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INFRARED MICROLENS ARRAYS BASED ON CHALCOGENIDE PHOTORESIST, FABRICATED BY THERMAL REFLOW PROCESS

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A maximum sag limited to 1.3 μm is achieved when using chalcogenide glassy (ChG) films of the As-S or As-Se systems for fabrication of IR microlens arrays applying the modified proximity method, the gray scale, or continuous tone photolithography with classical UV exposure sources. Using the thermal reflow method one can extend this range. For realization of this method, a new photoresist material based on a modification of the ChG film structure by the introduction of iodine atoms was developed. An $AsSeI_{0.1}$ composition was selected as the optimum material giving a significant decrease in melting temperature, without appreciable loss of photosensitive properties. AFM measurements of $AsSeI_{0.1}$ microlenses produced by the thermal reflow method were performed during the reflow process. The gain in the maximum sag of the microlens compared with the modified proximity method and gray scale or continuous tone lithography is about two times.

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1. Introduction

Microlenses and microlens arrays can be found in an increasing number of optoelectronic applications, such as optical communication and computing, CCD cameras, faxes, imaging systems and IR technology [1-4]. Microlens arrays have been fabricated by a variety of techniques, including distributed index planar techniques [5], resin thermal reflow [6] and laser beam ablation [7]. The most common and widely used technique is photolithography in which the photosensitive material that is deposited on the substrate is exposed through a mask by tailored light distribution. Usually 3D-structures having the form of the microlens arrays are generated into a photoresist material [6,8], and then transferred by anisotropic etching into a robust material [9], transparent in the spectral range for which the microlens arrays are intended. Anisotropic etching is not a very simple process, therefore, its elimination would be very desirable in microlens fabrication.

Recently, a new technology for fabrication of microlens arrays for the IR was proposed which has the potential to eliminate this process step [10-13]. This technology is based on the use of chalcogenide glasses that are simultaneously effective photoresists and very good IR optical materials [14-16]. ChG photoresists have many advantages, such as very high resolution, photosensitivity in a wide spectral range, high values of refractive index, transparency in the IR range, and the ability to be used as positive or negative resists depending on the developer used [11,12,15]. These unique properties create new possibilities for the development of microlens arrays for IR-applications.

The method proposed is essentially the direct one-step formation of a 3D microlens array using dependence of the etching rate on the illumination intensity typical of chalcogenide photoresists [10-13]. IR microlens arrays were successfully fabricated using the above discussed technique with ChG As-S and As-Se photoresists [10-13]. In spite of many advantages, these

microlens arrays also have some drawbacks. The maximum sag in the microlenses is limited to 1.3 μm when gray scale or continuous tone lithography with classical UV exposure sources is used. The importance of the maximum sag achievable is shown in the Table 1, where S is the sag, ω the width and f the focal length of a cylindrical lens. All the values in the table are in mm, and for the refractive index the value 2.7, typical for the As-Se chalcogenide glasses, was taken. One can see that the focal length can be made much shorter if the sag is increased.

Table 1. Dependence of focal length on the sag value for different cylindrical lens width.

S	1.3	2.0	1.3	2.0	1.3	2.0
ω	10	10	15	15	20	20
f	6.0	4.28	13.1	8.9	23.0	15.3

The reason for the sag limitation is the photodarkening of the ChG film upon exposure. This effect is identified by a decrease in the transmission of the material which accompanies the photoinduced structural transformations in ChG films [17,18]. The photodarkening effect does not present a problem when low sag values are desired (below 1.0 ÷ 1.3 μm) but due to this effect there is a self-limitation process that limits the thickness that can be exposed. Another drawback in previously fabricated microlenses is a not very good shape of the convex surface formed in the direct one-step formation of microlenses.

