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Optimization of the depth of focus based on the analysis of the diffraction orders in the pupil plane

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The evolution of the depth of focus has been studied using a simple geometrical analysis of the diffraction orders in the pupil plane. This analysis is based on the observation that the diffraction orders participating to the interactions must be symmetrical with respect to the optical axis. The center of the gravity of the areas of the different diffraction orders captured by the pupil is evaluated as a function of pitch, numerical aperture and wavelength. Analytical expressions have been derived. They give which illumination settings (partial coherence) optimise the DOF for conventional, annular and quadrupole illuminations. The impact of the diffraction orders on the evolution of the DOF through pitch curve was also studied. The appearance of a peak in the DOF versus pitch curve, for annular and quadrupole cases is caused by the perfect symmetry between the diffracted waves interacting together.

Keywords: Optical lithography; Depth of focus; Diffraction orders; Isofocal

1. Introduction

As the size reduction of the elementary components of integrated circuits is outpacing the introduction of shorter exposure wavelengths and higher numerical aperture lenses, lithographers must look into other solutions such as resolution enhancement techniques (alternated PSM [1], attenuated PSM [2], scattering bars [3], double exposure [4], off axis illumination) in order to extend the limits of the optical lithography.

A mandatory step to further optimise the photolithographic process is the understanding of the

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optical phenomena in the pupil plane. Several papers have shown [5–7] that the optimal depth of focus (DOF) is reached when the beams captured by the pupil are symmetrical to the optical axis. This means that the shape of the beams incident onto the mask impact the distribution of the diffraction orders in the pupil plane. This is why the illumination used in the circuit printing goes more and more to a symmetrical shape (from conventional to annular, quadrupole and dipole).

The evolution of the depth of focus as a function of the pitch is studied in this paper. The measured DOF corresponds to the 0% energy latitude of $\pm 10\%$ of targeted dimension which in this paper is 100 nm. This evolution of the DOF is studied using a simple geometrical analysis of the diffraction orders in the pupil plane. The barycentre of the areas of the different diffraction orders captured by the pupil is evaluated through the pitch, wavelength (λ) and NA, and all steps of the analytical calculation are described. We compare the theoretical DOF optimisation using the center of the gravity (COG) analysis with a simulation of the aerial image at 193 nm wavelength and 0.63 NA and show that the analytical optimisation gives the same results and works faster. Finally, we study the impact of the diffraction orders positions on the evolution of the DOF curve versus feature pitch and partial coherence using the position of the barycentres.

2. Area and barycentre of the diffracted orders through pitch

2.1. Theoretical background

Fig. 1a shows a schematic sketch of a lithographic system [8,9]. It consists of four parts: illumination optics, mask, projection optics and wafer. The light that falls onto the mask can be considered as a sum of plane waves with different angles of incidence. These plane waves are diffracted by the mask into the several directions [10]. Here we will limit our study to the zero and first orders of diffraction (0, 1 and -1) because in the case of low k_1 imaging most of the contribution comes from these orders. We will consider only one-dimensional patterns.

A feature on a mask is reproduced on the wafer by a light interference process from the diffracted orders. Considering the coherence properties of lithographic light sources, we consider that two beams interfere if they come from the same source point. In the case where the feature pitch is small enough, as we can see in Fig. 2, from the source S1, P_{-1} interacts with P_0 . The first-order contribution P_1 is not captured by the pupil. We have here only an interaction between two beams (-1 and 0). We have the

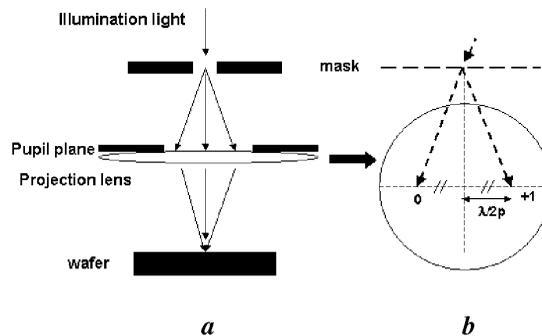


Fig. 1. Schematic sketch of a lithographic system.

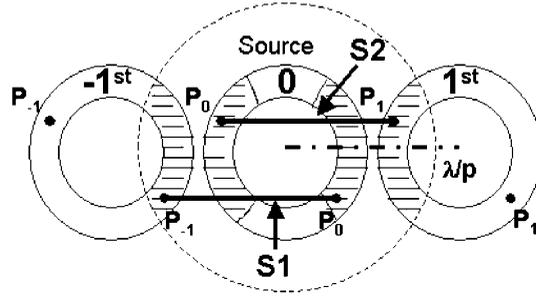


Fig. 2. Diffracted waves captured by the pupil plane.

same with another source point S2 where only P_0 and P_1 interact together because the pupil does not capture P_{-1} .

