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Diffractive structures for testing nano-meter technology

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We investigated two optical methods for characterizing submicron structures. Average errors of a few nanometers can be determined by the far-field diffraction metrology utilizing diffractive structures having enhanced sensitivity to fabrication errors. The scanning spot metrology is well suited for analyzing lithographic 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 nm-µm regime. The ability to measure the relief parameters and 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 non-destructive testing, testing of large areas, and testing of large aspect ratio structures having sub-µm lateral dimensions. Current techniques for measurement are optical microscopy (including conventional, confocal and near-field techniques)[1], scanning electron microscopy[2] (SEM), and scanning probe microscopy[3] (SPM). None of these techniques, however, is capable of providing rapid accurate sub-µm measurements over larger areas.

To address these requirements, we investigated the use of far-field diffraction metrology utilizing diffractive structures having enhanced sensitivity to fabrication errors in linewidth and etch depth. An important point to note here is that this technique determines the average error, and is unable to determine local errors such as single line defects.

Secondly, we introduce scanning spot metrology of chrome masks which involves illuminating the mask with a small spot size focused laser beam and measuring the total transmitted power as the mask is scanned. Algorithms for extraction of edge locations from the detector signal are discussed, and applied to the characterization of a modulated grating mask.

2. FAR - FIELD DIFFRACTION METROLOGY

A fabrication technology can be best characterized, if specific structures with sensitive and easy-to-measure properties are realized. Grating structures provide ideal test elements for far-field diffraction metrology, since they split an illuminating laser beam into a discrete array of diffraction orders. Gratings with small periodicities p in the order of the optical wavelength λ produce only a very limited number n of propagating diffraction orders ($n < p/\lambda$). If the grating period becomes smaller than the read-out wavelength, only the zero order will be generated and can be used for the characterization. For regular gratings, the intensity distribution in the far-field depends strongly on the relief shape, the illumination angle and the wavelength.

The basic principle of far-field metrology is to measure the intensity distribution of the diffraction orders as a function of the incidence angle or the wavelength and then, to determine the relief shape and depth by numerical modelization. Previous published results have demonstrated the capability of this technique to rapidly and very accurately measure large aspect ratio sub-µm feature over larger areas[5,6]. Problems with this technique arise, if the lateral position accuracy of the lithographic process has to be determined. In the case of a regular grating, position errors produce a continuous blur of the diffraction orders, which is difficult to measure. For this task, we have investigated modulated grating structures. Position sensitive elements are obtained by designing pulse-position modulated gratings which generate a well defined intensity function[4] in the first diffraction order of the carrier grating. An appropriate measurement signal is obtained by encoding a fan-out function[5] which produces a discrete set of equally intense light spots in the first order. Positioning errors affect directly the fan-out function and therefore, introduce uniformity errors in the far-field. The average position error within the illuminated field is determined by adding a statistical Gaussian distributed position error to the ideal modulated grating structure and calculating the corresponding uniformity error in the far-field that matches the uniformity measurement.

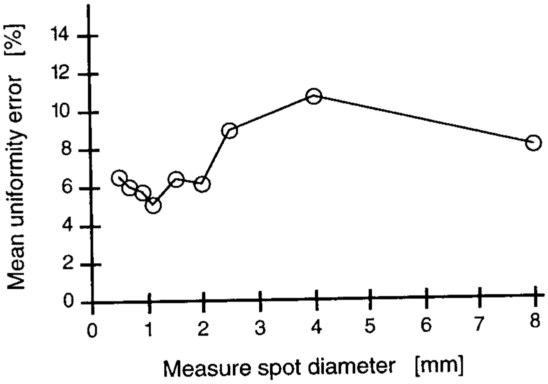

Fig. 1. Measured uniformity error in function of the beam diameter.

Experimental results have been obtained by characterizing a high resolution e-beam written mask with a carrier grating period equal to 1 µm. The modulation of the 9 beam fan-out function has a period equal to 125 µm and introduces locally position modulation up to 50 nm. We have measured the uniformity error as a function of the illumination diameter (see Fig. 1). For small beam diameters, the uniformity error decreases and reaches a minimum of 5% for a diameter equal to 1 mm. This minimum value corresponds to the case, when one scan field of the e-beam writer is illuminated. The decrease of the uniformity error with the beam diameter can be explained by the fact that the statistical errors are better averaged out.

