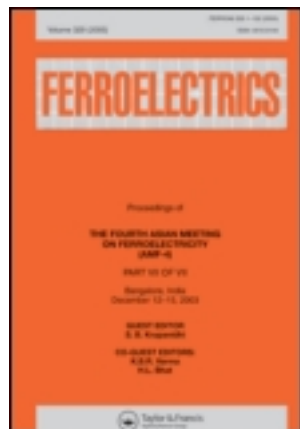


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Effect of Fabrication Parameters on the Characteristics of Fresnel Lens and Piezoelectric Transducers

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A two-mask fabrication process of a four-level Fresnel lens was used to evaluate its characteristics through investigating the effect of SU-8 photoresist on the profile of the focusing lens. A two-step deposition of ZnO films was applied to develop a feasible fabrication of a piezoelectric transducer with the structure Al/ZnO/Pt/Ti/SiO₂/Si under reasonable conditions, which include deposition pressure of 0.7 Pa and 1.3 Pa, RF power of 100 W and 178 W, and sputtering gas ratio Ar:O₂ = 1:3 and 1:1 for first and second step deposition, respectively. Highly c-axis textured ZnO films were successfully obtained through two-step deposition process.

Keywords Fresnel lens; piezoelectric transducer; ultrasonic focusing ejector; Zinc oxide (ZnO); sputtering

1. Introduction

An ultrasonic focusing lens and a piezoelectric transducer are the key components constructing an ultrasonic focusing ejector [1–6], which is capable of ejecting small droplets of controlled diameter from a free liquid surface by focusing high-frequency acoustic waves without using a nozzle. Among the ultrasonic focusing lenses, which were investigated and fabricated, such as a spherical lens, a reflection wall, a Fresnel lens [7–9], a self-focusing acoustic-wave liquid ejector [10], and a new type of lens using an air chamber as an acoustic reflector [11], Fresnel lenses offer advantages of planar geometry and relative ease of fabrication over other forms of lenses, but the geometry is critical for efficient focusing, and thus tight control of the thickness of lens elements is usually required. Therefore, the design and fabrication of “binary” acoustic Fresnel lenses, which use multiple-phase levels

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to approximate the curvature of a spherical focusing field and offer high efficiencies, were carried out.

Among the materials used to produce piezoelectric transducers and sensors, ZnO is a promising material that has been well studied and widely applied owing to its good piezoelectric properties and high electro-mechanical coupling coefficient. Various deposition techniques, which have been employed and developed such as sputtering [12–14], metal-organic chemical vapor deposition, and pulsed laser deposition to enhance high-quality ZnO films. The influences of deposition conditions on the properties of ZnO films have also been investigated, such as bottom electrode materials [15–17], sputter power [16, 17], deposition pressure, substrate temperature [17, 18], and argon and oxygen (Ar:O₂) gas flow ratio [15, 17–19]. In this study, a two-mask fabrication process employing SU-8 photoresist (PR) to fabricate the four-level Fresnel lenses was carried out. The influences of SU-8 PR on the profile of Fresnel lens were also discussed. In addition, a two-step deposition was employed using the RF magnetron sputtering method to investigate the effects of deposition parameters on the structural properties of ZnO films. The highly c-axis textured ZnO films were successfully deposited on Pt/Ti/SiO₂/Si substrate through two-step deposition process.

2. Experimental details

2.1. Fabrication of Fresnel Lenses

With high viscosity and good photosensitivity, SU-8 negative PR was widely used in the lithographic applications employing a thick film and high aspect ratio of a micro-structure. Tens and even hundreds of micrometer thickness of the PR layer can be obtained in a single coating process. Besides, other advantages of SU-8 PR in micro-electro-mechanical systems include low-cost, low optical absorption in the near-UV range, high thermal and chemical stability, and good resolution with vertical sidewall profiles. In this fabrication, SU-8 PR was used due to its good properties and suitable for deep reactive-ion etching (DRIE).

