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Modelling slip flow in micro/nano gaps with moving boundary

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ABSTRACT

The analytical solution models have been constructed to describe the slip flow in the micro/nano gaps with moving boundary, including the case of immersion lithography. The two-dimensional computational fluid dynamics models are established to validate them. The results show that the slip flow varies with time and tends to a steady state quickly. The transient and steady states are investigated respectively to overall describe the slip flow, and there are significant differences between the slip and non-slip flow. Moreover, the stationary liquid on moving wall may be generated when the direction of pressure-driven flow is opposite to the direction of shear flow. This phenomenon is important to prevent liquid leakage during wafer scanning, and the corresponding parameters are optimized to improve the quality of advanced immersion lithography.

1. Introduction

Boundary slip on solid surfaces in micro/nano devices has been confirmed in many recent studies [1], and it is an important manifestation of surface forces [2], especially for the superhydrophobic surface with large slip length. It brings new flow behaviors and plays an important role in the micro/nano devices [3]. So it should not be ignored in the manufacturing processes including immersion lithography and nanoimprint lithography [4]. For immersion lithography, the high refractive index liquid is inserted into the micro-gap between the final lens element and moving wafer shown in Fig. 1. In order to prevent liquid leakage [5], the superhydrophobic coatings on wafer have been used and they may lead to large boundary slip [6,7] of the immersion flow. The slip effect changes the status of immersion flow such as the flow status, liquid renovation and even the flow stress on lens element [8]. Thus the slip model with moving boundary is desirable for the more precise description and control of immersion flow in advanced immersion lithography.

In this paper, the analytical solution models based on the continuum assumption with slip condition are constructed to describe the slip flow with moving boundary covering immersion cases. The similar methods have been adopted in recent papers [9–11] to study the characteristics of micro-flow. The remainder of the paper is organized as follows. Section 2 presents the analytical solutions of the governing equations with initial boundary conditions. Section 3 compares the analytical solutions with numerical solutions. The detailed research of the slip flow in the two typical stages is given in Sections 4 and 5, respectively. The text ends with the conclusion in Section 6.

2. Analytical solution of the slip flow model

The slip-flow in micro-gap consists of pressure-driven flow and shear flow, and its velocity distribution $u_{\text{gap}}(t,y)$ illustrated in Fig. 2 can be estimated by

$$u_{\text{gap}}(t,y) = u_p(y) + u_{\text{i}}(t,y) \tag{1}$$

where t represents time, y is the distance from a position in liquid to wafer, the first item $u_p(y)$ indicates the velocity driven by differential pressure between inlet and outlet, and the $u_i(t,y)$ ($i = 1, 2$) denotes the velocity due to moving wall.

For the pressure-driven flow, the velocity $u_p(y)$ with Navier slip boundary satisfies the following governing equations with the boundary conditions

$$\begin{cases} \frac{d^2u_p(y)}{dy^2} = -\frac{1}{\mu}\frac{\Delta p}{L}, \\ u_p(0) = b\frac{du_p}{dy}, \quad y = 0, \\ u_p(h) = 0, \quad y = h, \end{cases} \tag{2}$$

where Δp is the differential pressure between inlet and outlet, μ indicates liquid viscosity, L represents the gap length, b denotes the slip length of boundary, and h signifies the thickness of liquid.

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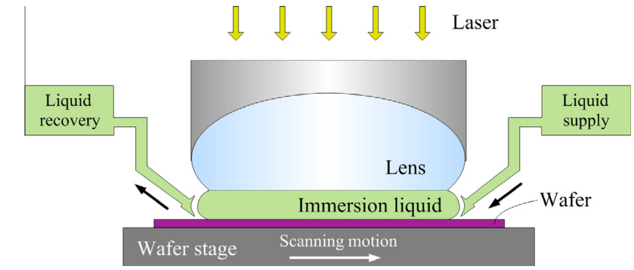

Fig. 1. Schematic diagram of immersion lithography equipment.

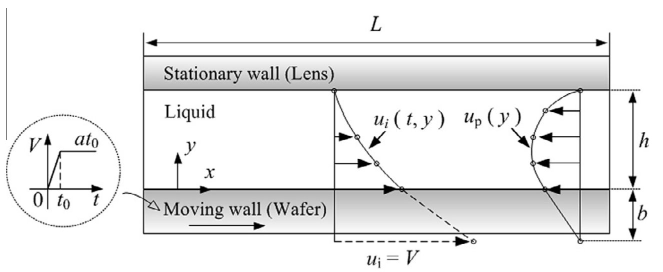

Fig. 2. Velocity distribution of slip flow in micro/nano gaps.

