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A simulation model on photoresist SU-8 thickness after development under partial exposure with reflection effect

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The negative photoresist SU-8 is often used to fabricate thick micro structures. It was known that reflection from the interface between SU-8 and the substrate surface would affect the thickness after development and profile of SU-8 structures. However, the model to predict the thickness after development of SU-8 under reflection effect has not been reported yet. Here, a simulation model to predict SU-8 thickness after development under partial exposure with reflection effects is proposed. Two kinds of SU-8 micro structures with different exposure dosages and coated thickness are fabricated on glass substrates to demonstrate the capability of the proposed model. For different exposure dosages or coated SU-8 thickness, the maximum difference between simulated and experimental results is shown to be less than 3.1%, which verifies the accuracy of the proposed model. © 2014 The Japan Society of Applied Physics

1. Introduction

The negative photoresist SU-8 patented by IBM in 1989 is particularly well-suited for thick-film applications, because it can be spin-coated by a conventional spinner at hundreds of µm thickness and patterned with conventional UV exposure systems. SU-8 also has low optical absorption, good thermal stability and chemical resistance during photolithography in the near-UV range.[1,2] Various studies have described the properties and processing parameters of SU-8.[3,4] Due to its chemical stability, as well as good mechanical and optical properties, SU-8 has been widely used in micro-electro-mechanical systems (MEMS),[5,6] such as molds,[7] sensors,[8] radio frequency devices,[9] micro electrodes,[10] wave-guide networks,[11] micro-optics,[12] and microfluidic systems.[13]

The thickness after development of negative photoresist is directly related to the absorbed energy of the photoresist. It is also known that the reflection between SU-8 and the substrate surface may affect the absorbed energy of SU-8.[14] However, most literatures focused on studying SU-8 under full exposure,[5–14] very few work investigated reflection effect on thickness after development of SU-8 under partial exposure. Chuang et al.[15] utilized dosage-controlled UV exposure and anti-reflection coating to reduce the reflection effect on thickness after development of SU-8 in fabricating sealed micro channel. In simulations, there were some studies[16,17] to model sidewall profiles of SU-8 structures affected by diffraction due to the air gap between the mask and photoresist surface, and Kang et al.[18] further included substrate reflection effect in modeling SU-8 sidewall characteristics. However, all these models are based on Fresnel diffraction theory,[19] and can not be used to predict the deviation on SU-8 thickness after development due to reflection effect.

Here, for partial exposure on SU-8, a simulation model is proposed to estimate SU-8 thickness after development under the reflection effect with known thickness after development of SU-8 without the reflection effect. Two kinds of SU-8 micro structures are fabricated to demonstrate the accuracy of the proposed model. One of micro structures is fabricated to investigate the thickness after development of SU-8 under different exposure dosages with and without reflection effect at the same coated thickness. And the other is fabricated to investigate the reflection effect on thickness after development of SU-8 at different coated thickness. Both experimental results will be used to demonstrate the accuracy of the proposed simulation model.

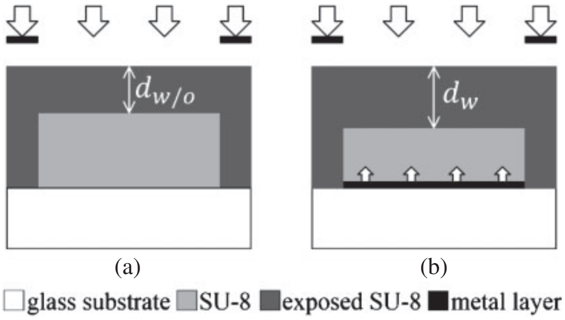


Fig. 1. Schematic diagrams on SU-8 thickness after development under partial exposure: (a) without the reflection effect; (b) with reflection effect.

2. Analytical model

Under partial exposure, when the reflection between SU-8 and the substrate surface is significant, the thickness after development of SU-8 structures will be affected. In Fig. 1(a), reflection between SU-8 and the transparent glass substrate is sufficiently small to be regarded as zero. By contrast, as shown in Fig. 1(b), incident light will be reflected from the metal layer on substrate surface back to SU-8. Then, under partial exposure, thickness after development with reflection (d_{w}) would be thicker than thickness after development without reflection ($d_{\mathrm{w/o}}$) due to larger absorbed energy. Here, for partial exposure on SU-8, we try to develop a simulation model to estimate SU-8 thickness after development under the reflection effect with known thickness after development of SU-8 without the reflection effect.

Based on the Beer–Lambert law,[20] the transmitted light intensity I through a layer of material with thickness z can be related to the incident intensity I_0 as

$$I = I_0 e^{-\alpha z}, \tag{1}$$

where z denotes the path length. The absorption coefficient (or linear absorption coefficient) is α. However, the absorp-

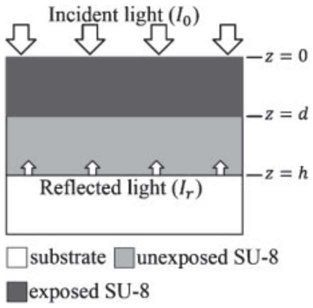


Fig. 2. Schematic diagram of SU-8 exposure process with reflection effect.

tion coefficient of photoresist will be changed during the exposure process. Therefore, a modified absorption coefficient α_m model[21] is needed:

$$\alpha_{\mathrm{m}} = (\alpha_{\mathrm{e}} - \alpha_{\mathrm{u}})\frac{d}{h} + \alpha_{\mathrm{u}}, \tag{2}$$

where α_e is the absorption coefficient of exposed photoresist, α_u is the absorption coefficient of unexposed photoresist, h is coated SU-8 thickness, and d is the thickness after development of SU-8 under partial exposure.

