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Binary Pseudo-Random Gratings and Arrays for Calibration of Modulation Transfer Function of Surface Profilometers

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1. Introduction

Development and application of state-of-the-art x-ray optics with sub-Angstrom rms roughness and sub-microradian slope variation requires adequate development of surface profilometers and measurement methods [1,2]. The standard list of output parameters of a profilometer measurement that includes values of roughness (residual slope) averaged over an area and along a sample line does not provide a sufficient description of the surface that can be used for local finish polishing or for evaluation of performance of the optic in a particular application. Moreover, the measured surface height (slope) distributions are affected by the unknown instrumental response function, also known as the Point-Spread Function (PSF) [3] that is convolved with the ideal surface profile inherent for the surface under test (SUT). The PSF contains contributions from the instrument's optical system, detector, signal processing, software algorithm, and environmental factors [3]. Generally, these contributions are difficult to account for separately. Additional complication of finding the instrumental response function and corresponding correction of the measurement result arises due to the convolution operation.

In many applications, rigorous information about the expected performance of the optic can be obtained from a statistical description of the surface topography based on power spectral density (PSD) distributions of the surface height and slope (see e.g., Refs. 4-7 and references therein). For example, the measured PSD distributions provide a closed set of data necessary for three-dimensional calculations of scattering of light by the optical surfaces [8-10].

Of course, the instrumental PSF still causes distortion of the surface PSD distribution obtained via a straightforward transformation of the measured distribution of the residual surface heights. The distortion of the surface PSD distribution can be modeled with the modulation transfer function (MTF), which is defined over the spatial frequency bandwidth of the instrument [3,4]. In this case, the measured PSD distribution can be presented as a product of the squared MTF and the ideal PSD distribution inherent for the SUT. Therefore, the instrumental MTF can be evaluated by comparing a measured PSD distribution of a known test surface with the corresponding ideal numerically simulated PSD. The square root of the ratio of the measured and simulated PSD distributions gives the MTF of the instrument.

In recent work [11,12], the high efficiency of use of a binary pseudo-random grating (BPRG) as a standard one dimensional (1D) test surface for measurement of the MTF of a MicromapTM-570 interferometric microscope has been experimentally demonstrated. For an 'ideal' microscope with an MTF function independent of spatial frequency out to the Nyquist frequency of the detector array, with zero response at higher spatial frequencies, a BPR grating would produce a flat 1D PSD spectrum, independent of spatial frequency. For a 'real' instrument, the MTF is found as the square root of the ratio of the PSD spectrum measured with the BPR grating to the 'ideal,' spatial-frequency-independent, PSD spectrum.

In the present work, we describe application of binary pseudo-random gratings (BPRG) and arrays (BPRA) as effective 1D and 2D test surfaces suitable for calibration of different surface profilometers, including a number of interferometric microscopes and scatterometers.

2. Binary Pseudo-Random Arrays

BPRA structures are described with uniformly redundant arrays (URA) [13], possessing both high throughput (50%) and a flat 2D power density spectrum (when sampled below the Nyquist frequency).

Figure 1 presents a Scanning Electron Microscope (SEM) micrograph of a part of a binary pseudo-random array with the lateral size of an elementary feature of 200 nm and height of the structure of about 120 nm. The BPRAs were fabricated by using nanolithography facility available at the Center for X-Ray Optics of the Materials Science Division, LBNL [14].

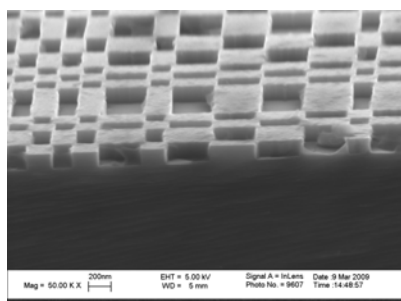


Figure 1: SEM micrograph of a part of a binary pseudo-random array with the lateral size of an elementary feature of 200 nm and the height of about 120 nm. Notice the near 90 degree sidewall slope and the squareness of the tops of the peaks. These features are in line with what is considered, for our purposes, an ideal array.

