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Reflection/transmission confocal microscopy characterization of single-crystal diamond microlens arrays

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Using the method of photoresist reflow and inductively coupled plasma dry etching, we have fabricated microlens arrays in type-IIa natural single-crystal diamond, with diameters down to 10 μm. The surface profile of the microlenses was characterized by atomic force microscopy and was found to match well with a spherical shape, with a surface roughness of better than 1.2 nm. To characterize the optical properties of these diamond microlens arrays, a laser scanning reflection/transmission confocal microscopy technique has been developed. This technique enabled the surface profile of the microlenses to be measured simultaneously with optical parameters including focal length and spot size, opening up an application area for confocal microscopy. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1695101]

Refractive microlenses with diameters of a few micrometers to a few hundred micrometers have received much attention, due to their numerous applications in, for example, optical communications, optical data storage, digital displays, and laser beam shaping.[1,2] Recently, microlenses made of III-nitride materials and sapphire have become attractive for such applications as integrating with micro-size light-emitting diode (micro-LED) arrays[3–6] and vertical cavity surface-emitting lasers.[7,8] To broaden the scope of applications of these devices, high-quality microlens arrays with wide optical transmission bandwidth and high thermal conductivity are urgently required. Here, we report success in fabricating and characterizing microlens arrays in *single-crystal* diamond, with diameters as small as 10 μm. These single-crystal diamond microlenses would have an impact where optical absorption and scattering need to be minimized and/or maximum thermal conductivity is important. As well as producing diamond microlenses, we propose and demonstrate a characterization method based on confocal microscopy, which rapidly and accurately allows the optical parameters of the lenses to be determined.

The diamond used in this study is type-IIa natural single-crystal diamond in platelet form. Type-IIa diamond is virtually free of nitrogen impurities, and consequently, exhibits superior optical and thermal properties.[9] The high purity results in high ultraviolet transmission down to approximately 230 nm and an absence of infrared absorption in the 7–10 μm band. At room temperature, type-IIa diamond has an exceptionally high thermal conductivity, approximately six times that of copper (by comparison, type Ia is only twice that of copper).[10] Thus, when integrated with light emitters, microlenses made of single-crystal diamond can also serve as excellent heat spreaders to improve the heat dissipation of the light emitters. Furthermore, in the short wavelength region (green/blue to deep ultraviolet), type-IIa diamond has a refractive index close to that of GaN, thus diamond microlenses are a good choice to integrate with micro-size GaN based photonic devices for short wavelength applications.

In order to precisely and directly characterize these single-crystal diamond microlens arrays, a reflection/transmission laser scanning confocal microscopy (LSCM) technique has been developed. This system enabled the surface profile of the microlenses to be recorded simultaneously with the focal power of the lens. LSCM has been used extensively in biology, medicine, and materials science due to its ability to produce extremely high-quality images of specimens, termed optical sections, at various depths.[11] Due to its point detection properties, confocal microscopy should be able to measure the light intensity distribution inside and outside a miniature optical component such as a micro-size light emitter or lens. For these measurements, confocal microscopy has the advantage of providing three-dimensional (3D) optical images with a high spatial resolution.

For microlens characterization, it is extremely beneficial to use both confocal reflected and transmitted light imaging modes, i.e., to collect reflection and transmission optical sections simultaneously. The experimental setup of the laser scanning reflection/transmission confocal microscope is shown schematically in Fig. 1. Light at 488 nm from a mixed gas Kr/Ar laser was directed into a commercial (Bio-Rad MRC1024ES) scan head. The output from the scan head was then coupled into an upright microscope (Nikon E600FN). A mirror was placed just below the microscope stage to direct collimated green light into the back surface of the lens arrays. This light was provided by a 10 mW miniature diode-pumped, frequency-doubled Nd:YAG laser operating at 532 nm. The output from this laser was expanded 16 times using a Galilean telescope expander, before being sent into the microscope. Both the reflected blue and transmitted green light were collected by the objective lens (20×, 0.75 NA) before passing back through the scan head where the beams were detected by two photomultipliers after a dichroic mirror. In

