High extraction efficiency InGaN micro-ring light-emitting diodes

H. W. Choi[a] and M. D. Dawson
Institute of Photonics, University of Strathclyde, Glasgow G4 0NW, United Kingdom

P. R. Edwards and R. W. Martin
Department of Physics, University of Strathclyde, Glasgow, G4 0NG, United Kingdom

(Received 4 August 2003; accepted 10 October 2003)

Light-emitting diodes (LEDs) based on an interconnected array of GaN/InGaN micro-ring elements have been demonstrated. The devices have electrical characteristics similar to those of conventional broad-area devices. However, due to the large surface areas provided by the sidewalls, the extraction efficiency is greatly enhanced. Intense light emission at the periphery of the micro-rings is observed upon excitation by an electron beam, suggesting scattering of the photons which are extracted through the sidewalls. The devices provide a doubling in total light output compared to a broad-area reference LED of equal light-generation area. © *2003 American Institute of Physics.*
[DOI: 10.1063/1.1630352]

Micron-scale light-emitting diodes have been a research area of considerable interest recently, with most emphasis being placed on the InGaN/GaN materials system.[1] While it is generally agreed that these micro light-emitting diodes (micro-LEDs) offer higher light output efficiencies compared to their broad-area (BA) conventional LED counterparts, the exact mechanism responsible for the improved performance of the devices is still a subject of debate. Dai *et al.* reported on an increase in internal quantum efficiency in micro-disk LEDs, explained by a reduction of piezoelectric field due to strain relaxation.[2] However, our findings have suggested that the enhanced light output from micro-LEDs can be largely accounted for by increased extraction efficiency.[3]

Sidewalls in micro-LEDs play an important role in the extraction of light from the mesa structure. In a typical disk-format micro-LED array, a single micro-disk element has a diameter of ~10 μm and an etched mesa height of ~1 μm. This corresponds to a surface-area (top plus sidewall) to light-generation-area ratio (ξ) of 1.4. A higher ratio is desirable, as there then exist more pathways by which the generated photons can escape. Consequently, the concept of a micro-ring geometry is brought to mind. In a micro-ring element with an external diameter of 10 μm and an internal diameter of 5 μm, ξ has a value of 1.8. Hence, adoption of a micro-ring element geometry holds promise for the fabrication of highly efficient LEDs.

In this letter, we report on the design, fabrication, and performance of micron-scale GaN-based LEDs composed of ring-geometry emitter elements. The micro-ring design is commonly used in the fabrication of optical components such as resonators, filters, and modulators,[4,5] but has not been adopted for semiconductor-based emissive devices, although optical studies on InGaN micro-ring structures have been reported.[6,7] The benefits of the micro-ring LEDs are explored in this work, and their characteristics critically compared to micro-disk geometry and conventional geometry LEDs.

In order to make a fair comparison, LEDs based on the micro-ring, micro-disk, and conventional "broad area" geometry are fabricated from the same wafer, each with identical total light-generation (top) surface area equivalent to 120×400 μm^2. The LED structure consists of a 25 nm GaN buffer layer, 3.2 μm of Si-doped GaN, a three-period InGaN/GaN multi quantum well (MQW) targeted for emission at ~470 nm, topped with a 0.25 μm Mg-doped GaN epilayer, grown on the *c*-plane of a sapphire substrate. Processing of the devices begins with the formation of mesa structures using inductively coupled plasma dry etching. An additional masking step was needed to pattern the micro-ring and micro-disk networks in the active region. The micro-disk network consists of 12×13 elements each having a diameter of 20 μm, while the micro-ring network consists of 15×16 elements, each having an external (internal) diameter of 20 μm (12 μm). In order to achieve conformal metal coverage across the micro-ring structures, an anisotropic etch recipe was employed, which resulted in the formation of tapered sidewalls. Details of the fabrication process have been published elsewhere.[8]

Prior to metal deposition, a 40-nm-thick SiO_2 layer was deposited onto the sample by electron-beam deposition, which acts as an isolation layer. The contact areas are exposed by a lift-off process. Finally, the metal layers, including the spreading and pad layers, were deposited by electron-beam evaporation patterned by a lift-off procedure. The choice of metal is Ti/Al (20/200 nm) for the *n*-contact pad and Ni/Au (30/30 nm for current spreading, 20/200 nm for pad) for the *p*-contact. A detailed schematic diagram of the micro-ring device is illustrated in Fig. 1. The $I-V$ characteristics of the devices were measured with an HP4155 parametric analyzer. Power measurements were made on bare chips mounted on TO-8 headers with a calibrated power meter having a Si detector (detector area 1×1 mm^2), in an integrating sphere. Additionally, the radiation pattern of the light emission was determined by moving the detector in the arc of a circle around the normal to the surface of the device at fixed distance from the device.

