Contribution of Polychromatic Illumination to Optical Proximity Effects in the Context of Deep-UV Lithography

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ABSTRACT

In this paper, various optical proximity effects are evaluated as a function of spectral properties of excimer laser illumination. Sensitivity of linewidth biasing and line-end pullback to spectral bandwidth and its variations is investigated using computer simulations based on PROLITH software. Studies are performed for isolated and dense lines ranging in size from 150nm to 130nm using projection lens numerical aperture of 0.7 and KrF illumination. Results show that a non-linear, through-pitch critical dimension sensitivity to laser bandwidth variation introduces additional feature biasing, which can not be compensated with optical proximity correction techniques, and can result in an additional shift of the iso-dense bias. Also, line-end pullback of isolated lines exhibits a non-linear response to bandwidth resulting in up to 7nm of pullback per 0.1pm of bandwidth change.

Keywords: optical proximity effects, laser bandwidth, chromatic aberrations

1. INTRODUCTION

In our previous work, we demonstrated that changes in spectral properties of the illumination light affect the fidelity of the projected aerial image [1, 2]. Broadening of the illumination spectrum results in a deteriorated image contrast and log-slope, which leads to a degradation of several important lithographic process parameters such as exposure latitude, mask error enhancement factor, and iso-dense bias. The impact of polychromatic illumination light on imaging is related to chromatic aberrations in dioptric lens systems, which result from dispersion in the optical material [3, 4]. Chromatic aberration effects can be mitigated with a spectrally line-narrowed light source such as an excimer laser. Nevertheless, even the nearly monochromatic sub-picometer bandwidths cannot be ignored, especially when using a low-k_1 lithography.

In conditions, when target feature sizes are approaching the resolution limit of the optical system, the assumption that the exposure process replicates the mask pattern starts to break down. Pattern deviations from the target manifest themselves as critical dimension (CD) biasing, corner rounding and line-end pullback, which are known as optical proximity effects. Typical pattern distortions are shown in Figure 1.

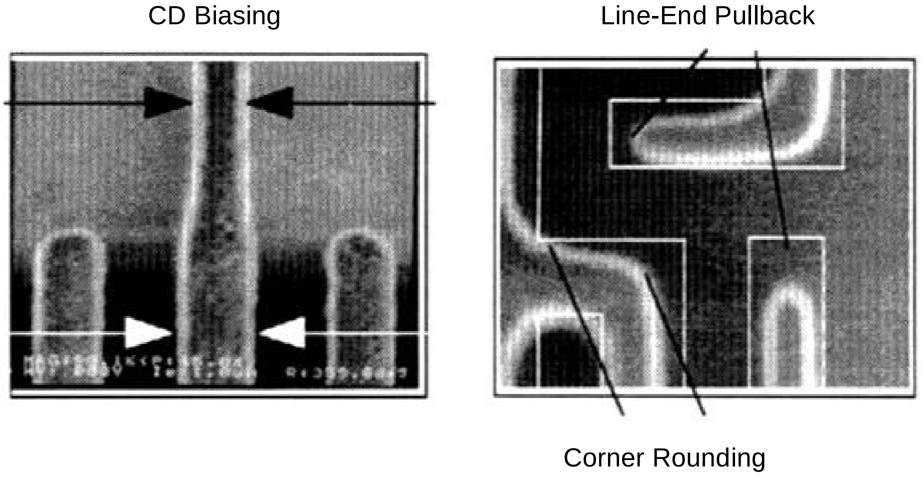

Figure 1. Different types of pattern distortions.

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Since optical proximity effects are well characterized, they can be compensated for by pre-distorting the patterns on the mask using a variety of techniques known as optical proximity correction (OPC). One of the common approaches for OPC design is based on simulation models, where OPC solutions are determined based on a lithography model for a given set of imaging and process conditions. However, the overwhelming majority of these models use the approximation of an "ideal" illumination with a monochromatic light. Thus, it is important to assess the level of influence of illumination spectral bandwidth and its changes on optical proximity effects.

