# Out-of-Plane Refractive Microlens Fabricated by Surface Micromachining

C. R. King, L. Y. Lin, and M. C. Wu

*Abstract*—**A novel refractive microlens standing perpendicular to the substrate has been fabricated for the first time with surface-micromachining techniques. The microlens has a focal length of 670 $\mu$m and a diameter of 300 $\mu$m. The optical axis of the microlens is precisely defined by photolithography and can be pre-aligned to other surface-micromachined micro-optical elements integrated on the same substrate. The focusing and collimating abilities of the lens are successfully demonstrated. The refractive microlens offers higher efficiency compared with diffractive lenses, and is very useful for high-performance free-space micro-optical bench applications.**

THE SURFACE-MICROMACHINED micro-optical bench approach provides a promising technology to monolithically integrate free-space optical systems on single silicon chips, and the technique has broad applications in optical data storage, sensing, display, and optoelectronic packaging [1]–[3]. Out-of-plane microlenses are key components of the micro-optical bench. Micro-Fresnel lenses standing perpendicular to the substrate have been demonstrated using microhinge technology [1], [2]. The advantages of Fresnel lenses include compatibility with planar microfabrication processes, precise definition of focal length and optical axis using photolithography, and the ability to pre-align the lenses with other elements on the micro-optical bench [4]. Excellent optical performance has been demonstrated, however, the efficiency of the lens is low, due to the use of binary diffractive optics in the design of the lenses. The theoretical diffraction efficiency limits are 10% for binary-amplitude Fresnel lenses and 41% for binary-phase Fresnel lenses [5]. The efficiency can be improved by employing more levels in the design of the lens, however, the diffractive lenses are still wavelength dependent. These difficulties can be effectively overcome with the use of refractive lenses. Therefore, easily manufacturable, out-of-plane refractive microlenses are highly desirable for high-performance free-space integrated micro-optical systems.

Refractive microlenses have been in use for some time in various forms, but until now have always been either mounted directly on, or etched into, the surface of a substrate [6]–[9]. In this letter, we report on the fabrication and characterization of a novel out-of-plane refractive microlens. By combining the micro-optics fabrication techniques with micromachining technology, a three-dimensional refractive microlens with a 300-$\mu$m lens diameter and a 670-$\mu m$ focal length has been demonstrated.

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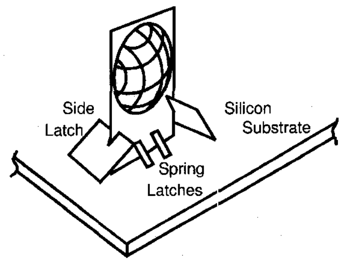


Fig. 1. Schematic diagram of the three-dimensional refractive microlens mounted on a surface-micromachined vertical plate.

As illustrated in the diagram in Fig. 1, the design consists of a reflowed-photoresist microlens mounted on a surface-micromachined supporting plate. The support plate is held perpendicular to the substrate by integrated micro-spring latches and separate side-latches. Polysilicon hinges restrain the support plate and side latches to the substrate [10]. Side-latches are included to provide better mechanical strength for the device and to precisely define the 90° angle with the substrate. The entire assembly is fabricated in a two-step process: surface-micromachining of the support-plate structure using photolithographically-defined polysilicon and silicon dioxide layers on a silicon substrate, and subsequent deposition of the microlens onto the plate. The lens is positioned on the plate so that its optical axis is aligned with the rest of the micro-optical bench after the plate is rotated up from the surface.

The microlens is fabricated with the reflow technique. Two successive layers of AZ 4620 photoresist are spun onto the chip, resulting in a thickness of up to 20 $\mu$m. Photolithography is used to define the size and precise position of the lens over the supporting plate. The chip is then placed in a convection oven at 200 °C for 20 min, causing reflow of the photoresist, which takes on a closely spherical surface shape due to surface tension forces. The reflow technique applied with this resist has been previously demonstrated in the fabrication of in-plane microlenses with diameters from 30 to 500 $\mu$m [6], and F-numbers ranging from F/1 to F/5 [7]. An advantage of AZ 4620 over some other resists used for microlens fabrication [8], [9] is its resistance to spreading during reflow—the lens maintains a constant diameter. Another advantage is its chemical and thermal stability after reflow. The resist demonstrates low solubility in solvents and relative hardness after reflow, and has