2.1.1. Sample preparation

A 4-inch silicon wafer was used as the substrate for fabricating the Fresnel lenses. It was firstly cut into some square samples with a dimension of 40 mm × 40 mm before being rinsed in acetone, isopropyl alcohol and de-ionized (DI) water to remove any particles or chemical substances on their surfaces. Subsequently, nitrogen gas was used to remove most of DI water on the surface of silicon substrates before taking a prebaking at a temperature of 120°C for 15 minutes on a hotplate for the purpose of full dehydration. The samples were kept on the hotplate to gradually cool down to room temperature.

2.1.2. Fabrication process of Fresnel lens

In this study, we developed a feasible fabrication of Fresnel lens using two masks associated with two etching steps. In our previous experiments, we employed a SiO₂ layer as a hard mask in DRIE for the fabrication of Fresnel lens. However, we encountered the problem of non-uniform photoresist coverage because of the high aspect ratio (ratio of the feature height to its width) of the lens. Hence, one or two outer ring group of the fabricated Fresnel

lenses was not obtained the shape as designed. Therefore, a two-mask process employing SU-8 PR in the lithography was applied for the purpose of solving the above problem.

Several sets of cleaned substrates were tested to examine the relationship between spin coating speed and thickness of the PR layer. Each sample was coated at a low speed (1000 rpm) for 30 seconds and a high speed (from 3000 to 7000 rpm) for 60 seconds to obtain a particular thickness of PR layer following by a soft-baking. The samples were baked at 60°C to 90°C with different baking times. Exposure dose is also one of most important factors that determine the resolution of exposed patterns, and therefore, various exposure doses were applied to see their influence. Post exposure baking (PEB) and development time were also investigated with the same purpose.

The four-level Fresnel lens was designed and fabricated for the ultrasonic ejector working at a resonant frequency of 100 MHz. The maximum radial distance and the step height of the Fresnel lens were designed as 244 μm and 4.55 μm , respectively. In this study, the inductively coupled plasma technology was used for the silicon etching (Machine type: STS Multiplex ICP). The fabrication processes of acoustic focusing lens were carried out by two cycles corresponding to two different masks. In the first cycle of the fabrication processes, the Si substrate was etched with the depth of $2h$, where h is the step height of Fresnel lens. And then, the wafer was aligned and exposed with 2nd mask and repeated the same processes with the Si etching depth of h in the second cycle. The fabrication process of Fresnel lens is briefly described in Fig. 1.

2.2. Fabrication of piezoelectric transducer

To develop a feasible condition for fabricating ZnO thin film piezoelectric transducers, we have investigated the influences of each deposition parameter on the c-axis preferred

