Modeling of a Phase-Shifting Mask

K. Harazaki, T. Hayashi, K. Fujii and T. Inufushi
VLSI Development Laboratories, Sharp Corporation
2613-1, Ichinomoto-cho, Tenri 632, Japan

Recently, various practical applications of phase-shifting technologies to VLSI optical lithography have been introduced to achieve higher imaging resolution [1], [2]. The performance of these technologies strongly depends on the types of phase-shifting masks called *shifters*, and specially on the shape uniformity of the shifters. However, few quantitative models describing the topographical effects of the optical phase-shifts have been reported.

In this paper we present a new optical imaging model for nonuniform phase-shifters in order to accurately simulate the image intensity at the image plane of the projection system (see Fig.1).

Based on Hopkins' theory [3], we propose a new distribution function of the image intensity at the image plane:

$$I(x, y)=\iiiint [B_0(x_1-x_2, y_1-y_2)K(x-x_1,y-y_1)K^*(x-x_2,y-y_2)) \\ -S(x_1, y_1)S^*(x_2, y_2))]dx_1dy_1dx_2dy_2 \qquad (1)$$

Where B_0 is the mutual intensity, K is the coherent transfer function, and S is a newly defined function named the *mask function*. Asterisks indicate the conjugated form. The mask function S is defined by the product of the topographical function G multiplied by the transmission function F without phase-shift, since the image intensity is proportional to the transmission intensity which is much influenced by the topography of the nonuniform shifter. Thus S is given by

$$S(x', y')=G(x', y')F(x', y') \qquad (2)$$

Next, we provide G with actual examples of two types of nonuniform phase-shifters as shown in Fig. 2b and Fig. 2c. For comparison of the phase-shift effects, we also examine the conventional mask without shifters in Fig. 2a. The G for each type is given by

$$G(x', y')=\begin{cases} 1.0 & \text{Conventional type (3)} \\ 2g_0J_1(\sqrt{x'^2+y'^2}/\gamma)/(\sqrt{x'^2+y'^2}/\gamma) & \text{Convex type (4)} \\ 2g_1J_1((\sqrt{x'^2+y'^2}-p)/\gamma')/((\sqrt{x'^2+y'^2}-p)/\gamma') & \text{Concave type (5)} \end{cases}$$

Where g_0 and g_1 are normalized constants, J_1 represents the Bessel function of first kind, γ and γ' are the configuration constants determined by the topography of the shifter, and p is the maximum peak position of the post-transmission intensity. The spatial coordinates of p can be found between the mask and the projection lens.

Fig. 3 gives the calculated I(x, y) of three types of masks with the window width L=0.3 μm. Clearly, the topographical effects significantly influence the I(x, y) profiles, and the contrast can be improved most by the use of a convex type mask. Although the validity of the convex type mask has not yet been confirmed experimentally, the simulated results suggest the usefulness of this new type of phase-shifting mask.

The use of our model will enable new phase-shift application technologies to be developed, for example the optimization of shifter's shapes and the development of new mask patterns.

---

[1] T. Terasawa et al., *Proc. of SPIE's symp.*, vol. 1088, pp. 25-33, 1989
[2] K. Nakagawa et al., *IEDM Tech. Dig.*, pp. 817-820, 1990
[3] B. J. Lin, *IEEE Trans. on Electron Devices*, vol. ED-27, pp. 931-938, 1980