2. SIMULATION OF THE POLYCHROMATIC ILLUMINATION

The impact of laser bandwidth on optical proximity effects is studied using computer simulations based on PROLITH software. The bandwidth simulation model uses an input illumination spectrum and a set of Zernike coefficients as a function of illumination wavelength. This simulation model and the methodology used are discussed in great detail in our previous publication [1]. Both illumination spectra and chromatic aberrations inputs in this study are determined experimentally. The spectra were measured on a commercial KrF excimer laser using a high-resolution double-pass grating spectrometer. An example of a laser spectrum is shown in Figure 2a. Commonly, a laser spectrum is described in terms of its full-width-at-half-maximum (FWHM) bandwidth, which corresponds to the spectral width at the 50% level of its maximum intensity (Figure 2a). Another, a more accurate description of a laser spectrum is given in terms of 95% of its integrated spectral energy (E95%), as shown in Figure 2b. In this study, we use several spectra with bandwidth ranging from 0pm FWHM/E95% (monochromatic light) to 0.8pm FWHM or 2.5pm E95%. The E95% to FWHM bandwidth ratio for all spectra used is maintained constant at about 3.1.

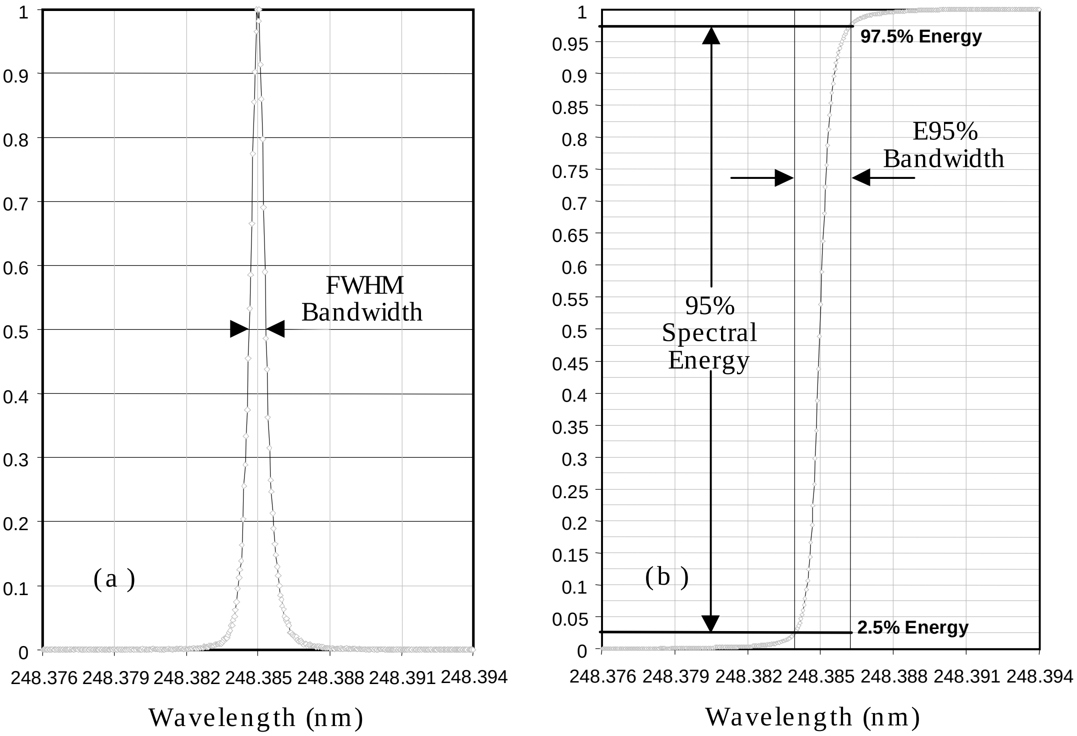

Figure 2. Different specifications of laser bandwidth: **(a)** full-width-at-half-maximum and **(b)** 95% of integrated spectral energy.

Chromatic aberration results used in this study were acquired experimentally on a modern 0.68*NA* step-and-scan system [3]. Figure 3 shows the through-wavelength measurement of Zernike coefficients corresponding to defocus *Z4*, 3-rd order spherical *Z11*, and 5-th order spherical *Z22* aberrations. Defocus shows the largest sensitivity to the change of wavelength measured at 77.6 mwaves/nm, which corresponds to about 0.25μm of focus per picometer of wavelength. As described by M. Terry et al. [3], Z4 is the only coefficient among the 27 reconstructed terms that shows significant sensitivity to the wavelength change, and it is more than 20 times greater than the next largest coefficient, Z11. Thus, for the simplicity, in this study we consider chromatic defocus as the only aberration interfering with illumination spectra, and all of the simulations assume a slope of 0.25 μm/pm.

