Photomask metrology using a 193 nm scatterfield microscope

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ABSTRACT

The current photomask linewidth Standard Reference Material (SRM) supplied by the National Institute of Standards and Technology (NIST), SRM 2059, is the fifth generation of such standards for mask metrology. The calibration of this mask has been usually done using an in house NIST ultra-violet transmission microscope and an Atomic Force Microscope (AFM). Recently, a new optical reflection scatterfield microscope has been developed at NIST for wafer inspection, Critical Dimension (CD) and overlay metrology purposes.

Scatterfield microscopy relies on illumination engineering at a sufficiently large Conjugate Back Focal Plane (CBFP) of the microscope.[1] Our new scatterfield reflection microscope uses 193 nm excimer laser light as well as sophisticated configurations to allow measurement of both the image plane and the Fourier plane using full-field and angle-resolved illumination. By reducing the wavelength compared to many current metrology tools that work in the visible light and near ultra-violet range, we have made substantial improvements in image resolution[2] and commensurate gains in sensitivity to geometrical parameters.

We present a preliminary study on the use of this new microscope to calibrate and measure features of this SRM photomask. The 193 nm scatterfield microscope is used in full-field mode with a NA range from 0.12 to 0.74 using our scatterfield imaging method. Experimental results obtained on isolated lines for different polarization states of the illumination are presented and discussed. Pitch measurements are compared to the measurements done on our NIST Ultra-Violet (UV) transmission microscope.

Keywords: Photomask metrology, isolated line metrology, 193 nm wavelength, scatterfield microscopy .

1. INTRODUCTION

Optical dimensional metrology benefits are well known (*i.e.* high throughput, non-destructive imaging, *etc.*). Its disadvantages are generally thought to be limited resolution, nonlinearity at small feature sizes, and proximity effects. These limitations however, can be mitigated through proper instrument and measurement process modeling. While conventional optical image resolution is limited by the available wavelength, measurement resolution is extensible with the use of modeling.

From a metrological point of view it is better to calibrate an artifact in the conditions where it is used; in transmission mode at 193 nm wavelength for a contemporary lithography photomask. Our UV transmission optical microscope has many similarities to traditional wafer exposure techniques used in lithographic stepper as well as our new 193 nm scatterfield reflection microscope (working at the wavelength used in steppers).

Typically, optical mask metrology and wafer exposure differ only in tool parameters such as magnification, wavelength, numerical aperture (NA) and the coherence parameter. The relevant mask parameters such as chrome thickness, chrome complex index of refraction n and k, and substrate thickness are identical. These facts give optical photomask metrology an inherent advantage over other techniques since the same medium, light, is used in the measurement process as well as the lithography process.

Mask lithography inspection and characterization is a crucial step in lithography. NIST provides a Standard Reference Material binary mask printed in antireflecting chrome on quartz substrate (see fig: 3). It contains certified isolated linewidths and spacewidths (or trenches) from nominal 0.25 μm to 32 μm and pitches from

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0.5 μm to 250 μm, all traceable to the definition of the meter. These features have been calibrated previously on the NIST UV transmission microscope at a wavelength of 365 nm.[3]

A new 193 nm optical reflection scatterfield microscope has been developed at NIST for wafer inspection, Critical Dimension (CD) and overlay metrology purposes. By reducing the wavelength we expect to improve the resolution on linewidth measurements.[2] The goal of this preliminary study is to evaluate the possibility in measuring and calibrating future SRM mask using this new microscope.

We will first present our new 193 nm scatterfield microscope, then our first results on full-field Fourier imaging for optical indexes measurements. Measurements on linescale target to determined pitch measurements have been conducted. Finally, isolated linewidth and spacewitdh measurements are presented and discussed.

2. 193 NM SCATTERFIELD MICROSCOPE

Figure 1 shows a schematic of the 193 nm scatterfield microscope. Its set up enables simultaneous measurement of the Fourier plane and a high magnification imaging plane for two different illumination modes: full-field and optical fiber scanning. The light source is a multimode pulsed excimer laser at 193 nm wavelength. The laser beam is shaped to a circular beam using a 2 mm diameter aperture before diffusing at the source plane through a customized rotating Deep Ultra-Violet diffuser to homogenize the beam and reduce the speckle (spatial coherency of the laser beam). The source image at the diffuser is imaged onto the CBFP and relays to the Back Focal Plane (BFP) of a catadioptric objective lens through a series of lens groups, while a conventional field stop is imaged onto the sample plane.

