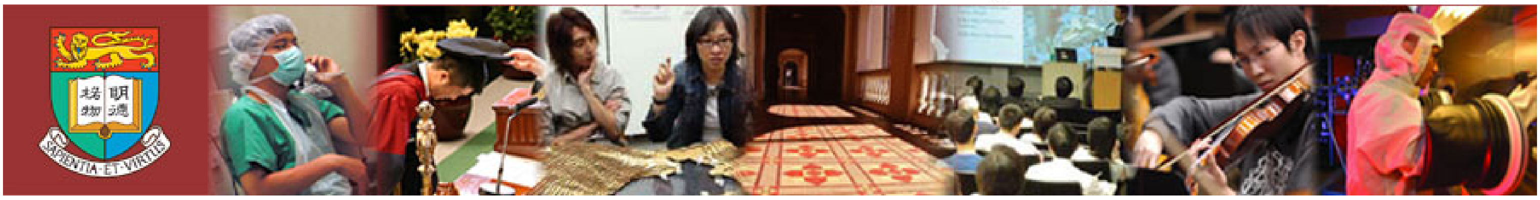

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Microlens Array on Flip-Chip LED Patterned With an Ultraviolet Micro-Pixelated Emitter

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***Abstract*—A direct-write lithographic technique for the fabrication of micro-lens arrays with an ultraviolet (UV) micro-light-emitting diode (LED) array serving as an exposure source is reported. Polymer microlens arrays of high optical quality have been fabricated on the sapphire side of a flip-chip truncated-conic (TC) LED. The properties of the lenses are evaluated by optical microscopy and atomic force microscopy. The determined focal length is close to the predicted value. The effects of microlens integration on the optical properties of the LED are investigated.**

***Index Terms*—Direct-write, micro-lens, micro-light emitting diode (micro-LED).**

I. INTRODUCTION

COMPACT AlGaN ultraviolet (UV) light-emitting diodes (LEDs) have been demonstrated as excellent replacements for mercury lamps in specific applications such as chemical and biological excitation, air and water purification, as well as medical diagnostics and therapy by virtue of their shorter wavelengths [1]. The efficiencies and functionalities of such emitters can be enhanced by sectioning the emissive region into micrometer-scale pixel arrays that are either interconnected or individually addressable. Such micro-LED arrays have previously been demonstrated for micro-display purposes, but are developed as an exposure tool for photolithography in this work [2]. Eliminating the need for the fabrication of a photomask for every design in traditional photolithography, direct-write lithography using UV micro-LED arrays offers an efficient yet cost-effective solution. Due to the micrometer dimensions of individual pixels, the emission optical power density is comparable to conventional UV light sources. By scanning the exposure source across large areas, a two-dimensional pattern can be exposed onto a UV sensitive material such as photoresist by-passing the need for a photomask.

In this work, the emitter array is not merely used as an exposure source; it is used for the direct patterning of a functional micro-lens array on a visible-light InGaN LED device. Integration of microlens arrays is one of many ways for increasing light extraction efficiency in an LED, being one of many forms of surface roughing techniques. Typical microlens fabrication techniques include thermal reflow of photoresist [3], self-assembling of microspheres as microlenses [4] and ink-jet processing [5]. In this work, we demonstrate an alternative method of forming microlenses via a direct-write lithographic technique, using a 64-elements UV linear micro-LED array as an exposure source illuminating upon a UV epoxy coating. A microlens array each with near-spherical profile is formed spontaneously after development, attributed to the Lambertian emission pattern of each micro-LED emitter.

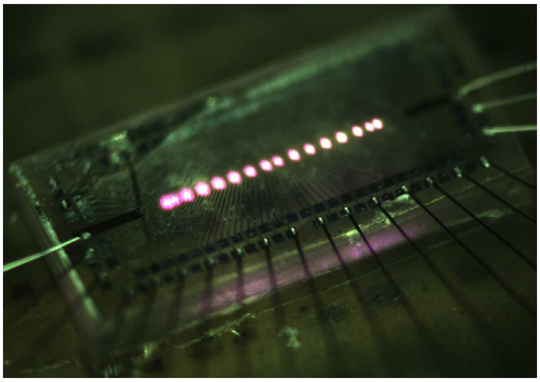

Fig. 1. Illuminated UV micro-LED linear array.