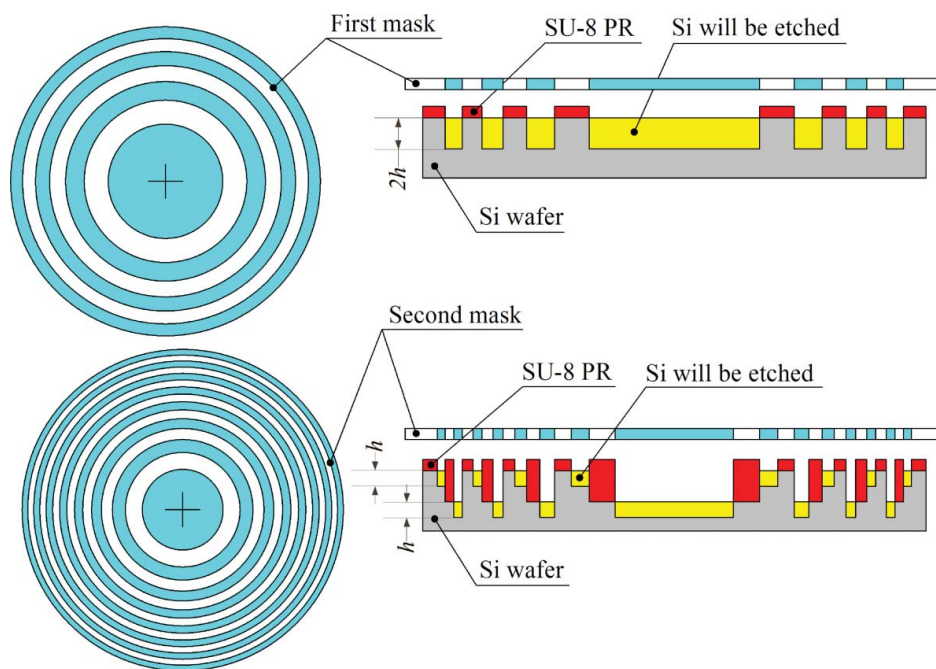


Figure 1. Fabrication process of Fresnel lens.

orientation of ZnO film. The deposition pressure, RF power and sputtering gas flow ratio were subsequently examined to find the most reasonable deposition condition. In this study, we would develop another technique of fabrication of ZnO thin film piezoelectric transducer. The deposition process was divided into two stages, which included an approximate 100 nm-thick ZnO film deposited at a lower deposition pressure of 0.7 Pa, RF power of 100 W and sputtering gas flow ratio Ar:O₂ of 1:3, followed by the second layer of ZnO film deposited until a thick enough film fulfilled under fabrication conditions such as deposition pressure of 1.3 Pa, RF power of 178 W and sputtering gas flow ratio Ar:O₂ of 1:1. In all the experiments, we fixed the substrate temperature at 380°C and the distance between the 4-inch target and substrate of 45 mm. We also deposited the ZnO film with only deposition conditions of the second step (i.e. deposition pressure of 1.3 Pa, RF power of 178 W and sputtering gas ratio Ar:O₂ of 1:1) since the beginning of the deposition to make a comparison with ZnO films deposited by a two-step deposition process.

Pt was considered as one of the best materials used to make a bottom electrode for ZnO piezoelectric transducer due to its small lattice difference with ZnO film. Especially, after taking a thermal treatment of Pt, ZnO(002) peak intensity was increased. Therefore, the bottom electrodes in all our experiments were also annealed in air at 600°C for 1 h from room temperature in increments of 10°C/min to make Pt electrode become highly oriented. Hence, a ZnO film was deposited on a Pt(150 nm)/Ti(20 nm)/SiO₂(150 nm)/Si substrate.

The thickness and the XRD pattern of the ZnO films were measured by a Dektak³ST α -step surface profiler and a Siemens D5000 diffractometer, respectively. Finally, Al evaporation and patterning were carried out to produce the top electrode to complete the fabrication of the piezoelectric transducer. Interdigital transducers with 6 μ m line-width and line-to-line spacing were fabricated on the ZnO film surface by a conventional photolithographic technique and the lift-off process. Each transducer has a 24 μ m period and 1.2 mm aperture. The number of the finger pair is 64 and the propagation distance between the input and output transducers is 3 mm. The transducer performance was measured by Agilent 8720ES network analyzer.

3. Results and discussion

The four-level Fresnel lenses were successfully fabricated through a two-mask process employing SU-8 PR in the lithography. The manner has revealed some advantages in the fabrication such as a thick PR film was obtained in a single spin coating; vertical sidewall of a high aspect ratio feature was also confirmed after exposure and development. However, we have also encountered some difficulties such as non-uniform film after spin coating, bubble problem on PR layer after soft-baking, diffraction and partial cross-link of PR during exposure, overdevelopment, etc. To confirm the relation between film thickness and spin-coating speed of the PR layer, some experimental trials were performed. After spin-coating at 1000 rpm for 30 seconds and at a higher speed, including 3000, 4500, 6000 and 7500 rpm for 60 seconds, the film thickness of 13.9, 10.5, 9.3 and 8.9 μ m were obtained, respectively. The relationship between the PR film thickness and spin-coating speed of the PR layer was shown in Fig. 2. Hence, a desired thickness can be determined. Through several trials, it showed that the PR film spin-coated at over 6000 rpm that satisfied the expected thickness with smooth surface, and then it was used in all the experiments.