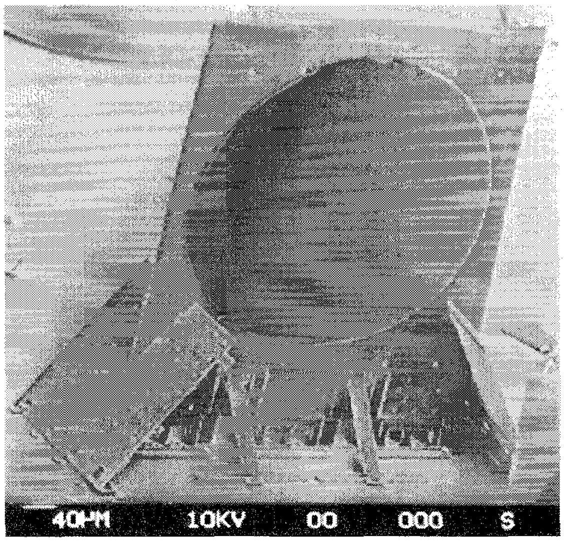


Fig. 2. SEM micrograph of the fully assembled refractive microlens. The lens is 300 $\mu$m in diameter.

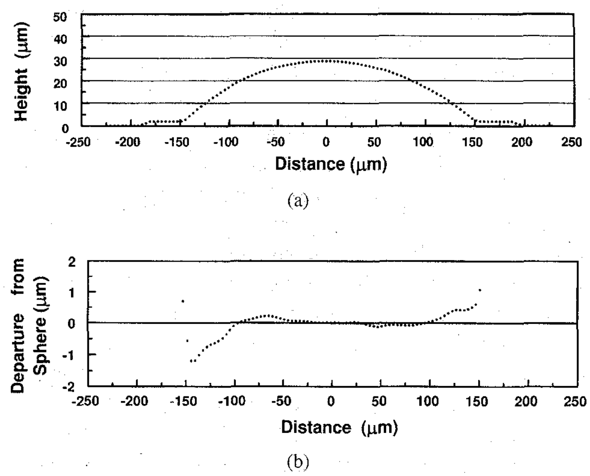


Fig. 3. (a) Surface profile of the plate-mounted microlens. The thickness of the support-plate is visible next to the lens. (b) Departure from a spherical surface profile for the microlens surface.

been used as a dielectric material in industrial manufacturing of thin-film recording heads for computer hard drives [11].

The three-dimensional structure is assembled after a releasing etch in hydrofluoric acid, which dissolves the sacrificial silicon dioxide layers. A scanning electron micrograph (SEM) of the final structure is shown in Fig. 2. The lens has a diameter of 300 $\mu$m and a center height (sag height) of 30 $\mu$m. The results of a Tencor Alpha-Step 200 Profilometer scan of the plate-mounted lens are shown in Fig. 3(a). The profilometer results are consistent with a spherical surface with a radius of curvature of 432 $\mu$m, referenced to the sag height. The departure from a perfectly spherical surface is plotted in Fig. 3(b). Fabrication parameters affecting the quality of the spherical profile of the lens are detailed in [7]. The data show that the lens has a surface which is spherical to within less than 0.5 $\mu$m over a central diameter of 220 $\mu$m.

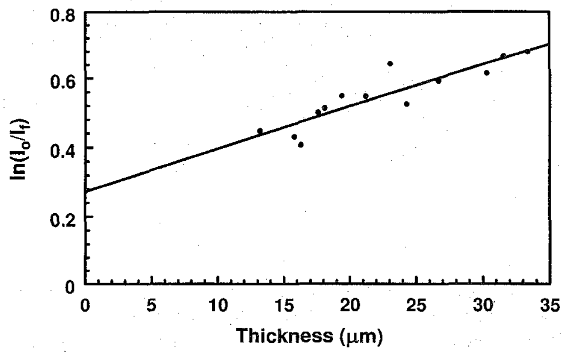


Fig. 4. Absorption versus thickness of AZ 4620 photoresist.

