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T. YANO✉
S. SHIBATA
T. KISHI

Fabrication of micrometer-size glass solid immersion lens

Department of Chemistry and Materials Science, Graduate School of Science and Engineering, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8552, Japan

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ABSTRACT A micrometer-size solid immersion lens (μ-SIL) of glass with a super-spherical shape is obtained using a simple preparation procedure. Soda-lime–silica glass particles are melted on a glassy-carbon substrate with a surface of optical grade and cooled to room temperature. The obtained glass particles are transparent and have a super-spherical shape. Their shapes are found to satisfy the conditions of the SIL function for evanescent-field optics. Fine uneven surface textures of an integrated circuit with the depth of about 20 nm are clearly recognized using the prepared μ-SIL, and 1.8 times higher horizontal resolution than without the μ-SIL is also attained. It was ensured that the glass μ-SIL works as the evanescent-field optics to visualize the nanometer-scale structure.

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1 Introduction

Near-field technology has been gathering much attention because it can circumvent the optical diffraction limit to visualize objects smaller than the optical wavelength. In the past decade, various types of optical devices (probes) for near-field optical phenomena have been developed [1]. Solid immersion lenses (SILs) are the objective lens first introduced by Mansfield and Kino [2], and one of the representative near-field optical probes using an evanescent field. There are two types of SIL; a hemispherical SIL and a super-spherical one. The wavelength of the evanescent field emerging from the bottom flat surface of a SIL is reduced by a factor of the refractive index n. The optical resolutions of a hemispherical SIL and a super-spherical one are improved by n and n^2, respectively, and enable us to obtain super-resolution images of objects with a dimension much smaller than the wavelength of light. A SIL is considered to be a promising new probe in the fields of optical data storage and high-resolution luminescence microscopes, where the decreasing spot size is an important pursuit to increase the bit density and the collection efficiency of the emitted photons from the target, respectively.

The probe shape must be controlled strictly to realize the near-field optical function. In the case of a super-spherical SIL, it should have a thickness $a(1+1/n)$, where a and n are the radius and the refractive index of the sphere, respectively. As shown by Yoshita et al. [3], the aberrations and allowances of the dimension of the lens for the SIL function are quite severe;

$$|b| < \lambda/4\sqrt{n^2-1}; \quad (1)$$

the aspheric error, and

$$|d| < \lambda/4n\left(n\sqrt{n^2-1}-n^2+1\right); \quad (2)$$

the thickness error are required for a super-spherical SIL.

Under these conditions, the effective view field with the size

$$2r < \frac{1}{n}\sqrt{2a\lambda/\left(\sqrt{n^2-1}-n+1\right)}; \quad (3)$$

the view field

can be obtained. When $\lambda = 450$ nm and $n = 1.6$ are considered, $|b| < 141$ nm and $|d| < 168$ nm should be attained to realize the desired spatial resolution. The characteristic shape of super-spherical form satisfying these conditions cannot be fabricated easily, while the hemispherical one can be made by adopting the technique of semiconductor fabrication processes [4].

Glass is one of the most favorable materials for a SIL, because it has good optical homogeneity, a wide optical window, and a wide variety of refractive indices. Therefore, glass materials have often been employed for SILs in previous studies [5–7]. However, the available size of a small SIL has been limited ($2a > 0.5$ mm) because it has been obtained by grinding or polishing a spherical ball lens, where the precision according to (1) and (2) is required. The control of the size to less than a micrometer is unavailable for the mechanical polishing, and as a result the yield of the fabrication of SILs becomes very low. Therefore, a new fabrication process to obtain high-precision SILs has been required.

In this paper, we report a new fabrication method of a glass micrometer-SIL (μ-SIL). The new method employs a very simple process to prepare a super-spherical shape. A small a is shown to give one of the pathways to circumvent these severe restrictions on the shape parameters. With this method, the aspheric

✉ Fax: +81-3-5734-2845, E-mail: tetsuji@ceram.titech.ac.jp

error is reduced to satisfy (1), and the thickness error and the grade of the bottom flat plane of the glass particles can be readily controlled. Finally, the near-field optical function using the obtained SIL is demonstrated.

2 Experimental

The glass particles of typical silicate glass (soda-lime–silica glass, $n_d = 1.515$) with the grain size of 5–100 μm were placed on the glassy-carbon (g-c) substrates. Two grades of g-c substrates were prepared by polishing. They have the arithmetic average roughnesses $Ra = 3.8$ and 11 nm. The fine glass particles on g-c substrates were heated to 800 °C in the atmosphere $H_2/N_2 = 1/5$ and held (melted) for 30 min. After that, they were cooled to room temperature at a rate of 10 K/min. The resulting glasses were observed by a scanning electron microscope (SEM) and an optical microscope (OM), and the shape factors of the glass particles were obtained.

