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Characterization of stray light of ArF lithographic tools: Modeling of power spectral density of an optical pupil

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Abstract

Stray light (also called 'flare') in optical lithography is unwanted scattered light and is characterized by power spectral density (PSD) of an optical pupil. The PSD is evaluated on commercial dry and wet (immersion) ArF (193 nm) lithographic scan tools by means of a modified disappearing pad test (so-called Kirk test). Doughnut-type pads are suggested for this disappearing pad test, which verifies that double ABC and fractal PSD describe the measured stray light better than Gaussian PSD both in the dry and the wet tools. The evaluated PSD is confirmed by the measurements of printed features on wafer.

Keywords: Stray light; Flare; Lithography; Power spectral density (PSD); Point spread function (PSF) of scattering; Immersion

1. Introduction

Stray light is incoherent light that does not follow the normal optical path and degrades lithographic performances [1–3]. In the previous work [3], we evaluated the stray light as constructing Power Spectral Density (PSD) of the lens pupil surface of lithographic tools from the 'disappearing pad test' known as 'Kirk test' [1]. PSD, a function for surface roughness in statistics, serves as a characteristic function of how far and much stray light reached on an imaging plane in optics [2–5].

The image without stray light, $I(\mathbf{r})$ is blurred in the presence of stray light and the image with stray light, $I^{\mathrm{SL}}(\mathbf{r})$ is then given by

$$I^{\mathrm{SL}}(\mathbf{r}) = (1-\mathrm{TIS})\cdot I(\mathbf{r}) + \mathrm{PSD}\otimes I(\mathbf{r})|_{<\mathrm{field}} \quad \left(\text{with } \mathrm{TIS} \equiv \int\int_{<\mathrm{field}} \mathrm{PSD}(\mathbf{r})\mathrm{d}\mathbf{r}\right) \tag{1}$$

$\mathbf{r}$ is a position vector normalized by wavelength, λ. '$\otimes$' denotes convolution and '*field*' indicates that the range of this convolution integral is limited in an exposure-field size. TIS in Eq. (1) is 'total integrated scatter' and means the portion of scattered light. TIS is typically as small as a couple of percents.

In this work, we characterize thoroughly the PSD from the disappearing pad tests for ArF lithographic tools including an immersion tool. Doughnut-shape pads are introduced to the disappearing pad test for the determination of appropriate functional forms for PSD.

2. The functional forms of PSD

Some functional forms for PSD have been suggested [2–5], each having their own set of to-be-determined parameters (Table 1). "r" is used as a variable of a scalar quantity instead of the vector "$\mathbf{r}$", as rotational symmetry is assumed for the PSD. Here, we modify the PSD forms as applying so-called "double PSD". This is explained as follows. When multiple scattering processes are concerned, the total PSD can be expressed as the convolution of each PSD corresponding to each process [4]. In the previous work, we applied the *double* PSD as assuming *double* scattering processes [3]. In this case, the convolution can be approximated with two PSD functions depending on the range of r or their sum.

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Table 1
Functional forms of double PSD. When w_2 or $K_2 = 0$, the PSD will be single type

Gaussian	ABC	Fractal
$\frac{1}{\sqrt{2\pi}}\left\{\frac{w_1}{\sigma_1}\exp\left(\frac{-r^2}{2\sigma_1^2}\right)+\frac{w_2}{\sigma_2}\exp\left(\frac{-r^2}{2\sigma_2^2}\right)\right\}$	$\begin{cases}\frac{A}{(1+Br^2)^{(n1+1)/2}} & r < r_t \\ \frac{K_2}{r^{n2+1}} & r_t < r\end{cases}$	$\begin{cases}\frac{K_1}{r^{n1+1}} & \mathrm{rmin} < r < r_t \\ \frac{K_2}{r^{n2+1}} & r < r_t\end{cases}$ n : spectral index, $1 < n < 3$

All the PSD models are plotted in Fig. 1(a). Except for small r, the ABC model is very similar to the fractal model. In fact, their functional forms will be the same when $Br^2 \gg 1$. This allows us to use the fractal model for the second PSD of the ABC model in Table 1. The ABC and the fractal PSDs appear as a straight line of slope of "-n" in a logarithmic scale.

