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An AC phase measuring interferometer for measuring dn/dT of fused silica and calcium fluoride at 193 nm

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ABSTRACT

A novel method for the measurement of the change in index of refraction vs. temperature (dn/dT) of fused silica and calcium fluoride at the 193 nm wavelength has been developed in support of thermal modeling efforts for the development of 193 nm-based photolithographic exposure tools. The method, based upon grating lateral shear interferometry, uses a transmissive linear grating to divide a 193 nm laser beam into several beam paths by diffraction which propagate through separate identical material samples. One diffracted order passing through one sample overlaps the undiffracted beam from a second sample and forms interference fringes dependent upon the optical path difference between the two samples. Optical phase delay due to an index change from heating one of the samples causes the interference fringes to change sinusoidally with phase. The interferometer also makes use of AC phase measurement techniques through lateral translation of the grating. Results for several samples of fused silica and calcium fluoride are demonstrated.

Keywords: grating interferometer; photo-thermal measurements; optical properties; phase shift interferometry; refractometry; 193-nm lithography calcium fluoride; fused silica.

1. Introduction

The development of improved exposure tools for semiconductor photolithography requires better knowledge of optical properties of the optical materials used in the systems than has been previously available. Recent designs for exposure tools operating at the 193 nm ArF excimer laser wavelength employ refractive elements like fused silica and calcium fluoride extensively. While fused silica is widely used for its low coefficient of thermal expansion, the thermal effects on the index of refraction of fused silica is a significant parameter even at visible wavelengths—a property that is not widely appreciated. At 193 nm, these materials can absorb enough laser radiation to create deleterious thermal effects on the index of refraction that affect the system wavefront quality. Computer-based modeling is used to predict and compensate for the thermal effects,¹ but imperfect knowledge of the thermo-optical coefficient (dn/dT -- variation of index of refraction with temperature) of the candidate materials at the operational wavefront can limit the accuracy of thermal models. While Malitson's² measurements down to 213 nm and Ghosh's³ models for the index of refraction and dn/dT for fused silica indicate a rapid variation with wavelength and temperature near the 193 nm ArF excimer laser wavelength, specific measurements at 193 nm are lacking in the recent literature. Furthermore, there is the possibility that dn/dT may vary with the manufacturing processes that produce various grades of each material. For example, fused silica is produced by flame hydrolysis or by chemical vapor deposition, which can result in varying concentrations of OH radicals within the material. Therefore, a careful measurement of dn/dT is required for the currently available grades of optical material.

Historically, interferometric techniques for the measurement of temperature-induced refractive index variation have used, among others, the Rayleigh configuration.⁴ A more recent measurement⁵ used a Fizeau configuration and was capable of measuring material thermal expansion as well. These configurations make use of direct fringe counting techniques and are limited to the detection of fringe intensity peaks, rather than use of AC or phase shift interferometric methods that offer finer resolution. Also, the Fizeau configuration requires a source with a sufficient coherence length to account for the unequal path nature of the interferometer, and is thus limited in available sources and wavelengths. Current ArF lasers operating at 193 nm have a line width that limits the coherence length to about 40 microns, requiring an equal path interferometer configuration.

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2. Principle of Operation

The interferometer described here was developed to accommodate short coherence length sources, including excimer lasers, arcs, or incandescent sources. It is a near-common path interferometer that uses a diffraction grating as both the wavefront amplitude division element and as a phase or frequency shifting element for direct optical phase measurements by AC or phase shift techniques.

The interferometer consists of a collimated source, which can be a narrow band spectral source or a laser, a grating, and a concave spherical mirror. Three samples and three path length compensator assemblies are placed between the grating and the mirror. The mirror is positioned to reimage the grating back on itself near the mirror center of curvature.

The interferometer operates as follows: [Refer to fig. 1, which shows an unfolded representation of the optical path.] A laser beam incident on the grating is divided by diffraction into three wavefronts—a zero order W_0 , and plus and minus orders W_{+1} and W_{-1} . (Higher diffractive orders may also exist, but are not relevant to the analysis.) Each of the beams traverses through a sample window A, B, or C, and is reflected off of the mirror to retrace its path back through the sample to be reimaged onto the grating. At the grating, each of the three beams is diffracted again into three diffracted orders. Consider now the plus and minus diffracted orders that have passed through sample B. The minus one order W_0B_{-1} overlaps and interferes with the zero order $W_{+1}A_0$, while W_0B_{+1} overlaps and interferes with order $W_{-1}C_0$. A shift in optical path in any one of the beams will shift the phase of the interference pattern generated by the overlapping beams. Because each of the paths experience the same number of diffractive and transmissive passes through the grating, the overlapping beams have the same overall diffraction efficiency. Thus the fringe contrast in each path can achieve 100 percent.

