Enhancement of light extraction in ultraviolet light-emitting diodes using nanopixel contact design with Al reflector

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We report on a nanopixel contact design for nitride-based ultraviolet light-emitting diodes to enhance light extraction. The structure consists of arrays of Pd ohmic contact pixels and an overlying Al reflector layer. Based on this design a twofold increase in the light output, compared to large area Pd square contacts is demonstrated. Theoretical calculations and experiments reveal that a nanopixel spacing of 1 μm or less is required to enable current overlap in the region between the nanopixels due to current spreading in the p-GaN layer and to ensure current injection into the entire active region. Light emitted in the region between the nanopixels will be reflected by the Al layer enhancing the light output. The dependence of the light extraction on the nanopixel size and spacing is investigated. © *2010 American Institute of Physics*. [doi:10.1063/1.3334721]

Nitride-based ultraviolet (UV) light-emitting diodes (LEDs) have attracted great interest due to their potential applications in the fields of water purification, phototherapy, and solid state lighting. Although progress has been made in the epitaxy and fabrication technologies of these devices, low external quantum efficiency is observed. Several methods such as the use of photonic crystals,[1] roughening of LED surfaces,[2] patterning of substrates,[3] and shaping of LED dies[4] have been investigated to improve the light extraction efficiency. The use of micropixel-LEDs[5] and omnidirectional reflectors with microcontacts[6] has been shown to result in enhanced light output from near-UV LEDs. When moving deeper into the UV region, metals such as Ag which are reasonable reflectors in the visible range can no longer be used. At the same time, transparent or reflective ohmic contacts to p-AlGaN are difficult to fabricate. Al is a good reflector (reflectivity ~0.92) in the entire UV spectrum because of its high extinction coefficient and low refractive index. However, due to its low work function of 4.26 eV,[7] it does not form an Ohmic contact to p-doped GaN. For Al-based contacts on p-AlGaN layers the performance is even worse. Pd, on the other hand, results in low resistance ohmic contacts ($\rho_c <= 10^{-3}$ Ω cm^2) but is not transparent in the UV region and its reflectivity in the UV spectral range is low (reflectivity ~0.4).

In this work, we propose a nanopixel LED design to enhance light extraction in UV LEDs using nanopixel contacts of Pd and an Al reflector. Unlike previous reports,[6] the nanopixel spacing in this design is less than 4 μm so that current can also be injected in the region between the contacts due to current spreading in the p-current spreading layer. A schematic cross-sectional view of the structure is shown in Fig. 1. The structure consists of a two dimensional array of Pd nanopixel contacts, with dimensions ranging between 4×4 μm^2 and 1×1 μm^2, and spaced 1–4 μm apart. If the spacing (d) between the nanopixels is sufficiently small, a large portion of the current will flow into the region between the nanopixels due to current spreading in the p-doped layer. This results in the almost homogenous injection of current throughout the entire active region of the mesa structure. Light emitted in the region just below the nanopixels, toward the p-side of the diode, will be absorbed or poorly reflected by the Pd, while the light emitted in the region between the nanopixels will be highly reflected by the Al layer. The light extraction efficiency of the device can thus be increased if current overlap is obtained i.e., the nanopixel spacing is in the order of the current spreading length in the p-AlGaN current spreading layer. Hence, optimization of both the size (l) and spacing (d) between the nanopixels is necessary to maximize the light extraction.

To determine a suitable spacing (d) between the nanopixels, the three-dimensional current spreading in an UV LED device, emitting at 380 nm, was simulated using the SPECLED software.[8] Keeping the nanopixel size constant at 1×1 μm^2 and varying the nanopixel spacing from 1 to 4 μm, current spreading in the 200 nm thick p-GaN layer was investigated. Figure 2 shows the simulated current density injected in the active region. For a nanopixel spacing of 4 μm, the density of the current injected in the region exactly in the middle of the imaginary line joining two neigh-