In order to overcome these drawbacks one can use the thermal reflow method that avoids exposure problems and leads to improvement of the shape of the lenses. Using a binary mask containing holes or slits, islands of 3D binary shape can be formed that can be then transformed to 3D plano-convex microlenses. This is done by heating the material close to the melting point, causing reflow and formation of the desired 3D shape. However for this method a ChG photoresist with a lower melting temperature is necessary, since the working melting temperatures of the binary As-S and As-Se films are too high (above 250 ÷ 290 °C), complicating the fabrication procedure.

2. Properties of three-component ChG photoresists

A new photoresist material with lower melting temperature can be prepared if the ChG structure is modified by introducing iodine atoms. This general tendency was previously known [19], but lowering the melting temperature is accompanied by some loss of photosensitive properties. In our case, it was necessary to keep the photoresist property and to have a high enough photosensitivity (large contrast of dissolution, determined as a ratio of dissolution rates in non-illuminated and illuminated areas of the film).

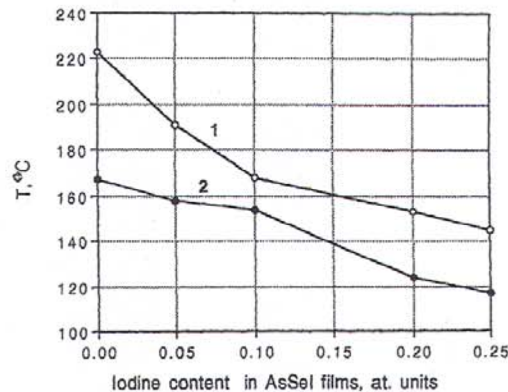

Fig. 1. Dependence of initial melting temperature (1) and softening temperature (2) in AsSeI films on iodine content.

A three-component ChG photoresist material was found that combines a lower melting temperature with high enough photosensitivity. A special method of initial melting temperature measurement was developed (method of sliding down of the chalcogenide glass drop along the sloping wall of the test-tube). The softening temperature was determined by the scratch disappearance method [20,21]. Both values were measured at a heating rate of 10-12 K/min, a rate usually used for relaxation measurements. The dissolution contrast γ values were obtained for a weak polychromatic source of illumination and for He-Ne laser light illumination using the negative selective developer based on monoethanolamine. The results obtained are shown in Figs. 1, 2.

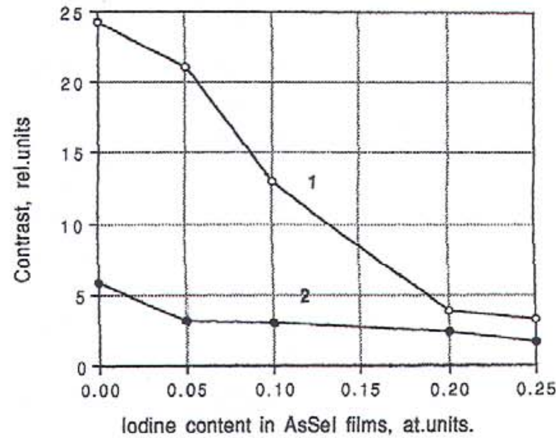

Fig. 2. Dissolution contrast as a function of iodine content in AsSeI films irradiated with He-Ne laser light of 240 mW/cm^2 intensity (1) and with light of 300 W halogen - cycle lamp (2).

Based on these data, the $AsSeI_{0.1}$ composition, a compromise between the improvement due to lower melting temperature and degradation of contrast of dissolution, was selected for microlens arrays fabrication. Some $AsSeI_{0.1}$ photoresist properties (dependences of dissolution contrast on the illuminating light intensity and on the illumination time) important for microlens fabrication, are shown in Figs. 3, 4.