We define the relevant wavefronts at the interference plane to be

$$\begin{aligned} W_{+1}A_0 &= e^{i\left(\frac{2\pi}{\lambda}OPD_A - \phi_G\right)}, & W_0B_{-1} &= e^{i\left(\frac{2\pi}{\lambda}OPD_B + \phi_G\right)} \\ W_{-1}C_0 &= e^{i\left(\frac{2\pi}{\lambda}OPD_C + \phi_G\right)}, & W_0B_{+1} &= e^{i\left(\frac{2\pi}{\lambda}OPD_B - \phi_G\right)} \end{aligned} \quad (1)$$

where OPD_i is the optical path in each of the sample paths and ϕ_G is the relative phase of the diffraction grating relative to the incident beam. It may be shown from simple application of Fourier theory that the phase of a diffracted order from a grating is proportional to the lateral position of the grating lines relative to the zero order input beam. As the grating is translated, a positive diffractive order increases in optical phase relative to the zero order, while a negative order experiences the opposite effect. Lateral displacement of the grating by one grating pitch will change the phase of a diffracted order by 2π radians. So ϕ_G is a term that is temporally modulated in a known manner. This effect will subsequently be used for temporal modulation of the interference fringes for AC phase measurements.

The detected interference terms are given by amplitudes

$$\begin{aligned} M &= W_{+1}A_0 + W_0B_{-1} \\ &= e^{i\left(\frac{2\pi}{\lambda}OPD_A - \phi_G\right)} + e^{i\left(\frac{2\pi}{\lambda}OPD_B + \phi_G\right)} \\ R &= W_0B_{+1} + W_{-1}C_0 \\ &= e^{i\left(\frac{2\pi}{\lambda}OPD_B - \phi_G\right)} + e^{i\left(\frac{2\pi}{\lambda}OPD_C + \phi_G\right)} \end{aligned} \quad (2)$$

where M and R are “measurement” and “reference” interference signals, respectively. The intensities of the signals are the square magnitudes of each of these amplitudes, and are given by

$$\begin{aligned} I_M(\phi_G) &= 2 + 2\cos\left(\frac{2\pi}{\lambda}(OPD_A - OPD_B - 2\phi_G)\right) \\ I_R(\phi_G) &= 2 + 2\cos\left(\frac{2\pi}{\lambda}(OPD_B - OPD_C - 2\phi_G)\right) \end{aligned} \quad (3)$$

If ϕ_G varies continuously linearly in time, both signals vary sinusoidally in time. The relative phase shift between signals M and R is then a direct measure of the phase difference between these two interference paths. Then:

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$$\begin{aligned}\phi_M - \phi_R &= \frac{2\pi}{\lambda} [(OPD_A - OPD_B) - (OPD_B - OPD_C)] \\ &= \frac{2\pi}{\lambda} [(OPD_A + OPD_C) - 2OPD_B]\end{aligned}\quad (4)$$

The double pass optical path difference in each OPD is represented by

$$OPD_i = 2(R - (n_i - 1)t_i) \quad (5)$$

where R is the radius of curvature of the mirror, n_i is the index of refraction and t_i is the sample thickness. The last two parameters are a function of temperature, so the change in optical path can be represented in differential form as

$$\begin{aligned}\Delta OPD / 2 &= \Delta((n-1)t) \\ &= \Delta(n-1) + (n-1)\Delta t \\ &= t \frac{dn}{dT} + (n-1)t \left(\frac{1}{t} \frac{dt}{dT} \right) \Delta T \\ &= t(\kappa + (n-1)\alpha) \Delta T\end{aligned}\quad (6)$$

where t , κ , α , and ΔT are the sample length, temperature coefficient of index (dn/dT), thermal expansion coefficient, and temperature change from a specific initial temperature, respectively. Substituting into eqn. (3), then the intensity variations in the interferometer associated with temperature changes in each of the samples is given by

$$\begin{aligned}I_M(\phi_G) &= 2 + 2 \cos \left(\frac{2\pi}{\lambda} 2(t(\kappa + (n-1)\alpha)\Delta T_A - t(\kappa + (n-1)\alpha)\Delta T_B - 2\phi_G) \right) \\ I_R(\phi_G) &= 2 + 2 \cos \left(\frac{2\pi}{\lambda} 2(t(\kappa + (n-1)\alpha)\Delta T_C - t(\kappa + (n-1)\alpha)\Delta T_B - 2\phi_G) \right)\end{aligned}\quad (7)$$

then the corresponding phase difference between signals M and R is represented by the difference in the arguments of the cosine terms in (7):

$$\phi(M - R) = \frac{2\pi}{\lambda} 2t(\kappa + (n-1)\alpha)(\Delta T_A + \Delta T_C - 2\Delta T_B) \quad (8)$$

