Fabrication of a 100% fill-factor silicon microlens array

Yan Jianhua(闫建华)†, Ou Wen(欧文), and Ou Yi(欧毅)

Institute of Microelectronics, Chinese Academy of Sciences, Beijing100029, China

Abstract: A simple method has been developed for the fabrication of a silicon microlens array with a 100% fill factor and a smooth configuration. The microlens array is fabricated by using the processes of photoresist (SU8-2005) spin coating, thermal reflow, thermal treatment and reactive ion etching (RIE). First, a photoresist microlens array on a single-polished silicon substrate is fabricated by both thermal reflow and thermal treatment technologies. A typical microlens has a square bottom with size of 25 μm, and the distance between every two adjacent microlenses is 5 μm. Secondly, the photoresist microlens array is transferred to the silicon substrate by RIE to fabricate the silicon microlens array. Experimental results reveal that the silicon microlens array could be formed by adjusting the quantities of the reactive ion gases of SF_6 and O_2 to proper values. In this paper, the quantities of SF_6 and O_2 are 60 sccm and 50 sccm, respectively, the corresponding etch ratio of the photoresist and the silicon substrate is 1 to1.44. The bottom size and height of a typical silicon microlens are 30.1 μm and 3 μm, respectively. The focal lengths of the microlenses ranged from 15.4 to 16.6 μm.

Key words: thermal reflow; microlens array; RIE; SU8-2005 photoresist

DOI: 10.1088/1674-4926/33/3/034008 **PACC:** 4278C; 4280A

1. Introduction

The micro opto electro mechanical system (MOEMS) has many applications, such as detectors and emitters to boost optical efficiency. Also, a two-dimensional microlens array is likely to be combined with other microoptical structures to play an important role in optical sensor arrays, projection systems, biomedical systems, and optical interconnection. In particular, microlevels offer several features, including significantly reduced wavelength sensitivity compared to conventional microlenses, the possibility of realizing large numerical apertures, and, generally, high focusing efficiency[1, 2]. At present, various microlens fabrication methods such as thermal reflow forming[3, 4], the stereolithography technique[5, 6], and the hot embossing process[7] have been developed. The microlens has been fabricated from a few tens of microns to perhaps a few hundreds of microns in size. These fabrication techniques for microlens arrays are used both in order to reduce the cost and improve the characteristic of optical and mechanical properties. However, the fill factor of a microlens is a major engineering challenge, because it is difficult to fabricate a 100% fill-factor microlens array.

In this paper, we present a detailed process for fabricating a silicon microlens array with 100% fill factor and smooth configuration, and reveal the requirements for manufacturing the photoresist microlens array with thermal reflow technology and forming the silicon microlens array with RIE technology.

2. Fabrication process

To fabricate the silicon microlens array with 100% fill factor, a detailed process flow is shown in Fig. 1. Single-polished silicon is used as substrate. First, 1.17-μm-thick of SU8-2005 photoresist is spin-coated on the substrate, then the photoresist is patterned by photolithography to form a cubic photoresist array, in which a typical one has a bottom size of 25 μm [Fig. 1(a)], the distance between every two adjacent cubic photoresist is 5 μm. Secondly, the photoresist microlens array is fabricated by thermal reflow and thermal treatment[8] technologies, as shown in Figs. 1(b) and 1(c). The time-temperature graphs of the thermal reflow and thermal treatment are shown in Fig. 2(a). Experimental results show that different heating rates, cooling rates and heating temperatures have different effects on the vector height of the microlens. First of all, the vector height of the microlens increases as heating rate increases, as shown in Fig. 2(b). Besides, a rapid cooling could change the original convex microlens due to the effect of pressure variation, as shown in Fig. 2(c), or it could cause many cracks in the photoresist microlens because the coefficient of thermal expansion of the basic photoresist is high [$(10–80)\times10^{-6}$ ℃$^{-1}$]. Lastly, the vector height of the microlens has the maximum value at the temperature of 250 ℃. Consequently, in this paper, the heating rate, the cooling rate and the heating temperature are 10.5 ℃/min, 2.5 ℃/min and 250 ℃, respectively. After

