Achieving Low Wavefront Specifications for DUV Lithography; Impact of Residual Stress in HPFS® Fused Silica

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ABSTRACT

As optical lithographers push to extend optical lithography technologies to create smaller features with higher NA, lower k_1 values and shorter wavelengths, transmitted wavefront specifications for HPFS® fused silica blanks continue to tighten. Corning has developed and implemented manufacturing changes to produce synthetic fused silica blanks with very low wavefront distortion.

HPFS® fused silica blanks are typically certified for acceptance using an interferometer operating at a wavelength of 632.8nm. As the market demands increasingly tighter homogeneity specifications, it has become critical to understand the sources of variation in wavefront measurements. Corning has recently initiated a study to identify those sources of variation.

One glass attribute being studied is the impact of residual stress on the wavefront. It is known that residual stresses can alter the refractive index of fused silica. To obtain the residual stress measurements, birefringence measurements were obtained at 632.8nm for comparison to wavefront measurements at 632.8nm.

The relationship between residual birefringence and transmitted wavefront measurements, at 632.8nm on Corning HPFS® fused silica blanks, is explored in this paper.

Keywords: Interferometry, Birefringence, Wavefront Distortion, HPFS® Fused Silica, Code 7980, Refractive Index, Hinds Exicor™, Zygo Interferometer, MetroPro

1. INTRODUCTION

The Semiconductor industry demands high performance optical materials for projection systems with highly uniform index of refraction properties and low birefringence. Additionally, as higher numerical aperture systems are developed, projection elements become dimensionally larger and more challenging to make. State-of-the-art projection optics require low wavefront distortions and low birefringence values. These two properties of fused silica are two unique ways to characterize and quantitatively describe optical aberration performance in lens material and are the two properties that consistently require improvement as DUV technologies are enhanced.

Since any amount of aberration results in image degradation, specification levels are established for each lens system and are dependent on the application. These specifications are driven by image and resist requirements for microlithographic applications. Stray light, which can be created from imperfections in the lens material, can cause an anomaly called flare, which reduces the image contrast and generally degrades the quality of the lithography. Optical aberrations in the projection or illuminator system can lead to loss of contrast or a reduced depth of focus. As shorter wavelength technology is pursued, resist and process demands will require that aberration tolerance levels be reduced further. [1]

Additionally, a high level of residual birefringence in an optical component can lead to an aberration of light rays in an imaging system and thus affect the imaging quality of wafers. Therefore any optical components used in an optical lithographic instrument should have a low level of residual birefringence.[5]

Due to these strong requirements, Corning continues to deliver HPFS® 7980 fused silica optics with these qualities by improving and developing manufacturing processes to meet new specification requirements.

For the optics manufacturer, it is important to understand the relationship between birefringence and wavefront distortion to determine cause and effect.

What is considered a "low level of birefringence"? Is birefringence impacting today's wavefront measurements on fused silica blanks? What can photoelastic theory tell us about the relationships among stress, wavefront distortion, and birefringence? The results of this paper are intended to enhance and expand our existing knowledge of these properties and determine if birefringence is a cause of wavefront distortion in HPFS® blanks. This knowledge will determine which future actions are pursued to improve refractive index uniformity and reduce wavefront distortions.

2. MEASUREMENT TECHNIQUES

2.1 Interferometry Measurements

Corning uses sophisticated interferometer techniques to characterize and quantify optical aberrations. Fifteen samples were measured with a resolution of 1.11mm/pixel at the Corning Canton Plant in Canton, New York.

The wavefront distortion, caused by refractive index inhomogeneities, was measured using a Zygo Mark IV GPI phase measuring interferometer with a circularly polarized HeNe laser. The wavefront measurements were then analyzed using Zygo MetroPro software, version 7.3.2. MetroPro is a GUI (Graphic User Interface) for operating Zygo interferometers and analyzing data.

