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Effect of substrate curvature on thickness distribution of polydimethylsiloxane thin film in spin coating process*

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The polymer spin coating is critical in flexible electronic manufaction and micro-electro-mechanical system (MEMS) devices due to its simple operation, and uniformly coated layers. Some researchers focus on the effects of spin coating parameters such as wafer rotating speed, the viscosity of the coating liquid and solvent evaporation on final film thickness. In this work, the influence of substrate curvature on film thickness distribution is considered. A new parameter which represents the edge bead effect ratio (r_e) is proposed to investigate the influence factor of edge bead effect. Several operation parameters including the curvature of the substrate and the wafer-spin speed are taken into account to study the effects on the film thickness uniformity and edge-bead ratio. The morphologies and film thickness values of the spin-coated PDMS films under various substrate curvatures and coating speeds are measured with laser confocal microscopy. According to the results, both the convex and concave substrate will help to reduce the edge-bead effect significantly and thin film with better surface morphology can be obtained at high spin speed. Additionally, the relationship between the edge-bead ratio and the thin film thickness is like parabolic curve instead of linear dependence. This work may contribute to the mass production of flexible electronic devices.

Keywords: spin coating, non-planar substrate, film thickness distribution, edge-bead effect

PACS: 81.15.–z, 68.15.+e, 47.85.mb, 68.55.–a **DOI:** 10.1088/1674-1056/27/6/068104

1. Introduction

Spin coating is currently the predominant technique to produce uniform thin films with the thickness values on the order of micrometers and nanometers in the electronics and other industries.[1–6] For micro-electro-mechanical system (MEMS) devices, part of photoresist films are used as final structures of devices. Therefore, the thickness of the film determines the design of device and its uniformity is highly required. It is difficult to apply a highly uniform film to a planar substrate over a large area ($\phi > 30$ cm) with a highly controllable and reproducible film thickness due to the fluid dynamic behaviors.[7,8] In many cases, the coating material is polymeric and is used in the form of a solution from which the solvent evaporates. Centrifugal force is one of the driving forces to make the solution move outward along the radial direction. The viscous force and surface tension cause a thin residual film to be retained on the flat substrate. Several processing parameters involved in the spinning process are dispensing volume, final spin speed, substrate flatness, solution viscosity, solution concentration, spin time, etc.[9–11] The importance of spin coating is manifested in its widespread application in science and industry. It is thus desirable to gain a detailed understanding of the spin coating process from both an experimental and a theoretical point of view.[12]

The pioneering analysis of spin coating was performed more than fifty years ago by Emile *et al.*[13] who considered the spreading of a thin axisymmetric film of Newtonian fluid on a planner substrate rotating with constant angular velocity. According to the Emslie's model, Washo *et al.*[14] considered the effects of different droplet dispense methods on the thickness of the film based on the Navier–Stokes equation to obtain the corresponding model and formula in 1977. They assumed that the spin coating method was a disk rotation system, and the solution used was Newtonian fluid. The effects of Coriolis force, fluid gravity, solvent evaporation, substrate wettability, and the interface properties of air and solution have not been taken into account. However, this model directly reveals the essential dynamics of the spin coating process for future studies. After that, Bornside and Lawrence investigated the viscosity of the polymer solution and the effect of the spin angle on film thickness based on the ideal mechanic model established by Emslie. They revealed that the overall concentration of the polymer solution is constant and only the concentration near the free surface boundary layer is varied.[15,16] However, Bornside and Lawrence did not consider the influences of gradual curing of free surface on solvent evaporation rate and solution concentration. Mouhamad Y *et al.*[17] studied the dynamics of polymer film formation in the spin coating process.

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A semi-empirical model was proposed to permit the calculation of the solvent evaporation rate and the temporal evolution of the solute volume fraction and solution viscosity. Solvent evaporation is one of the main determinants of film curing, which has a significant effect on the film thickness. Moreover, the change of solution concentration directly affects the rheological properties of the solution. Also, it will affect the uniformity of film thickness distribution.

The edge-bead effect is one of the most critical problems, which affects the film thickness distribution. Mack C *et al.*[18] investigated the edge-bead formation mechanism which has been understood in terms of a surface tension of the resist fluid. At the edge of the coated liquid film, the surface should have a curvature larger than that in the flat central region. It reveals that the Laplace pressure due to the surface tension acting as smoothening the curvature distribution around the edge region. Na J Y *et al.*[19] characterized the effect of the spin-coating time on the microstructure evolution during semiconducting polymer solidification to establish the relationship between this parameter and the performances of the resulting polymer field-effect transistors (FETs). According to the results, a short spin-coating time of a few seconds, dramatically improved the morphology and molecular order in a conjugated polymer thin film. Shiratori S[20] establishes a new model to predict the dominant physics for the double-peaked edge-bead formation process. It has been concluded that the capillary flow which was caused by the evaporation of the solvent, was the dominant physics for the double-peak formation.