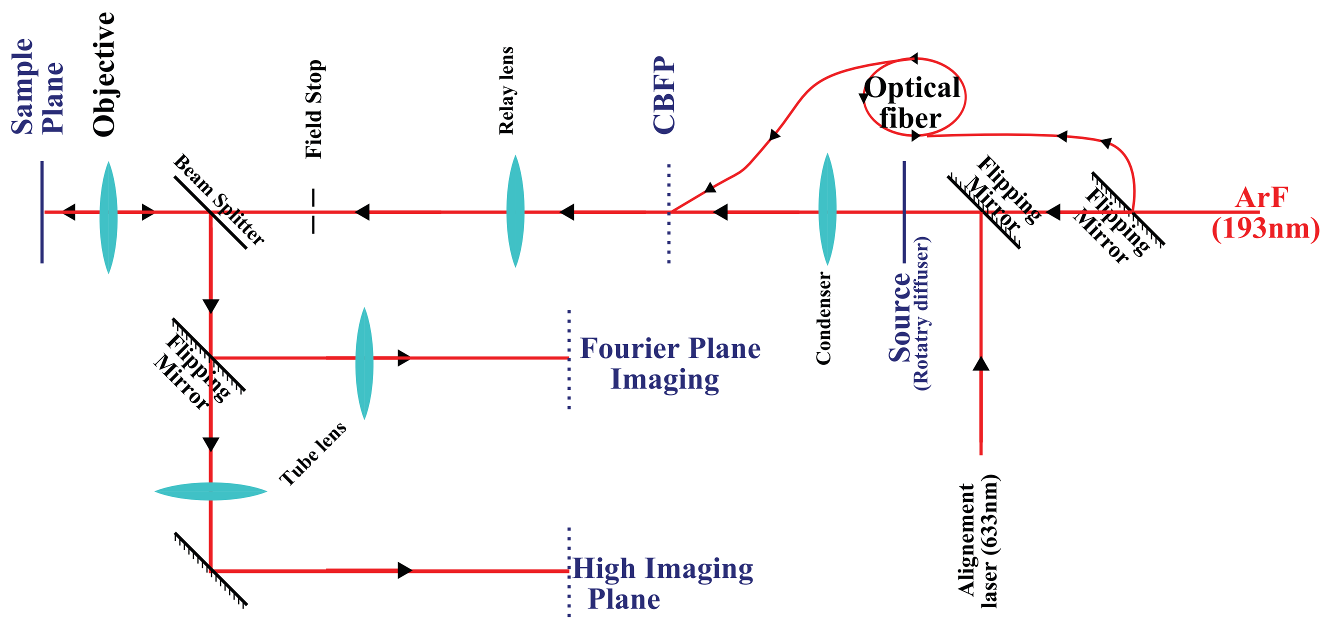


Figure 1. Schematic diagram of the 193 dark-field scatterfield microscope.

The CBFP is uniquely designed to be telecentric so that the optical axis of the optical fiber system coincides with the chief optical rays while being scanned.[2]

The illumination beam at the sample plane has a defined NA from 0.12 to 0.74 ($\approx 6^\circ$ to $\approx 48^\circ$), limited by the catadioptric infinity-corrected objective lens. A pellicle beam splitter splits off the collected light from the objective to one of two Charge-Coupled Device (CCD) sensors. A flipping mirror in the collection path after this beam splitter allows the reflected beam from the sample to be directed either towards a Fourier imaging plane or a high magnification imaging CCD.

