InGaN/GaN quantum well interconnected microdisk light emitting diodes

S. X. Jin, J. Li, J. Y. Lin, and H. X. Jiang

Citation: Applied Physics Letters **77**, 3236 (2000); doi: 10.1063/1.1326479

View online: http://dx.doi.org/10.1063/1.1326479

View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/77/20?ver=pdfcov

Published by the AIP Publishing

InGaN/GaN quantum well interconnected microdisk light emitting diodes

S. X. Jin, J. Li, J. Y. Lin, and H. X. Jiang[a)]
Department of Physics, Kansas State University, Manhattan, Kansas 66506-2601

(Received 28 August 2000; accepted for publication 28 September 2000)

Interconnected microdisk light-emitting diodes (μ-LEDs) have been fabricated from InGaN/GaN single quantum wells grown by low pressure metal organic chemical vapor deposition. These interconnected μ-disk LEDs fit into the same device area taken up by a conventional broad-area LED. The performance characteristic of these interconnected μ-disk LEDs, including $I-V$ and $L-I$ characteristics as well as electroluminescence spectra have been measured and compared with those of the conventional broad-area LEDs. For interconnected μ-disk LEDs, while V_F, the forward biased voltage at 20 mA, was slightly increased, the emission efficiency was increased by as much as 60% over the conventional LEDs for a fixed device area. The results thus suggested that replacing a conventional broad-area LED with an interconnected μ-disk LED, the external quantum efficiency can be significantly enhanced. Finally, the fabrication processes of the interconnected μ-disk LEDs are almost the same as those of the conventional broad-area LEDs. It is thus expected the total yield of these interconnected μ-disk LEDs to be the same as the conventional broad-area LEDs. The present method of utilizing interconnected μ-disk LEDs for improving the brightness of LEDs is applicable to other semiconductor LEDs as well as polymer and organic LEDs. © *2000 American Institute of Physics.* [S0003-6951(00)04546-0]

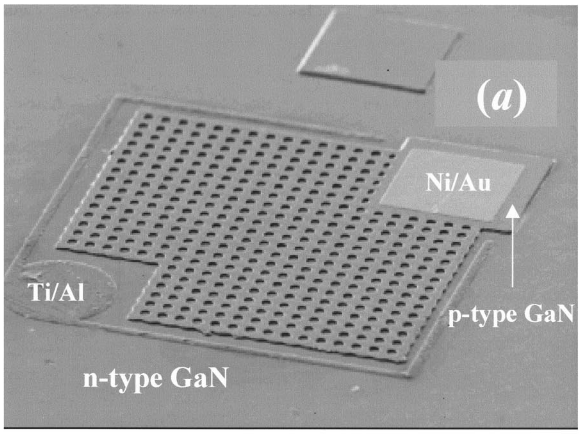
III-nitride wide band gap semiconductors have recently attracted considerable interest due to their applications for optoelectronic devices, which are active in the blue and ultraviolet (UV) wavelength regions and electronic devices capable of operation at high temperatures/high power conditions.[1,2] 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). For instance, although broad-area LEDs possess advantages of being simple to design, have a low temperature sensitivity, and operate without threshold, they suffer from some limitations such as the poor extraction efficiency of light, the wide spectral width, and the large divergence of the output. Microsize light emitters may overcome some of these limitations. 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 line width, the directionality of the emission, and enhanced quantum efficiency, all of which warrant fundamental investigations.[3]

Microdisk and microring cavities have been fabricated previously from InGaN/GaN and GaN/AlGaN quantum wells (QWs) by photolithographic patterning and plasma dry etching.[4–6] Enhanced quantum efficiency (QE) and optical resonant modes have been observed in these microcavities. Resonant optical modes in microsize GaN pyramids prepared by lateral epitaxial overgrowth (LEO) have also been observed.[7] Optically pumped lasing actions have also been achieved in GaN microsize pyramids prepared by LEO,[8] in GaN microdisks prepared by reactive-ion etching,[9] and in microsize GaN vertical cavity surface emitting-laser structures.[10] 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.[11] 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. These previous studies have shown the promises of III-nitride microsize light emitters and laid the groundwork for the fabrication of future advanced microsize devices based on III nitrides.

In this letter, we report the design, fabrication, and characterization of interconnected μ-disk LEDs. The work was motivated by our previous observation of an enhanced QE in individual μ-LEDs. 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 a 3.5 μm of silicon doped GaN, a 30 Å undoped InGaN active layer, and a 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 $5\times10^{17}\,\mathrm{cm}^{-3}$ (mobility 12 cm^2/V s) and n-layer concentrations of $1.6\times10^{18}\,\mathrm{cm}^{-3}$ (mobility 310 cm^2/V s).