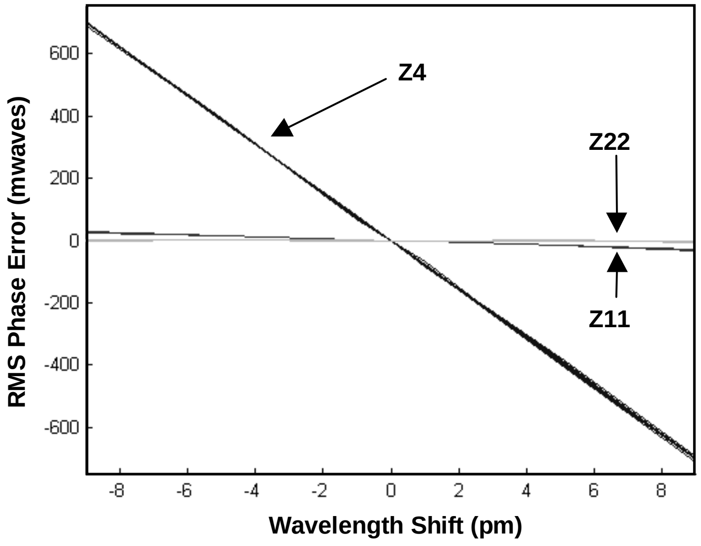

Figure 3. Sensitivity of Zernike coefficients *Z4*, *Z11*, and *Z22* to the change of wavelength [3].

3. BANDWIDTH EFFECTS ON CD BIASING

As demonstrated in previously published work, polychromatic imaging of isolated and dense features is different in nature [2]. This suggests that through-pitch imaging may have a non-linear sensitivity to bandwidth. In order to verify this statement, let us evaluate the through-pitch imaging of a 150nm line as a function of laser bandwidth. The following parameter settings were assumed in this simulation study: lens numerical aperture *NA* of 0.7, partial coherence σ of 0.75, KrF illumination at nominal central wavelength of 248.327 nm, aerial image threshold level of 31.5%, full scalar model.

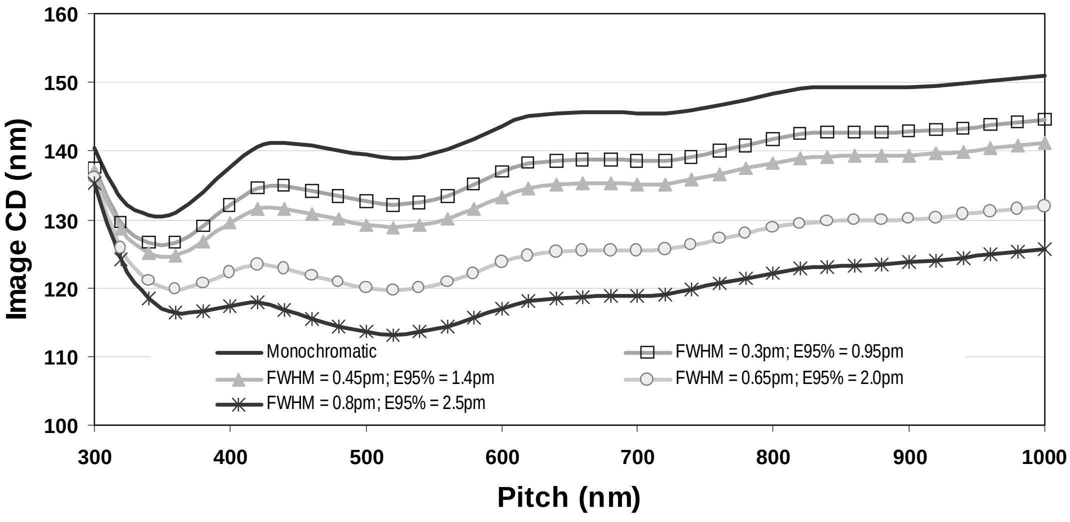

Figure 4. Sensitivity of through-pitch image CD to laser bandwidth.

As shown in Figure 4, imaged lines are very sensitive to the change of pattern density or pitch. Also it is apparent that laser bandwidth changes the through-pitch CD response and introduces an additional CD bias. As expected, isolated and semi-dense features, with a pitch of 450nm and larger, exhibit greatest sensitivity to the bandwidth, while its effect on pure dense lines is nearly negligible. This can be seen clearly in Figure 5, where image CD bias represents bandwidth-induced bias compared to the monochromatic result in percent.

