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Modeling the Effects of Excimer Laser Bandwidths on Lithographic Performance

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ABSTRACT

In many respects, excimer lasers are almost ideal light sources for optical lithography applications. Their narrow bandwidth and high power provide two of the main characteristics required of a light source for high-resolution imaging. However, for deep-UV lithography projection tools with no chromatic aberration correction in the imaging lens, even the very narrow bandwidth of an excimer laser may lead to image degradation.

This paper describes the assumptions and methodology used for modeling of the impact of laser bandwidth on the lithographic process. In particular, the chromatic aberrations of an imaging lens combined with real laser spectra are used to include the impact of laser bandwidth into the lithographic simulation model. The effect of the bandwidth on aerial image critical dimensions, depth of focus, and exposure latitude are investigated using PROLITH/2 simulation software. Studies are performed for isolated and semi-isolated lines ranging in size from 240 nm to 140 nm.

Simulation results show that the impact of the bandwidth is lithography process dependent. In general, increased laser bandwidth decreases both the aerial image contrast and log-slope. Also, larger bandwidths can result in the loss of exposure latitude.

Keywords: excimer laser, bandwidth, chromatic aberrations, lithography simulation.

1. INTRODUCTION

The limitations of acceptable optical lens materials at 248nm and 193nm wavelengths have meant that projection lenses for KrF and ArF lithography have been fabricated primarily with fused silica. Although fused silica is a very good lens material (high transparency, low thermal expansion, relatively easy to polish), the unavailability of a second material type with a different refractive index in projection lenses results in chromatic aberrations. Chromatic aberrations emerge since the index of refraction of any optical material changes with wavelength, and hence, the imaging behavior of a lens also varies with wavelength. Certain lens designs allow to partially correct for chromatic aberrations by building projection lenses with more than one optical material in such way that different variations with wavelength can be made to counteract each other. However, if a lens is made with only one optical material such as fused silica, chromatic aberrations are inevitable.

The detrimental effects of chromatic aberrations for an uncorrected lens can be mitigated only by using a light source with a very narrow range of wavelengths. Spectral line-narrowed excimer lasers have served this purpose for deep-UV lithography. Today's lasers have bandwidths in the sub-picometer range, providing nearly monochromatic illumination for refractive projection lenses. Nevertheless, although eximer laser bandwidths are small, the lack of chromatic correction in lenses means that the bandwidth cannot be ignored.

2. SIMULATION METHODOLOGY AND ASSUMPTIONS

Simulation of the effects of chromatic aberrations employs a technique similar to that proposed by Yan et al. [1]. The main effect of changing the exposure wavelength for a non-chromatic corrected lens is a change in the position of the focal plane. Over a fairly wide range of wavelengths, this change in focus is essentially linear with the change in the nominal wavelength (i.e., the central wavelength of the illumination spectrum). Yan reported a slope of 0.15 μm focus shift for a 1 pm shift in the illumination spectrum central wavelength [1] for a 0.42 NA deep-UV lens. Today's higher NA projection lenses have slopes close to twice this amount. The wavelength response of a lens can be determined experimentally by manually changing the central wavelength of the laser and using the imaging sensor of the stepper to monitor the shift in focus that results. Figure 1 shows an example of such a measurement.

