and (b) μ-LED measured under dc biased conditions for several different forward currents.

that of μ-LEDs, $j_{\mu\text{-LED}}$. This is demonstrated in Fig. 2(b), which indicates that $j_{\mu\text{-LED}}$ is a factor of 5 larger than j_{LED}, by noting the fact that j_{LED} has been multiplied by a factor of 5 in Fig. 2(b).

The enhanced current density in μ-LEDs is partly due to the contact schemes of our LEDs. Furthermore, our measurements have also indicated that current spreading is more effective in devices of smaller sizes. Another interesting feature is that the current density versus voltage, or $j-V$ characteristics of the conventional LEDs and μ-LED can be scaled to become an identical curve, as indicated by the fact that two $j-V$ curves shown in Fig. 2(b) followed exactly the same trend after scaling j_{LED} by a factor of 5. This scaling behavior clearly indicates that both μ-LEDs and the broad-area LEDs have similar $I-V$ and emission characteristics.

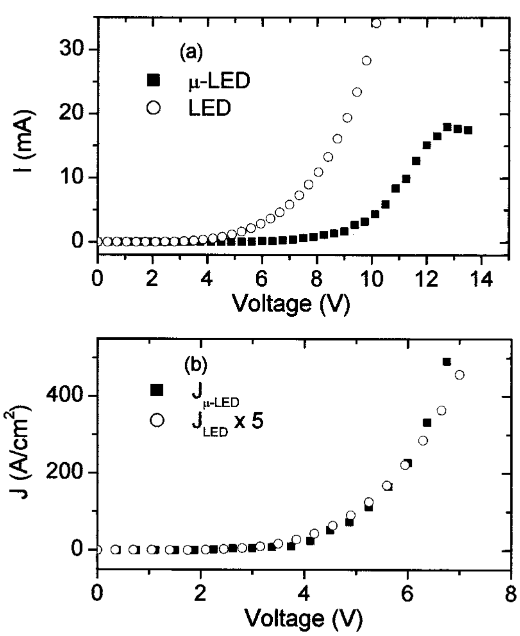

FIG. 2. (a) $I-V$ and (b) current density vs bias voltage ($j-V$) characteristics of unpackaged InGaN/GaN QW conventional broad-area (open circles) and μ-LED (solid squares) measured at room temperature. Current density of the board-area LED, j_{LED}, in (b) has to be multiplied by a factor of 5 in order to scale the $j_{\text{LED}}-V$ curve with that of $j_{\mu\text{-LED}}-V$. Here, the current densities were calculated by divide current by the contact areas.

The 300 K EL spectra of GaN μ-LEDs and broad-area LEDs have been measured under different direct current (dc) biased conditions. Figure 3 shows the results for a representative (a) broad-area LED and (b) a μ-LED. The main emission peaks of the EL spectra is around 408 nm with a full width at half maximum (FWHM) of about 20 meV and is due to the band edge transition in the InGaN active region. These characteristics are similar to the Nichia's Si-doped InGaN/GaN double-heterostructure violet LEDs.[1] The emission energy peak position E_p of the EL spectra of the broad-area LEDs slightly shifts toward lower emission energies with an increase of injection current. A secondary peak near 412 nm becomes visible when the injection current is above 40 mA. In comparison with the broad-area LEDs, the spectral peak position of the μ-LEDs EL spectra remains unchanged with injection current and is slightly blueshifted with respect to the broad-area LED. Moreover, the FWHM of the μ-LED EL spectra is also narrower (15 meV). These differences may be related to (the band filling and) a partial strain relief in μ-LEDs due to the reduced lateral sizes, but remain to be investigated. Most interestingly, we can achieve higher EL intensities in a single μ-LED than in a broad-area LED. For example, Fig. 3 shows that the relative intensity level is around 1.6 at 3.2 mA in the μ-LED, while that in the broad-area LED is around 1.3 at 50 mA.

The total light output power as a function of forward current, or the $L-I$ characteristics, has been measured for these unpackaged μ-LEDs by the probing method. Due to the probing measurement configuration, the output power can be measured only in the sapphire substrate side. In such a configuration, the total optical loss is at least 50%. The

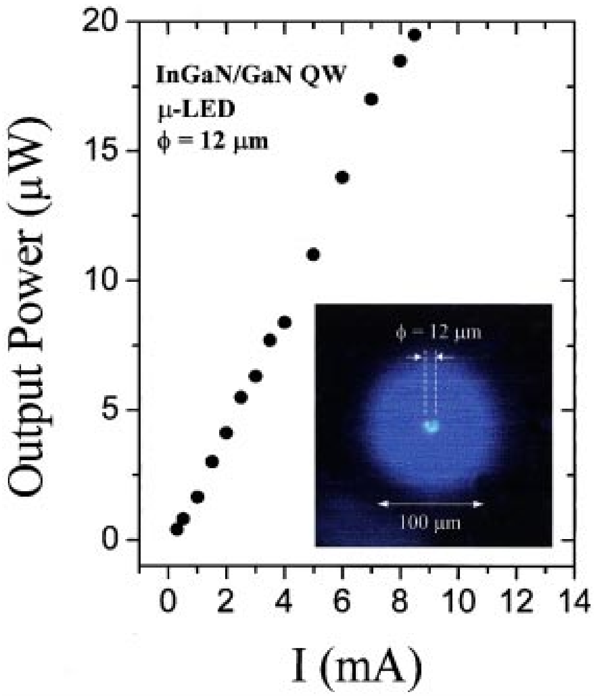

FIG. 4. (Color) The total output power as a function of forward current ($L-I$ curve) for one of our unpackaged InGaN/GaN QW μ-LED measured in the sapphire substrate side. The inset is an optical microscope image taken from the top of the μ-LED. The bright spot of 12 μm in diameter in the center is the area of μ-LED operating at a forward current of about 5 mA.

result for a representative μ-LED is shown in Fig. 4. The inset of Fig. 4 is an optical microscope image taken from the top of a μ-LED under a biased condition of about 5 mA. We see that we can achieve 20 μW output power in a 12 μm LED at a forward current of 8 mA despite the great optical losses due to the present measurement scheme. Compared with the output power of about 40 μW at a forward current of 10 mA and 90 μW at 20 mA of Nichia's packaged broad-area violet LEDs ($0.9\,\mathrm{mm}\times 0.9\,\mathrm{mm}$) fabricated from InGaN/GaN double heterostructures without employing codoping and other improvement methods,[1] the results exhibited by our μ-LEDs (fabricated from similar structures) are quite promising. Our results indicate that the quantum efficiency (per unit area) is much higher in μ-LEDs than that in the conventional broad-area LEDs. The enhanced quantum efficiency in μ-LEDs may be an inherent attribute due to microsize effects as well as a more efficient usage of injected current.

In summary, we have fabricated III–nitride microsize LEDs by using InGaN/GaN QW structures. Photolithographic patterning, ICP dry etching, and metal contact deposition by sputtering have been employed. Device characteristics have been measured and compared with those of conventional broad-area LEDs. The quantum efficiency per unit area was found to be enhanced greatly in μ-LEDs over the broad-area LEDs. Although the micro-optoelectronic devices including μ-LEDs, μ-LED array, μ lasers, and vertical cavity surface emitting lasers have advantageous attributes over the edge-emitting devices, further improvements in material quality as well as in microsize ohmic contacts, p-type contacts in particular, are needed. Furthermore, due to the insulating nature of the sapphire substrates, packaging and bonding of these microdevices could present another challenge.

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