Microelectronic Engineering 143 (2015) 81–85

Contents lists available at ScienceDirect

Microelectronic Engineering

journal homepage: www.elsevier.com/locate/mee

Mechanical deflection of a free-standing pellicle for extreme ultraviolet lithography

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ARTICLE INFO

Article history:
Received 3 November 2014
Received in revised form 28 March 2015
Accepted 3 April 2015
Available online 11 April 2015

Keywords:
EUV
EUVL
Mechanical
Deflection
Deformation
Pellicle

ABSTRACT

In extreme ultraviolet lithography (EUVL), a pellicle is a thin (a few nanometers in scale) protective membrane that can prevent the mask from suffering from defects. However, this thin film can be easily deformed by gravity and other forces. Although the hexagonal-shaped mesh support structure can decrease the stress caused by external pressure, its structural shape can degrade the image quality on the wafer. Therefore, studying the deflection of a free-standing EUV pellicle is needed. We revisited the plate theory and found that a nonlinear deflection term should be added to the deflection equation. The deflection of a 50 nm thick polysilicon pellicle is about 100 μm for a full-scale (100 mm × 100 mm) pellicle. Previously, researchers have tried to include graphene in multi-layer EUV pellicles in order to enhance the mechanical properties of the film. We found that the addition of graphene did not cause any serious deflection problems. This study shows that a free-standing EUV pellicle without mesh support can be used without any noticeable deflection effect on the pattern fidelity.

1. Introduction

Higher resolution patterns on chips (22 nm half-pitch or below) can be realized by using 13.5 nm wavelength extreme ultraviolet (EUV) light [1]. However, printable defects on the reticle should be mitigated to be suitable for the high-volume manufacturing (HVM) environment of EUV lithography (EUVL) [2]. In order to make defect-free reticles at high yields in manufacturing processes, using a pellicle is necessary the pellicle helps protect the masks from defects [3]. However, the thickness of the pellicle should be nanometer thin because most materials show high absorption at the EUV wavelength. This thickness is very small compared to the area that covers a full-scale (6″) mask [4]. Because of this very thin membrane, researchers believe that the deflection of the pellicle by gravity is very large and the mechanical properties of the pellicle are thus one of the important issues [5]. A honeycomb-shaped mesh support structure was suggested to increase the structural stability and to enhance the mechanical properties of the EUV pellicle [6]. However, the edge diffraction and nonhomogeneous absorption caused by the structural characteristics of the honeycomb-shaped mesh support can induce a non-uniform intensity on the mask and wafer. Local critical dimension (CD) variation on top of the wafer can also be caused [7,8]. For these reasons, if possible, using a pellicle without mesh support is preferred; therefore, the deflection of a free-standing pellicle should be further studied. In order to derive the deflection results, the proper material and membrane deflection model for the free-standing EUV pellicle must be selected. Therefore, we considered inorganic material candidates that have a double pass transmission larger than 80% at the EUV wavelength and revisited the plate theory for studying membrane deflection by using the mechanical properties of the EUV pellicle.

In this paper, we suggest a deflection equation with a third-order nonlinear deflection term and show how much gravity deflects the EUV pellicle. We also present the nonlinear deflections calculated by analytic and finite element methods (FEM) for various high transmission EUV materials. In addition, the deflection of the multi-layer EUV pellicle, which can improve the mechanical properties, is shown. Our goal in this study is to show the results of analytic nonlinear deflection and to compare these with the 500 μm deflection limit during exposure reported by ASML [9]. We also discuss the feasibility of free-standing EUV pellicles based upon their nonlinear deflection results.

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http://dx.doi.org/10.1016/j.mee.2015.04.012
0167-9317/

2. Deflection analysis model of the free-standing EUV pellicle

2.1. Boundary conditions of the EUV pellicle

The equation of elastic thin film deflection is well-known and has been derived by many authors [9–18]. In this paper, we focused on the nonlinear deflection theory obtained by Timoshenko et al. [18]. In order to describe the analytical model of pellicle deflection, the appropriate boundary conditions should be applied to the deflection equation. A square membrane shape is initially chosen for the pellicle model. The four edges of the pellicle are clamped by the frame and gravity is uniformly applied in the direction normal to the membrane surface, as schematically shown in Fig. 1. The clamped edges at the boundary can be expressed as:

$$(w)_{x=\pm a/2}=0,\quad (w)_{y=\pm a/2}=0,\quad \left(\frac{\partial w}{\partial x}\right)_{x=\pm a/2}=0,\quad \left(\frac{\partial w}{\partial y}\right)_{y=\pm a/2}=0, \tag{1}$$

