Investigation of Photothermal Effects on the Liquid Field during the Exposure Process in Immersion Lithography

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Abstract. Immersion lithography has been extending technology nodes to the sub-20nm regime of semiconductor manufacturing. Keeping the immersion liquid pure and uniform as well as avoiding residual droplets during high speed scanning motion are two challenges faced by the development of immersion lithography. During the exposure process of immersion lithography, the heat of the incident beam may cause the temperature rise of the immersion fluid which could result in the image placement on the silicon wafer. For this reason, the photothermal effects of the immersion fluid field during the exposure process are investigated in this paper to ensure the high-quality and stable-flowing of the immersion fluid, and consequently the accuracy of the pattern image transferred on the silicon wafer. Results obtained in this paper can provide solid guidance and definitely accelerate the development of the immersion lithography in the sub-20nm regime.

1. Introduction
Over the past decade, immersion lithography has been extending technology nodes to the sub-20nm regime of semiconductor manufacturing [1-3]. Keeping the immersion liquid pure and uniform as well as avoiding residual droplets during high speed scanning motion are two challenges faced by the development of immersion lithography [4-6]. During the exposure process of immersion lithography, the heat of the incident beam may cause the temperature rise of the immersion fluid which could result in the image placement on the silicon wafer. For this reason, the photothermal effects of the immersion fluid field during the exposure process are investigated in this paper to ensure the high-quality and stable-flowing of the immersion fluid, and consequently the accuracy of the pattern image transferred on the silicon wafer.

2. Theoretical analysis of the immersion field during the exposure process
Figure 1 illustrates the schematic of the heat transfer of the immersion field during the exposure process. As shown in Figure 1, the incident beam passes through the objective lens to the immersion field, and then reaches the photoresist and the underneath wafer at last. The heat from the incident beam can be transferred to the immersion field by heat conduction, thermal convection, and radiation.

Therefore, the energy equation of the immersion field can be expressed as:
\[
\frac{\partial}{\partial t}(\rho E) + \nabla \cdot (\bar{v}(\rho E + p)) = \nabla \cdot (k_{\text{eff}} \nabla T) - \sum_j h_j \bar{J}_j + \left( \bar{\tau}_{\text{eff}} : \bar{\nabla} \right) + S_h \tag{1}
\]
where \(E\) and \(T\) denote the total energy and temperature of the immersion fluid respectively; \(\rho\) and \(k_{\text{eff}}\) present the density and the effective thermal conductivity of the fluid; \(h_j\) and \(J_j\) represent the enthalpy...
and diffusion flux of the component \( j \) respectively; \( S_h \) denote the heat generated by the radiant heat source.

The equation of radiative transfer can be written as:

\[
\frac{1}{c} \frac{\partial}{\partial t} I_v + \hat{\Omega} \cdot \nabla I_v + (k_v,s + k_v,a) I_v = j_v + \frac{k_v,a}{4\pi} \int I_v \, d\Omega
\]

(2)

where \( I_v \) and \( j_v \) denote the spectral radiance and the the emission coefficient of the field respectively; \( k_v,s \) and \( k_v,a \) represent the scattering opacity and the absorption opacity respectively; and \( \Omega \) is the radiation angle.

Theoretically, the temperature distribution of the immersion field could be obtained by solving Equations (1) and (2) simultaneously. However, it is extremely difficult to solve these two nonlinear partial differential equations, thus the analytical solution is essentially unlikely to acquire. Therefore, the commercial software FLUENT is utilized in this research to simulate the immersion fluid field during the exposure process, and the temperature distribution of the immersion fluid field can be obtained numerically.

3. Investigation of photothermal effects on the immersion field

3.1 A two-dimensional model of the immersion field during the exposure process

A 2-D geometric model of the immersion field during the exposure process is shown in Figure 2. The material properties and the geometric dimensions of the immersion field are presented in Table 1. The parameters of the incident beam are also illustrated in Table 1. The temperature at the injection and recovery ports are set as the room temperature (20°C). It should be noted that in this research, the photothermal effect on a single chip, not many chips, is investigated during the exposure process.

Figure 1. Schematic of the heat transfer of the immersion field during exposure.

Figure 2. The 2-D geometric model of the immersion field.
Table 1. Parameters and dimensions utilized in the simulations.