Formation of bubbles on the PR film surface, which appeared during soft-baking, was a serious problem. It directly affects the fabrication result. Hence, the coated samples were transfer to a hotplate to bake at a temperature of 60° and 90°C for 60 minutes for each stage due to its thickness. Exposure is a crucial step in lithography. The fabrication of Fresnel

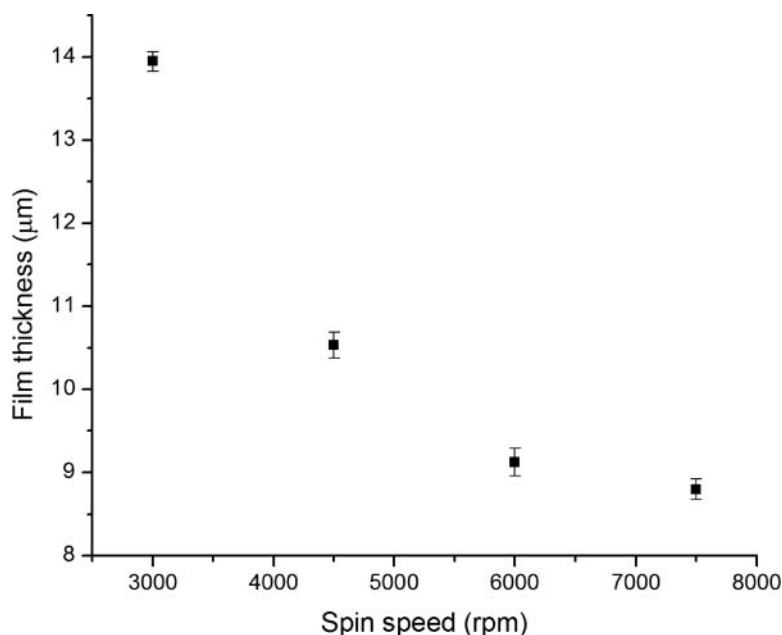


Figure 2. Relationship between film thickness and spin-coating speed of PR layer.

lenses could be stopped if exposure energy was unsuitable for high resolution pattern on PR surface. With a thickness of PR approximate $10\ \mu\text{m}$, a necessary exposure dose larger than $170\ \text{mJ}/\text{cm}^2$ may result in good exposure resolution [20]. Therefore, various exposure energies, which included 170, 200, 220, 250, and $300\ \text{mJ}/\text{cm}^2$, were tried to find the most appropriate dosage. To consider the influence of exposure dose on the PR film, the PEB and development time were chosen in advance. Here, 60 minutes was chosen for PEB at 90°C and then the samples were immersed in a beaker containing developer solution for 4 minutes in an ultrasonic cleaner. The measurement results showed that the best resolution of pattern on PR films was archived with an exposure dose of $220\ \text{mJ}/\text{cm}^2$.

Figure 3 presents a top view and surface profile of the pattern on PR film with exposure doses of 220 and $300\ \text{mJ}/\text{cm}^2$. Low exposure dosages tend to make the feature become slopped with the top wider than the bottom because the exposure dose decreases as the transferred depth was increased. That means the exposure does not create enough acid to enable sufficient cross linking during PEB. On the contrary, as shown in Fig. 3(b) and (d), the PR in outer trenches was not stripped during the development process after a dosage of $300\ \text{mJ}/\text{cm}^2$ was used in exposure. This probably caused by over-exposure, that means the dosage with a strong energy has made the top layer of the exposed area become cross-linked and changed its refraction index. The UV source transferred through that layer will be refracted to consolidate the bottom part of the lateral area of such small trenches. This problem was not occurred with a dosage of $220\ \text{mJ}/\text{cm}^2$ as shown in Fig. 3(a) and (c). A high vertical resolution pattern was taken shape on PR film even small vertical features. The shown sidewall of outer trenches seems not very vertical and does not reach the substrate surface. However, this is due to the resolution of measurement device. In fact, the following silicon etching has confirmed that argument.

