THREE-PHASE PHOTOMASK

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There are two conventional approaches to improving the resolution of optical lithography: to use higher numerical aperture (NA) projection lens or shorter exposing wavelength. Recent high NA i-line (wavelength $\lambda = 365\text{nm}$) steppers can fabricate 0.5-0.4 μm -rule devices. KrF excimer laser ($\lambda = 248\text{nm}$) steppers have potential resolving power up to 0.3 μm . However, at the same time, these approaches reduce the depth of focus (DOF). Theoretically the resolution R and the DOF are given by

$$R = k_1\lambda/\text{NA}, \quad \text{DOF} = k_2\lambda/\text{NA}^2, \quad (1)$$

where k_1 and k_2 are process factors. The lack of sufficient focus latitude causes a serious problem to lithography processes.

In recent years phase-shifting methods have been studied intensively since the methods improve both the resolution and the DOF simultaneously. Among various phase-shifting methods the one proposed by Levenson [1] is known to be most effective. This method introduces a 180-degree phase difference between the light beams passing through neighboring open areas in mask patterns. The main drawback of this method is that it can be applied solely to simple periodic patterns. In case of non-periodic patterns the images of the neighboring open areas cannot be separated completely as shown in Figure 1 (a).

In this report we propose a new phase-shifting method to overcome the above problem. Figure 1 (b) is a typical example of our phase-shifting mask. The mask is characterized by three different phase areas, 0, 120, and 240 degrees. Since 240 degree is same as -120 degree the relative angles of these three phases are +120 or -120 degree. As shown in the figure the images of every open areas are clearly distinguished.

Figure 1: Mask patterns and corresponding light intensities on wafers: (a) Levenson type and (b) three-phase ($L/S = 0.3 \mu\text{m}$, i-line, $NA = 0.5$, the coherence factor $\sigma = 0.3$ for Levenson type and 0.6 for the three-phase mask).

Figure 2: Image contrasts of L/S patterns: (a) L/S width dependence at defocus = 0 μm and (b) defocus dependence at L/S width = 0.3 μm (i-line, $NA = 0.5$, $\sigma = 0.3$ for Levenson type and 0.6 for the conventional and three-phase masks).

In Figure 2 we quantitatively estimate the resolving power and the focus latitude of our new method. Compared with the conventional method our method significantly enhances both the resolving power and the focus latitude. Image contrast of about 60 to 70 percent is known to be necessary to separate adjacent lines. For i-line steppers our method resolves lines and spaces of 0.3 μm pitch with $\pm 0.9 \mu\text{m}$ DOF.

Our new phase-shifting mask, three-phase mask, possesses many desirable properties: pattern flexibility, high resolution and large focus latitude. Further studies might be required for practical applications.

Reference

- [1] M.D. Levenson, N.S. Viswanathan, and R.A. Simpson, *IEEE Trans. Electron Devices*, **29**(1982)1828.