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Meniscus Studies in Water Immersion Optical Lithography at 193 nm

Kiran J. Sonawane

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MENISCUS STUDIES IN WATER IMMERSION OPTICAL LITHOGRAPHY AT 193 nm

By
Kiran J. Sonawane

A Thesis Submitted in Partial Fulfillment of the Requirement for the

MASTER OF SCIENCE IN
COMPUTER INTEGRATED MANUFACTURING

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February, 2005
Meniscus Studies in Water Immersion Optical Lithography at 193 nm

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ABSTRACT

A new approach for optical patterning that interposes a liquid between an exposure tool’s projection lens and a wafer to achieve better depth of focus and resolution over conventional projection lithography is known as “Immersion Lithography”. As industry focus is getting shifted towards the liquid immersion lithography to manufacture the commercial immersion tools, study of fluid flow and distribution is getting very crucial. The focus of this experimental work was to capture fluid flow and distribution and meniscus behavior on both bare and photoresist-coated glass wafers as well as silicon wafers and address one of the major challenges of immersion; presence of bubbles in the liquid between the lens and the wafer.

A liquid meniscus is created by supplying water through a nozzle onto bare and photo-resist-coated silicon and glass wafer surfaces. This meniscus is formed in the gap between the nozzle end and top surface of the wafer. The meniscus behavior is studied by varying wafer speed, the gap between the nozzle and the wafer, and mass flow rate using high-speed photography. The characteristics of circular nozzle, rectangular nozzle and nozzle lens unit with integral supply and suction port were examined under a variety of operating parameters. Nozzle geometry is of interest in Liquid Immersion Lithography. The use of degassed water is explored in an effort to eliminate any gas evolution. The results indicate that the meniscus shape and the contact angle depend on the wafer surface. Also presence of water droplets on the incoming wafer surface may break meniscus and trap bubbles. This work provides important insight into the field of meniscus behavior and bubble influence in liquid immersion lithography.
# Table of contents

1. **INTRODUCTION** .................................................................................................................. 1  
   1.1. **INTRODUCTION TO IMMERSION LITHOGRAPHY** ......................................................... 1  
   1.2. **INTRODUCTION TO FLUID ISSUES IN LITHOGRAPHY** ............................................... 5  
   1.3. **FLUID ISSUES FROM EXPERIMENTAL POINT OF VIEW** .......................................... 7  

2. **LITERATURE REVIEW** ....................................................................................................... 8  
   2.1. **PREVIOUS WORK ON RELATED TO MENISCUS STUDIES** ........................................... 8  
   2.2. **OBJECTIVES OF THE PRESENT STUDY** ...................................................................... 17  

3. **EXPERIMENTAL SETUP** .................................................................................................... 18  
   3.1. **EXPERIMENTAL INVESTIGATION OF FLUID FLOW AND MENISCUS BEHAVIOR** ........ 18  
   3.2. **DESIGN GUIDELINES FOR ROTATING WAFER AND LIQUID DELIVERY SYSTEM** ........ 18  
   3.3. **DESIGN CONSIDERATIONS FOR CIRCULAR NOZZLE STUDIES** ............................... 20  
   3.4. **DESIGN CONSIDERATIONS FOR RECTANGULAR NOZZLE STUDIES** ......................... 23  
   3.5. **DESIGN CONSIDERATIONS FOR NOZZLE LENS STUDIES** ......................................... 26  
   3.6. **EFFECT OF DISSOLVED GASES AND NEED FOR DEGASED WATER** ............................ 28  
   3.7. **HIGH-SPEED CAMERA** ............................................................................................... 29  
   3.8. **WATER MANAGEMENT SYSTEM** .................................................................................. 29  

4. **MANUFACTURING** ............................................................................................................. 30  
   4.1. **DESIGN DETAILS OF WAFER MOUNTING FIXTURE** .................................................... 30  
   4.2. **DESIGN DETAILS OF RECTANGULAR NOZZLE DETAILS** ............................................ 31  
       4.2.1. **45° NOZZLE** ............................................................................................................. 31  
       4.2.2. **60° NOZZLE** ............................................................................................................ 32  

5. **EXPERIMENTAL PROCEDURE** ............................................................................................ 33  
   5.1. **PROCEDURE FOR MAKING DEGASED WATER** ............................................................. 33  
   5.2. **EXPERIMENTAL SETUP AND EXPERIMENTAL PROCEDURE** ................................... 35  

6. **CALCULATIONS** ................................................................................................................... 37  
   6.1. **MASS FLOW FOR NOZZLE DESIGN** ............................................................................. 37  
   6.2. **LINEAR VELOCITY** ....................................................................................................... 39  

7. **RESULTS AND DISCUSSION** ............................................................................................. 40  
   7.1. **RESULTS FOR CIRCULAR DESIGN** .............................................................................. 40  
       7.1.1. **Meniscus Flow Pattern** .......................................................................................... 40  
       7.1.2. **Advancing and Receding Contact Angle** ............................................................... 42  
       7.1.3. **Meniscus Stability** .................................................................................................. 44  
   7.2. **RESULTS FOR RECTANGULAR DESIGN** ....................................................................... 47  
       7.2.1. **Contact angle on Glass and photoresist wafer** ....................................................... 47  
       7.2.2. **Effect of Nozzle angle** ............................................................................................ 49  
       7.2.3. **Instability of Meniscus** .......................................................................................... 50  
       7.2.4. **Effect of non-degassed water** ................................................................................ 54  
       7.2.5. **Bubble Entrapment** ............................................................................................... 57
7.2.6. Meniscus characteristics ................................................................. 58
7.2.7. Flow Visualization ........................................................................ 59
7.3. Results for Nozzle Lens Design with Integral Supply and Suction Ports ... 60
  7.3.1. Meniscus Flow Pattern ................................................................. 60
  7.3.2. Operating Suction and Discharge Pressure Effect ......................... 62