Current flow in the micro-disk and micro-ring devices is physically confined to the vertical direction due to the geom-

[a]Electronic mail: anthony.choi@strath.ac.uk

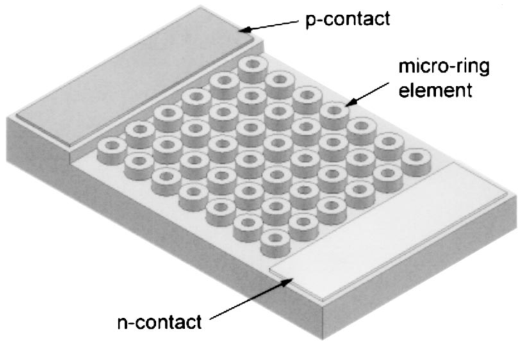

FIG. 1. Schematic diagram of a micro-ring LED (not to scale).

etry of the mesa structures, ensuring efficient use of the injected carriers. Nevertheless, the turn-on and operating voltages of micro-ring devices are marginally higher compared to the micro-disk LED, which in turn is marginally higher than the conventional LED, as shown from the $I-V$ characteristics in Fig. 2. The higher threshold voltages can be attributed to the effective contact area to the *p*-type GaN layer of the devices.[9] The micro-ring device is essentially an interconnected array of individual micron-sized devices, each with their own ohmic contact. In each device, the effective ohmic contact area (the planar area of the micro-ring) is of the order of 10^2 μm^2: about 200 times smaller than a conventional LED. Due to the granular nature of the alloy across the metal–semiconductor interface, the effective contact area is even smaller. As a result, a larger resistive drop may be expected across the contact. The same argument applies to the micro-disk LED, which has a larger contact area than the micro-ring LED. On the other hand, the higher operating voltage can be accounted for by the presence of a plasma-damage region parallel to the sidewall. Since the micro-ring network is patterned by dry etching, plasma damage exists on the sidewalls, resulting in the formation of a depletion layer. Not only does this result in the deterioration of the electrical properties, the effective light-generation area of the MQW region is also reduced. Fortunately, the effect of plasma damage is not significant as the width of the depletion layer (on the sidewall) has been reported to be of the order of 10 nm.[10] Nevertheless, such parallel conduction is indeed reflected in the $I-V$ plot of the micro-ring device, in which three distinct regions are observed. At voltages between 2 and 3 V, conduction is dominated by current flow in the depletion layer.

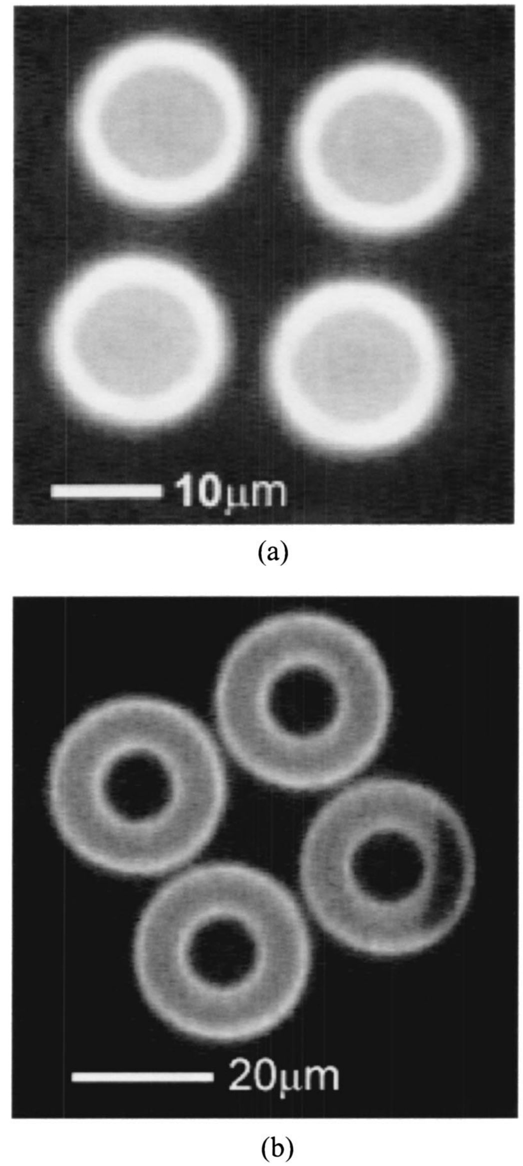

FIG. 3. Micro-photograph showing (a) micro-ring and (b) micro-disk elements excited by a broad electron beam. Bright rings of light are observed at the periphery of the structures.