Figure 2 shows the illustration of the SU-8 structure under partial exposure from incident light and reflected light. The absorbed energy of SU-8 from incident light is

$$E_{\mathrm{a}} = \int_0^{t_{\mathrm{exp}}} I_0 - I_0 e^{-\alpha_{\mathrm{m}} h}\, dt, \tag{3}$$

where E_a is energy absorbed from incident light, I_0 is incident light intensity, t_{exp} is exposure time, α_m is the absorption coefficient of SU-8, and h is coated thickness of SU-8.

Reflected light intensity at substrate surface, I_r, from the incident light can be expressed as

$$I_{\mathrm{r}} = R I_0 e^{-\alpha_{\mathrm{m}} h}. \tag{4}$$

The reflectivity between SU-8 and the substrate surface, R, can be expressed as[20]

$$R = \frac{(n_1 - n_2)^2 + (k_1 - k_2)^2}{(n_1 + n_2)^2 + (k_1 + k_2)^2}, \tag{5}$$

where n_1 is SU-8 refractive index and n_2 is substrate refractive index (real part of complex index of refraction), k_1 is SU-8 extinction coefficient and k_2 is substrate extinction coefficient (imaginary part of complex index of refraction). Here, k_1 (SU-8 extinction coefficient) is sufficiently small to be regarded as zero. Thus, absorbed energy of SU-8 from reflected intensity can be expressed as

$$E_{\mathrm{b}} = \int_0^{t_{\mathrm{exp}}} (R \cdot I_0 e^{-\alpha_{\mathrm{m}} h})(1 - e^{-\alpha_{\mathrm{m}} h})\, dt. \tag{6}$$

Therefore the absorbed energy of SU-8 from both incident and reflected light can be expressed by the sum of Eqs. (3) and (6) as

$$E = E_{\mathrm{a}} + E_{\mathrm{b}} = I_0 \int_0^{t_{\mathrm{exp}}} (1 + R \cdot e^{-\alpha_{\mathrm{m}} h})(1 - e^{-\alpha_{\mathrm{m}} h})\, dt. \tag{7}$$

With a specified unit thickness Δh, and let thickness after development of SU-8 d to be $n\Delta h$, where n is a positive integer. Once d is determined experimentally, n can be decided corresponding to a specified unit thickness Δh. Therefore, trapezoidal rule can be used to approximate Eq. (7), the integration form of absorbed energy of SU-8, as

$$E = \sum_{i=1}^{n} (a_i \Delta t_i + b_i \Delta t_i), \tag{8}$$

$$\begin{aligned} a_i = {} & \{I_0(1 - e^{-\{\alpha_{\mathrm{e}}(i-1)\Delta h + \alpha_{\mathrm{u}}[h-(i-1)\Delta h]\}}) \\ & + I_0\{1 - e^{-[\alpha_{\mathrm{e}} i\Delta h + \alpha_{\mathrm{u}}(h - i\Delta h)]}\}\}/2, \\ b_i = {} & \{R I_0 e^{-\{\alpha_{\mathrm{e}}(i-1)\Delta h + \alpha_{\mathrm{u}}[h-(i-1)\Delta h]\}} \\ & \times \{1 - e^{-\{\alpha_{\mathrm{e}}(i-1)\Delta h + \alpha_{\mathrm{u}}[h-(i-1)\Delta h]\}}\} \\ & + R I_0 e^{-[\alpha_{\mathrm{e}} i\Delta h + \alpha_{\mathrm{u}}(h - i\Delta h)]}\{1 - e^{-[\alpha_{\mathrm{e}} i\Delta h + \alpha_{\mathrm{u}}(h - i\Delta h)]}\}\}/2, \end{aligned}$$

$$\sum_{i=1}^{n} \Delta t_i = t_{\mathrm{exp}}, \tag{9}$$

where Δt_i is the exposure time for the thickness after development of SU-8 to increase an unit thickness Δh from $(i-1)\Delta h$ to $i\Delta h$, $a_i\Delta t_i$ is absorbed energy in the period of Δt_i from incident light, and $b_i\Delta t_i$ is absorbed energy in the period of Δt_i from reflected light. When parameters Δh, h, α_e, α_u, and R are known, a_i and b_i $(i = 1, 2, \ldots, n)$ can be calculated, where Δt_i still needs to be identified. Then the increment of absorbed energy while thickness after development of SU-8 increasing from $(i-1)\Delta h$ to $i\Delta h$ by both incident and reflected light can be expressed as

$$\Delta E_i = (a_i + b_i)\Delta t_i, \ i = 2, \ldots, n. \tag{10}$$

By considering SU-8 photoresist to be homogeneous initially, when the thickness after development of SU-8 increases an unit thickness Δh, the increment of absorbed energy on SU-8, ΔE_i, is assumed to be the same, i.e.,

$$(a_1 + b_1)\Delta t_1 = (a_2 + b_2)\Delta t_2 = \cdots = (a_n + b_n)\Delta t_n. \tag{11}$$

Then Δt_i $(i = 2, \ldots, n)$ can be expressed in terms of Δt_1,

$$\Delta t_i = \frac{a_1 + b_1}{a_i + b_i}\Delta t_1, \ i = 2, \ldots, n. \tag{12}$$

Substituting Eq. (12) into Eq. (9) gives

$$\sum_{i=1}^{n} \left(\frac{a_1 + b_1}{a_i + b_i}\right)\Delta t_1 = t_{\mathrm{exp}}. \tag{13}$$

Therefore, once t_{exp} is given, Δt_1 can be determined, as well as Δt_i $(i = 2, \ldots, n)$.