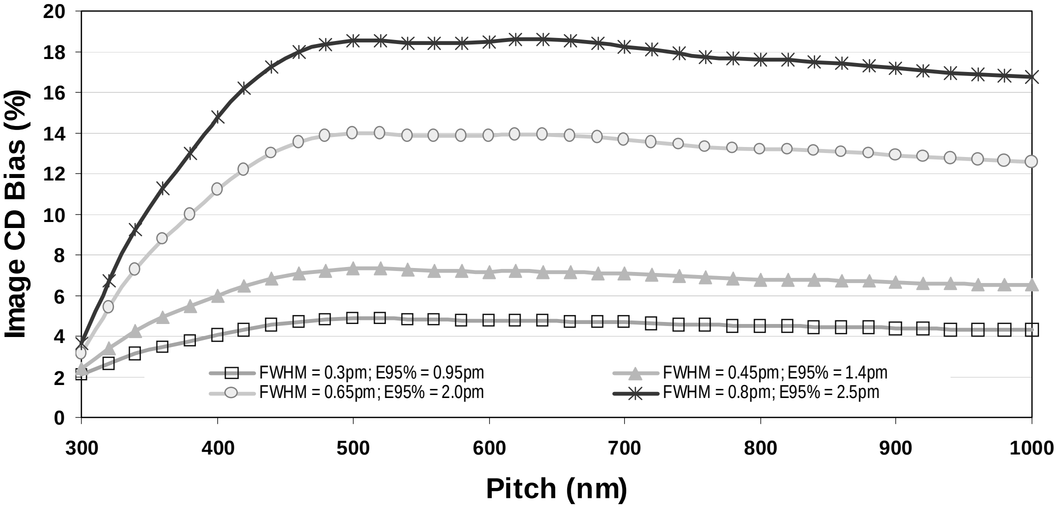

Figure 5. Percent image CD bias of 150nm lines, through-pitch and as a function of bandwidth.

Figure 6 captures the bandwidth-induced CD iso-dense bias of 150nm lines. This result represents the CD bias between isolated line with a pitch of 1000nm and a pure dense line with a pitch of 300nm.

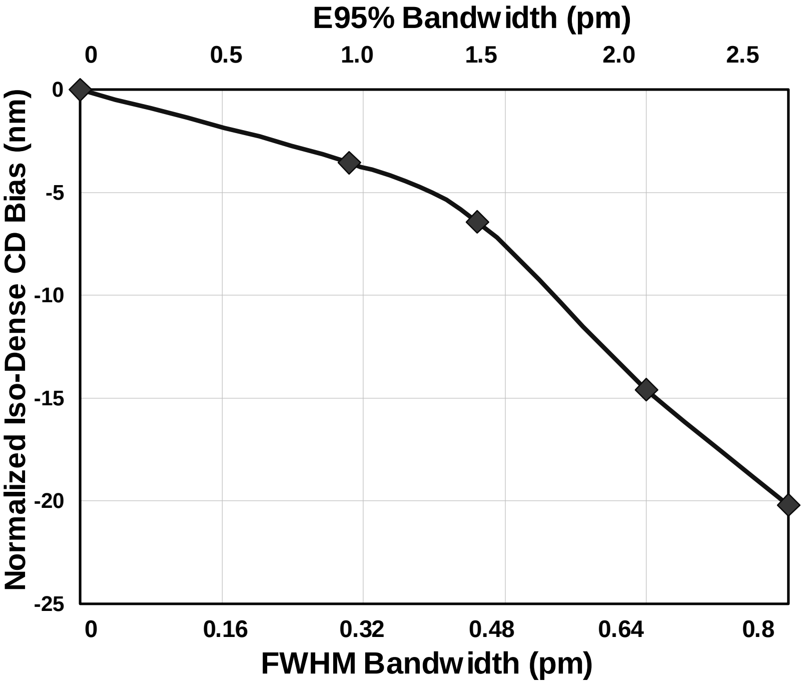

Figure 6. Normalized iso-dense CD bias versus laser bandwidth.

As shown in Figure 6, the absolute iso-dense bias changes by about 20nm due to 0.8pm FWHM/2.5pm E95% bandwidth compared to the result corresponding to the monochromatic light.