Even though spin coating has been universally used in the industry for a long time, more theoretical and experimental study are still in great demand to improve the machining technology.[21–24] The influence of the curvature of the substrate on the uniformity of film thickness distribution has not been studied in depth. If the interaction between the polymer and the substrate is strong, it will affect the dynamic behaviors of the polymer segments on the surface of the substrate. And this can also induce the non-uniformity of film thickness distribution. The present work is to clarify the effects of spin coating substrate and spin speed on film thickness distribution. Also, the dominant physics of edge-bead phenomena is investigated. An accurate analysis of spin coating will permit better design and control of the process in its various applications.

2. Experimental procedure

The polymer film was formed by spin coating of PDMS (Sylgard184 Silicone Elastomer, Dow Corning, Midland, MI) solution which is formed by mixing the prepolymer and curing agent of PDMS in a 10 : 1 ratio by mass with a spin coater (KW-4A, SETCAS Electronics Co., Ltd) as shown in Fig. 1. In each group, about 20-ml PDMS solution droplet was placed in the substrate and the spin coating process was done for 30 s. After the spin coating process, the whole spin-coated substrate was dried in the oven at 90 °C for 60 min. The film surface morphology and film thickness were measured by laser confocal microscopy (Keyence VK-X250). Polished silicon wafers (size: 2 inch, 1 inch = 2.54 cm) in different curvatures were used as the spin coating substrate to study the influence of film thickness distribution. Substrate deformation induced by the vacuum suction system of the spin coater was very small compared with by other parameters such as spin speed or fluid viscosity and can be ignored in this study.

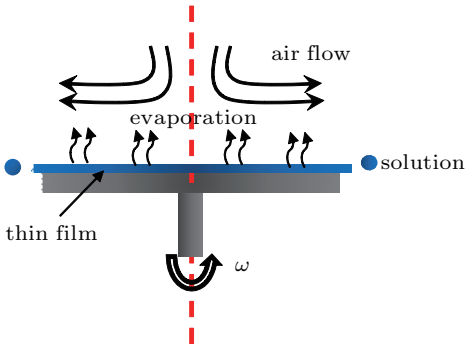


Fig. 1. (color online) Schematic diagram of process for PDMS solution spin coating.

3. Results and discussion

3.1. Spin coating on a planar substrate

In this part, the polished silicon wafer is used as the planar substrate with the PV (Peak–Valley) value smaller than 5 μm. Five groups of experiments with various speeds (1000 rpm, 2000 rpm, 3000 rpm, 5000 rpm, 8000 rpm) are done to study the influence of spin speed on film thickness distribution. The film thickness distribution is measured along the radial direction as displayed in Fig. 2 and the substrate center is set as the zero point of the *x* axis. Based on the results, the film thickness decreases with the increasing of spin speed and the film thickness distribution becomes more homogeneous with spin speed increasing. The fluid in the center of the substrate is driven out by the centrifugal force. With the increasing of spinning speed, the driving force increases as well and more liquids are spun out of the substrate which will make the film thinner. The total average film thickness is shown in Fig. 3.

It could be concluded that the film thickness is nonlinearly related to spin speed. The largest total average film thickness is 41.9 μm at a spin speed of 1000 rpm with large edge-bead effect area, and the edge-bead thickness is about 60 μm. In this work, the edge-bead effect area refers to the area near the wafer edge and the film thickness increases sharply in this region. The smallest total average film thickness is 3.25 μm with a smaller edge-bead effect area with a thickness of 4.4 μm at a spin speed of 8000 rpm. The edge-bead effect is mainly due to the fact that the fluid properties dictate a constant angle at the solid/liquid/gas interface and a

thick edge-bead is confined at the wafer edge. And the Laplace pressure will move fluids from the side to the upper region. Another reason for such a film pattern is the increasing of friction with air at the periphery, resulting in forming a dry skin at the edge and impeding fluid flow.[20] As a result, the fluid in the center of the substrate, which is still kept being driven out by centrifugal force, begins to flow over the dry film and dries, resulting in buildup at the edge-bead. The spreading of a thin, viscous, film of liquid under the external centrifugal force is comprised of two regions. The first region is a flat region and the dynamics of which is determined by the balance between driving forces and viscous dissipation. The second region is near the advancing front, the curvature of which is governed by the interplay between the liquid surface tension and the driving force. When the spinning is stopped, the force balance suddenly changes due to a loss of the centrifugal force. At this stage, the liquid motion is dominated by the Laplace pressure, and it quickly moves fluids from the side to the upper region. In this way, the single edge-bead is formed shortly after the spin-stopping.[25–27]

