Evaluation of Template Releasing Energy in Nanoimprint Lithography

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To investigate template releasing process in nanoimprint lithography, template releasing energy from resist polymer is evaluated under various conditions using test rig. The template releasing energy is proportional to the surface energy of the template, however it does not depend on rigidity of the system and template lifting speed.

Keywords: nanoimprint, adhesion, releasing energy, surface energy, template

1. Introduction

In nanoimprint lithography[1,2], adhesion and/or friction between template and resist is important issues in template releasing process, because the resist might be peeled off from the substrate or fractured, which causes fatal defects. Those defects in the template releasing process directly impact on process yield and crucial importance in industrial applications.

There have been several reports on eliminating defects by applying an anti-sticking coating on the template surface[3] or resist material. There have been several reports on evaluation of anti-sticking agents or resist materials by measuring the releasing forces when a template is detached (removed) from a resist polymer. In these studies, the releasing forces are mostly evaluated by the template releasing forces.[4,5] However, quantitative measurement of the template releasing forces is very difficult because the absolute values strongly depend on rigidity of each equipment and/or insufficient holding of the template and substrate, etc.

On the other hand, evaluation of anti-sticking layer or resist materials has largely been confined to reports on the contact angle for water droplets on the surface of these materials, and only a few

reports have attempted template releasing materials or method based on mechanical point of view. Based on fracture mechanics[6] which is also used for such purposes as evaluating the adhesion of silicon on insulator (SOI) wafers, Taniguchi[7] et al. observed the cracks between resist and template to extract releasing energy to be required to cleave them apart. Using a similar method, Houle[8] and S. Garidel et al.[9] reported on the quantitative evaluation of surface energy for releasing agents and UV resists, and discussed the differences in releasing energy arising from the resist composition and template releasing direction. Also, Landis et al.[10] measured the fracture stress in various crack directions against patterned template. However, the previous works did not take care of process conditions such as relations between surface free energy and releasing energy.

In this study, we developed the template release equipment which evaluated displacement and load for releasing and in-situ observe the releasing process. Using the system, we evaluated the releasing energy for template releasing process.

2. Experiment Procedure

Figure 1 shows a schematic diagram of the test rig for template releasing energy. A resist is coated

on the template and a quartz plate is put on the resist. By UV exposure, the resist is glued on the quartz plate. Then the quartz plate is lifted up by rod, which are placed 60 mm from the center of the template in an axial symmetry.

The displacement of the quartz plate is measured by optical sensors (Keyence Si-F01), which are placed 30 mm from the center of the template. The nominal resolution is 1 nm.

The loads on the lifting rods are measured using conventional load cells (Minebea CB17-3K-11). To eliminate the energy loss at the side wall of the template, the edge of the template is tapered by 45 degree chamfering.

Figure 1. Schematic diagram of the test rig

3. Evaluation of template releasing energy

In this report, the template releasing energy $G_{de-molding}$ is defined as the required energy per unit area to release a resist from a template. On the basis of a classical fracture theory⁸⁾, the surface energy γ is expressed as being one-self half of the fracture energy G_c per unit area to create a new surface owing to crack propagation. We extract the fracture energy G_c as the template releasing energy $G_{de-molding}$ to separate the resist from the template, as defined in the following equation :

$$G_{de-molding} \equiv G_c = 2\gamma \quad (1)$$

Figure 3 illustrates a diagram of crack propagation between the template and the resist. The quartz plate is stable position at displacement δ_{start} and load f_{start} , as shown in Fig. 2 (a). When additional load is applied, the crack grows to a new stable length, as illustrated in Fig. 2 (b), where the displacement is δ_{end} and the load is f_{end} . The amount of strain energy in the quartz plate $U_{elastic,start}$ before crack propagation and the externally applied energy $U_{external}$ balances the amount of strain energy in the quartz plate

Figure 2. Schematic of crack propagation in releasing process

$U_{elastic,end}$ after crack propagation, the elastic energy consumption in the resist ΔU_{resist} and the amount of energy consumption for template releasing $U_{de-molding}$ as expressed by

$$U_{elastic,start} + U_{external} = U_{elastic,end} + U_{de-molding} + \Delta U_{resist} \quad (2)$$

The strain emerging at $U_{elastic,start}$ and $U_{elastic,end}$ are expressed as follows:

$$U_{elastic,start} = \frac{1}{2} f_{start} \delta_{start} \quad (3)$$

$$U_{elastic,end} = \frac{1}{2} f_{end} \delta_{end} \quad (4)$$

The energy $U_{external}$ is given by sum of integration of the applied load f_n and displacement δ_n of each rod:

$$U_{external} = \int_{\delta_{start}}^{\delta_{end}} f d\delta \quad (5)$$

ΔU_{resist} is derived under assumption that the resist is stretched in nominal direction as follows:

$$\Delta U_{resist} \approx \frac{1}{2} \cdot \left(\frac{f_e^2}{S_e E} - \frac{f_s^2}{S_s E} \right) \cdot d \quad (6)$$

where E and d are the elastic modulus and initial thickness of the resist, respectively. S_e and S_s are the adhesion areas between the resist and

plate before and after crack propagation.

