Optimizing the fluid dispensing process for immersion lithography

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(Received 3 June 2004; accepted 4 October 2004; published 14 December 2004)

The concept behind immersion lithography is the insertion of a high refractive index liquid in the space between the final projection lens of an exposure system and the device wafer to improve the overall resolution of the exposure process. Computational fluid dynamics (CFD) simulations were performed in order to investigate the process of initially filling the lens-wafer gap with immersion fluid. The CFD models were used to investigate the effects of dispense velocity, gap height, and fluid dispense angle on the fill process; specifically on the possibility of air entrainment. The simulations revealed that there is an optimal region in the parameter space of gap height and dispense velocity for which the gap fills completely. Outside of this region, either excessive inertial or surface tension forces cause an undesirable, incomplete filling process. The optimal region was found to shift somewhat based on the fluid dispense angle. Finally, experiments were performed to verify the CFD models. The CFD simulations and the experimental results were in good agreement, both qualitatively with regard to the shape and evolution of the free surface and quantitatively with regard to the velocity of the contact line. © 2004 American Vacuum Society. [DOI: 10.1116/1.1824065]

I. INTRODUCTION

Immersion lithography has been proposed as a method for extending optical lithography resolution to 45 nm and below.1 The premise behind immersion lithography is to improve resolution by increasing the index of refraction in the space between the final projection lens of an exposure system and the device wafer by inserting a high index liquid in place of the low index air that currently fills the gap. The liquid in the gap is an optical element and therefore must have a uniform index of refraction. To this end, the gap must be completely filled with liquid (water for 193-nm lithography with other fluids being evaluated for 157-nm lithography2) and air bubbles cannot be tolerated.

In order for immersion lithography to be practical, the introduction of liquid into the wafer-lens gap must not adversely impact the overall manufacturing process. Since the immersion fluid acts as an optical component during the lithographic process, it must retain a high and uniform optical quality. It is critical that the fluid management system reliably and rapidly fill the entire lens-wafer gap,3 maintain the fill under the lens throughout the entire exposure process, and ensure that no bubbles are entrained during filling or scanning. Optimization of the fluid dispensing process is essential to the success of immersion lithography; therefore, two- and three-dimensional (2D and 3D) computational fluid dynamics (CFD) models have been developed to simulate the filling process. Several previous studies have used CFD simulations to investigate potential problems that may arise when the immersion lithography process is operating in a quasisteady manner; these problems include fluid heating4,5 and air entrainment due to free surface flows over wafer topology.6 The simulations presented in this work parametrically study the filling process that must occur prior to initiation of immersion exposures. The parameters investigated include the fluid dispense velocity and angle as well as the gap height between the lens and the wafer.

An optimal region in the parameter space of fluid velocity and gap height is identified. The region is delineated on one side by a critical Reynolds number, above which the dispense jet impinges on the wafer forming a thin film that does not completely fill the gap. On the other side, the region is delineated by a critical Weber number, below which a meniscus is formed from the dispense port and crawls along the lens. The subsequent rupture of the meniscus upon its eventual contact with the wafer is likely to entrain unacceptable air bubbles. The fluid dispense angle has an effect on the location of this optimal region.

In order to verify some aspects of the CFD simulations, the model predictions were compared with an experiment in which water was used to fill a gap that replicates the lens-to-wafer gap in an immersion lithography tool. There was good agreement between the CFD and experimental results, both qualitatively in terms of the shape of the free surface and its progression across the gap and quantitatively in terms of the velocity of the filling process.

The use of 2D CFD models for the parametric studies and 3D CFD models for experimental verification was required by practical constraints. It was important to verify that the CFD models were predictive and therefore some experimental comparison was required; however, the experimental apparatus involved 3D flow and therefore a 3D CFD model.

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II. CFD MODELING RESULTS

Figure 1(a) shows a schematic of the filling process used in the two-dimensional CFD simulations. Immersion fluid (water for these simulations) was dispensed with a uniform velocity from a port adjacent to the lens surface. The lens and dispense port are positioned at the same distance from a wafer which is stationary for the simulations and experiments described in this article. The progress of the filling process is monitored after the initiation of the fluid dispense.

The CFD simulation results showed that the fluid dispense process is sensitive to a number of parameters including the fluid dispense velocity, the wafer-to-lens gap height, and the fluid dispense angle. Three different gap heights (i.e., 0.3 mm, 0.6 mm, and 0.9 mm) were examined in a parametric study; for each height, the fluid dispense velocity was varied from 0.0 to 3.0 m/s. The parametric studies showed that the dispense process behavior falls into different regimes depending on these process variables, as illustrated in Fig. 1(b). The simulation was conducted with the three gap heights only; the connecting line shown in the graph is qualitative, to illustrate the trend of the simulation results.

