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Characterization of Photoresist Using Speckle Fields
- A Theoretical Investigation -

Thomas Meinecke*, Damien P. Kelly**, Stefan Sinzinger*

** Fachgebiet Technische Optik, Technische Universität Ilmenau*
*** Fachgebiet Optik-Design, Technische Universität Ilmenau*

mailto:thomas.meinecke@tu-ilmenau.de

Gray scale lithography consists of numerous sophisticated fabrication steps making it necessary to characterize the process of substrate structuring. We expose the photoresist with random intensity, i.e. speckle fields instead of conventional specific test patterns and observe their behavior in Fourier plane caused by coherent illumination of this processed substrate.

1 Introduction

In order to reliably fabricate structures using a lithographic process, it is essential to properly characterize the photoresist material that is used. Generally this is done by carefully fabricating test structures and using these to illuminate the photoresist with a specific pattern. Here we wish to use a different type of patterned illumination - a speckle field. There appear to be several advantages to this approach, (i) a speckle field is easy to generate using a coherent light source and a diffuser, (ii) the complex amplitude of the resulting light field obeys well known statistical distributions. The scattered light representing a speckle field distribution with intensity I_{Sp} impinges on the substrate coated by photoresist. This photoresist is sensitive to the exposure E_{Sp}:

$$E_{Sp} = I_{Sp} \times T_{Exp}\,, \qquad (1)$$

where T_{Exp} is the exposure time. For initial observations we assume linear photoresist with a thickness of some wavelengths, see Eq. 1. In the following numerical analysis, we have carefully chosen our sampling rate such that the spatial variations in the output speckle field are adequately sampled, i.e. the average speckle size is chosen to 8/π of pixel size [1].

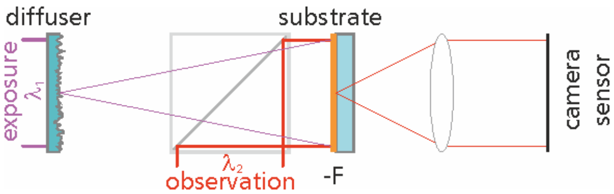

Fig. 1 *Experimental setup and process steps.*

2 Modeling of the Lithographic Process

Material changes in the photoresist structure at a specific location are assumed to depend on the amount of light energy incident on the photoresist at that point, i.e. the height distribution of the substrate is determined by the exposure. The amount of energy deposited is assumed to be linearly related to the intensity of the incident illumination. The intensity distribution of the illumination follows a negative exponential probability density function $PDF(I_{Sp})$ (with the mean value of $\langle I_{Sp} \rangle$ [2])

$$PDF(I_{Sp}) = \frac{1}{\langle I_{Sp} \rangle} \exp\left(- \frac{I_{Sp}}{\langle I_{Sp} \rangle} \right), \qquad (2)$$

whose statistics are transferred into the exposure E_{Sp} and ultimately in the height distribution d. When this substrate is then illuminated with a probing coherent plane wave, see wavelength λ_2 in Fig. 1, the phase distribution is given by the following expression:

$$d \propto E_{Sp}^{(1)};\ \varphi = 2\pi \,\mathrm{mod}\left(d/\lambda, \lambda \right). \qquad (3)$$

We note that the phase φ is wrapped. We examine the statistical properties of the scattered wave field by recording its Fourier plane distribution with a CCD array, see Fig. 1. In order to compare the effects of different exposure times on the statistical properties of the scattered field, the intensities from different exposure times are normalized to their total power.

3 Results

First we consider the influence of exposure to phase of complex structure function in object, i.e. substrate plane (see Fig. 2).

Low exposures imply that only parts of the photoresist microstructure are significantly changed due to the statistical nature of the illuminating intensity. This produces a high DC (unscattered) part and minor scattered part.

For long exposures there are two dominant effects: (i) Uniformly random distributed phase is imparted to a probing plane wave, (ii) the auto-correlation of the phase function was found to narrow as the exposure time increases. This is attributed to the phase wrapping effect described by Eq. 3. This effect can be seen in Fig. 2.

