Birefringence dispersion in fused silica for DUV lithography

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ABSTRACT

A shift to shorter wavelength radiation sources along with improvements in the quality of lithography grade optical materials has driven the production of integrated circuits with smaller feature sizes. Optical characterization of these materials, in some cases, is performed at visible wavelengths due to the complexity level associated with measuring in the DUV. Birefringence measurements of stepper lens blanks, for example, are typically measured at 633nm using a Helium Neon laser source. However, knowledge of the correlating DUV birefringence values is needed for determining the acceptable magnitude of birefringence in the material and for predicting the magnitude of loss in CD contrast. In this paper we report results on how the birefringence in Corning's HPFS® synthetic silica glass changes at the DUV wavelengths used in lithography systems. An examination of the wavelength dependent stress-optic response that produces birefringence was performed and found to increase from 633nm to 193nm. Birefringence in lithography stepper lens elements degrades imaging performance so an understanding of its dispersion is important for system designs.

Keywords: Birefringence, dispersion, optical lithography, polarization, synthetic silica glass

1. INTRODUCTION

Shorter wavelength radiation sources and improvements in the quality of the optical materials used in microlithography stepper systems have been two of the driving forces towards production of integrated circuits with smaller feature sizes. Fused silica lens elements in current lithography tools possess high internal transmission, high index homogeneity, low induced absorption and low birefringence. While absorption and transmission measurements are performed at the actual use wavelength using a Deuterium lamp, testing of refractive index homogeneity and stress birefringence are often conducted at 633nm using a Helium Neon laser source. To date, most commercially available ellipsometry or polarimetry birefringence measurement systems operate at 633nm[1]. This wavelength is typically used due to the complexity level associated with measuring in the DUV. However there is an increasing interest in understanding how birefringence trends at the 248nm & 193nm wavelengths used in lithography tools.

Birefringence is a photoelastic effect often used to analyze stress in isotropic optical materials[2]. It is a direct measure of the refractive index difference between two orthogonal axes in a plane perpendicular to the beam path axis. For a light beam propagating through a material along the 'z' direction, birefringence would be defined as:

$$\text{Birefringence} = n_x - n_y \qquad (1)$$

where 'n_x' and 'n_y' are the refractive indices seen by light when polarized in the 'x' and 'y' directions respectively. In non-crystalline isotropic materials such as fused silica, generation of this index difference is typically associated with stress induced during material forming, improper annealing, material finishing or mounting.

Knowing the sample birefringence, one can determine the induced stress difference between the two principal stress axes from the relationship[2]:

$$\text{Birefringence} = n_x - n_y = R * (\sigma_x - \sigma_y) \qquad (2)$$

where 'σ_x' and 'σ_y' are the average stress along the 'x' and 'y' directions and 'R' is the stress optic coefficient for the material, expressed in units of nm/cm/MPa.

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The stress optic coefficient is both material and wavelength dependent and defines the amount of birefringence produced per unit stress for light traveling through the material. A relationship to the material stress optical constants q_{11} and q_{12} can be derived as:

$$R = n_o^3/2 * (q_{11} - q_{12}) \qquad (3)$$

where q_{11} and q_{12} are the tensor components describing the material photoelastic effect. To understand the dispersion of birefringence in the DUV we have examined the dispersion of the stress optical coefficient in Corning's HPFS® synthetic silica glass.

In a birefringent optical element the refractive index difference produces a change in the polarization state of light propagating through the element. For example, linearly polarized light traveling through a birefringent lens element would experience a phase change and become elliptically polarized with the ellipticity depending on both the birefringence magnitude and the stress axis direction with respect to the polarization axis. Measurement of sample birefringence for determining the stress optic coefficient exploits this polarization dependence. An examination of the difference in the beam polarization state with and without the sample is performed from which the sample birefringence value is extracted[3].