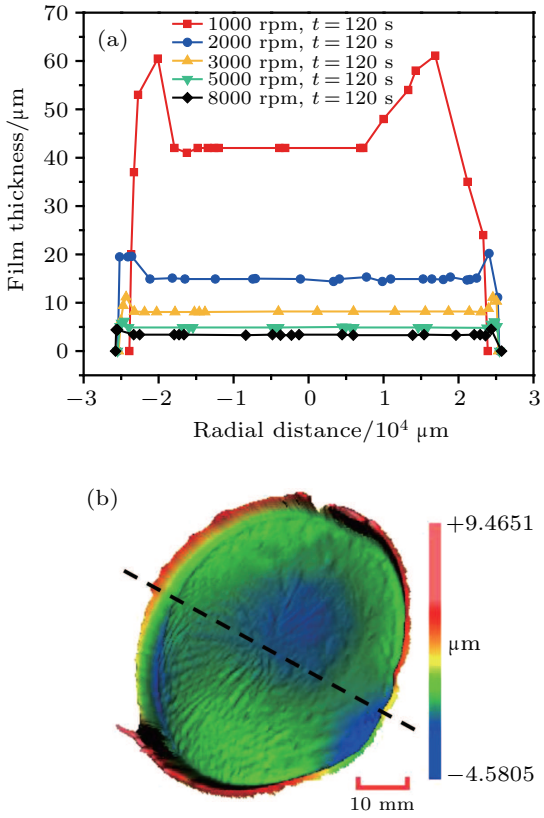


Fig. 2. (color online) (a) Film thickness distributions along radial direction on a planar substrate with various spin speeds (1000 rpm, 2000 rpm, 3000 rpm, 5000 rpm, 8000 rpm). Substrate center is set as zero point of x axis. (b) Film surface topology with spin speed 3000 rpm.

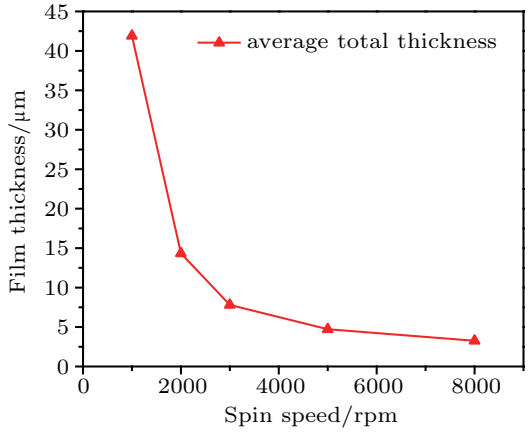


Fig. 3. (color online) Relationship between average film thickness and spin speed.

3.2. Spin coating on slightly deformed substrate

In this part, spin coating on the different slightly deformed substrates is investigated in detail. As shown in Fig. 4, the convex and concave silicon substrates are used as the spin coating substrate with various spin speeds 1000 rpm, 3000 rpm, and 5000 rpm. In order to make the convex substrate (Fig. 4(a)), a thin and small gasket is placed in the center region of the polished silicon wafer and the edge of the wafer is glued on a circular stainless steel sheet which is larger than the silicon wafer. Then, the whole substrate deformation is measured by Taylor Hobson 3D (three-dimensional) profiler. In this part, the center deformations of the convex substrate are 250 μm and 400 μm. Since the stiffness of the stainless steel sheet is large enough, the deformation induced by the vacuum suction system of spin-coater is ignored. For the

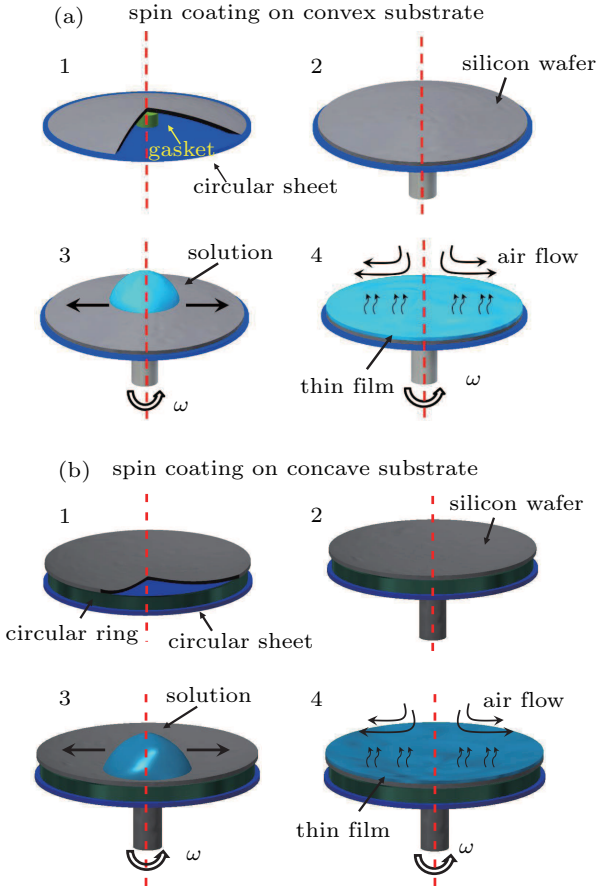


Fig. 4. (color online) (a) Schematic diagram of process of spin coating on convex substrate and curing on convex substrate. (b) Schematic diagram of process of spin coating on concave substrate and curing on convex substrate.

convex substrate with deformation of 250 μm, three groups of experiments with spin speeds of 1000 rpm, 3000 rpm, and 5000 rpm are conducted. For the convex substrate with deformation of 400 μm, the same procedures as those in the case of 250 μm are adopted.