Figure 1 schematically illustrates the diagram of the setup of the SIL microscope. The prepared glass μ-SIL with 15-μm radius was used. A Hg lamp was used as a light source for the illumination of the object. The objective lens with a numerical aperture NA = 0.45 and a band-pass filter of the F-line (the center wavelength of the window is 486 nm and its width is ∼ 20 nm) were used as optics. Around 486 nm, the Hg lamp emits light with a continuous broad spectrum. An integrated circuit (IC) chip and a photolithography mask were used for the testing of μ-SIL resolution. The surface morphology of the IC chip was scanned by the SEM and an atomic force microscope (AFM) in advance. A μ-SIL was placed on these objects and the images through the μ-SIL were recorded by a CCD camera.

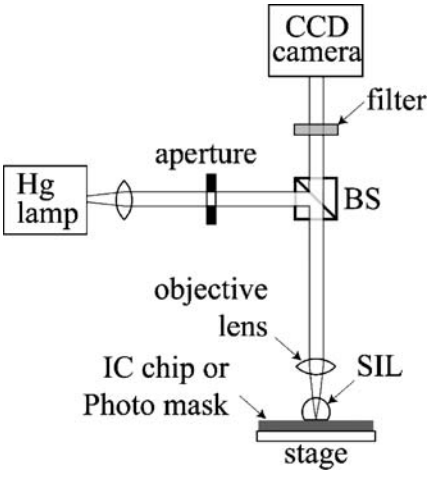

FIGURE 1 Schematic illustration of optics for the observation of an IC chip or photolithography mask through the fabricated μ-SIL. BS: beam splitter

3 Results and discussion

Figure 2 shows a SEM image of the typical glass particles with the size of about 30 μm. All of the glass particles became super-spherical as shown in Fig. 2a, and their optical transparency was confirmed by the OM. Their shapes commonly consist of a curved surface and a flat one. The curved surface is very smooth and has high sphericity. The aspheric errors $|b|$ measured from SEM images of several glass particles with the size around 30 μm ranged from 105 to 257 nm, and were comparable with the value shown in Sect. 2. The flat surface was formed at the bottom by the contact of the glass melt with the g-c substrate. Thus, the degree of smoothness of the bottom surface of the μ-SIL was shaped by the substrate it contacts.

Figure 2b illustrates a droplet of the glass melt on the g-c substrate. At high temperature, glass becomes a viscous 'liquid' and has a high surface tension. On a g-c substrate, the forces of the surface tension are balanced at high temperature according to Young–Dupre's equation [8, 9]. High sphericity of the curved surface reveals that the asphericity due to gravity is small, and the surface tension of the melt decides the shape of the droplet in the micrometer-size region.

Figure 3 shows the relationship between the refractive index n and the contact angle θ. The inset figure is the plot of the contact angle θ; the θ values were

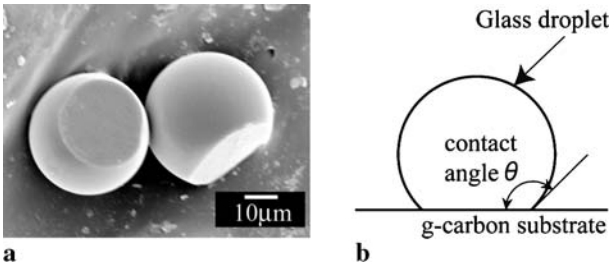

FIGURE 2 An example of a SEM photograph of μ-SILs prepared on a g-carbon substrate with $Ra = 3.8$ nm (**a**), and the schematic illustration of the glass droplet on a g-carbon substrate (**b**)