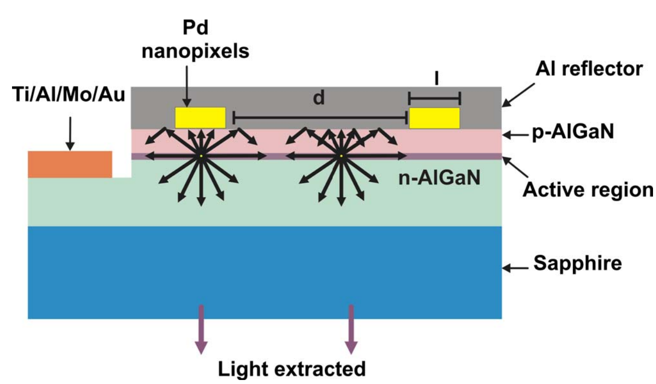

FIG. 1. (Color online) Schematic cross-sectional view of nitride-based nanopixel UV LED with Pd contacts and Al reflector layer.

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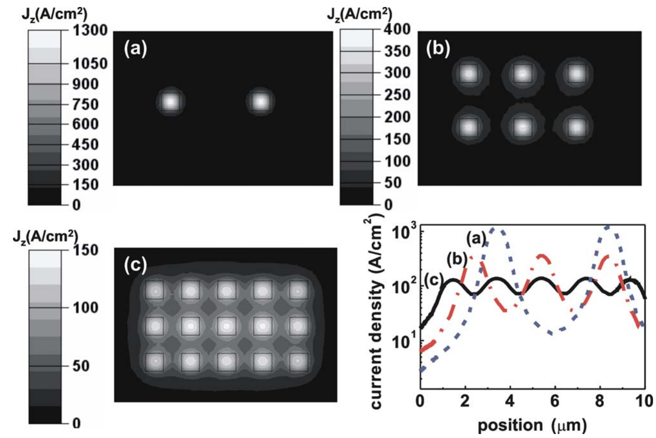

FIG. 2. (Color online) Simulation of the current injection in the active region for nanopixel AlInGaN LEDs with nanopixel size 1×1 μm^2 and nanopixel spacing (a) 4 μm, (b) 2 μm, and (c) 1 μm. The total current is constant. In the graph the injection current density as a function of the position along a line through the center of the nanopixels is shown for the different structures.

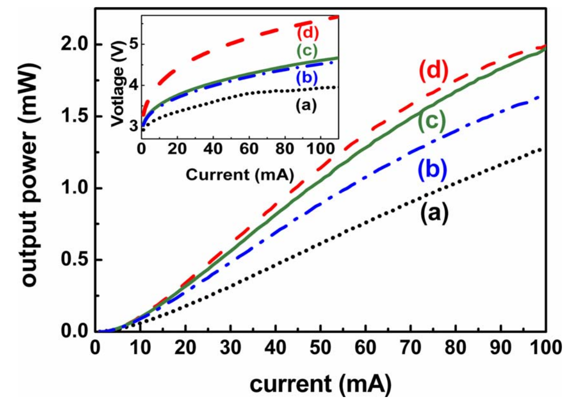

FIG. 3. (Color online) dc L-I characteristics of nanopixel AlInGaN LEDs with (a) square contact (150×150 μm^2) (b) nanopixel size=4×4 μm^2, nanopixel spacing 4 μm (c) nanopixel size=2×2 μm^2, nanopixel spacing 2 μm and (d) nanopixel size=1×1 μm^2, nanopixel spacing 1 μm. Inset: dc V-I characteristics for the structures [(a)–(d)].

boring pixels is 13 A/cm², indicating that there is no current overlap in the region between the pixels. The injected current between the nanopixels is too low for efficient light emission. The ratio (r) of the current density injected in the middle of two neighboring pixels to that in the center of the nanopixel is ~0.01. As the spacing is decreased to 2 μm some current overlap can be observed. The minimum current density injected in the region between the nanopixels is 36 A/cm² while r increases to ~0.1. For a nanopixel spacing of 1 μm, the minimum current injected in the region between the nanopixels is 73 A/cm² and r is ~0.53. This strong overlap of the current in the region between the nanopixels results in emission from the entire active region. Hence a 1 μm or less spacing between nanopixels is required to obtain light emission from the entire region.