The remaining 5 % uniformity error is essentially due to systematic errors inside one scan field. The simulation has shown that the 5 % error corresponds to a mean lateral position error equal to 50 nm inside one scan field. For larger beam diameters, the uniformity error increases. In this case, more than one scan field are illuminated and larger stitching errors between the scan fields change the statistics. As a consequence, stitching errors in the order of 100 nm have been determined. If a sufficient number of scan fields is illuminated, the stitching errors are also averaged out and again a low uniformity error equal to 8 % is reached. A more accurate characterization of the systematic errors inside one scan-field is possible, if not only the intensity but also the relative phase of the fan-out beams is measured.

3. SCANNING SPOT METROLOGY

In contrast to the far-field diffraction metrology, the scanning spot metrology yields information about local fabrication errors of lithographic masks. The experimental setup involves illuminating the structure with a small spot size laser beam and measuring the total transmitted power as the mask is scanned. If the laser spot size and the minimum feature size 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 appropriated signal processing algorithms.

The scanning spot metrology is essentially based on the concept of knife edge scanning of a laser beam[6]. Consider the case of a one-dimensional knife-edge illuminated with a focused Gaussian laser beam. 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 as the mask is scanned, can be written in terms of the complementary error function[7]

$$P_T(x) = \frac{P_0}{2}\,\mathrm{erfc}\left(\frac{a_0 - x}{w_0/\sqrt{2}}\right), \qquad (1)$$

where w_0 is the beam radius at $1/e^2$, and P_0 is the incident power. 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. (1). Figure 2 displays experimental data obtained using 20X and 100X microscope objectives together with their best fits. A beam radius of 1.08 µm and 3.02 µm is respectively obtained.

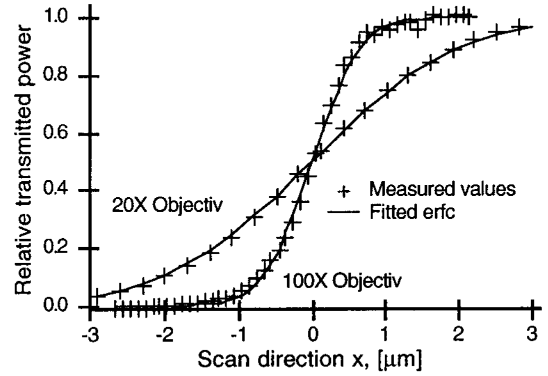

Fig. 2. Measured intensity while scanning a knife edge through the focus of two different laser spots.

Applying the concept of knife-edge scanning to a grating mask, which consists of several opaque and transparent zones, the transmitted power can directly be expressed by

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

where a_i and b_i are the edge locations of the grating mask. As before, estimates of the incident power, the beam radius, and the edge location can be obtained, in principal, by fitting the above function to the experimental transmitted power data.

The ability to extract edge informations from $P_T(x)$ in the case of multiple edges greatly depends on the relationship of the beam radius w_0 to the minimum feature size of the mask being examined. This is illustrated in Fig. 3 which shows the contrast of the function $P_T(x)$ as the period to beam radius ratio is varied for an equal line/space grating illuminated with a Gaussian laser beam.

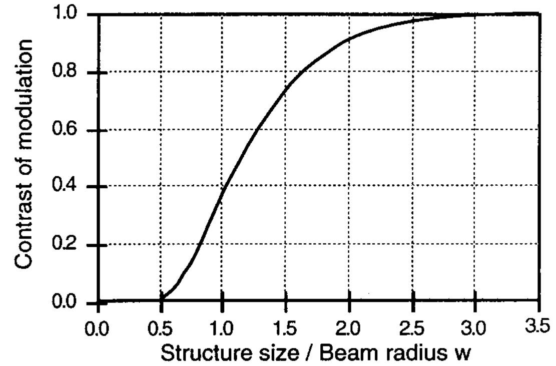

Fig. 3. Contrast of modulation versus the period to beam radius ratio.