For a substrate with different reflectivity R', but the same coated SU-8 thickness (h), specified unit thickness Δh, and exposure time (t_{exp}), thickness after development of SU-8 d' is expressed as $p\Delta h$, where p is a positive integer. Then the relationship of $\Delta t'_j$ [exposure time during thickness after development of SU-8 increasing from $(j-1)\Delta h$ to $j\Delta h$ on substrate with R'] becomes

$$\sum_{j=1}^{p} \left(\frac{a'_1 + b'_1}{a'_j + b'_j}\right)\Delta t'_1 = t_{\mathrm{exp}}. \tag{14}$$

Since the increment of absorbed energy to increase the thickness after development of SU-8 with an unit thickness Δh is assumed to be the same, then

$$(a_1 + b_1)\Delta t_1 = (a'_1 + b'_1)\Delta t'_1. \tag{15}$$

Substituting Eq. (15) into Eq. (14) and combining Eq. (13) give

Table I. Optical parameters of glass substrate, Cr, and SU-8 photoresist.

Refractive index of glass, n_{glass}	1.56
Refractive index of SU-8,[22] $n_{\text{SU-8}}$	1.63
Refractive index of Cr,[23] n_{Cr}	1.86
Extinction coefficient of Cr,[23] K_{Cr}	2.68
Absorption coefficient of exposed SU-8,[21] α_{e} (cm^{-1})	49
Absorption coefficient of unexposed SU-8,[21] α_{u} (cm^{-1})	38
Reflectivity between SU-8 and glass substrate, R_{glass}	0.0004
Reflectivity between SU-8 and Cr layer, R_{Cr}	0.37

$$\sum_{j=1}^{p}\left(\frac{a_1+b_1}{a'_j+b'_j}\right)\Delta t_1 = t_{\mathrm{exp}} = \sum_{i=1}^{n}\left(\frac{a_1+b_1}{a_i+b_i}\right)\Delta t_1. \qquad (16)$$

If one set of thickness after development of SU-8 ($d = n\Delta h$) and exposure time on the substrate with reflectivity R is obtained from experimental data at a known coated thickness h, then a_i, b_i, a'_j, b'_j, can be calculated by given parameters (Δh, α_{e}, α_{u}, R, R'). The value p then can be calculated by Eq. (16), and the thickness after development of SU-8 ($d' = p\Delta h$) on the substrate with different reflectivity R' at the same coated thickness and exposure time can be determined as well.

3. Experiments

To verify the accuracy of the proposed model, two SU-8 micro structures are designed and fabricated to investigate the reflection effect on the thickness after development of SU-8 photoresist associated with different exposure dosages and coated thickness. One approach uses cuboid structures to measure the deviation on thickness after development with and without reflection effect under different exposure dosages at the same coated thickness. The other approach uses bridge structures to measure the deviation on thickness after development with and without reflection effect at different coated thickness under the same exposure dosage. The SU-8 photoresist used here is Microchem SU-8 2075, the substrate is soda-lime glass, and the reflected layer is a sputtered Cr layer. The optical parameters used here are listed in Table I.

3.1 Cuboid structures

Figure 3 shows the fabrication process of two SU-8 cuboid structures made from the same coated thickness, where one has reflection effect and the other one does not have reflection effect. Two glass substrates are used here. First, an 1000 Å Cr layer is deposited only on the left surface of the top glass substrate to be the reflected layer. Then Cr layer is deposited on the middle of the other glass substrate to define the area for later back-side partial exposure, as shown in Fig. 3(a). Photoresist SU-8 is then spin-coated on the bottom glass substrate and soft baked. After rehydration, the glass substrate with patterned reflection Cr layer is reversed and placed on the top of coated SU-8, as shown in Fig. 3(b). Photoresist SU-8 is then exposed by back-side partial exposure, where the right cuboid only receives the dosage from back-side partial exposure and the left cuboid is expected to absorb more energy due to the reflection effect, as shown in Fig. 3(c). After development with the Microchem SU-8 developer, two cuboid structures, with and without reflection effect, can be obtained. The left cuboid is expected to be thicker than the right one, as shown in Fig. 3(d). With this fabrication process design, it ensures that two SU-8 structures with and without reflection effect are fabricated from the same SU-8 at the same coated thickness, exposure dose, and development time. Different back-side exposure time (t_{exp}) will be applied to the SU-8. Thickness after development with the reflection effect (d_{w}) and without the reflection effect ($d_{\mathrm{w/o}}$) then can be compared.