To demonstrate the viability of the nanopixel LED design experimentally, AlInGaN LEDs emitting at 390 nm with Pd nanopixel contacts and an Al reflector layer were fabricated. The layer structures were grown by metal-organic vapor phase epitaxy on (0001) oriented 2 in. sapphire substrates.[9] The structure consists of a GaN:Si buffer layer, a five-period InGaN/InAlGaN multiquantum well active region, a 10 nm thick $Al_{0.23}GaN$:Mg electron blocking layer, and a 200 nm thick GaN:Mg current spreading layer.[10] LEDs were fabricated using standard chip processing technology. 150×150 μm^2 mesa structures were etched using inductively coupled plasma in a chlorine atmosphere down to the n-GaN current spreading layer. An array of 30 nm thick nanopixel Pd contacts was fabricated on the mesa structure and annealed in nitrogen ambient at 530 °C to form ohmic contacts. Arrays with nanopixel contact sizes 4×4, 2×2, and 1×1 μm^2 and spacings of 4, 2, and 1 μm along with conventional large-area square contacts (150×150 μm^2) were fabricated on the same wafer for comparison. Ti/Al/Mo/Au layers were then deposited on the n-GaN surface. Finally Al/Pt/Au layers were deposited on the mesa structures. Electrical and optical measurements were made on-wafer under dc and pulsed current injection conditions at room temperature. The light-output power versus current (L-I) characteristics were measured by directly placing the wafers on a calibrated silicon detector with the light extracted from the sapphire side of the LED. For pulsed measurements the pulse width and frequency were 1.5 μs and 1 kHz, respectively.

Typical L-I characteristics for nanopixel LEDs, with different nanopixel sizes 4×4, 2×2, and 1×1 μm^2 and spacing 4, 2, and 1 μm, respectively, but identical fill factor (Pd contact area/mesa area) of 25%, along with a conventional 150×150 μm^2 square contact LED (100% fill factor) are shown in Fig. 3. It can be clearly observed that the light output increases with decreasing nanopixel size and spacing. At 20 mA the nanopixel LEDs with nanopixel sizes 4×4, 2×2, and 1×1 μm^2 show a 55, 78, and 90% increase in the light-output power, respectively, compared to the conventional square contact. From the voltage-current (V-I) characteristics shown as an inset in Fig. 3, it can be seen that at 20 mA the forward voltage for the nanopixel LEDs is much larger than that for the conventional square contact LED. This can be attributed to the decrease in the effective total contact area and increase in contact resistance due to structural imperfections arising from the fabrication of contacts with small dimensions. Maximum wall plug efficiencies of 4.4%, 5.1%, 4.6%, and 3.4% are obtained for the nanopixel LEDs, with different nanopixel sizes 4×4, 2×2, and 1×1 μm^2 and the 150×150 μm^2 square contact LED, respectively.

Optical microphotographs of the nanopixel LEDs, at a total current of 15 mA, taken from the polished back surface of the sapphire are shown in Fig. 4. For the LED with nanopixel size of 4×4 μm^2, no light is emitted in the region between the contacts demonstrating that a distance of 4 μm is too large for significant current overlap. Furthermore, the area from which light is emitted is larger than that of the nanopixels indicating that due to current spreading in the p-GaN layer, light is also emitted in the region surrounding the nanopixels. Reflection from the Al layer results in increased intensity observed at the edges of the nanopixels. For the LED with nanopixel size of 2×2 μm^2 also no light is emitted in the area between the nanopixels while for the LED with nanopixel size of 1×1 μm^2, the entire active region appears to emit light. This compares well with the result obtained from simulations, that nanopixel spacing (d) of 1 μm or less is necessary for current overlap.

The V-I characteristics for nanopixel LEDs with a fixed nanopixel size of 1×1 μm^2 and with nanopixel spacing 4,