8. CONCLUSIONS ......................................................................................... 63

9. REFERENCES ............................................................................................ 65
List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1-1: IMMERSION LITHOGRAPHY</td>
<td>................................................................. 3</td>
<td></td>
</tr>
<tr>
<td>Figure 1-2: PRINCIPLE OF IMMERSION LITHOGRAPHY</td>
<td>........................................................................ 4</td>
<td></td>
</tr>
<tr>
<td>Figure 2-1: THE IMPACT OF N-HEPTANE DROPLET ON A STAINLESS STEEL SURFACE AT 24 °C (A BUBBLE CAN BE SEEN TO FORM AT THE POINT OF CONTACT)</td>
<td>.............................................................. 9</td>
<td></td>
</tr>
<tr>
<td>Figure 2-2: COMPARISON OF (A) THE RESULTS FROM THE MODEL OF HARLOW AND SHANNON (1967) (B) WITH THE EXPERIMENTAL OBSERVATIONS FROM CHANDRA AND AVEDISIAN STUDY OF DROPLET SHAPE DURING THE IMPACT OF A DROPLET ON A SURFACE AT 24 °C</td>
<td>........................................................................ 10</td>
<td></td>
</tr>
<tr>
<td>Figure 2-3: NUMERICAL FREE SURFACE CONFIGURATION AND VELOCITY VECTOR FIELD OF A DROPLET IMPINGING ON A FLAT PLATE WITH PRESSURE DISTRIBUTION ALONG THE SURFACE</td>
<td>........................................................................ 11</td>
<td></td>
</tr>
<tr>
<td>Figure 2-4: NUMERICAL FREE SURFACE CONFIGURATION AND VELOCITY VECTOR FIELD OF A DROPLET IMPINGING ON A FLAT PLATE WITH Re= 1500, We=62.5 and Fr= 42.86</td>
<td>........................................................................ 12</td>
<td></td>
</tr>
<tr>
<td>Figure 2-5: SMALL WATER CLUSTERS ON PLATINUM SURFACE</td>
<td>........................................................................ 13</td>
<td></td>
</tr>
<tr>
<td>Figure 2-6: SINGLE DROPLET ON AN INCLINED PLATINUM SURFACE. m = 1.15X10-6 KG, T = 22°C, Ts = 22°C; A) α = 28°, B) α = 36°, C) α = 40°, D) α = 56°, E) α = 67°, F) α = 79°, G) α = 86°</td>
<td>........................................................................ 14</td>
<td></td>
</tr>
<tr>
<td>Figure 2-7: CONTACT ANGLES VERSE SURFACE INCLINATION ANGLE</td>
<td>........................................................................ 15</td>
<td></td>
</tr>
<tr>
<td>Figure 2-8: PLOT OF RECEDING AND ADVANCING CONTACT ANGLES VERSES SURFACE VELOCITY</td>
<td>........................................................................ 16</td>
<td></td>
</tr>
<tr>
<td>Figure 3-1: WAFER MOUNT AND LEVELING SYSTEM FLANGE</td>
<td>........................................................................ 19</td>
<td></td>
</tr>
<tr>
<td>Figure 3-2: WAFER RUN OUT ELIMINATION</td>
<td>........................................................................ 20</td>
<td></td>
</tr>
<tr>
<td>Figure 3-3: CIRCULAR NEEDLE NOZZLE</td>
<td>........................................................................ 21</td>
<td></td>
</tr>
<tr>
<td>Figure 3-4: DESIGN OF EXPERIMENTAL APPARATUS FOR CIRCULAR NOZZLE</td>
<td>........................................................................ 22</td>
<td></td>
</tr>
<tr>
<td>Figure 3-5: DESIGN SCHEMATIC FOR RECTANGULAR NOZZLES</td>
<td>........................................................................ 23</td>
<td></td>
</tr>
<tr>
<td>Figure 3-6: DETAILS OF RECTANGULAR NOZZLE/LENS UNIT</td>
<td>........................................................................ 24</td>
<td></td>
</tr>
<tr>
<td>Figure 3-7: DESIGN OF EXPERIMENTAL APPARATUS FOR RECTANGULAR NOZZLE</td>
<td>........................................................................ 25</td>
<td></td>
</tr>
<tr>
<td>Figure 3-8: DETAILS OF NOZZLE WITH SUCTION AND SUPPLY PORT</td>
<td>........................................................................ 26</td>
<td></td>
</tr>
<tr>
<td>Figure 3-9: DESIGN OF EXPERIMENTAL APPARATUS FOR NOZZLE WITH SUCTION AND SUPPLY PORT</td>
<td>........................................................................ 27</td>
<td></td>
</tr>
<tr>
<td>Figure 3-10: ROTATING WAFER AND RECTANGULAR NOZZLE ASSEMBLY</td>
<td>........................................................................ 29</td>
<td></td>
</tr>
<tr>
<td>Figure 4-1: DRAWING SKETCHES OF FIXTURE USED TO MOUNT WAFER ON ALUMINUM HUB, (SCALE 1:2, MACHINE USED: MILLING MACHINE)</td>
<td>........................................................................ 30</td>
<td></td>
</tr>
<tr>
<td>Figure 4-2: DRAWING SKETCHES OF RECTANGULAR NOZZLE (45° ANGLE), (SCALE 2:1, MACHINE USED: MILLING AND GRINDING MACHINE)</td>
<td>........................................................................ 31</td>
<td></td>
</tr>
<tr>
<td>Figure 4-3: DRAWING SKETCHES OF RECTANGULAR NOZZLE (60° ANGLE), (SCALE 2:1, MACHINE USED: MILLING AND GRINDING MACHINE)</td>
<td>........................................................................ 32</td>
<td></td>
</tr>
<tr>
<td>Figure 5-1: DEGASSED WATER DELIVERY SYSTEM</td>
<td>........................................................................ 33</td>
<td></td>
</tr>
<tr>
<td>Figure 5-2: EXPERIMENTAL SCHEMATIC DIAGRAM OF MENISCUS SETUP</td>
<td>........................................................................ 35</td>
<td></td>
</tr>
<tr>
<td>Figure 7-1: CONTINUOUS MENISCUS ON BARE GLASS (SIDE VIEW), (GAP = 0.7MM, MASS FLOW RATE = 12.3 MG/S, VELOCITY = 0.4M/S)</td>
<td>........................................................................ 40</td>
<td></td>
</tr>
<tr>
<td>Figure 7-2: MENISCUS ON GLASS (BOTTOM VIEW), (GAP = 0.85MM, MASS FLOW RATE = 16.5 MG/S, VELOCITY = 0.25 M/S)</td>
<td>........................................................................ 41</td>
<td></td>
</tr>
</tbody>
</table>
Figure 7-3: Contact Angle (Water on Bare Glass), (gap = 0.85 mm, mass flow rate = 16.5 mg/s, velocity = 0.25 m/s) ................................................................. 42
Figure 7-4: Contact Angle (Water on Photoresist), (gap = 0.85 mm, mass flow rate = 16.5 mg/s, velocity = 0.25 m/s) ................................................................. 43
Figure 7-5: Breaking Meniscus on Bare glass, (gap = 0.7 mm, mass flow rate = 15.8 mg/s, velocity = 1 m/s) ................................................................. 44
Figure 7-6: Breaking Meniscus on Photoresist-Coated Wafer, (gap = 0.7 mm, mass flow rate = 2 mg/s, velocity = 0.2 m/s) ................................................................. 45
Figure 7-7: Trapped Bubble in Meniscus, (gap = 0.7 mm, mass flow rate = 12.3 mg/s, velocity = 0.4 m/s) ................................................................. 46
Figure 7-8: Meniscus Shape and Contact Angle (45° Nozzle) ................................................................. 47
Figure 7-9: Meniscus Shape and Contact Angle (60° Nozzle) ................................................................. 48
Figure 7-10: Side-By-Side Nozzle Angle Comparison ................................................................. 49
Figure 7-11: Effect of Residual Water on Wafer Surface, (gap = 0.3 mm, mass flow rate = 1.1 g/s, velocity = 0.25 m/s) ................................................................. 50
Figure 7-12: Meniscus Instability, (gap = 0.3 mm, mass flow rate = 1.3 g/s, velocity = 1.0 m/s) ................................................................. 52
Figure 7-13: Bubble Attachment on Lens Surface during Refill (Particles in solution), gap = 0.5 mm, mass flow rate = 5 g/s, velocity = 1.0 m/s) ........ 54
Figure 7-14: Bubble Stuck on Nozzle Surface (DI Water-Not Degassed), (gap = 1.0 mm, mass flow rate = 0.5 g/s, velocity = 0.25 m/s) .......... 55
Figure 7-15: Bubble Entrapment, (gap = 0.3 mm, mass flow rate = 1.1 g/s, velocity = 0.25 m/s) ................................................................. 57
Figure 7-16: Breaking Meniscus, (gap = 1.0 mm, mass flow rate = 1.1 g/s, velocity = 1.0 m/s) ................................................................. 58
Figure 7-17: Flow Visualization, (gap = 0.5 mm, mass flow rate = 5 g/s, velocity = 1.0 m/s) ................................................................. 59
Figure 7-18: Continuous Meniscus on Glass wafer, (gap = 0.4 mm, mass flow rate = 1.1 g/s, velocity = 0.5 m/s) ................................................................. 60
Figure 7-19: Breaking Meniscus on Glass wafer, (gap = 0.4 mm, mass flow rate = 0.5 g/s, velocity = 1 m/s) ................................................................. 61
Figure 7-20: Suction of Wafer due to Surface Tension and Pressure Forces ........ 62
List of Tables

Table 1: Calculation of mass flow for needle design .............................................. 37
Table 2: Calculation of mass flow for nozzle design ............................................. 38
Table 3: Speed calculation for needle design ......................................................... 39
Nomenclature