The effects of microlens integration on the light extraction efficiency and emission characteristics of an LED are investigated. The microlens array is patterned using this direct-write method onto the entire sapphire face of a flip-chip LED.

II. EXPERIMENTAL DETAILS

The linear micro-LED array is fabricated on an AlGaN/GaN LED wafer with central wavelength of 370 nm (near-ultraviolet), supplied by Nitride Semiconductors Co., Japan. This is an ideal wavelength for most UV-sensitive materials including conventional i-line photoresists. The linear array consists of 64 pixels in a single row, each of which is a 10-μm square, with a centre-to-centre spacing of 15 μm. The detailed fabrication process has been reported in [6]. All the pixels share two common n-contact pads on either end of the row array, while they each have their individual p-contact pads. The device is diced by UV laser-micromachining and die-bonded to a ceramic dual-in-line side-braze package and subsequently wire-bonded. The final packaged device with several illuminated pixels is shown in Fig. 1.

The schematic diagram in Fig. 2 illustrates the experimental setup for the patterning sequence. A projection lens, consisting of a pair of fused silica double convex lenses, collects and focuses the divergent ultraviolet light from each pixel onto the imaging plane. In the optical setup, the collection and focusing lenses (with diameters of 25 mm) have focal lengths of 25 mm and 15 mm respectively, giving a theoretical projection ratio of 5:3. In practice, the actual imaging ratio depends on a number of factors, including exposure duration, quality of the optics and

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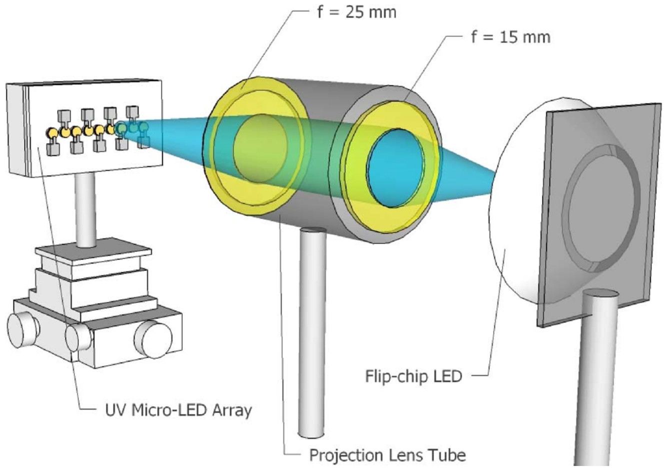

Fig. 2. Schematic diagram showing the image projection setup (not to scale).

sensitivity/resolution of the epoxy. The exposure device was mounted onto a three-axis motorized micro-manipulator for precise alignment and translation. Once it has been well-aligned and the beam focused the designated micro-LEDs pixels were turned on for exposure. Programmed translation of the micro-manipulator enabled the beams to be scanned across the plane, thereby creating an arrayed pattern.

The proposed microlens array is to be patterned on the fine-polished sapphire surface of a flip-chip-bonded InGaN truncated-conical (TC) LED with emission center wavelength of $\sim$ 470 nm. The TC-LED can be summarized as an LED of circular geometry with inclined sidewall facets produced by rotary UV laser micro-machining, whose top and base diameters are $\sim$ 1.7 mm and $\sim$ 1.3 mm respectively. Details and merits of the TC-LED structure and the laser micro-machining process are described in detail in [7] and [8]. For sample preparation, a thin layer of UV-epoxy (Norland 81) is spin-coated onto the large and circular sapphire surface of the LED chip. With a low viscosity of 300 cps and requiring low curing energy of 2 Joules/cm^2, it is ideal for rapid direct-write. By varying the exposure and development times, the curvature of microlens could be controlled. After optimization of parameters, microlenses are formed after 5 s of exposure under UV micro-LED exposure driven at a voltage of 4.5 V, followed by 5 seconds of development in acetone. At this voltage, each pixel draws 1.18 mA of current and emits 80 nW of optical power (measured with a calibrated Si photodetector) corresponding to an optical power density of $\sim$ 80 mW/cm^2, making it comparable to that of a mercury UV lamp used in traditional photolithography ($\sim$ 125 mW/cm^2). The micro-LED source is translated to produce a hexagonal microlens pattern, as shown in Fig. 3(a), together with the schematic diagram of the whole packaged device with microlens array on its sapphire side in Fig. 3(b). The focal length of the microlens is calculated and experimentally verified, and the performance of the microlens-integrated LED evaluated.

