Key process study in nanoimprint lithography

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Abstract: Nanoimprint lithography (NIL) is widely used in the fabrication of nano-scale semiconductor devices for its advantages of high resolution, low cost, and high throughput. However, traditional hard stamp imprinting has some drawbacks such as short stamp lifetime, bad uniformity in big areas, and large particle influence. In this paper, a flexible intermediate polymer stamp (IPS) is proposed to solve the drawbacks mentioned above. Meanwhile, we use a method of temperature-pressure variation imprinting to improve the resist liquidity in the process of imprinting, and eventually we achieve high quality patterns. This method combined with IPS has been used to fabricate a high quality grating whose half pitch is 50 nm.

Key words: nanoimprint lithography; soft mold; temperature-pressure variation

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1. Introduction

Nanoimprint lithography (NIL), proposed by Stephen Chou in 1995, is a novel process in nanometer-scale pattern fabrication[1]. Compared with traditional photolithography, NIL, which is not been confined by the optical diffraction limit, has a higher resolution[2−4]; also, in contrast to E-beam lithography (EBL), the cost of NIL is extremely low. Due to the advantages of NIL, it has been widely used in manufacturing photonic crystal[5], distributed feedback (DFB) laser reflection grating[6], micro rings[7], sub-wavelength wire grating[8], micro circuits,[9] and other nanostructures.

NIL is based on the flow behavior of resist and mechanical contact embossing. However, the direct mechanical contact method suffers several drawbacks. First and foremost, owing to the fact that substrate can never be absolutely flat and clear, direct hard stamp imprinting will cause incomplete filling and result in pattern distortion in rough areas. Secondly, direct hard stamp imprinting may cause damage to the hard stamp, which is the key point of NIL. It will increase the cost of NIL and stop it being widely applied to industrial device manufacture.

In order to overcome these problems, soft molds such as PDMS[10] and PMMA[11] were developed. The soft mold used here has several obvious advantages compared with the hard one. (1) Particles sticking on the mother stamp will be pulled off by the polymer film during mold replication, so that the mother stamp will be cleaned and the newly defined soft son stamp will be much better. (2) Even though there are undulations or particles on the substrate surface, the soft son stamp can self-adapt to the substrate, largely reducing incomplete filling defect areas and preventing probable damage to the mother stamp and substrate. (3) The soft stamp is ideally anti-adhesive to the imprint resist，hence without destroying patterns, demolding process will become very easy.

In this paper, a flexible intermediate polymer stamp (IPS)[12, 13] is used as a soft mold to improve the imprinting pattern qualities. In addition, we use a method of temperature-pressure variation in the imprint process to enhance the liquidity of the resist in order to achieve a better pattern. Lastly, we fabricate a 50 nm half pitch grating with this method.

2. Experiments

Figure 1 demonstrates the detailed implementation scheme of soft mold imprinting. The fabrication process of a patterned soft mold is shown in Fig. 1(a). Here it was fabricated by pressing a hard stamp against the polymer film through thermal NIL at a high temperature above the glass transition temperature (T_g) of IPS. We can obtain a perfect replicated pattern on a soft mold through exactly controlling the temperature and pressure. For the T_g of IPS is 120 ℃, so 150 ℃ and the pressure of 40 bar were used in the thermal NIL in order to obtain good patterns.

Then, as shown in Fig. 1(b), the soft mold was used to transfer patterns onto a final substrate by a simultaneous thermal and ultraviolet (UV) imprint process at a temperature far below the T_g of IPS. We first cleaned the substrate in acetone, isopropanol, and deionized water, and dried with N_2 flow. Then a UV-curable resist was spin-coated on the substrate and baked on a hot plate at 95 ℃ for 3 min. Next, the soft mold was imprinted into the resist under a certain pressure and temperature; after the resist had filled all the concaves between the resist and substrate, a UV ray was applied to cure the resist and finally the soft mold was pulled off. Here, the T_g of the IPS and resist are 120 ℃ and 60 ℃ respectively, 70 ℃ and a pressure of 20 bar were carried out in the UV NIL process. In the whole NIL process, we used a method of temperature-pressure variation to improve the filling effects of the resist to achieve better patterns, as shown in Fig. 2.