Considering the significance of this result, it is apparent that the effects of polychromatic illumination need to be incorporated in model-based OPC design. Nevertheless, it is important to note that the spectral bandwidth naturally fluctuates over the lifetime of consumables and modules of the laser. Since an OPC design is implemented for a specific operating condition, any short- or long-term instability in spectral performance of the laser would result in a change of iso-dense bias, which could not be compensated by an OPC solution. Also taking into account that there are tool-to-tool spectral performance differences, it becomes quite difficult to incorporate a generic OPC solution which would yield highest performance across large family of tools in use. Thus, it is also important to achieve a high level of bandwidth stability and tool-to-tool performance repeatability in order to maintain the effectiveness and consistency of OPC performance over the process lifetime.

4. IMPLICATIONS ON LINE-END PULLBACK

Another commonly known pattern distortion is called line-end pullback. This distortion becomes more and more relevant as the critical dimensions continue to shrink, especially for logic applications [5]. In this section, we focus on the interaction effects between line-end pullback and polychromatic illumination.

As feature sizes shrink and projection lens NA increases, the variation of the line-end pullback as a function of defocus becomes more significant. Figure 7 depicts the shortening as a function of focus for a 150nm isolated line-end facing a 150nm passing line. Results in Figure 7 show that the line-end pullback is strongly sensitive to defocus, which suggests that it should be sensitive to chromatic wavelength effects as well.

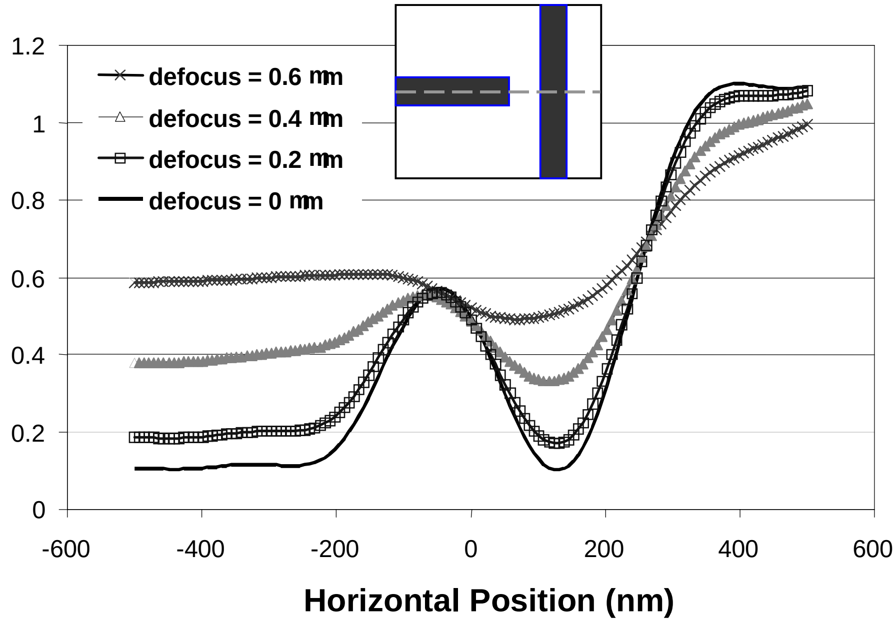

Figure 7. Line-end pullback of 150nm isolated lines as a function of defocus. This result assumes lens *NA* of 0.7 and partial coherence factor σ of 0.75. The inset depicts a top-down view of the photomask layout and the cross-section line.

In order to evaluate spectral bandwidth implications on line-end pullback, the imaging performance of 150nm and 130nm lines was evaluated. Similarly to the previously discussed work, this simulation study assumes KrF illumination, lens *NA* of 0.7, and partial coherence factor σ of 0.75. In Figure 8, two-dimensional contour plots of 130nm isolated lines as a function of laser bandwidth are shown. Intensity threshold level of 31% is used to achieve the target image CDs in the case of monochromatic illumination. Also, the plots contain contours of the mask features in order assist the visual assessment of resultant image changes.