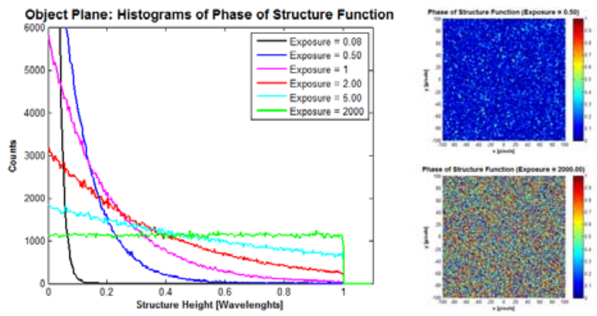

Fig. 2 *Histograms of phase distribution of complex structure function at various exposures (left) and examples of 100x100 pixel central subsections of corresponding distributions (top right: low exposure of 0.5 – bottom right: high exposure of 2000) in the object plane.*

The phase function in object (structure) plane influences the scattered field in Fourier plane as follows:

Generally the intensity statistics obey a negative exponential distribution defined by a mean parameter (see Eq. 2) remaining constant due to the normalization of the total power (see Fig. 3 left).

The phase statistics of the structure function influence the corresponding characteristics of intensity statistics: A smaller decay of the phase PDF in object plane leads a broader spread of actual intensity fluctuations tending to uniform intensity distribution (see Fig. 3 right).

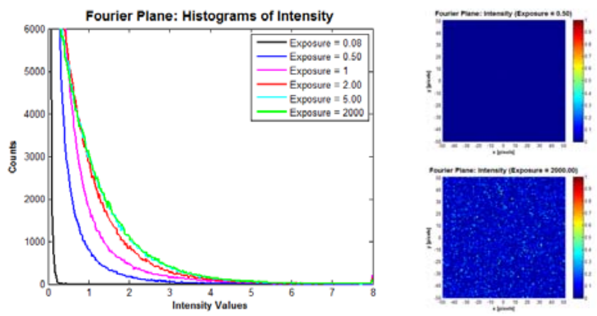

Fig. 3 *Intensity histograms (left) driven by various exposures and examples of 50x50 pixel central subsection (top right: low exposure of 0.5 – bottom right: high exposure of 2000) in Fourier plane.*

The DC bias is effected by the phase distribution in object plane: A more uniform phase PDF lowers the DC intensity, scattering the light more effectively. After an exposure time of 5, the DC content in the scattered signal is approximately 2.63%, see diagram in Fig. 4. This confirms the common habit of using diffuser plates with a roughness of some wavelengths for the generation of fully developed speckle fields in lab setups.

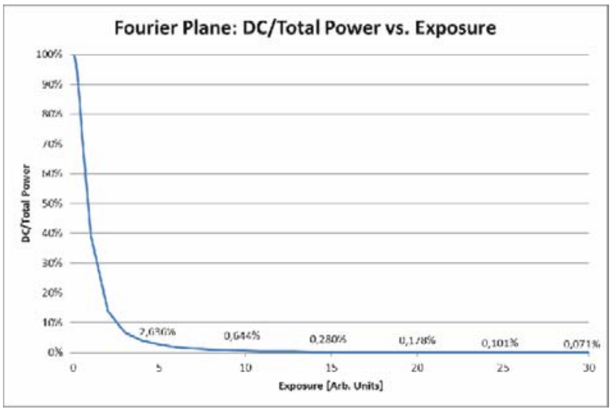

Fig. 4 *The relationship of DC intensity to total power in Fourier plane. This DC bias can be modified effectively within a small range of substrate depth height up to closely 5 wavelengths.*

4 Conclusions

In summary by varying the speckle exposure on photoresist either a high power concentration or nearly a uniform lower distribution can be adjusted [3]. Conversely the exposure can be retrieved by observing the DC/Total Power ratio.

References

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