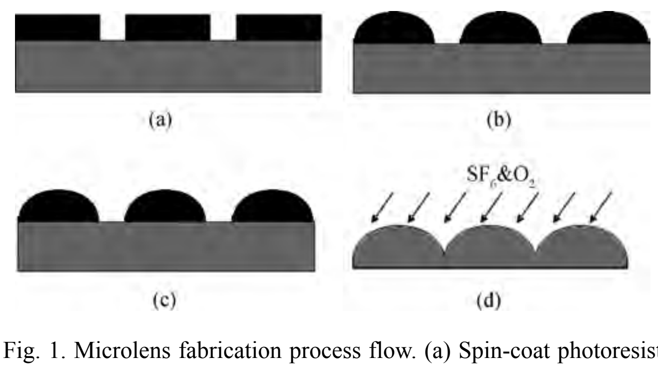

Fig. 1. Microlens fabrication process flow. (a) Spin-coat photoresist and photolithography. (b) Thermal reflow. (c) Thermal treatment. (d) Pattern transfer.

† Corresponding author. Email: terryyan0@gmail.com
Received 25 August 2011, revised manuscript received 30 October 2011

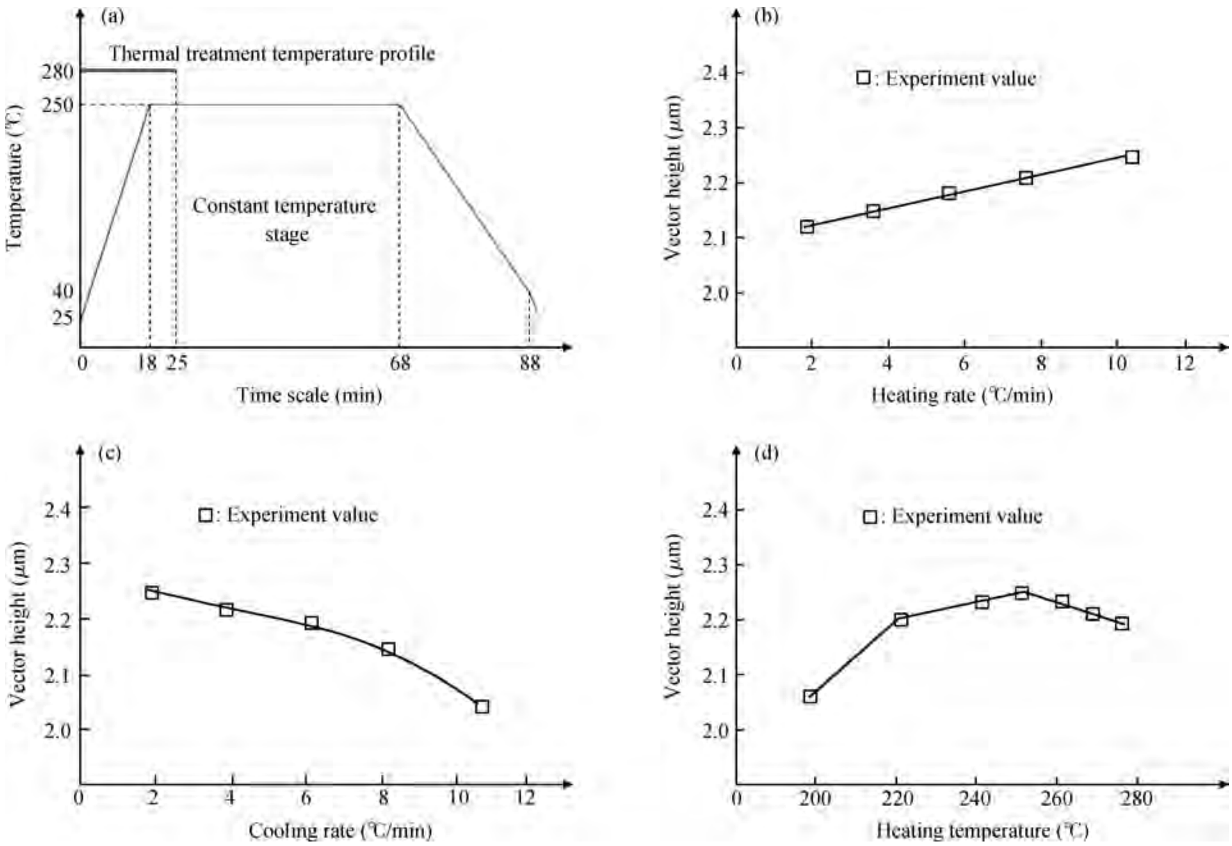

Fig. 2. (a) Time–temperature curve of thermal reflow and treatment. (b) Effect of different heating rates on the vector height of the microlens. (c) Effect of different cooling rates on the vector height of the microlens. (d) Effect of different heating temperatures on the vector height of the microlens.

thermal reflow, the microlens array is placed into an incubator with a temperature of 280 ℃ for its reparation to form a new microlens array with a smaller surface roughness (Ra), this process is called thermal treatment. Thirdly, the silicon microlens array is fabricated with 100% fill-factor by RIE transfer technology. Under the conditions including pressure of 130 mTorr and power of 80 W, in this paper, the quantities of the reactive ion gases of SF_6 and O_2 are 60 sccm and 50 sccm, respectively. Results show that the etch rates of the SU8 photoresist and the silicon substrate are 0.78 μm/min and 1.12 μm/min, respectively, the etch ratio is 1 to 1.44. There are two main factors that are helpful for the fabrication of a 100% fill-factor microlens array. First, the reactive ions have an anisotropic nature, and the direction of the iron diffusion is not always perpendicular to the substrate when the pressure is relatively low. Secondly, the different etch ratios cause the etch rate of the silicon substrate to be larger than that of the photoresist microlens. Thereby, a series of continuous silicon microlenses are fabricated, as shown in Fig. 1(d).

3. Results and discussion

