Optical Behavior of Pellicles

Pellicles have been used to protect photomasks from particles since the late 1970s [1]. A thin, transparent polymer film stretched over a rigid frame is glued to the business side of a photomask to keep particle contaminants from landing on the patterns (Figure 1). The pellicle is a sufficient distance away from the mask patterns so that moderate-to-small sized particles that land on the pellicle will be too far out of focus to print.

Most early pellicles used nitrocellulose (the same stuff used to make photographic film and ping pong balls), with an index of refraction of about 1.5 in the 350 – 450 nm wavelength range. For broadband projection printing, a pellicle thickness of 2.85 µm is common. Antireflection coatings (either evaporated calcium fluoride or spin-coated fluorocarbon polymers) are often coated on one or both sides of the pellicle to improve the transmittance. With the advent of quasi-monochromatic g-line and i-line steppers, the nitrocellulose pellicles were thinned to about 720 nm [2] so that thin-film interference effects could be used to maximize the transmittance (to greater than 99%).

Nitrocellulose absorbs appreciably below about 350 nm, so amorphous fluoropolymers (such as Teflon AF and Cytop) are used for KrF and ArF pellicles. Since these materials have low refractive indices (near 1.34 at 248 nm and 1.40 at 193 nm), it is difficult to find antireflective coatings that work well (the required refractive index of the AR material would be less than 1.3). Thus, single layer pellicles are the most common at these wavelengths. A typical ArF pellicle will have a complex refractive index of $n+i\kappa = 1.40 + i0.0001$ and a thickness of 828 nm.

While designed to protect the mask from particles, pellicles are in fact optical elements within the imaging system. Their distance from the mask (on the order of 5 mm) puts them in the far field (the Fraunhofer diffraction region), so that pellicles can be treated like pupil filters. Thus, to understand the impact of pellicles on imaging, one must simply determine the transmittance of an arbitrary plane wave through the pellicle. Thin film optical calculations will yield the intensity transmittance ($T_{pellicle}$) and change in phase of light ($\Delta\phi_{pellicle}$) as it passes through the pellicle.

The intensity transmittance will be a function of both the angle of incidence and the polarization of the light. Since absorption by the pellicle will be small, the reflection and transmission coefficients can be assumed to be real, giving [3]

$$T_{pellicle} = \frac{T_{12}^2\, e^{-\alpha D/\cos\theta_2}}{1 + R_{12}^2\, e^{-\alpha 2D/\cos\theta_2} - 2R_{12}\, e^{-\alpha D/\cos\theta_2}\cos(4\pi n_2 D\cos\theta_2/\lambda)} \tag{1}$$

where 1 and 2 refer to air and pellicle, respectively, and where

$$T_{12} = \tau_{12}\tau_{21}, \quad R_{12} = (\rho_{12})^2, \quad \alpha = 4\pi\kappa_2/\lambda$$

For each polarization, s and p, the Fresnel reflection and transmission coefficients are

$$\rho_{12-s} = \frac{n_1\cos(\theta_1) - n_2\cos(\theta_2)}{n_1\cos(\theta_1) + n_2\cos(\theta_2)}, \quad \tau_{12-s} = \frac{2n_1\cos(\theta_1)}{n_1\cos(\theta_1) + n_2\cos(\theta_2)}$$

$$\rho_{12-p} = \frac{n_1\cos(\theta_2) - n_2\cos(\theta_1)}{n_1\cos(\theta_2) + n_2\cos(\theta_1)}, \quad \tau_{12-p} = \frac{2n_1\cos(\theta_1)}{n_1\cos(\theta_2) + n_2\cos(\theta_1)}$$

The two angles θ_1 and θ_2 are of course related by Snell's law,

$$n_1\sin(\theta_1) = n_2\sin(\theta_2)$$

This transmittance is maximized when the argument of the cosine in equation (1) is a multiple of 2π, *i.e.*, when the thickness of the pellicle D is set to

$$D = \frac{m\lambda}{2n_2\cos\theta_2} \tag{2}$$

where m is an integer. For a 193.3 nm wavelength pellicle with $n_2 = 1.4$ at normal incidence ($\cos\theta_2 = 1$), $m = 12$ gives an optimal thickness of 828.4 nm.