At low fluid dispense velocity the liquid forms a hanging droplet that does not immediately touch the wafer surface. As more liquid is added to the droplet it tends to crawl along the hydrophilic lens surface; eventually the meniscus touches the wafer and at this point it breaks very rapidly, as shown in Fig. 1(c). This behavior is undesirable because the sudden rupture of the meniscus is unpredictable and may entrain macroscopic air bubbles that can be clearly identified in Fig. 1(c). This air cannot escape from the meniscus to wafer gap during the rupture process and therefore forms small bubbles under the influence of surface tension forces. At each gap height, a series of simulations at progressively lower dispense velocities was used to delineate the transition from a completely filled gap to this meniscus crawl behavior, as shown in Fig. 1(b). The specification of this transition is somewhat qualitative but is based on the extent to which the meniscus has progressed in the direction of the gap at the time when it touches the wafer.

At very low fluid dispense velocities, the inertia of the dispensed fluid is insufficient to overcome surface tension and break the meniscus. Thus it has the chance to crawl along the lens. The transition into this behavior is therefore governed by a balance between fluid inertia and surface tension which constitutes the Weber number (We):

\[ \text{We} = \frac{\rho u^2 D}{\sigma}, \]

where \( \rho \) and \( \sigma \) are the density and surface tension of the fluid, \( D \) is the length scale associated with the dispense port, and \( u \) is the dispense velocity. Note that the Weber number as defined in this way is independent of gap height which is consistent with the results shown in Fig. 1(b), in that the gap was necessary to yield quantitative agreement. Unfortunately, the use of a 3D CFD model to carry out the parametric studies would require a prohibitive amount of computational time. Therefore 2D CFD models were used for the parametric studies of the underlying physics. The correlation between the 2D and 3D results has been observed experimentally; for example, it is possible to experimentally observe the transition between impinging jet and optimal dispense at a constant gap height by increasing the velocity using the experimental test facility described in this paper. In other testing, the transition between meniscus crawl and optimal dispense behavior has been observed when the dispense velocity is reduced. While the experimentally observed transition velocities are not exactly equal to those shown in the paper, they are nominally consistent with the critical Weber number and Reynolds number identified by the 2D CFD model.
height has only a very small effect on the fluid dispense velocity at the onset of the meniscus crawl behavior.

At very high fluid dispense velocities the fluid inertia is sufficient to create a thin, high velocity fluid film on the wafer surface; if the fluid film is sufficiently thin, the gap does not entirely fill with liquid, as shown in Fig. 1(d). This behavior is also undesirable. At each gap height, a series of simulations at progressively higher dispense velocities was used to delineate the transition from a completely filled gap to this impinging jet behavior, also shown in Fig. 1(b). The specification of this transition is more clear than the meniscus crawl transition as it is based entirely on whether an unfilled region persists adjacent to the dispense port.

The thickness and velocity of the fluid layer that is formed on the wafer can be approximately determined by balancing fluid momentum and shear in the thin film while enforcing that the mass carried by the film is consistent with the dispensed mass flow rate. If the fluid momentum is large enough then the thickness of the liquid film is less than the gap height and impinging jet behavior occurs. The transition into this behavior is therefore governed by a balance between fluid inertia and viscous shear which constitutes a Reynolds number \( Re \):

$$ Re = \frac{\rho v h}{\mu}, $$

where \( h \) is the gap height and \( \mu \) is the fluid viscosity. Notice that this Reynolds number is proportional to the gap height, which is consistent with the results shown in Fig. 1(b) in that the transition velocity decreases as the gap height increases.

These two extreme cases bracket a range of acceptable dispensing velocities. An acceptable dispense velocity is characterized as being sufficiently high so that the meniscus immediately breaks directly under the dispense port but small enough so the entire gap is filled, resulting in the rapid and controlled fill process shown in Fig. 1(e). Figure 1(b) illustrates that the range of acceptable dispensing velocities narrows as the gap height increases.

Figure 2 overlays the CFD results onto lines associated with a constant Weber number and Reynolds number. Notice that the transition from optimal dispense to impinging behavior is approximately consistent with a transition Reynolds number \( Re \) of 750 and the transition from optimal dispense to meniscus crawl behavior is approximately consistent with a transition Weber number \( We \) of 1. There is some discrepancy between the transitions associated with these critical values of Weber and Reynolds number and the transitions predicted by CFD, particularly at larger gap heights. These discrepancies can be partly explained by the fact that the transition between dispense behaviors is actually a gradual change rather than an abrupt one and therefore the determination of the critical dispense velocities that delineate these regions relies both on judgment and the resolution of the
velocities used in the CFD simulation. Also, the physics of the problem changes as the gap increases; for example, a larger gap allows the meniscus that forms on the lens to expand laterally by a greater amount prior to contacting the wafer and as a result the length scale associated with the Weber number is no longer directly related to the dispense port as given by Eq. (1).