Interconnected μ-disk LEDs with two different individual μ-disk diameters, $d=9$ and 12 μm, were fabricated by photolithographic 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. A scanning electron microscopy (SEM) image and an optical microscope image of one of our fabricated interconnected InGaN/GaN QW μ-disk LEDs are shown in Figs. 1(a) and 1(b), respectively. As shown in Fig. 1, more than one hundred μ-disks are interconnected and fit into an area of $300\,\mu$m $\times 300\,\mu$m. A transparent film of Ni/Au was deposited to connect the p-type ohmic contacts of each individual μ-LEDs in a net-like configuration. Though the fabrication

[a)]Electronic mail: jiang@phys.ksu.edu



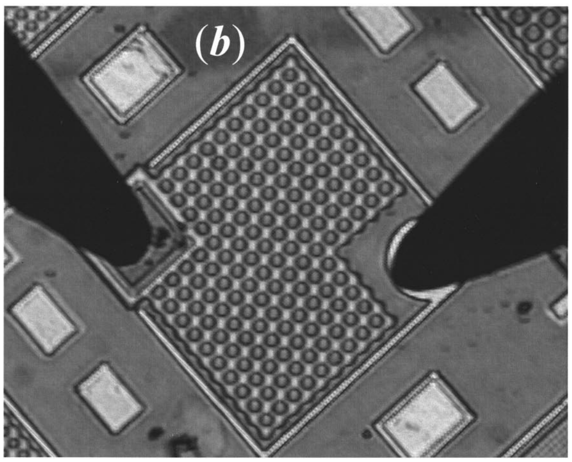


FIG. 1. (a) SEM and (b) optical microscope images of one of our interconnected μ-disk LEDs fabricated from InGaN/GaN QW structures. As illustrated in these images, about 200 μ disks are interconnected and fit into an area of 300 μm$\times$300 μm.

of these interconnected μ-LED arrays require different designs of masks than the conventional broad-area LEDs, the fabrication processes are almost identical to those of the conventional broad-area LEDs. This fact suggests that the total yield of the interconnected μ-disk LEDs should be the same as the conventional broad-area LEDs. Conventional broad-area LEDs with the same device area $(300\times300\,\mu\text{m}^2)$ were also fabricated from the same wafer for comparison studies.

The $I-V$ characteristics of μ-disk LEDs and a conventional broad-area LED fabricated from the same wafer are plotted in Fig. 2. The forward bias voltage at 20 mA, V_F, for the interconnected μ-disk LEDs ($V_F=4.1$ and 4.4 V for $d=9$ and 12 μm LEDs) is increased slightly over the conventional broad-area LED($V_F=3.8$ V) due to the reduction in the total active area as well as the total p-type contact area. The 300 K electroluminescence (EL) spectra of the interconnected μ-disk LEDs and broad-area LEDs have been measured at forward current 20 mA, which are shown in Fig. 3. The EL spectral shapes of the interconnected μ-disk LEDs and the conventional broad-area LED are quite similar. However, more light is produced by the interconnected microdisk LEDs at all experimental conditions, despite the fact that the total active area of an interconnected μ-disk LED is only about 60% of a broad-area LED of the same device area.

Figure 4 shows the light output power versus (a) forward current and (b) input power for the interconnected μ-disk

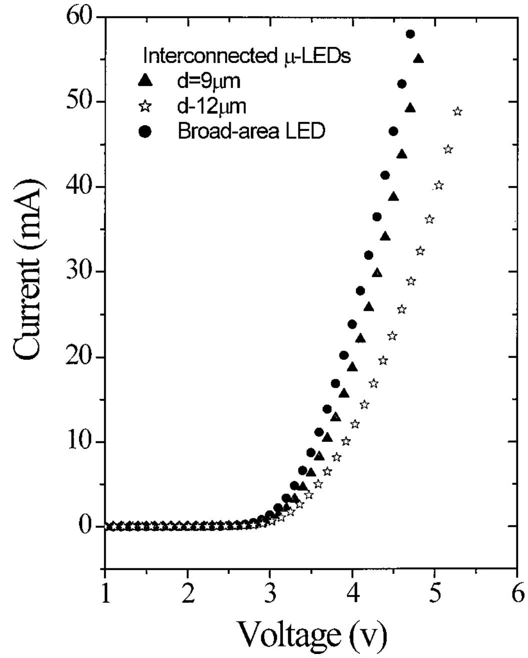


FIG. 2. Comparison of $I-V$ characteristics of interconnected InGaN/GaN QW μ-disk LEDs and a conventional broad-area LED fabricated from the same wafer measured on the top surface of unpackaged chips. Interconnected μ-disk LEDs comprise about 200 μ disks of diameters of 9 or 12 μm and occupy the same device area as the conventional broad-area LED (300 μm$\times$300 μm).