The shape and the position of these beams in the pupil plane have a great impact on the lithographic performance: if two beams are symmetrical to the optical axis, the DOF is at maximum [5,6] (Fig. 1b). In the case of partially coherent illumination (conventional, annular or quadrupole illumination), as described by Abbe's theory [11], we can extend this to a set of source points. To evaluate the symmetry of a group of beams, we use the position of the COG of the diffracted order areas (-1 and 1) captured by the lens. Considering that the interference of two symmetrical plane waves provides a theoretically infinite depth of focus, we can infer that if the positions of the COG of two groups of beams (0 and -1) are symmetrical, we optimise the DOF.

2.2. Area and COG of the diffracted orders captured by the pupil plane

In order to evaluate the COG of the diffracted orders captured by the pupil plane, we need to derive an analytical expression representing the area of these diffracted orders. For that, we make use of the Hopkin's [7] treatment as follow: we consider the projection lens pupil as a circle C_1 having NA (r_1) as radius and the diffracted first-order area as a circle (C_2) having partial coherence σ (r_2) as radius. Fig. 3 shows an illustration of this for a conventional illumination. In the annular and quadrupole cases we are dealing with circular shapes as well and we only have to adapt the following expressions to them.

All interaction surfaces can be computed easily as a superposition of portions of circles. Everything

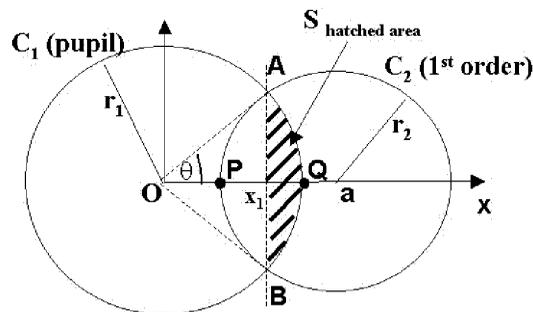


Fig. 3. Schematic illustration of the projected lens (C_1) and 1st diffracted order (C_2).

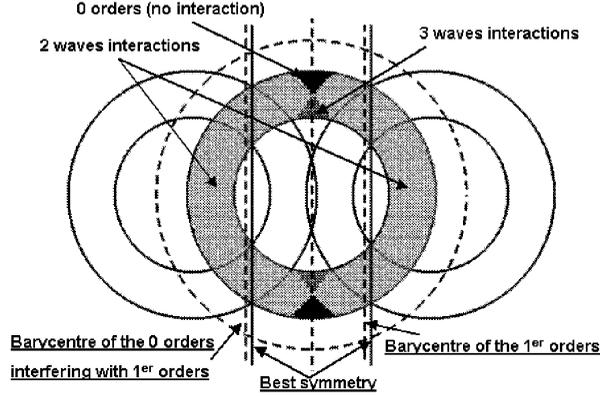


Fig. 4. Illustration of the presence of several interactions at the pupil plane for an annular illumination and position of the COGs of the -1 and 1 diffracted orders captured by the pupil able to interfere with order 0.

resume to the determination of the area and the center of gravity of an arc (e.g., hatched area of Fig. 3). The overlap area between C_1 and C_2 corresponds to the first diffracted orders area captured by the pupil plane interfering with the 0 orders.

$$S_{\text{hatched area}} = r_1^2 \times \text{Arctan}\left(\frac{\sqrt{r_1^2 - x_1^2}}{x_1}\right) - x_1 \times \sqrt{r_1^2 - x_1^2} \quad (1)$$

$$x_{\text{g,hatched area}} = \frac{2}{3} \frac{r_1^3 \times \sin \theta - x_1^3 \times \tan \theta}{r_1^2 \times \theta - x_1^2 \times \tan \theta} \quad (2)$$

with $x_1 = 1/(2a) \cdot [r_1 - r_2 + a^2]$, a the position of the centre of C_2 , r_1 and r_2 the radii of the two circles C_1 and C_2 and θ the semi-angle of the arc AB.