This optimal thickness, however, only produces the maximum transmittance for normally incident light. Figure 2 shows the intensity transmittance of a 193 nm pellicle over a range of incident angles. The maximum angle of interest is determined by the NA of the objective lens and is given by (for a 4X projection system)

$$\sin\theta_{max} = \frac{NA}{4} = NA_m \tag{3}$$

where NA_m is the numerical aperture on the mask side of the imaging lens. For a numerical aperture of 1.0, this maximum angle is 14.5°; for NA = 1.2 it increases to 17.5°; and for NA = 1.35, the maximum angle is 19.7°. As can be seen from Figure 2, the impact of the pellicle on the intensity of diffracted light will be *apodization*, a reduction in the amplitude of high spatial frequency (high angle) light. And since the two polarizations show different amounts of apodization, the imaging behavior of each polarization will be influenced differently by the pellicle.

Likewise, the phase change of the light can be calculated from the electric field transmission of the pellicle. This phase change can be thought of as coming from two components: $\Delta\phi_{geometric}$, a simple geometric light path through the pellicle, and $\Delta\phi_{interference}$, the impact of multiple reflections inside the pellicle:

$$\Delta\phi_{geometric} = \frac{2\pi D}{\lambda}\left[n_1(1-\cos\theta_1)-n_2(1-\cos\theta_2)\right]$$

$$\Delta\phi_{interference} \approx (\rho_{12})^2 \sin(4\pi n_2 D\cos\theta_2/\lambda)$$

$$\Delta\phi_{pellicle} = \Delta\phi_{geometric} + \Delta\phi_{interference} \tag{4}$$

where the phase change is relative to the phase of normally incident transmitted light (see Figure 3). Since the interference contribution to the phase of the transmitted light depends on the square of the air-pellicle reflection coefficient, this contribution will be both small and polarization dependent. Over the range of angles shown in Figure 3, the geometric phase change is as large as 65°, whereas the interference-caused phase change varies by about ±1°. The difference in phase between the two polarizations reaches about 0.5° for NA = 1.35 (see Figure 4).

The impact of the geometric phase change can be best understood by expanding the cosines in the expression as a function of the sine of the incident angle.

$$\Delta\phi_{geometric} = \frac{2\pi n_1 D}{\lambda}\left[\frac{1}{2}\left(1-\frac{n_1}{n_2}\right)\sin^2\theta_1 + \frac{1}{8}\left(1-\left[\frac{n_1}{n_2}\right]^3\right)\sin^4\theta_1 + ...\right] \tag{5}$$

The first term in the series is like paraxial defocus. Thus, the primary effect of the phase behavior of the pellicle is a change in the best focus position of the reticle. Letting $n_1 = 1$, the shift in reticle focus (δ) caused by the pellicle (considering only the geometric term for now) is

$$\delta = D\left(1-\frac{1}{n_2}\right) \tag{6}$$

Of course, this effect is easily compensated for by a small shift in the reticle position (a shift of only 237 nm is required for a standard 193 nm pellicle compared to the no-pellicle case). The interference term will also contribute to the shift in reticle best focus, dependant on the NA used, so that 210 – 260 nm of total focus shift can result.

The second term in the series results in spherical aberration. However, here the interference term begins to dominate. Considering again the standard 193 nm pellicle and looking at a numerical aperture of 1.35 as a worst case, about 2.4 mwaves (0.46 nm) of 3rd order spherical aberration is caused by the pellicle [4]. This is a significant fraction of the total amount of wavefront error that can be expected of a good 1.35 NA imaging system, and so it cannot be ignored. Fortunately, most high-end lithography tools have the ability to correct for 3rd order spherical aberration, and so this effect of the pellicle is not devastating. Higher order spherical aberrations terms are about one order of magnitude smaller or more, and thus will be neglected here.