To demonstrate the advantages of the temperature-pressure variation method, we fabricated two photonic crystal patterns with soft mold imprinting using the same experimental conditions for comparison: one used the method of temperature-

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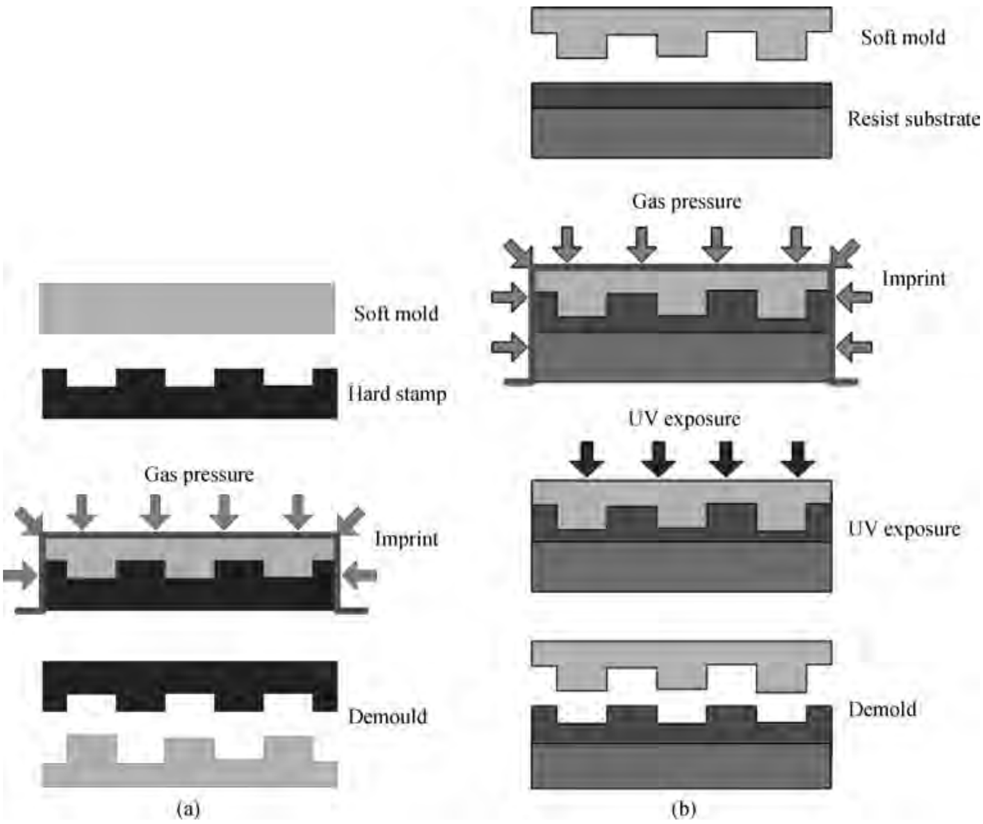

Fig. 1. Schematic diagram of the process flow of the soft mold scheme. (a) Fabrication of a soft mold. (b) Imprint with the soft mold and UV imprint process.

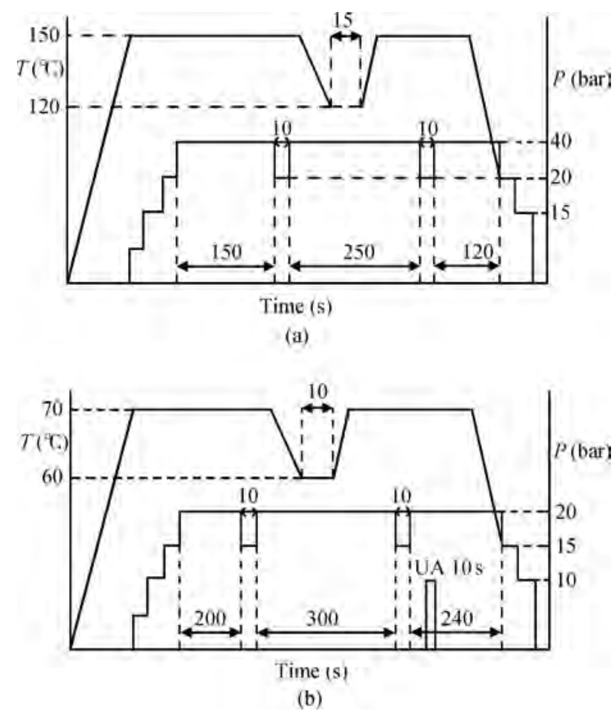

Fig. 2. Temperature-pressure variation imprint process of (a) soft mold fabrication and (b) pattern transfer to substrates.

pressure variation and the other did not. In order to demonstrate advantages of a soft stamp, a thermal NIL process directly using a hard silicon stamp imprinting against the substrate was also carried out as a comparison. A thermoplastic polymer imprint resist named mr-7020E, produced by Micro Resist Technology Ltd., was used here. During the imprint, the 7020E resist was spin-coated on a badly cleaned 2 inch diameter single-side polished silicon substrate at a thickness of 200 nm. In order to minimize the defect area, the thermal NIL was carried out at 150 ℃, and a pressure of 40 bar for the same time as the soft stamp scheme. Finally, we used soft mold imprinting and the method of temperature-pressure variation to fabricate a 50 nm half pitch grating.