2. EXPERIMENTAL

The experimental setup used for measuring birefringence and determining the stress optic coefficient is shown in Figure 1. For measurements at 633nm and 248nm linearly polarized light was produced using Glan Taylor polarizers with a 10^5:1 extinction ratio. A pair of polarizing beam splitter cubes was used for tests at 193nm with a 200:1 extinction ratio. To ensure measurement of the maximum sample birefringence, the incident light was polarized at 45^0 to the principal stress axis. In the experiments the sample principal stress axis was vertically oriented and corresponded to the axis in which loads were applied. Zero order ¼ wave plates centered at the individual wavelengths were also used. Each wave plate was oriented with the slow axis at 45^0. With the wave plate configured in this geometry the elliptically polarized beam emerging from the birefringent sample is transformed back to linear polarization. The analyzer (2nd polarizer) was mounted on a precision rotation stage and oriented at -45^0. In this arrangement and with no sample in the beam path, the polarization axes of the polarizer and analyzer are perpendicular resulting in extinction of light through the 2 polarizers.

Measurements at 633nm were performed using a Class IIIB Helium Neon laser. A PIN-type silicon photoconductive detector with an internally mounted preamplifier was used for light detection at this wavelength. Measurements at 248nm and 193nm were conducted using Lambda Physik LPX 100 excimer lasers. The incident fluence for both 248nm & 193nm tests was unmeasureable due to detector sensitivity but estimated to be $< 0.01 mJ/cm^2$/pulse, thus preventing any potential glass densification during testing. An aperture was also used allowing a beam diameter of 2mm. The sample dimension used for the tests was 6x6x15mm. These pieces were cut from Corning's 7980 HPFS® synthetic silica glass.

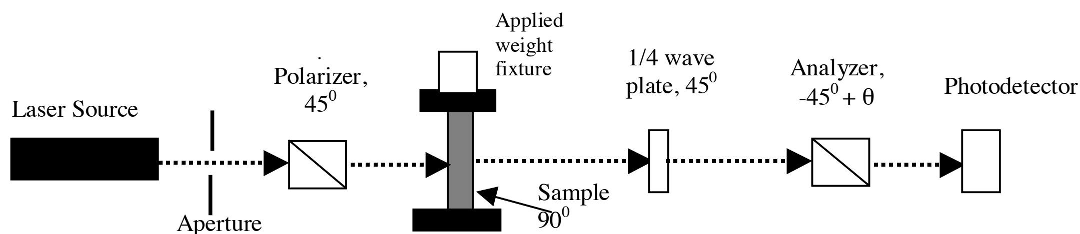

Figure 1. Experimental Setup

Figure 2 shows the fixture used for applying a uniaxial compressive stress to the samples. The apparatus consisted of an air driven piston shaft for applying the load. An air flow regulator was used to vary the amount of applied pressure. The applied weight was measured using a MDB-10 ultra precision mini load cell from Transducer Techniques Inc. The electro-mechanical transducers within the load cell translates the applied weight into voltage and has the capability of measuring compressive pressure ranging from 0 – 1.24MPa.

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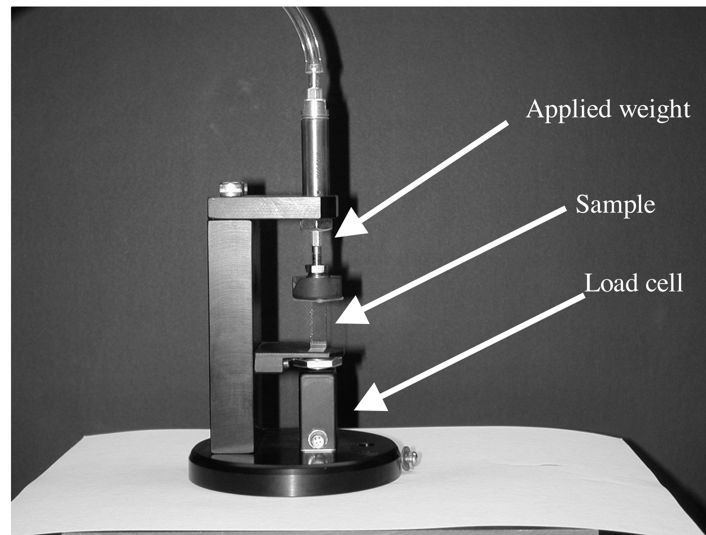