NA  Numerical Aperture
DOF Depth of Focus
R  Resolution limit
k_1  Constant
k_2  Constant
Re  Reynolds number
We  Weber number
Fr  Froude number
T  Surface temperature, K
V  Linear velocity, m/s
h  Gap between wafer surface and nozzle end, m
L  Nozzle length, m
W  Nozzle Width, m
R  Equilibrium bubble radius
r  Radius of uniform circle on which constant motion takes place, m

Greek Symbols

α  Angle of inclination (surface inclination)
σ  surface tension
ω  angular velocity, rad
θ  Maximum angle of incidence
η  Refractive index of medium
λ  Wavelength
1. INTRODUCTION

1.1. Introduction to Immersion Lithography

Since last 150 years immersion liquids have been used in optical lithography. A lot of experiments were performed by using air and oil as an immersion fluid. Initially experiments have been performed with low-index air (\( \eta = 1.00029 \)) between lens and wafer. Abbe (1880) was the first one who used oil as an immersion fluid instead of air. While performing the experiment Abbe used oil between a microscope objective and glass. The refractive index of oil matched with the refractive index of glass on either side. This resulted in avoiding the effects of refraction at the interfaces. This method became famous as a “Homogeneous Immersion”. Zeiss also conducted some experiments by using oil as a medium in 1880s. Abbe and Zeiss (1880) developed oil immersion systems by using oil (which has same refractive index as of the Glass).

Numerical aperture (NA), Resolution limit of the optical exposure system (R) and depth of focus (DOF) are three prominent parameters in the field of immersion lithography. The conventional system or Dry lithography uses air or gas as a medium. In immersion lithography some kind of liquid is used in the space between the objective lens and wafer. The formula for Numerical aperture (NA) of projection optics is given by:

\[ \text{NA} = \eta \sin \theta \]  \hspace{1cm} (1)

where, \( \theta \) is the maximum angle of incidence and \( \eta \) is the refractive index of the medium. Numerical Aperture for immersion lithography is higher than dry lithography because liquid is the medium in case of immersion lithography and refractive index of liquid (typically 1.3 to 1.4) is generally higher than that of air (1.00029) or gas. (Considering the angle of incidence \( \theta \) is same in both the cases.)

The formulae for resolution limit and Depth of Focus are given below:

\[ R = k_1 \lambda / \eta \sin \theta \] \hspace{1cm} (2)

where, \( k_1 \) is constant.

\[ \text{DOF} = k_2 \eta \lambda / \text{NA} \] \hspace{1cm} (3)

where, \( k_2 \) is constant.
The Equations indicate that DOF is directly proportional to \( \eta \) (refractive index) which concludes that DOF of immersion lithography is increased by factor of \( \eta \) compared with dry lithography, assuming NA is same in both the cases. Hence, the principle of increasing the index of refraction of the space between lens and wafer by using a liquid which has high refractive index than the refractive index of air comes into play for immersion lithography and several experiments have been performed in search of the ideal fluid for immersion lithography.

It is not easy to choose the wavelength for next generation lithography considering the feasibility of technology as well as the cost of the tools involved. A short wavelength of the exposure light is preferred in optical lithography. In case of wavelength of 157 nm, additional resolution enhancement is a must to make the technology more feasible and a lot of associated risks are involved in this method. Also the challenges of shorter wavelength methods become very difficult, as an alternative method of using 193-nm wavelength technology comes into play for sub-65-nm device nodes.

**Principle of Immersion Lithography Technology:**

Use of an immersion fluid in the space between the bottom surface of lens and wafer changes the path of light significantly. It offers following benefits compared with dry lithography:

- DOF is enhanced for the given numerical aperture.
- Immersion lithography makes it possible for lens designs with \( NA > 1 \). It gives an enhanced resolution.
Definition of Immersion Lithography:

As per International Sematech, a new approach for optical patterning that interposes a liquid between an exposure tool’s projection lens and a wafer to achieve better depth of focus and resolution over conventional projection lithography is called as “Immersion Lithography.”

![Figure 1-1: Immersion Lithography](image)

Fig. 1-1 from Owa S. etc al. (2004) and Fig. 1-2 from Nellis G. etc al. (2004) helps in understanding the principle behind the immersion lithography. Fig. 1-1 shows schematic representation of the principle of immersion lithography. The gap between the bottom surface of the lens and wafer surface is filled by an immersion liquid. Liquid supply and liquid recovery are critical parameter along with the design of lens projection. Fig. 1-2 shows the simulation study diagram for immersion lithography. It helps in understanding the study of test section which is the gap between lens and wafer surface filled with fluid.
Ideal fluid for Immersion Lithography:

Primarily the choice of immersion fluids is based on their transparency as well as the need to satisfy the following requirements:

- Refractive index should be greater than 1
- Compatible with Photo-resist as well as material of lens so that it does not affect lens, wafer surface and exposure process
- Non-contaminating
- Low optical absorption at 193 nm

The use of water as an immersion fluid in case of 193 nm exposure is the most effective solution in current situation. Water satisfies all the necessary requirements as follows:

- Water is transparent to below 0.05 cm\(^{-1}\) at 193 nm.
- The refractive index of water is 1.437 at 193 nm.
- At 193 nm water has minimum reaction with photo-resist material as well as with lens material. This reaction can be further reduced by modifying the resist material.
- DI Water (standard and degassed) or Ultra pure water limits the critical concerns of wetting, cleaning and drying.
- Water has absorption of <5% at working distances of up to 6mm.
A lot of imaging simulations results comes to the conclusion that 193 nm immersion lithography (NA=1.05 to 1.23) has equivalent performance to F2 (157nm) dry (NA=0.85 to 0.93) lithography. Also recent industry symposia hosted by SEMATECH showed 193 nm immersion lithography is feasible technology. The importance of this technology will spread soon in the manufacturing arena.

1.2. Introduction to Fluid Issues in Lithography

In spite of 193 nm being more beneficial than 157-nm dry lithography; it faces some problems which need to be encountered to make 193-nm immersion lithography as a promising technology. A lot of experimental and simulation studies helped in solving some of the problems.

- The way fluid gets introduced in the gap between the lens and the wafer is one of the crucial factors for the feasibility of immersion lithography. There are two methods:
  - Passive Filling Process: Liquid is dispensed on the top surface of wafer as a puddle and this movement of wafer and liquid takes place together under the lens.
  - Active Filling Process: Liquid is introduced at the edge of the lens in the form of jets and wafer moves under the lens.

- The direction of wafer: A lot of simulation studies were done to find out the effect of wafer direction on the filling process of fluid. First moving the wafer from right to left direction that is in the direction of fill process, results are obtained. Then results are obtained when wafer is moving at the same velocity but in opposite direction that is against the filling process. But there is very little difference found between the two cases.

- Bubble prevention and elimination: One of the major hydrodynamic problems for immersion lithography is production of bubbles in water during exposure. There are various causes for the production of bubbles. The turbulence between liquid and the resist surfaces during the scanning process and outgassing of the resist are two prominent causes for the production of
bubbles. Bubble causes scattering-induced flare which impairs the aerial image. Also aerial image gets further degraded because of superimposition of some portion of scattered aerial image with original aerial image. Bubble not only causes scattering but also cause defects if they are attached to the surface of wafer. Therefore, Prevention and elimination of bubbles needs immediate attention. Lots of studies have been done to understand how the bubble formation occurs and it has been found out that degassing is the most effective method for the elimination of bubbles. There are several methods of producing degassed water. Even though we obtained perfectly degassed water, still lifetime of degassed water is a major concern because water will dissolve air through the boundary. A lot simulation study has been done and it has been found out that air dissolution is faster when the water is not stationary because of the presence of the random flow inside water and air dissolution into the center area is prevented by fresh supply of water by local fill method.