All the experiments above were performed with the Etire3 machine from Obducat Ltd. The pattern quality inspection was done by using an AFM (atomic force Microscope, Veeco NanoScope MultiMode), an SEM (scanning electronic microscope, JOEL JSM-6700F) and an optical microscope (Olympus BX51).

3. Results and discussion

3.1. Temperature–pressure variation imprinting

Figure 3 shows the AFM images of the photonic crystal patterns. Figure 3(a) is the direct imprinting pattern, we can easily find that the photonic crystal pattern is not standard circular but similar rectangular, and the depth of this pattern is inhomogeneous. The reason why this deformation occurs is that the imprinting resist lacks liquidity in directly imprinting, so the resist can hardly fill all the concaves completely. Figures 3(b) and 3(c) demonstrate the AFM images of the temperature–pressure variation imprinting pattern. By using this

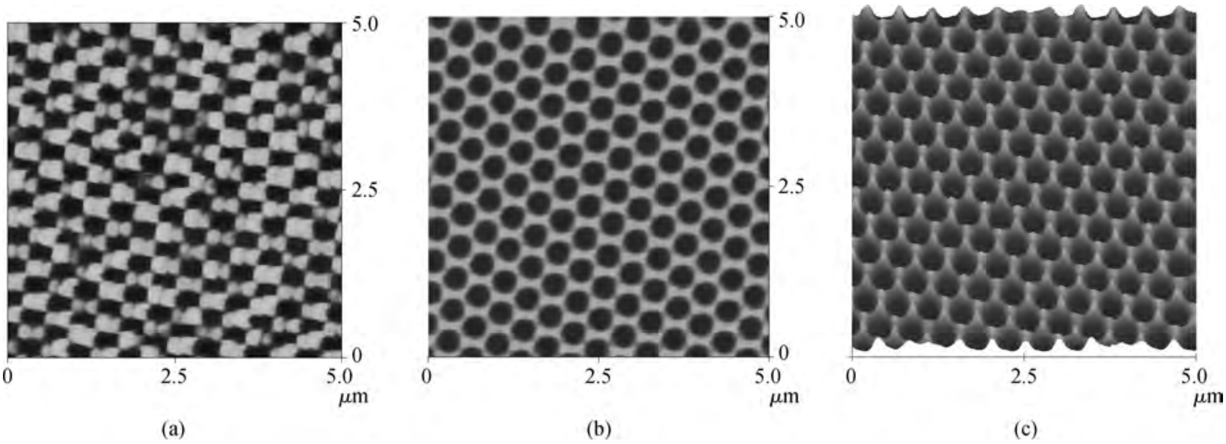

Fig. 3. AFM images of the photonic crystal pattern. (a) 2d image of the direct imprint. (b) 2d image of the temperature–pressure variation imprint. (c) 3d image of the temperature–pressure variation imprint.

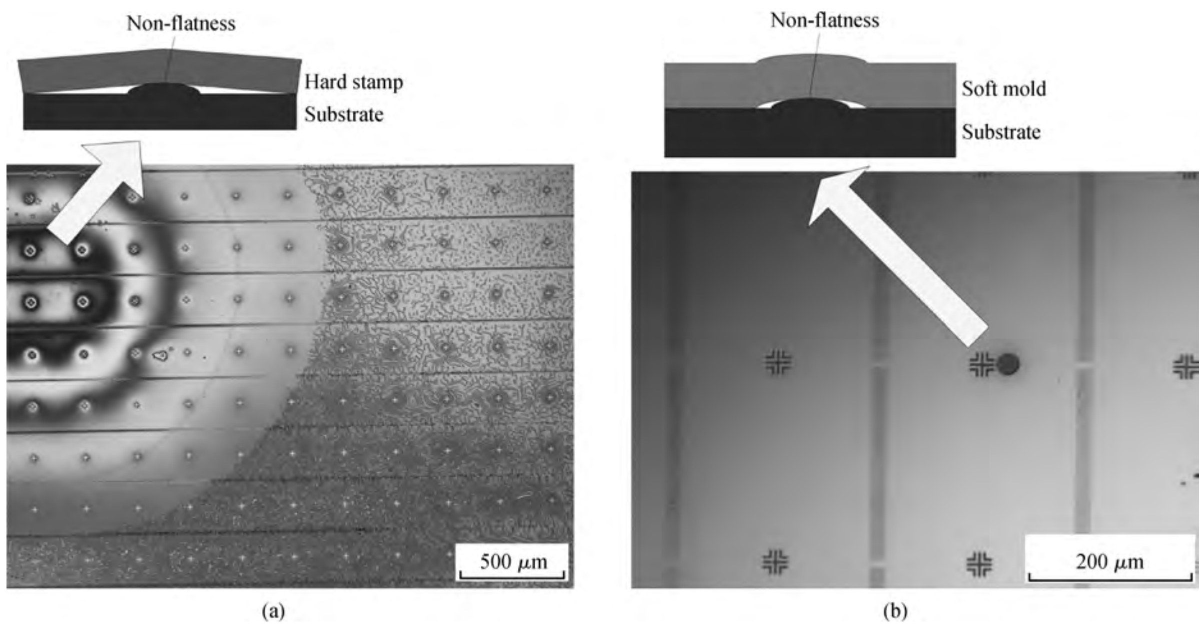

Fig. 4. Particle influence in (a) hard stamp thermal NIL and (b) soft mold UV NIL.