Figure 4 illustrates a top view and its surface profile of a 100 MHz Fresnel lens after the first cycle of fabrication. The trench width and its side-wall were clearly shown. However,

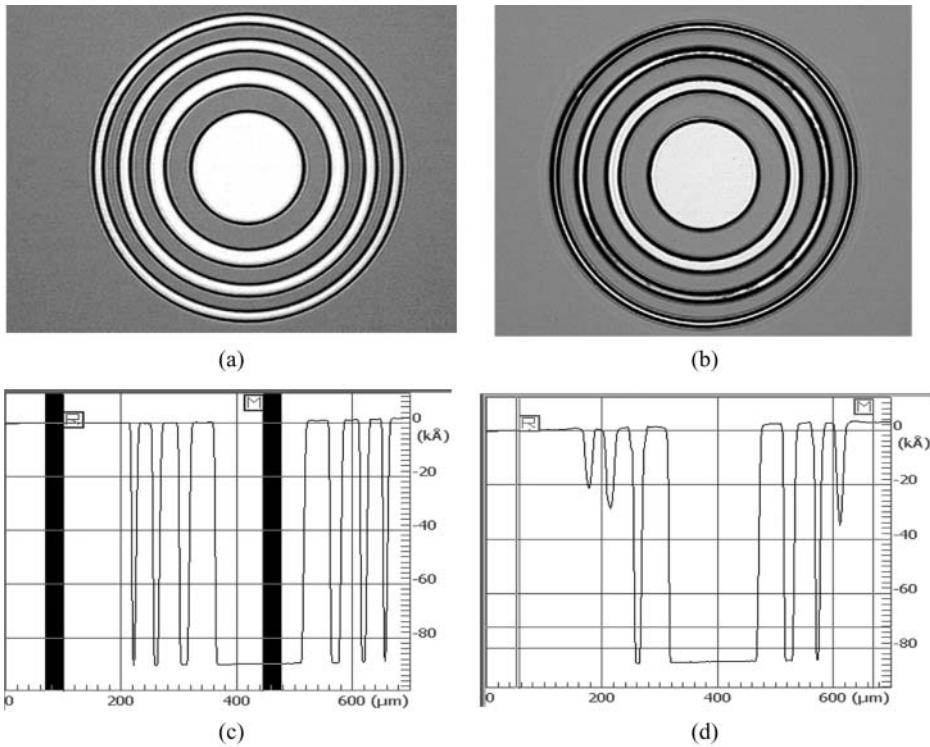


Figure 3. Top view and surface profile of PR patterns after exposure and development: (a), (c) exposure energy: 220 mJ/cm²; (b), (d) exposure energy: 300 mJ/cm².

the side-wall of the outermost trench is not very uniform and it has a little disagreement with the designed value. This phenomenon probably causes by the loading effect because of its high aspect ratio. And hence, a wafer in a smaller open area etches more slowly compared with that in a larger one. The second cycle of fabrication of Fresnel lens was

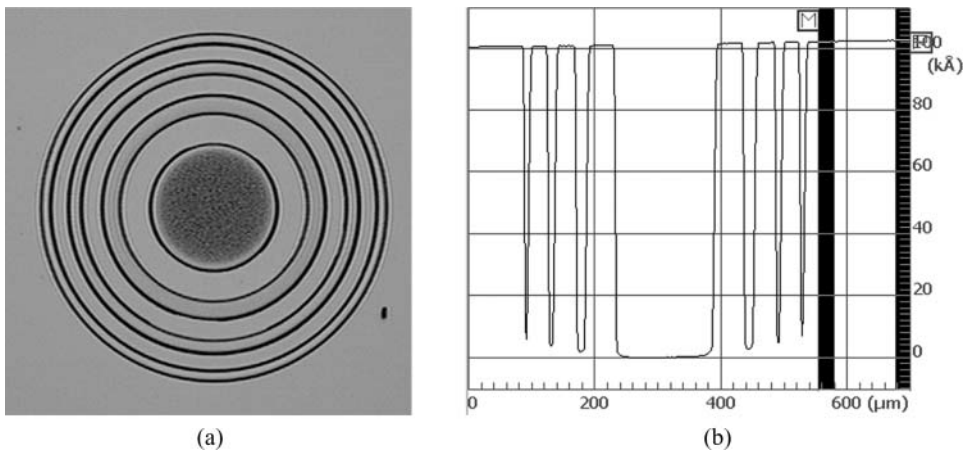


Figure 4. First cycle of fabrication of Fresnel lens: a) top view; b) surface profile.