The lens blanks are thermally stabilized and made transparent by utilizing index-matching oil. A HeNe laser beam is transmitted through a lens blank. While the laser beam is passing through the glass, the phase of the laser light is being altered due to the index of refraction variations. An interference pattern is formed when the measuring wavefront of the interferometer combines with a reference wavefront. The pattern formed is indicative of the phase variation and, therefore, the index variation. By making measurements of this pattern, the interferometer can determine what the relative index of refraction is for a matrix of points (or pixels) over the aperture of test.[2] The result is a refractive index map of the part which can be analyzed for wavefront distortions.

Aberrations can be represented with Zernike polynomials, however for the purposes of this study, only the homogeneity (peak to valley) and RMS (root mean square) values were recorded.

2.2 Birefringence Measurements

The same parts measured for homogeneity were shipped to Hinds Instruments, Inc in Portland Oregon for birefringence measurements. A spacing resolution of 5mm was utilized.

Hinds Instruments has developed a new birefringence measurement instrument known as the EXICOR™ system. It employs photoelastic modulator (PEM) technology to achieve high sensitivity, repeatability, and fast measurements. The system simultaneously determines both the birefringent magnitude and direction in a sample.[3] The instrument employs a low birefringence photoelastic modulator for modulating the polarization states of a HeNe laser beam. After the modulated laser beam passes through the sample, two detecting channels analyze the polarization change caused by the sample. Hinds's EXICOR™ software then calculates and analyzes the measurement data. [4] The Exicor™ system determines the residual birefringence in optical components with a sensitivity of 0.005nm for magnitude and <1° for birefringence angle. [5]

The parts were thermally stabilized at room temperature until fluctuations in birefringence measurements ceased to exist.

Residual birefringence is typically the result of thermal history of the fused silica sample. It is characterized by a difference in speeds of light (or refractive indices) for two orthogonal linear polarizations of light passing through the sample. Birefringence of an optical element produces a relative phase shift between the two polarization components of the passing light. The net phase shift integrated along the light beam path traversing the sample is called the retardation (or retardance) of a sample.[5]

Maximum absolute birefringence values, in units of nm/cm, were recorded for this study.

3. DATA

Fifteen HPFS® 7980 Excimer Grade fused silica samples were measured for birefringence and homogeneity at 632.8nm. The results are summarized in Figure 1. A 90% clear aperture was used to evaluate the data. The homogeneity values ranged from 0.37-0.74 ppm, RMS values ranged from 0.005-0.015 waves, and the maximum absolute birefringence values ranged from 0.07-0.45 nm/cm.

Figure 1: Summary of Corning HPFS ® Fused Silica Homogeneity and Birefringence Measurements

Sample #	Diameter [mm]	Thickness [mm]	Clear Aperture [mm]	Dn [ppm]	RMS [waves]	Maximum Absolute Birefringence [nm/cm]
A	195	51.1	176	0.37	0.005	0.13
B	175	48.2	158	0.56	0.008	0.26
C	195	68.1	176	0.74	0.015	0.17
D	200	55.1	180	0.47	0.007	0.40
E	175	50.3	158	0.50	0.007	0.29
F	180	49.8	162	0.41	0.009	0.19
G	230	45.2	207	0.64	0.010	0.40
H	230	45.1	207	0.72	0.010	0.07
I	220	55.7	198	0.52	0.009	0.40
J	220	54.8	198	0.48	0.009	0.45
K	175	49.5	158	0.63	0.010	0.15
L	220	45.1	198	0.43	0.006	0.30
M	180	50.5	162	0.39	0.005	0.21
N	160	47.3	144	0.39	0.005	0.26
O	175	51.9	158	0.55	0.007	0.29
Average	195	51.2	176	**0.52**	0.008	**0.26**
Maximum	230	68.1	207	**0.74**	0.015	**0.45**
Minimum	160	45.1	144	**0.37**	0.005	**0.07**

4. RESULTS

4.1 Results of Birefringence Measurements

The birefringence of HPFS® fused silica is extremely low. The average maximum absolute birefringence was 0.26 nm/cm for all 15 parts. The maximum was 0.45nm/cm and the minimum was 0.07nm/cm. Typically, higher birefringence values can be observed on the circumference of each HPFS® fused silica due to mechanical grinding operations on the outer diameter of the parts. These stresses are not observed within the clear aperture of the parts. This edge stress can be observed in Figures 2B, 3B, and 4B.