The CBFP has a module which can operate in two different modes: full field and angular scanning. The full-field mode can be setup with several apertures to control the illumination intensity distribution. The angular scanning mode has a fiber illuminator configuration to improve the angular and intensity illumination homogeneity as compared to aperture scanning the CBFP.[2]
The scatterfield microscope can be arranged in many different configurations for measurement in the Fourier plane, yielding combinations of the Jones reflection matrix components. By scanning the CBFP with an aperture, the reflected intensity of the specular and the intensity of the higher diffraction orders can be measured as function of the incident angles and polarization noted by $I^{\Phi}_{P,A}(\theta)$. P and A are respectively the angle of the polarizer and the angle of the analyzer respectively as referenced to the main coordinates (x, y). Φ is the scanning direction angle.
Reflected intensity on the primary axes Ox' and Oy' of the Fourier plane corresponds to the reflected diagonal components of the Jones matrix: R_p and R_s; at other locations in the Fourier plane have a mix of both polarizations. In the microscope, the polarization is fixed using a cartesian coordinate system $(\vec{x}, \vec{y})$ although the Jones basis $(\vec{p}, \vec{s})$ is local and depends on the wave vector $(\vec{p} \wedge \vec{s} = \vec{k}/|\vec{k}|)$.

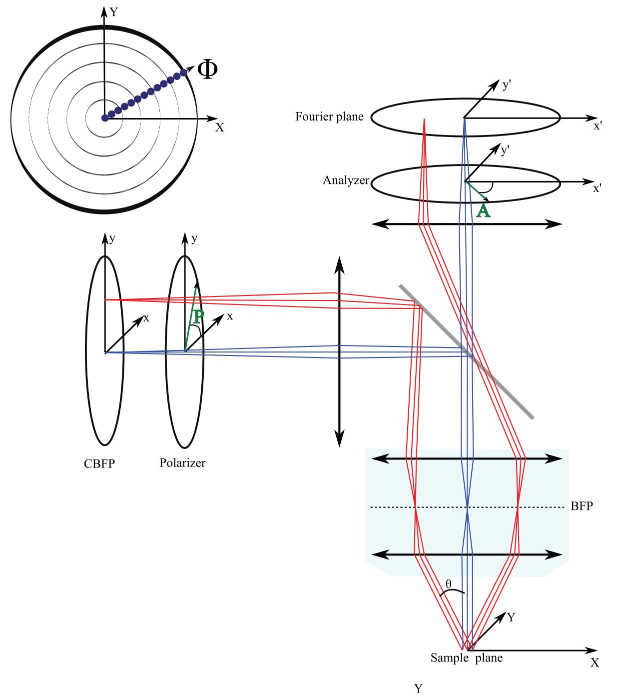


Figure 2. Schematic of the 193 nm scatterfield microscope in angle resolved scanning mode.

3. MEASURAND DEFINITION OF THE PHOTOLITHOGRAPHY MASK

NIST provides **S**tandard **R**eference **M**aterial (SRM) for photolithography mask metrology as well as for line scale microscope calibration. Both of SRM 2056 photmask standard and SRM 2800 linescale are succinctly described in figure 3 and 4.

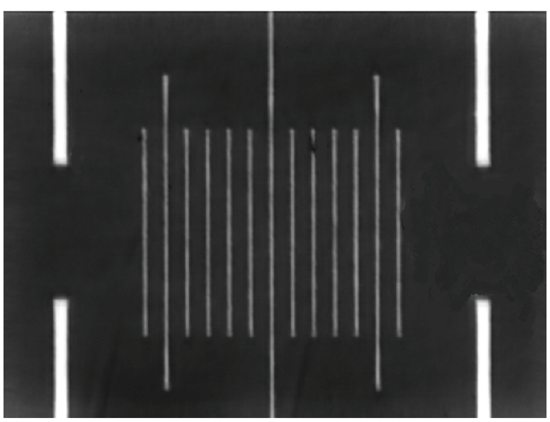


Figure 3. High magnification image of the SRM 2800 pitch calibration target.

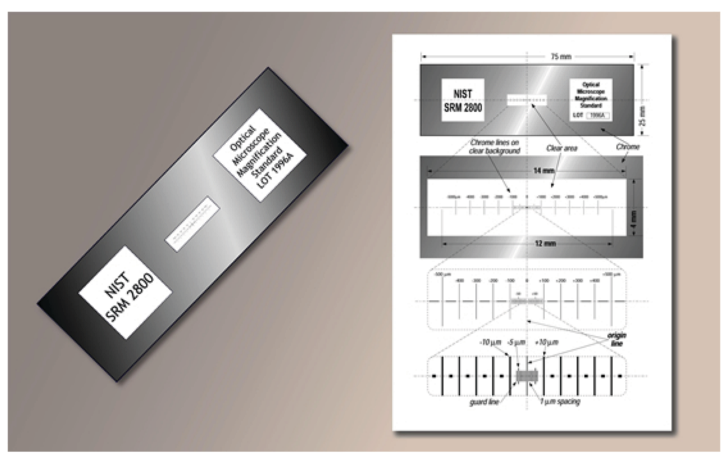


Figure 4. NIST SRM 2800 Line scale. This SRM consists of a pattern of parallel lines whose nominal distance from centerlines from 1 μm to 5 μm.

