

Scanning spot metrology for testing of photolithographic masks

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Abstract. We investigated an optical method for characterizing submicrometer structures of photolithographic masks, enabling fast and non-destructive testing over large areas. The scanning spot metrology provides accurate information about edge locations of opaque structures on chrome masks. Algorithms for the extraction of edge locations from the detector signal are discussed and applied to the characterization of a modulated grating mask. Local fabrication errors of the order of 10 to 50 nm can be detected.

Subject terms: optical metrology; knife-edge method; submicrometer structures; photolithographic masks.

1 Introduction

Advancement in the areas of phase shift optical lithography, e-beam lithography, and x-ray lithography have enabled the realization of very fine relief structures in the nanometer to micrometer range. The ability to measure the relief parameters and the absolute position accuracy of these structures is of obvious importance, not only to determine if the desired structure has been realized but also to optimize the fabrication process. The wish list for metrology includes nondestructive testing, testing of large areas, and testing of large-aspect-ratio structures having submicrometer lateral dimensions. Current techniques for measurement are optical microscopy¹ (including conventional, confocal, and near-field techniques), scanning electron microscopy² (SEM), and scanning-force microscopy.³ None of these techniques, however, is capable of providing rapid accurate submicrometer measurements over larger areas.

Optical testing methods have been applied to address these requirements. The relevant parameters of a lithographic process, i.e., the depth and width of a gratinglike test structure, can be determined by scattering an incident laser beam at the structures and measuring the far-field intensity distribution. Previously published results have demonstrated the capability of far-field measurements to rapidly and very accurately measure large-aspect-ratio submicrometer feature over larger areas.⁴ The main drawback is that these techniques determine only the average parameters, and they are unable to determine local errors such as single-line defects.

Therefore, we investigated scanning spot metrology, which provides accurate information about edge locations of opaque structures on chrome masks. The method involves illuminating the mask with a small-spot-size focused laser beam and measuring the total transmitted power as the mask is scanned. In the following, we introduce the basic principle and discuss algorithms for extraction of edge locations from

the detector signal. Finally, the scanning spot metrology is applied to the characterization of a modulated grating mask having an average grating period of 8 μm .

2 Scanning Spot Metrology

2.1 Principle

In contrast to far-field diffraction metrology, scanning spot metrology yields information about local fabrication errors of lithographic masks. The experimental setup is shown in Fig. 1. A test structure is illuminated with a focused laser beam and the total transmitted power is measured as the mask is scanned. An integrating sphere with a large entrance aperture is used to measure the total transmitted power. If the laser spot size and the feature sizes on the mask are of comparable dimensions, the detector signal will alternate between high and low values as alternating lines and spaces are illuminated. The edge position information can then be extracted using appropriate signal processing algorithms.

Scanning spot metrology is essentially based on the concept of knife-edge scanning of a laser beam.⁵ Consider the case of a 1-D knife-edge illuminated with a focused Gaussian laser beam. The intensity distribution of the incoming beam is given by

$$I(x,y) = \frac{2P_0}{\pi w_0^2} \exp\left(-2 \frac{x^2 + y^2}{w_0^2}\right) = I_1(x)I_2(y), \quad (1)$$

where w_0 is the beam radius at $1/e^2$ and P_0 is the incident power. Note, that $I(x,y)$ is separable in x and y . Using a coordinate system where the beam is centered at the location $u = x$ and the edge is located at $u = a_0$, the total transmitted power when the mask is scanned can be written in terms of the complementary error function⁶ as

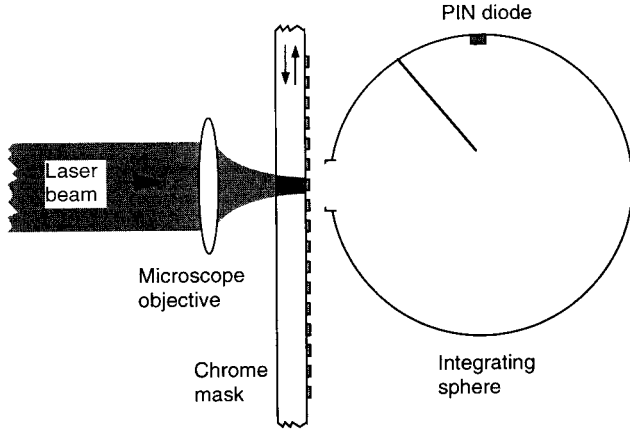


Fig. 1 Experimental arrangement of the scanning spot metrology.