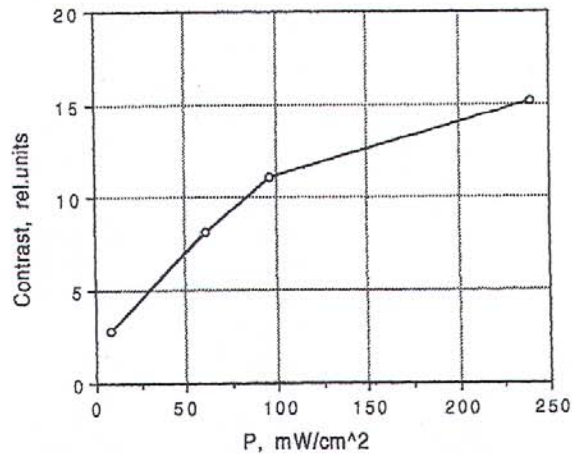

Fig. 3. Dissolution contrast as a function of He-Ne laser light intensity for 0.88 mm thick $AsSeI_{0.1}$ film. Irradiation time 15 min.

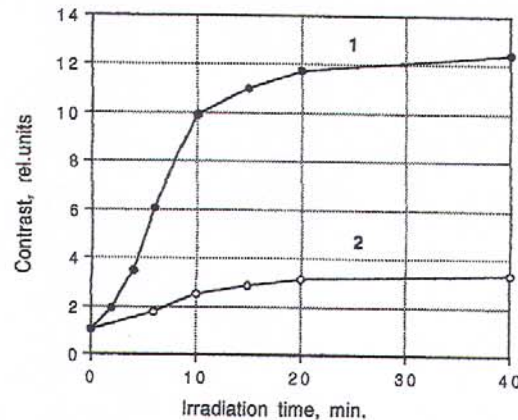

Fig. 4. Dissolution contrast as a function of He-Ne laser light irradiation time for 0.88 mm thick $AsSeI_{0.1}$ film. Light intensity 96 mW/cm^2 (1) and 8 mW/cm^2 (2).

An additional attractive peculiarity of the $AsSeI_{0.1}$ photoresist is its increased elasticity due to iodine atoms that give to chalcogenide glass thermoplastic properties [22]. With increased elasticity it is expected that microlenses fabricated with the $AsSeI_{0.1}$ photoresist will be able to work in a wide temperature range in spite of the large differences of thermal expansion coefficients of chalcogenide glasses and substrate materials.

We investigated the possibility of preparation on the base of the $AsSeI_{0.1}$ photoresist, of microlens arrays capable to work at liquid nitrogen, temperature. For this aim we put down many times in the Dewar vessel with liquid nitrogen, the pirex glass plates covered with AsSe and $AsSeI_{0.1}$ films and, after next heating them to room temperature either in the air atmosphere or in the ethanol, we investigated the process of cracks formation in the film. It was demonstrated that the AsSe films have low thermal-shock resistance because cracks in films were observed after 2-4 thermal-shocks. The $AsSeI_{0.1}$ films were much more stable (40-50 thermal-shocks). Especially good results were obtained when the films were heated in ethanol. In this case, no cracks were observed in the $AsSeI_{0.1}$ films after many thermal cycles.

3. Fabrication and properties of microlenses

An ~820 nm $AsSeI_{0.1}$ photoresist layer was deposited by vacuum thermal evaporation onto an oxide glass substrate. A contact binary photomask containing slits for cylindrical microlenses was used. Samples were exposed using a 200 W halogen lamp and then developed in the negative photoresist mode in a mono-ethanolamine developer for 25 seconds in order to achieve 3D binary shapes. The thermal reflow procedure consisted of step heating of the binary shapes at intervals of 10 °C from 170 °C to 240 °C for 5 minutes at each interval. (The working melting temperature is usually higher than the initial melting temperature shown in Fig. 1). After a short relaxation time, AFM topography measurements tracked the formation of the plane-convex shape. Step heating of this particular sample resulted in lenses, with a gain of 1.4 (from 820 nm in the initial film to 1130 nm sag) with small shrinkage of the initial diameter. Fig. 5 shows the formation of $AsSeI_{0.1}$ cylindrical microlenses made by the thermal reflow method with step heating. However, direct heating to 220 °C resulted in a higher gain (> 2). The measured sag in this case is about 1.9 μm and the base width is 13.7 μm. Thus, higher gain is obtained in a one step treatment. In all cases, the microlenses obtained by the thermal reflow method had a very good convex surface.