NIST SRM 2059 is an antireflecting etched chrome binary photomask on a 152 mm × 152 mm × 6.35 mm (6.0 in × 6.0 in × 0.25 in) quartz substrate. It contains calibrated isolated lines and spaces ranging from 0.25 μm to 32 μm (see fig. 3). The certified values are traceable to the definition of the meter with expanded (k=2) uncertainty typically 18 nm for linewidth and spacewidth, and 6 nm for pitch (maximum uncertainty of 25 nm for linewidths and spacewidths and 9 nm for pitch). It is available from the NIST Office of Standard Reference Materials.[4] Nomimal line- and spacewidths in the A,B, D, and E rows are from 0.25 μm to 32 μm. The left C row pitch pattern has line arrays with center-to-center spacings of 0.5 μm, 1.0 μm, and 2.0 μm. The position of the center of each line relative to the center of '0' line is reported, ranging from 0.5 μm to 250 μm. The lines below '0' and beyond '250' are proximity effect guard lines.
The right C-row pitch pattern has 2 lines width nominal 1.0 μm pitch plus two guard lines.
The F-row is not calibrated. This pattern is replicated in eight places in different orientations near the center of the mask. Only one of these replicas is calibrated at NIST.

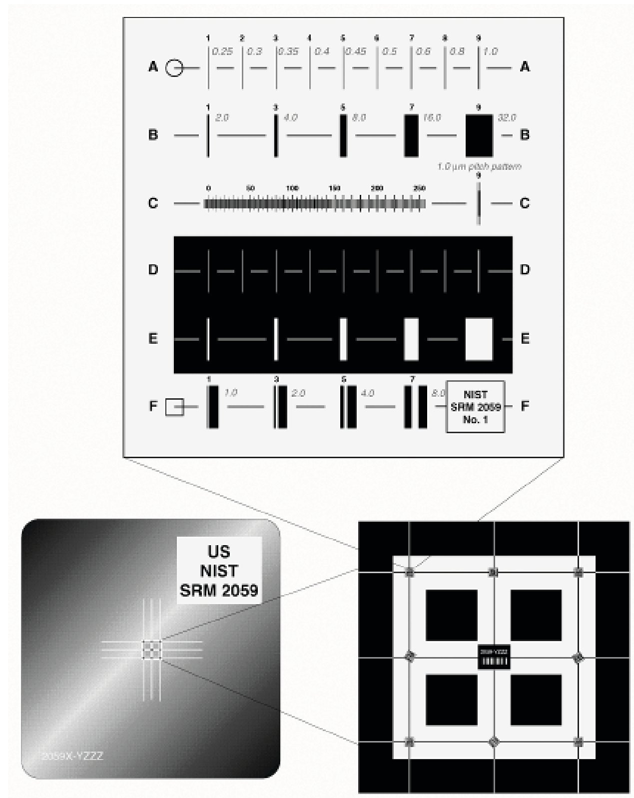


Figure 5. NIST SRM 2059 photomask linewidth standard.