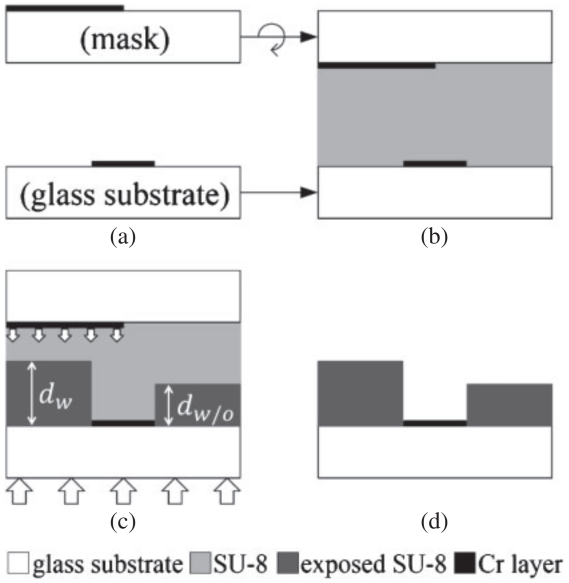


Fig. 3. Fabrication of cuboid SU-8 structures by back-side partial exposure.

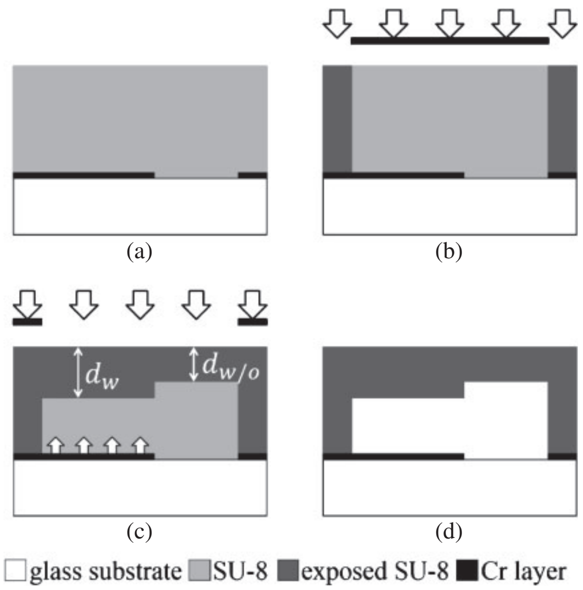
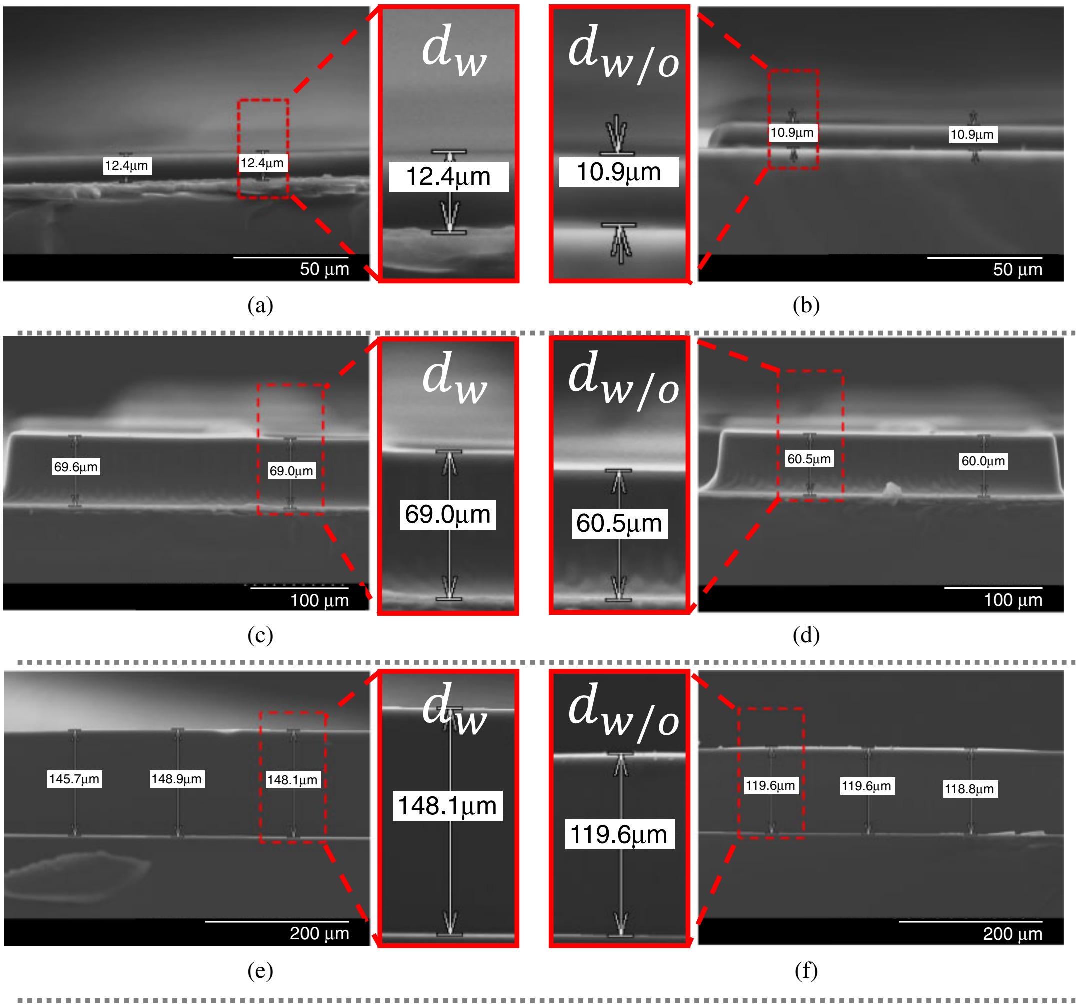


Fig. 4. Fabrication of SU-8 bridge structure by front partial exposure.