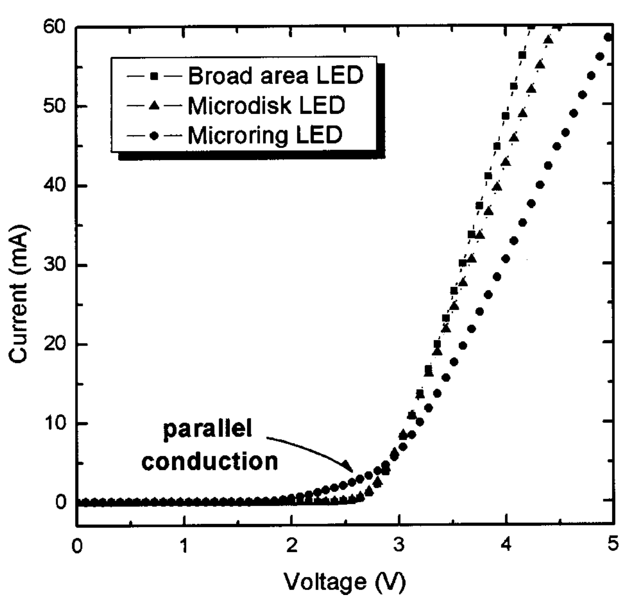

FIG. 2. $I-V$ characteristics of the micro-ring, micro-disk, and BA LEDs.

In order to verify the effect of enhanced sidewall area on the light extraction efficiency, several micro-disk and micro-ring MQW structures were excited by an electron beam as an excitation source, as shown in Figs. 3(a) and 3(b). The electron beam was defocused to provide uniform light generation across the structures. Apart from the expected light emission from the planar regions, bright rings of light were observed from the periphery of the structures. The origin of the light at the periphery is the forward scattering of photons traveling in the plane of the MQWs. In a large-area structure, most of these photons are re-absorbed before reaching the edge, since the mean absorption length of light (at 470 nm) is approximately 10 μm.[11] In micron-scale structures, most of the lat-

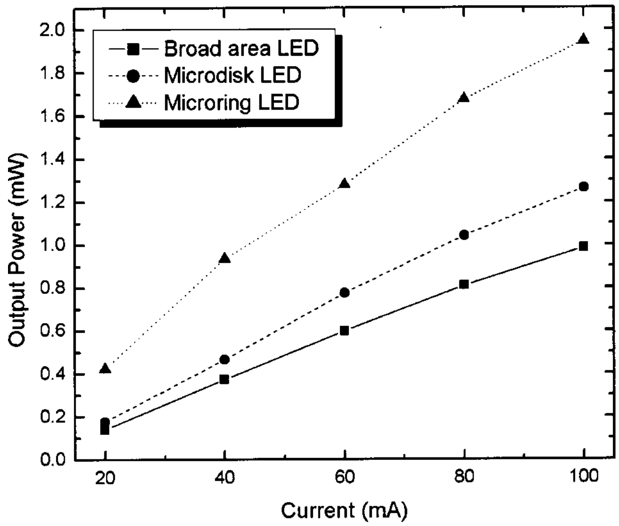

FIG. 4. $L-I$ characteristics of the micro-ring, micro-disk, and BA LEDs.

erally propagating photons can reach the sidewalls without suffering absorption. A fraction of these photons are subsequently scattered in all directions (due to the sidewall roughness), and a fraction of the light is emitted in the forward direction, resulting in the observation of a bright ring of light along the periphery. There is an added advantage of light extraction through sidewalls as compared to light extraction from the top planar surface: the etched sidewalls have a certain degree of surface roughness, which promotes light transmission and reduces light reflection.