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. The metrology issue, therefore, is to accurately and precisely determine the linewidth and space widths of each line/space pair.

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 the edge locations (a_i, b_i). In any multi-parameter optimization problem the computer time required rapidly increases as the dimension of the parameter space is increased. However, consideration of all edges simultaneously may not be necessary, since the response $P_T(x)$ primarily depends on a few neighbor edges. We have therefore decided to limit the edge extraction algorithm to only contain local optimizations, which also results in increased computational efficiency.

To obtain a good initial guess of the edge locations, the data were normalized to have a mean value of 0.5, corresponding to an average fill factor of the modulated grating structure. The initial guess of the edge locations of the mask are then obtained from the intersection of the normalized measurements with a line drawn at the 0.5 level. Initial guess of the beam radius and total incident power are made using knife edge technique at the first edge of the grating structure.

The scanning spot metrology technique was experimentally applied to a modulated grating structure on a chrome mask. The carrier grating has a period of 8 μm and modulations up to 500 nm. Light from a He-Ne laser was focused on the structure using a microscope 20X objective. Figure 4 shows the measured normalized transmitted power $P_T(x)$ obtained as the mask was scanned on a high precision translation stage.

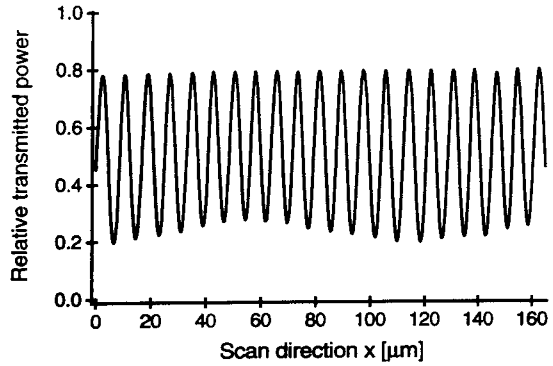

Fig. 4. Measured relative transmitted power as function of the illuminated location on the mask.

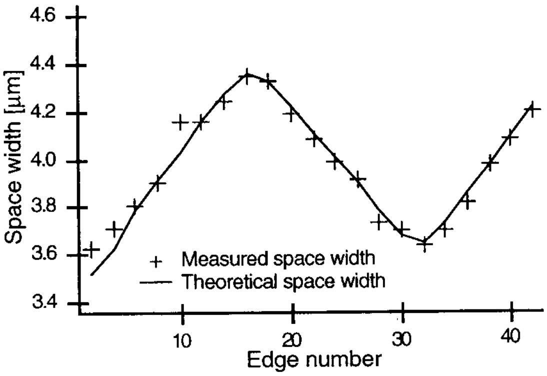

Fig. 5. Space width for each edge number.

Note that the maximum intensity remains almost constant, indicating that the space widths are hardly varying while the minima levels change due to variations in linewidth, which corresponds exactly to the encoding technique of the grating structure. Applying the edge extraction algorithm, the linewidth and space width can be determined.

Figure 5 shows the space width extracted from the transmitted power measurements along with theoretical data used to generate the mask. Local fabrication errors between 10 nm - 50 nm can be easily detected.

4. CONCLUSIONS

The ability to measure the relief parameters and absolute position accuracy of very fine relief structures in the nm-μm regime is of importance in modern micro-engineering. The wish list for metrology includes non-destructive testing, testing of large areas, and testing of large aspect ratio structures having sub-μm lateral dimensions.

To address these requirements, we investigated the use of far-field diffraction metrology utilizing diffractive structures having enhanced sensitivity to fabrication errors in linewidth and etch depth. Average fabrication errors of opaque and transparent structures in the order of a few nanometers can be determined.

Furthermore, we have introduced scanning spot metrology of lithographic masks. Algorithms for extraction of edge locations from the detector signal are discussed. In contrast to the far-field diffraction metrology, this methods yields information about local errors.

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