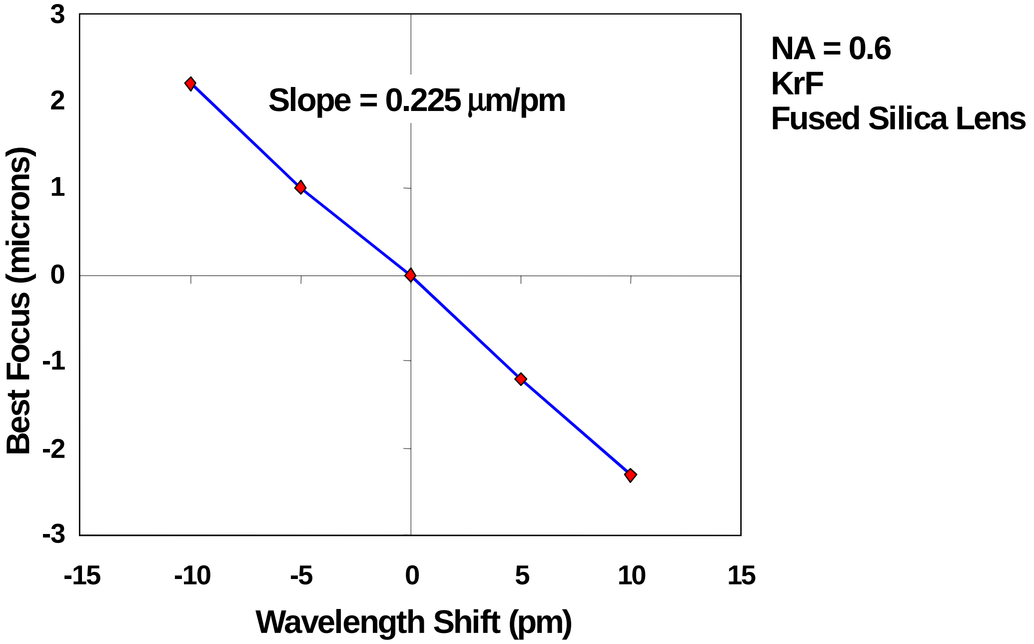

Figure 1. Measurement of best focus as a function of central wavelength shows a linear relationship with a slope of 0.225 μm/pm for this 0.6 NA projection lens.

Given the change in focus with change in wavelength, the use of a broadband illumination spectrum means that each wavelength in the spectrum will produce an aerial image with a different best focus. The total aerial image will be a sum of the aerial images at each focal position, weighted by the relative intensity of each wavelength in the illumination spectrum. The behavior of this chromatic aberration in a way resembles the FLEX technique, which is based on multiple focal plane exposures [2]. Latest versions of PROLITH/2 [3] incorporate these types of effects plus any other impact of chromatic aberration using a more general aberration-based image averaging scheme. At each wavelength in the laser spectrum a 36 term Zernike polynomial can be defined. Since different wavelengths can affect imaging performance in a variety of ways, the individual Zernike coefficients can be changed as a function of wavelength in a very general, arbitrary way.

As an example, the response of wavelength as a focus shift can be modeled using the third fringe Zernike polynomial term (see reference 4 for a complete description of the Zernike polynomial used here). The coefficient of this Zernike term Z_3 can be related to a focus shift $\Delta\delta$ by

$$Z_3 = \Delta\delta \frac{NA^2}{4\lambda_o} = (slope)\Delta\lambda \frac{NA^2}{4\lambda_o} \tag{1}$$

where λ_0 is the central wavelength of the illumination spectrum. Thus, if the focus shift as a function of wavelength is known, a value of Z_3 for each wavelength in the illumination spectrum can be computed from the equation (1).

For simulation purposes, different actual laser spectra measured on a variety of commercially available Cymer lasers were used. In this work the full-width-at-half-maximum (FWHM) definition of the bandwidth is used to characterize laser spectra. Figure 2 illustrates examples of different KrF laser spectra:

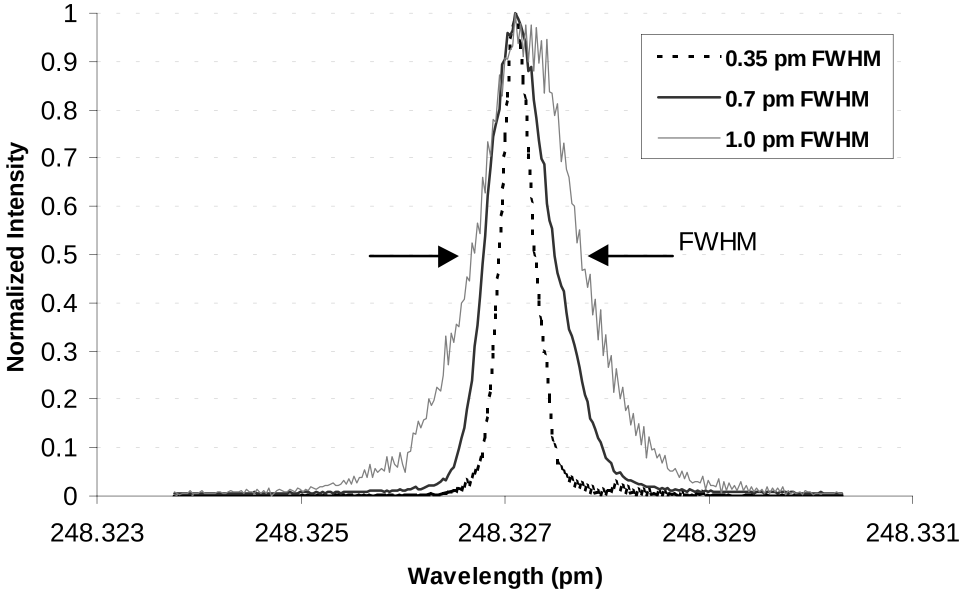

Figure 2. Examples of different KrF excimer laser spectra.

3. GENERAL SIMULATION RESULTS

In order to understand the impact of laser bandwidth on the lithographic process in the presence of chromatic aberrations, we started from investigation of the aerial image of a 180 nm isolated line. Figure 3 shows how increasing bandwidth degrades the aerial image. For these simulations the following input parameters were used: $NA = 0.6$, $\sigma = 0.75$, $\lambda_0 = 248.3271$ nm. Laser spectra with 0.5 pm, 1.2 pm, 2.1 pm bandwidths at FWHM and a monochromatic light source were used in this simulation study, and a chromatic aberration focus response of 0.225 µm/pm was assumed.

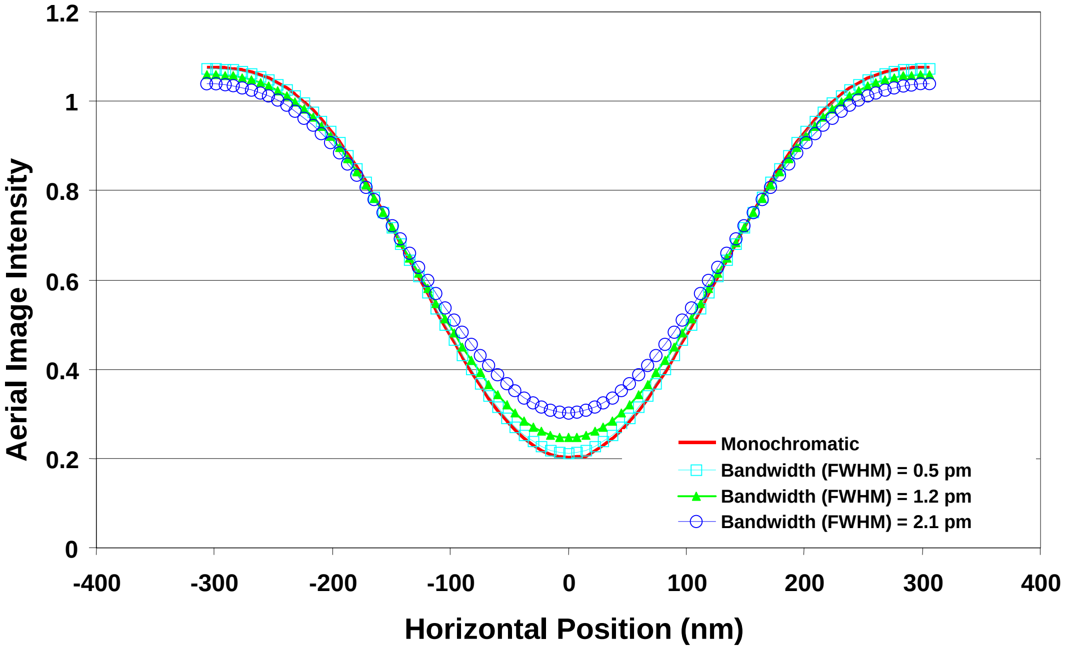

Figure 3. Degradation of the aerial image of a 180 nm line (500 nm pitch) with increasing laser bandwidth for a chromatic aberration response of 0.225 µm/pm.

As can be seen in Figure 3, increasing bandwidth causes noticeable image degradation. For the conditions and the feature size used here, FWHM bandwidths above 1.2 pm show significant loss of aerial image contrast and log-slope.