3.1. Relationship between vector height of the silicon microlens and the quantities of SF_6 and O_2

Experimental results reveal that different compositions of SF_6 and O_2 affect the vector height and configuration of the silicon microlenses during the RIE process. In addition, different silicon spherical microlens arrays with a wide variety of vector heights (2–9 μm) could be fabricated by adjusting the quantities of SF_6 and O_2. The larger the amount of SF_6 is, the higher the silicon microlens will be; whereas, the larger amount of O_2 is, the lower the silicon microlens will be. The reason is that SF_6 is the main reactive etch gas for silicon substrate, while O_2 is the main reactive etch gas for SU8-2005 photoresists.

However, under the preconditions that the pressure and power are constant values of 130 mTorr and 80 W, respectively, when fixing the quantity of SF_6 to 60 sccm, results show that the silicon microlenses have sunken profiles if the amount of O_2 is lower than 40 sccm. The reason would be that the gas of SF_6 has an isotropic nature and the diffusion irons of SF_6 will etch the silicon under the photoresist microlens if the quantity of O_2 is too low. Experiments show that the best compositions of SF_6 and O_2 are 60 sccm and 50 sccm, respectively.

3.2. Silicon microlens array forming

The SEM image of the photoresist microlens array fabricated by thermal reflow and RIE transfer technologies are shown in Fig. 3. The cubic photoresist array, with vector height and bottom size of 1.17 μm and 25 μm, respectively, is formed by lithography. As shown in Fig. 3(a), the distance between every two adjacent microlenses is 5 μm. Figure 3(b) shows the top-view image of the photoresist microlens array, whose outline profiles is shown in Fig. 3(c). The x-coordinate unit is μm, and the y-coordinate unit is Å. The parameters of the