3.2 Bridge structures

The front partial exposure is also applied to the SU-8 to further examine the reflection effect on the thickness after development at different coated thickness by fabricating SU-8 bridge structures. Figure 4 shows the fabrication process for coating SU-8 2075 below 240 µm. An 1000 Å Cr layer is deposited on part of the glass substrate left surface



(a) (b)

(c) (d)

(e) (f)

Fig. 5. (Color online) Experimental results of different thickness after development with/without reflection effect, where the exposure dosage is (a, b) 20 mJ/cm^2, (c, d) 60 mJ/cm^2, and (e, f) 100 mJ/cm^2.

by the lift-off process to act as the reflected layer. The area without Cr layer at right surface is for the control structure without reflection effect, as shown in Fig. 4(a). Photoresist SU-8 is then spin-coated and soft baked. After rehydration, SU-8 photoresist is exposed by front full exposure to define two bridge support posts first, as shown in Fig. 4(b). SU-8 photoresist is then exposed by front partial exposure to define the suspended bridge structure. The left part of the bridge will absorb more energy than the right part because of the reflection effect, as shown in Fig. 4(c). After development, bridge structure can be fabricated, and Fig. 4(d) shows that the left part of the bridge is expected to be thicker than the right part of the bridge. This kind of design also ensures consistent fabrication process control. A single SU-8 bridge structure can provide two portions with and without reflection effect, and both portions should have the same initial coated thickness, exposure dose, and development time. The deviation on thickness after development due to reflection effect at different coated thickness will be measured and simulated to further examine the accuracy of the proposed model.

4. Results and discussion

4.1 Cuboid structures

Cuboid structures are fabricated here to investigate the relationship between exposure dosages and deviation on thickness after development at the same coated thickness of SU-8. In fabrication, the SU-8 photoresist around 150 μm thick is spin-coated and then soft-baked at 65 °C for 10 min and at 95 °C for 30 min. After rehydration for over 30 min, the photoresist is exposed by I-line (365 nm) to different dosages and then post-exposure bake (PEB) at 65 °C for 3 min and at 95 °C for 10 min. Final development is performed for 8 min with a Microchem SU-8 developer, followed by a second spray/wash with isopropyl alcohol (IPA) for another 10 s. The area of cuboid structure is 500 × 300 μm^2, and the thickness after development of cuboid structure depends on exposure dosage. Different back-side partial dosages ranging from 20 to 120 mJ/cm^2 are applied with increments of 20 mJ/cm^2.

Figure 5 shows scanning electron microscope (SEM) images of the fabricated cuboid structures. The initial coated thickness of SU-8 photoresist is around 150.0 μm and the exposure dosages are 20, 60, and 100 mJ/cm^2. At the exposure dose of 20 mJ/cm^2, thickness after development d_w (with the reflection effect) is around 12.4 μm [Fig. 5(a)], and thickness after development $d_{w/o}$ (without the reflection effect) is around 10.9 μm [Fig. 5(b)]. The thickness after development with or without reflection effect is close due to low exposure dose. However, with larger exposure dose, such as 60 mJ/cm^2, thickness after development d_w is around

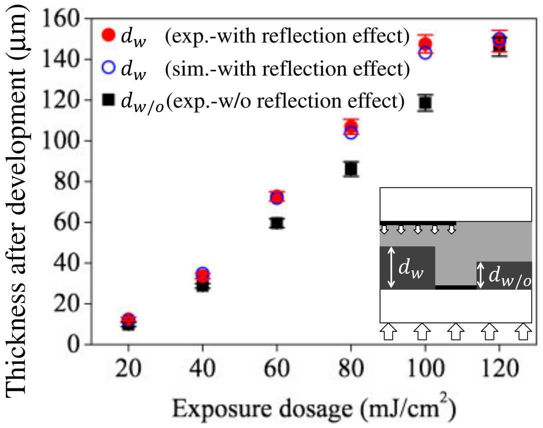


Fig. 6. (Color online) Experimental and simulated results of thickness after development (with/without reflection effect) at coated thickness around 150 μm by back-side partial exposure.

Table II. Parameters in simulation model with back-side partial exposure. Optical parameters are listed in Table I.

Coated thickness, h (μm)	150
Specified thickness, Δh (μm)	0.1
Exposure time,[a] t_{exp} (s)	2/4/6/8/10/12
Reference thickness after development,[b] $d_{\text{w/o}}$ (μm)	9.8/28.8/59.6/86/ 118.6/146.1

a) Incident intensity I_0 is calibrated to be $10.0 \pm 0.2\,\text{mW/cm}^2$.
b) Experimental data.

69.0 μm [Fig. 5(c)] and thickness after development $d_{\text{w/o}}$ is around 60.5 μm [Fig. 5(d)]. Thickness deviation due to reflection is 8.5 μm. The difference becomes more evident due to stronger reflected light. The thickness after development d_{w} is almost fully exposed at 100 mJ/cm^2 [Fig. 5(e)] and thickness after development without reflection effect $d_{\text{w/o}}$ is around 119.6 μm [Fig. 5(f)]. Thickness deviation is about 28.5 μm. It is shown that reflection did cause thicker thickness after development of SU-8, especially at larger exposure dosage.

