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Size dependence of III-nitride microdisk light-emitting diode characteristics

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Individual microdisk blue-light-emitting diodes (μ-LEDs) of varying diameters from 5 to 20 μm have been fabricated from InGaN/GaN quantum wells. Size effects on the μ-LED characteristics, including $I-V$ and $L-I$ characteristics, have been measured. The transient behavior of the μ-LEDs has also been studied. It was found that the turn-on time is on the order of our system response (30 ps) and the turn-off time is on the order of 0.2 ns and shows a strong size dependence. The ability of two-dimensional array integration with advantages of high speed, high resolution, low temperature sensitivity, and applicability under versatile conditions make III-nitride μ-LEDs a potential candidate for light sources in short-distance optical communications. [DOI: 10.1063/1.1376152]

III-nitride wide-bandgap semiconductors have recently attracted considerable interest due to their applications for optoelectronic devices, which are active in the blue and ultraviolet (UV) wavelength regions and electronic devices capable of operation at high temperatures/high power conditions.[1,2] The recent success of the III-nitride edge emitters, including blue light-emitting diodes (LEDs) and laser diodes, is encouraging for the investigation of microcavity lasers and microsize LEDs (μ-LEDs). New physical phenomena and properties begin to dominate as device lateral size or the vertical length approaches the wavelength of light, including modified spontaneous emission, such as emission lifetime, the spectral linewidth, the directionality of the emission, and enhanced quantum efficiency, all of which warrant fundamental investigations.[3] The microsize LEDs and lasers offer benefits over edge emitters including the ability to fabricate arrays of individually controllable pixels on a single chip and enhanced quantum efficiency. In addition, III nitrides are grown on sapphire substrates, which are transparent to light and, hence, can serve as a nature surface for output coupling, reducing the steps for device packaging. III-nitride microsize LEDs may be used for short distance optical communications and optical interconnects in computers. The microsize LEDs have advantages of easy coupling to optical fibers and allow the integration of a dense two-dimensional (2D) array onto a single chip.

Microdisk and microring cavities have been fabricated previously from InGaN/GaN and GaN/AlGaN quantum wells (QWs) by photolithography patterning and plasma dry etching.[4–6] Enhanced quantum efficiency (QE) and optical resonant modes have been observed in these microcavities. Most recently, we have fabricated electrically pumped InGaN/GaN QW individual μ-disk LEDs with a diameter of about 10 μm and it was shown that the QE was higher in μ-disk LEDs than in the conventional broad-area LEDs.[7] The enhanced QE in μ-LEDs may be an inherent attribute due to microsize effects as well as a more efficient usage of injected current. By interconnecting together hundreds of μ-LEDs and inserting them into the same device area taken up by a conventional broad-area LED, we have achieved an overall 60% increase in emission efficiency.[8] We have also demonstrated the operation of a prototype III-nitride microdisplay with a dimension of $0.5\times 0.5\,\mathrm{mm}^2$ (consists of 10×10 pixels with pixel size of about 10 μm) by integrating an individually addressed 2D μ-LED array.[9] In this letter, we report the size dependence of III-nitride μ-LED characteristics. The original LED wafers were grown on sapphire substrates with 30 nm GaN buffer layers by low pressure metalorganic chemical vapor deposition. The device structure includes 3.5 μm of silicon doped GaN, ten periods of Si doped superlattice consisting of alternating layers of AlGaN (50 Å)/GaN (50 Å), 0.05 μm of Si doped GaN, a 30 Å undoped InGaN active layer, followed by 14 periods of Mg doped superlattice consisting of alternating layers of AlGaN (50 Å)/GaN (50 Å), and 0.5 μm Mg doped GaN epilayer. The structure was then thermally annealed at 950°C for 5 s in nitrogen in a rapid thermal-annealing furnace to activate Mg acceptors. This process produced room temperature p-layer concentrations of $5\times 10^{17}\,\mathrm{cm}^{-3}$ (mobility 12 $\mathrm{cm}^2/\mathrm{V\,s}$) and n-layer concentrations of $1.6\times 10^{18}\,\mathrm{cm}^{-3}$ (mobility 310 $\mathrm{cm}^2/\mathrm{V\,s}$).

Individual μ-disk LEDs of varying diameters from 5 to 20 μm were fabricated by photolithography patterning and inductively coupled plasma dry etching. Bilayers of Ni (20 nm)/Au (200 nm) and Al (300 nm)/Ti (20 nm) were deposited by electron beam evaporation as p- and n-type ohmic contacts. The p-type contacts were thermally annealed in air at 500 °C for 5 min and the n-type contacts were thermally annealed in a nitrogen ambient at 650 °C for 5 min. A dielectric layer was deposited by e-beam evaporation after the μ-LEDs' formation for the purpose of isolating p-type contacts from the etch-exposed n-type layer. Figure 1(a) shows an atomic force microscope (AFM) image of a fabricated μ-LED. As can be seen from Fig. 1(a), the p-type contact was connected to the top p layer by opening a hole through the insulating dielectric layer. The size of the p-type contact is about 4 μm in diameter. Figure 1(b) shows optical microscope images, taking from the top (p-type contact side), of