It is easy to obtain the solution of the ordinary differential Eq. (2), which reads

$$u_p(y) = \frac{\Delta p}{2\mu L}\left(\frac{bh^2}{h+b} + \frac{h^2}{h+b}y - y^2\right). \tag{3}$$

Obviously, the $u_p(y)$ is reduced to the velocity of Poiseuille flow when $b = 0$, and it is independent of time, which plays an important role in the research of steady slip-flow.

For the shear flow, it is generated by moving wall which moves at a constant speed after a stage of acceleration movement generally. To describe the flow at the acceleration stage, the governing equation of liquid velocity is given by

$$\frac{\partial u_1}{\partial t} = \mu\frac{\partial^2 u_1}{\partial y^2} \tag{4}$$

with the Navier slip boundary conditions

$$\begin{cases} t = 0: \quad u_1 = 0, \\ y = 0: \quad u_1 - b\frac{\partial u_1}{\partial y} = at, \\ y = h: \quad u_1 = 0. \end{cases} \tag{5}$$

The analytical solution of Eq. (4) with the conditions (5) can be solved by using Duhamel's principle and variable separation technique, and it reads

$$u_1 = \sum_{n=1}^{\infty} Y_n(y)\int_0^t C_n(\tau)e^{-\mu\lambda_n^2(t-\tau)/h^2}d\tau + at - \frac{aty^2}{h^2} \tag{6}$$

where

$$C_n(\tau) = \frac{\int_0^h\left(\frac{ay^2}{h} - \frac{2\mu a\tau}{h^2} - a\right)Y_n(y)dy}{\int_0^h (Y_n(y))^2 dy} \tag{7}$$

and

$$Y_n(y) = \frac{b\lambda_n}{h}\cos\left(\frac{\lambda_n y}{h}\right) + \sin\left(\frac{\lambda_n y}{h}\right), \tag{8}$$

in which λ_n ($n = 1,2,3\ldots$) denote the positive solutions of the equation $\tan(\lambda) = -b\lambda/h$.

After the stage of acceleration movement ($t \in [0, t_0]$), the wall moves at a constant speed. To describe the following stage of uniform movement, the governing equation with new initial boundary conditions is constructed as

$$\begin{cases} \frac{\partial u_2}{\partial t} = \mu\frac{\partial^2 u_2}{\partial y^2}, \\ t = 0: \; u_2 = u_1(t_0, y), \\ y = 0: \; u_2 - b\frac{\partial u_2}{\partial y} = at_0, \\ y = h: \; u_2 = 0. \end{cases} \tag{9}$$

By the similar methods, the analytical solution of problem (9) is obtained as

$$u_2 = \sum_{n=1}^{\infty} Y_n(y)\left[B_n e^{-\mu\lambda_n^2 t/h^2} + \frac{h^2 D_n}{\mu\lambda_n^2}\left(1 - e^{-\mu\lambda_n^2 t/h^2}\right)\right] - \frac{at_0 y^2}{h^2} + at_0, \tag{10}$$

where

$$B_n = \frac{\int_0^h\left(u_1(t_0, y) + \frac{at_0 y^2}{h^2} - at_0\right)Y_n(y)dy}{\int_0^h (Y_n(y))^2 dy} \tag{11}$$

and

$$D_n = \frac{-2a\mu t_0\int_0^h Y_n(y)dy}{h^2\int_0^h (Y_n(y))^2 dy}, \tag{12}$$

in which $Y_n(y)$ is given in Eq. (8). The detailed solving processes of $u_i(t,y)$ are given in the Appendix.

Based on the convergence theorem in series theory, it is proved that the series (6) and (10) are convergent. In the following, we get the solutions with high precision when the value of $n = 600$. In addition, the corresponding parameters used in this model are listed in Table 1.

3. Validation of the analytical solution model by CFD simulation

To verify the analytical solution models of slip flow, the two-dimensional computational fluid dynamics (CFD) models is developed. It is conducted by software FLUENT 6.3 with pressure-based, unsteady flow and absolute velocity formulation. To achieve the Navier-slip in CFD simulation, the boundary model illustrated in Fig. 3 is established to satisfy

$$u_{wall} = \frac{Vd + u_{cell}b}{b+d} \tag{13}$$

where u_{wall} denotes the wall velocity, d is the distance between the wall surface and the center of mesh cell which is closest to the moving wall, and u_{cell} indicates the velocity of the mesh cell. This boundary model is implemented by the method of user-defined functions in the simulation. Based on the analytical solutions and simulation results of slip flow, the non-dimensional velocity in the gap center due to moving wall is shown in Fig. 3.

Table 1
The parameters for the slip models.

Parameter	Symbol	Value
Gap height	h	0.01–300 μm
Slip length	b	0.01–0.5h
Acceleration	a	10 m/s^2
Wall velocity	V	0–10 m/s
Liquid viscosity	μ	10^{-3} Pa s
Gap length	L	100 mm
Differential pressure between inlet and outlet	Δp	0–10000 Pa