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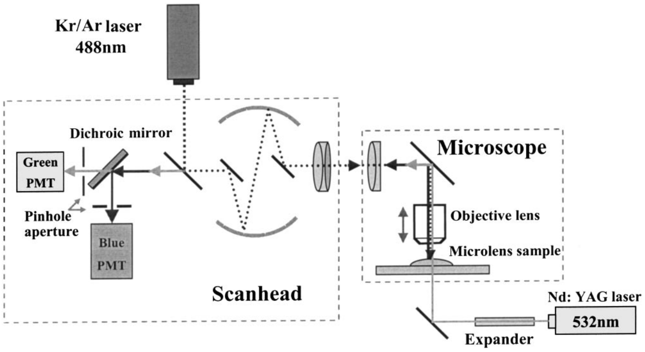

FIG. 1. Schematic diagram of the laser scanning reflection/transmission confocal microscope.

order to ensure that each detector only saw one light source, narrow passband filters (488 ± 5 and 540 ± 20 nm) were mounted before each detector. Using the pinhole apertures in the scan head it was possible to reject light from outside the focal plane. The software control of the system enabled complete 3D images or $X-Z$ optical sections through the lenses and focused beam to be obtained. In our previous calibrations of the confocal system, the axial and lateral resolutions had been measured to be 0.8 (±0.1) μm and 0.25 (±0.02) μm, respectively, at a wavelength of 488 nm.[12]

Type-IIa natural single-crystal diamond microlens arrays were fabricated by the technique of photoresist reflow and inductively coupled plasma (ICP) etching. ICP dry etch technology allows control of selectivity between the diamond substrate and the photoresist mask, permitting adjustment of the lens properties. In this work, high-density O_2/Ar plasma gas was used for ICP etching. By optimizing etch parameters, a high etch rate of 230 nm/min of diamond has been achieved. More details of the fabrication process will be reported elsewhere.

A 3D atomic force microscopy (AFM) image of representative diamond microlenses fabricated as above is shown in Fig. 2. The diameter of these particular lenses is 18 μm at substrate surface with a height of 1.5 μm. By fitting the observed lens surface profile, it was confirmed that the microlenses had a spherical shape. For optical applications, the microlenses should have a very smooth surface. The AFM measurements show that the single-crystal diamond microlenses have a rms surface roughness value of 1.2 nm for a scanned area of 1.0 $\mu\mathrm{m}\times1.0$ μm. This measured roughness is in the same range as for the untreated single-crystal diamond and is much smaller than that obtained from the ICP etched polycrystalline diamond lenses (15 nm),[13] showing the high surface quality of these single-crystal lenses.

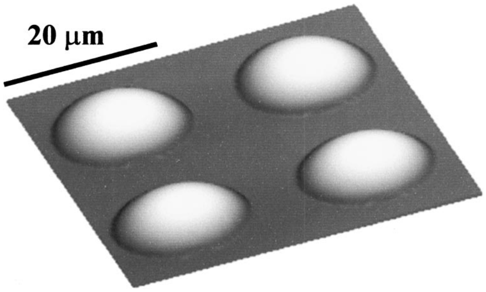

FIG. 2. A three-dimensional AFM image of diamond microlenses with diameter 18 μm.