To make the concave substrate, a circular sheet and a ring of stainless steel are used. As presented in Fig. 4 (b), the ring diameter is about 50 mm and the circular sheet diameter is about 56 mm. Firstly, the ring is glued to the sheet. Then, the silicon wafer center is glued to the center of the circular sheet. Finally, the whole substrate deformation is measured by the Taylor Hobson 3D profiler. In this part, the center deformation of the concave substrate is 330 μm.

3.2.1. Planar and convex substrate

As displayed in Fig. 5(a), the film thickness distributions along the radial direction on a planar substrate and convex substrate (center deformation: 250 μm) at the spin speed of 1000 rpm, 3000 rpm, 5000 rpm are compared with each other. According to the results, the film thickness on the convex substrate decreases with the increase of spin speed and the largest film thickness occurs in the edge region. The flat region average film thickness (h_a), the largest film thickness (h_l), and the edge-bead effect ratio (r_e) are shown in Table 1. The edge-bead effect ratio (r_e) is defined as the ratio of the width of the edge-bead effect region to the film thickness of the substrate in this work. The flat region film thickness is obtained by calculating the average value of the film thickness of five points along the radial direction, and the points are chosen from the flat region of the film, which is far away from the edge region. The largest film thickness (h_l) is the largest value of the whole polymer film. When it is at the spin speed of 1000 rpm, the film thickness of planar substrate is about 41.90 μm which is larger than that of convex substrate 29.01 μm. And the edge-bead effect ratio of planar substrate $r_e = 605.01$ is also much larger than that of the convex substrate. If the spin speed is increased and the other parameters are kept the same, the film thickness of both substrate decrease. As presented in Fig. 5(a), when the spin speed is 3000 rpm, the film thickness of planar and the convex substrate are 8.19 μm and 8.66 μm and the difference was 0.47 μm. For 5000 rpm, the film thickness of planar and the convex substrate are 4.91 μm and 5.00 μm and the difference is 0.09 μm. Therefore, the influence of substrate on film thickness is significant under the low spin speed such as 1000 rpm or smaller.

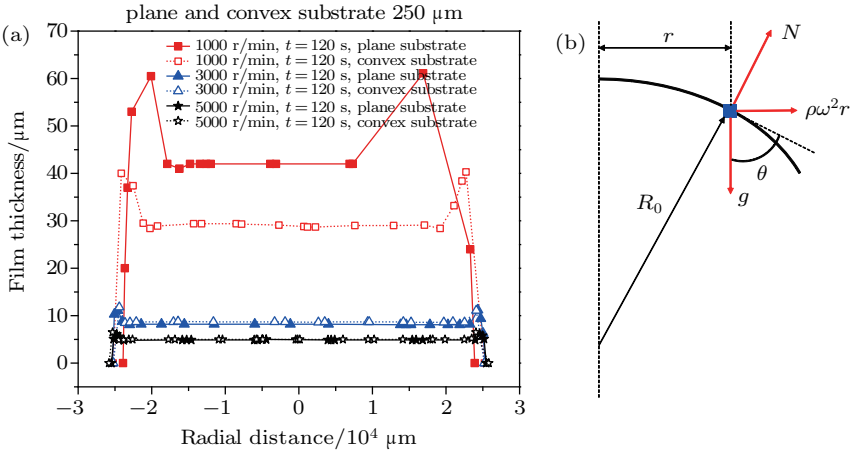


Fig. 5. (color online) (a) Film thickness distributions along radial direction on planar substrate and convex substrate (center deformation 250 μm) at spin speeds of 1000 rpm, 3000 rpm, and 5000 rpm. Substrate center is set as the zero point of x axis. (b) Mechanical schematic plot of PDMS micro-unit on convex substrate during spin coating.

The mechanical schematic plot of the PDMS micro-unit on the convex substrate during spin coating is presented in Fig. 5 (b), where N is the driving force of the unit element and it is also the resultant force of the gravity and centrifugal force. Using cylindrical polar coordinates (r, θ, z) with origin in the center of rotation, the z axis perpendicular to the plane, and the radial coordinates r and θ rotating with the plane at angular velocity ω, the balance between viscous and centrifugal forces per unit volume for Newtonian fluid on a planar substrate is given by

$$-\eta\left(\mathrm{d}^2v/\mathrm{d}z^2\right) = \rho\omega^2 r, \tag{1}$$

where η denotes the absolute viscosity, ρ the density, v the velocity in the radial direction

However, for the convex substrate, the balance is given by

$$-\eta\left(\frac{\mathrm{d}^2v}{\mathrm{d}z^2}\right) = \rho\omega^2 r\sin\theta + g\cos\theta, \tag{2}$$

$$\frac{r}{R_0} = \cos\theta, \tag{3}$$

and the thickness h is given by

$$h(r,t) = \left[h_0^{-2} - \frac{2t}{3\eta R_0}\left(\frac{\rho\omega^2 r^2}{\sqrt{R_0^2 - r^2}} + 2\rho\omega^2\sqrt{R_0^2 - r^2} - 2g\right)\right]^{-1/2}, \tag{4}$$

where h_0 is the initial film thickness at the moment $t = 0$ and $r = 0$, R_0 is the radius of curvature of the substrate.[28]

Table 1. Characteristics of film thickness and edge-bead effect ratio for the planar, convex, and concave substrate at different spin speeds.