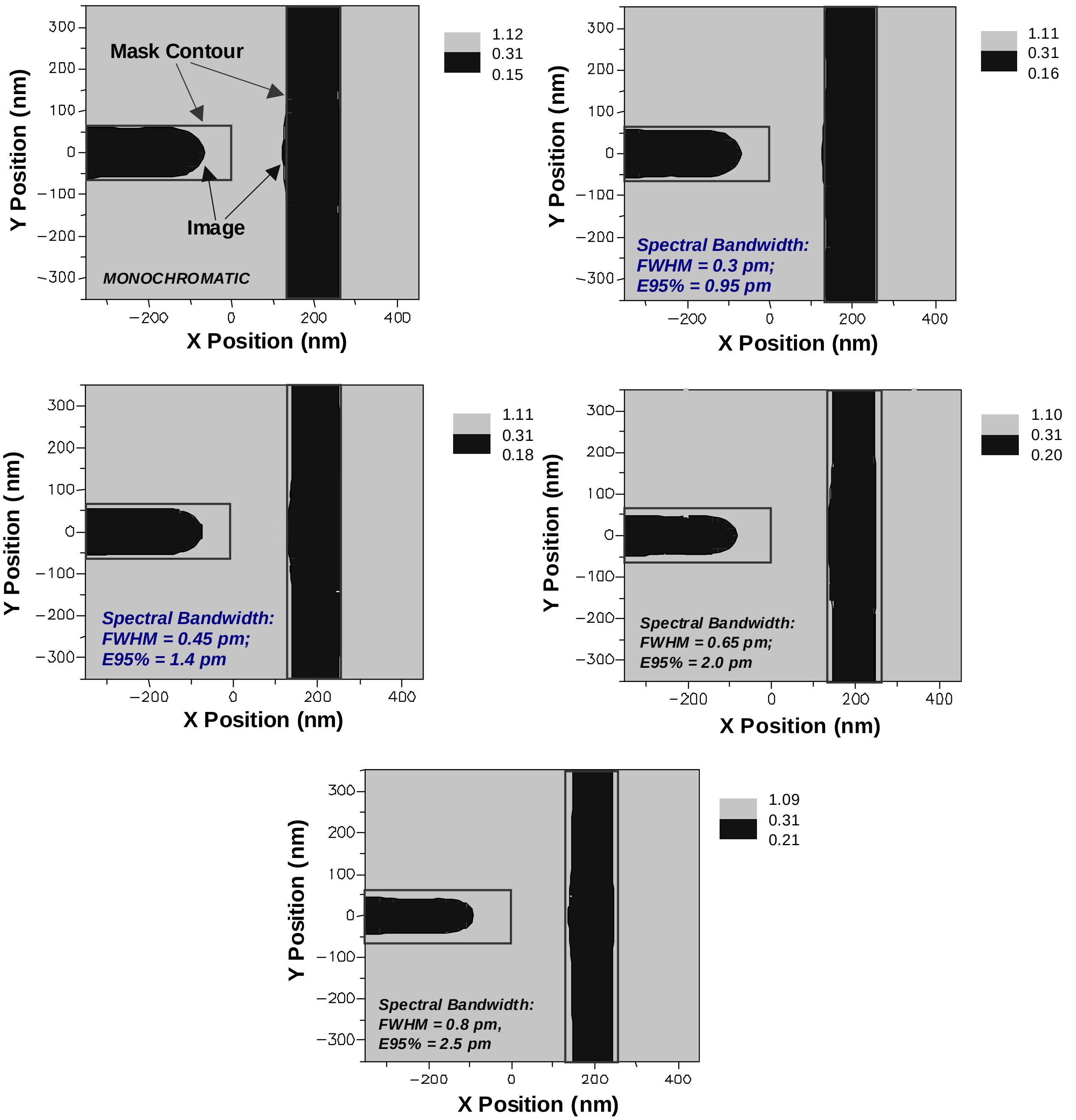

Figure 8. Laser bandwidth effects on line-end shortening of 130nm isolated lines.

As shown in Figure 8, line-end shortening of 130nm lines exhibits significant sensitivity to the increase of laser bandwidth. Similar data was also obtained for 150nm lines. It is easier to interpret these results by analyzing the image cross-sections corresponding to different bandwidth values. Figure 9 shows aerial image cross-sections of 150nm (Figure 9a) and 130nm (Figure 9b) isolated lines.