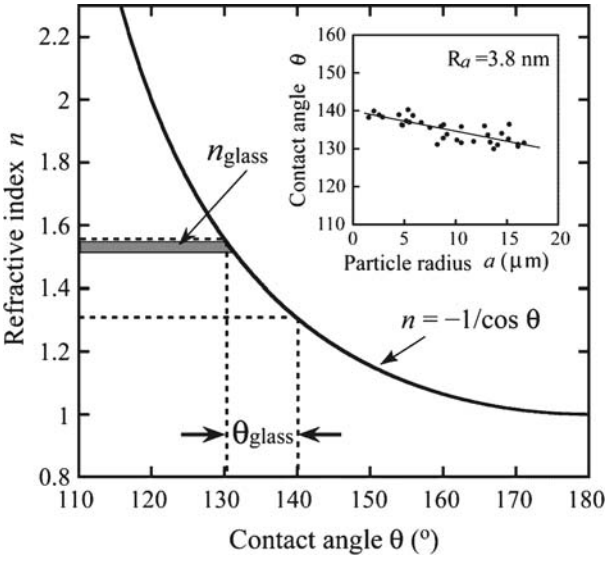

FIGURE 3 The theoretical relationship between contact angle θ and the refractive index n for a SIL. The *inset* is a plot of the contact angle θ against the particle radius a of the prepared SILs on the g-c substrate with $Ra = 3.8$ nm. The *line* was drawn as a guide for the eyes only. θ_{glass} and n_{glass} represent the range of the contact angle θ of the obtained SILs and the variation of the refractive index n of soda-lime–silica glass in the visible-wavelength region, respectively

measured directly from SEM images (side view) or calculated using the size of the flat circular bottom surface of the glass particles against a and the a values were measured from the spherical part. The contact angle θ was within a range of 130–140° and decreased gradually with increasing a.

A SIL is required to have the characteristic dimension to realize its optical function. As shown in Fig. 3, n and θ must satisfy the theoretical relation

$$n = -1/\cos\theta. \tag{4}$$

The SIL of soda-lime–silica glass ($n_d = 1.515$) has to have $\theta = 131°$. The obtained glass particles with 15-μm radius are found to satisfy this relation well. According to (2), the thickness error of this particular particle is estimated to be $|d| < 195$ nm, which corresponds to the error $< \pm 1°$ in θ. There is still the scatter of θ (in other word, the scatter of thickness) due to the homogeneity of glass, but it is indicated that this simple process is able to give a reasonably good shape and a small variance of thickness to all of the prepared SILs.

On the other hand, the angle θ of the SIL prepared on a g-c substrate with $Ra = 11$ nm was 140° for $a = 15$ μm, which is 9° larger than that of the SIL prepared on a g-c substrate with $Ra = 3.8$ nm. The interfacial energy between glass melt and substrate is dependent on the grade of the substrate. Therefore, the grade of the substrate roughness can become another control factor to determine the SIL shape according to Wenzel's equation [10]:

$$\cos\theta_W = r_W \cos\theta, \tag{5}$$

where θ_W and r_W are the apparent contact angle and the ratio of the actual contact surface area to the apparent one, respectively.

Figure 4a and b show the images of an IC chip surface by the SEM and the atomic force microscope (AFM), respectively. An IC chip has stripe textures; the thinnest one has a width of about 1.2 μm. In Fig. 4c, the cross-section profile along the white line in Fig. 4b is shown. The respective stripe is found to have fine uneven structures about 20 nm in depth on the top surface.

In Fig. 5a, a μ-SIL on an IC chip is shown. The stripes of the IC chip surface are clearly observed. Figure 5b shows the image obtained by focusing the IC chip surface through the μ-SIL. The size of the view field was about 5-μm diameter, and the stripe textures of the IC chip surface are clearly seen. The most important is the appearance of the shaded line in the respective stripe. These shaded stripes are the uneven surface structures on the strips found in an AFM image. This reveals that the μ-SIL succeeds in visualizing quite fine uneven structures about 20 nm in depth. The incident light surely forms the evanescent field at the bottom surface, and detects the structures much smaller than the wavelength of the incident light. The effective view field was calculated as $2r < 3.8$ μm from (3), and agrees well with the image in Fig. 5.

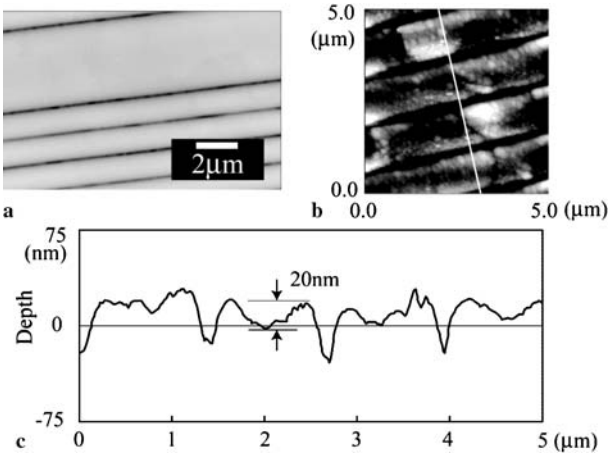

FIGURE 4 (**a**) SEM and (**b**) AFM observation results of IC chip surface. The cross-section profile of the *white line* in the AFM image is shown in (**c**)

