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# Nitride microlens arrays for blue and ultraviolet wavelength applications

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Nitride microlens arrays with sizes as small as 10 $\mu$m in diameter have been fabricated on GaN and AlN epilayers using the method of photoresist reflow and inductively coupled plasma dry etching. The focal lengths of the microlenses varied from 7–30 $\mu$m as determined by theoretical fitting as well as by the near-field scanning optical microscopy measurement. Scanning electron and atomic force microscopies were used to obtain the surface profile of the microlenses which were found to match very well with hemispherical fitting and a surface roughness value around 1 nm was obtained. Nitride microlens arrays would be naturally chosen for green/blue to deep ultraviolet wavelength applications. In addition, nitride microlenses offer the possibility of integrating nitride-based microsize photonic devices as well as of coupling light into, out of, and between arrays of III-nitride emitters for other applications, such as spatially resolved fluorescence spectroscopy studies of biological and medical systems and optical links, thereby further expanding the applications of III nitrides.  [DOI: 10.1063/1.1579872]

Microlenses have been studied extensively due to the numerous applications they offer in areas, such as optical communication, optical computing for data or computer links, and optoelectronic devices such as charged-coupled device arrays for collecting light power needed to increase the sensor sensitivity and in laser beam shaping.[1–3] Group-III-nitride semiconductors have excellent physical and chemical properties making them suitable for applications in harsh environments. A great number of active devices, such as light-emitting diodes (LEDs) and laser diodes, photodetectors, and transistors fabricated from the nitride materials, have been demonstrated. Fabrication of microlens arrays based on the III-nitride materials would broaden the scope of applications of these semiconductors to include integration of micro-optical elements especially for the short-wavelength covering the green/blue to deep ultraviolet (UV) (200 nm) region. This would take advantage of the relatively mature manufacturing techniques already developed for the III-nitride materials, including smooth and high rate etching using high-density plasma. Nitride microlens arrays would be important components for the integration of nitride optoelectronic devices such as blue/UV emitters and detectors.

Our group has reported a prototype blue microdisplay fabricated using InGaN/GaN quantum-well-based LED wafers.[4] A nitride-based microlens would find great attraction in microdisplay applications. Park *et al.*[5] reported the fabrication of microlens using sapphire, a material used as a substrate for the growth of nitride semiconductors and which could be used in short-wavelength applications. However, for integration of nitride-based optoelectronic devices, the best choice would be microlenses based on nitrides.

In this letter, we report the fabrication and characterization of microlens arrays with diameters as small as 10 $\mu$m based on GaN and AlN epilayers. We have achieved a focal length variation from 7–30 $\mu$m as determined by theoretical fitting as well as by the near-field scanning optical microscopy (NSOM) measurement. A surface roughness of about 1 nm was obtained for II-nitride microlens, which is typical of good-quality GaN and AlN epilayers.

GaN (AlN) epilayers used in this study were grown to a thickness of 3–3.5 $\mu$m by metalorganic chemical vapor deposition on sapphire substrates with a 30 nm GaN (AlN) low-temperature buffer layer. The sources used were trimethylgallium, trimethylaluminum, and ammonia. To fabricate the microlens, we used the photoresist reflow and dry etching method described in literature.[5–7] In this method, a thick photoresist layer is spun onto the substrate material and patterned by standard photolithography into cylindrical posts. When subsequently baked, surface tension causes them to take up hemispherical shapes. The preformed resist is then used as an etch mask to transfer the hemispherical shape onto the substrate material. In this work, we used an AZ 4260 photoresist to pattern an array of circular resist posts of various sizes, which was then baked on a hot plate. An inductively coupled plasma etching system with chlorine-based high-density plasma gas was employed for dry etch-