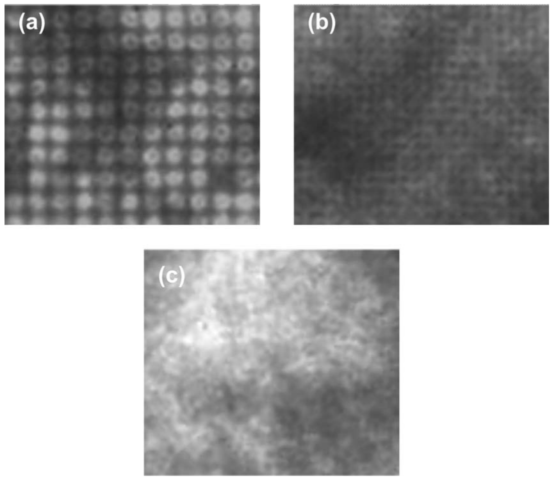

FIG. 4. Optical microphotographs of the nanopixel AlInGaN LEDs with (a) nanopixel size $=4\times4\ \mu m^2$, nanopixel spacing 4 μm, (b) nanopixel size $=2\times2\ \mu m^2$, nanopixel spacing 2 μm, and (c) nanopixel size $=1\times1\ \mu m^2$, nanopixel spacing 1 μm at 15 mA total current.

2, and 1 μm along with a conventional $150\times150\ \mu m^2$ square contact LED are compared in the inset of Fig. 5. This corresponds to filling factors of 4%, 11%, 25%, and 100%, respectively. The forward voltage increases as the spacing between the nanopixels increases due to the decrease in the effective total contact area. This results in dissimilar levels of heating in the different LEDs. Hence, for comparison between the devices, L-I characteristics were measured under pulsed conditions as shown in Fig. 5. For a pulse width of 1.5 μs and a 0.15% duty cycle, at 20 mA, the nanopixel LEDs with fill factors 4%, 11%, and 25% show a 101, 114, and 103% increase in the output power, respectively, compared to the conventional square contact. For nanopixel LEDs with different fill factors, the light output could increase due to the following reasons: (i) increase in current density (at low currents), (ii) enhanced reflection at the Al reflector along the increased perimeter of the p-contact and (iii) enhanced reflection at the Al reflector due to current overlap in the region between the nanopixels. At high currents the nanopixel LEDs with spacing of 2 and 1 μm show a larger output than the LED with spacing of 4 μm. This effect could be an indication that current overlap and concurrently enhanced light reflection at the Al reflector occurs for the LEDs with smaller nanopixel spacing at high currents. It can be seen from Fig. 5, that the nanopixel LED with spacing of 1 μm results in the highest conversion efficiency considering that its operating voltage is the lowest of all nanopixel LEDs. The maximum wall plug efficiencies of the nanopixel LEDs with fill factors 4%, 11%, and 25% and the large area square contact are determined to be 2.5%, 3.9%, 4.6%, and 3.4%, respectively. We believe the light output power can be increased further by additionally decreasing the nanopixel size and spacing to the sub-micron region.

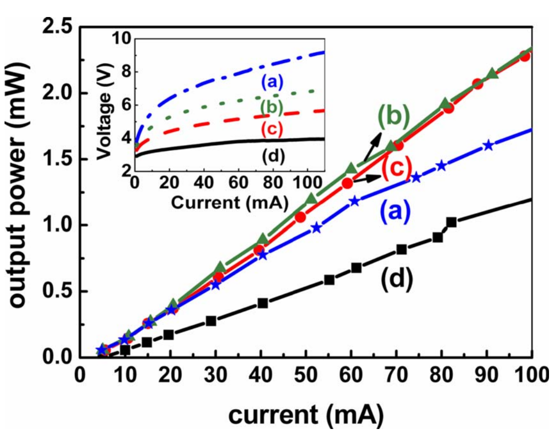

FIG. 5. (Color online) Pulsed L-I characteristics of nanopixel AlInGaN LEDs with nanopixel size of $1\times1\ \mu m^2$ and nanopixel spacing (a) 4 μm, (b) 2 μm, (c) 1 μm, and (d) square contact ($150\times150\ \mu m^2$). Inset: dc V-I characteristics for the structures [(a)–(d)].

In conclusion, we have demonstrated a nanopixel LED design with an Al reflector which results in enhanced light extraction in UV LEDs. A 90% increase in the light output power of a 390 nm AlInGaN LED is shown for nanopixel LEDs with a nanopixel size of $1\times1\ \mu m^2$ and spacing of 1 μm as compared to the conventional square contact geometry under dc conditions. Optimization of the nanopixel size (l) and spacing (d) can lead to further enhancement in light output. In the deep UV region, where transparent or reflective ohmic contacts are difficult to fabricate, the nanopixel contact design will be an excellent technique to enhance light extraction.

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