- Supply of water and recovery: There are three approaches for the liquid delivery and recovery.
  - Stage immersion: To submerge the whole stage needs a pool of water and requires significant engineering. So this option is not practically possible.
  - Wafer Immersion: It is not possible to give quick motion to wafer because it will create unstable motion of water.
  - Local fill method: This is the most feasible method and currently under consideration. In this method water is dispensed between lens and the wafer by using a nozzle and surface tension helps in maintaining the puddle of the water. This method is useful at least for the exposure at the center area of the wafer. There are still some problems (edge shot issues) exists for the exposure near the edges of the wafer.

- Precise measurement of water parameter: Critical parameters of water from immersion lithography point of view are measured with the help of
International Sematech and NIST standards. The values which are necessary for the design of projection optics are reported by NIST as follows:

- \( \eta(\lambda) = [1.43664 + -0.00002 (21.5^\circ C, 193.39 \text{ nm})] \)
- \( \frac{d \eta}{dT} = -1.0 \times 10^{-4} \text{K}^{-1} \)
- The absorption coefficient for 193-nm is reported as 3% absorption by 1mm thickness of water.

These readings have been noted by using air-saturated water. So measurements need to be taken with degassed water. Also there are some issues like type of resist for water immersion, thermal aberration by exposure light and full field projection optics needs to be explored in detail from feasibility point of view.

1.3. **Fluid Issues from experimental point of view**

Importance of prototype tool is increasing in the liquid immersion lithography environment. So nozzle geometry is of interest in liquid immersion lithography. But there are few obstacles in the path of successful making of the nozzle lens system like bubbles in the liquid between the lens and wafer surface and meniscus instability and the interaction of immersion fluid on the wafer surface.

The focus of this experimental work was to capture fluid flow and distribution and meniscus behavior on both bare and photoresist-coated glass wafers as well as silicon and address one of the major challenges of immersion; bubbles in the liquid between the lens and the wafer. The experiment is concentrated on getting the information on meniscus stability, advancing and receding contact angle by varying parameters such as wafer speed and gap between nozzle and wafer, and mass flow. Both bare and photoresist-coated glass and silicon wafers are used to capture the fluid flow.
2. LITERATURE REVIEW

2.1. Previous work on related to meniscus studies

Previous studies on meniscus were mainly focused on theoretical and experimental aspects of evaporating meniscus geometry. But very little information is available on the meniscus study at room temperature. During the early part of the 20th century, study of motion of liquid and the effect of evaporation from the edges of drop in a Droplet Impinging process has been done. Since photography is the crucial factor for close observation of geometrical parameters of droplet, major progress in this field was carried out with the development of high-speed photography.

Chandra and Avedisian (1991) studied the collision dynamics of a liquid droplet on a solid metallic surface by using a flash photographic method. A lot of study was done on the dynamics of droplet impact with impact energy as the main parameter. But surface temperature was the primary parameter in the experimental study of deformation process which was conducted by Chandra and Avedisian. During the study, they have observed the entrapment of bubble in a single droplet as shown in the Fig. 2-1. The bubble is originated when the droplet contacts the surface at the point of impact at $t = 1$ ms and then it rose above the surface into the droplet. They have given two possible mechanisms for the formation of bubble within the droplet considering the temperature of the droplet lower than its normal boiling point.

1. Entrapment of air at the liquid–solid interface during impact: Deformation of the liquid during the impact process can cause the air entrapment which leads to formation of bubble within the droplet.

2. Reduction in the liquid pressure below its saturation vapor pressure causes a phenomenon known as cavitation within the liquid.
Figure 2-1: The Impact of n-heptane droplet on a stainless steel surface at 24 °C  
(A bubble can be seen to form at the point of contact)

As shown in Fig. 2-2, the results from the model of Harlow and Shannon (1967) are compared with the experimental observations from the study of evolution of droplet shape during the impact of a droplet on a surface at 24 °C conducted by Chandra and Avedisian (1991). The differences they found are summarized as below:

1. In reality the film stopped moving because initially the internal pressure which is responsible for the motion dissipates as water starts spreading until the pressure can not overcome the resistance to the motion because of the viscous effects at solid –liquid interface. But in the model analysis, the film is predicted to spread without bound.

2. The predicted existence of the jet is different than the observed jet structure.
Figure 2-2: Comparison of (a) the results from the model of Harlow and Shannon (1967) (b) with the experimental observations from Chandra and Avedisian study of droplet shape during the impact of a droplet on a surface at 24 °C.
Hatta et al. (1995) have studied a) the deformation behavior of a liquid droplet impinging on a flat solid surface at room temperature and b) the flow field inside the droplet by numerical simulation as well as by experimental study. They have considered water as a liquid in the first case and n-heptane is used in the second case. They have used MAC-type solution method for the simulation study. The surface tension parameter was also taken into consideration.

Figure 2-3: Numerical free surface configuration and velocity vector field of a droplet impinging on a flat plate with pressure distribution along the surface
Figure 2-4: Numerical free surface configuration and velocity vector field of a droplet impinging on a flat plate with $Re=1500$, $We=62.5$ and $Fr=42.86$

As shown in the Fig. 2-3, evolution of the free surface and the velocity vector field for the case of water as a liquid with $Re = 1500$, $We = 62.5$, $Fr = 42.86$ is presented. Fig. 2-4 shows the pressure distribution along the solid surface for the same parameters. In this case $p=0$ represents the ambient pressure and negative value of pressure means the value lower than the ambient pressure. Also at every time stage, the magnitude of velocity vector is common. The pressure at the impinging region when the droplet hits the solid surface is higher than the pressure at the periphery and it results in rapid expansion of water film on the solid surface. And this collision dynamics of a water droplet on a solid surface is explained
by using the results from numerical and experimental observation study. The effects of viscous stresses and surface tension have been taken into account and emphasis is given to the analysis of whole deformation after the collision with the surface. It has been found out that water film formed by droplet impinging on a solid surface began to recoil from the peripheral region towards the center after the radius has reached to its maximum value. Also the calculated deformation process was in agreement with the experimental study results. So the final conclusion was deformation process of a liquid on a solid surface was not only depend on the Weber number, Reynolds number but also depend on other parameters such as initial kinetic energy of a droplet, the interaction of physical properties of a liquid with a solid surface and the affinity at the solid/liquid interface.

![Figure 2-5: Small water Clusters on platinum surface](image)

Kandlikar et al. (2001) have done experimental work as well as simulation work study for water liquid droplet in contact with a platinum surface. They measured the contact angle of water on a platinum surface under saturated conditions and in a vacuum container using de-ionized and degassed water as a fluid in the experimental study. The advancing, receding and equilibrium contact angles are measured on a horizontal as well as on an inclined platinum surface to 20, 30 and 40 degrees. The measurements of contact angles are conducted as a function of size of droplet and surface orientation.
Configurations of the small cluster of water on the platinum surface are shown in the Fig. 2-5. The orientation of each water molecule is different from the rest of the water molecules because of the hydrogen bonding of water molecules.

Fig. 2-6 shows the single droplet on a tilted platinum surface with a varying angle of inclination.

![Images of droplets on inclined surfaces]

Figure 2-6: Single Droplet on an Inclined Platinum Surface. \( m = 1.15 \times 10^{-6} \) kg, \( T = 22^\circ C \), \( T_s = 22^\circ C \); A) \( \alpha = 28^\circ \), B) \( \alpha = 36^\circ \), C) \( \alpha = 40^\circ \), D) \( \alpha = 56^\circ \), E) \( \alpha = 67^\circ \), F) \( \alpha = 79^\circ \), G) \( \alpha = 86^\circ \)

Fig. 2-7 shows the effect of surface inclination upon the advancing and receding contact angles. It shows that the advancing and receding contact angles vary between the limiting values.
Surface cleanliness is also an important parameter which affects the contact angle. The experiment has been done by cleaning the platinum surface by acetone, DI water and bottled compressed air stream. It has been concluded that surface cleaning technique has a significant influence on the contact angle behavior.

Kuan and Kandlikar (2003) have studied the effect of motion of meniscus by conducting an experimental study on a smooth, rotating and heated copper surface. This study provides quantitative information of the shape and size of stable meniscus as well as moving meniscus. The contact angle (advancing as well as receding contact angle) of the stationary meniscus was found to be almost independent of heat flux and flow rate.

