TILTED PARABOLOIDAL REFLECTIVE LENS FOR FAR INFRARED SENSOR FABRICATED BY MASK WITH RECTANGULAR OPENINGS

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ABSTRACT

A tilted paraboloidal reflective lens for focusing far infrared (FIR) rays has been devised. Tilted paraboloids with smooth surface and vertical walls were fabricated by two-step etching using microloading effect with a mask which had rectangular openings of various sizes. FIR light was focused by a 30-degree-tilted paraboloid lens. The size of a real image of an FIR source was 110 μm, which agrees with a lens formula.

INTRODUCTION

FIR sensors (i.e. temperature sensors) are widely used for many applications, such as detecting human in security systems, measuring temperature of a food in a kitchen utensil. In general, a thermography, a commonly used FIR imager, has been expensive because lenses for FIR have been made of material like germanium that is difficult to be machined. Reflective lenses can reduce the cost of FIR imagers, because any material can be used as a lens as long as it is coated some metal (such as gold and aluminum), which have high-reflectivity for FIR.

A paraboloid can focus rays that are parallel to the central axis of the paraboloid (Figure 1A). But the paraboloid can not focus rays from a certain angle (Figure 1B). When the central axis of a paraboloid is tilted and parallel to an incident angle of FIR, the rays are focused at the focal point of the paraboloid (Figure 1D).

The tilted paraboloids must have (1) depth varying in two independent directions, (2) smooth surface, and (3) vertical walls. Vertical walls are needed to densely arrange lenses. By assembling the lens array to some FIR sensor array, a high-sensitive and directional FIR sensor can be achieved.

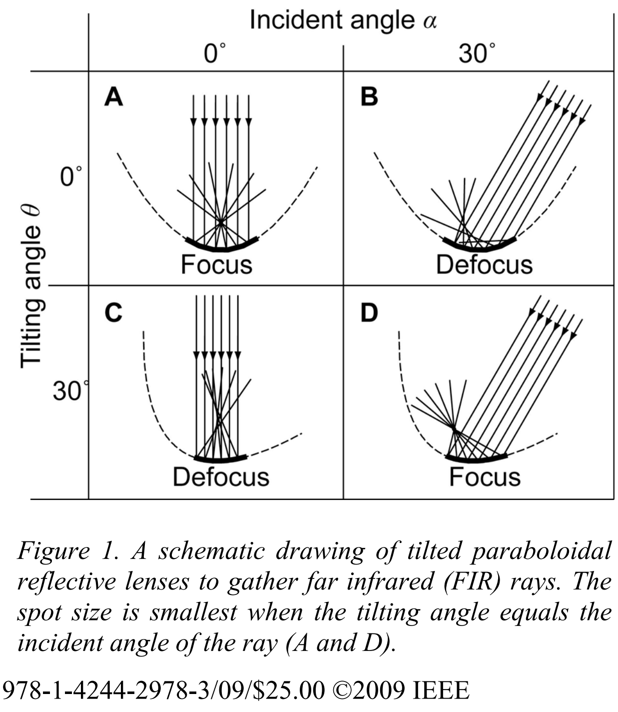

Figure 1. A schematic drawing of tilted paraboloidal reflective lenses to gather far infrared (FIR) rays. The spot size is smallest when the tilting angle equals the incident angle of the ray (A and D).

In a past research [1], two-step silicon etching was employed to fabricate a paraboloid lens array; the first step was anisotropic etching and the second was isotropic etching. However, tilted paraboloids can not been achieved by that method, because one mask opening corresponds one paraboloid. Arbitrary structures, whose depth varies in two directions, can be fabricated using microloading effect [2, 3] or grayscale mask [4, 5]. In the grayscale mask method, three dimensional resist profiles are transferred to silicon by a reactive ion etching. A disadvantage of that method is rough surface, because it is difficult to control the etching selectivity of silicon and the resist. Microloading effect is used in this paper.