Fig. 4 shows a drawing of the pupil plane for an annular illumination with 193 nm wavelength, 400 nm pitch, 0.63 NA and $0.50\sigma_{\text{in}}/0.80\sigma_{\text{out}}$. In dotted lines, we have the position of the first diffraction order COG captured by the pupil and the position of the COG of the 0 order which interfere with them. In solid, we find the position of the best symmetry which is located at $\pm \lambda/(2p)$.

More than the position of the COG, it also shows the number and areas of the interactions generated between the diffracted orders captured by the lens. These diffracted orders do not participate only to a two-wave interaction (between $1/0$ and $-1/0$ orders). When the pitch becomes larger, we can have different scenarios as, for example, interaction between $1/0$, $-1/0$, $1/0 - 1$ (three-wave interaction) and presence of the 0 order illustrated in the Fig. 4.

3. DOF optimisation based on the symmetry of the diffracted waves

3.1. DOF optimisation methods based on the position of the COG

The depth of focus can be optimised using the center of the gravity method. This method consists of optimising or symmetrizing the COG position of the diffracted orders interacting together. That

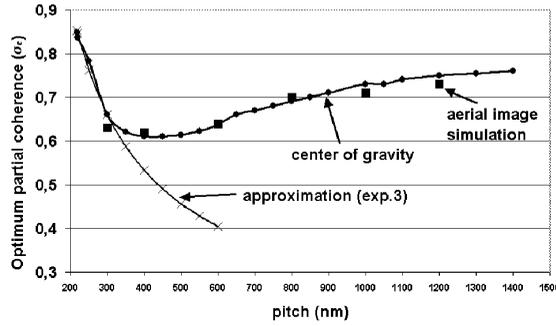


Fig. 5. Determination of the optimum σ_c through the pitch using aerial image simulation, COG and approximated (expression 3) methods for 0.63 NA and annular illumination.

means matching the COG positions with the best symmetrical COG positions, which are $\pm \lambda/(2p)$ (Fig. 4). For a given wavelength, pitch, NA and for every illumination shape, the partial coherence is optimised until matching the COG positions of the captured -1 and 1 diffracted orders to the optimum COG positions. Fig. 5 shows the optimum σ_c found using the COG method for varying pitches. It is compared with the results of a full aerial image simulation (black squares). It can be seen that the agreement between the two methods is very good over the full range of pitch. This confirms the interest of our approach which provides much faster results. Another example is given in Fig. 6 where the depth of focus for a 120/200-nm grating is shown for different NAs. In both cases a clear optimum is observed. Using the optimisation method based on symmetry, the predicted optimum σ_c (0.63 and 0.74) are in very good agreement with those (0.63 and 0.73) determined by a full aerial image simulation study with Solid C.

On the other hand, the DOF can also be optimised for annular and quadrupole illumination. In the case of quadrupole, since increasing the pole radius σ_r does not affect the position of the COG, the classical formula deduced considering coherent illumination still holds (cf. Eq. (4)). In the case of annular illumination, the shape of the interfering orders is more complicated. However, we have remarked that we can, as a rule of thumb, apply the expression (3) for dense pitches and for an annular ring fixed at 0.3. Fig. 5 confirms the validity of this approximation for dense pitches.

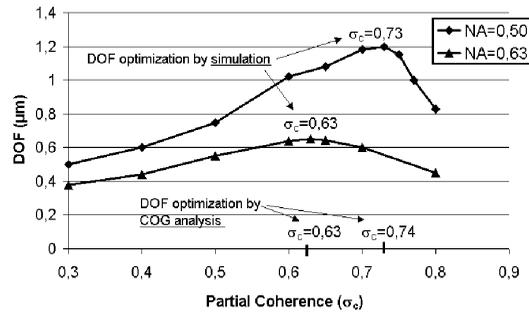


Fig. 6. Simulation results of the DOF through σ_c and NA for 320 nm pitch and 100 nm target feature for an annular illumination.

$$\sigma_c = \frac{\sigma_{in} + \sigma_{out}}{2} = \frac{\lambda}{2 \times p \times NA} + 0.15 \text{ for annular} \quad (3)$$

$$\sigma_c = \frac{\lambda}{\sqrt{2} \times p \times NA} \text{ for quadrupolar} \quad (4)$$

We can notice that today the usual σ_c is between 0.4 and 0.7. From Fig. 5, we see that for a 0.63 NA and annular illumination the optimum σ_c is obtained only in the range between 0.6 and 0.7. In the quadrupole case (0.63 NA), we verified that the range of the optimum σ_c is 0.4 and 0.7.