$$P_T(x) = \int_{a_0}^{\infty} I_1(x) dx \int_{-\infty}^{\infty} I_2(y) dy = \frac{P_0}{2} \operatorname{erfc} \left(\frac{a_0 - x}{w_0/\sqrt{2}} \right). \quad (2)$$

Thus, when a knife-edge scan is made, the unknown quantities are, in the most general case, the incident power, the beam radius, and the edge location. They are found by iteratively fitting the experimental data to the function given in Eq. (2). Figure 2 displays experimental data for a knife-edge scan together with their best fits, which are obtained using 20 \times and 100 \times microscope objectives. Beam radii of 3.02 and 1.08 μm , respectively, are obtained. Smaller illumination spots can be obtained by optimizing the incident beam diameter with respect to the aperture of the microscope objective.

Applying the same concept but replacing the knife edge by an amplitude grating consisting of a series of opaque and transparent zones, the transmitted power can directly be expressed by

$$P_T(x) = \frac{P_0}{2} \sum_{i=0}^N \left[\operatorname{erfc} \left(\frac{a_i - x}{w_0/\sqrt{2}} \right) - \operatorname{erfc} \left(\frac{b_i - x}{w_0/\sqrt{2}} \right) \right], \quad (3)$$

where a_i and b_i are the edge locations of the grating mask. Whereas the knife-edge technique is mainly used to determine beam profiles, the grating-edge technique enables measuring the location of the edges of the grating.

2.2 Edge Extraction Algorithm

The ability to extract edge information from $P_T(x)$ in the case of multiple edges greatly depends on the ratio of the beam radius w_0 and the feature sizes s on the mask. Figure 3 shows the contrast of the function $P_T(x)$ as a function of the ratio s/w_0 for a grating with 50% duty cycle. For the example of a beam radius of 1 μm (Fig. 2, 100 \times objective), submicrometer structures with feature sizes down to 0.5 μm could be characterized.

For modulated grating structures, the local maximum and minimum values of $P_T(x)$ are no longer constant and change as the linewidth or space width varies, according to the contrast function in Fig. 3. The information on the edge position can be obtained by determining the local maximum and min-

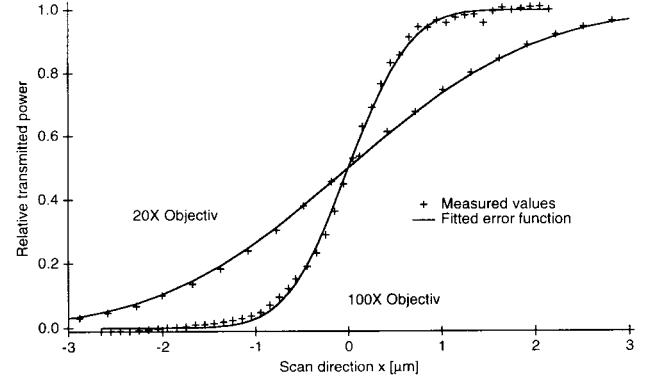


Fig. 2 Measured intensity while scanning a knife edge through the focus of two different laser spots generated by 20 \times and 100 \times microscope objectives.

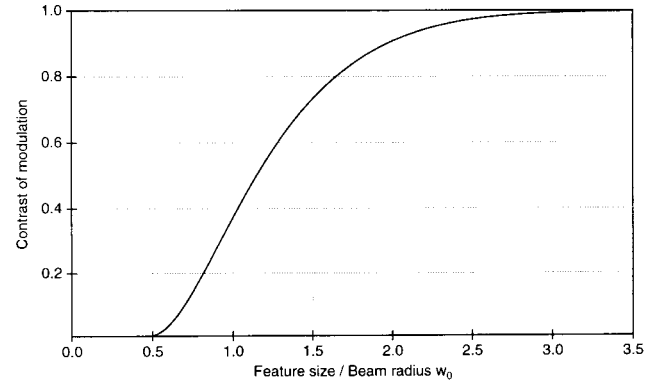


Fig. 3 Contrast of modulation versus the linewidth-to-beam-radius ratio.

imum of the measured transmission function. The accuracy of the edge position detection, however, is then limited directly by the accuracy of the translation stage used to scan the mask. The metrology issue, therefore, is to determine the linewidth and space widths of each line/space pair by fitting, as in the case of knife-edge metrology, the theoretical total transmitted power function, given by Eq. (3), to the measured values. In the ideal case, an optimization over all parameters would be done. The parameters to be determined include the incident power P_0 , the beam radius w_0 , and all edge locations (a_i, b_i).