Reflectivity R_{glass} between SU-8 and the glass substrate is 0.0004 (Table I). This is practically negligible; therefore, reflected light intensity from the glass substrate can be considered as zero in simulation. Reflectivity R_{Cr} between SU-8 and the Cr layer is 0.37 (Table I) and reflected light intensity from the Cr layer is calculated using Eq. (4). Figure 6 shows the experimental and simulation results of thickness after development of cuboid structures by back-side partial exposure dosages from 20 to 120 mJ/cm^2.

The experimental results show that, at the same coated SU-8 photoresist thickness (150.0 μm), the thickness after development increases steadily and approximately linearly with increasing exposure dosages. Thickness after development with the reflection effect is always thicker than thickness after development without the reflection effect. When the exposure dose increases from 20 to 100 mJ/cm^2, the deviation on thickness after development due to reflection effect increases from 2.5 to 28.9 μm. At dosage of 120 mJ/cm^2, deviation is practically negligible, since cuboid SU-8 structures with and without reflection effect are both fully exposed. By using experimental data listed in Table II, simulated thickness after development with reflection effect can be calculated by Eq. (16) with optical parameters listed in Table I. The simulation results also indicate that increasing the exposure dosage is accompanied by increasing deviation on thickness after development (Fig. 6). The simulated and experimental results on thickness after development with reflection effect are very close. The maximum difference between the simulated and experimental results is 3.1% at dosage of 100 mJ/cm^2. This confirms the validity of the proposed model for estimating SU-8 thickness after development with the reflection effect.

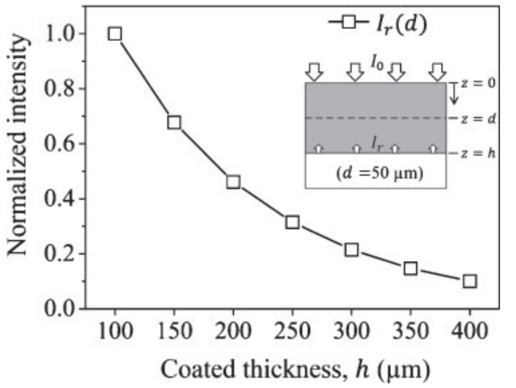


Fig. 7. Simulation results of normalized reflected intensity at the thickness after development of 50 μm with different coated thickness.

Table III. Simulation parameters of reflected intensity in front partial exposure. Optical parameters are listed in Table I.

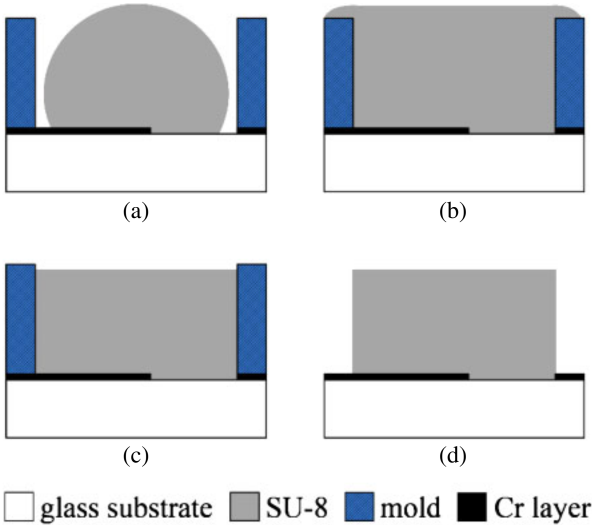
Coated thickness, h (μm)	100/150/200/250/300/350/400
Path depth, z (μm)	50
Thickness after development, d (μm)	50

4.2 Bridge structures

The second test uses bridge structures to investigate the relationship between coated thickness and deviation on thickness after development due to the reflection effect.

Figure 7 shows the simulated reflected intensity variations at the thickness after development of 50 μm due to different coated thickness by using Eqs. (2), (4), and (5) with parameters listed in Tables I and III. As coated thickness (h) increases from 100 to 400 μm, the normalized reflected intensity reduces from 100% to around 10%. Therefore, increasing coated thickness may efficiently reduce the reflection effect on thickness after development.