3. Micromap™-570 measurements

The developed BPRAs samples were used to calibrate the MTF of the Micromap™-570 and ZYGO-7300 interferometric microscopes. Figure 2 illustrates the effectiveness of the calibration.

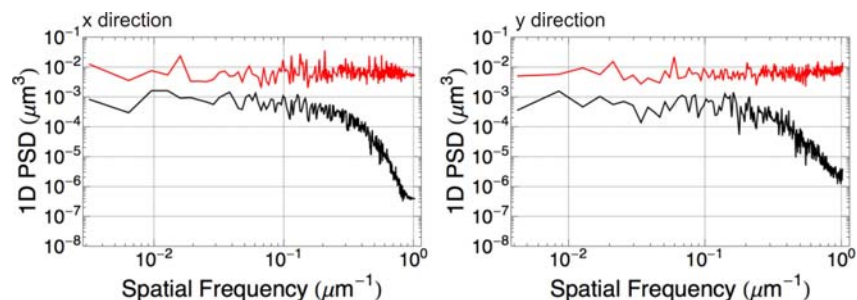


Figure 2: 1D PSD measurements along the x and y directions of the BPRAs with 200 nm elementary step (black lines) along with PSD's obtained after applying experimentally determined MTF correction (red lines). Measurements were made with 20× objective.

4. Scatterometer measurements

Measurements of the Bidirectional Scatter Distribution Function (BSDF) [9] were made with a CASI™ scatterometer [15] with a 488 nm wavelength source on a wafer with BPRAs patterns etched with 200 nm, 400 nm, and 600 nm minimum feature size. The source angle of incidence was at a near-normal angle of 5°. The measurements were made with the sample oriented so that one axis of the grid pattern was in the plane of incidence with the detector angle scanned between ±90° relative to the surface normal. The BSDF curves for all three patterns are shown on the left in Fig. 3. The two peaks in the wings of the scatter curves are from the first order diffraction from the 600 nm elementary size for the 488 nm illumination wavelength. The 1D PSD curves on the right in Fig. 3 are the result of reduction of the 2D PSD distributions computed from the BSDF curves. The PSDs from the negative angles are folded over into the positive frequency domain so that both curves are plotted on the same positive frequency axis. The PSD curves are essentially flat over most of the spatial frequency range, indicating that this BPRAs does indeed perform as a white noise surface.

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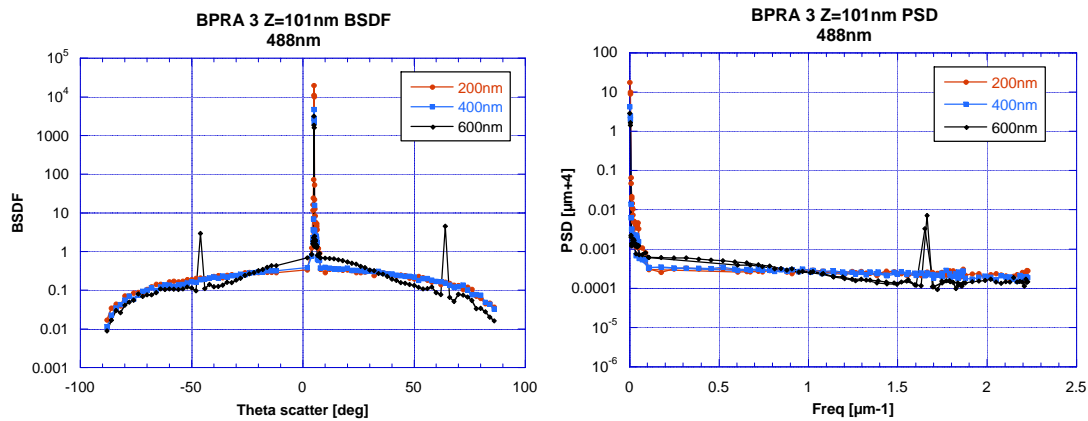


Figure 3: (left) Scatterometer BSDL measurements on each of the three patterns at a 488 nm illumination wavelength. First order diffraction from the 600 nm pattern feature size is evident in the corresponding curve. (right) Reduced 2D PSD curves computed from the BSDL for the three patterns. The nearly-horizontal lines indicate the white-noise nature of the BPRA.

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