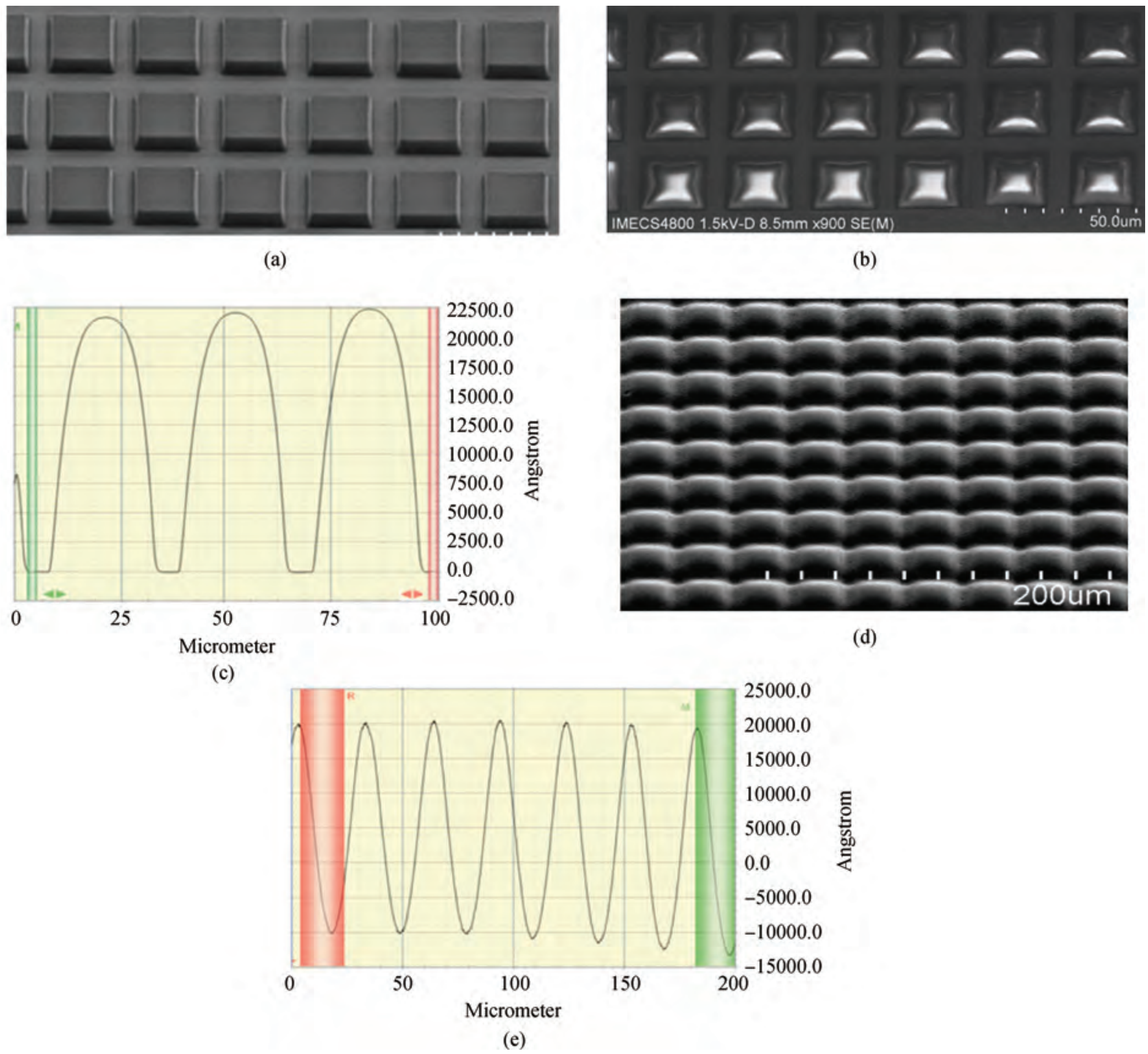

Fig. 3. (a) Form cubic photoresist by lithography. (b) Top view of the photoresist microlens array. (c) Outline profiles of the photoresist microlens array. (d) Top view of the silicon microlens array. (e) Outline profiles of the silicon microlens array.