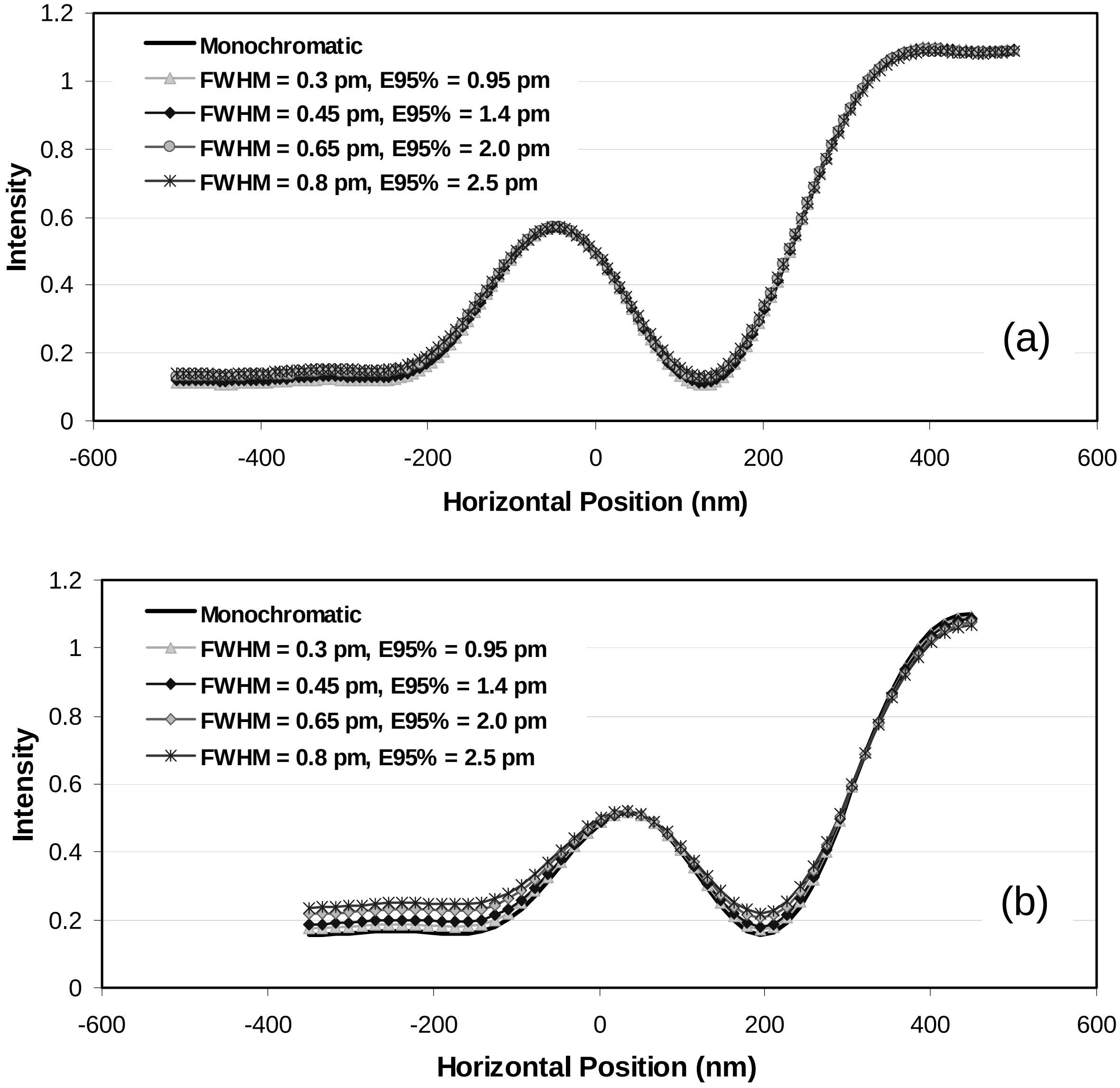

Figure 9. Image cross-sections of 150nm (a) and 130nm (b) isolated lines as function of bandwidth.

It is commonly known that with the decrease of the CDs and the k_1 factor, the lithographic imaging becomes more difficult. In approaching the optical resolution limits of the imaging system, aerial image fidelity degrades and the image quality shows larger dependence to various imperfections of the imaging system, such as in the mask, lenses, and the illumination. In Figure 9, the image sensitivity to the spectral bandwidth is also shown to follow these trends. An increased image sensitivity is observed with the reduction of CDs from 150nm to 130nm. It can be noticed that the aerial image background level of 130nm lines is nearly 50% higher compared to the 150nm lines, which results in a greater degradation of the image contrast and log slope.