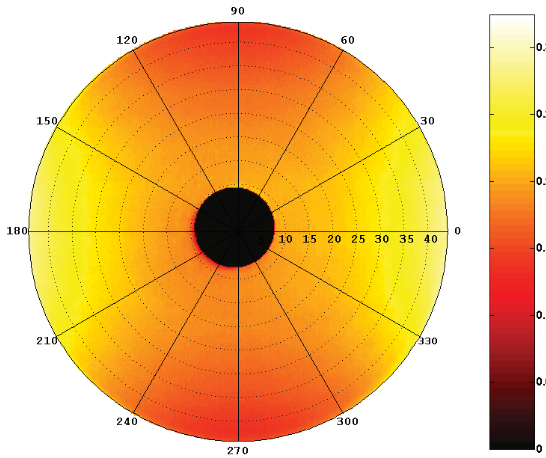
4. MATERIAL OPTICAL INDEX MEASUREMENT

Optical Fourier imaging measurements performed in visible light have shown an improvement on thickness and optical indexes measurement compared to ellipsometric measurement.[5] As the 193 nm scatterfield microscope can also provide optical Fourier transform imaging, this technique is used to measure the optical properties of the different materials present on the SRM mask.
The optical properties of chrome are difficult to measure because of a gradient of chrome oxide creating an optical index gradient in the chrome layer.[6] For simplicity, we will in this preliminary study, model the chrome as a perfect homogeneous material.[7] The microscope tool function has been measured using a blank silicon wafer previously characterized using a 193 nm goniometer. That measurement provided the thickness and optical indexes of the native oxide. Silicon optical properties are well-known and can be considered as known values. Full-field Fourier measurements on quartz and chrome on quartz (see fig. 6) have also been performed. Simulations of the chrome layer on quartz have shown that chrome is perfectly opaque to 193 nm wavelength for a 100 nm nominal thickness of our SRM photomask. Thus, from a optical properties point of view the chrome on quartz can be consider to be bulk chrome material.

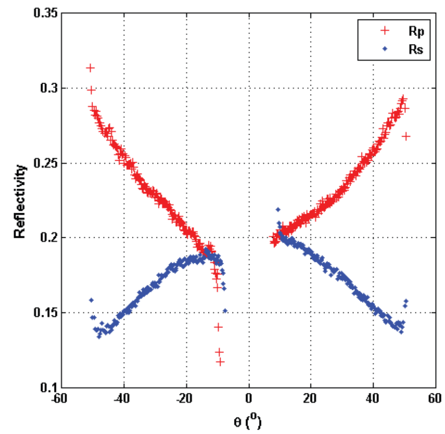
The asymmetry of the Fourier plane in fig. 6 induced by the presence of the polarizing beam-splitter, prevents a good fit between theoretical and experiment data. The 193 nm scatterfield microscope required additional experiment alignment improvements before becoming capable of performing accurate measurements given the difficulty of implementing a polarizing system at this wavelength.

5. PITCH AND LINE MEASUREMENTS

This section describes high magnification imaging of photomask targets. The first part presents result on pitch measurements using a calibrated CCD on the SRM 2056 mask. The second part describes isolated line and space measurements for both polarized and unpolarized full-field illumination.



(a) Full-field Fourier imaging.



(b) Chrome reflectivity (R_p, R_s).

Figure 6. Full-field Fourier chrome reflectivity at 193 nm. The Fourier image shows a small asymmetry of the Fourier plane induced by the presence of the polarizing beam-splitter. This microscope had been previously aligned and optimized for unpolarized light, the polarized displaced the alignment, frustrating the fitting

5.1 Pitch measurements

The SRM 2800 line scale artifact has been used to calibrate the CCD in order to estimate the size of a pixel in the sample plane. This artifact (see fig: 4) has been calibrated in NIST using a UV transmission microscope.
In this preliminary study, we have calibrated the CCD only along the x-direction (perpendicular to the lines) and only on the center of the field of view. The method used to determine the pixel size from the pitch calibration is presented elsewhere.[8] This method involves correlation of the line profile.
Usually pitch measurement is performed using large pitches but because as our field of view is small (around 40 μm) we only used the small calibrated line scale on the center of the SRM 2800 (see fig. 3) to calibrate our CCD pixel size. From the correlation algorithm used, the pixel size has been calculated to be: (40.28 ± 0.05) nm (k = 3). The uncertainty on the pixel size takes only into account the standard deviation of the measurements. Using this value, we have measured the line scale target on the SRM 2056 photolithography mask (see fig. 7).