The impact of laser bandwidths on critical dimension (CD) variations of isolated lines with different sizes was evaluated using an aerial image threshold model. In this study the following input parameter settings were used: $\sigma = 0.75$, $\lambda_0 = 248.3271$ nm, aerial image threshold at 30%, $NA = 0.6$, 0.7, and 0.8. The simulations were performed for isolated lines ranging from 240 nm to 140 nm. The chromatic aberration response was assumed at 0.225 µm/pm. As shown in Figure 4, increased laser bandwidth results in greater CD change of isolated lines with respect to the monochromatic case. Also it can be noticed that laser bandwidth effects increase with larger projection lens NAs and smaller feature sizes.

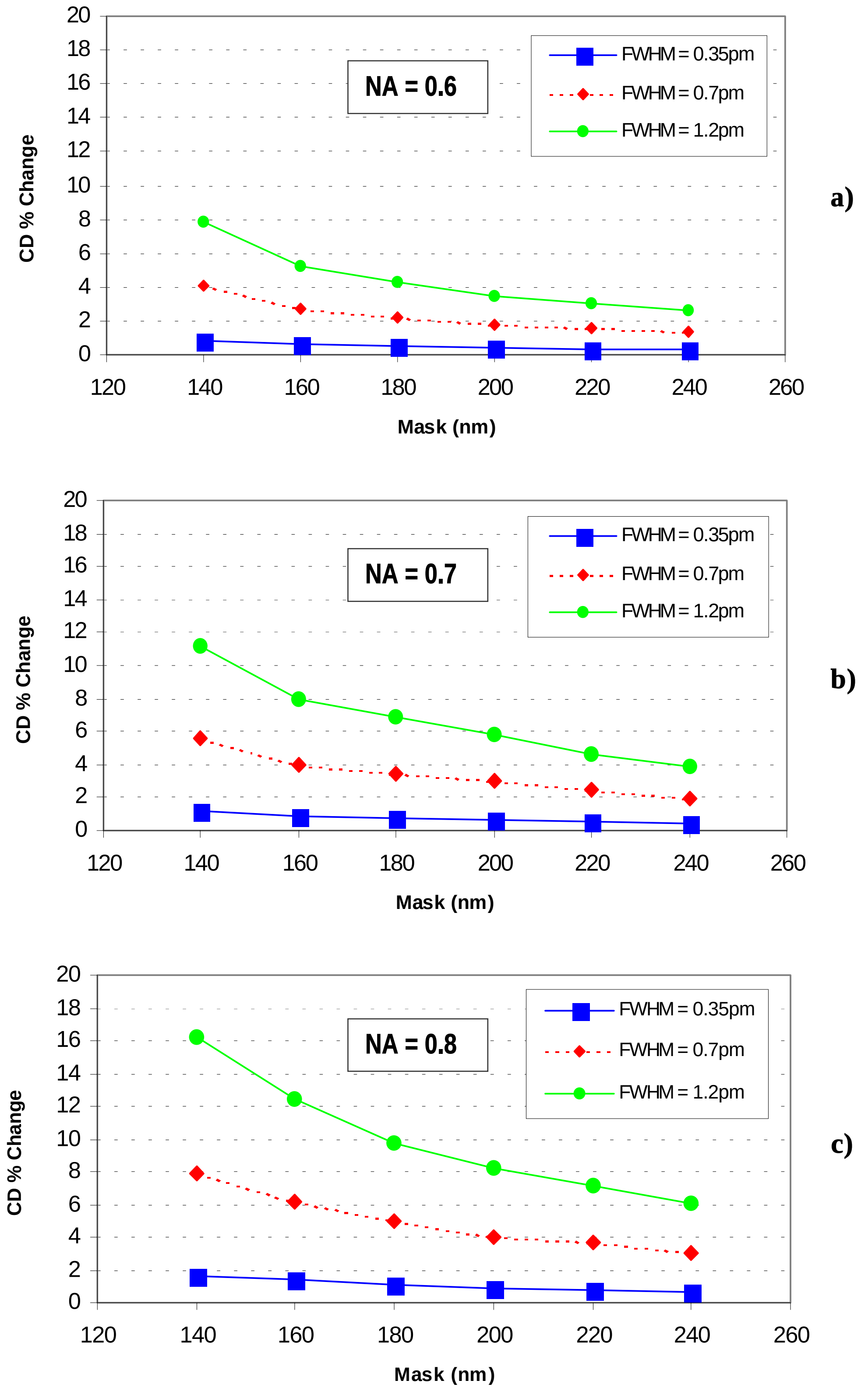

Figure 4. Impact of laser bandwidth on aerial image CD change (%) of isolated lines with respect to the monochromatic illumination for different lens NAs: **a)** *NA* = 0.6; **b)** *NA* = 0.7; and **c)** *NA* = 0.8.