A three-dimensional structure that was fabricated by two-step isotropic etching using a mask with circular openings arranged at even intervals had an arbitrary shape and a smooth surface [2]. However vertical walls can not be fabricated by that way. In [3], vertical walls were available using ICP-RIE at first etching. The width of the mask was constant for a smooth surface, but the depth

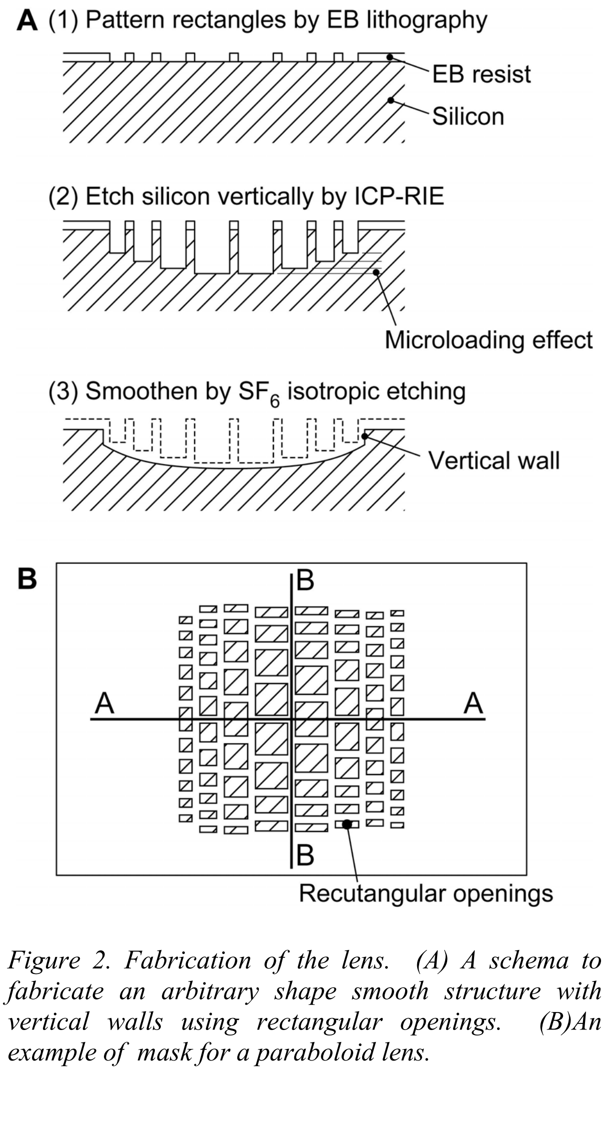

Figure 2. Fabrication of the lens. (A) A schema to fabricate an arbitrary shape smooth structure with vertical walls using rectangular openings. (B)An example of mask for a paraboloid lens.

varied only in one direction because the mask had only square openings.

In this paper, two-step etching that consists of ICP-RIE, for which a mask with rectangular openings and constant width was used, and another smoothing etching satisfied abovementioned three requirements.

FABRICATION

The lenses were fabricated by following steps (Figure 2A). An electron beam (EB) resist layer on a silicon wafer was patterned by EB lithography. Then, the silicon wafer was vertically etched by ICP-RIE to depths according to the areas and the shapes of mask openings. Trenches with different depths were formed. Finally, the surface was smoothed by removing sidewalls of trenches using isotropic RIE.

The etched depth depends on the area of openings (Figure 3(a)). The thinner the mask width between the openings is, the smoother the resulting surface is. The mask width was fixed to 200 nm. Adopting rectangular openings enabled an arbitrary shape though the mask width was fixed.

The mask design procedure is as follows. Firstly, a width of rectangles on a certain line (along B-B direction in Figure 2(b)) is determined corresponding to the average depth on the line according to the relationship shown in Figure 3(a). Then, the other side length of the rectangle is calculated from depth of that point. The eventual etched depth varies with the aspect ratios of the rectangles, which is the ratio of the short side to the long side (Figure 3(b)).

A lens array that has 5 tilted paraboloid lenses was fabricated (Figure 4). The tilting angle was from 0° to 60° by 15°. The lenses ware 200 µm in width and placed at 220 µm intervals. The shapes of the fabricated lenses were measured with a laser microscope (Figure 5). The profile along A-A agrees with the designed one. The profile along B-B is slightly different at edges, because the aspect ratios of the rectangles at the edges are so small that the etched surface got shallow due to the effect shown in Figure 3(b). The arithmetic surface roughness was about 100 nm, which was smooth enough for FIR lens, because it was 1% of the wavelength of FIR (~10 µm).