From the analysis of the transmittance of a standard 193 nm pellicle, it is clear that the main impact of the pellicle on imaging is apodization – a reduction in the amplitude of the higher spatial frequency light passing through the lens. Since different pitch patterns will produce different diffraction angles, the most significant lithographic impact of this apodization will be

on the CD through pitch curves so important to optical proximity correction (OPC) [5]. Of course, finding suitable AR materials for coating both sides of the pellicle would significantly mitigate these problems, as would using a thinner pellicle. At the least, model-based OPC must include pellicle-induced apodization in its simulations.

Acknowledgements

References

1. Vincent Shea, Walter Wojcik, "Pellicle Cover for Projection Printing System", US Patent #4,131,363, filed on Dec. 5, 1977.

2. Ron Hershel, "Pellicle protection of integrated circuit (IC) masks", SPIE Vol. 275 (1981) pp. 23 - 28.

3. Similar formulas for the case of no absorption can be found in Born and Wolf, <u>Principles of Optics</u>, Sixth Edition, Pergamon Press (Oxford: 1980), p. 62.

4. The authors of the following paper calculated 3.0 mwaves of 3rd order spherical aberration for this same case, with the added spherical aberration caused by moving the wafer position to adjust for the focus shift induced by the pellicle: Karsten Bubke, *et al*., "Pellicle Induced Aberration and Apodization in Hyper NA Optical Lithography", *PMJ Photomask and Next-Generation Lithography Mask Technology XIII*, SPIE Vol. 6283 (2006) p. 628318.

5. Kevin Lucas, *et al*., "Optical issues of thin organic pellicles in 45nm and 32nm immersion lithography", *BACUS Photomask Technology 2006*, SPIE Vol. 6349 (2006) p. 63490K.
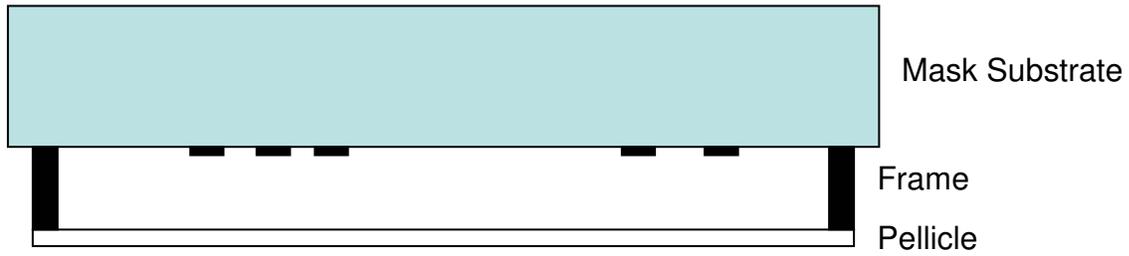
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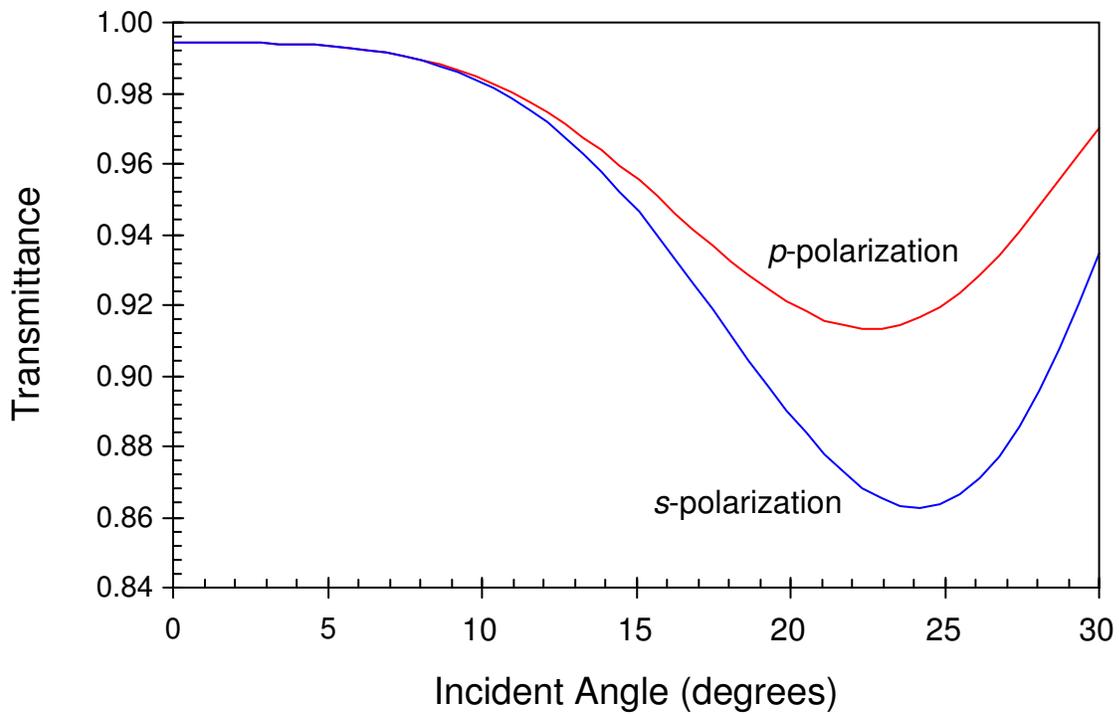Figure 1. Pellicle mounted on a photomask (not to scale).