Figure 2-7: Contact Angles verse Surface Inclination Angle
Fig. 2-8 shows the graph of contact angle (advancing and receding angle) vs. surface velocity. Zero velocity point in the graph indicates the stationary meniscus. The surface temperature parameter is considered while conducting the experimental observations. With increase in the surface velocity, the receding contact angle of meniscus decreases and reaches up to a lower value and then remains constant for the further values of surface velocity. The change in advancing contact angle with respect to surface velocity is not distinct enough to notice. The value of advancing contact angle is seen to be constant around the value of 115°.

Liquid immersion lithography provides 193-nm lithography by replacing the air with water meniscus between the lens and the wafer. The water needs to meet several criteria in order to function effectively:

1. The temperature of the water should be precisely controlled to within 0.01 °C.
2. The water should be free of air bubbles.
3. The meniscus should be stable during the motion of the lens over the wafer surface.
To provide satisfactory answers to the above requirements, an experimental study is undertaken to study the fluid mechanics of water meniscus trapped between the lens and a moving meniscus. The use of degassed water is explored in an effort to eliminate any gas evolution. Specifically, the following objectives are set for the present work.

2.2. **Objectives of the present study**

Objectives of the present work are as follows:

1. Develop an apparatus to investigate meniscus behavior and fluid flow on both bare and photoresist-coated glass and silicon wafers.
2. Obtain information on meniscus stability, advancing and receding contact angle by varying parameters such as wafer speed and gap between nozzle and wafer, and mass flow by recording images with a high-speed camera.
3. Study the bubble entrapment at the meniscus front.
5. Effect of dissolved gases and need for degassed water.

Details of the experimental setup and results are presented in the next sections.
3. EXPERIMENTAL SETUP

3.1. Experimental Investigation of fluid flow and Meniscus Behavior

Experiments were conducted to capture fluid flow and meniscus behavior on both bare and photoresist-coated glass and silicon wafers. The characteristics of circular and rectangular nozzles were examined under a variety of operating conditions. The rectangular nozzle was incorporated into a lens blank for a seamless transition between the nozzle and lens interface. Wafer speed, gap between nozzle and wafer, and mass flow were varied, and images were recorded with a high-speed camera at frame rates of 125 frames per second (fps) to 1000 fps. Flow visualization experiments were also performed using water containing a concentration of 2 and 10 μm beads.

3.2. Design guidelines for Rotating wafer and liquid delivery System

The experiment required a rotating wafer and a liquid delivery system to form the meniscus. A rotating wafer system that is capable of variable speeds was developed. A portion of the bottom of the wafer needed to be accessible in order to film bottom views of the meniscus on glass wafers. A precision spindle and belt and pulley system was developed to accomplish this. A leveling system was incorporated to allow for the elimination of the run out of a mounted wafer to within 0.0127 mm as shown in Fig. 3-1.

A fixture was designed for locating and attaching an aluminum hub in the center of a wafer surface. The hub is then screwed to the leveling system flange using three 10-32 screws at 120°. The flange has three spring plungers at 120° that produce a force of approximately 3 lbs each in the fully compressed position. The aluminum hub is screwed down to the flange surface, and then the screws are backed off until there is a slight gap between the hub and the flange surface. The wafer is slowly rotated and each of the three screws is tightened as the wafer run-out is monitored and eliminated using a test indicator as shown in Fig. 3-2.
The liquid delivery system is used to dispense water through the nozzle onto the wafer surface. It consists of a circular or rectangular nozzle, a flow meter, and an IV pouch. The nozzle is positioned above the wafer surface as shown in Fig. 3-3. The gap between the wafer surface and the end of the nozzle was varied throughout the experiment. A circular nozzle was made from a syringe needle. The diameter of the hollow needle was 1 mm, and the needle was held perpendicular to the wafer surface.

Figure 3-1: Wafer Mount and Leveling System Flange
3.3. Design Considerations for Circular Nozzle Studies

The experimental parameters for the circular nozzle study were:

- Velocity range: 0.16 m/s – 1.23 m/s
- Mass flow range: 1.4 mg/s – 16.5 mg/s
- Four types of wafers were used in this experiment: bare and photoresist-coated glass and silicon
- The gap between the wafer and needle nozzle was varied from 0.4 mm - 1.0 mm
- The fluid for the experiment was DI Water (standard and degassed)
- The diameter of the circular needle nozzle was 1 mm
Figure 3-3: Circular Needle Nozzle
Fig. 3-4 shows a diagram of the experimental apparatus for the circular nozzle and the location of the high-speed camera, nozzle and rotating wafer.

Figure 3-4: Design of Experimental Apparatus for circular Nozzle
3.4. **Design Considerations for Rectangular Nozzle Studies**

After performing the experiments with the circular nozzle, rectangular nozzle/lens units were designed and manufactured. One unit was designed with a 45° angle of inclination and another unit was designed with a 60° angle of inclination. The design schematic for the rectangular nozzles is shown in Fig. 3-5.

- Nozzle Dimensions: 1 mm x 10 mm
- Lens Dimensions, L x W: 10 mm x 10 mm
- Gap Size, h: 0.3 mm, 0.5 mm, 1.0 mm
- Nozzles were designed with two angles of inclination: 45° and 60°

![Design Schematic for Rectangular Nozzles](image)

**Figure 3-5: Design Schematic for Rectangular Nozzles**

The Design details for the rectangular nozzles are given in Figs. 3-6(a, b, c). The characteristics of both designs were studied under a variety of operating parameters, which are given below:

- Velocity range: 0.25 m/s – 1.0 m/s
- Mass flow range: 0.5 g/s – 5.0 g/s
- Four types of wafers were used in this experiment: bare and photoresist-coated glass and silicon.
- The gap between the wafer and rectangular nozzle was varied from 0.3 mm - 1.0 mm.
- The fluid used for the meniscus experiment was DI Water (standard and degassed).
- Water containing a concentration of 2 and 10 μm beads was used to perform the flow visualization experiments.

(a) Side View of Rectangular Nozzle/Lens Unit

(b) Rear View of Rectangular Nozzle

(c) Bottom View of Rectangular Nozzle

Figure 3-6: Details of Rectangular Nozzle/Lens Unit
Fig. 3-7 shows a diagram of the experimental apparatus for the rectangular nozzle and the location of the high-speed camera, nozzle and rotating wafer.

Figure 3-7: Design of Experimental Apparatus for Rectangular Nozzle
3.5. Design Considerations for Nozzle Lens Studies

After performing the experiments with the circular nozzle, rectangular nozzle/lens, Nozzle lens units with integral suction and supply port were designed and manufactured. The design schematic for the rectangular nozzles is shown in Fig. 3-8(a, b).

![Bottom View of Nozzle with suction and supply port](image)

(a) Bottom View of Nozzle with suction and supply port

![Side View of Nozzle with suction and supply port](image)

(b) Side View of Nozzle with suction and supply port

Figure 3-8: Details of Nozzle with suction and supply port
Design Details of Nozzle with suction and supply port:

- Nozzle was designed with two ports:
  a. Suction Port (angle 180°)
  b. Supply Port: (angle 120°)
  c. Depth of suction slot: 15.25 mm
  d. Depth of supply slot: 15.25mm

Fig. 3-9 shows a diagram of the experimental apparatus for nozzle with suction and supply port and the location of the high-speed camera, nozzle and rotating wafer.

Figure 3-9: Design of Experimental Apparatus for Nozzle with suction and Supply port

The characteristics of this design were studied under a variety of operating parameters, which are given below:

- Velocity range: 0.25 m/s – 1.0 m/s
- Mass flow range: 0.5 g/s – 5.0 g/s
- Type of wafer used in this experiment: Glass wafer
• The gap between the wafer and rectangular nozzle was varied from 0.25 mm – 0.5 mm.
• The fluid used for the meniscus experiment was DI Water (standard and degassed).