To qualify the external energy $U_{external}$, we need the displacement δ at the lifting rod. However, the displacement of the quartz plate δ^* is measured by the optical sensor, as shown in Fig. 1. We estimate the displacement δ at the lifting rod by numerical calculation using the finite element method (FEM) based on the displacement δ^* at the optical sensor position, as demonstrated in Fig. 3. The correction factor in the peeling mode is 0.32. As a result, the template releasing energy per unit area $G_{de-molding}$ is derived as follows:

$$G_{de-molding} = U_{demolding} / \Delta S$$

$$= (U_{es} + U_{external} - U_{ee} - \Delta U_{resist}) / \Delta S \quad (7)$$

where ΔS is the newly revealed fresh surface area according to the releasing process.

Figure 3. Estimation of the displacements of quartz plate.

4. Experimental process and conditions

A template is bonded on to the base unit, and a UV-curable resist polymer is coated on it. To promote successful releasing without sticking defects, we use OPTOOL-DSX (Daikin Industries) as an anti-sticking layer on the template surface. The template size is 10 mm², and the quartz plate is 150 mm² and 2 mm in thickness.

The resist is PAK-01 (TOYOGOSEI), which is a solvent-soluble polymer for UV nanoimprinting. The initial thickness of the resist is typically 10.0 μm. A quartz plate as a substrate is put on the resist and cured by UV exposure through the quartz plate. The surrounding atmosphere was purged with nitrogen to eliminate oxygen inhabitation for UV curing. After the resist is cured, the resist is released from the Si template by lifting the quartz plate up with rods.

Cracks between the template and the resist are

observed by using a video camera to investigate crack propagation in the releasing process, as shown in Fig. 4.

Figure 4. Observation of the releasing

5. Experimental result

Template releasing energy between resist and template are investigated in variation with process conditions such as system rigidity, template surface energy, template releasing speed under the peeling mode.

5.1. Dependence on system rigidity

To verify the test rig and extraction procedure of template releasing energy, we examined the dependence on the system rigidity by alternating the thickness of the quartz plate as one of the components of the system. The thickness of the quartz plates are varied from 2 to 6 mm.

Figure 5(a) shows the relation between the rod displacement and load for various thicknesses of the quartz plate to examine the stability of the rigidity of the system. As the thickness of the quartz plate increases, which means the rigidity increases, the releasing force increases and the displacement decreases. Figure 5(b) shows the extracted surface energy between the resist and template. The lifting speed of the rod was 1 μm/sec. The template releasing energy between the resist and template does not depend on the thickness of the quartz plate, which means the releasing energy is independently evaluated on rigidity of the system.

5.2. Dependence on surface energy of template

To assist successful releasing, we usually use OPTOOL-DSX as an anti-sticking layer to decrease the surface energy of the template. To verify the dependence of the template releasing energy on the template surface energy, the template surface energy is modified by UV Ozone exposure to be 804, 645 and 302 mJ/cm², which are equivalent to contact angles for water droplet of 20°, 60° and 100°, respectively. We use virgin templates under nitrogen ambient to

eliminate Ozone generation and oxygen inhabitation for UV resist. The lifting speed of the rods was $1.0 \mu\text{m/sec}$.

a) Displacement-force curve.

b) Template releasing energy vs. thickness of the quartz plate

Figure 5. Dependence of template releasing energy on the quartz thickness. (Rod lifting speed: $1 \mu\text{m/sec}$, Contact angle for water droplet on the template: 88°)

Figure 6(a) shows the relation between the rod displacement and load in variation with the contact angle θ for water droplet on the template. As the contact angle decreases (increment of the surface energy of template), the displacement and releasing force increase.

Figure 6(b) shows the relation between the surface energy of the template and the template releasing energy. The template releasing energy is proportional to the surface energy of the template, which is reasonable result.

a) Displacement-force curve

b) Template releasing energies in variation with surface energy of the template. Rod lifting speed: $1 \mu\text{m/sec}$, Quartz thickness: 2mm)

Figure 6. Dependence of template releasing energy on surface energy of template

5.3. Dependence on lifting speed

One of the interesting issues is the lifting speed whether slow lifting speed is better or not. The lifting speed of the rods is varied from 500 nm/sec , to $10 \mu\text{m/sec}$ to investigate dependency on the lifting speed.

Figure 7(a) shows displacement and load of the lifting rod in various lifting speeds. As the rod lifting speed increases, the template releasing load increases. However, the template releasing energy does not depend on the lifting speed of rod as shown in Fig. 7(b). In other word, the template releasing energy does not depend on the lifting speed, which makes sense from fracture dynamics viewpoint that the template releasing events are

a) Displacement-force curve

b) Template releasing energy

Figure 7. Dependence of surface energy on lifting speed of the rod. (Quartz thickness: $2.0 \mu\text{m}$, Contact angle for water droplet on the template: 88°)

related to the template releasing energy. However, the velocity is so slow in our experiment and further investigations should be done in high speed or impact releasing.

6. Conclusion

In nanoimprint lithography, template releasing energy between the resist and template is verified in template releasing process. The system

evaluates the template releasing energy regardless of the rigidity of a system. The template releasing energy is proportional to the surface energy of the template, however it does not depend on the releasing speed. These results help understanding template releasing phenomena in quantitatively to evaluate the template releasing energy required for template releasing rather than the template release force.

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