Laser bandwidth can also affect the focus-exposure process window. As introduced by the previous considerations, the process window is modified according to the amount of chromatic aberration and width of the spectrum. The simulations shown in Figure 5 assume a 0.18 μm process patterned with UV5 photoresist on ARC DUV18 anti-reflective coating.

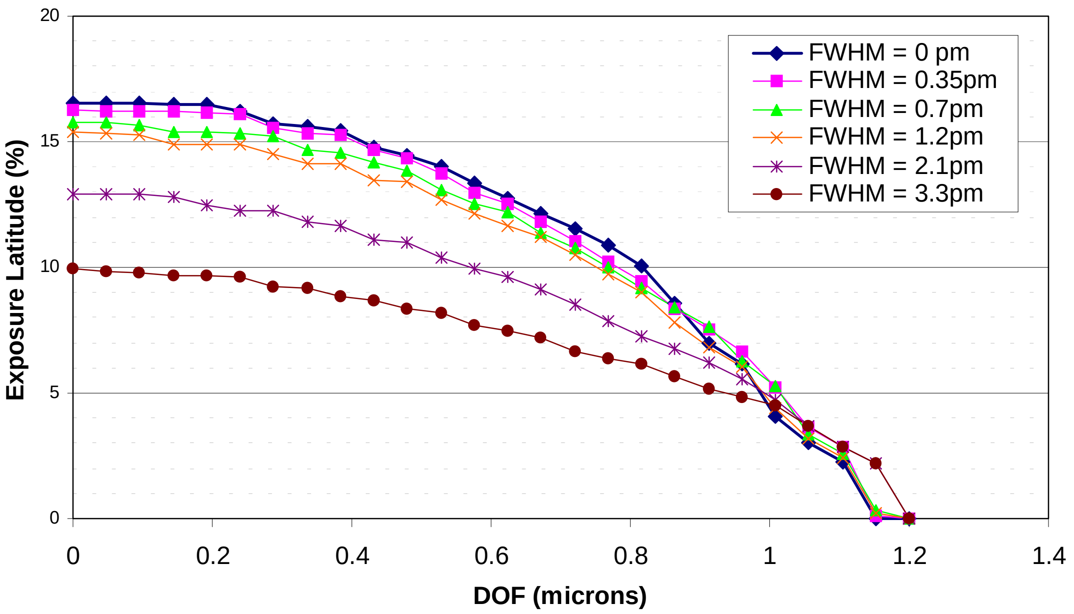

Figure 5. Sensitivity of the focus-exposure process window to laser bandwidth. Numerical aperture of the lens is set at 0.6 and partial coherence factor σ at 0.75.

Exposure latitude is defined as the range of exposure energies that keeps the linewidth within ±10% from the nominal size over the focus range specified. Depth of focus is the range of focus in which features print within ±10% from the nominal size over the specified exposure range.

For a given process, Figure 5 demonstrates how the process windows are greatly improved with tighter bandwidth light sources. Reduction of the FWHM bandwidth below 0.7 pm still shows the benefits to the process by improving the exposure latitude at a given depth of focus. Interestingly, increased chromatic aberrations have a similar effect on the lithographic process window as increased amounts of spherical aberration [5].

4. CONCLUSIONS

The effects of laser bandwidths on the lithographic process can be evaluated using computer simulations. The bandwidth simulation model described in this paper utilizes PROLITH/2.

The results show that larger bandwidths reduce the aerial image contrast and loge-slope of isolated lines. Such effects can lead to CD variations and reduction of process latitude, especially when shrinking feature sizes and increasing projection lens NAs. The biggest impact of larger bandwidth is loss of exposure latitude.

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