method, the photonic crystal pattern is much better, and the shape of the pattern is a standard circle instead. In addition, the depth of the pattern is uniform in large areas. The results show that the pattern fabricated by using temperature–pressure variation imprinting is nearly the same as the hard stamp, which proves that the method can transfer patterns precisely.

3.2. Soft mold imprinting

Figure 4(a) shows a typical picture of particle influence in the direct hard stamp thermal NIL process, gradually changed resist color forming a radiating shape around the particle as said in Refs. [14, 15]. It is in fact caused by the particle making a space variation between the two pressing plates. Although high pressure, high temperature, and a thick resist can improve the resist flow, the large hollow space between two pressing plates is still very difficult to fill. The defect center, which looks black, indicates that the substrate has been damaged when such high pressure was applied on the small particle.

In contrast, Figure 4(b) shows the influence of particles with a diameter of about 10 μm on the soft stamp scheme process. Even though particles are very close to the grating pattern, there is nearly no bad influence. This should be attributed to the self-adapting feature of the soft stamp. All the results highlight the great abilities of the soft stamp to minimize the influence of dust and non-flatness and improve the pattern yield of large area imprinting.

3.3. 50 nm half pitch grating pattern imprinting

Figure 5 displays the SEM images of a 50 nm half pitch grating pattern, which was fabricated by using a soft mold and the method of temperature-pressure variation imprinting. As shown in Fig. 5(a), the grating is uniform with the duty cycle of 0.5 and the half pitch of 50 nm, which meets the design of hard stamp. Figure 5(b) gives the image of grating in a larger area and the darker area demonstrates the low-lying area. From the picture we find that though the substrate is out of flatness,

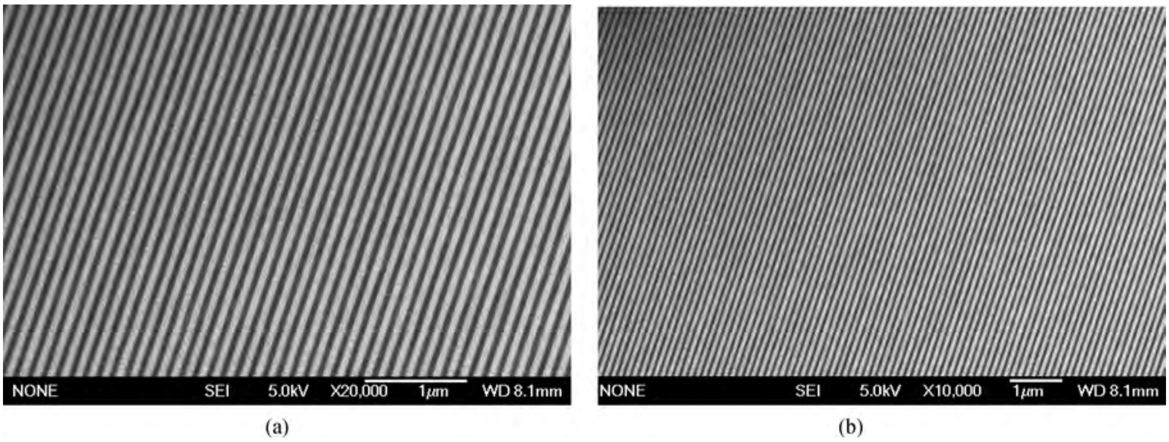

Fig. 5. SEM images of 50 nm half pitch grating (a) at 20000 times magnification and (b) at 10000 times of magnification.

we can also obtain a perfect grating pattern with the help of soft mold imprinting. Both images prove the practicability of our method for the fabrication of nanoscale patterns.

4. Conclusion

Traditional hard stamp imprinting still has some drawbacks, such as short stamp lifetime, bad uniformity over large areas, and great particle influence. In order to overcome these problems, a flexible intermediate polymer stamp is proposed for UV soft imprinting. From the contrast experiment between direct imprint and soft mold imprint, we can easily find a lot of benefits of the soft mold in improving uniformity over big areas. In addition, we recognize the role of the temperature-pressure variation method in enhancing the liquidity of the resist from the contrast experiment of photonic crystal imprinting. We have used this method and IPS to fabricate a high quality grating and its half pitch is 50 nm. All the results confirm the practicality of this process in small line width imprint.

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