Refractive sapphire microlenses fabricated by chlorine-based inductively coupled plasma etching

Si-Hyun Park, Heonsu Jeon, Youn-Joon Sung, and Geun-Young Yeom

We have fabricated refractive sapphire microlenses and characterized their properties for what we believe to be the first time. We use thermally reflown photoresist lenslet patterns as a mask for chlorine-based dry etch of sapphire. Pattern transfer to the mechanically hard and chemically inert sapphire substrate is made possible by an inductively coupled plasma etch system that supplies a high-density plasma gas. Processed sapphire microlenses exhibit properties close to the ideal and operate nearly in the diffraction limit. © 2001 Optical Society of America

OCIS codes: 220.4000, 220.3630.

1. Introduction

Because of their small size and dense two-dimensional array formation, microlenses have received much attention in laser beam shaping and coupling, image sensing, and other related functions in photonics. Among various microlens-fabrication techniques that have been developed so far, the most popular is the method of photoresist reflow followed by dry etch, because of its simplicity and versatility regardless of lens materials.[1–3] In this method a thick photoresist (PR) layer is photolithographically patterned into a cylindrical post and subsequently melted at an elevated temperature, resulting in a spherical lenslet preform that is due to surface tension. This preform is then used either as a PR microlens as it is[4,5] or as a reactive-ion-etch mask to transfer the PR microlens perform to the underlying substrate material. The method has been successfully used in fabricating microlenses of various materials, including semiconductors[1,2] and dielectrics.[3]

Sapphire, however, is known to be an excellent material in its own right.[6] Sapphire exhibits high internal transmittance from 150 nm in vacuum UV to 6000 nm in the mid-IR. Sapphire also possesses an extreme mechanical hardness so that it can hardly be scratched, except by a few substances other than itself such as diamond or boron nitride. In addition, sapphire is chemically inert and insoluble in most substances. It has exceptionally high thermal conductivity and strength so that its Young's modulus is roughly five times higher than that of fused silica. Because of these advantageous properties, sapphire optical elements have a variety of applications for which other optical materials cannot be used, for example, in both physically and chemically harsh environments. Lately, sapphire has been successfully and massively used as a substrate material for the growth of GaN-based short-wavelength light-emitting devices despite a large lattice mismatch between the two material systems.[7] Forming microlenses directly on the GaN-grown sapphire substrate offers a unique opportunity for monolithic integration of active and passive optical elements on the same chip, implying the possibility of constructing compact high-performance GaN-based optoelectronic devices.

However, sapphire is a material whose processing is known to be extremely difficult. Even hydrogen fluoride fails to etch sapphire at temperatures below 300 °C. The extreme difficulty in processing hinders any substantial breakthrough in fabricating optical components from sapphire, other than macrosized sapphire lenses manufactured by the conventional grinding and polishing method. In this paper we report on the success in fabricating sapphire microlenses whose sizes are as small as 40 μm in diameter and describe the details of their fabrication and characterization with an emphasis on the inductively coupled plasma (ICP) etch,[8] crucial for sapphire processing.

S.-H. Park and H. Jeon (hsjeon@phya@snu.ac.kr) are with the School of Physics and Inter-University Semiconductor Research Center, Seoul National University, Seoul 151-747, Korea. Y.-J. Sung and G.-Y. Yeom are with the Department of Materials Engineering, Sung-Kyun-Kwan University, Suwon 440-746, Korea.

Received 11 January 2001; revised manuscript received 2 May 2001.