	Flat region average film thickness (h_f)/μm	Largest film thickness (h_l)/μm	Edge-bead effect ratio (r_e)
Planar: 1000 rpm	41.90	61.10	605.01
Planar: 3000 rpm	8.19	11.20	346.43
Planar: 5000 rpm	4.91	6.20	344.63
Convex: 1000 rpm	29.01	40.30	331.05
Convex: 3000 rpm	8.66	11.80	490.76
Convex: 5000 rpm	5.00	6.50	415.14
Concave: 1000 rpm	27.42	36.20	481.69
Concave: 3000 rpm	8.76	11.10	710.00
Concave: 5000 rpm	5.19	6.10	519.34

At a slow spin speed of 1000 rpm, the centrifugal force is not strong enough to overcome the liquid surface energy and thus the curvature of the solution is like a flat droplet. According to Eq. (4), the convex substrate will obtain more driving force which could encourage the fluid flow towards the wafer edge and more liquids are spun out of the wafer. Therefore, with lower spin speed, the middle region film thickness with convex substrate was much smaller than with the planar substrate. However, with higher spin speed, the influence of centrifugal force increases sharply and the curvature of the substrate will not affect the film thickness significantly. For the edge part, the unit linear velocity increases and the viscosity decreases all of a sudden, so the film thickness changes quickly. The edge-bead thickness is also smaller than that of the planar substrate due to the thinner film. As mentioned above, if the spinning stops, the force balance suddenly change due to a loss of the centrifugal force. In this case, the liquid motion is dominated by the Laplace pressure, and it quickly moves fluids from the side to the upper region.

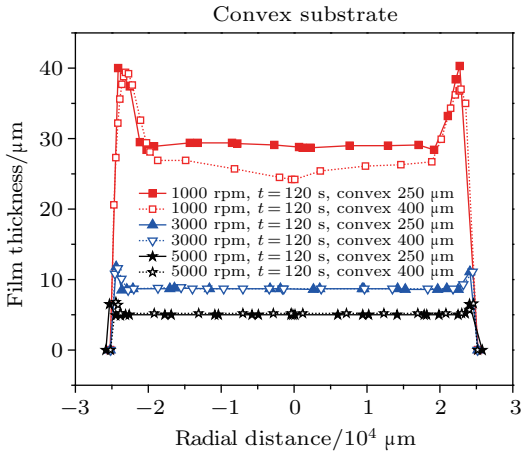


Fig. 6. (color online) Film thickness distribution along the radial direction on a convex substrate (center deformation 250 μm/400 μm) at the spin speed of 1000 rpm, 3000 rpm, 5000 rpm. The substrate center is set as the zero point of x axis.

Convex substrates with different center deformations are also discussed in this experiment. Based on the results in Fig. 6, the film thickness distribution at high spin speed changes slightly with the center deformation. However, at a slow spin speed, the film thickness at the center region changes distinctly. When the deformation is about 250 μm, the flat region film thickness is about 29.01 μm. But if the deformation is about 400 μm, the flat region film thickness is about 25.69 μm. Based on these results, it can be concluded that large substrate deformation will accelerate the solution flowing to the edge region but the main fact is still at the spin speed. And the centrifugal force is the main driving force during the spin coating process.

3.2.2. Planar, convex and concave substrate

Figure 7 shows that the film thickness distributions along the radial direction on a planar, convex and concave substrate (center deformation of convex substrate 250 μm, center deformation of the concave substrate 250 μm) at spin speeds of 1000 rpm, 3000 rpm, 5000 rpm are compared with each other. Generally speaking, the film thickness on the three kinds of substrates decreases with spin speed increasing and the largest film thickness occurs in the edge region. At low spin speed, the influence of substrate is more significant than at high spin speed. When it is at the spin speed of 1000 rpm, the film thickness of concave substrate is about 27.42 μm which is smaller than that of convex substrate (29.01 μm). If the spin speed is increased and other parameters are kept the same, the film thickness values of both substrates decrease. As presented in Fig. 7(b), when the spin speed is 3000 rpm, the film thickness values of concave and convex substrate are 8.76 μm and 8.66 μm and their difference is 0.10 μm. For 5000 rpm (Fig. 7(c)), the film thickness values of concave and convex substrate are 5.19 μm and 5.00 μm and their difference is 0.19 μ m. It could be concluded that the substrate deformation cannot influence the film thickness distribution significantly at high spin speed. For the concave substrate as shown in Fig. 7(d), the balance between viscous and centrifugal forces per unit volume of Newtonian fluid on a planar substrate is described by

$$-\eta\left(\frac{\mathrm{d}^2 v}{\mathrm{d}z^2}\right) = \rho\omega^2 r\cos\theta - g\sin\theta, \tag{5}$$

where η denotes the absolute viscosity, ρ the density, v the velocity in the radial direction