III. RESULTS AND DISCUSSION

A three-dimensional atomic force microscope (AFM) surface morphology scan of the lens array is shown in Fig. 4(a), together with the cross-sectional contour plot of a single lenslet in Fig. 4(b). The blue curve in the same figure represents the plot of a circular profile. Comparing the profiles, the microlens is determined to be near-spherical with the exception of a notch at the center. The M-shaped cross-sectional profile of the microlens originates from the emission characteristics of the UV micro-LED light source. Fig. 4(c) shows a plot of the emission distribution of a single micro-LED pixel, exhibiting an identical M-shaped profile as the microlens. Such a profile is due to the large contributions of sidewall emissions compared to top emission. Based on Fig. 4(b), the microlens can be fitted to the curve of a sphere with diameter $D = 11.7\ \mu\text{m}$ [9]. The refractive index of the epoxy at the emission wavelength of 470 nm is 1.56. The focal length (f) can thus be evaluated as 10.4 μm [10].

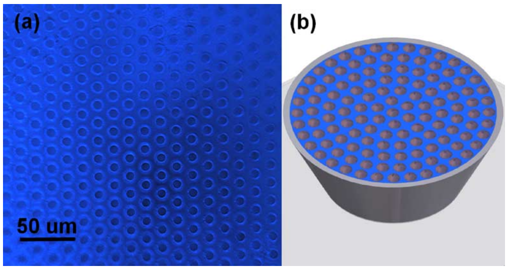

Fig. 3. (a) Planar view of microlens patterned on sapphire face of LED chip. (b) Schematic diagram of the microlens-integrated LED assembly.

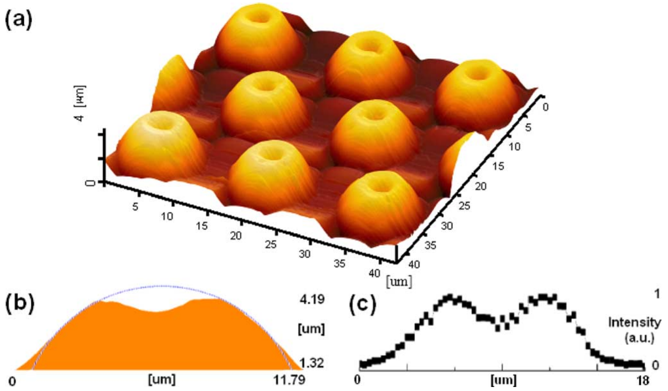

Fig. 4. (a) AFM surface plot of 3 × 3 microlenses; (b) cross-sectional profile of a single microlens; (c) emission line intensity scan across a single micro-LED pixel.

To verify this value, an optical measurement of the focal length was carried out by scanning and observing the images formed by the lenses using an optical microscope. An identical 2 by 3 microlens array was patterned onto a glass slide under the same exposure and development conditions. The glass slide was then placed onto the stage of the microscope, with a laser source placed beneath [11]. The collimated beam passes through the microlenses, with the pattern at different focus planes observed from above. The bases of the lens array are observed in the lower image of Fig. 5(b), while an array of bright spots are observed in the upper image when focused onto the focus plane of the lenses. The vertical displacement Δh between the planes, determined from the focus offset, corresponds to the focal length (f), and is found to be $\sim$ 12 μm, correlating with the predicted value.