0003-6935/01/223698-05$15.00/0

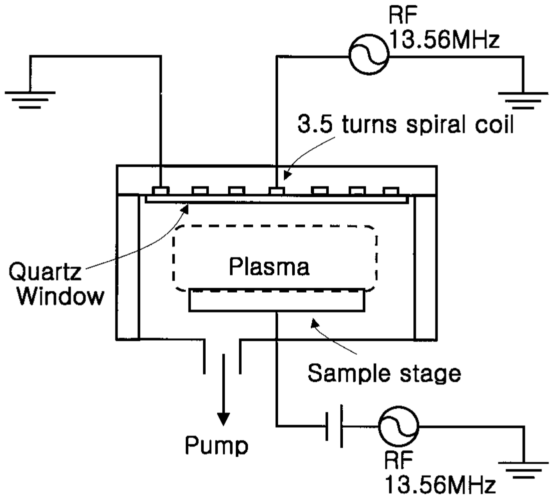

Fig. 1. Schematic diagram of the ICP dry-etch system. The top-loaded rf coil is a planar spiral copper coil with 3.5 turns.

2. Fabrication

We use the well-known PR-reflow and dry-etch method to fabricate sapphire microlenses, and the basics of the method are well described in the literature.[1–3] The PR used in our experiments is AZ-1518 manufactured by Hoechst, and the sapphire substrates are (0001)-oriented 2-in. (~5-cm) wafers from Shinkosha. An array of circular PR patterns with various diameter sizes is defined on a sapphire substrate by the standard photolithographic technique. The PR patterns are then baked on a hot plate. Above the glass transition temperature the PR patterns start to flow. At the initial stage of the reflow process the PR patterns become concave, the center being thinner than the circumference. As the temperature is further increased, the viscosity of the PR decreases, and the patterns eventually become convex with the center of each pattern the thickest. The smaller the diameter of the circular PR pattern, the lower the temperature required for convex shape formation. When the PR layer thickness and the baking temperature are 1.8 μm and 200 °C, pattern diameters below 70 μm produce convex PR lenslets in a reproducible manner. Throughout the experiments the PR baking time is kept at 5 min for consistency, but we did not observe any noticeable change in PR lenslet curvature even for baking durations beyond 5 min.

Subsequent pattern transfer to the sapphire substrate is done with an ICP system, which provides a chlorine-based high-density plasma gas.[9,10] Figure 1 shows a schematic diagram of the ICP system. The chamber wall is made of surface-oxidized aluminum, prohibiting the chamber itself from being etched during the etching process, whereas the sample stage inside the chamber is made of copper. The quartz window, which separates the rf coil from the chamber, is situated 100 mm above the copper plate. The rf coil is a planar 3.5-turned gold-coated copper spiral. The system is equipped with two 13.56-MHz rf power generators, one for the inductively coupled plasma and the other applied to the sample stage for maintaining a dc bias voltage. The inductive power delivered to the system is in the range of 600–800 W. A pair of mechanical and turbo pumps are used for chamber evacuation, and the base pressure is maintained at 30 mTorr during the etching process. With the gas mixture of BCl_3 and Cl_2 at a ratio of 1:1, a high etch rate of ~200 nm/min is obtained. Details of sapphire etching can be found in Refs. 9 and 10. We emphasize here, though, that it is mainly the high plasma density available in the ICP system that is responsible for the high etch rate, leading to the success of sapphire microlens fabrications, though the proper choice of etch gases and the detailed optimizations of etch conditions are important concerns as well.

After an etching long enough for the complete removal of the lenslet-shaped sacrificial PR masks, spherical microlenses are formed on the underlying sapphire substrate. Since the etch rate of sapphire is lower than that of the PR itself, ~0.6 in ratio, lens curvature is changed after the dry etch.

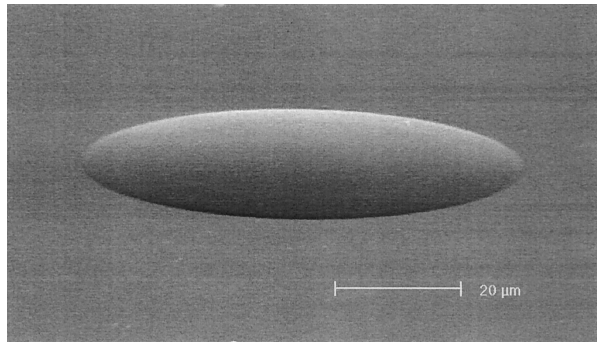

Fig. 2. Perspective SEM image for a sapphire microlens with lens diameter of 60 μm.