LEDs of disk diameters of $d=9$ and 12 μm and for a conventional broad-area LED measured on the top (p-type GaN side) of unpackaged chips. We should point out that the actual total output powers of these LEDs should be much higher than the measured values shown here since most of the light emission was not collected from these unpackaged chips. The intriguing result shown in Fig. 4 is that the power output increases significantly in the interconnected μ-disk

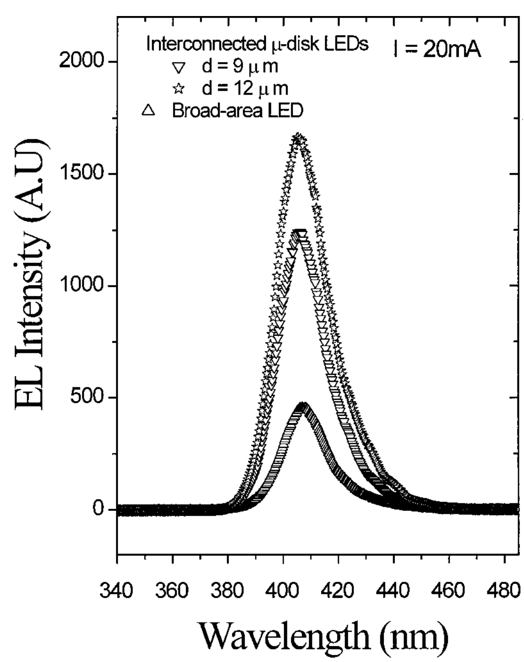


FIG. 3. Comparison of EL spectra of interconnected μ-disk LEDs with a conventional broad-area LED fabricated from the same InGaN/GaN QW wafer measured on the top surface of unpackaged chips at 20 mA.

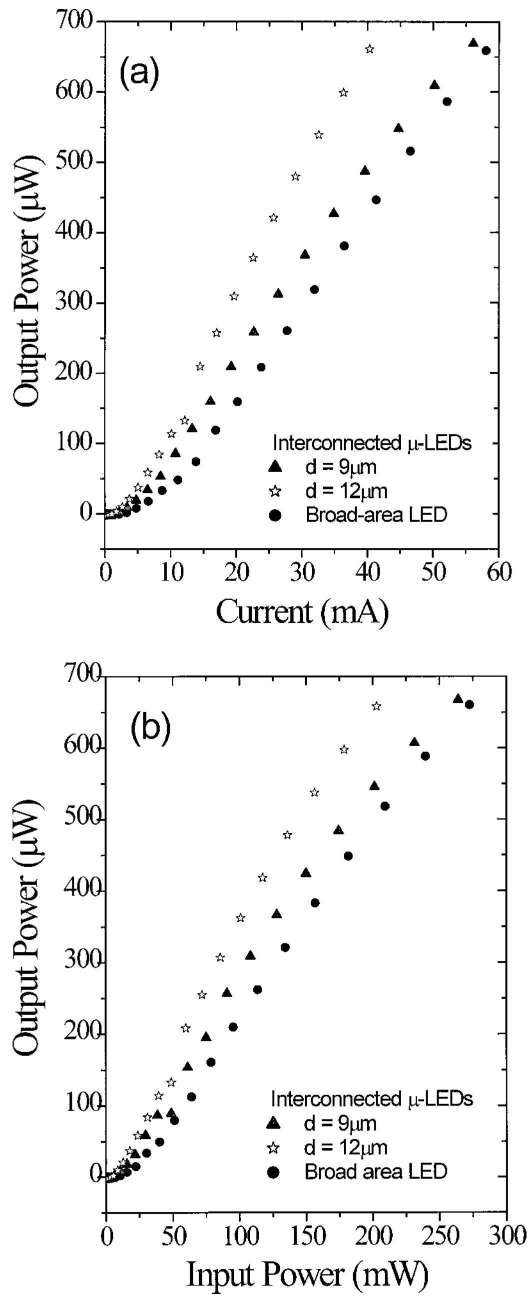


FIG. 4. Light output power vs (a) forward current and (b) input power for the interconnected μ-disk LEDs and a conventional broad-area LED measured on the top surface (p-type GaN side) on unpackaged chips. Actual total output powers of these LEDs should be much higher than the measured values shown here since most of the light emission was not collected from these unpackaged chips.