EXPERIMENTS

Since silicon is transparent in FIR, the surface of the lenses should be coated by a metal film to enhance reflectance. The reflectance as a function of thickness of a metal film was measured using an FIR source (Helioworks Inc., KE-8523) and an FIR camera (Wuhan Guide Infrared Co., Ltd., GUIDIR IR106) (Figure 6). The incident angle

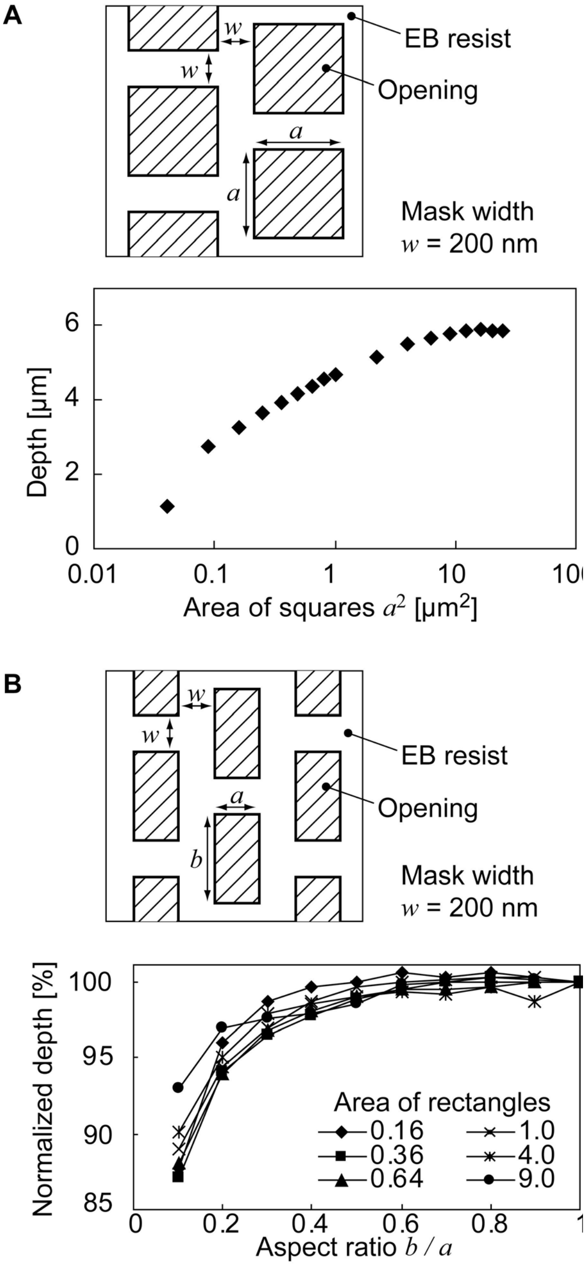

Figure 3. Relationship between etched depth and shape of openings. (a) Etched depth as a function of area of square openings. As the area gets larger, the depth increases as the area increases due to a microloading effect. (b) Effect of aspect ratio on the etched depth, which was normalized by the depth of a square opening (i.e. the depth when the aspect ratio was 1).

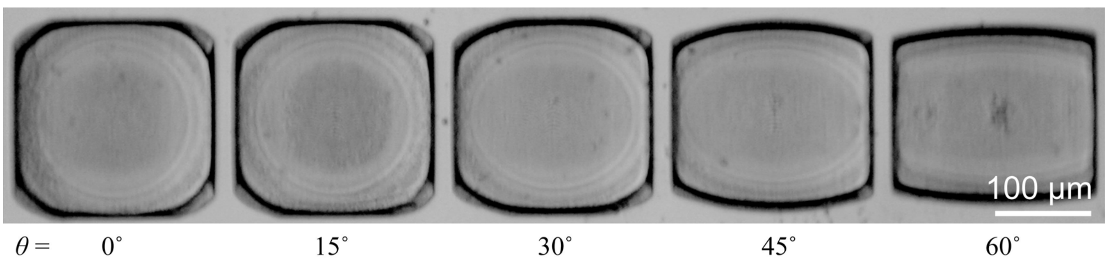

Figure 4.A photograph of lenses. The tilted angle was from 0° to 60° by 15°.

from an FIR source was 45°. Reflected power was measured with an FIR camera. The reflectance of aluminum was larger than that of gold when the film was thicker. The reflectance of 40-nm-thick aluminum was 80%.