4.2 Results of Homogeneity Measurements

The homogeneity measurements of the HPFS® fused silica blanks were typical for the part sizes tested. The average homogeneity value was 0.52 ppm for all 15 parts. The maximum was 0.74ppm and the minimum was 0.37ppm.

4.3 Influence of Stress in Interferometry: Exploring Photoelastic Relations Between Stress and Optical Index Changes

In simple terms, birefringence is the *difference* of two indices of refraction whereas wavefront measurements are a measure of the variation in *average* index.

There are two set of constants that are typically used to describe photoelastic behavior of materials. These are the stress-optical constants, which are denoted as q_{mn}, and the strain-optical constants, which are denoted p_{mn}. In an optically isotropic medium, only two components of these two tensors are unique.[6] These may be taken as the 11 and 12 components: q_{11} and q_{12} or p_{11} and p_{12}.

For the following discussion, the principle stress axes are those coordinate axes that make the stress tensor a diagonal matrix. We denote them as x, y, and z, but in a cylindrical lens blank one usually replaces x and y with radial and tangential coordinates. Other than notation, none of the equations would be affected by such a choice.

The photoelastic tensor components are defined in terms of distortions of the "ellipsoid of wave normals", which is actually a sphere in an isotropic, stress-free sample.[6] They are expressed in terms of variations in $1/\varepsilon$, where ε=dielectric constant. The dielectric constant ε is related to the index of refraction n by

$$\varepsilon = n^2 \qquad (1)$$

To examine variations in n instead of variations in $1/\varepsilon$, we use the relation

$$\Delta n = -\frac{1}{2}(n_0)^3 \Delta\left(\frac{1}{e}\right) \qquad (2)$$

where n_0 is the index of refraction in the absence of stress or strain.

From the definition of the strain-optical constants and the discussion above, and for isotropic materials, we have the relations

$$(\Delta n)_x = (-n_0^3/2)\,(p_{11}\, e_x + p_{12}\, e_y + p_{12}\, e_z)$$
$$(\Delta n)_y = (-n_0^3/2)\,(p_{12}\, e_x + p_{11}\, e_y + p_{12}\, e_z)$$
$$(\Delta n)_z = (-n_0^3/2)\,(p_{12}\, e_x + p_{12}\, e_y + p_{11}\, e_z) \qquad (3)$$

where e_x, e_y, and e_z are the strains along the principle axes (denoted x, y, and z), and $(\Delta n)_x$ is the index change due to the strains for light polarized along principle axis x, $(\Delta n)_y$ for light polarized along y, and $(\Delta n)_z$ for light polarized along z.

The analogous expressions in terms of stress instead of strain are

$$(\Delta n)_x = (-n_0^3/2)\,(q_{11}\,\sigma_x + q_{12}\,\sigma_y + q_{12}\,\sigma_z) \qquad (4a)$$
$$(\Delta n)_y = (-n_0^3/2)\,(q_{12}\,\sigma_x + q_{11}\,\sigma_y + q_{12}\,\sigma_z) \qquad (4b)$$
$$(\Delta n)_z = (-n_0^3/2)\,(q_{12}\,\sigma_x + q_{12}\,\sigma_y + q_{11}\,\sigma_z) \qquad (4c)$$

where the σ's are now stresses along the principle axes.