LEDs over the conventional broad-area LED, consistent with the EL measurement result of Fig. 3. At 20 mA, the output power increases from 160 μW for a conventional LED to 220 μW and 315 μW for interconnected μ-disk LED of $d=9\ \mu$m and $d=12\ \mu$m, respectively. As illustrated in Fig. 4(b), we can achieve an overall QE enhancement over 60% in interconnected μ-disk LEDs.

The output power of LEDs, P_{output}, depends on the internal QE, η_{int}, and extraction efficiency C_{ex},

$$P_{\mathrm{output}} \sim \eta_{\mathrm{int}} C_{\mathrm{ex}}. \quad (1)$$

An increase of P_{output} in the interconnected μ-disk LEDs is due the enhancement of both the internal quantum efficiency (η_{int}) and extraction efficiency (C_{ex}). It is known that increasing in η_{int} is an inherent attribute of microcavity effect as well as a more efficient usage of injected current, which has been observed previously in individual μ-disk LEDs.[11] However, enhancement of extraction efficiency C_{ex} is probably more important here. The increased extraction efficiency in the interconnected μ-disk LEDs has also been demonstrated through the photoluminescence measurements (not shown). It is well recognized that C_{ex} is only a few percent in conventional broad-area LEDs due to the total internal reflection occurring at the LED–air interface. It can be realized that the emitted light is much easier to leak out in the interconnected μ-disk LEDs than in the conventional broad-area LEDs. It is thus expected that C_{ex} is increased significantly in these interconnected μ-disk LEDs. Though the total active area is reduced, enhancements in both η_{int} and C_{ex} improved the overall QE of the interconnected μ-disk LEDs over the conventional broad-area LEDs.

In summary, we have fabricated and characterized interconnected μ-disk LEDs based on InGaN/GaN QWs. Device characteristics have been measured and compared with those of conventional broad-area LEDs. A significant increase in quantum efficiency in the interconnected μ-disk LEDs of more than 60% over the conventional LEDs of the same device areas has been achieved, which was attributed to the enhancements in both the internal quantum efficiency and extraction efficiency in these interconnected μ-disk LEDs. Enhancing the emission efficiencies of LEDs is a key step for many applications such as super-bright LEDs for lighting, full color displays, etc. The present method of utilizing the interconnected μ-disk LEDs for improving the brightness of LEDs is applicable to other semiconductor LEDs as well as polymer and organic LEDs. In particular, UV/blue LEDs based on III nitrides are currently being used to generate white light by coating the chips with phosphors. In such an application, the use of the present method to generate highly efficient UV/blue photons could be beneficial.

The research is supported by grants from NSF (DMR-9902431 and INT-9729582), DOE (96ER45604/A000), ONR, ARO, and BMDO.

[1] S. Nakamura and G. Fasol, *The Blue Laser Diode* (Springer, New York, 1997).
[2] H. Morkoc, S. Strite, G. B. Gao, M. E. Lin, B. Sverdlov, and M. Burns, J. Appl. Phys. **76**, 1363 (1994).
[3] R. K. Chang and A. J. Campillo, *Optical Processes in Microcavities* (World Scientific, Singapore, 1996).
[4] R. A. Mair, K. C. Zeng, J. Y. Lin, H. X. Jiang, B. Zhang, L. Dai, H. Tang, A. Botchkarev, W. Kim, and H. Morkoc, Appl. Phys. Lett. **71**, 2898 (1997).
[5] R. A. Mair, K. C. Zeng, J. Y. Lin, H. X. Jiang, B. Zhang, L. Dai, A. Botchkarev, W. Kim, H. Morkoc, and M. A. Khan, Appl. Phys. Lett. **72**, 1530 (1998).
[6] K. C. Zeng, L. Dai, J. Y. Lin, and H. X. Jiang, Appl. Phys. Lett. **75**, 2563 (1999).
[7] H. X. Jiang, J. Y. Lin, K. C. Zeng, and W. Yang, Appl. Phys. Lett. **75**, 1899 (1999).
[8] S. Bidnyk, B. D. Little, Y. H. Cho, J. Karasinski, J. J. Song, W. Yang, and S. A. McPherson, Appl. Phys. Lett. **73**, 2242 (1998).
[9] S. Chang, N. B. Rex, R. K. Chang, G. Chong, and L. J. Guido, Appl. Phys. Lett. **75**, 166 (1999).
[10] T. Someya, R. Werner, A. Forchel, M. Catalano, R. Cingolani, and Y. Arakawa, Science **285**, 1905 (1999).
[11] S. X. Jin, J. Li, J. Y. Lin, and H. X. Jiang, Appl. Phys. Lett. **76**, 631 (2000).