3. Sapphire Microlens Characterizations

A. Physical Properties

Figure 2 is a scanning electron microscopy image of a processed sapphire microlens with a lens diameter of 60 μm. Of great importance for an optical element is its surface topography, since it directly affects the resultant beam quality. We carefully optimized the etching conditions so that the surface topography of the etch-terminated surface is smooth for optical applications, without much sacrifice of the etch rate. Figure 3 shows an atomic force microscope (AFM) image of a portion of the sapphire microlens surface. The rms roughness is approximately 0.23 nm for the scanned area of 1 μm × 1 μm, proving the high surface quality of the ICP-etched sapphire.

When it is assumed that the photoresist mask has a spherical shape with a constant radius of r_p before the etching, the resultant sapphire lens profile be-

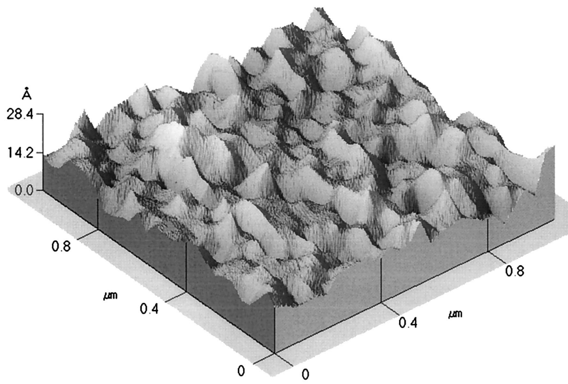

Fig. 3. Sapphire microlens surface topography imaged by an AFM. The measured rms surface roughness over the scanned area of 1 µm × 1 µm is 0.23 nm.

comes ellipsoidal and the corresponding radius of curvature is given[1] by

$$R(x) = \frac{r_p}{k}\left[1 - (1 - k^2)\left(\frac{x}{r_p}\right)\right]^{3/2}, \tag{1}$$

where x is the distance from the center and k is the etch-rate ratio of sapphire to PR mask. When the second term in the brackets of Eq. (1) is negligible, the lens shape can be approximated to a spherical one with the radius of curvature

$$R \approx r_p/k. \tag{2}$$

In our case k is measured to be ~0.59. Thus if only the central region of the microlens ($x/r_p < 0.25$) is of interest, the second term in the brackets of Eq. (1) becomes 0.04 at most. So the sapphire microlens can be approximated to be circular, its curvature radius given by relation (2).

Lens shapes for both PR and sapphire microlenses are measured by a stylus profilometer (Tencor Alpha-Step 500), and the measured data are fitted to a circle. An example of the measurement results is shown in Fig. 4. In that particular case the PR microlens has the maximum height of 2.87 µm, and the radius of curvature obtained by fitting is r_p = 95.9 µm. The corresponding numbers for the sapphire microlens after etching are 1.68 µm and R = 157.6 µm, respectively. The etch-rate ratio k obtained from the values for r_p and R by use of relation (2) is 0.61, very close to the directly measured value of 0.59. Within the measurement resolution we did not observe any directional dependence of the lens profile. This result is consistent with the circularly symmetric image of a laser beam transmitted through the microlens, which was confirmed by an independent spot profile measurement, described below. We attribute this result to the dominance of the physical etching nature in our chlorine-based ICP-etching process.