Figure 2. Fixture for applying weight to sample

The stress optic coefficient was determined at each wavelength by subjecting the test sample to a uniaxial compressive stress. The sample birefringence was then evaluated as a function of the optical retardation introduced into a linearly polarized beam. This retardation is related to the angle of rotation for the analyzer which causes light extinction through the two polarizers. For birefringence measurements, the analyzer position was first determined at which light extinction "null" occurs without a test sample in the beam path. To measure birefringence with a sample in the beam path, the analyzer was then rotated to the new null position. For each test, birefringence was calculated as:

$$B(\mathrm{nm/cm}) = \frac{\Delta\theta(\mathrm{degrees}) * \lambda(\mathrm{nm})}{180(\mathrm{degrees}) * t(\mathrm{cm})} \qquad (4)$$

where $\Delta\theta$ = angular difference between light extinction analyzer positions with and without sample; units of degrees,
λ = measurement wavelength; units of nm,
t = part thickness; units of cm.

3. RESULTS AND DISCUSSION

Figures 3-5 show the plots of birefringence versus applied stress as measured for the different wavelengths. A linear fit was performed on the data and the stress optic coefficient value extracted from the slope of the equation describing the fit. Birefringence measurements at 633nm were performed using an automated polarimeter unit with a precision of < 0.1nm/cm. At this wavelength the stress optic coefficient was determined to be 35 ± 1 nm/cm/MPa, in agreement with the value measured on Corning's 7940 material[5]. A higher compressive load was applied to the sample to improve the accuracy of birefringence measurements performed manually at 248nm and 193nm. Table I shows the summarized results for the stress optic coefficient determined for the other wavelengths. These 'average ± 1σ' results are based on the individual stress optic coefficient value measured on various samples.

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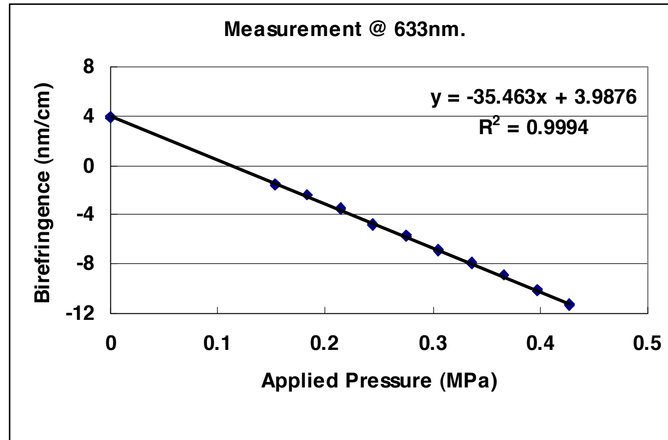

Figure 3: Evaluation of Stress Optic Coefficient measured at 633nm.

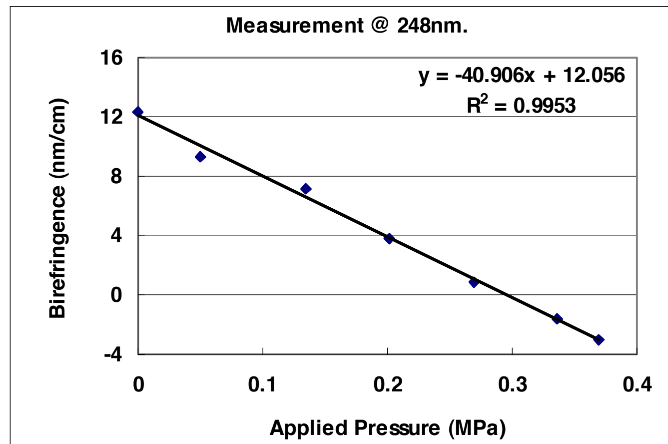

Figure 4: Evaluation of Stress Optic Coefficient measured at 248nm.