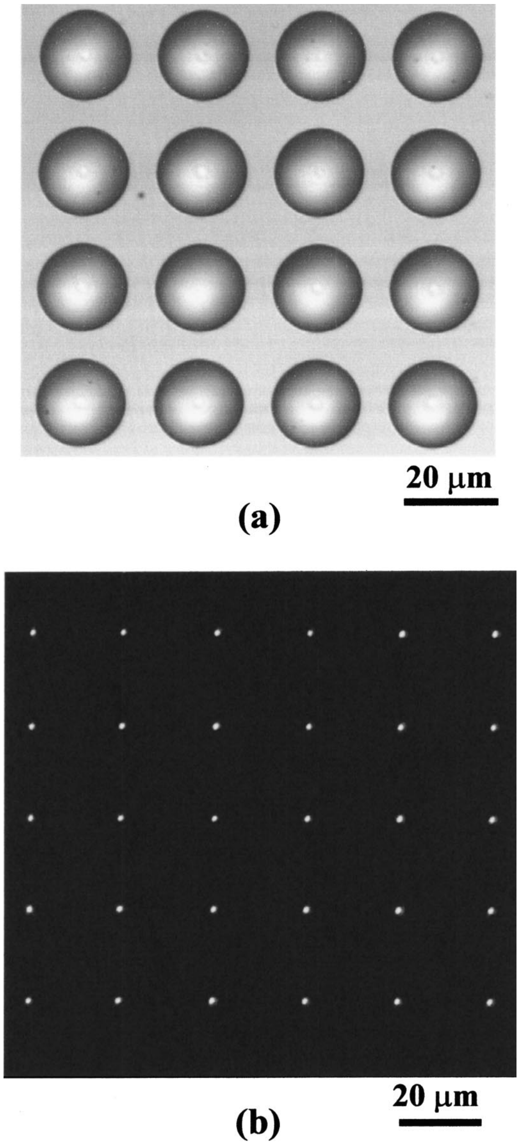

FIG. 3. (a) Confocal plane view reflection image of the diamond microlens array. (b) Confocal plane view transmission section at the focal plane of the microlens array.

Using the paraxial ray approximation, the focal length f of a thin plano-convex lens can be calculated using the relation

$$f=R/(n-1), \tag{1}$$

where n is the refractive index of the lens material and R is the curvature radius. For type-IIa single-crystal diamond, n is 2.42 at a wavelength of 530 nm.[14] The curvature radius R can be estimated from the measured values of the microlens diameter d at substrate surface and height h via

$$R=((d/2)^2+h^2)/2h. \tag{2}$$

Using this relation, the curvature radius of the microlenses shown in Fig. 2 is estimated to be $R=27.8$ μm. The optical parameters of the microlenses can be directly measured by using the reflection/transmission laser scanning confocal microscope. Whereas the plane-view-reflection sections reveal the structural topography of the microlenses, the plane-view-transmission sections provide information about

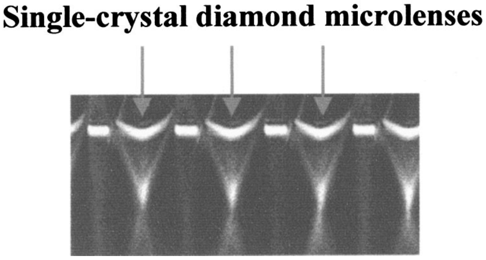

FIG. 4. Confocal reflection/transmission $X-Z$ scan image of the diamond microlens array.

the focal properties of the lenses, such as the light intensity distribution. A reflection section focused at the substrate surface of the diamond microlens array of lens diameter $d = 18\ \mu$m is shown in Fig. 3(a). Figure 3(b) shows the transmission section collected at the focal plane of the diamond microlens array. It is evident that at this plane, all the lenses have a sharp focal spot, demonstrating high uniformity of the single-crystal microlens array. From Fig. 3(b), the beam spot size at the focal point was measured to be $\sim 1.4\ \mu$m.

To fully determine the focal power of the lens, cross-sectional ($X-Z$ sections) reflection and transmission scans have also been performed. Whereas a cross section of the microlens is shown in the reflection $X-Z$ section, the transmission image reveals how light rays propagate through and are focused by the microlenses. For full lens characterization, it is useful to merge these cross-sectional reflection and transmission images into one image. Such a merged cross-sectional image of the diamond microlens array of lens diameter $d = 18\ \mu$m is shown in Fig. 4. It should be noted that in this image, the vertical and horizontal length scales are slightly different. It can be seen clearly that collimated light rays, after they pass through the lenses, converge on a focal point. The distance from this focal point to the lens is the focal length of the lens. From this image, the focal length of the diamond lenses is measured to be $21 \pm 1.0\ \mu$m. This measured focal length is quite close to the calculated value of 19.6 μm, confirming that the fabricated diamond lenses have a high-quality surface profile. A diamond microlens array with lens diameter $d = 10\ \mu$m has also been characterized by the confocal microscope. For these lenses, the measured focal length is $10 \pm 1.0\ \mu$m, which also agrees well with the calculated value. Using this confocal microscope, it is also possible to measure the optical aberrations of microlenses.

In summary, type-IIa single-crystal diamond microlens arrays have been fabricated by using the method of photoresist reflow and ICP dry etching. AFM measurements show that these diamond microlenses are of high structural quality. With excellent optical and thermal properties, these microlenses will enable applications in photonics and optoelectronics. A laser scanning reflection/transmission confocal microscopy technique was developed to characterize microlenses. It was demonstrated that this is a tool for characterizing miniature optical components and devices, opening up an application area for confocal microscopy.

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