In order to quantify the line-end pullback as a function of bandwidth, a simple threshold resist model is used. Figure 10 shows results for both 150nm and 130nm lines assuming an image threshold level of 31%.

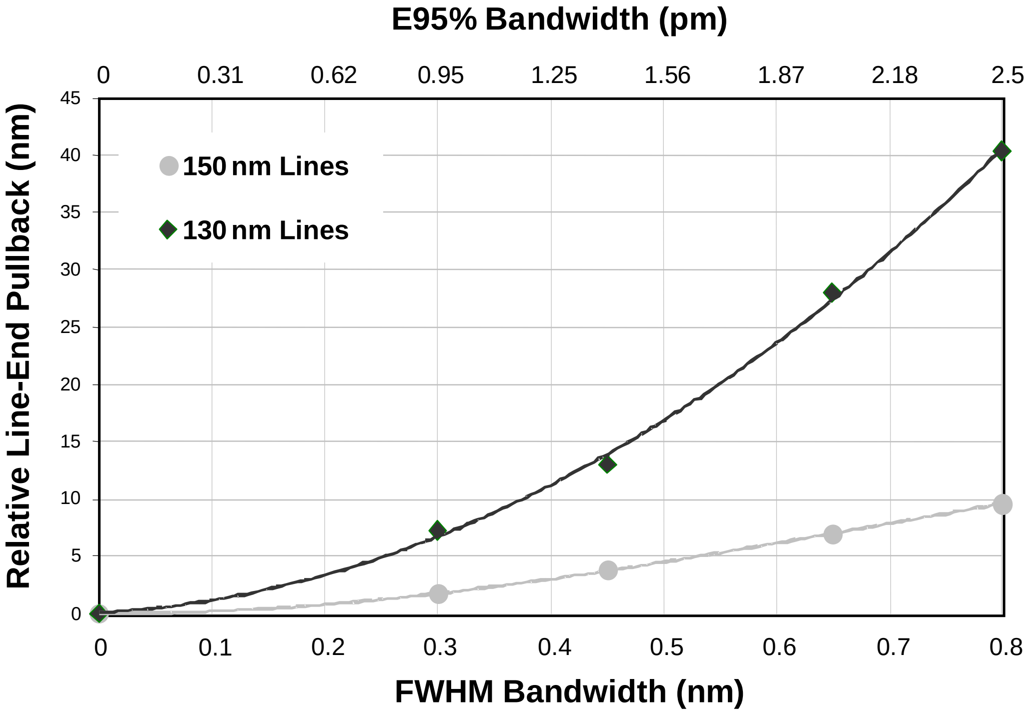

Figure 10. Line-end pullback of 150nm and 130nm isolated lines as function of bandwidth.

As depicted in Figure 10, the line-end pullback sensitivity to the increase of spectral bandwidth exhibits a monotonically increasing behavior. Near the operating range of excimer lasers used in production, where bandwidth specification is close to 0.5pm FWHM and 1.4pm E95%, the pullback sensitivity slope is about 3nm per 0.1pm of FWHM or 0.3pm of E95% for 150nm lines. It is about 7nm per 0.1pm of FWHM or 0.3pm of E95% for 130nm lines. The magnitude of this result is due to the fact that the target feature sizes are imaged close to the optical resolution limit, especially in the case of 130nm lines where k_1 factor is 0.37. Also this effect could be possibly reduced with the application of OPC, which is a topic of further interest.

5. SUMMARY AND CONCLUSIONS

In this paper, the impact of polychromatic illumination on optical proximity effects has been evaluated using computer simulations. The results show that the changes in spectral bandwidth induce an iso-dense CD bias due to the difference in the imaging response of isolated and dense features. In the case of 150nm lines, the image CD bias changes by about 2 to 3nm per 0.1pm of FWHM bandwidth or 0.3pm of E95%. The increase of bandwidth also induces a line-end pullback. 150nm isolated lines show about 3nm of end pullback per 0.1pm of FWHM or 0.3pm of E95% bandwidth, while the line-end pullback of 130nm features changes with a slope of 7nm per 0.1pm of FWHM or 0.3pm of E95%. These results point to the importance of the laser bandwidth considerations in model-based OPC methods, and highlight the significance of spectrally narrow and stable illumination sources for the demanding needs of today's state-of-the-art lithography.

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