However, for the convex substrate, the balance is described by

$$\frac{r}{R_0} = \sin\theta. \tag{6}$$

And the thickness h is given by

$$h(r,t) = \left[h_0^{-2} + \frac{2t}{3\eta R_0}\left(-\frac{\rho\omega^2 r^2}{\sqrt{R_0^2 - r^2}} + 2\rho\omega^2\sqrt{R_0^2 - r^2} - 2g\right)\right]^{-1/2}, \tag{7}$$

where h_0 is the initial film thickness at the moment $t = 0$ and $r = 0$, R_0 is the radius of curvature of the substrate.[29,30]

According to the results, it is much easier to obtain the polymer film of more uniform thickness with a convex or concave substrate. The concave substrate will force the liquid flow towards the center region based on Eqs. (5) and (7). If the spin speed is lower than 1000 rpm, the film is quite thick and more liquids moves towards the center region. If the spin speed is higher than 1000 rpm, the centrifugal force is increased sharply and the curvature of the substrate will not influence the uniformity of the film.

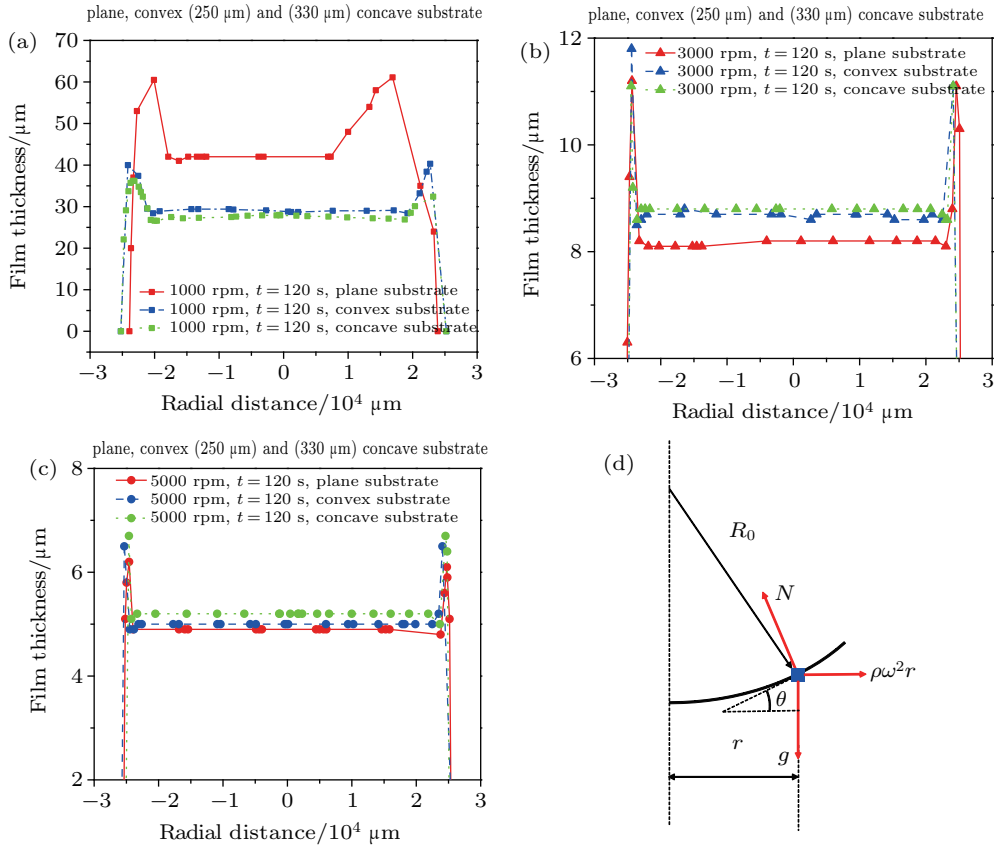


Fig. 7. (color online) Film thickness distributions along the radial direction on a planar, convex, and concave substrate (center deformation for convex substrate 250 μm, center deformation for the concave substrate 330 μm) at spin speeds of (a) 1000 rpm, (b) 3000 rpm, (c) 5000 rpm. The substrate center is set as zero point of x axis. (d) Mechanical schematic diagram of PDMS micro-unit on the concave substrate during spin coating.

3.3. Curing on the slightly deformed substrate

In order to study the dynamic behaviors of PDMS solution after spin-coated on a silicon wafer, the wafer with a concave deformation in the center region is dried in the oven. To make the concave substrate, a device is designed as displayed in Fig. 8. Firstly, the wafer substrate is glued to a circular stainless steel sheet in the center region. And then, the silicon wafer is spun coated with the solution. Thirdly, the whole substrate deformation is placed on the device shown in Fig. 8(c) to make a concaved substrate. In Fig. 8(c), the spin-coated wafer was glued on the back with a micrometer head to control the deformation. What is more, the accurate wafer deformation is measured by Taylor Hobson 3D profiler. In this part, the center deformation of the concave substrate is 450 μm. Finally, the whole device with spin-coated wafer is dried in the oven at 90 °C for 60 min.

