# SIMULATION OF FOCUS EFFECTS IN PHOTOLITHOGRAPHY

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## ABSTRACT

We describe a simple model and an efficient simulation for bulk imaging within a resist layer during photobleaching. It gives a first-order correction to the conventional vertical propagation model, and explains the non-symmetric focus offset dependence of developed resist images printed with lenses of small focal depth.

In projection optical lithography the imaging of a photomask on a photosensitive resist layer results in latent image formation. The conventional vertical propagation (VP) model assumes the incident light is transmitted vertically after crossing the air-resist interface. Theoretically, positive and negative focal plane offsets (relative to the resist surface) yield symmetrical results. However, when the depth of focus decreases to a distance of order the layer thickness, the exposure can never have the same focus at all layer depths. Recent measurements in submicron lithography indicate that bulk imaging can no longer be neglected. A basic non-symmetry is evident in cross sections of developed resist profiles obtained for positive and negative focus offsets {1,2}. The empirical focus-exposure plot displays corresponding asymmetry.

Consider a planar resist layer in cross-section, with lateral coordinate x, and depth coordinate $z>0$, where $z=0$ marks the air-resist interface (Fig.1). Latent image formation is driven by the exposing intensity distribution $I(x,z)$, which must be determined throughout the resist film. Corrections to the VP model must consider the "bulk image" projected into the resist by virtue of the obliquely incident wavefronts. A rigorous description of the bulk image is given by the macroscopic Maxwell equations, whose solution is computationally expensive. We have devised a simpler, first-order model of bulk imaging which is easily visualized, and appears to qualitatively describe focus offset position asymmetries in submicron lithography.

We first consider a non-reflecting substrate. When the focal plane of the projection lens coincides with the resist surface ($z_F \equiv 0$), a condition of increasing defocus occurs with increasing depth. Yeung {3} has considered the bulk image at the start of bleaching, and suggested that to a good approximation $I(x,z)$ obeys

$$I(x,z) \propto \widetilde{I}_D(x), \qquad \text{with} \quad D = z/n_R \ ,$$

where $\widetilde{I}_D(x)$ is the defocussed image intensity that would have existed in air at a displacement D from the plane of focus, if the resist were absent. Our bulk image model generalizes the equivalent defocus in air to arbitrary focal plane offsets $z_F \neq 0$ (shown in Fig.1 for $z_F>0$) and asserts that

$$I(x,z) = I_{\downarrow}(x,z) = \widetilde{I}_{D_\downarrow}(x) \cdot i_{\downarrow}(z), \qquad \text{with} \quad D_{\downarrow} = z/n_R - z_F \ .$$

The function $i_{\downarrow}(z)$ introduces the effect of absorption, given by Beer's law, and is the intensity that exists at depth z when a plane wave of unit flux is incident normal to the surface of the resist. It also contains the photobleaching-induced time dependence of the bulk image. For a reflecting substrate we add the reflected image

$$I_{\uparrow}(x,z) = \widetilde{I}_{D_\uparrow}(x) \cdot i_{\uparrow}(z), \qquad \text{with} \quad D_{\uparrow} = (2t_R - z)/n_R - z_F \ ,$$

as illustrated in Fig.2. The upward attenuation factor $i_{\uparrow}(z)$ is associated with the normal ray as it returns from the base of the resist. It includes the reflection coefficient at the resist-substrate interface. Our final expression for the net bulk image intensity with a reflecting substrate is the incoherent sum

$$I(x,z) = I_{\downarrow}(x,z) + I_{\uparrow}(x,z).$$

Our bulk image model neglects standing wave effects, behaving as if the latent image has an implicit post exposure bake. It also neglects other coherence effects, and for example should not be applied to fully coherent imaging under conditions of image reversal or doubling. On the optimistic side, our model is similar in representation to the vertical propagation model, and is thus easily simulated with only modest increase in computation time. We have incorporated it into the SPESA photolithography simulator {4}, which has extensive capabilities for quantitative process characterization and resist profile analysis.

