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Impact of the non-uniform intensity distribution caused by a meshed pellicle of extreme ultraviolet lithography

Ki-Ho Ko [a], Jin-Goo Park [a], Jin-Ho Ahn [b], Michael Yeung [c], Eytan Barouch [d], Hye-Keun Oh [a,*]

[a] Hanyang University, Ansan-si 426-791, Gyeonggi-do, Republic of Korea
[b] Hanyang University, Seongdong-gu, 133-791 Seoul, Republic of Korea
[c] Fastlitho, San Jose, CA 95126, USA
[d] Boston University, Boston, MA 02215, USA

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ABSTRACT

A physical optics simulation was performed to simulate intensity non-uniformity on a wafer passing through an extreme ultraviolet meshed pellicle. The non-uniformity is directly related to the coherence radius of the illumination and the mesh parameters. The intensity non-uniformity was reduced when using illumination conditions with a larger coherence radius in a fixed mesh pitch. The circular illumination $\sigma_r = 0.5$ can accommodate a five times larger pitch than the dipole illumination $\sigma_r = 0.1$. An aerial image simulation for a 16 nm half-pitch pattern was also performed to confirm the critical dimension uniformity (CDU) caused by the meshed pellicle. The CDU is directly proportional to the non-uniformity on the wafer in order to determine suitable mesh parameters that produce a small CDU through a non-uniform intensity distribution calculation. The non-uniformity on the wafer should be less than 0.2% in order to achieve the desired CDU less than 0.1 nm.

1. Introduction

Extreme ultraviolet (EUV) lithography is the most feasible technology for producing nodes smaller than 16 nm. Even though high-resolution patterning is possible due to the very short wavelength of EUV (13.5 nm), it still has some limitations for realization in mass production [1–3]. One of the critical problems is control of the mask defect during lithography processes [4–8]. The pellicle has been widely used in optical lithography to protect the mask from various contaminations and can reduce the cost for changing and cleaning the patterned mask. However, it is very difficult to apply the pellicle to EUV lithography because of the strong absorption at the 13.5 nm EUV wavelength [9]. Inorganic materials like silicon with a thickness of tens of nanometers could be used to achieve high transmission. Unfortunately, the extremely thin film can easily sag and be damaged in the exposure process due to gravitational force and the accelerating force of the scanner [10,11]. Thus, a mesh-supported pellicle is suggested to stabilize the thin film during the process [12–17]. A hexagonal-shaped mesh has the highest rigidity and largest open area among various shapes including rectangles or triangles. Therefore, a repetitive hexagonal array mesh support with a height of several micrometers was chosen for this study as a support for the pellicle film [18]. The open area of the mesh is also very important because of the high transmission requirement of the pellicle.

Most of the light passing through the mesh is absorbed and diffracted, resulting in an irregular intensity distribution on the mask; this may consequently cause pattern deformation [19]. Nevertheless, the irregular intensity distribution is affected only by the structural characteristics of the mesh, so it can be avoided using suitable mesh parameters. Simple geometrical approaches were considered to simulate the intensity distribution on the wafer passing through the meshed pellicle for a blank mask using the physical optics model. In addition, simulation of a 16 nm half-pitch pattern was also performed to estimate the effect of the non-uniform intensity distribution on critical dimension (CD) uniformity.

2. Geometrical approach of the mesh shadow

The EUV light passing through the mesh is totally absorbed by mesh with a much larger thickness than that of the pellicle film. Fig. 1 illustrates the generation of a mesh shadow on the mask and wafer. In Fig. 1, *A* represents one ray originating from the source. The ray is partially blocked by a portion of mesh *B*, so that the intensity on the wafer reflected from the *C* region will be degraded, which may cause pattern deformation. The distance (*R*) between the position on the mask of *B* and the shadowed position

* Corresponding author.
E-mail address: hyekeun@hanyang.ac.kr (H.-K. Oh).

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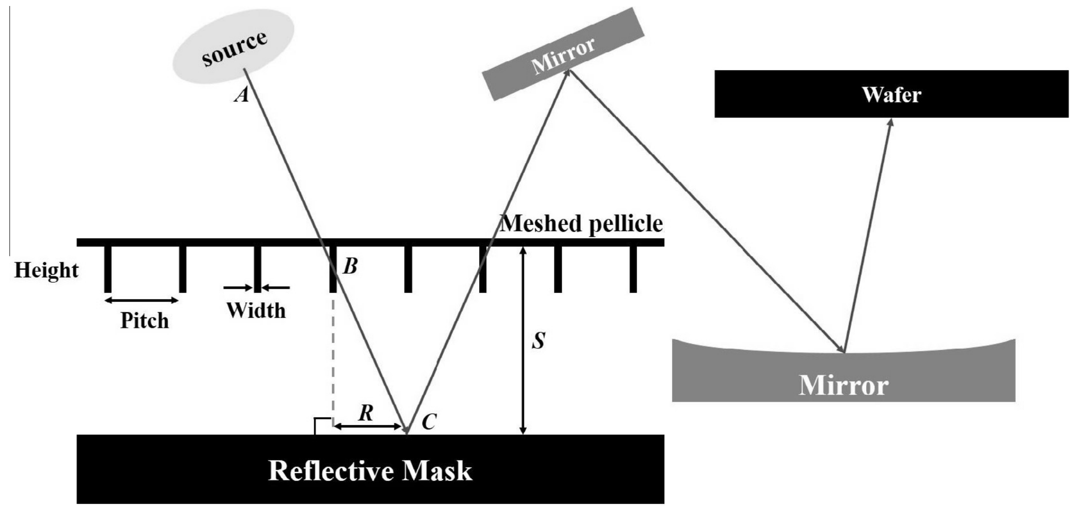