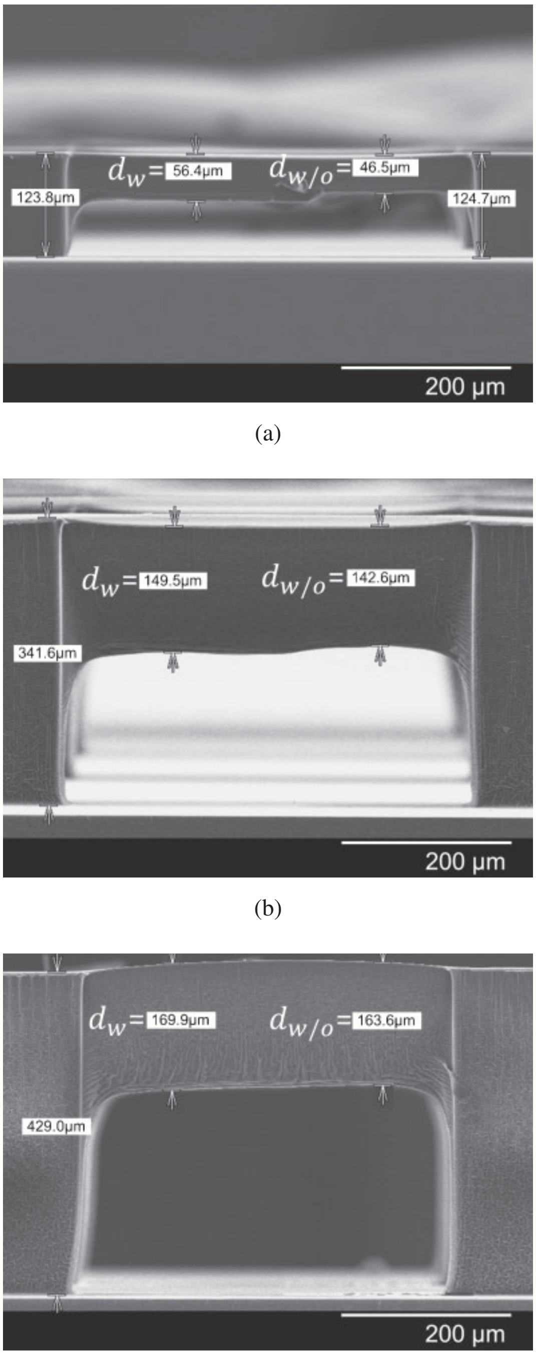
To experimentally investigate the relationship between coated thickness and deviation on thickness after development due to the reflection effect, it needs to coat SU-8 thicker than 300 μm. The conventional spinner method can only coat SU-8 2075 up to 240 μm with single coating according to the Microchem SU-8 2075 data sheet.[22] Previously, over 300-μm-thick SU-8 could be obtained using the multiple coating method; however, this method created other problems, such as non-uniform surfaces, difficult to control soft-baked time, and air bubbles between layers. This study uses a mold method to coat over 300-μm-thick SU-8 photoresist. Figure 8 shows a mold coating method. A metal mold is attached to the glass substrate with the designed Cr layer pattern, and the


(a) (b)

(c) (d)

Fig. 8. (Color online) Mold method for coating over 300-μm-thick SU-8 2075.

height of the metal mold is determined by the required SU-8 photoresist thickness. SU-8 2075 is then injected into the mold, as shown in Fig. 8(a). To evenly spread SU-8 photoresist, it is spun at 500 rpm for 5 to 10 s with an acceleration of 100 rpm/s. Figure 8(b) shows that SU-8 may overflow. Therefore a solid metal plate is used to scrape the overflown SU-8 on the mold edge. SU-8 photoresist is then placed on a horizontal plane for 30 min to improve the uniformity of coated thickness, as shown in Fig. 8(c). After the removal of the mold, SU-8 is soft baked at 65 °C for 20 min and then soft baked at 95 °C for 2 h to have ultra-thick coated SU-8 photoresist, as shown in Fig. 8(d). Then for fabricating bridge structure, after rehydration for over 30 min, the photoresist is exposed by I-line (365 nm), and PEB at 65 °C for 5 min and at 95 °C for 30 min. Final development is performed for 30 min with a Microchem SU-8 developer, followed by a second spray/wash with IPA for another 10 s. The beam length of bridge structure is 500 μm, the beam width of bridge structure is 300 μm, and the beam thickness depends on exposure dosage.



(a)

(b)

(c)

Fig. 9. Experimental results of thickness after development at different coated thickness by front partial exposure; (a) coated thickness is around 124 μm with exposure dosage of 60 mJ/cm^2, (b) coated thickness is 341.5 μm with exposure dosage of 90 mJ/cm^2, (c) coated thickness is 429.0 μm with exposure dosage of 90 mJ/cm^2.

Figure 9 shows SEM images of typical fabricated bridge structures. At the exposure dosage of 60 mJ/cm^2 with coated thickness of SU-8 around 124 μm, Fig. 9(a) shows that the thickness after development of the left bridge structure (d_{w}) and right bridge structure ($d_{\text{w/o}}$) are 56.4 and 46.5 μm, respectively, i.e., deviation on thickness after development due to reflection effect is 9.9 μm. Figure 9(b) shows the SU-8 bridge structure at the exposure dosage of 90 mJ/cm^2 with coated thickness around 341.6 μm by using the mold method. The thickness after development of the left bridge structure (d_{w}) and right bridge structure ($d_{\text{w/o}}$) are 149.5 and 142.6 μm, respectively, i.e., thickness deviation is 6.9 μm. For coated thickness around 429 μm with the exposure dosage of 90 mJ/cm^2, thickness after development of the left bridge structure (d_{w}) and right bridge structure ($d_{\text{w/o}}$) are 169.9 and 163.7 μm, respectively, i.e., thickness deviation due to reflection is 6.2 μm, as shown in Fig. 9(c). In general, it needs longer development time to remove thicker photoresist. If the photoresist to be removed is hard to be reached by the developer, it will also need longer development time. The bridge structure shown in Fig. 9 is an enclosed structure, where the unexposed SU-8 is located at the middle, which makes developer more difficult to reach. Therefore, comparing to cuboid structure shown in Fig. 5, longer development time is needed for bridge structure.