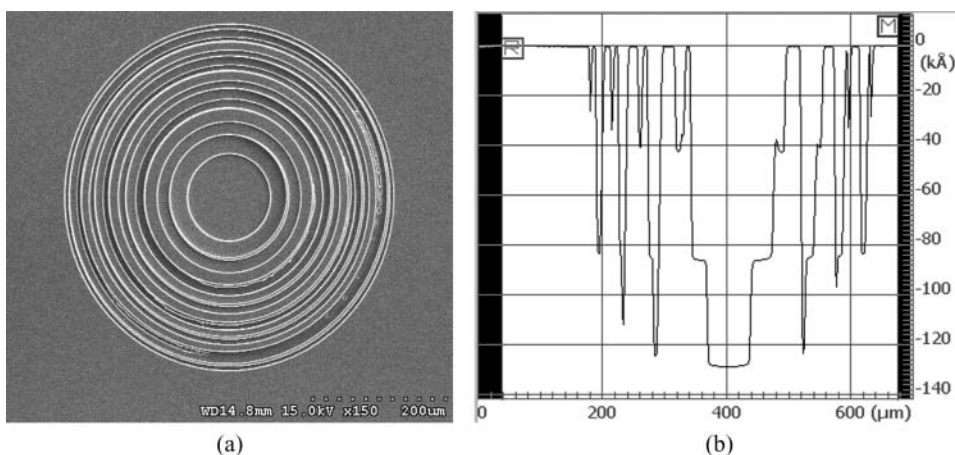


Figure 5. Second cycle of fabrication of Fresnel lens: a) top view; b) surface profile.

repeated with the same manner as the first one. This also included spin-coating, soft-baking, exposure, PEB, development and Si etching. However, the radial error of fabricated Fresnel lens was depended on the alignment process because of employment of a second mask. The thickness of PR film was also larger due to it has to cover the depth of trenches in the first fabrication cycle. Therefore, some technological parameters of the lithography needed to be adjusted, especially dosage of exposure and development time. With high exposure energy as 300 mJ/cm^2 , the image of exposed PR layer of the second cycle of fabrication showed quite clear even there still exists some PR in small inter trenches. It may cause by a “T-topping” effect due to a thick film of such a high viscosity PR as SU-8. This problem was solved by applying a lower exposure dose to avoid the phenomenon of change of the refraction index between the top and lower PR layers. And, therefore, a dosage of exposure about 270 mJ/cm^2 was used. Hence, the pattern image of exposed PR was much clearer that can be used for the second silicon etching to complete the fabrication of Fresnel lenses.

Figure 5 shows a top view and surface profile of a fabricated Fresnel lens. Main features of Fresnel lens were taken shape such as the radial distances and height step. Almost four-level ring groups were created. However, some problems were still existed such as some pieces of thin wall remaining in the lens step, and the fourth level was not formed at the outmost ring group as we designed. These problems were probably resulted by (1) the misalignment in the second lithography, this may cause to remain some thin wall parts (as shown in Fig. 6), (2) the loading effect because of its high aspect ratio as mentioned above, and (3) under-development occurred at some outer area while some parts of inner features were collapsed due to low mechanical stability at the bottom. The fourth level of almost ring group of fabricated Fresnel lens was clearly shown in Fig. 6, especially, the fourth level of the outermost ring group was also observed. It means the resolution of surface profile depends on the resolution of measurement tool; it may not detect the deep and small feature such as the outermost trench of fabricated lens. We are considering some measures to get reasonable technological parameters, especially in the second development process.