The observation of the bright rings of light raises questions concerning the directionality of the emitted light. There is an issue over whether the micro-LED geometries merely favor light emission in a particular direction, or provide an overall improvement to the extraction efficiency of the device. In order to clarify this point, the total output powers of the devices were measured using an integrating sphere, such that light emitted in all directions from the LED can be collected. The $L-I$ curves are shown in Fig. 4. At an injection current of 100 mA, the micro-disk LED emits 30% more light than the BA device (with an equal light generation area). This can be attributed to the large sidewall surface area for light extraction. With an even higher surface-area to light-generation-area ratio, the micro-ring LED emits 100% more light than the BA LED, providing solid evidence that the sidewalls facilitate light extraction.

The directionality of light emission is also explored through the angular radiation patterns plotted in Fig. 5, obtained as mentioned previously. From this plot, no significant differences in the angular dependence of the emitted light were observed between the micro-ring and BA devices. As such, conventional LED packages would be suitable for the micro-ring LEDs. Apart from the benefits of increased light extraction efficiencies, it is believed that there potentially are more implications associated with the geometry of the devices. For instance, the micro-rings may act as "wells" for the insertion of phosphors or polymers in the fabrication of white-light LEDs.

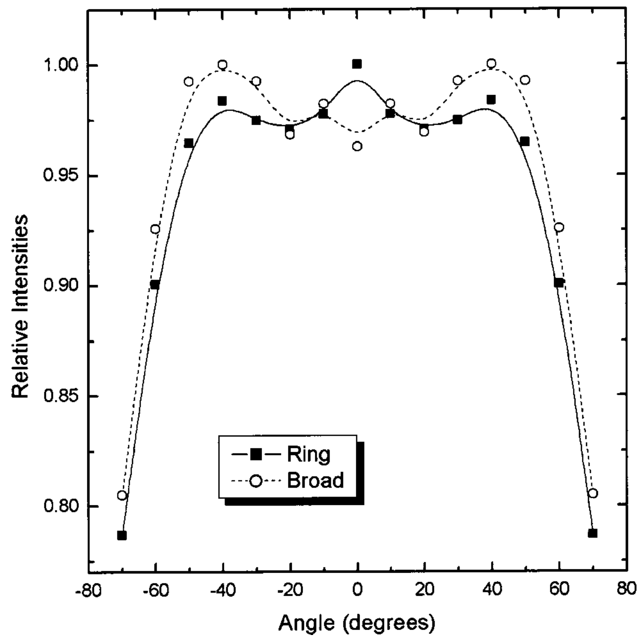

FIG. 5. Angular dependence of the light emission from the micro-ring and BA LEDs.

In summary, an InGaN micro-LED array with a micro-ring geometry has been demonstrated. The device has similar electrical characteristics to a conventional BA LED. However, due to its large surface-area to light-emission-area ratio, the extraction efficiency of the structure is enhanced. From the light output measurements, a 100% increase in light emission is recorded over a conventional broad area LED of equivalent emitter area.

[1] S. X. Jin, J. Li, J. Y. Lin, and H. X. Jiang, Appl. Phys. Lett. **77**, 3236 (2000).
[2] L. Dai, B. Zhang, J. Y. Lin, and H. X. Jiang, J. Appl. Phys. **89**, 4951 (2001).
[3] H. W. Choi, C. W. Jeon, M. D. Dawson, P. R. Edwards, R. W. Martin, and S. Tripathy, J. Appl. Phys. **93**, 5978 (2003).
[4] F. Demangeot, J. Frandon, M. A. Renucci, O. Briot, B. Gil, and R. L. Aulumbard, Solid State Commun. **100**, 207 (1996).
[5] A. Onischenko and J. Sarma, IEE Proc.: Optoelectron. **143**, 67 (1996).
[6] 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).
[7] K. S. Kim, P. R. Edwards, H. S. Kim, R. W. Martin, I. M. Watson, and M. D. Dawson, Phys. Status Solidi **228**, 169 (2001).
[8] H. W. Choi, C. W. Jeon, M. D. Dawson, P. R. Edwards, and R. W. Martin, IEEE Photonics Technol. Lett. **15**, 510 (2003).
[9] N. Blanc, P. Gueret, P. Buchmann, K. Datwyler, and P. Vettiger, Appl. Phys. Lett. **56**, 2216 (1990).
[10] E. D. Haberer, M. Woods, A. Stonas, C.-H. Chen, S. Keller, M. Hansen, U. Mishra, S. DenBaars, J. Bowers, and E. L. Hu, Mater. Res. Soc. Symp. Proc. **639**, G11.21.1 (2000).
[11] O. Ambacher, W. Rieger, P. Ansmann, H. Angerer, T. D. Moustakas, and M. Stutzmann, Solid State Commun. **97**, 365 (1996).