To obtain a good initial guess of the incident power, the data are normalized to have a mean value of 0.5, corresponding to the average fill factor of the modulated grating structure. The initial guess of the edge locations of the mask are the positions for which the normalized transmission is 0.5. The start-up value of the beam radius is determined using the knife-edge technique at the first edge of the grating structure. In any multiparameter optimization problem the computer time required rapidly increases as the dimension of the parameter space is increased. Consideration of all edges simultaneously may not be necessary, however, because the response $P_T(x)$ primarily depends on a few neighboring edges. The edge extraction algorithm is therefore limited to local optimizations of a maximum of only two parameters at the time. During optimization, not only are the edge locations varied, but the estimates of the beam radius and the total incident power are also readapted. Because the initial guesses

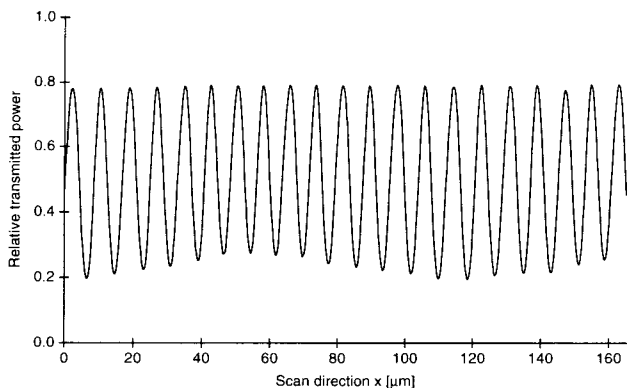


Fig. 4 Measured relative transmitted power as a function of the illuminated location on the mask.

of the parameters are quite good, the optimization algorithm converges rapidly and good repeatability of the edge location algorithm is obtained.

2.3 Results

The scanning spot metrology technique was experimentally applied to a modulated grating structure on a normal reflectivity chrome mask. The grating consists of a series of opaque and transparent zones with average period of $8 \mu\text{m}$ and lateral modulations up to 500 nm . Light from a HeNe laser was focused on the structure using a $20\times$ microscope objective. The light was linearly polarized (TE), however no polarization effects are expected in the presented measurement technique. Figure 4 shows the measured and normalized transmitted power $P_T(x)$, obtained when the mask is scanned on a high-precision translation stage with 25-nm step resolution.

Note that the maximum intensity remains almost constant, indicating that the space widths are hardly varying, whereas the minimum levels change because of variation of the linewidth, which corresponds exactly to the used encoding technique of the grating structure.⁷ Applying the edge extraction algorithm, the linewidth and space width can be determined. Figure 5 shows the linewidth extracted from the transmitted power measurements compared with the theoretical data as used to generate the mask. Local fabrication errors between 10 and 50 nm can be easily detected. The origins are deviation errors of the e-beam during writing, but also the result of a difference between the grid of the e-beam writer and of the theoretical data. The errors are measured within one scan field of the e-beam writer, therefore no stitching errors are observed.

3 Conclusions

We introduced scanning spot metrology of lithographic masks that enables a fast estimation of local errors over large scanning areas. Algorithms for the extraction of edge locations from the detector signal were discussed and applied to the characterization of a modulated grating mask with a typical structure size of $4 \mu\text{m}$. Local fabrication errors of the order of 10 to 50 nm were detected. With an illumination beam focused down to $1 \mu\text{m}$ spot size, submicrometer structures can also be tested. The limited depth of focus, however, will then require an autofocus system to control the spot diameter.

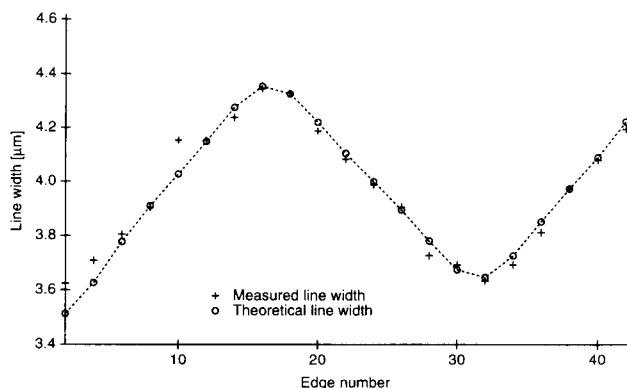


Fig. 5 Linewidth for each edge number.

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Hans Peter Herzog: Biography and photograph appear with the paper "High-carrier-frequency fan-out gratings fabricated by total internal reflection holographic lithography" in this issue.



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