Figure 7 shows the XRD patterns of the ZnO films deposited by one and two-step deposition methods. The results show that the quality of the ZnO film was improved when it was deposited by a two-step method. The ZnO films deposited by a two-step method possess better film quality with smaller full width at half maximum intensity (FWHM) of

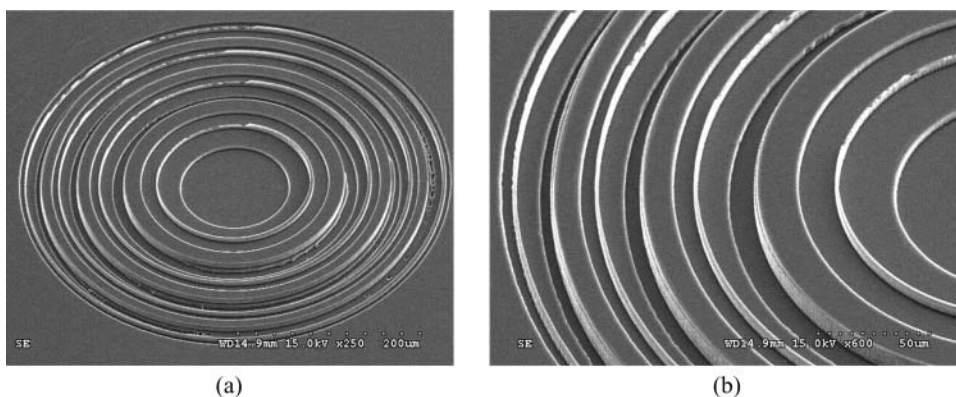


Figure 6. Oblique view of fabricated Fresnel lens.

the ZnO(002) plane and higher intensity ratio (I_{002}/I_{100}). The narrower FWHM of the ZnO film indicates that the crystallinity of the films is better, and there is little misalignment of the lattice planes parallel to the substrate surface. The c-axis preferred orientation of ZnO film is one of the most important factors for the piezoelectric transducer of an ultrasonic ejector. The first step of the deposition with a high O_2 concentration as 75% produced small and uniform grain size of ZnO thin film and a smooth surface film, which is expected to enhance the adhesion between ZnO film and Pt layer, especially significant for growing thick ZnO film. Besides, the highly c-axis textured ZnO film was obtained under the deposition condition of the second step even with a higher growth rate.

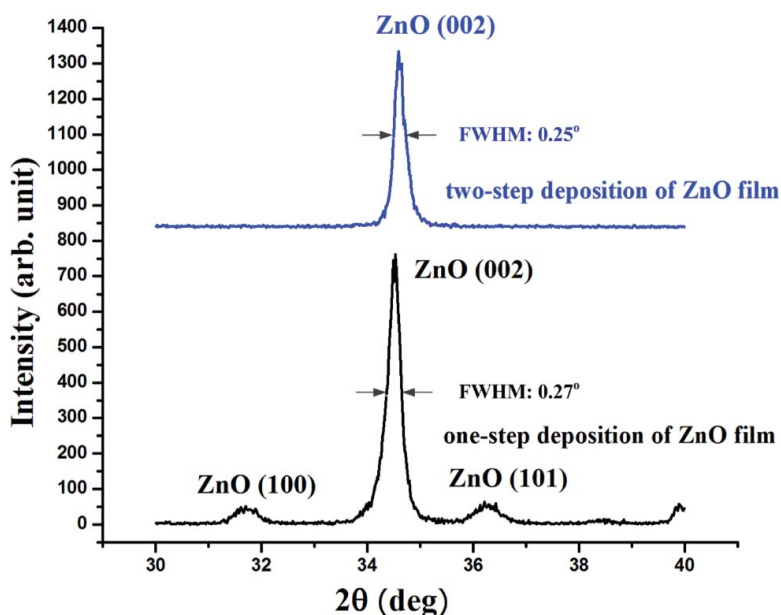


Figure 7. XRD pattern of ZnO films deposited by one- and two-step deposition methods (Figure available in color online).