The film thickness distributions along the radial direction of the planar substrate and the concave substrate (center deformation 450 μm) at the spin speed of 1000 rpm and 3000 rpm are displayed in Fig. 9. For each spin speed, three sets of experiments are performed. For the first set, the solution is spun and dried on a planar substrate. For the second set, the solution is spun on a concave substrate and dried on a planar substrate. For the third set, the solution is spun on a planar

substrate and dried on a concave substrate. There is a significant difference among the three sets of experiments at the speed of 1000 rpm. The film thickness is largest when the solution is spun and dried on a planar substrate. If the solution is spun on a concave substrate and dried on a planar substrate, the film thickness is smallest. However, if the spin speed is 3000 rpm, the difference among the three sets is not obvious. The concave substrate could influence the film thickness at low spin speed, such as lower than 1000 rpm. At low spin speed, the film thickness is about 25 μm–40 μm which is much larger than at high spin speed. Before curing, the solution of the coated film with larger thickness is more likely to move towards the center region. Therefore, the edge-bead ratio could be reduced and the film thickness will be more homogeneous. If the concave substrate is used in the spin coating process, both the curvature of substrate and the centrifugal force influence the solution spreading. However, the solution cannot flow freely because of the evaporation and solidification process.

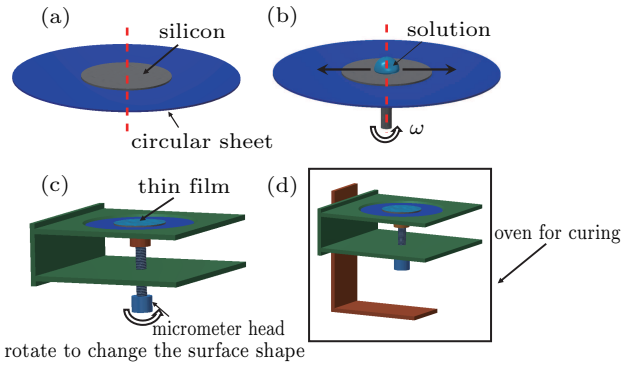


Fig. 8. (color online) Schematic diagrams for the process of spin coating on a planar substrate and curing on the concave substrate.

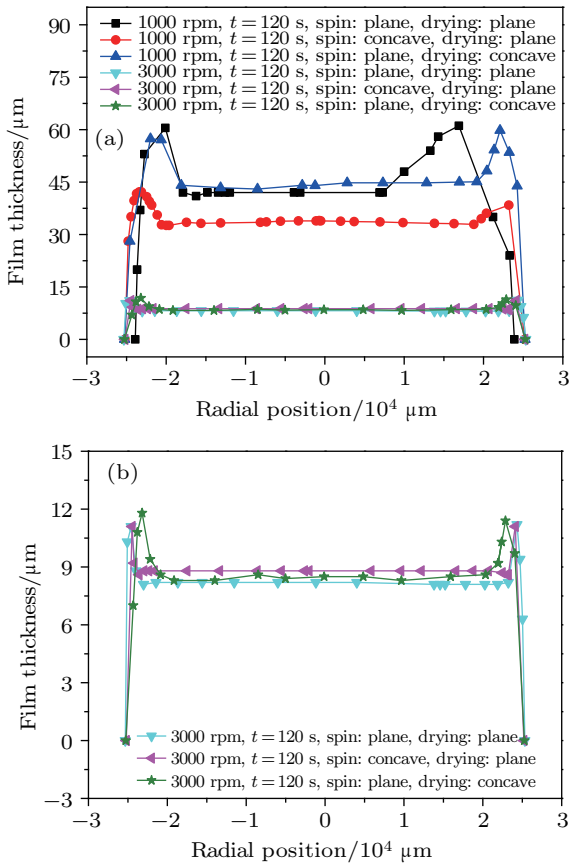


Fig. 9. (color online) (a) Film thickness distributions along radial direction on planar substrate and concave substrate (center deformation 450 μm) at spin speeds of 1000 rpm and 3000 rpm. (b) Film thickness distributions at the spin speed of 3000 rpm. The solution was spun on planar substrate ora concave substrate and dried on a planar substrate and a concave substrate separately. The substrate center is set as zero point of *x* axis.

3.4. Edge-bead formation and influencing factors

The polymer film suffers several physical changes such as a spreading process and a drying process, which results in a non-uniform distribution of the thickness. One of the most known thickness undulations is the "edge-bead effect" which appears as a thick ridge along a periphery of the substrate. The edge-bead causes serious problems such as a particulate contamination due to a crack of the bead by mechanical wafer handlers. The bead also stands as an obstacle for a proximity exposure. The mechanism of the edge-bead formation can be understood in terms of a surface tension of the resist fluid. At the beginning of the spin coating process, a specified volume of the liquid is dispersed in the center of the substrate. Then, it is spread by the centrifugal force, and the liquid flows radially outward across the substrate. When the spinning is stopped, the force balance suddenly changes due to a loss of the centrifugal force. At this stage, the liquid motion is dominated by the Laplace pressure. Since the curvature of the substrate has a steep gradient at the junction between the upper and the side regions of the substrate, Laplace pressure can reduce the curvature distribution, and it quickly moves fluids from the side to the upper region (Fig. 10).