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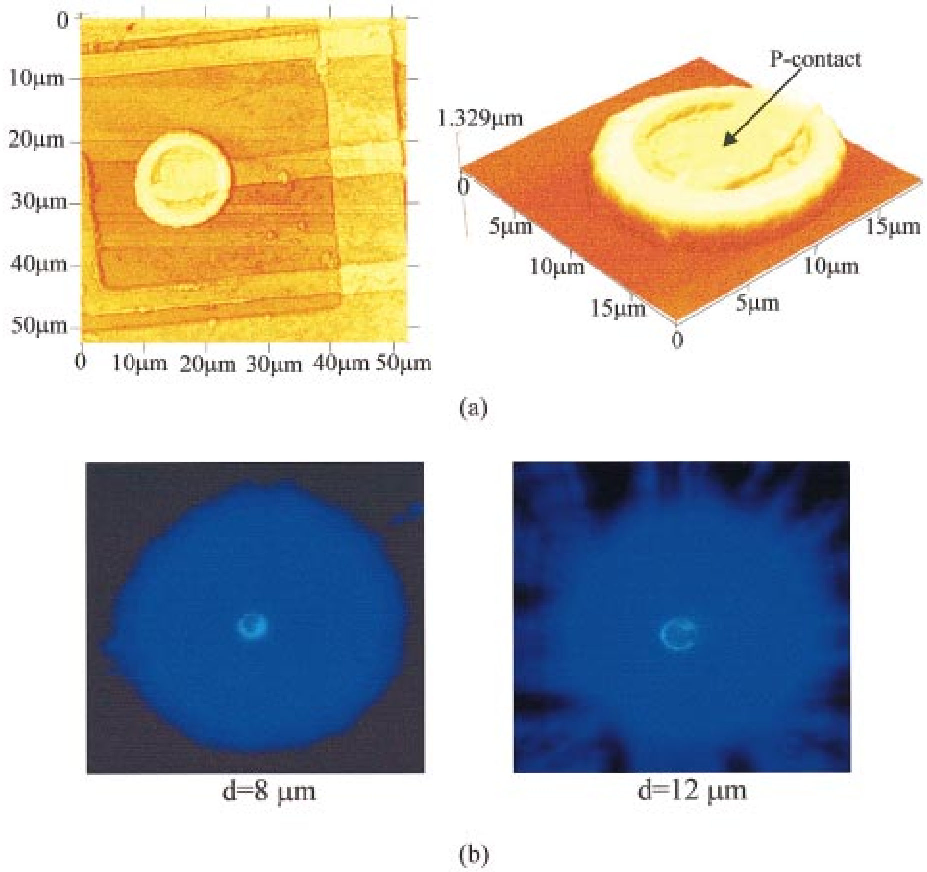

FIG. 1. (Color) (a) AFM image of a III-nitride μ-LED of diameter $d=12\ \mu$m. (b) Optical microscope images of two μ-LEDs ($d=12$ and 15 μm) in action.

two representative InGaN/GaN QW μ-LEDs with diameters $d=8$ and 12 μm in action with an injected current of 2 mA. The p-type contacts on the top layers are also visible in Fig. 1(b).

The $I-V$ characteristics of μ-disk LEDs of varying sizes and a conventional board-area LED ($300\times300\ \mu m^2$) fabricated from the same wafer are plotted in Fig. 2 in (a) linear and (b) semilogarithmic scales. It is clearly seen that the turn-on voltages for individual μ-LEDs are larger than that of the broad-area LED. Among the different sizes of μ-LEDs, the turn-on voltage increases with decreasing μ-LED size. The slope of the Log$I$ vs V plot in Fig. 2(b) reflects the ideality factor, $n(=1/\text{slope})$. It is clear that the ideality factor of μ-LEDs ($n=18.5$) is larger than that of the broad-area LED($n=6.4$). There is only a weak size dependence of ideality factor for the μ-disk LEDs. The larger ideality factor reflects the enhanced nonradiative recombination in μ-LEDs, which is most likely a result of enhanced surface recombination around the edge of the disk of μ-LEDs.

The emission wavelength of our μ-LEDs varies from green to purple (380–520 nm) by varying In content in the InGaN active layers. Figure 3 shows a room temperature electroluminescence (EL) spectrum of a purple μ-LED mea-

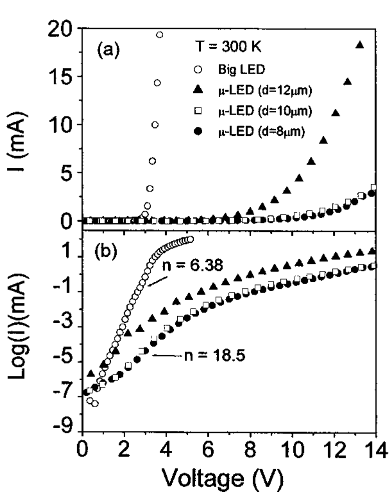

FIG. 2. $I-V$ characteristics of μ-LEDs of varying sizes ($d=8$, 10, and 12 μm) and a broad-area LED ($300\times300\ \mu m^2$) in (a) linear and (b) semilogarithmic plots.