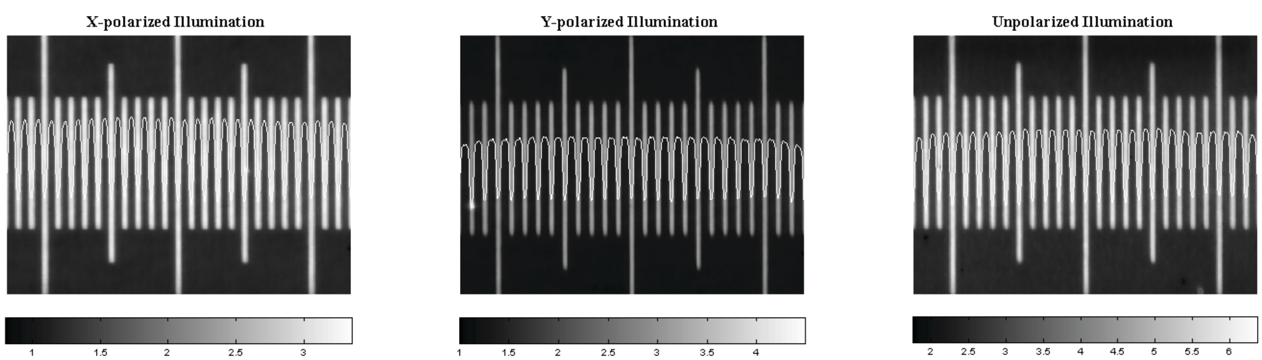


Figure 7. High magnification imaging of line scale targets on SRM 2056 mask. The profile of the lines is plotted over the image showing a good homogeneity.

The result of the pitch measurement are presented in the table 1.

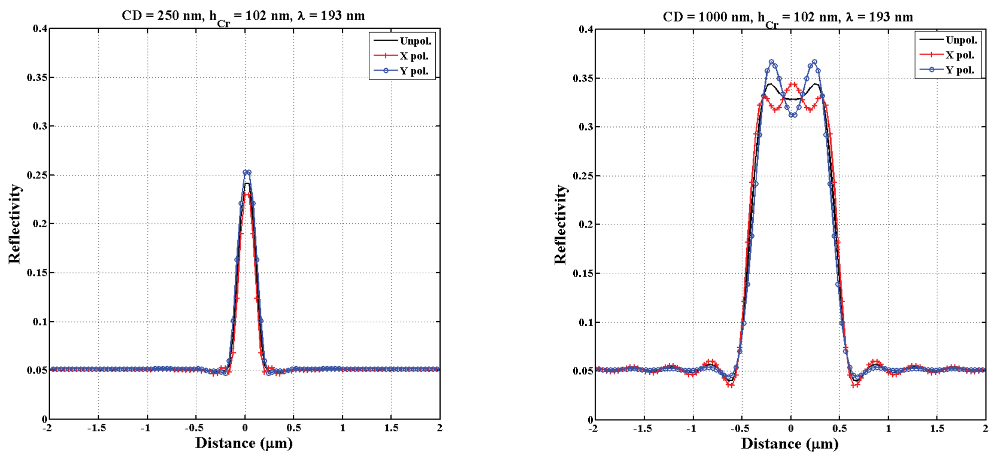
Table 1. Results of pitch measurements on the SRM 2056 mask. The reference values have been acquired using a UV transmission microscope fully traceable with the meter unit. The UV transmission calibration has been performed with unpolarized light.

	X-polarized	Y-polarized	Unpolarized	Reference
Pitch 1 (nm)	998.8 ± 0.5	998.5 ± 0.3	999.2 ± 0.3	1000.0 ± 2.8
Pitch 2 (nm)	4994.3	4994.7	4996.7	5000.3 ± 1.2

The polarization apparently has little or no influence on the pitch measurements. The results obtained are consistent with the calibrated values. Note that the uncertainties on the measured pitch only take into account the standard deviation of the measurements ; for larger pitch which appears once in the field-of-view, the uncertainty is not available. The measurement can be done more rigourously and the global uncertainties can be estimated.

5.2 Isolated line and space measurements

Isolated lines and spaces have been measured using full-field high magnification imaging (500x). A focus matrix algorithm based on maximum image contrast has been used to find the best focus. The CCD dark current and the glare (the signal measured in the absence of the sample) have been removed from raw image data. These have also been normalized using the quartz image for each polarization and for unpolarized illumination.