B. Optical Properties

Figure 5 shows the experimental setup used for the simultaneous measurements of focal length and

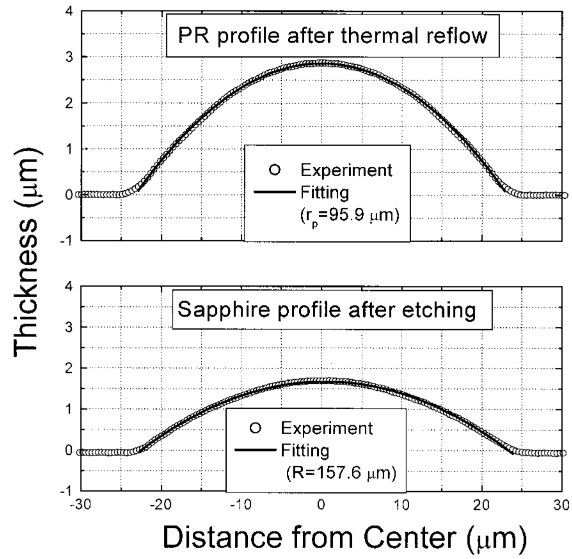

Fig. 4. Microlens profiles measured by a stylus profilometer for (a) the photoresist lenslet mask and (b) the processed sapphire microlens after dry etch.

beam spot size for the sapphire microlenses. It consists of a ×60 microscope objective lens (N.A. = 0.85) and a CCD camera. Sapphire microlenses are fabricated specifically on a two-sided polished sapphire substrate for transmission-type measurements. A sapphire microlens is mounted on a translational micropositioning stage with ±2-µm accuracy so that the position of the microlens can be controlled in a fine resolution. A 632.8-nm He–Ne laser is used as the light source, and the cross-sectional laser beam profile is imaged with the CCD camera. At the beginning of the process the sapphire microlens surface is focused first, and the translational stage reading is set to null, marking the reference position. Subsequently the microlens is moved away from the CCD camera while the image of laser beam is carefully monitored. At the point where the beam spot size becomes minimum, the reading on the translational stage indicates the focal length f while the intensity distribution recorded on the CCD camera corresponds to the profile of the He–Ne laser beam focused by the microlens. The ultimate resolution in the

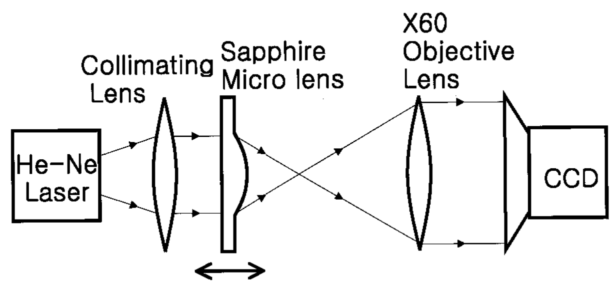

Fig. 5. Experimental arrangement for focal length and beam profile measurements. The sapphire microlens is mounted on a fine-resolution translational stage so that it can be moved back and forth during the measurements.

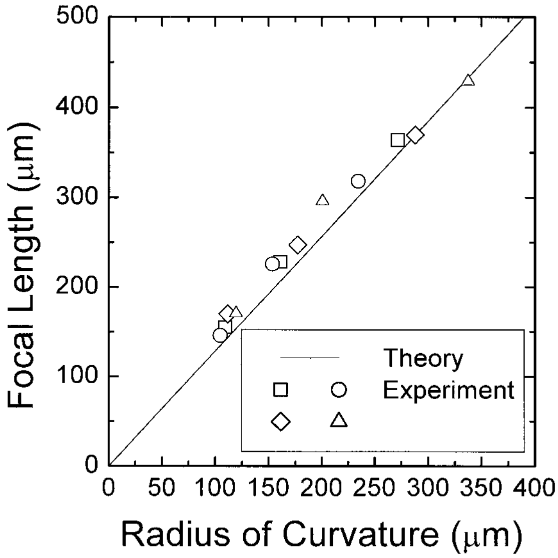

Fig. 6. Relationship between focal length and curvature radius of sapphire microlenses. Different symbols are used to distinguish between different sets of samples, whereas the solid line is based on the theory.