where w is the deflection of the middle plane ($z = 0$) along the z-axis due to gravity, a is the length and h is the thickness of the pellicle. The first two parts of Eq. (1) are taken from the Dirichlet boundary conditions, which indicate zero displacement at the edges of the pellicle. Alternatively, the last two parts of Eq. (1) are taken from the Neumann boundary conditions, which indicate the rigidity of the edge between the pellicle and the frame when bending occurs. The edge of the pellicle is rigid if those boundary conditions are zero, while the edge of the pellicle is flexible if the Neumann boundary conditions are not zero. In this paper, we assumed the frame would have high mechanical stability under the effect of gravity compared with the EUV pellicle. Therefore, the frame is assumed to be rigid and gravity is only applied to the pellicle. The uniform gravitational pressure q applied to the pellicle is given by:

$$q=\rho g h \tag{2}$$

where ρ is the density of the pellicle material and g is the gravitational acceleration. The value of gravitational acceleration used in this paper is 9.81 m/s^2.

2.2. Nonlinear deflection equation of the free-standing EUV pellicle

As discussed in the previous section, the boundary conditions of the free-standing pellicle should be applied to the corresponding deflection equation. We introduced the fourth-order differential governing equation of plate deflection, which was first obtained by Lagrange in 1811 [19], and can be expressed as:

$$\nabla^2(\nabla^2 w)=\frac{q}{D}, \tag{3}$$

where symbol ∇^2 is the two-dimensional Laplace's differential operator in the Cartesian coordinate representation and q is the external pressure applied to the pellicle. In Eq. (3), D indicates the flexural rigidity of the plane and can be described as:

$$\mathrm{D}=\frac{Eh^3}{12(1-\nu^2)}, \tag{4}$$

where E is Young's modulus and ν is Poisson's ratio, which can be determined from the material properties. Substituting the boundary conditions ((1) and (2)) and the flexural rigidity (4) to the governing Eq. (3) gives the deflection equation of the edge-clamped square plate under gravity, which can be expressed as:

$$w_0=3(1-\nu^2)\frac{\rho g a^4}{\pi^4 E h^2}, \tag{5}$$

where w_0 is the deflection at the center of the plate, a is the side or edge length of the square pellicle and ρ is the density of the material used for the EUV pellicle.

In order to solve the governing equation, we used the cosine-like general deflection solution that was presented by Timoshenko [18]. It should be noted that this solution exists under the assumption that the tensile strains ε_x, ε_y and the shear strain γ_{xy} along the lateral dimensions satisfy the linear relations given by:

$$\varepsilon_x=\frac{\partial u}{\partial x}, \tag{6a}$$

$$\varepsilon_y=\frac{\partial v}{\partial y}, \tag{6b}$$

$$\gamma_{xy}=\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}, \tag{6c}$$

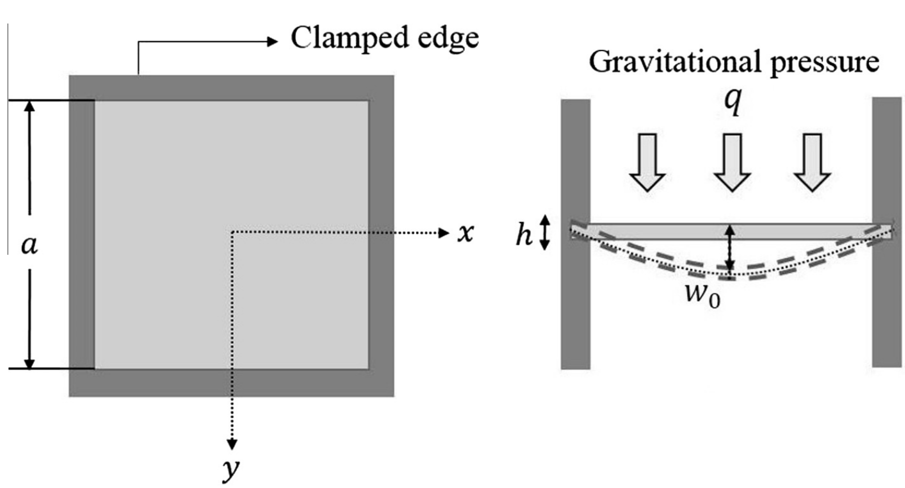

Fig. 1. Schematic representation of the deflection of a square EUV pellicle with clamped edges (under uniform gravitational pressure). The side length of the square pellicle is given as 'a' along the x and y-directions and the thickness 'h' and gravitational pressure 'q' are given and applied along the z-direction. The middle plane deflection at the center of the pellicle, expressed as w_0, is induced by gravity in the z-direction.