| Parameter                      | Symbol | Water  | Photoresist | Silicon Wafer |
|--------------------------------|--------|--------|-------------|---------------|
| Coefficient of thermal         | $k$    | 0.6 W/(m·K) | 0.2 W/(m·K) | 168 W/(m·K)  |
| conductivity                   |        |        |             |               |
| Specific heat capacity         | $c$    | 4182 J/(kg·K) | 1500 J/(kg·K) | 750 J/(kg·K) |
| Density                        | $\rho$ | 997 kg/m$^3$ | 1200 kg/m$^3$ | 2330 kg/m$^3$ |
| Coefficient of absorption      | $\kappa$ | 35 m$^{-1}$ | 5×10$^5$ m$^{-1}$ | 0 |
| Viscosity                      | $\mu$  | 0.001003 Pa·s | --         | --            |

| Parameter                      | Symbol | Value       |
|--------------------------------|--------|-------------|
| Height of immersion field      | $h$    | 1 mm        |
| Thickness of photoresist       | $h_p$  | 150 nm      |
| Thickness of silicon wafer     | $h_w$  | 625 μm      |
| Diameter of objective lens     | $l$    | 5 cm        |
| Dimension of chip              | --     | 25 mm × 32 mm |
| Parameters of Incident Beam    |        |             |
| Beam width                     | $d$    | 5 mm        |
| Power of light source          | $q$    | 20 w        |
| Illumination time              | $t_{scan}$ | 0.1 s     |

3.2 A 2-D model of the immersion field during exposure process

The temperature variation of the immersion field under the static condition is investigated at first. Since the silicon wafer keeps still, the immersion field will remain static. Then the heat of the incident beam is transferred to the immersion field via thermal conduction.

Since the temperature has the biggest variation along the central line of the incident beam, thus Figure 3 presents the variation of the temperature along the central line. As shown in Figure 3, the temperature in the immersion field arises quickly with the increase of the illumination time, but drops quickly with the increase of the layer position.

According to Mulkens et. al. [7], for the immersion field with the height of 1mm and NA of 1.1, if the image placement is limited to within 1nm, then the maximum difference of the temperature in the immersion field should be less than 100mK. However, it can be found in Figure 3 that the maximum difference of the temperature along the central line is more than 230mK. It indicates that the immersion fluid can’t remain static if the temperature difference in the immersion field needs to be diminished or controlled to be a lower value.

3.3 Photothermal analysis of the immersion field under the steady motion of the silicon wafer

As discussed in the previous section, the maximum temperature change in the static immersion field is far beyond the technical limit. Therefore the flowing of the immersion fluid is necessary to control the temperature difference in the immersion field. In this section, the temperature distribution of the immersion field is analyzed when the silicon wafer is under a steady motion.

The silicon wafer is scanned with a steady velocity of 0.25 m/s and the values of the parameters used in the simulations are listed in Table 1. The illumination time remains as 0.1s such that a single chip can be scanned completely. Figure 4 shows the standard deviation of the temperature in the
exposure area under the steady motion of the silicon wafer. It can be seen that the temperature difference in the immersion field quickly converges to a very small value. The maximum difference of the temperature in the immersion field is 86mK which is way below the technical limit of 100mK.

Figure 3. Temperature distribution along the central line of incident beam.

Figure 4. Standard deviation of the temperature in the exposure area at different time under the steady motion of the silicon wafer.

3.4 Photothermal analysis of the immersion field under the oscillatory motion of the silicon wafer

Results in Section 3.3 indicate that the steady motion of the silicon wafer can significant diminish the temperature difference in the immersion field, which can reduce the image placement on the silicon wafer during the exposure process. However, in reality, the silicon wafer is under a periodically oscillatory motion during the exposure process. Therefore the thermal analysis of the immersion field under the oscillatory motion of the wafer is conducted in this section.

Since the heat accumulated on the silicon wafer are absorbed by the immersion fluid and transferred to the downstream of the flow, thus the thermal effect will be increase gradually at the downstream of the exposure area. Therefore, the maximum temperature difference occurs at the rightmost end of the exposure area. Figure 5 illustrates the temperature distribution along the vertical direction of the rightmost end of the exposure area at different illumination times. The temperature
distribution under both the steady motion and the oscillatory motion are compared and shown in Figure 5. It can be seen that the temperature remains very stable for the immersion field which is more than 0.3mm higher than the surface of the silicon wafer. For the immersion field close to the surface of the wafer, the temperature distribution along the vertical direction of the rightmost end of the exposure area are quite similar, no matter under the steady motion or the oscillatory motion of the silicon wafer.

![Graph showing temperature distribution](image)

Figure 5. The temperature distribution along the vertical direction of the rightmost end of the exposure area at different illumination time.

4. Summary
In this paper, the photothermal effects of the immersion field during the exposure process of a single chip are analyzed. A 2-D numerical model of the static immersion field during the exposure process is constructed at first. Simulations reveal that the heat of the incident beam is primarily absorbed by the photoresist on the silicon wafer, and then conducted to the immersion liquid to cause the temperature rise of the immersion field. Results also indicate that the maximum temperature difference in the static immersion field is far beyond the technical limit of immersion lithography. Hence the immersion field under the steady motion and oscillatory motion of the silicon wafer is investigated. Results show that both motions of the silicon wafer can significantly diminish the maximum temperature difference in the immersion field to the level below the technical limit. Results obtained in this paper can provide solid guidance and definitely accelerate the development the immersion lithography in the sub-20nm regime.

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