To determine if the nonideal lens profile has any effect on the emission characteristics, optical ray-trace simulations are

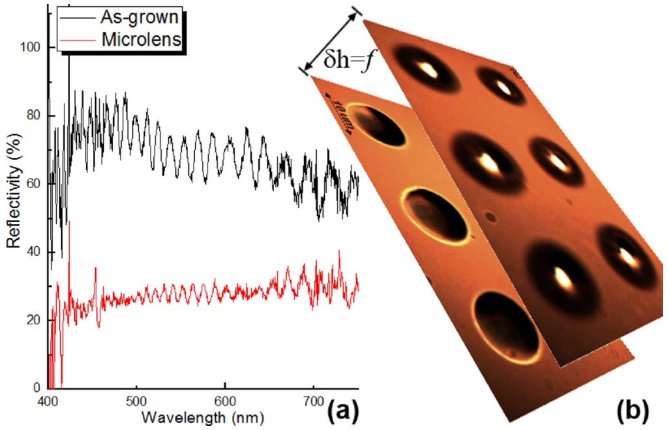

Fig. 5. (a) Reflectivity of microlens patterned surface, compared with as-grown. (b) Method of focal length determination.

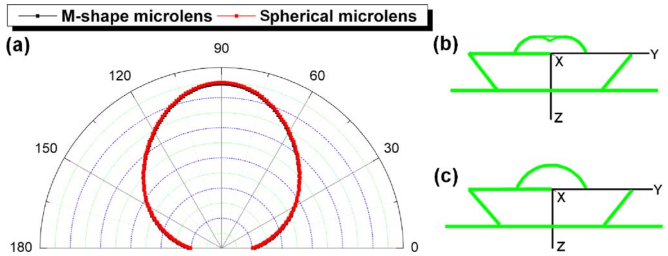

Fig. 6. (a) Ray-trace simulated emission patterns of microlens-integrated LEDs; (b) and (c) show models of the M-shaped microlens and spherical microlens used in the simulations.

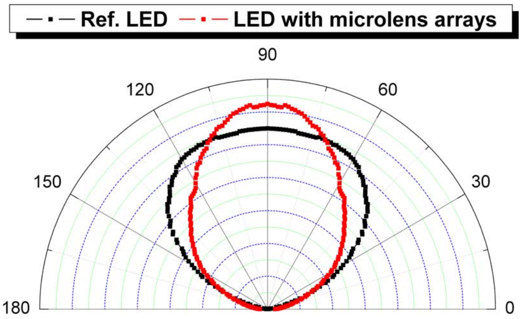

Fig. 7. Measured emission patterns of the microlens-integrated LED, compared with reference LED without microlens.

performed using a simplified model consisting of a single lenslet on an LED chip proportionally scaled-down in dimensions. The simulated angular-dependent emission pattern of an LED with microlens of M-shaped profile (shown in Fig. 6(b)) is compared with that of an LED with an ideal microlens (Fig. 6(c)). The results are plotted in Fig. 6(a), from which negligible effects are observed due to the nonideality in profile. This may be explained by the fact that the surface area of the notch represents only $\sim 11\%$ of the overall lens surface area.

The next comparisons are between LEDs with and without the direct-written polymer microlens. An optical reflectivity plot of the microlens-patterned surface, compared with an as-grown, are shown in Fig. 5(a); with microlenses, a significant reduction in reflectivity, thus enhanced transmission, is observed, which serves to assist with light extraction from the device. The emission patterns of the LEDs are plotted in Fig. 7. The emission pattern are measured by rotating a fiber probe coupled to a spectrometer about the device central axis in the range of -90° to 90°, in steps of 1°. A key observation is a significant reduction in beam divergence. The divergence half-angle γ of the LED with microlens is found to be 22° less than that of the reference bare LED (where γ is defined as the angle at which power intensity drops to $1/\sqrt{2}$ of its peak value). Concurrently, light intensity in the normal direction increased by $\sim 11.9\%$ due to the microlens array, attributed to redistribution of light as a result of the focusing lens, while the overall light emission was enhanced by $\sim 3.7\%$, including the effects of polymer absorption and interface reflections.

IV. CONCLUSION

A large-area polymer microlens array was directly patterned onto the sapphire face of a flip-chip LED, using an ultraviolet linear micro-LED array as the addressable exposure light source. The geometries, dimensions and the focal lengths of the microlenses are evaluated and their effects on the emission properties of LED are investigated. The microlens array plays an important role on increasing the light extraction efficiency and reducing the emission divergence angle.

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