With experimental data listed in Table IV and optical parameters listed in Table I, the thickness after development with reflection effect can also be simulated. Figure 10 summarizes the experimental and simulation results by front partial exposure at coated thicknesses around 122.7, 342.1,

Table IV. Parameters in simulation model with front partial exposure. Optical parameters are listed in Table I.

Coated thickness[a], h (µm)	122.7/342.1/426.7
Specified thickness, Δh (µm)	0.1
Exposure time[a], t_{exp} (s)	6/9/9
Reference thickness after development[a], $d_{\mathrm{w/o}}$ (µm)	46.5/143.1/162.8

[a] Experimental data and incident intensity I_0 is calibrated to be $10.0 \pm 0.2\,\mathrm{mW/cm^2}$.

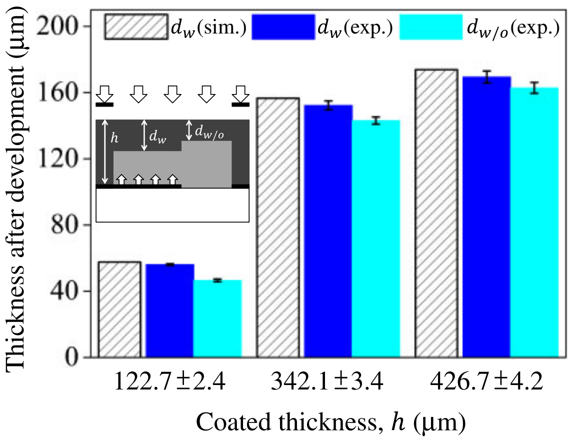


Fig. 10. (Color online) Experimental and simulation results of thickness after development at different coated thickness by front partial exposure.

and 426.7 µm. Thickness after development with reflection effect (d_{w}) is always thicker than thickness after development without reflection effect ($d_{\mathrm{w/o}}$) at three different coated thickness ranges. At the average coated thickness of 122.7 µm, the average of measured thickness after development with the reflection effect is 56.1 µm and the simulated thickness after development with the reflection effect is 57.6 µm. At the average coated thickness of 342.1 µm, the average of measured thickness after development with the reflection effect is 152.2 µm and the simulated thickness after development with the reflection effect is 156.6 µm. At the average coated thickness of 426.7 µm, the average of measured thickness after development with the reflection effect is 169.4 µm and the simulated thickness after development with the reflection effect is 173.8 µm. If thickness deviation due to reflection effect is divided by coated SU-8 thickness, so called thickness deviation ratio, the measured thickness deviation ratios are 7.9, 2.7, and 1.6% for average coated thicknesses of 122.7, 342.1, and 426.7 µm, respectively. And the simulated thickness deviation ratios are 9.2, 3.9, and 2.5% for coated thicknesses of 122.7, 342.1, and 426.7 µm, respectively. An increase in coated thickness effectively reduces the thickness deviation ratio. The simulated thickness deviations are shown to agree with the experimental results by front partial exposure, which further confirms the capability of the proposed simulation model in estimating SU-8 thickness after development with the reflection effect under partial exposure.

In further discussion, simulation errors may come from discrepancy between experimental variations and simulation parameters. Due to the limitation on our fabrication and measurement facilities, even under the same experimental condition setting, experimental results may not be the same. For example, in Fig. 6, coated thickness of SU-8 is set at 150 µm, but actual coated thickness is 150 ± 5 µm. In Fig. 10, thicker coated thickness of SU-8 exhibits wider distribution on thickness after development in experimental data. Also actual exposure dose could be slightly different from the setting value. For example, at exposure dose of $80\,\mathrm{mJ/cm^2}$ in Fig. 6, the simulated thickness after development with reflection effect is less than experimental result with reflection effect for about 2.9 µm. If exposure dose in simulation increases to $82.5\,\mathrm{mJ/cm^2}$, the simulated value will be thicker than experimental result for about 0.5 µm. Similarly, in Fig. 10, for example, at coated thickness of 342.1 ± 3.4 µm, the coated thickness and exposure dose setting in simulation are 342.1 µm and $90\,\mathrm{mJ/cm^2}$, respectively, which would lead simulation result larger than experimental data. If exposure dose in simulation is reduced to $87\,\mathrm{mJ/cm^2}$, simulated thickness after development with reflection effect will be less than average experimental result for about 0.9 µm. It indicates that the exposure dose used in simulations will affect the simulated thickness after development as well as the tendency on simulation errors in Figs. 6 and 10 directly.

5. Conclusions

This study proposes a simulation model to predict SU-8 thickness after development with reflection effect under partial exposure. Two kinds of SU-8 structures are fabricated to demonstrate the capability of the proposed model. Cuboid structures are fabricated by back-side partial exposure with and without the reflection effect to investigate the relationship between exposure dosage and deviation on thickness after development. The maximum difference between simulated and experimental results is 3.1%. Bridge structures are fabricated by front partial exposure to investigate the relationship between coated thickness and deviation on thickness after development due to reflection effect. The maximum difference between simulated and experimental results is 2.9%. Experimental and simulation results both confirm that the reflection effect causes deviation on thickness after development, larger exposure dosage causes larger thickness deviation, and increasing coated thickness can reduce the thickness deviation ratio. These results verify the accuracy of the proposed model in predicting thickness after development of negative photoresist SU-8 under partial exposure with reflection effect.

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