photoresist microlens such as bottom size and vector height are measured, and their values are 30.1 μm and 2.25 μm, respectively. According to the equal volume theory, the height of the photoresist microlens should be 2.34 μm after thermal reflow, but the height of the silicon microlens is smaller. The reason would be that the photoresist is heated to evaporation. Figure 3(d) shows the top-view image of the silicon microlens array and its outline profile is shown in Fig. 3(e). In the experiment, the etch time is 180 s. The vector height of the silicon microlens is about 3 μm, which is larger than that of the photoresist microlens because of the different etch ratio between the SU8-2005 photoresist and the silicon substrate.

3.3. Optical properties measurement

The experimental results for a typical silicon microlens array with 100% fill factor are shown in Fig. 4. A cross-section of a typical silicon microlens is shown in Fig. 4(a), and its surface profile measured by noncontact interferometric profilometry is shown in Fig. 4(b). The graphs show that the microlens with height of 3.0 μm has a smooth surface. The roughness measured by the step-meter is less than 30 nm, which is an excellent surface property for optical application.

The focal lengths of microlenses measured by using a refractive optical microscope ranged from 15.4 to 16.6 μm. The general form of the focal length is:

$$f = \frac{r}{n-1}, \tag{1}$$

where r is the radius of the microlens, and n is the index of refraction of silicon. According to the equal volume theory of a spherical ball, the radius of the microlens can be written as:

$$r = \frac{L^2}{8h} + \frac{h}{2}, \tag{2}$$

where L is the bottom size, and h is the vector height of the microlens. Combining Eqs. (1) and (2), and setting $L = 30$ μm and $h = 3$ μm, we can get that the theoretical value of focal length is 16.2 μm. Thereby the measured focal length of the microlens is within the error range.

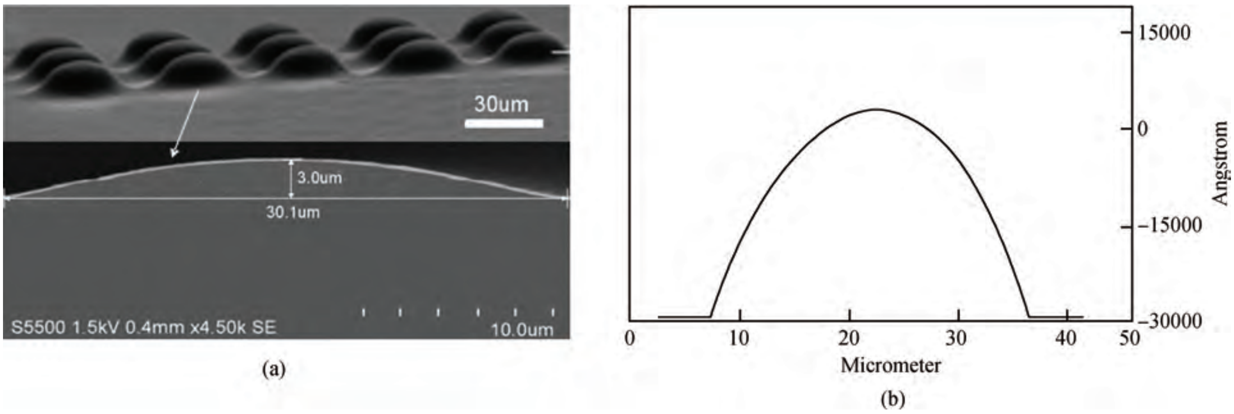

Fig. 4. (a) SEM image of the microlens array and cross-section of a typical silicon microlens. (b) Outline profiles of the silicon microlens.

4. Conclusion

We have successfully demonstrated a method which includes thermal reflow, thermal treatment and pattern transfer, to fabricate a silicon microlens array with 100% fill factor and a smooth surface. The dominant factor in fabricating a microlens array is the etch ratio between the photoresist and the silicon. The surface property of the microlens array is characterized, presenting smooth profiles with a uniform serial of focuses that range from 15.4 to 16.6 μm.

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