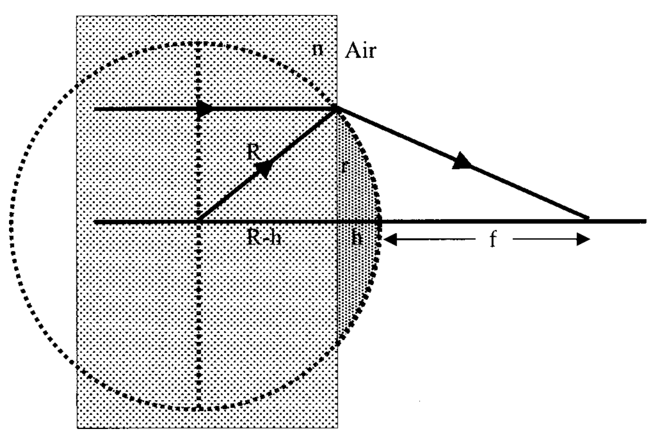


FIG. 1. Illustration of the physical parameters of the microlenses of focal length $f$. The microlens has radius $r$, height $h$, and $R$ is the radius of the complete sphere.

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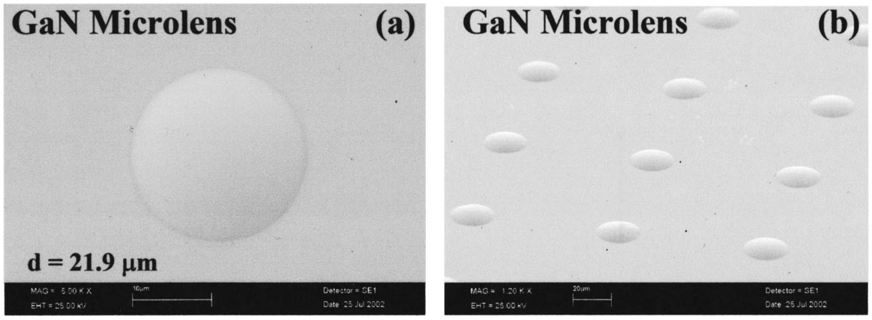


FIG. 2. SEM images showing (a) top view of a GaN microlens of diameter $d=21.9$ $\mu$m and (b) a 60° tilt view of a GaN microlens array in an area of about 80 $\mu$m×80 $\mu$m.

ing. The etch conditions were optimized to yield smooth and anisotropic etching of the III-nitride materials.

Figure 1 shows an illustration of the physical parameters of the planoconvex microlenses. The microlens structure has a radius $r$, diameter $d$ $(d=2r)$, and height $h$. The sphere of which the microlens is a part has radius $R$ and diameter $D$ $(D=2R)$. $R$ can be deduced from the measured values of microlens radius $r$ and height $h$ using the simple expression $R^2=(R-h)^2+r^2$ giving

$$R=(h^2+r^2)/2h. \quad (1)$$

Alternatively, $R$ can be extracted by first fitting the measured atomic force microscopy (AFM) profile using an expression for a circle. We obtained values of $R$ using these two methods and found them to agree well to within 1%–3%. We estimated the focal length $f$ of the planoconvex microlens using the relation

$$f=R/(n-1), \quad (2)$$

where $n$ is the refractive index of the III-nitride materials. For GaN, we used $n=2.4$ for a wavelength of 470 nm; and for AlN microlens, we used $n=2.1$ for a wavelength of 280 nm.[8] The wavelength value of 280 nm is of significance in applications for the detection of biological and chemical agents where the III-nitride-based optical elements would be of great importance.

