Mask-free photolithographic exposure using a matrix-addressable micropixellated AlInGaN ultraviolet light-emitting diode

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We report the integration of a UV-curable polymer microlens array onto a matrix-addressable, 368-nm-wavelength, light-emitting diode device containing 64×64 micropixel elements. The geometrical and optical parameters of the microlenses were carefully chosen to allow the highly divergent emission from each micropixel to be collimated into a narrow beam of about 8-μm diam, over a distance of more than 500 μm. This device is demonstrated as a photolithographic exposure tool, where the pattern-programmable array plays the role both of light source and photomask. A simple pattern comprised of two disks having 16-μm diam and 30-μm spacing was transferred into an i-line photoresist. © 2005 American Institute of Physics. [DOI: 10.1063/1.1942636]

Following the report of micropixellated light-emitting diodes (micro-LEDs) using InGaN-based semiconductor materials, a number of groups have been pursuing further development of this attractive concept. Such devices are anticipated to offer wide applicability in areas including microprojection displays, chemical and biological sensing devices, ophthalmology, and as exposure tools for photolithography. In particular, matrix-addressable ultraviolet (UV) microemitters are highly attractive as specialized photolithographic and photochemistry exposure tools, since arbitrary image patterns can be generated and transferred to a UV-sensitive material like a photoresist without the need to manufacture expensive photomasks. Furthermore, this could provide a simple approach to building three-dimensional (3D) structures via stereo photolithography. We have recently fabricated such ultraviolet micro-LED devices in a 64×64 matrix-addressable array at 368 nm (Ref. 4). In bare-chip operation, the emission from each microemitter is, however, found to have a large divergence so that appropriate and carefully designed micro-optics should be integrated to control and project the emission. Although microlenses can fairly readily be formed in various UV-transparent materials including AlN, sapphire, and diamond, soft photopolymeric materials offer advantages for custom design, controlled alignment, and monolithic integration using standard microfabrication techniques. In this letter, we report on the performance of a 64×64 element, 368-nm micro-LED device integrated with a UV-curable polymer microlens array. In addition, photolithographic exposure tests were performed with the integrated device, which is such demonstration of this capability.

The devices used in this study are 64×64 element matrix-addressable micro-LEDs, which have a 368-nm emission wavelength. They each consist of emitter pixels 20 μm in diameter with center-to-center spacing of 30 μm, giving an overall emission area of 1.91×1.91 mm². Full details of the epistucture, device geometry, and fabrication of these devices have been reported elsewhere. Each emitter pillar of 20-μm diam is side and rim covered by a thick metal sheath which serves as a p-metal line. This is contacted to a central disk (diam=16 μm) of thinner metal (a 7 nm/7 nm Ni–Au bilayer) on top of the pillar which defines the emission aperture. The divergence of the emitted beam through the aperture was directly measured to be of 75±3° full angle into air using the beam-sectioning capability of a confocal microscope and second-moment beam analysis. This important information is the basis of our custom design of microlenses for output beam collimation.

The polymer lens arrays were integrated onto the devices monolithically. The material used in this study is a UV-curable adhesive (NOA63, Norland Products, Cranbury, NJ, Licensing and Rights.)
USA) which can be spun on the wafer in any thickness depending on the spin-coating process conditions. In order to position the lens array at a designed height, the adhesive was spun and cured twice. An initial polymer thickness was specified by considering the device structure. The beam divergence of 75° into the air is equivalent to 38.5° in the polymer (which was measured to have a refractive index of 1.55 at 370 nm) according to Snell’s law. Considering our present design of the device, the maximum clearance of the bottom of the lens from the device top should be 20 μm to avoid crosstalk overlap with an adjacent beam. However, it is not possible to make a 30-μm-wide lens (which could collect nearly all of the light from the emitter 20-μm away) simply because it would merge with adjacent lenses during the photoresist reflow step in the fabrication. For practical reasons, therefore, we chose a 20-μm-wide mask pattern to produce a reliable lens structure. Using NOA63 polymer, which has a viscosity of 2000 cps at room temperature, a 22-μm thickness is readily obtainable with one spin coating at 4000 rpm. A microdisk array photoresist mask, formed by standard photolithographic patterning, was melted at 115 °C to form an almost perfectly spherical microlens. The mechanical clearance, measured with the confocal microscopy sectioning technique, was 3 nm rms were formed. The radius of curvature, Rc, and focal length, f, are calculated to be 12.1 and 21.9 μm, respectively, where the refractive index, n, is 1.55 at 370 nm.

