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Investigation on the critical velocity for liquid loss in immersion lithography

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ABSTRACT

Immersion lithography seeks to extend the resolution of optical lithography by filling the gap between the final optical element and the wafer with a liquid characterized by a high index of refraction. The semiconductor industry demands high throughput, leading to relatively large wafer scanning velocities and accelerations. For higher scanning velocities, an issue that has been identified is the deposition of the immersion liquid while confining a relatively small amount of liquid to the under-lens region. Liquid loss occurs at the receding contact line that forms when a substrate is withdrawn from a liquid, which potentially leads to defects on printed patterns. There has been substantial prior work relative to understanding and building semi-empirical correlations and numerical models to investigate this behavior of the receding three-phase contact line. In the current work, a new liquid injection and collection model with analytic solutions is presented and compared with experimental results, in which the critical velocity for liquid loss is mainly a function of the vacuum degree, the injection flow rate, the properties of the immersion liquid. This correlation allows the critical velocity to be predicted with a given gap height between wafer and lens using only a measurement of the injection speed and knowledge of the fluid properties. Experimentally, glycerin–water mixtures of varying viscosities and different injection flow rates were tested, with variable outlet vacuum degree and inlet speed, showing a mean average error within 12%. This correlation represents a useful tool that can serve to approximately guide the development of fluid control for immersion systems as well as to evaluate alternative immersion fluid candidates to minimize liquid deposition while maximizing throughput.

1. Introduction

The intention of immersion lithography is to increase the index of refraction in the space between lens and wafer by introducing a high refractive index liquid in place of the low refractive index air that currently fills the gap. It has been proved to be a practical technology extending optical lithography without significant changes to the manufacturing infrastructure used for decades [1,2].

Several engineering challenges accompany the insertion of the immersion fluid in a production tool, one of the most important being the confinement of a relatively small amount of liquid to the under-lens region. The semiconductor industry demands high throughput, leading to relatively large wafer scanning velocities and accelerations. For higher scanning velocities, an issue that has been identified is the deposition of the immersion liquid. Liquid deposition is undesirable; as the droplets evaporate they will deposit impurities on the substrate. In an immersion lithography tool, these impurities may be transmitted to the printed pattern as defects. Analysis has been completed by using computational fluid dynamics modeling, with the conclusion that the contact angle is a critical parameter determining the contact line behavior [3,4].

The current work aims at a new liquid injection and collection model in which the critical velocity for liquid loss is mainly a function of the vacuum degree, the injection flow rate, and the properties of the immersion liquid. The correlation allows critical velocity to be predicted for a given gap height between wafer and lens using only a measurement of injection speed and knowledge of the fluid properties. To verify modeling accuracy, fluid mixtures of varying viscosities are tested, with variable outlet vacuum degree and inlet speed, compared with experimental results.

2. Modeling

A schematic of the active filling and collecting model is shown in Fig. 1. The liquid with density ρ, surface tension σ, and viscosity μ, is dispensed onto a wafer and collected by certain vacuum at P_v. The head loss from liquid dispense port to collect port is composed of three parts: head loss h_{L_1}, bend loss h_B, and head loss h_{L_2}. The wafer movers under the stationary lens have a speed at v_s. A thin gap of height L_1 and width L exists between lens and wafer.

The flow field is divided into two regions: before flow-bend, and after flow-bend. In the before flow-bend region, it is assumed that

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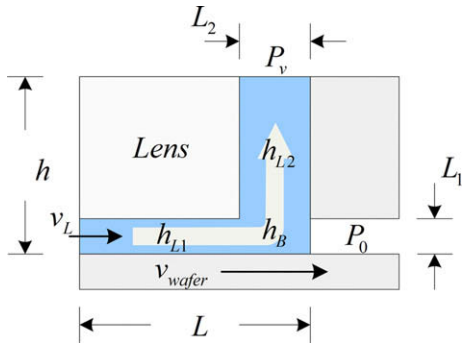

Fig. 1. Schematic of the important parameters that affect noncontact sealing boundaries. While wafer is moving, the liquid are injected and collected to maintain the optical uniformity beneath the stationary lens.

the flow is laminar and fully developed, driven by viscous shear and pressure gradients, which is the well know Couette–Poiseuille flow [5]. Taking the initial injecting velocity into consideration, the bulk velocity of the liquid in the filled region, v_D, could be defined as [6]:

$$v_D = v_L + \frac{v_s}{2} + \frac{L_1}{L}\left(\frac{\sigma}{3\mu} + \frac{v_s^2 \rho H}{24\mu}\right) \tag{1}$$

where σ is the surface tension of the liquid; H the height from the wafer surface to the collection port and L is the vertical length of the fluid over the wafer surface

In the after flow-bend region, it is assumed that the flow is steady and incompressible, which could be described by Bernoulli's theorem.

$$\left(\frac{p_0}{\gamma} + z_0 + \frac{v_0^2}{2g}\right) - \left(\frac{p_v}{\gamma} + H + \frac{v_v^2}{2g}\right) = h_B + h_{L_2} \tag{2}$$

where p_0 is the ambient pressure at the liquid free surface; $\gamma = \rho g$, the liquid volume weight; $z_0 = 0$, the vertical position near the wafer.The bend loss, h_B, described the head loss for liquid flow changing direction into collection channel, is given by [7]:

$$h_B = k_B \frac{v_v^2}{2g} \tag{3}$$

$$h_{L_2} = 32 \frac{\mu}{\gamma} \frac{h}{L_1^2} v_v \tag{4}$$

where v_v is the average velocity for liquid within collection channel.