3. Disappearing pad test

3.1. Disappearing pad test and PSD

We introduce two geometrical shapes of pads to the disappearing pad test on Cr binary masks: circular and doughnut pads in Fig. 2. The relation between the measured stray light and a pad is explained as follows. The intensity under the center of a pad, $I^{\mathrm{SL}}(\mathbf{r}=0)$ is evaluated from the factor of $E_{\mathrm{clear}}/E_{\mathrm{pad}}$ where E_{clear} is an exposure dose to clear the resist under *an open area* and E_{pad} is a dose to clear under *the center of the pad.* E_{pad} depends on the pad shape and size. From Eq. (1), $I^{\mathrm{SL}}(\mathbf{r}=0)$ can be expressed as:

$$I^{\mathrm{SL}}(\mathbf{r}=0) \approx I(\mathbf{r}=0) + \mathrm{PSD} \otimes m(\mathbf{r})|_{\mathbf{r}=0} \tag{2}$$

when "1-TIS" in the first term of Eq. (1) and "$I(\mathbf{r})$" in the second term are approximated as "1" and "$m(\mathbf{r})$", mask function, respectively. The first term in Eq. (2) comes not from stray light but from diffraction, which is often not negligible. The second term in Eq. (2) is the sole stray light contribution and can be obtained after the diffraction correction, i.e. "$E_{\mathrm{clear}}/E_{\mathrm{pad}} - I(\mathbf{r}=0)$". The second term in Eq. (2) takes the form:

$$\mathrm{SL}(R) \approx \int\int_{\substack{<\,\mathrm{field} \\ >\,R/\lambda}} \mathrm{PSD}(r) r\,\mathrm{d}r\,\mathrm{d}\theta \tag{3}$$

for a *circular* pad and

$$\mathrm{SL}(R_{\mathrm{i}}, R_{\mathrm{o}}) \approx \int\int_{\substack{<\,\mathrm{Ro}/\lambda \\ >\,\mathrm{Ri}/\lambda}} \mathrm{PSD}(r) r\,\mathrm{d}r\,\mathrm{d}\theta \tag{4}$$

for a *doughnut* pad. Here, the $m(\mathbf{r})$ in Eq. (2) is replaced with the boundary conditions in the integrals. In the experiments, stray light is measured depending on the size of the pad. PSD is then constructed from the fittings of the measurements with the dependency in Eq. (3) or (4) as one of the PSD functional forms in Table 1 is applied.

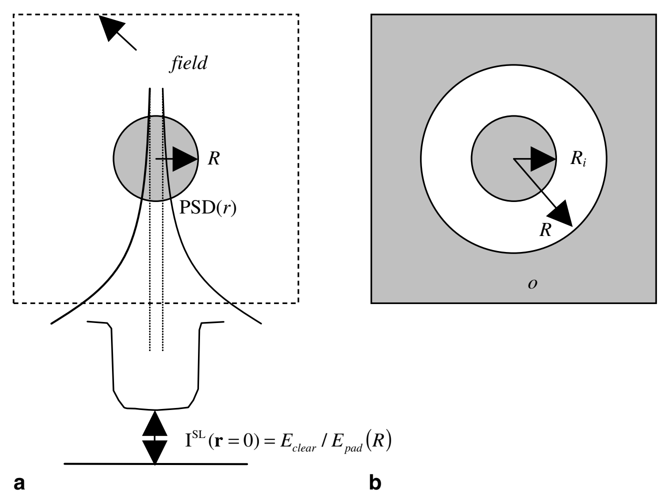

Fig. 2. Disappearing pad and PSD: (a) Circle and (b) Doughnut

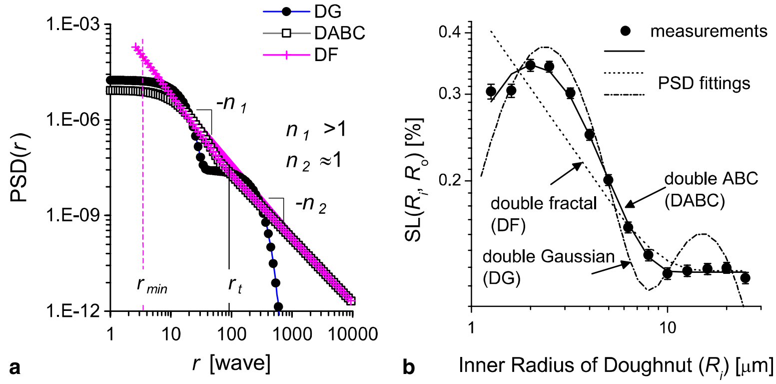

Fig. 1. Double PSD constructed from the disappearing pad test (doughnut, $R_{\mathrm{o}} = 3R_{\mathrm{i}}$) on an ArF dry tool. PSDs in (a) are obtained from the fittings in (b) based on the PSD models in Table 1.