From the I-V characteristics measured for individual emitter elements, it was confirmed that the integration process does not affect the device performance significantly. Although there is an apparent small increase (0.4 V) in turn-on voltage, the device resistance is improved by the annealing effect during the deposition of passivation oxide by plasma-enhanced chemical-vapor deposition (PECVD).

Figure 2 shows an actual beam profile emitted by one element of the integrated device, as measured by the confocal microscopy sectioning technique. The position of the lens and emitter element is indicated schematically in the figure. As a reminder, this confocal measurement method allows direct determination of the beam profile by the imaging of sequential sections of the emission, with axial and lateral resolutions of typically 0.8 (±0.1) and 0.25 (±0.1) μm, respectively. Although the scan head photodetectors are relatively insensitive below 400 nm, degrading signal to noise, it is quite clear that the microlens is effectively collimating the initially highly diverging beam from the emitter element. The collimated beam is measured to have an approximately 8-μm diameter and is well maintained over a 500-μm distance along the optical axis. Compared to the beam profile from a bare device, the emission is substantially controlled by the integrated microlens. In the ideal case, the clearance, L, is specified by considering the device structure. The focal length minus the lens height, so as to maximize the collimating capability of the lens. Therefore, we need to consider an effective focal length since the medium which the emitted light travels through is not identical across the lens. While the calculated f refers to the focal length in the image

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f = \frac{Rc}{n-1},
\]

\[
Rc = \frac{h^2 + D^2}{4h}.
\]
space (normally in air), the effective focal length in the object space filled with the polymer is determined by the following equation:  

$$f' = \frac{nRc}{n-1}.$$  

The effective focal length in the object space, $f'$, is calculated to be 34.1 $\mu$m. This means that the lens needs to be positioned no less than 34.1-$\mu$m away from the emitter surface. Considering the lens height of 8.4 $\mu$m, the corresponding value of $L$ is 25.7 $\mu$m. In our case, the $L$ value of 28 $\mu$m reasonably satisfies this requirement, within the degree of processing control in spin coating and dry etching. Although the selected $L$ value is large enough to allow a collimating action, it will, along with the lens diameter, affect the light-collecting efficiency. By a simple calculation, light emitted within 14.3° full angle can be collected by the lens. Considering the emission cone of 38.5° full angle in the polymer layer, some of the light could be coupled into the adjacent layer, some of the light could be coupled into the adjacent lens or simply refracted by the flat surface. However, we could not resolve any such background beam profile clearly, probably due to the limited sensitivity of the detector system.

In fact, the intensity of the emitted light at a high angle is much lower than at the beam center as shown in the inset of Fig. 2 (Ref. 6). Therefore, we believe that the refracted beam distributed outside of the collimating column has a very low intensity as far as the photolithographic exposure application is concerned. Also, by the fact that the polymer is highly transparent at the 370-nm region (98% down to 360 nm), it is believed that the amount of the absorption loss would be negligible for this application.

To confirm the selective exposure capability of the integrated device, i-line photoresist (Shipley S1805, 0.3-$\mu$m thick) was exposed using the microlens integrated device. The device was operated at 8 V to give an output power of about 1 $\mu$W. The photoresist was baked for 30 s at 115 °C and then exposed for 2 s. For comparison, a pattern generated by a pair of adjacent bare elements without microlenses is shown in Fig. 3(a). The exposed pattern is supposed to have two circular features, but due to the divergence of the emission they could not be resolved and merged into a large irregular shape. Figure 3(b), on the other hand, shows, after development, a pattern exposed by elements of the integrated device. Each of the circular features is separated by 30 $\mu$m vertically (adjacent elements illuminated) and 60 $\mu$m horizontally (alternate elements illuminated), corresponding to the emission pattern programmed onto the device. The central dimension of each feature is about 7 $\mu$m average width, which is smaller than the emitter aperture and the diameter of the collimating column as well. The light intensity varies across the beam diameter, hence the exposed area is diffused at the boundary and only the central area having enough dosage to transform the resist properties is fully developed.

In summary, we have integrated a microlens array onto a 64 X 64 matrix-addressable 368-nm micro-LED device using a UV-curable polymer material and a dry etching technique. By adjusting the mechanical clearance of the lens and the lens shape, the emitted beam was well collimated over 500 $\mu$m distance along the optical axis with about an 8-$\mu$m beam diameter. A pattern generated with the emitter device equipped with a microlens array was transferred to i-line photoresist. We believe that this application demonstration opens up exciting directions for AlInGaNP micropixelated emitters. Operation much deeper into the ultraviolet is possible using recent materials advances, and the device may also be pulsed in subnanosecond duration for nonlinear thresholding exposure effects. We note, furthermore, that self-aligned fabrication of integrated micro-optical elements is in principle possible using these methods.