Fig. 1. Shadowed position passing through the meshed pellicle on the mask for a zero-order incident ray. *A* is the starting point at the source and will be blocked by mesh *B*. *C* is the shadowed position of *B* on the mask. The distance between the position directly below the mask of *B* and the shadowed position on the mask *C* is *R*. *S* is the stand-off distance. Mesh parameters such as pitch, width, and height are also shown.

on mask *C* due to the oblique incidence angle of EUV can be simply stated as $R = S \cdot \tan\theta$, where θ is a 6° chief ray angle of a typical EUV illumination condition, and *S* is the stand-off distance.

The light source is not a single point, but it has an angular size that is defined by a partial coherence factor of σ. The light originating from different points on a fixed source produces shadows at different positions due to the varying angles of the incident rays within the illumination cone. Fig. 2 shows the shadowed mask region generated by different incident angles that have the same amount of attenuation. The decreased intensity across the shadowed region is the same; therefore, if the region is larger than the mesh pitch, the intensity of the whole region will be uniform due to the repetitive characteristics of the mesh. The shadowed region can be estimated from $S \cdot \tan\theta_{\max} - S \cdot \tan\theta_{\min} = R_{\max} - R_{\min} = \Delta R$. This region is identified as the smoothing region

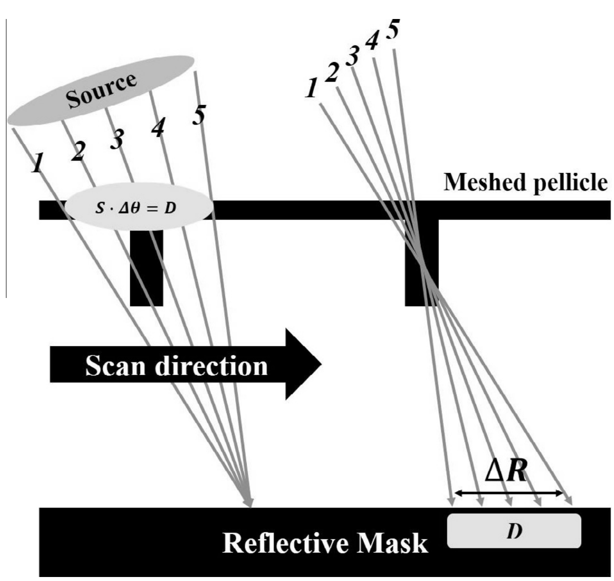

Fig. 2. Formation of the smoothing region generated by varying the incidence angle of the source, which has a finite angular size. The shadowed position *R* varies with the incident angle of the ray (1–5) and can be seen at the same attenuation in region *D*. The smoothing region *D* is determined by the coherence radius.

D, and it can be expressed as $D = \Delta R = \Delta(S \cdot \tan\theta) = S \cdot \sec^2\theta \cdot \Delta\theta$. *D* can be simplified to $D = S \cdot \Delta\theta$ because all of the angles are less than 10° in typical EUV illumination optics. Based on this discussion, the smoothing region *D* should be larger than the mesh pitch in order to reduce the non-uniform intensity distribution caused by the irregular attenuation.

Fig. 3 shows the illumination conditions of our simulations. A simple calculation for the smoothing region *D* was made with the illumination conditions used in the simulations. The angular diameter of the source on the wafer was approximately $2 \cdot \sigma_r \cdot \mathrm{NA} = 0.066$ rad with $\mathrm{NA} = 0.33$ and $\sigma_r = 0.1$ for dipole illumination. The angular diameter on the mask was $\Delta\theta = 0.066\ \mathrm{rad} \div 4 = 0.0165$ rad in the 4× reduction EUV illumination optics. At a 2 mm stand-off distance, the smoothing region *D* is $2\ \mathrm{mm} \times 0.0165 = 33\ \mu\mathrm{m}$, as observed in the mask. Based on this result, the smoothing region can be regarded as the angular diameter of the source on the pellicle plane; therefore, if the mesh pitch is smaller than the smoothing region, $D = 33\ \mu\mathrm{m}$, the entire mask plane will have approximately the same attenuation. In other words, there is no distinct mesh shadow on the mask when the smoothing region is larger than the pitch, causing improved intensity uniformity on the wafer.

Choosing the mesh pitch based on the coherence radius is very important to minimize the non-uniform intensity distribution caused by the mesh shadow. For a conventional circular case ($\sigma_r = 0.5$), the value of *D* is simply calculated as 165 μm because σ_r is five times larger than the dipole case. Notably, the above argument was based on a simple geometry. Under actual exposure conditions, all diffractions through the mesh should be included. Therefore, the intensity distribution on the wafer was simulated using the diffraction calculation.

3. Physical optics model for meshed pellicle simulation

The physical optics model was developed to simulate the wafer intensity distribution caused by the meshed pellicle. In the geometrical-optics model, a transmittance function $T(x, y)$ is used to describe the effect of the propagation of a ray of light through the pellicle. The amplitude and phase of $T(x, y)$ are the attenuation factor and phase change experienced by a light ray emerging from the point (x, y) on the pellicle plane after traveling in a straight line through the pellicle film and the mesh structure, respectively.