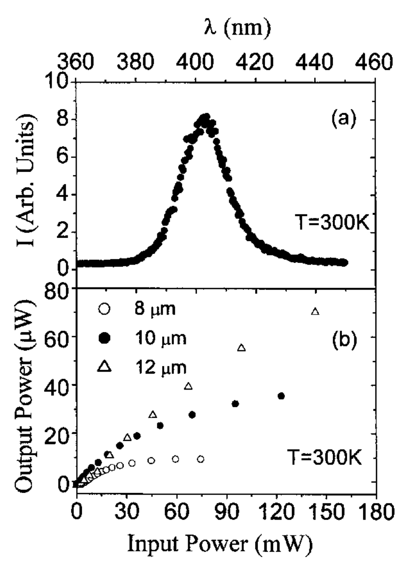

FIG. 3. (a) EL emission spectrum of a purple μ-LED. (b) Output power vs input power ($L-I$) plot of μ-LEDs of different sizes.

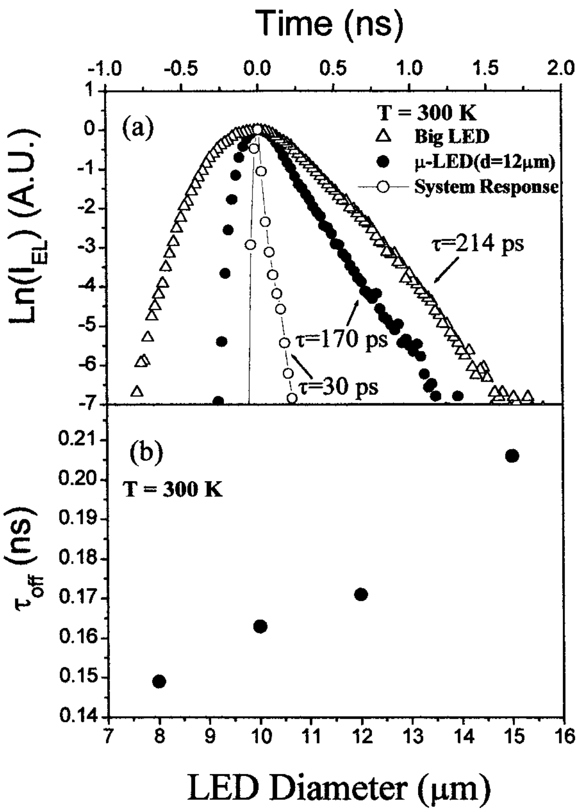

FIG. 4. (a) Transient response of a μ-LED and a conventional broad-area LED. (b) Size dependence of the turn-off time, τ_{off}, of μ-LEDs.

sured at a forward current of 2 mA. Figure 3(b) plots the output power versus input power measured from the sapphire substrate side for three unpackaged μ-LEDs of different sizes. Heating effects become more prominent as the size of μ-LEDs decreases. For μ-LEDs with $d=12\,\mu$m, the output power increases almost linearly with input power in the entire measured range. However, for μ-LEDs with $d=8\,\mu$m, the output power saturates at about 10 μW for input power above about 45 mW. As expected, heat dissipation is more difficult in μ-LEDs with reduced sizes, which causes power output saturation. However, we believe that further improvements can be made by appropriate packaging processes.

These μ-LEDs have potential applications in short distance optical communications. For these applications, the speed is one of the most crucial parameters, which has been measured by time-resolved EL.[10] In Fig. 4 we plotted (a) transient responses of a μ-LED and a conventional broad-area LED and (b) the size dependence of the ''turn-off'' time, τ_{off}, of μ-LEDs. The turn-on response is on the order of our system response (~30 ps) and it thus cannot be measured. However, the turn-off transient is in a form of single exponential and its lifetime, τ_{off}, can thus be determined. It was found that τ_{off} decreases with a decrease of μ-LED size. It reduced from 0.21 ns for $d=15\,\mu$m to 0.15 ns for $d=8\,\mu$m. This behavior is also expected since the effects of surface recombination are enhanced in smaller μ-LEDs. On the other hand, the increased operating speed may also be a result of an enhanced radiative recombination rate in μ-LEDs. With this fast speed and other advantages such as long operation lifetime, III-nitride μ-LED arrays may be used to replace lasers as inexpensive short distance optical links such as between computer boards with a frequency up to 10 GHz.

In summary, the size dependence of InGaN/GaN QW μ-LED characteristics has been studied. It was found that the turn-on and turn-off speeds of the μ-LEDs are very fast, on the order of subnanoseconds. The unique features of small size, fast speed, transparent sapphire substrate, and the capability of 2D array integration, make III-nitride μ-LEDs very attractive for applications in short distance optical links and optical communications.

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