3.6. Effect of Dissolved Gases and need for Degassed water

A gas bubble present in a continuous liquid phase is under equilibrium as a result of surface tension, pressure difference between gas and liquid, and buoyancy force due to differing densities in a gravitational field. The buoyancy force acts in the vertical direction and causes the bubble to distort from its spherical shape and rise upwards. For the small bubbles being considered here, the shape of the bubble can be considered to be spherical, and its diameter can be obtained from a force balance across a diametrical plane as shown in equation 1.

At equilibrium, neglecting the gravitational force, the surface tension force is balanced by the force due to excess pressure inside the gas bubble.

\[ 2\pi R \sigma = \pi R^2 (p_g - p_L) \]  

(4)

Thus the excess pressure inside the gas bubble is given by

\[ (p_g - p_i) = \frac{2\sigma}{R} \]  

(5)

Where \( \sigma \) is the surface tension of water and \( R \) is the equilibrium bubble radius. Figure 2 shows the variation of the excess pressure as a function of the radius of the bubble at a temperature of 20 °C.
3.7. High-speed Camera

A high-speed camera was used to capture the side view and bottom view images of the meniscus at recording rates of 125 - 1000 fps. Microscopic and zoom lenses (12-75 mm) were used to capture the images of the meniscus. The camera was mounted on a tripod for side-view recording and an XYZ table for bottom-view recording.

3.8. Water Management System

A water management system was necessary in this experiment in order to form a continuous meniscus on the wafer surface. The combination of air-pressure line and vacuum line was very effective in removing the excess water without any meniscus break-up. Fig. 3-10 shows the location of the air-pressure line and the vacuum line in the experimental setup.

![Figure 3-10: Rotating Wafer and Rectangular Nozzle Assembly](image)
4. MANUFACTURING

4.1. Design Details of Wafer Mounting Fixture

The drawing sketches of fixture used to mount wafer on an aluminum hub are shown in Fig. 4-1. Milling machine is used to perform drilling and milling operation on the fixture.

Figure 4-1: Drawing Sketches of Fixture used to mount wafer on aluminum hub, (Scale 1:2, Machine Used: Milling Machine)
4.2. Design Details of Rectangular Nozzle Details

4.2.1. 45° Nozzle

The drawing sketches of Rectangular Nozzle (45° angle) are shown in Fig. 4-2. Milling machine is used to perform drilling and milling operation on the fixture. Grinding machine is used to perform grinding operation on plastic part of nozzle lens.

Figure 4-2: Drawing Sketches of Rectangular Nozzle (45° angle), (Scale 2:1, Machine Used: Milling and Grinding Machine)
4.2.2. 60° Nozzle

The drawing sketches of Rectangular Nozzle (60° angle) are shown in Fig. 4-3. Milling machine is used to perform drilling and milling operation on the fixture. Grinding machine is used to perform grinding operation on plastic part of nozzle lens.

Figure 4-3: Drawing Sketches of Rectangular Nozzle (60° angle), (Scale 2:1, Machine Used: Milling and Grinding Machine)
5. EXPERIMENTAL PROCEDURE

5.1. Procedure for Making Degassed Water

Water contains various kinds of dissolved gases at various levels depending upon the temperature, solubility and exposure history. The requirement of the experiment is degassed and deionized water. The presence of dissolved gas can cause the occurrence of bubble. The schematic of the water delivery system to give degassed water is as shown in Fig. 5-1. It includes pressure chamber, heat exchanger, throttle valve, flow meter and condenser. Water is collected after passing through the condenser by opening the knob of flow meter. Pressure cooker is used as a vessel which gets pressurized after heating water inside the cooker.

Figure 5-1: Degassed Water Delivery System
The procedure for preparing the degassed method is described as follows:
The commercially available pressure cooker is filled with deionized water. This pressure cooker is equipped with different deadweights for different pressure settings above the atmospheric pressure. The pressure cooker is heated with the heating plate and once the desired 15 psi pressure is reached, then the deadweight is suddenly removed and pressure cooker is allowed to blow down and return to atmospheric pressure. The air dissolved in the water is forced out with the steam. This procedure is followed one more time. Then the water is passed through the condenser to reach at the room temperature. The degassed water is collected in a pouch by opening the valve and controlling the knob of flowmeter.
5.2. **Experimental Setup and Experimental Procedure**

The experimental setup is designed for delivering the de-ionized and degassed water through the nozzle on a wafer surface. The experiment procedure is same for all three kinds of nozzle which are listed as below:

- Circular Nozzle
- Rectangular Nozzle
- Nozzle Lens Design

![Experimental schematic diagram of meniscus setup](image)

**Figure 5-2:** Experimental schematic diagram of meniscus setup
Figure 5-2 shows the schematic of the water delivery system for meniscus study. It includes Nozzle, Degassed water pouch, a flow meter with attached regulator valve. The test section includes the wafer, mounting of wafer system.

Wafer is glued to a special aluminum hub with the help of super glue. Then it is mounted on another aluminum hub by using a fixture specially designed for locating and attaching an aluminum hub in the center of a wafer. The hub is then screwed to the leveling system flange and the aluminum hub is screwed down to the flange surface. Wafer mounting system is seating on the shaft which is connected to the shaft of the motor by using pulley and belt system. Rotational speed of motor is controlled by supplying voltage to motor with the help of digitally regulated power supply. The wafer surface is leveled with the help of leveling gauge indicator so that the wafer surface is parallel to the end of nozzle. This helps in maintaining the gap between wafer surface and nozzle end at the preset level. The needle is also positioned at certain radial distance from the center of wafer. This gives the necessary amount of relative velocity to the water delivered on wafer surface. The speed of the motor is adjusted by changing the voltage supply. Mass flow of water is controlled with the knob of flow meter. The reading is taken at the particular velocity of motor (which is at respective voltage) and gap between wafer surface and nozzle end and radial distance of nozzle these 2 parameters are fixed for the respective set of readings. Meniscus images are captured with the help of high speed camera and lens system. All videos and photo sequences are used to study the meniscus behavior and its characteristics.
6. CALCULATIONS

Mass flow and linear velocity of meniscus were important parameters which needed to be controlled in the experiment. So it was crucial to do the accurate measurement of these parameters. Mass flow was controlled by using the flowmeter and velocity of the meniscus was varied by changing the voltage supplied to motor.


While performing the experiment, mass flow was controlled by using the flowmeter and flowmeter reading was noted down for each observation. Table 1 shows the flowmeter reading and its respective mass flow for the needle design. Table 2 shows the flowmeter reading and its respective mass flow for the rectangular nozzle as well as for the nozzle with suction and supply port design.

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<tr>
<th>Flow-Meter Reading</th>
<th>Mass-flow (mg/sec)</th>
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<tr>
<td>32</td>
<td>1.84</td>
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<td>48.5</td>
<td>3.58</td>
</tr>
<tr>
<td>58</td>
<td>4.65</td>
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<td>63</td>
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<td>85</td>
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Table 1: Calculation of mass flow for needle design
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<th>Flow-Meter Reading</th>
<th>Mass-flow (g/sec)</th>
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<td>3</td>
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<tr>
<td>Max_without_Flowmeter</td>
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</table>

Table 2: Calculation of mass flow for nozzle design

Graph 1 of flow meter setting vs. mass flow is plotted by using the values in the table1 and table 2 for each nozzle design. The equation obtained from this graph is used to find out the mass flow value at any flow meter setting.