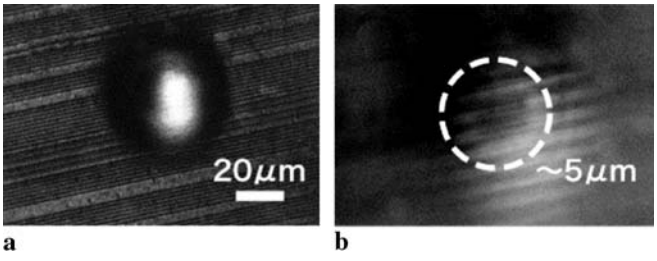

FIGURE 5 (**a**) A μ-SIL placed on an IC chip, (**b**) an image of the IC chip surface through the μ-SIL. The *broken circle* shows the view field with about 5-μm diameter. The *shaded stripes* show the fine uneven textures on stripe structures of the IC chip observed by AFM (Fig. 4b)

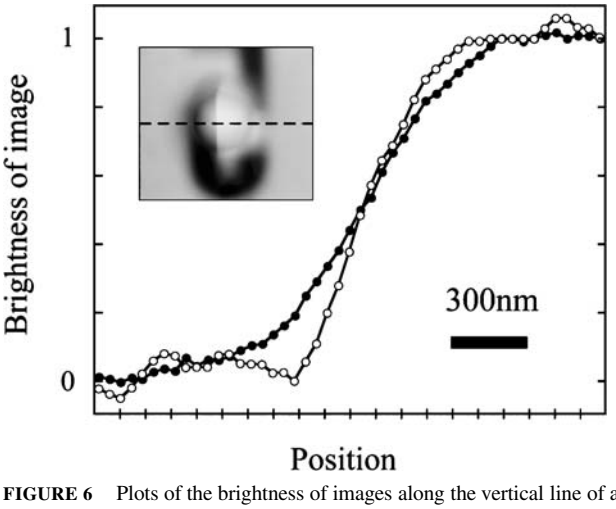

FIGURE 6 Plots of the brightness of images along the vertical line of an edge in the lithography mask using a SIL (*open circles*) and without the SIL (*closed circles*). The *inset* is the image of the edge through the prepared SIL

Finally, the horizontal resolution of this μ-SIL was examined. Figure 6 shows the image of the border line of the photolithography mask through the μ-SIL, and the brightness of the image on the broken line was plotted (open circles). Compared with the plots showing the brightness of the image without the μ-SIL (closed circles), about 1.8 times higher horizontal spatial resolution was obtained using the μ-SIL. This value does not reach the theoretical improvement, $n^2 (= 2.3)$, but is considerably higher than $n (= 1.515)$, indicating that the obtained glass particles have a great potential to be SIL devices to attain super-resolution. The large bandwidth of the band-pass filter used in front of the CCD camera and the residuals of the errors on the SIL shape would be the reasons why the resolution did not reach the theoretical improvement of the spatial resolution. The utilization of a light source with a narrow line width, like a laser, and more homogeneous glass samples would be preferable to attain larger optical resolution than this examination. The optimization of SIL shape, especially the thickness, would be effective to improve the spatial resolution, because many parameters, like particle size, *Ra* of the substrate, and the glass composition, are available to control the thickness precisely.

The most important finding in this study is the simple mass-preparation process of small SILs, because it does not require the polishing process with the precision less than a micrometer, but uses the natural force balance of the glass melts to satisfy the SIL dimension via self-regulation. The mechanics of surface and interfacial tensions of liquid and solid decide the shape factors of the SIL. The optimization of the materials and substrate, for example, would result in a high yield of the fabrication of this functional μ-SIL. Although the μ-SIL has a small view field of about 5 μm, it has a suitable dimension to be built on pick-up devices like the slider arm of data storage, for instance. The improvement of the index n of a μ-SIL and the size control should be considered further. Glass with $n > 2.0$ would promise $\mathrm{NA} > 1.2$ theoretically. The wetting condition of such glass melts should be controlled to have the contact angle $\theta \sim 120°$. The choice of the appropriate glass materials and substrate materials would be one of the best ways to give a suitable super-spherical shape via this simple fabrication process.

4 Conclusions

A micrometer-size super-spherical solid immersion lens (μ-SIL) of glass was prepared by a simple method using wetting properties of a glass melt. The glass μ-SIL works as evanescent-field optics to visualize fine uneven structures about 20 nm in depth on an IC chip and shows 1.8 times higher horizontal resolution.

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