In addition to the ability to reflow to a closely spherical surface with good chemical stability after reflow, the lens material must have low absorption at the desired wavelength. To determine the absorption coefficient of the AZ 4620 photoresist, several glass slides with different thicknesses of the resist were prepared, and subjected to the same reflow process as the lens. The intensity of a red HeNe laser beam ($\lambda = 633$ nm) was measured after passing through various thicknesses of the resist. The beam intensity after passing through the resist ($I_f$) is determined by the intensity incident on the glass slide ($I_0$), the transmission coefficient of the glass slide ($T$), the absorption coefficient of the resist ($\alpha$), and the thickness of the resist ($t$), according to the formula: $I_f = I_0 T \exp(-\alpha t)$; which yields the linear relation: $\ln(I_0/I_f) = \alpha t - \ln(T)$. The measured data is shown in Fig. 4. The value of the absorption coefficient, as determined from the slope of the line, is $\alpha = 0.012$ $\mu$m$^{-1}$, or $\alpha = 0.053$ dB/$\mu$m. The optical loss through the lens is estimated to be 0.70 dB, or a loss of intensity of 15%.

The microlens was tested to determine the collimating ability, focal length, and minimum focal spot size. A red HeNe laser was coupled to a single-mode fiber and used to illuminate the plate supporting the lens. The fiber was positioned to provide a collimated output. The collimated beam width (FWHM) was measured as a function of distance from the lens using a CCD camera, as shown in Fig. 5. The divergence angle for the collimated beam is 0.18°, compared to an angle of 3.3° for the fiber alone. The experiment also yields a value for the focal length of the lens, based on the distance between the fiber tip and the lens. This was measured as 670 $\mu$m, which agrees reasonably well with the focal length of 699 $\mu$m estimated from the shape of the lens and the refractive index of AZ 4620 ($n = 1.6176$).

To measure the focal spot size for the beam focused by the microlens, a collimated beam was used as an input light source. This beam was incident upon the plate-mounted lens, and the focal spot size was measured with a CCD camera through a microscope. The measured FWHM spot size of 2.2 $\mu$m compares to a theoretical diffraction-limited spot size of 1.3 $\mu$m.

The focal length of the microlens is set by controlling the initial thickness of the photoresist layer and the diameter of the lens, which is defined by photolithography. The resist

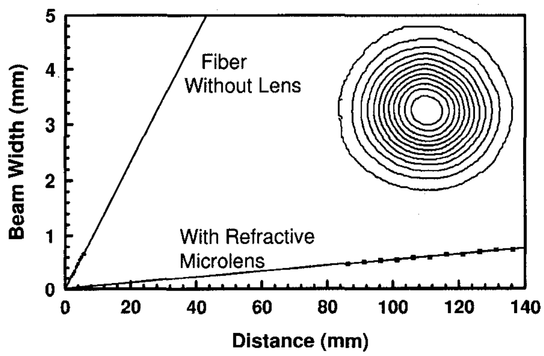


Fig. 5. The FWHM beam width of the light emitted from a single-mode fiber with and without collimation by the microlens. The insert shows an intensity contour plot of the collimated beam.

thickness required for a given radius of curvature $(R_c)$ for the lens may be calculated by equating the volume of the spherical portion representing the final lens shape to the volume of a cylinder representing the photoresist column before reflow [7], taking into account the loss of volume due to the evaporation of solvents.

In summary, a novel out-of-plane refractive microlens has been fabricated by combining the surface-micromachining technique with the reflow processes. The microlens has a focal length of 670 $\mu$m, and a diameter of 300 $\mu$m. Except for the dispersion of the lens material, the refractive micro-lens is wavelength independent, and offers a great improvement in efficiency over binary diffractive Fresnel lenses. The novel mounting system allows for monolithic integration of the refractive lens into the micro-optical bench, and can be used in the implementation of free-space optical interconnects, optical switches, and optical storage systems. The inclusion of refractive lenses constitutes an important advancement for the micro-optic bench approach to high-performance optical systems.

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