Stress and strain are related through the elastic properties of the material. For an isotropic material, only the Young's modulus E and the Poisson ratio ν are needed, and the relations are

$$e_x = (1/E)\,(\sigma_x - \nu\,(\sigma_y+\sigma_z))$$
$$e_y = (1/E)\,(\sigma_y - \nu\,(\sigma_z+\sigma_x))$$
$$e_z = (1/E)\,(\sigma_z - \nu\,(\sigma_x+\sigma_y)) \qquad (5)$$

The two descriptions of index change in Eqs. (3) and (4) must agree and be consistent with Eqs.(5), so we can deduce the relations between strain-optic and stress-optic coefficients

$$q_{11} = (1/E)\,(p_{11} - 2\,\nu\,p_{12})$$
$$q_{12} = (1/E)\,(p_{12} - \nu\,(p_{11}+p_{12})) \qquad (6)$$

If light is traveling down the z axis, then the birefringence of the sample is the difference between $(\Delta n)_x$ and $(\Delta n)_y$, i.e.

$$BR = (\Delta n)_x - (\Delta n)_y = (-n_0^3/2)\,(q_{11}-q_{12})\,(\sigma_x-\sigma_y) \qquad (7)$$

where σ_x and σ_y are now averaged along the light path through the sample.

Several other relations can be derived from the equations above. For example, in most cases the strain can be approximated as being isotropic in each small region of the sample (e.g. within each element of a finite element calculation). This leads to the isotropic approximation for index variation

$$(\Delta n)_{iso} = (-n_0^3/2)\,((p_{11}+2p_{12})/3)\,(e_x+e_y+e_z) \qquad (8)$$

The sum of the three strains $(e_x+e_y+e_z)$ is a fractional volume change, or the negative of a fractional density change. Thus Eq.(8) shows a linear proportionality between a density increase and an isotropic increase in index of refraction.

Considering light propagating down the z axis, we have

$$(\Delta n)_{avg} = (\Delta n_x + \Delta n_y)/2 = (-n_0^3/2)\,((q_{11}+q_{12})(\sigma_x+\sigma_y)/2 + q_{12}\,\sigma_z) \qquad (9)$$

This expression should represent the refractive index contribution to wavefront distortion measured by circularly polarized light used in interferometry. The measurement would actually detect $(\Delta n)_{avg}$ integrated through the sample thickness, so the result depends on all three principle stresses integrated through the sample thickness.

Focusing on stress and its connections to interferometry and birefringence, for light traveling down the z axis, Eqs.(4a), (4b), (7), and (9) are important.

$$(\Delta n)_x = (-n_0^3/2)\,(q_{11}\,\sigma_x + q_{12}\,\sigma_y + q_{12}\,\sigma_z) \qquad (4a)$$
$$(\Delta n)_y = (-n_0^3/2)\,(q_{12}\,\sigma_x + q_{11}\,\sigma_y + q_{12}\,\sigma_z) \qquad (4b)$$
$$BR = (\Delta n)_x - (\Delta n)_y = (-n_0^3/2)\,(q_{11}-q_{12})\,(\sigma_x-\sigma_y) \qquad (7)$$
$$(\Delta n)_{avg} = (\Delta n_x + \Delta n_y)/2 = (-n_0^3/2)\,((q_{11}+q_{12})(\sigma_x+\sigma_y)/2 + q_{12}\,\sigma_z). \qquad (9)$$

Eqs. (7) and (9) relate to birefringence and (circularly polarized) interferometry measurements, respectively.

The birefringence measurement depends only on the *difference* in principle stresses (σ_x-σ_y), while $(\Delta n)_{avg}$ or $(\Delta n)_x$, $(\Delta n)_y$ depend in a more complicated way on *all three* stress components σ_x , σ_y , and σ_z .