Figure 2. Pellicle intensity transmittance as a function of incident angle and polarization (pellicle n +iκ = 1.4 + i0.0001, thickness = 828 nm, and light of wavelength 193.3 nm).

Figure 3. Pellicle phase transmittance (in radians) as a function of incident angle (pellicle n +iκ = 1.4 + i0.0001, thickness = 828 nm, and *s*-polarized light of wavelength 193.3 nm).

Figure 4. The interference portion of pellicle phase transmittance as a function of incident angle and polarization (pellicle n +iκ = 1.4 + i0.0001, thickness = 828 nm, and light of wavelength 193.3 nm).

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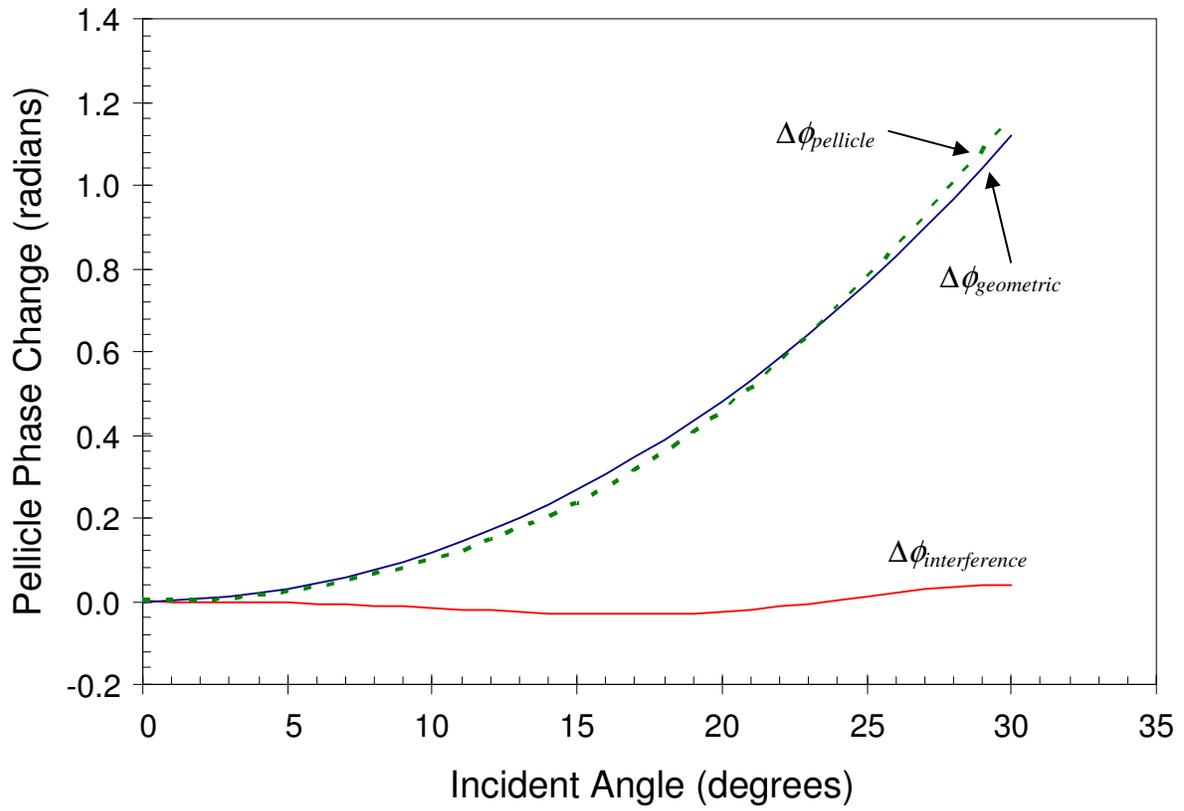
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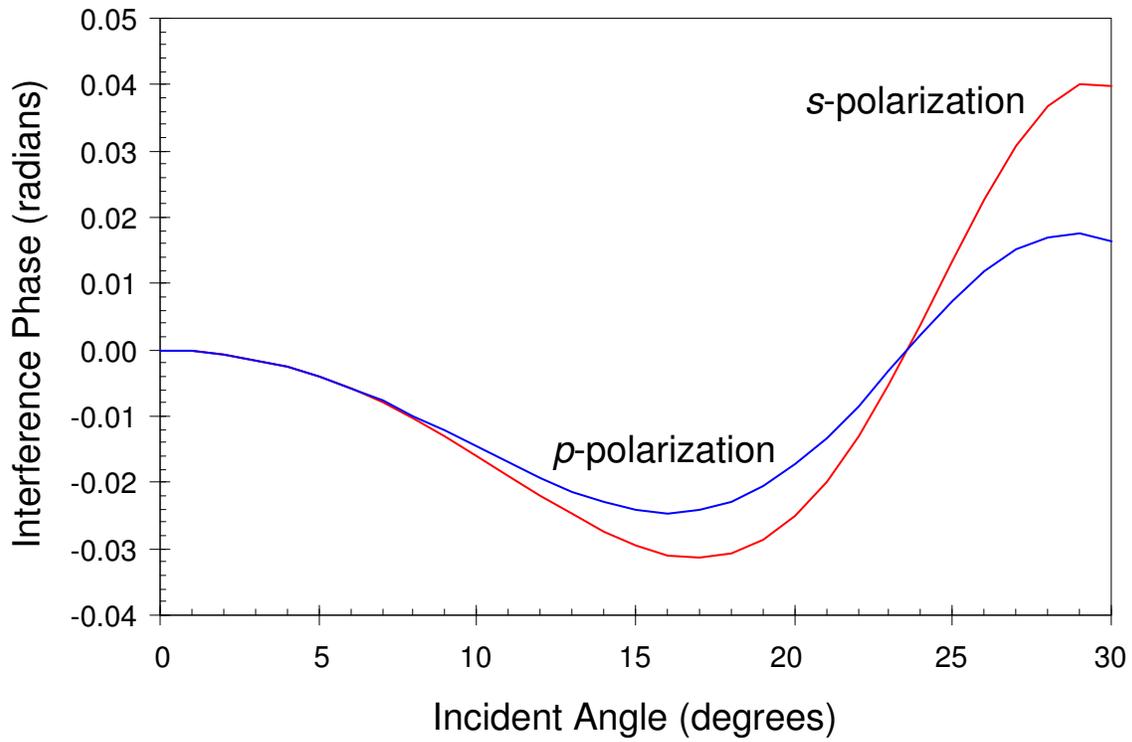
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