Partial Coherence: Off-Axis Imaging

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1. GOAL

The goal of this lab is to demonstrate the effects of off axis imaging. We will again modify the SMFL GCA 6700 wafer stepper with a different set of apertures to control the degree of partial coherence and evaluate image fidelity through a focus exposure matrix.

2. INTRODUCTION AND THEORY

Just as common as the use of partially coherent light in imaging, off-axis illumination (OAI) plays an important role in optical lithography. The illumination can take many different forms, such as monopole illumination, dipole illumination, quadrupole, QUASAR (QUAdropole Segmented Annular Ring), and Annular Illumination. Increasing use of customized illumination schemes designed for a particular mask pattern is evidence of this technique's popularity.

2.1 On-axis imaging

In this simple conventional case, where coherent on axis illumination is assumed for comparative purposes, illumination of a given photomask produces discrete diffraction orders. This can be seen schematically Figure 1.

![Figure 1: Coherent on-axis illumination of a grating. High term diffracted orders are not collected.](image)

Here the spatial frequency of the mask pattern results in the capture of only the 0th and ±1st diffraction orders. Increasing spatial frequency beyond the coherent resolution limit given in equation results in orders having an angular spread too high for the lens of a given NA to capture.

\[
R = \frac{0.5\lambda}{NA}
\]  

(1)

2.2 Off-axis imaging: monopole

Resolution can be increased beyond this coherent resolution limit by employing off axis monopole illumination, as seen in Figure 2. Here the shift in the angular character of the plane wave illumination results in the capture of 0th and 1st diffraction order, giving the minimum information necessary for image modulation.
2.3 Off-axis imaging: dipole
In dipole illumination, two different illumination angles are used. This allows the 0th and 1st order from each pole to be collected and imaged, resulting in a balance in intensity (i.e. more modulation). A view of diffracted orders and illumination pupil can be seen in Figure 3.

The dipole illumination scheme is optimal for features oriented perpendicular to the beams. In this case (where σ center is placed at the pupil’s edge) a resolution limit identical to incoherent illumination is possible.

\[
R = \frac{0.25 \lambda}{NA} \tag{2}
\]

Additionally, since each beam used for imaging travels the same distance through the lens, systems using this illumination technique theoretically have infinite depth of focus. For a given mask pitch, the illumination angle is determined by equation 3.

\[
\theta_{illum} = \sin^{-1}\left(\frac{0.5 \lambda}{d}\right) \tag{3}
\]

\[
NA = \frac{0.5 \lambda}{d} \tag{4}
\]

Further, the center location of each pole can be determined by equation 5.

\[
\sigma_{pole} = \frac{NA_{illum}}{NA_{obj}} \tag{5}
\]

Use on features normal to the beams (beyond coherent resolution limits) results in no diffraction orders being captured. For this reason this is not a practical illumination for many mask patterns. Annular illumination is often used, since any arbitrary pattern will have illumination normal to it.
3. PLANNED PROCEDURE

Calculate the optimal $\sigma_{\text{pole}}$ placements for the 0.8 $\mu$m and 0.6 $\mu$m pitch feature. Construct the apertures required for dipole illumination with $\sigma_{\text{rad}}$ of 0.17.

1. Obtain several bare 4" silicon wafers
2. Coat multiple wafers with photoresist on the SVG track, and measure the thickness with either the Nanospec or SpectraMap. Record the average thickness, $t_0$, for each.
3. Expose a single wafer on the GCA stepper with an exposure matrix.
   a. Using a radiometer to measure intensity, calculate exposure time for an approximate dose that will result in equal lines and spaces, which could be about twice as long the dose to clear (~110 mJ/cm$^2$). Homing the aperture blades of the field stop may assist data collection.
   b. Set the “Exposure Mode” switch under the keyboard to “Time Mode”
   c. Load the engineering test mask (ETM) and first wafer.
   d. Type: EXPO EMCR221
   e. PASS: 1
   f. Knowing that there are 81 die in a 9x9 array, choose initial and increment dose values that will center around the approximate dose to size.
      i. Begin with an exposure range from the dose to clear ($E_0$) to 3$E_0$. This will center the array on twice the dose to clear. If this is too broad, conduct a second more precise FEM.
   g. OVER: R
   h. Choose initial and incremental focus values so that the most recent best focus value, written on the console, is centered in the array. The GCA focus increments are in machine units, and there are about 50 machine units per micron. Use a focus step size of about 5 machine units.
   i. Do not run an open frame test.
   j. RETICLE BAR CODE: NONE (just hit “ENTER”)
   k. FLOOR #: enter the number of the slot where you loaded the mask.
   l. ALIGNMENT MARK PHASE (P/N/X): X
   m. After the keyboard prompts, press “RES”, wait for the laser sensor LED’s near the input boat to light up, then press “1st L” followed by “S/C”
   n. If a mistake is made, hold down the “CTRL” key and type a “C”. The screen should show a double colon. Type and “A”. This will abort the chain of commands, and you can start over at step 3d.
4. Develop the wafer on the SVG track
5. Observing the optimized lines and spaces, find the best die and determine focus and exposure window via microscope inspection. Record the dose process latitude and focus process latitude for vertical and horizontal features.
6. Take micrographs the optimized features at both orientations. Also take micrographs of features with un-optimized pitches.

Repeat for both optimized values of $\sigma_{\text{pole}}$.

4. DATA ANALYSIS

Does dipole illumination enable smaller pitches to be imaged versus on-axis illumination? Is there a tradeoff? How does feature orientation affect imaging capability? Is there a directionality bias? Explain dipole illumination’s effect on: feature orientation, exposure latitude, focus latitude, pitch range, and the smallest resolvable feature. How could the pitch range be improved while still using dipole illumination?