Fig.3 shows developed resist images simulated from our model for various focal offsets $\Delta z_F$, relative to $z_F = t_R/2n_R$, which places the refracted focus exactly in the middle of the resist layer. Comparison with the resist process measured by Kameyama et.al.{1} (reproduced in Fig.4) shows agreement with observed asymmetric behavior: rounded top profile (wafer moved towards the lens); flared base profile (away from the lens). Simulated focus-exposure plots, such as for cleared linewidth (Fig.5) and top linewidth (Fig.6), may be used to evaluate the optimum focus position within the resist layer. To interpret such curves, we describe the "effective defocus" concept.

REFERENCES

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{3} M.Yeung, Proc.Kodak Microelectronics Seminar, Kodak Pub.No.G-154, 115 (1985).
{4} D.A.Bernard, Microelectronic Eng., Vol.3, 379 (1985).

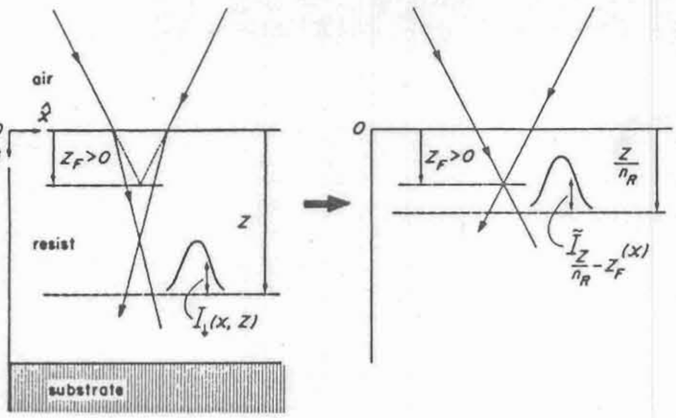


Fig.1 Construction of transmitted bulk image ($n_R$=refr index).

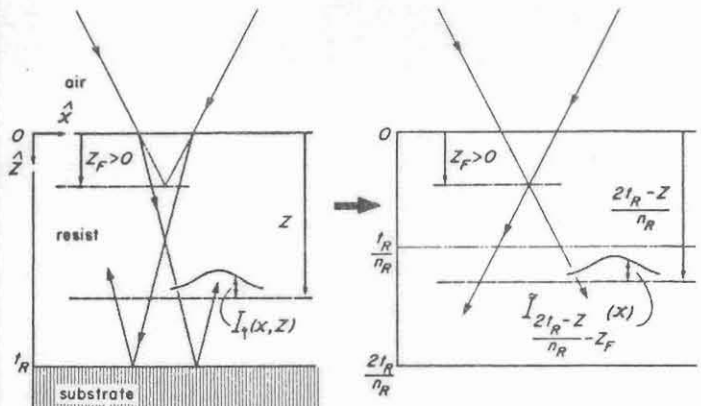


Fig.2 Construction of reflected bulk image.

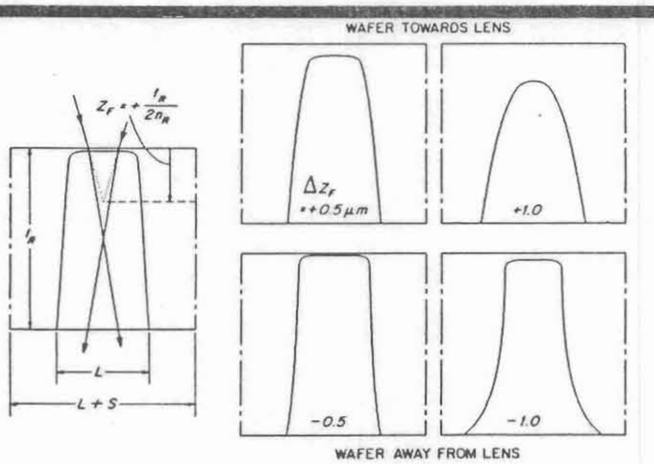


Fig.3 Simulation of developed resist profiles vs focus offset at constant dose (to be compared to Fig 4)