Graph 1: Graph of flowmeter setting vs. mass flow
6.2. **Linear Velocity**

Linear velocity of meniscus is one of the important parameter in the study of meniscus because it affects the shape of meniscus distinctly. The speed of the wafer is changed by controlling the voltage supply to motor which in turn rotates the wafer. The readings of the voltages and the speed of the wafer are recorded during the experiment. Table 3 shows the readings of wafer speed taken at respective voltage of motor. The equation (6) is used to calculate the linear velocity of meniscus is as shown below:

\[ V = r \cdot \omega \]  

(6)

where, \( V \) Linear Velocity (m/s)  
\( r \) Radius of Uniform circle on which constant motion takes place (m)  
\( \omega \) Angular Velocity (rad/sec)

Equation (7) is used to get the final value of linear velocity in m/sec after converting the rpm into rad/sec.

\[ V = (1.6 \cdot 0.0254) \cdot (rpm \cdot 2\pi) / 60 \]  

(7)

<table>
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<th>Voltage (V)</th>
<th>Speed (RPM)</th>
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<th>6 v</th>
<th>8 v</th>
<th>8.2 v</th>
<th>10.1 v</th>
<th>15.2 v</th>
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</tbody>
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**Table 3: Speed Calculation for Needle Design**
7. RESULTS AND DISCUSSION

Meniscus shape, advancing and receding contact angle and meniscus stability results for the circular as well as the rectangular nozzle design are presented in this section. All the images presented in the photo-sequence patterns in this section were obtained with a high-speed camera.

7.1. Results for Circular Design

7.1.1. Meniscus Flow Pattern

![Figure 7-1: Continuous Meniscus on Bare Glass (side view), (gap = 0.7mm, mass flow rate = 12.3 mg/s, velocity = 0.4m/s)](image)

Figure 7-1 shows the continuous meniscus on a glass wafer. The image is a side view. The water is supplied through the needle onto the wafer and the meniscus is formed in the gap between the wafer and needle end. Higher mass-flow and medium wafer velocity are the
factors that cause the meniscus to be continuous. The advancing contact angle of the meniscus is not sharp for the bare glass wafer.

Figure 7-2: Meniscus on Glass (Bottom View), (gap = 0.85mm, mass flow rate=16.5 mg/s, velocity = 0.25 m/s)

Figure 7-2 shows a continuous meniscus on a bare glass wafer. The images are a bottom view. The water is supplied through the needle onto the wafer and the meniscus is formed in the gap between the wafer and needle end. Figs. 7-2(1) to 7-2(4) are of equal time
interval (4 ms). Fig. 7-2(1) shows the first image of the continuous meniscus sequence. The continuous pattern of the meniscus is shown in Figs. 7-2 (2, 3, and 4).

### 7.1.2. Advancing and Receding Contact Angle

**Figure 7-3: Contact Angle (Water on Bare Glass), (gap = 0.85mm, mass flow rate =16.5 mg/s, velocity = 0.25m/s)**

Figure 7-3 shows the sequence of the contact angle formation on a bare glass wafer. The images are a side view. The advancing contact edge is not sharp in this case. Fig. 7-3(1) shows the droplet coming out of the needle. Fig. 7-3(2), 2 ms later, shows the drop of water touching the top surface of the wafer. Fig. 7-3(3) (1 ms later) and Fig. 7-3(4) (2 ms later) shows the developing meniscus with clear advancing contact edge forming.
Figure 7-4: Contact Angle (Water on Photoresist), (gap = 0.85 mm, mass flow rate = 16.5 mg/s, velocity = 0.25 m/s)

Fig. 7-4 shows the contact angle on a photoresist-coated wafer. The image is a side view. The advancing contact edge is very sharp in this case.
7.1.3. Meniscus Stability

Figure 7-5: Breaking Meniscus on Bare Glass, (gap = 0.7mm, mass flow rate = 15.8 mg/s, velocity = 1m/s)

Figure 7-5 shows the sequence of a breaking meniscus on a bare glass wafer from the side view. Meniscus breakage happened because of the high wafer velocity, low mass flow and large gap between the wafer surface and nozzle end. Fig. 7-5(1) shows the full meniscus.

Figures 7-5(1) to 7-5(4) are at equal time intervals of 8 ms. Fig. 7-5(2) shows the starting point of the meniscus breakage. Fig. 7-5(3) shows a further stage of the meniscus breakage, and Fig. 7-5(4) shows the empty gap between the wafer and the needle end because the meniscus has completely broken at that point.
Figure 7-6: Breaking Meniscus on Photoresist-Coated Wafer, (gap = 0.7mm mass flow rate = 2 mg/s, velocity = 0.2 m/s)

Figure 7-6 shows the sequence of a breaking meniscus on a photoresist-coated wafer from the side view. Meniscus breakage happened because of the high wafer velocity, photoresist surface characteristics, low mass flow and large gap between the wafer surface and nozzle end. Fig. 7-6(1) shows the water drop coming out of the needle. Fig. 7-6(2), 16 ms later, shows the complete meniscus. Fig. 7-6(3), 144 ms later, shows the meniscus breakage in progress. Fig. 7-6(4), 8 ms later, shows the final stage of the breaking meniscus.
Figure 7-7: Trapped Bubble in Meniscus, (gap = 0.7mm, mass flow rate = 12.3 mg/s, velocity = 0.4 m/s)

Figure 7-7 shows a trapped bubble in a water meniscus. The water is supplied through the needle onto a wafer and the meniscus is formed in the gap between the wafer and needle end. The bubble is generated within the meniscus and gets trapped inside the meniscus. The bubble stuck to the surface in the meniscus and did not move along the meniscus. The main reason for the presence of this bubble is gas in the water. Due to this observation, it is recommended that degassed water be used for meniscus experiments and liquid immersion lithography.
7.2. Results for Rectangular Design

7.2.1. Contact angle on Glass and photoresist wafer

a. (gap = 0.3mm, mass flow rate = 0.5 g/s, velocity = 1.0 m/s)

b. (gap = 0.5mm, mass flow rate = 1.9 g/s, velocity = 1.0 m/s)

c. (gap = 1.0mm, mass flow rate = 1.2 g/s, velocity = 1.0 m/s)

Figure 7-8: Meniscus Shape and Contact Angle (45° Nozzle)
The images in Fig. 7-8 are from an experiment performed using the 45° nozzle design. It also shows the difference between the meniscus shape on bare glass and the meniscus shape on a photoresist coating. The difference between contact angles on both surface types can be clearly seen.

**Figure 7-9: Meniscus Shape and Contact Angle (45° Nozzle)**

The images in Fig. 7-9 are from an experiment performed using the 60° nozzle design. It also shows the difference between the meniscus shape on bare glass and the meniscus shape on a photoresist coating. The difference between contact angles on both surface types can be clearly seen. A comparison of the images in Fig. 7-8 and Fig. 7-9 also
shows the difference in meniscus shapes and contact angles for the two different angles of inclination. A side-by-side comparison for the two different angles of inclination is shown in Fig. 7-10.

7.2.2. Effect of Nozzle angle

45° Nozzle

60° Nozzle

Rectangular Nozzle

Meniscus

a. (Glass Wafer: gap =1.0mm, mass flow rate=1.1 g/s, velocity =1.0 m/s)

45° Nozzle

60° Nozzle

b. (Photoresist-Coated Wafer: gap = 0.5mm, mass flow rate =1.9 g/s, velocity =1.0 m/s)

Figure 7-10: Side-By-Side Nozzle Angle Comparison

Figure 7-10 shows a side-view comparison of meniscus shape and contact angle on bare glass and photoresist-coated wafers for the two nozzle angle designs.
7.2.3. Instability of Meniscus