Assuming there were no liquid loss and air entraining and according to the structure shown in Fig. 1, it is ready to obtain the relationship between v_0 and v_v as follows:

$$v_v = v_0 \frac{L_1}{L_2} \tag{5}$$

By substituting Eqs. (1), (3)–(5) into Eq. (3), it is possible to derive In Eq. (6). The bulk velocity v_0 represents the maximum flow rate for liquid collection, and the bulk velocity v_D shows the flow rate for liquid dispense. The critical wafer scanning speed appears as v_s when $v_D = v_0$, and the liquid leaks on wafer when $v_D > v_0$. The loss coefficient k_B is a structure-defined value, and should be decided during experiments.

$$\begin{cases} v_D = v_L + \frac{v_s}{2} + \frac{L_1}{L}\left(\frac{\sigma}{3\mu} + \frac{v_s^2 \rho h}{24\mu}\right) \\ v_D \leqslant v_0 \\ v_0^2 \frac{1}{2g}\left(1 - k_B \frac{L_1^2}{L_2^2} - \frac{L_1^2}{L_2^2}\right) - v_0 \frac{32\mu}{\gamma} \frac{L}{L_1 L_2} = \frac{p_v}{\gamma} + h \end{cases} \tag{6}$$

The correlation expresses that, in certain immersion unit with active liquid filling structure, the critical wafer velocity for liquid loss is mainly a function of the liquid injection velocity (flow rate), the vacuum degree, and the viscosity of the immersion liquid.

3. Experimental facility

The similar experimental facility as previous work was used, composed of a hydraulic circuit to control the liquid injecting and collecting pressure, and a high-speed camera system to record boundary movement of the flow field within lens–wafer space, as shown in Fig. 2, and specifically described in Ref. [8]. The locating platform was composed of Bayside M150R-0400 and M150R-0300 driven by two servo-actuator driver, YASKAWA SGMAH04AAA41 and SGDM04ADA, connected to a PMAC2A-PC/104 control card. The maximum speed is 650 mm/s, and the repeatable accuracy ± 5 μm.

An immersion unit prototype was designed and implemented, aiming at integrated within an experiment platform for lithography scan-step moving and exposing [8]. A schematic of the immersion unit prototype is illustrated Fig. 3, with working principle described in Ref. [8]. The wafer motion is oscillatory and characterized by velocities as high as 650 mm/s and accelerations as high as twice the acceleration of gravity. The distance between immersion unit (also the lens) and the glass replacing wafer is 1 mm.

Measurement uncertainties for experiment set-up were estimated. The uncertainty on the immersion unit prototype structural parameters was ±0.1%, flow rate was ±0.5%, and pressure was ±0.5%, respectively.

4. Experimental verification of model

As in the modeling part, In Eq. (6) has expressed the correlation between the critical wafer velocity v_s, liquid injection velocity v_L, the vacuum degree P_v and the immersion liquid viscosity μ. However, the loss coefficient k_B has to be decided before the In Eq. (6) can be applied on a certain structure of immersion unit.

Experiments for immersion prototype with physical structure and liquid parameters listed in Table 1 were carried out, and re-

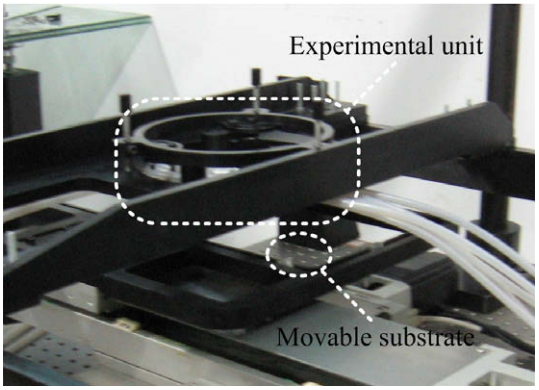

Fig. 2. Immersion unit prototype.

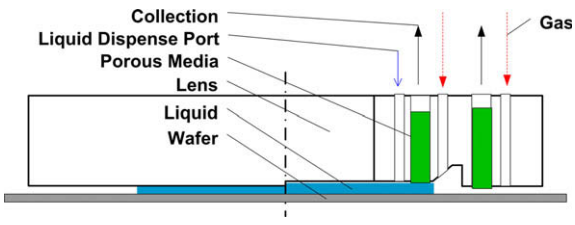

Fig. 3. Schematic of the immersion unit.