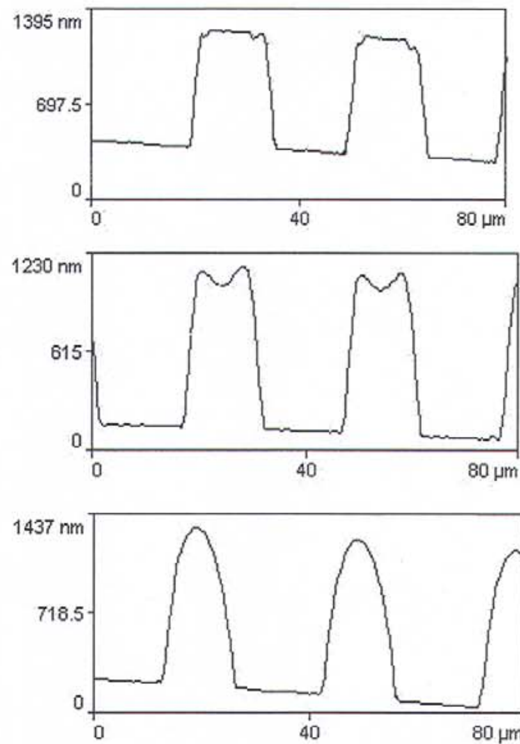

Fig. 5. Profiles of As-Se-I cylindrical microlenses produced by the thermal reflow method with step heating. After initial photolithography (a), after heating to 220 °C (b) and after heating to 240 °C (c).

AFM measurement of $AsSeI_{0.1}$ cylindrical microlenses made by the thermal reflow method at 220 °C are demonstrated in Fig. 6. The cylindrical microlens arrays had the following parameters:

Sag S = 1.89 µm;
Length of single lens: L = 5 000 µm;
Width of single lens: ω = 13.7 µm;
Pitch: 30 µm;
Focal length (λ=0.5 µm): f = 8 µm;
Array size: 50×5 (5 rows with 50 microlenses).

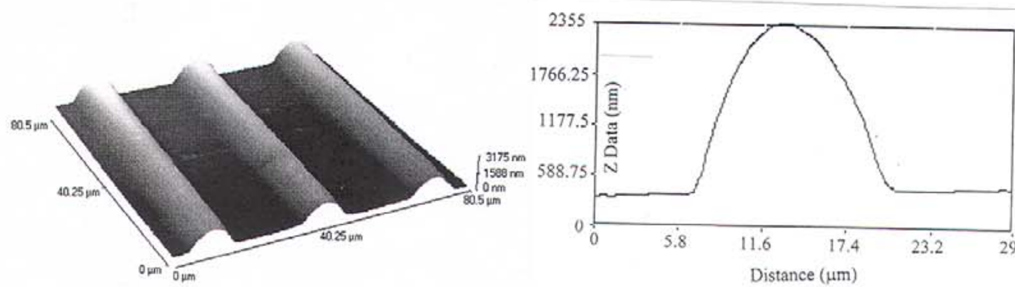

Fig. 6. As-Se-I cylindrical microlenses produced by the thermal reflow method.

4. Conclusions

$AsSeI_{0.1}$ ChG glassy films are shown to be a suitable material for fabrication of IR microlens arrays. Using photolithography and the thermal reflow method, the maximum sag limit caused by the photodarkening effect is partly eliminated. The gain in the maximum sag of the microlens compared with the modified proximity method and gray scale or continuous tone lithography is about 2. A one step thermal treatment was shown to give the best results in the fabrication of cylindrical microlens arrays.

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