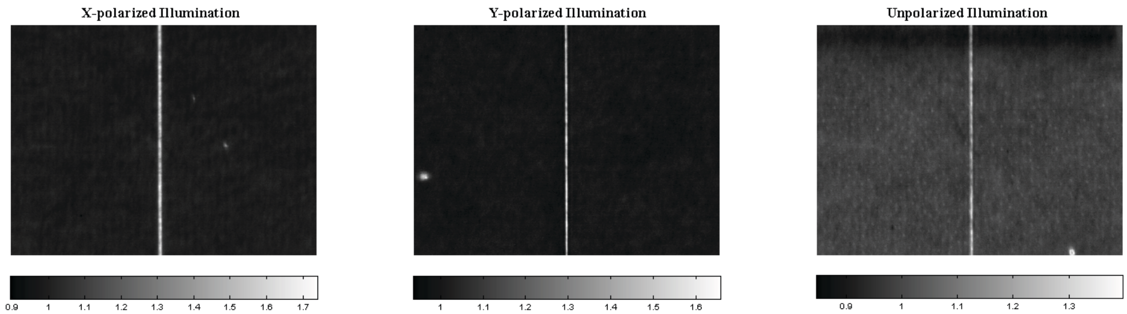
(a) 250 nm isolated line.

(b) 1000 nm isolated line.

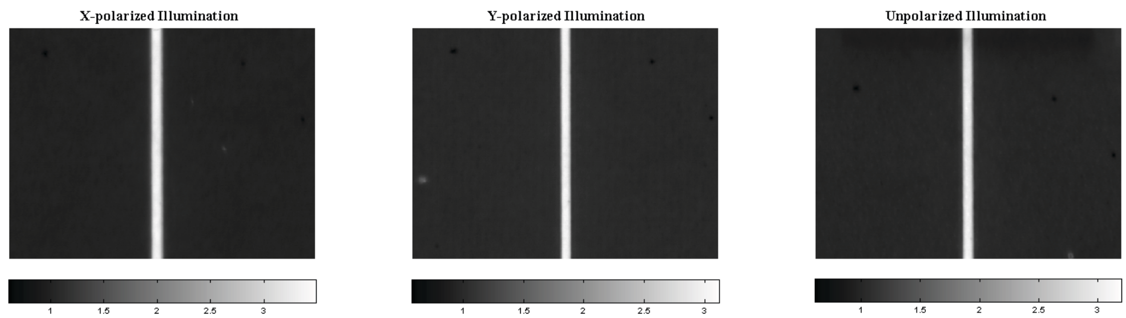
Figure 8. Theoretical high magnification intensity profiles of isolated lines. The simulation have been done using RCWA (period > 10 × Linewidth, high number of harmonics), incoherent illumination. $N_{\text{Chrome}} = 1.48 + 1.76i$ and $N_{\text{Quartz}} = 1.56$.[7]

The quality of the isolated space high magnification imaging is less than that for isolated lines as the focus matrix algorithm is not optimal for this kind of structure. A special focusing algorithm will need to be developed. These images still show speckles due to the partial coherency of the light which reduces our spatial resolution and needs to be addressed to acquire accurate measurements.

For the small chrome line on quartz, the experimental results are consistent with the theoretical data. According to the theoretical data (see fig. 8), we should observe high frequency oscillations on the edge of the profile line (diffraction limited images). Some explanations are possible: the first relies on the high rounding of the real line profile which reduces but does not make disappear edge diffraction. The second most reasonable explanation is the partial coherency of our illumination which reduces the spacial resolution of our images. Finally, the last explanation relies on a defocus image: the best focus found by our algorithm is not the right one and the image is off focus,. Nevertheless, a through focus images study has been performed on the 1 μm line and no oscillation were observed on the intensity line profile. The edge diffraction needs some more investigation.

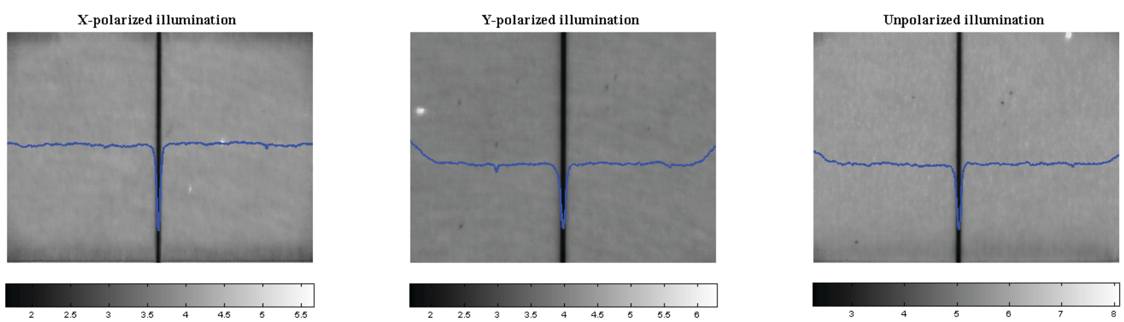


(a) 250 nm isolated line.