From Eqs. (4a) and (4b), the knowledge of the two variables $(\Delta n)_x$ and $(\Delta n)_y$ is *not* enough to determine the three stress variables σ_x , σ_y , and σ_z . Thus, in principle, interferometry and birefringence measurements down a single axis do not give enough information to determine the principle stresses. In practice, however, one or even two of the principle stresses may be small enough to ignore, in which case the other two or one stresses *can* be determined from knowledge of $(\Delta n)_x$ and $(\Delta n)_y$.

What is the point?

Because wavefront distortion and birefringence both involve variations in the index of refraction, one may be tempted to think that one causes the other. This is false. One may be tempted to think that they are always strongly correlated, for example, both caused by the same underlying stresses. It is true that stress can cause both wavefront distortion and birefringence, but the degree of correlation between the two can be highly variable. The point is this: under some circumstances, wavefront distortion and birefringence should be strongly correlated, while in other circumstances, they should be uncorrelated.

For example, looking at Eqs. (7) and (9), suppose a stress σ_z was developed through processing. This stress would have no effect at all on the birefringence (as measured down the z axis), but would indeed change $(\Delta n)_{avg}$ and thus alter the wavefront distortion. On the other hand, suppose we examine wavefront distortion and birefringence near the edge of a lens blank. In this case, we can usually treat the principle axes as radial and tangential, and the radial stress has to vanish as we approach the edge. Taking the tangential stress as σ_x, we see from Eqs. (7) and (9) that a larger σ_x will alter both the birefringence and $(\Delta n)_{avg}$ together. Thus, in this case, they will be correlated. As a third example, suppose σ_x and σ_y are both increased together. Then the birefringence is unaffected but the wavefront distortion is altered in a way that is uncorrelated to birefringence. Finally, an obvious connection between stress-induced wavefront changes and birefringence is shown in the laser compaction of fused silica, both in the theoretical model and in the experimental measurements.[7,8]

Of the four cases discussed, only two predict a strong correlation between wavefront distortion and birefringence. The real answer for any given process or thermal history must be determined by measurements of both birefringence and wavefront distortion on the same pieces of glass. Because the radial stress vanishes near the edge, the edge region especially can be evaluated for correlations between birefringence and wavefront distortion. In a process that produces larger tangential stresses, a correlation is expected. In our samples, with low levels of birefringence as shown in Figures 2B, 3B and 4B, there is no correlation.

4.4. Typical Wavefront and Birefringence Map Patterns

The birefringence map from the Hinds Exicor™ system was visually compared to the Zygo MetroPro software wavefront distortion map for each part. Figures 2-4 show typical examples of the wavefront map (on left, clear aperture) compared to the birefringence map (on right, full aperture). In these examples, there is no relationship between the homogeneity and birefringence patterns.