Figure 2(a) shows the top view scanning electron microscopy (SEM) image of a GaN microlens of diameter $d=21.9$ $\mu$m, while that in Fig. 2(b) shows a microlenses array of about 80 $\mu$m×80 $\mu$m at a 60° tilt view. GaN microlenses will be transparent down to a wavelength of about 370 nm. For deep UV applications down to 200 nm, AlN microlens is needed. In Fig. 3(a), we show the AFM line profile of an AlN microlens with a circular fitting where the microlens is shown to fit excellently with a spherical surface profile. The diameter of this microlens is about 11.6 $\mu$m with a height of 1.2 $\mu$m. The fitting shows the microlens is part of a sphere of diameter $D=30$ $\mu$m. To determine the smoothness of the microlens surface, we measured the AFM surface profile of an AlN microlens, shown in Fig. 3(b) and obtained a root-mean-square roughness value of 1.1 nm for a 1 $\mu$m×1 $\mu$m scanned area. This value is very close to that of our as-grown AlN epilayers.[9] A three-dimensional (3D) AFM profile and an SEM image of the AlN microlens are shown in Figs. 3(c) and 3(d), respectively. For an optical element, great care has to be taken to ensure that the surface topography is smooth and spherical, as this will evidently affect the quality of the focused beam. The excellent topography and smoothness of the surface of our nitride microlenses are indications that they are of high optical quality.

To verify the calculated focal lengths of the microlens, NSOM measurements have also been employed to determine the focal length of one GaN microlens whose diameter $d$ was 10.8 $\mu$m, height $h=1.6$ $\mu$m, and a theoretical focal length 7.0 $\mu$m. In this method, a parallel laser beam of wavelength 400 nm was directed to the microlens, and the focused emergent laser beam intensity profile was collected by the NSOM probe tip. The distance between the probe tip and microlens was varied to obtained a position at which a maximum amount of intensity in the center of the microlens was detected. In this position, the distance between the microlens and the probe tip gives the focal length. Figure 4 shows the laser beam intensity profile when the probe tip was at three different heights above the microlens. The focal length, in this case, was determined to be about 7.3 $\mu$m, which is very close to the calculated value of 7.0 $\mu$m and shows that our microlens is of excellent quality.

Table I summarizes the various parameters of GaN and AlN microlenses, showing that we have achieved a focal length variation from 7–30 $\mu$m. The microlens radius $r$ and height $h$ are measured by AFM, while spherical radius $R$ was

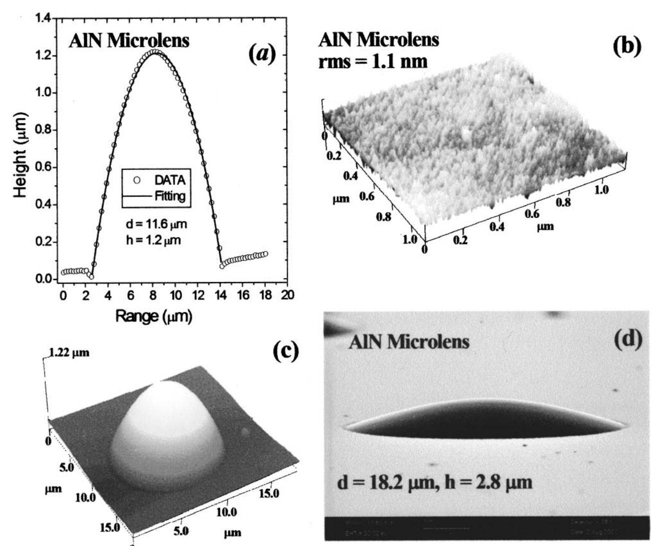


FIG. 3. (a) AFM line profile of AlN microlens with a circular fitting. The fitted diameter ($d$) and height ($h$) of the microlens is about 11.6 $\mu$m of 1.2 $\mu$m, respectively. The fitting shows the microlens is part of a sphere of diameter $D=30$ $\mu$m. (b) AFM surface profile of the microlens. The root-mean-square roughness is 1.1 nm, which is close to that of the as-grown AlN epilayers. (c) A 3D AFM image of the AlN microlens. Note that the vertical and horizontal scales are different. (d) SEM image of the AlN microlens, with a diameter $d=18.2$ $\mu$m and height $h=2.8$ $\mu$m.