A real image of an FIR source focused by a lens tilted by 30° and coated by 50-nm-thick aluminum was observed with the FIR source and the FIR camera (Figure 7 and 8). The incident angle was 30°, which is same as the tilting angle of the lens under test. The size of a focal spot was 110 µm. The power at the center of the spot was 8 times larger than that at the background. The size of the source was 7 mm, the distance between the source and the lens was 85 mm, and the distance between the lens and the spot was 1.2 mm, the spot size and the focal length calculated from a lens formulas were 100 µm and 1.18 mm, respectively. These results show that the lens was useful for focusing FIR.

CONCLUSION

Tilted paraboloidal reflective lenses have been devised. The lenses were fabricated by two-step etching using microloading effect. The mask had rectangular openings and a constant width. An arithmetic surface roughness of the fabricated lens was about 100 nm, which was smooth enough for FIR. FIR was focused by a 30-degree-tilted lens. The focal length of the lens and the size of a real image of an FIR source agree with theoretical predictions. The power at the spot center was 8 times larger than that at the background.

ACKNOWLEDGEMENTS

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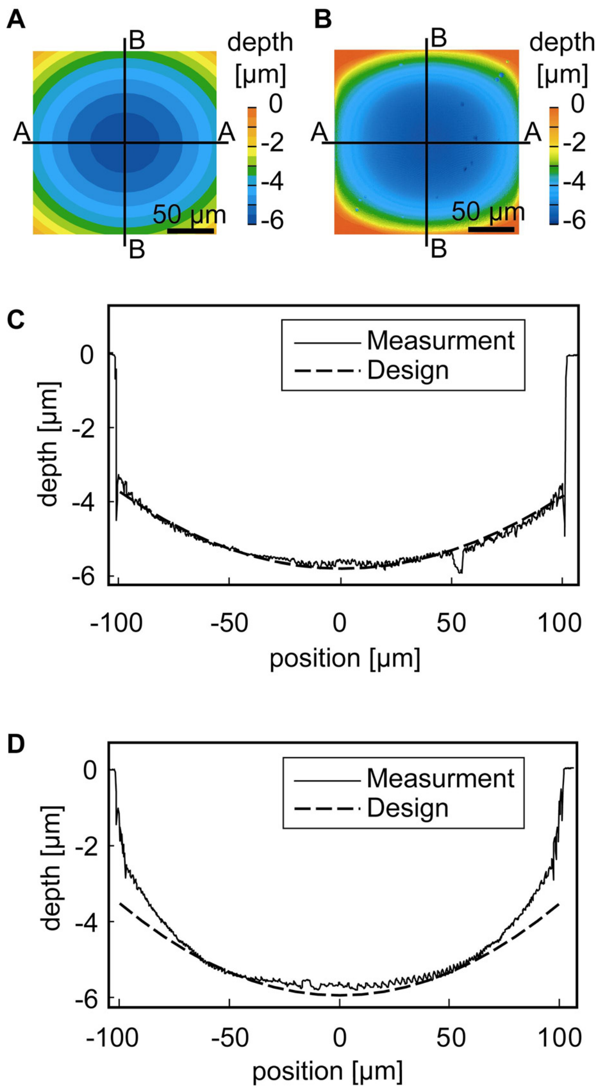

Figure 5. Shapes of a 30°-tilted lens measured with a laser microscope. (a) A contour plot of designed shape. (b) A contour plot of measured shape. (c) A-A profile of a lens that is tilted by 30° in A-A direction. (d) B-B profile of the same lens.