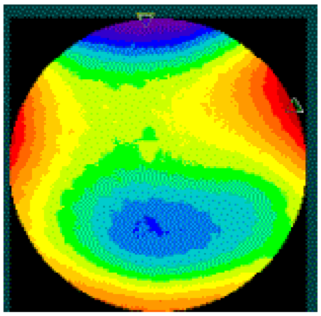

Figure 2A: Sample F: Zygo Wavefront Map: $\Delta n \leq 0.41$ppm

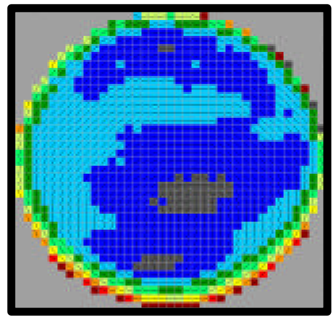

Figure 2B: Sample F: Hinds Birefringence Map: Birefringence ≤ 0.19nm/cm

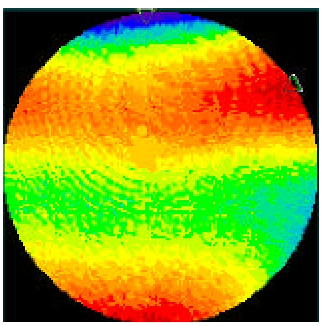

Figure 3A: Sample M: Zygo Wavefront Map $\Delta n \leq 0.39$ppm

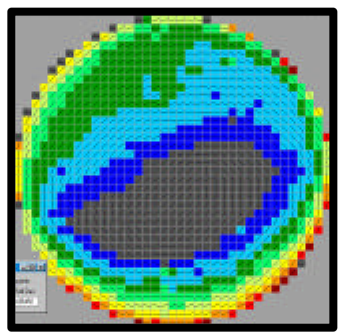

Figure 3B: Sample M: Hinds Birefringence Map: Birefringence ≤ 0.21 nm/cm

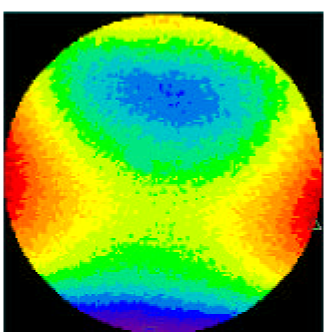

Figure 4A: Sample E: Zygo Wavefront Map $\Delta n \leq 0.50$ ppm

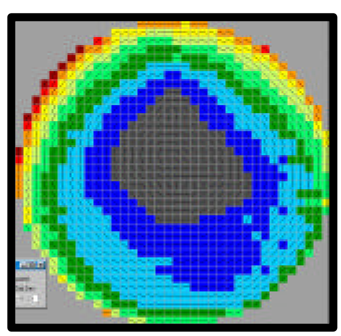

Figure 4B: Sample E: Hind's Birefringence Map Birefringence ≤ 0.29nm/cm

5. CONCLUSIONS

In simple terms, birefringence is the *difference* of two indices of refraction (for orthogonal polarizations) whereas wavefront measurements are a measure of the variation in *average* index. While both effects are related to index variations, and both can be influenced by stress, their degree of correlation can range from perfectly correlated to uncorrelated, depending on circumstances.

Our study concludes that for Excimer grade HPFS® fused silica with typical homogeneity values less than 0.75 ppm and birefringence values less than 0.45nm/cm, there is no correlation between homogeneity and birefringence measurements.

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REFERENCES

1. J.R. Sheats, B. W. Smith, *Microlithography Science and Technology*, pages 27, 28, 223, 195-268, Marcel Dekker, Inc, New York, (1998).
2. Zygo Corporation, *Fundamentals of Interferometry and Optical Testing I*, Customer Education, page 35, (1996)
3. B. Wang, "Measurement of Excimer Laser Induced Birefringence in Fused Silica and Calcium Fluoride", in *Metrology, Inspection, and Process Control for Microlithography XIV*, Neal T. Sullivan, Editor, Proceedings of SPIE Volume **3998** (2000).
4. B. Wang, T.C. Oakburg, " A new instrument for measuring both the magnitude and angle of low level linear birefringence", *Review of Scientific Instruments*, American Institute of Physics, Volume **10**, Number 10, pages 3847-3854 (October 1999).
5. B. Wang, P. Troccolo, "Measurement of Residual Birefringence in Photomask Blanks", *Part of the 19th Annual BACUS Symposium on Photomask Technology*, Proceedings of SPIE Volume **3873**, pages 544-553, (1999).
6. M. Born and E. Wolf, *Principles of Optics*, 6th edition, Pergamon Press, New York, pages 703-705, (1980).
7. D. C. Allan, C. Smith, and N. F. Borrelli, "Measurement and analysis of compaction in fused silica", *Symposium on Laser Induced Damage in Optical Materials*, Proceedings of SPIE Volume **3578**, 16-26 (1998).
8. N. F. Borrelli, C. Smith, D. C. Allan, and T. P. Seward III, "Densification of fused silica under 193-nm excitation", *Journal of the Optical Society of America,* Volume **14**, 1606-1615 (1997). See especially Figs. 6 and 7.