Additional CFD simulations showed that the dispensing behavior is affected by the fluid dispense angle. Figure 3(a) illustrates the three dispensing angles investigated in this work, i.e., 0°, 30°, and 60°, with the positive angles indicating that the fluid is directed towards the lens. For a moderate dispense angle (e.g., 30°), the same regions of behavior exist but the transitions are shifted. The inertia of the fluid in the direction perpendicular to the wafer is reduced when the fluid is dispensed at an angle. Both the meniscus crawl and impinging jet transitions are proportional to this fluid inertia and therefore both lines shift upwards; a higher dispense velocity is required to yield the same inertia. This effect is shown Fig. 3(d) which contains the original points delineating the dispense process regimes for the 0° fluid dispense angle case as well as additional points for a gap height of 0.3 mm and fluid dispense angles of 30° and 60°. Note that for a 30° fluid dispense angle, indicated by the triangles in Fig. 3(d), both the meniscus crawl transition and impinging jet transition, shown in Fig. 3(b), are shifted to higher velocities. For a 60° dispense angle, the meniscus crawl transition again moves to a higher velocity. However, the impinging jet transition no longer occurs. Instead a new behavior is exhibited in which the fluid remains attached to the lens and tends to pull air into the gap, as shown in Fig. 3(c).

III. EXPERIMENTAL VERIFICATION

In order to verify some aspects of the CFD model, the simulated dispensing process was compared with an experiment in which a metered amount of water was used to fill a controlled lens-to-wafer gap. Figure 4(a) shows a schematic of the experiment. The progress of the filling process was monitored using a camera that was mounted over a glass window (which takes the place of the lens element). Figure 4(b) shows a cut-away view of the mounting fixture and indicates passages for the dispense and recovery of water. Figure 4(c) is a solid model of the bottom of the holder which shows the recesses in the structure used to manifold the water to the dispense and recovery ports.

A three-dimensional CFD model was developed with the goal of replicating the actual experimental geometry as closely as possible, as shown in Fig. 4(d). The details of the recessed dispense port, the recessed recovery port, and the gap can be identified in the CFD model. The experiment was carried out at the same flow rate but varying gap heights. Three of these experiments were simulated, including 0.5 mm, 1.0 mm, and 1.5 mm gap heights. Figures 5(a) and 5(b) show pictures of the fluid front that forms as the immersion
fluid fills a 0.5 mm and 1.5 mm gap, respectively. Notice that the fluid front formed for the smaller gap is much flatter across its advancing edge than for the larger gap. This difference is related to whether the dispense flow rate is sufficient to fill the entire width of the gap at the rate that the leading edge of the meniscus is drawn through the gap by surface tension. The CFD simulations for the filling process for the same gaps, shown in Figs. 5(c) and 5(d), show similar behavior. Quantitative comparisons between the experiments and the CFD simulations are shown in Figs. 6(a), 6(b), and 6(c), where the distance between the water front to the dispense port measured along the center of the circular glass window is shown as a function of time relative to the initiation of the fill process for the 0.5 mm, 1.0 mm, and 1.5 mm gaps, respectively. The results from the CFD simulations and the experiments are in very good agreement.

IV. SUMMARY AND CONCLUSIONS

Two-dimensional CFD models were used to investigate the effects of fluid dispense velocity, gap height, and fluid dispense angle on the process of filling the lens-wafer gap prior to immersion lithography. The simulations revealed that an optimal region exists in the space of fluid dispense velocity and gap. The position of this region shifts as the fluid dispense angle is changed.

A three-dimensional CFD model was developed in order to replicate an experiment in which a controlled fill is monitored through a glass window. The simulation results agreed well with the experimental observations both quantitatively in terms of the progression of the fluid front with time and qualitatively in terms of the shape of the fluid front.

ACKNOWLEDGMENTS

The UW research was funded by DARPA/ARL and the Semiconductor Research Corporation (SRC). The UNM portion of the work was funded by International SEMATECH and by the ARO/MURI program in Deep Subwavelength Optical Nanolithography. Computer support was provided by the Intel Corporation and Microsoft.


Fig. 6. Distance from the fluid front to the dispense port along the centerline of the glass window measured from experimental results and predicted by the CFD simulations for (a) 0.5 mm gap, (b) 1.0 mm gap, and (c) 1.5 mm gap.