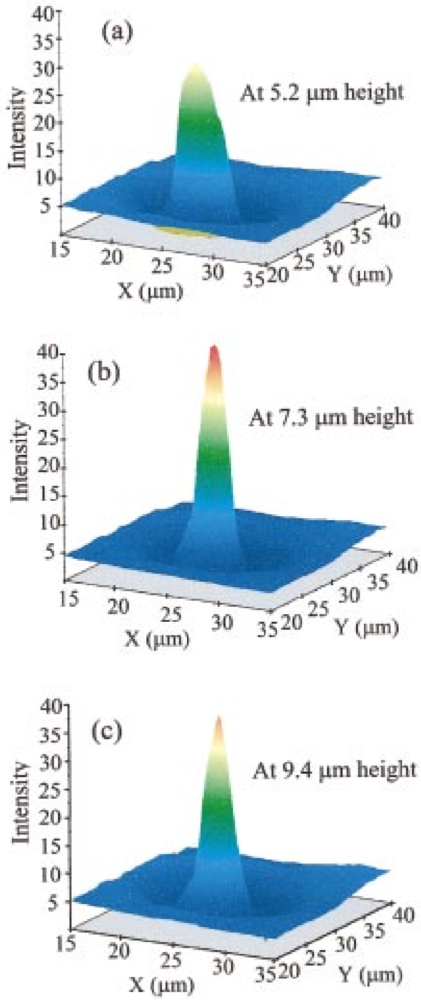


FIG. 4. (Color) NSOM beam profile of a GaN microlens when the probe tip is at three different heights of (a) 5.2 $\mu$m, (b) 7.3 $\mu$m, and (c) 9.4 $\mu$m above the microlens. The maximum intensity in the center of the probed plane is obtained at a height of 7.3 $\mu$m above the microlens, corresponding to the focal length of the microlens.

obtained using the methods explained herein. The focal length $f$ was calculated at wavelength $\lambda=470$ nm (280 nm) for GaN (AlN). The III-nitride semiconductor materials have attracted tremendous interest for various optoelectronic and microelectronic device applications. Not only can these materials be used for blue/UV photonic devices, but also their material properties allow them to withstand extreme conditions of temperature, chemical, and radiation exposure. The nitride-based microlens arrays will be a much-needed tool toward achieving monolithic integration of optical elements based on these semiconductors. This will open doors in applications of the nitride semiconductors in areas such as microdisplay for hands-free and high mobility devices, optical communications, computing, and medical research.

TABLE I. The parameters of GaN and AlN microlenses. The lens radius $r$ and height $h$ are measured values, while the focal length $f$ and the spherical radius $R$ are obtained from theoretical fitting. Different sizes of the microlenses shown were obtained by varying the resist mask baking conditions or by using masks of different sizes.

| GaN | | | | AlN | | | |
|---|---|---|---|---|---|---|---|
| $r$ ($\mu$m) | $h$ ($\mu$m) | $R$ ($\mu$m) | $f$ ($\mu$m) | $r$ ($\mu$m) | $h$ ($\mu$m) | $R$ ($\mu$m) | $f$ ($\mu$m) |
| 5.4 | 1.6 | 9.8 | 7.0 | 5.8 | 1.2 | 14.9 | 13.6 |
| 6.0 | 1.0 | 18.0 | 12.9 | 6.1 | 1.1 | 17.8 | 16.2 |
| 5.5 | 1.2 | 12.5 | 9.0 | 8.3 | 1.3 | 24.6 | 22.4 |
| 6.1 | 0.6 | 32.2 | 23.0 | 8.5 | 2.5 | 15.2 | 13.8 |
| 9.4 | 3.0 | 15.4 | 11.0 | 10.1 | 2.5 | 20.9 | 19.0 |
| 11.6 | 1.7 | 42.6 | 30.4 | | | | |

In summary, we have fabricated microlens arrays based on the III-nitride materials. The microlenses had high-quality surface profiles as determined by SEM and AFM measurements. The theoretical focal lengths showed excellent agreements with those determined by NSOM measurements. Our work provides a basis for expanding the applications of the III-nitride materials to include optical element integration covering deep UV wavelength regions.

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