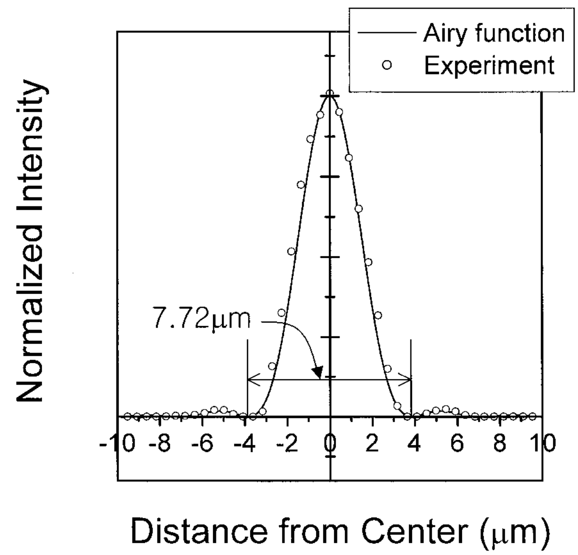

Fig. 7. Measured intensity distribution of the laser beam at the focal length of a sapphire microlens. The curve drawn over the experimental data is the theoretical Airy pattern for a circular aperture.

beam profile measurement is one pixel of the CCD chip by definition, which in our case is $\sim$0.325 μm.

Figure 6 shows the relationship between focal length and curvature radius measured for a number of sapphire microlenses. Different symbols are used to distinguish between microlenses fabricated under different dry-etching conditions. The solid line is the theoretical curve based on the fundamental equation relating the radius of curvature to the paraxial focal length for a spherical plano–convex microlens:

$$f = R/n - 1, \tag{3}$$

where R is the curvature radius of the lens and n is the refractive index of the lens material. We assume that $n = 1.78$ for sapphire at the He–Ne laser wavelength of 632.8 nm.[11] Good agreement exists between the experimental results and the theory. At the focal point of a lens the cross-sectional intensity profile is given by the well-known Airy function,

$$I(x) = I_0 \left\{ 2 \frac{J_1\left[\pi \dfrac{x}{\lambda(f/D)}\right]}{\left[\pi \dfrac{x}{\lambda(f/D)}\right]} \right\}^2, \tag{4}$$

where J_1 is the first-order Bessel function. λ and D are the wavelength of light and the lens diameter, respectively; I_0 is the peak intensity; and x is the distance from the intensity peak. The intensity distribution measured for a sapphire microlens is displayed in Fig. 7, showing a distinct Airy pattern with at least one well-resolved pair of sidelobes. The diffraction-limited spot size, defined as the distance between the first two zeros on both sides of the main peak, is theoretically given as $2.44\lambda(f/D)$. Table 1 summarizes optical characteristics of the sapphire microlenses with various lens diameters, in which the experimentally obtained focal length and beam spot size are compared with the theoretical ones. All the data support close agreement between experimental and theoretical results.

The f-ratio, defined as f/D and therefore closely related to the beam spot size, is among the important lens parameters from a practical point of view. As far as processing is concerned, there seems to be no lower-bound limit in the f-ratio, since for a given lens diameter the aspect ratio of the PR lenslet preform can be made large up to any desired level by means of simply increasing the PR layer thickness. An excessively large aspect ratio, however, causes departure from the paraxial limit and thus produces spherical astigmatism of the lens.

Table 1. Summary of the Measurements of Focal Length and Beam Spot Size for a Few Sets of Sapphire Microlenses Fabricated under Different Conditions[a]

Sample Group	Diameter	Focal Length (Theory)	Focal Length (Exp.)	Spot Size (Theory)	Spot Size (Exp.)
1	40	140.5	155.3	5.43	5.44
	50	206.1	228.5	6.37	6.73
	60	348.0	364.0	8.95	8.94
2	40	134.5	146.0	5.19	4.00
	50	196.9	225.8	6.08	7.05
	60	300.4	318.0	7.73	7.72
3	40	143.6	169.9	5.54	5.40
	50	227.5	247.0	7.03	6.69
	60	369.1	369.6	9.50	8.30
4	40	153.3	170.8	5.92	5.81
	50	257.6	296.3	7.96	8.01
	60	432.7	429.0	11.13	8.89

[a]All values in micrometers.