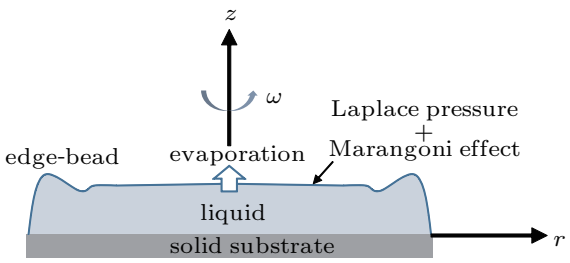


Fig. 10. Schematic diagram of a thin film flow.

The characteristics of film thickness and edge-bead effect ratio for the planar, convex and concave substrate at different spin speeds are displayed in Table 1. The results demonstrate that the edge-bead effect ratio depends more on film thickness instead of substrate curvature. As presented in Fig. 11(a), the relationship between the edge-bead ratio and the thin film thickness is like a parabolic curve for the experimental results. When the film thickness is 29.01 μm, the curve reaches the

lowest point and the edge-bead ratio is 331.05. If the film thickness is smaller than 29.01 μm, the edge-bead ratio decreases from 710 to 331.05. However, if the film thickness keeps on increasing, the edge-bead ratio increases. In order to clarify the relationship between film thickness and edge-bead ratio, a two-dimensional (2D) model is made in this work. Due to the discontinuity and non-differentiability derived from the physical differences of fluids, it is hard to provide a precise method to solve the equations at the fluid interface. The level set method is used to handle the deformable interfaces between the droplets and the ambient air. The "wetted wall" is used as the boundary between the liquid and the substrate.

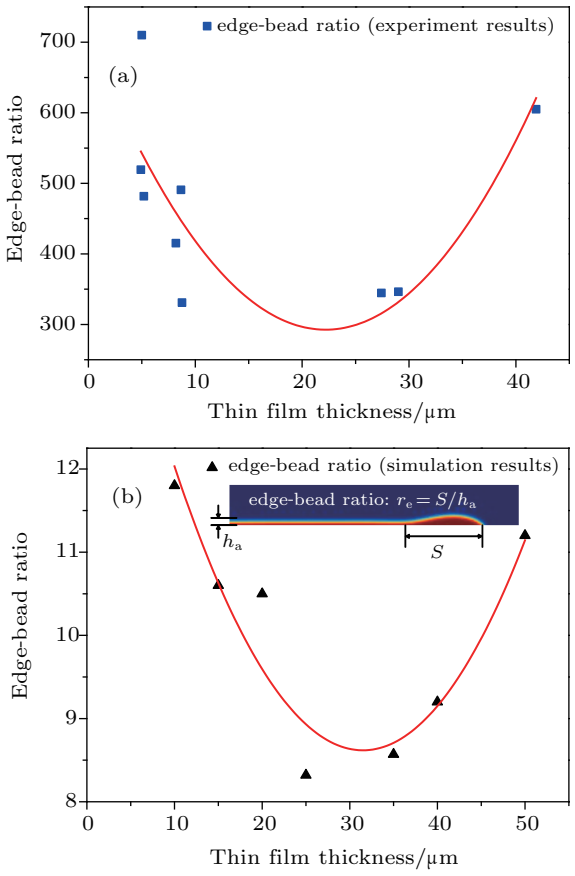


Fig. 11. (color online) (a) Experimental and (b) simulation results of edge-bead effect ratio versus thin film thickness.

A scaled-down model is set up to avoid the large calculation cost. The calculation is based on finite element method (FEM) and the weighted residual approach in the weak solution form is obtained. The minimum element size is 0.002 mm and the maximum element size is 0.045 mm. The simulation results are shown in Fig. 11(b), the relationship between the edge-bead ratio and the thin film thickness is also like a parabolic curve. The lowest point can be obtained when the film thickness is about 25 μm. As mentioned before, the Laplace pressure dominates the fluid motion and it is the driving force for edge-bead formation process. If the film thickness decreases, the radius of edge-bead curvature will decrease. This will result in the increasing of Laplace pressure and the edge-bead was manipulated by larger driving force. However, the decreasing of film thickness induces large fluid viscosity and this will increase the flow resistance in the edge-bead region. For the edge-bead phenomenon, which is formed shortly after the spinning, both the two effects come into play in the edge-bead formation process. This leads to the generation of extreme points as obtained both in the experiments and simulations.

4. Conclusions

In this paper, to clarify the influences of substrate and spin speed on thin film thickness distribution in the spin coating process, both the experimental and theoretical investigations are presented. With the help of the laser confocal microscope, the film thickness can be described more accurately. It can be concluded that at high spin speed ($>$ 1000 rpm), the film thickness is mainly manipulated by the centrifugal force instead of other parameters such as curvature of the substrate. However, at low spin speed, the film thickness distribution largely depends on the curvature of the substrate. Additionally, an interesting phenomenon about the edge-bead effect of the spin-coated film is observed. It is the convex and concave substrate that will lead to smaller edge-bead effect than that of a planar substrate. Also, the edge-bead ratio is mainly influenced by the film thickness and its relation to thickness is in the form of a parabola-like curve. It seems that the edge-bead effect is mainly induced by the Laplace pressure and solution viscosity. It is worth further studying.

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