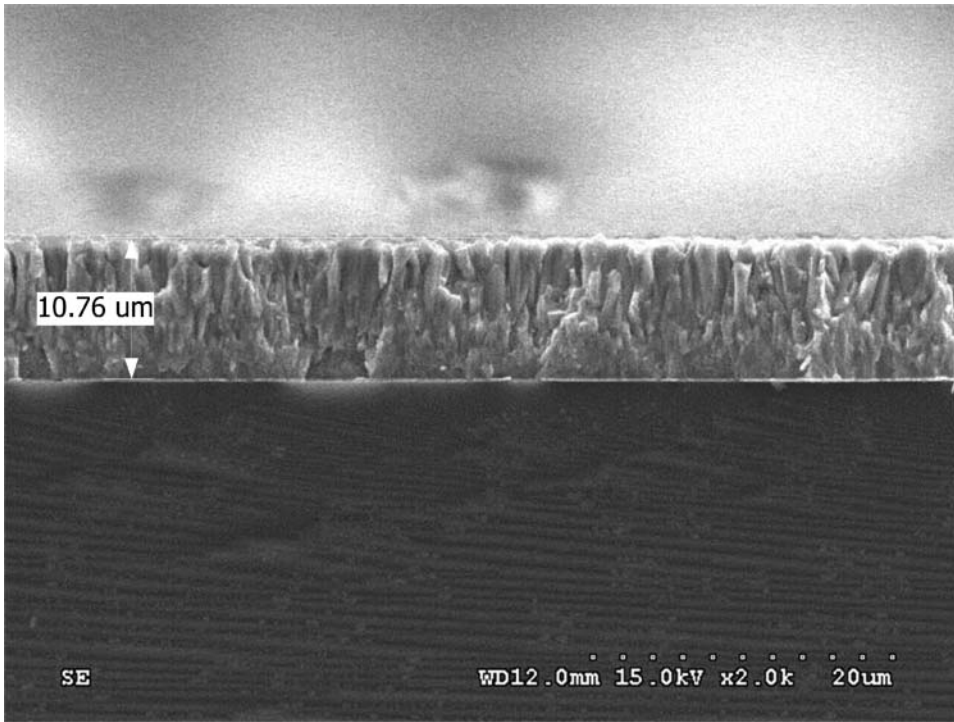


Figure 8. Cross-sectional image of ZnO films deposited by the two-step deposition methods.

Figure 8 shows the SEM image of the ZnO film with thickness of about $10.76\ \mu\text{m}$, it exhibits the ZnO film was grown with column structure. That means the c-axis preferred orientation of ZnO film is confirmed. Through applying this deposition manner, a deposition rate of ZnO film about $2\ \mu\text{m/h}$ was obtained, the preferred (002) orientation of ZnO film was confirmed, and the adhesive strength of ZnO film on the substrate was improved. Those are expected for the piezoelectric device employing a thick ZnO film. Therefore, the two-step deposition method was considered in this study because it satisfies the requirement of the device with reasonable characteristics. The performance of the piezoelectric transducer was finally analyzed in terms of its frequency response. The resonant frequency was about 186.5 MHz for the $15.28\text{-}\mu\text{m}$ -thick ZnO film. The measured resonant frequency is smaller than the simulated value (200.95 MHz). This is presumably because the mass loading effects caused by the electrodes on ZnO film leading to the actual resonant frequency are lower than the simulated results. These results are similar to those published by Huang and Kim [10].

4. Conclusions

A feasible fabrication process of Fresnel lens was proposed, examined and successfully fabricated by using SU-8 PR with a two-mask process. The precise profile of the focusing lens can be obtained and improved by adjusting the fabrication parameters in the lithography process, such as soft-baking, exposure and post-exposure baking processes. In addition, a two-step deposition of ZnO film was employed to produce a preferred c-axis orientation of the piezoelectric ZnO film. This fabrication was proposed and confirmed that it can

satisfy the requirements of piezoelectricity for growing thick ZnO films through analyzing the influences of the deposition conditions by one- and two-step method on the structural properties of ZnO films.

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