Figure 7-11: Effect of Residual Water on Wafer Surface, (gap = 0.3mm, mass flow rate = 1.1 g/s, velocity = 0.25 m/s)
The meniscus becomes unstable and forms surface waves at the leading edge due to the effect of residual water as shown in Fig. 7-11. Fig. 7-11(1) shows the leading edge of the meniscus on the rectangular nozzle-lens unit. Figs. 7-11(1) to 7-11(6) are at equal time intervals of 2 ms. Figs. 7-11(2) and 7-11(3) show the onset of meniscus instability. Figs. 7-11(4) and 7-11(5) show the waviness of the meniscus. Figs. 7-11(6), 7-11(7) (4 ms later) and 7-11(8) (4 ms later) show the waviness of the meniscus that led to the formation of bubbles and created a complete disturbance of the meniscus. This will become more prominent for larger slots (25 mm). Therefore, actual testing with the scale model of the nozzle is recommended.
Figure 7-12: Meniscus Instability, (gap = 0.3mm, mass flow rate = 1.3 g/s, velocity = 1.0 m/s)
Figure 7-12 shows the instability of the meniscus on a glass wafer from the bottom view. The water is supplied through the nozzle onto a glass wafer and the meniscus is formed in the gap between glass wafer and nozzle end. Fig. 7-12(1) show the complete meniscus formed in the gap between the wafer surface and the rectangular nozzle/lens unit. Figs. 7-12(2) (4 ms later) and 7-12(3) (12 ms later) show the wavy edge of the meniscus leads to instability. Fig. 7-12(4), 4 ms later, shows the same instability in the meniscus shape. Fig. 7-12(5), 2 ms later, shows that meniscus is becoming stable again.
7.2.4. Effect of non-degassed water

Figure 7-13: Bubble Attachment on Lens surface during Refill (particles in solution), (gap = 0.5mm, mass flow rate = 5 g/s, velocity = 1.0 m/s)
Figure 7-13 shows a bubble stuck to the lens blank surface during refill. The experiment was performed on a glass wafer. The images were captured from the bottom with a high-speed camera. Fig. 7-13(1) shows a meniscus of water containing a concentration of 2 and 10 μm beads that is formed between the lens blank surface of the rectangular nozzle unit and the wafer surface. Figs. 7-13(1) to 7-13(7) are at equal time intervals of 2 ms.

Figures 7-13(2) to 7-13(6) show the photo-sequence of water droplet gradually going away from the lens surface. Fig. 7-13(7) shows a bubble stuck on the lens surface.

Figure 7-14: Bubble Stuck on Nozzle Surface (DI Water-Not Degassed), (gap =1.0mm, mass flow rate =0.5 g/s, velocity =0.25 m/s)
Irrespective of the flow coming out of nozzle, the bubble remains stuck on the surface of the nozzle as shown in Fig. 7-14. Fig. 7-14(1) shows the bubble formed on the nozzle surface and a partially developed meniscus that was formed at that point. Figs. 7-14(2) (4 ms later), 7-14(3) (10 ms later) and 7-14(4) (4 ms later) shows that throughout the sequence the bubble does not move with the meniscus movement. This Experiment was performed on a glass wafer. The main reason for the presence of this bubble is gas in the water, so it is recommended that degassed water be used for meniscus experiments and liquid immersion lithography.
7.2.5. Bubble Entrapment

The breaking of a meniscus can lead to bubble entrapment as shown in Fig. 7-15. This experiment was performed on a bare glass wafer, and the images are bottom view. Small bubbles of 10-80 μ size were seen after the breakage. Bubbles became smaller due to absorption in degassed water. Fig. 7-15(1) shows the breaking point of the meniscus at the edge. As the meniscus starts breaking, it forms two bubbles as shown in Fig. 7-15(2) (8 ms later). These two bubbles get absorbed in the water gradually as shown in Fig. 7-15(3) (4 ms later) and Fig. 7-15(4) (2 ms later).
7.2.6. Meniscus characteristics

Figure 7-16 shows the breaking of a meniscus on a bare glass wafer from the bottom view. The flow coming out of the nozzle breaks into two streams and the meniscus is observed at the outer and inner edges of the nozzle/lens unit. Fig. 7-16(1) shows the meniscus at the outer and inner edge and that the meniscus is beginning to break at the outer edge. Fig. 7-16(2), 6 ms later and Fig. 7-16(3), 8 ms later, both show the further stages of a
breaking meniscus at the outer edge. Fig. 7-16(4), 18 ms later, shows the full meniscus only at the inner edge and how a meniscus only remains towards the back of the lens blank area at the outer edge and center.

7.2.7. Flow Visualization

Figure 7-17: Flow Visualization, (gap = 0.5mm, mass flow rate=5g/s, velocity =1.0 m/s)

Flow visualization experiments were performed using water containing a concentration of 2 and 10 μm beads as shown in Fig. 7-17. These experiments were performed on a glass wafer. This image was captured from the bottom with a high-speed camera.
7.3. Results for Nozzle Lens Design with Integral Supply and Suction Ports

7.3.1. Meniscus Flow Pattern

Figure 7-18: Continuous Meniscus on Glass wafer, (gap = 0.4 mm, mass flow rate = 1.1 g/s, velocity = 0.5 m/s)
Figure 7-18 shows the sequence of a continuous meniscus on a Glass wafer from the bottom view. The water is supplied through supply port of nozzle and is getting sucked at suction port. The meniscus is formed in the gap between the wafer and nozzle. Higher mass-flow and High suction pressure with medium wafer velocity are the factors that cause the meniscus to be continuous.

![Figure 7-18: Continuous Meniscus on Glass Wafer](image)

Figure 7-19 shows the sequence of a breaking meniscus on a Glass wafer from the bottom view. Meniscus breakage happened because of the high wafer velocity, high suction pressure, low mass flow and large gap between the wafer surface and nozzle end. Fig. 7-

![Figure 7-19: Breaking Meniscus on Glass Wafer, (gap = 0.4 mm, mass flow rate = 0.5 g/s, velocity = 1 m/s)](image)
19(1) shows the starting of meniscus from the supply end. Fig. 7-19(2)(9 ms later) and Fig. 7-19(3)(2 ms later) shows the meniscus breakage in progress. Fig. 7-19(4)(9 ms later) shows the final stage of the breaking meniscus.

7.3.2. Operating Suction and Discharge Pressure Effect

![Diagram of supply and suction ports with wafer and nozzle](image)

**Figure 7-20: Suction of Wafer due to Surface Tension and Pressure Forces**

Figure 7-20 shows the suction of wafer due to the surface tension and pressure forces. This is the practical problem occurred while performing the experiment. As soon as the amount of suction pressure increases for low gap, wafer gets suck towards suction port which breaks the meniscus. So the proper balance needed to maintain between the gap between the wafer surface and nozzle and suction pressure. The operating suction and discharge pressures are very important to prevent the suction of the wafer toward the suction port, thereby effectively stopping liquid flow, and mechanical damage to the wafer.
8. CONCLUSIONS

Stability of Meniscus was one of the important aspects of the experimental work done for the circular as well as the rectangular nozzle design. All the images presented in the photo-sequence patterns in this section were obtained with a high-speed camera. Wafer surface, linear velocity, mass flow and gap between the nozzle and wafer surface are the various parameters which needed to be controlled to get the desired full stable meniscus. Use of degassed water is also one of the major factors which help in obtaining the stable shape of full meniscus. The main conclusions of the experimental study are as shown below:

1. It is possible to obtain stable meniscus under the lens. The ranges of operating parameters under which a stable operation can be achieved need to be established for a specific nozzle system.

2. Bubble entrapment may be caused by interface waves in meniscus.

3. Bubble stuck on lens or inlet piping may stay there for a while unless degassed water is used – degassed water is recommended.

4. Presence of water droplets on the incoming wafer surface may break meniscus and trap bubbles.

5. The operating suction and discharge pressures are very important to prevent the suction of the wafer toward the suction port, thereby effectively stopping liquid flow, and mechanical damage to the wafer.

6. Contact angle and meniscus shape depend on wafer surface.

7. The apparatus developed at RIT allows for flow visualization using high-speed camera and micro scale particle tracking.
8. The shape of the meniscus is different on quartz and photo-resist surfaces due to different advancing contact angles.

9. Bubble entrapment is not seen to be a problem on quartz surface.

10. Photo-resist surface with its surface texture may cause some concerns—need to validate.

11. Setup is ready for actual testing with rectangular nozzles and jets with different inclinations.
9. REFERENCES


International SEMATECH.