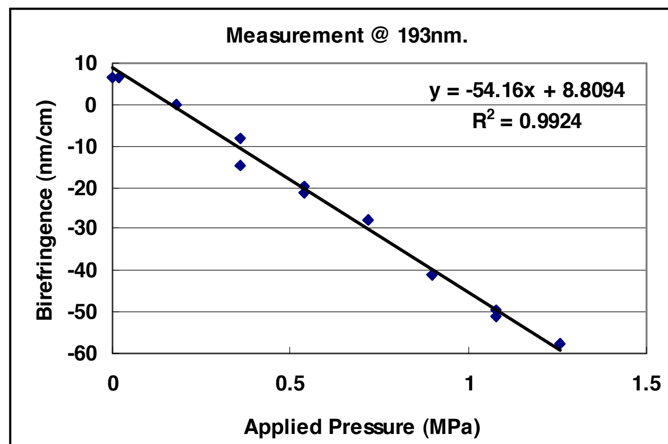

Figure 5: Evaluation of Stress Optic Coefficient measured at 193nm.

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Wavelength (nm)	633	248	193
Stress Optic Coefficient (nm/cm/MPa)	35 ± 1	42 ± 1	51 ± 3

Table 1: Measured stress optic coefficient values.

Previous studies on the wavelength dependence of the stress optical coefficient for fused silica has shown a parallelism between the normalized spectral dispersion of birefringence in quartz and the normalized spectral dispersion of the stress optic coefficient in fused silica[6,7]. A spectral dispersion equation describing the stress optic coefficient was derived as:

$$R(\lambda) = R(\lambda_o) * \frac{n(\lambda_o)}{n(\lambda)} * \frac{\lambda^2}{\lambda_o^2} * \frac{(\lambda_o^2 - \lambda_1^2)}{(\lambda^2 - \lambda_1^2)} * \frac{(\lambda^2 - \lambda_2^2)}{(\lambda_o^2 - \lambda_2^2)} \qquad (5)$$

where λ is the wavelength of interest, λ_0 is the normalizing wavelength, $R(\lambda_0)$ is the stress optic coefficient for the normalizing wavelength, λ_1 = 121.5nm and λ_2 = 6900nm.

Using equation 5, the calculated stress optic coefficient at 248nm is 43 nm/cm/MPa, a 23% increase from the 633nm value. This was calculated using 633nm for the normalizing wavelength and $R(\lambda_0)$ = 35 nm/cm/MPa, as determined from our measurements. From our experimental data the stress optic coefficient at 248nm was measured as 42 ±1 nm/cm/MPa, a 20% increase from the value measured at 633nm but in good agreement with the dispersion equation.

An approximation of the 193nm stress optic coefficient using equation 5 was estimated as 53 nm/cm/MPa, again using 633nm as the normalizing wavelength. This is a 50% increase from the stress optic coefficient measured at 633nm and likewise, a 50% increase in birefringence. At 193nm our experimental results indicated a stress optic coefficient of 51±3 nm/cm/MPa, corresponding to a 46% increase against the 633nm value.

The difference in values can be attributed to differences in the quality of the fused silica, in particular the different ‘water’ content. Also, equation 5 was generated from stress optic values using plate glass and non-Corning synthetic silica glass.

4. SUMMARY

In this report we have discussed birefringence and its relation to induced sample stress and the stress optic coefficient. Results from measurements of the stress optic coefficient in Corning’s HPFS ® have shown an increase in the value when measured from the visible to 193nm. Similarly, birefringence shows an increasing trend as the operating wavelength decreases. At 248nm and 193nm, birefringence increases by 20% and 46%, respectively in comparison to the value measured at 633nm.

In microlithography exposure tools birefringence in optical elements results in distortion of the projected image wavefront. This produces a loss in CD contrast and consequently degrades the image being patterned on a silicon wafer. In catadioptric lens set utilizing polarized light, birefringent elements introduces a phase retardation whereby producing an undesirable polarization state. Similarly this impacts the wavefront formation and imaging contrast. With a catadioptric lens approach becoming the possible design choice for 157nm lithography, such an effect is critical. Therefore, the need for low birefringent materials may become critical for controlling image quality and reducing feature sizes in DUV lithography.

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