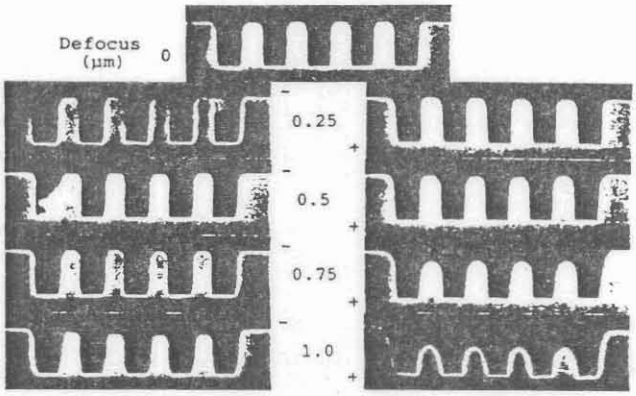


Fig.4 Measured resist profiles from Ref 1. L=S=0.6μm, patterned with 0.6 NA g-line Nikon lens. Resist thickness is 1.2μm.

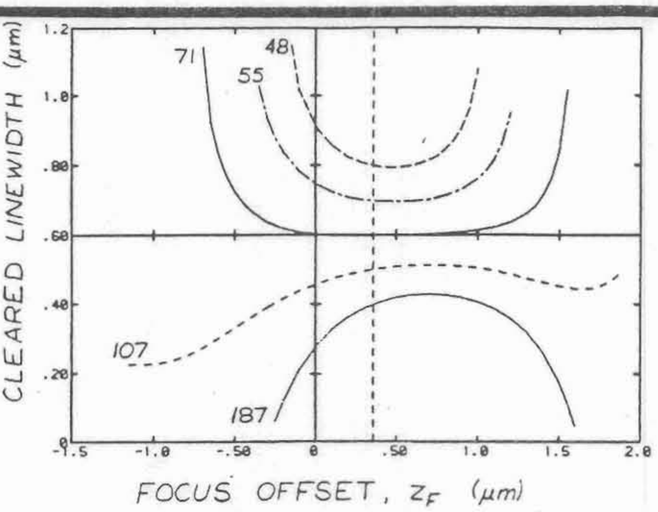


Fig.5 Simulated focus-exposure plot associated to Figs 3&4. Five isodose curves are labeled.

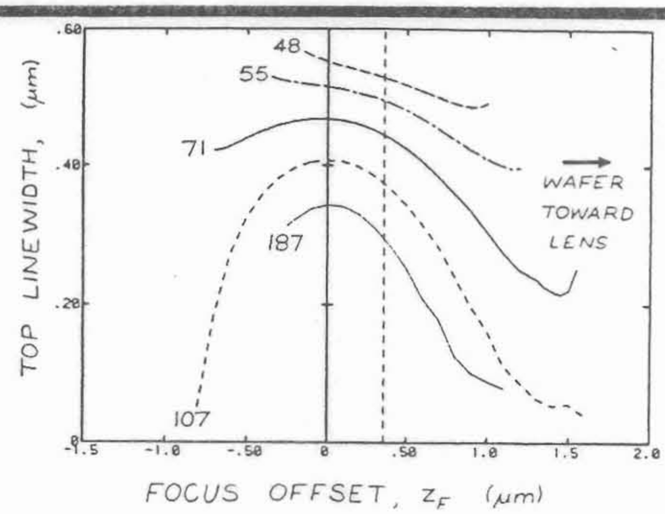


Fig.6 Basic asymmetry of bulk image is clearer in F-E plot of top linewidth vs focus offset.