3.2. Impact of the diffracted waves symmetry on the DOF curve versus pitch

Fig. 7 shows the DOF variation through pitch and σ_r for a quadrupole illumination. σ_c is fixed at 0.55. We also add to this figure the simulated results of the COG positions around the peaks. As expected, we observe that the peaks correspond to the perfect symmetry between the 1 and -1 diffracted orders captured by the pupil plane and the 0 orders interacting with them. At these peaks, we have the situation that the COG positions and the best symmetry positions coincide (Fig. 4). We also see that the amplitude of the peak is larger for a more coherent illumination (for a smaller σ_r). Larger σ_r tend to destroy the perfect two waves interference effect (which theoretically leads to an infinite depth of focus).

The case of annular illumination and fixed σ_{out} is shown in Fig. 8. Here we can observe another trend. The DOF decreases when the pitch increases. This can be attributed to the evolution of the isofocal CD [12]. It becomes smaller and move away from the target CD when the pitch increases thus decreasing the depth of focus. Peaks, corresponding to the symmetry of interfering diffraction orders discussed above, are also visible.

These two causes of variation of the DOF (position of the isofocal CD and the symmetry of the diffraction orders) are also the explanation for the shape of the curves shown in Fig. 9. Here quadrupole illumination is concerned and both σ_c and σ_r vary. The decrease of DOF with increasing pitch as well as the symmetry peak previously mentioned can be observed on this graph. However, for certain illumination settings, a clear second peak can be observed. It is due to the incoming of the

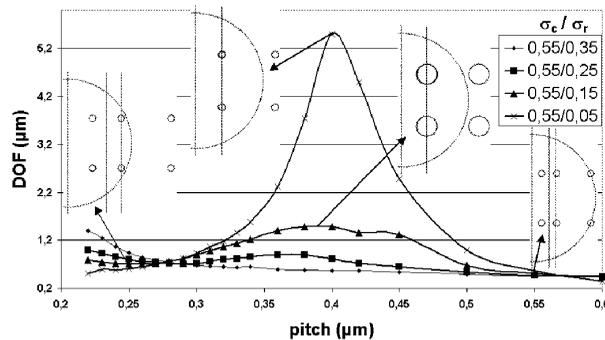


Fig. 7. DOF through pitch and σ_r for 100 nm target feature and quadrupole illumination (NA=0.63). σ_c is fixed at 0.55.

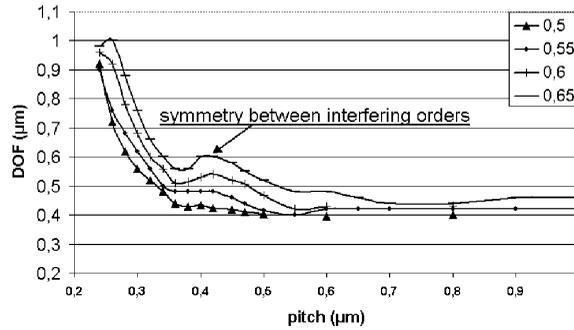


Fig. 8. DOF through pitch and σ_c for 100 nm target feature and annular illumination (NA=0.63). σ_{out} is fixed at 0.80.

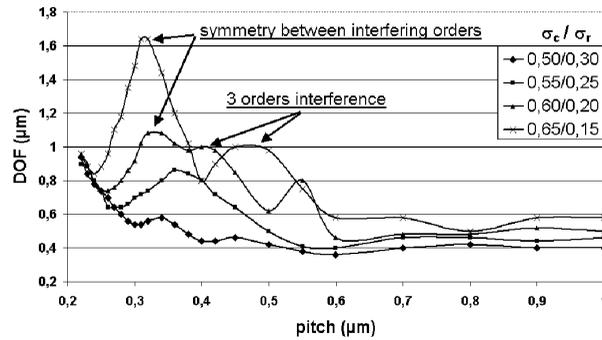


Fig. 9. DOF through pitch, σ_c and σ_r for 100 nm target feature and quadrupole illumination (NA=0.63).

third-order diffraction in the pupil leading to three waves interference that lowers the position of the isofocal CD. Again, more coherent illumination leads to sharper peaks.

4. Conclusions

In this paper, we have analysed the evolution of the depth of focus as function of the pitch. The partial coherence and the shape of the diffracted waves in the pupil plane have been confirmed to be of major importance. Our analysis is based on the position of the COG of the interfering waves that should be symmetrical. All the analytical calculations have been described. Finally, The shape of the DOF versus pitch curves has been completely explained. The influence of the position of the isofocal CD and the symmetry of the diffracted waves has been emphasized.

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