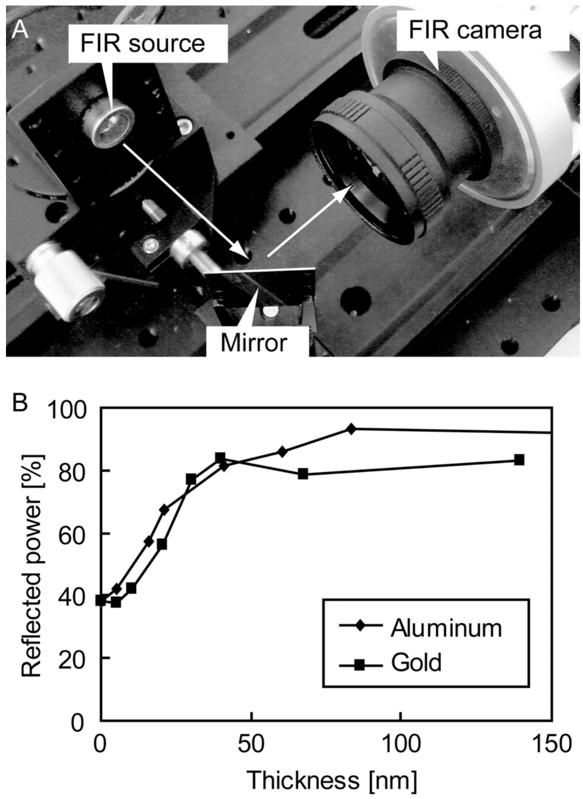

Figure 6. FIR reflectance as a function of thickness of metal films deposited on a silicon wafer. The incident angle was 45°. The power of reflected FIR rays was measured by FIR camera.

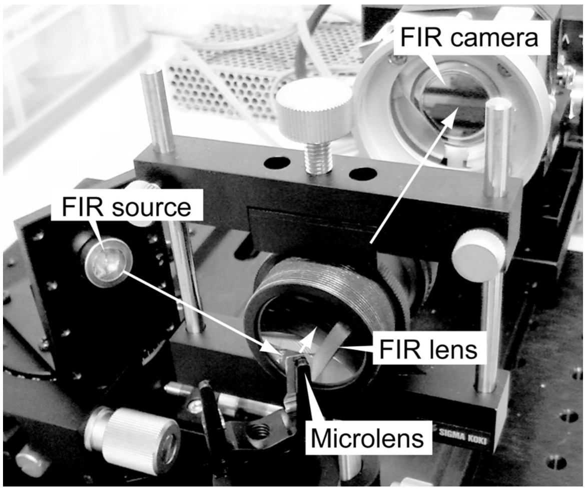

Figure 7. A photograph of experimental setup. The incident angle was 30°.

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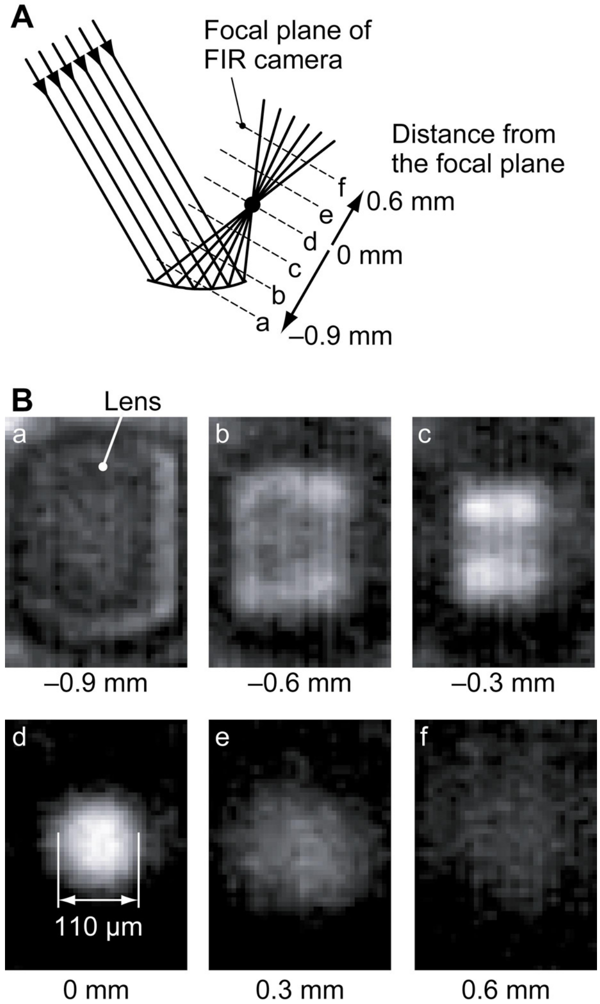

Figure 8. FIR images of a spot by the lens. The diameter of the spot was about 90 µm. The lens can be seen in (a), and a real image of the FIR source by the lens can be seen in (d).