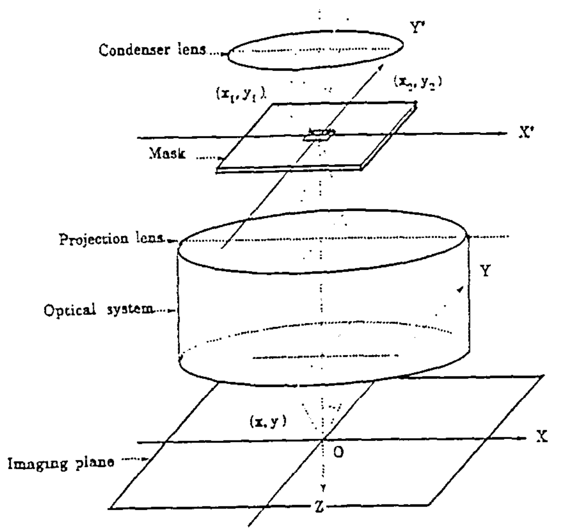
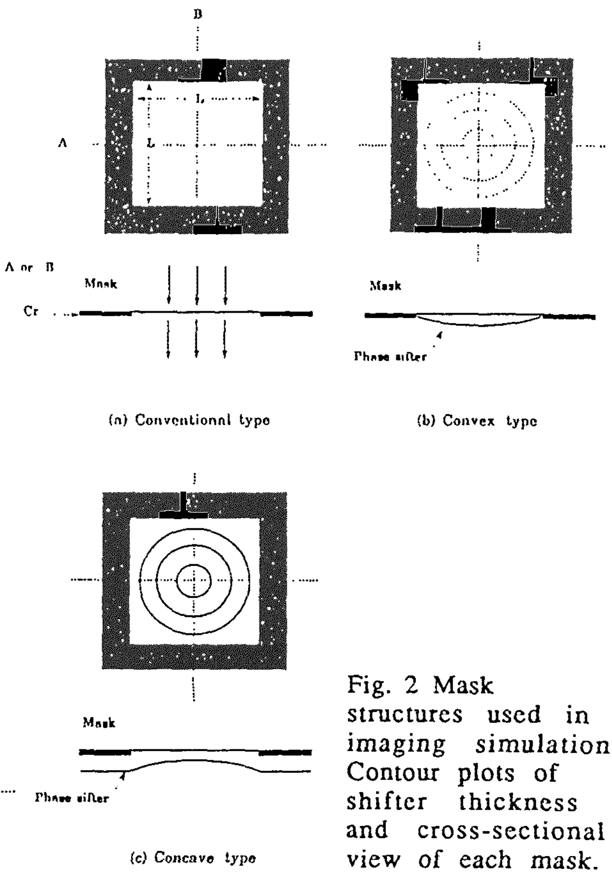


Fig.1 Schematic view of the projection system.

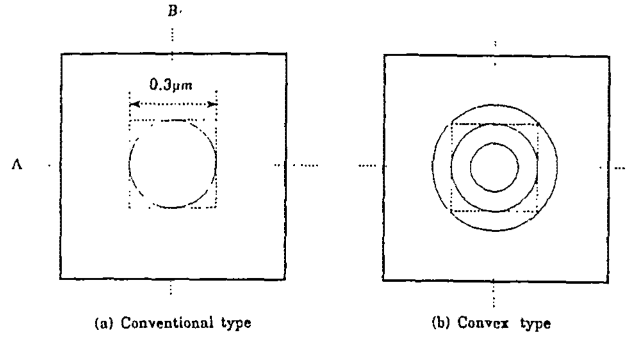


(a) Conventional type

(b) Convex type

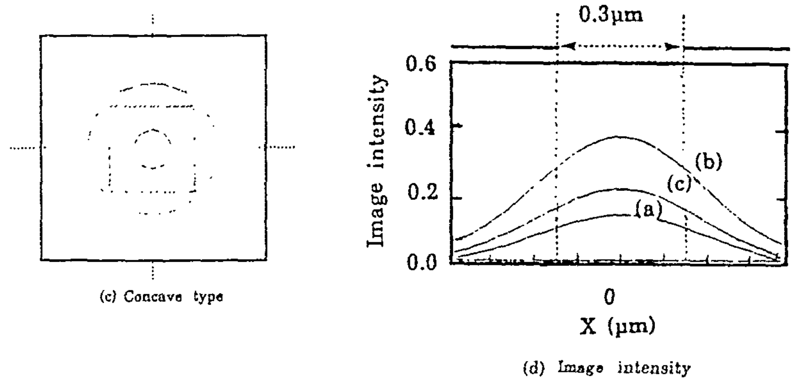
(c) Concave type

Fig. 2 Mask structures used in imaging simulations. Contour plots of shifter thickness and cross-sectional view of each mask.



(a) Conventional type

(b) Convex type



(c) Concave type

(d) Image intensity

Fig.3 Contour plots of image intensity and cross-sectional view of each mask. Exposure conditions, λ=365nm, NA=0.45, σ=0.5, defocus=0, no aberration.