4. Discussion and Conclusions

Microlenses and microlens arrays have various applications in photonics, whereas sapphire has its own excellent merits, such as high transmission from UV to mid-IR, extreme hardness, and chemical inertness. Merging of the two, namely, sapphire microlenses, will therefore find unique applications that no other material can offer. Micro-optic elements that need to be operated in harsh environments, or GaN light-emitting devices integrated with on-chip microlenses, could be good application examples.

Using the method of PR reflow and dry etch, we have successfully fabricated sapphire microlenses, which is enabled by the ICP-etch system with a high-density plasma etch gas. Processed sapphire microlenses show excellent surface topography as confirmed by the AFM measurements. Physical lens profiles are measured, from which focal lengths and curvature radii are deduced. The resultant focal lengths are in good agreement with theoretical values. The measured beam profile shows a distinct Airy pattern, and the focused beam spot size determined from the Airy pattern is close to the value estimated in the diffraction limit. These facts indicate that our sapphire microlenses are of high quality. To the authors' best knowledge, this is the first demonstration of fabricating micro-optic elements from sapphire.

The authors are grateful to Y. J. Park and O. Nam at Samsung Advanced Institute of Technology (SAIT) for their valuable discussion. This research was supported by funds from SAIT through the BK21 University–Industry Cooperation program and from the Ministry of Commerce, Industry, and Energy (MCIE) under contract B51-990-3303-00-1-3.

References

1. O. Wada, "Ion beam etching of InP and its application to fabrication of high radiance InGaAsP light emitting diodes," J. Electrochem. Soc. **131,** 2373–2380 (1984).
2. M. B. Stern and T. R. Jay, "Dry etching for coherent refractive microlens arrays," Opt. Eng. **33,** 3547–3551 (1994).
3. N. C. Craft and A. Y. Feldblum, "Optical interconnects based on arrays of surface emitting lasers and lenslets," Appl. Opt. **31,** 1735–1739 (1992).
4. Z. D. Popovic, R. A. Sprague, and G. A. N. Connell, "Technique for monolithic fabrication of microlens arrays," Appl. Opt. **27,** 1281–1284 (1988).
5. S. Haselbeck, H. Schreiber, J. Schwider, and N. Streibl, "Microlenses fabricated by melting a photoresist on a base layer," Opt. Eng. **32,** 1322–1324 (1993).
6. R. W. Cahn, P. Haasen, and E. J. Kramer, eds., *Materials Science and Technology* (VCH, Weinheim, 1993), Chap. 2, pp. 85–101.
7. See, for example, S. Nakamura and G. Fasol, *The Blue Laser Diode* (Springer, Berlin, 1997), Chap. 2.
8. For a general overview see M. A. Lieberman and A. J. Lichtenberg, *Principles of Plasma Discharges and Materials Processing* (Wiley, New York, 1994), Chap. 12.
9. H. S. Kim, D. H. Lee, Y. J. Sung, Y. H. Lee, G. Y. Yeom, J. W. Lee, S. H. Chae, and T. I. Kim, "Inductively coupled plasma etching of sapphire wafer," in *Proceedings of the 1st UK Nitride Conference* (Institute of Physics, Glasgow, 1999), p. 10.
10. Y. J. Sung, H. S. Kim, Y. H. Lee, J. W. Lee, S. H. Chae, Y. J. Park, and G. Y. Yeom, "High rate etching of sapphire wafer using $Cl_2/BCl_3/Ar$ inductively coupled plasmas," Mater. Sci. Eng. B **82,** 50–52 (2001).
11. E. D. Palik, ed., *Handbook of Optical Constants of Solids II* (Academic, San Diego, 1991), Chap. 2, pp. 498–500.