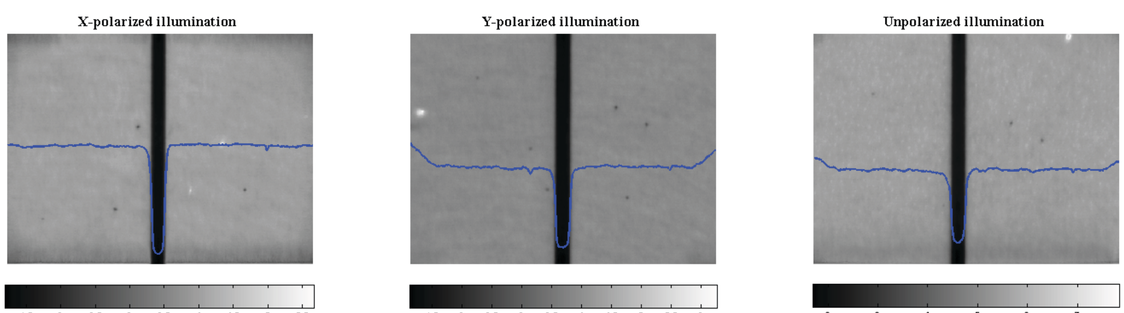


(b) 1000 nm isolated line.

Figure 9. High magnification imaging of line scale targets on SRM 2056 mask for polarized and unpolarized light. The partial coherence of the illumination source creates speckle patterning in the high magnification images reducing the spatial resolution.

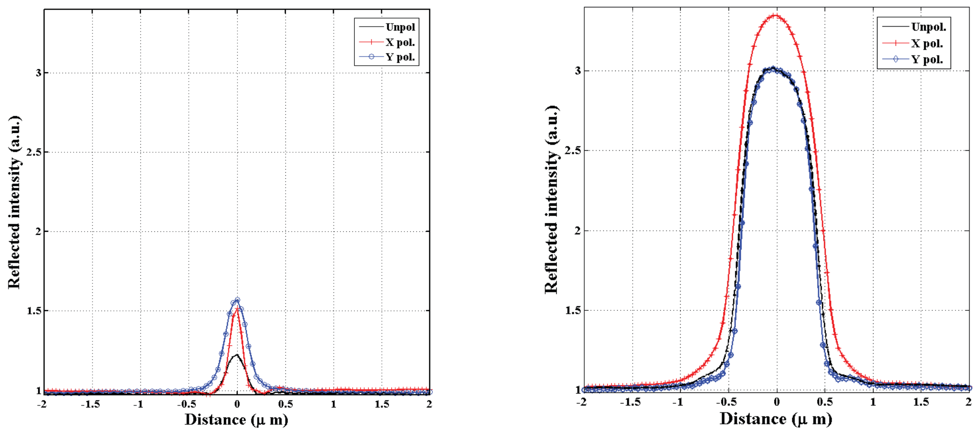


(a) 250 nm isolated trench.



(b) 1000 nm isolated trench.

Figure 10. High magnification imaging of isolated space (trench) on SRM 2056 mask for polarized and unpolarized light.



(a) 250 nm isolated line. (b) 1000 nm isolated line.

Figure 11. High magnification profiles of line scale targets on SRM 2056 mask. Unpolarized images have been acquired at a different energy source to avoid CCD saturation and keep high signal/noise ratio, explaining why the sum of both polarizing line profile is not equal to the unpolarized line profile (without taking into account the small beam-splitter absorption).

6. CONCLUSION AND PERSPECTIVE

The 193 nm scatterfield microscope has shown its capability for measuring isolated lines and spaces as well as on pitch measurements on photomask. Nevertheless, some alignment and source improvement is still required in order to be able to perform accurate measurements.
Future works will focus on improving the microscope, performing a complete CCD calibration, and measuring accurately the tool function. Moreover, additional customization of the illumination will be performed.

7. ACKNOWLEDGEMENT

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