This is the equation of a straight line with slope $\frac{2\pi}{\lambda} 2t(\kappa + (n-1)\alpha)$ and independent variable $(\Delta T_A + \Delta T_C - 2\Delta T_B)$ provided that κ and α are the same for each of the three samples, and are constant over the temperature range of interest. Thus, by tracking individual temperatures of the samples and measuring the total resultant phase shift between the reference and measurement channels, change in optical phase vs. temperature change between samples can be plotted.

If the phase ϕ_G of the grating can be made to vary linearly in time, then the two detected signals M and R vary sinusoidally in time. The grating phase can also be advanced in discrete steps that are a fraction of the grating pitch. By translating the grating in a known fashion, the relative phases of the signals can be deduced by one of a number of methods commonly employed in heterodyne or phase shift interferometry.⁶ Among others, zero-crossing based phase measurements can be used with a continuous translation of the grating, while phase shift in discrete steps is appropriate for the "multiple bucket" approach⁷ employed in a number of commercial phase measuring interferometers.

In the current instrument, the grating was translated with a electrostrictively actuated micrometer driven by a sawtooth waveform voltage. The phase difference between the two signals was made using a zero-crossing measurement because it was easily implemented with an available digital signal processing oscilloscope. Any phase measurement algorithm is only good to modulo 2π . Total phase changes greater than one fringe of OPD were tracked using a software phase unwrapping, or multiple fringe counting algorithm.

While conceptually more complex, this three beam interferometer is more stable than a two beam equal-path Michelson interferometer because the three beams allow for drift compensation. In a two beam instrument, one would measure the interference phase shift between a measurement beam and a reference beam. A single detector then measures the phase shift

in the interference fringes vs. temperature. If either beam drifts in path length due to movement of a retro-reflective mirror it is impossible to separate the drift from an intended thermal change, especially since both paths may lie 90 degrees from one another. In contrast, this interferometer uses common elements throughout, namely the grating and the return sphere. The interferometer is insensitive to a tilt of the return sphere or a lateral drift in the grating element as the detectors sensing both the M and R beams will see equal phase shifts during a system drift. A change in the spacing between the grating and return sphere is slightly sensitive, but not to the degree that a conventional two beam interferometer would experience because the angle between the two beams is reduced.

3. System Design

3.1 Optical Design

The interferometer was designed to accommodate existing material samples developed for a related material damage study. For a sample thickness of 10 mm and an estimated dn/dT of 15 to 25 parts/million/ $^{\circ}C$, (ppm/ $^{\circ}C$) the resulting fringe shift was estimated to be

$$\begin{aligned}\frac{d\phi}{dT} &= 2\pi \left(2 \frac{\kappa}{\lambda} t \right) = 2\pi \left(2 \frac{20 \text{ ppm}/^{\circ}C}{193 \text{ nm}} 10 \text{ mm} \right) \\ &= 2\pi \cdot 2.1 \text{ rad}/^{\circ}C \\ &= 2.1 \text{ fringes}/^{\circ}C\end{aligned}$$

The sample dimensions are 10 by 20 by 40 (± 0.1) mm. with parallelism between opposite faces better than 2 arc min. These dimensional tolerances exceed the coherence length of a 193 nm ArF excimer laser source (40 micron), so path length and wedge compensators must be included in the optical configuration. The path length/wedge compensator in each path is a Risley prism consisting of a pair of 2 degree wedged prisms made from the same material as the test samples. Angle magnitude adjustment is accomplished by counter-rotating the elements of the prism pair, while the orientation of the wedge is controlled by rotation of the prism pair together about the optical axis. Path length adjustment is performed by decentration of one prism with respect to the other. A 1 mm decentration results in a path length change of 20 microns, a dimension that is easily controlled with a fine pitch screw.

Analysis of the design of the interferometer using a standard optical design program (ZEMAX⁸) shows that it is relatively insensitive to misalignments of the sample cell. For example, rotation of the sample cell by 1 minute of arc results in a phase shift of less than 0.01 fringes at 193 nm, so small rotations of the sample cell due to system drift would be negligible.

3.2 Grating/phase shifter:

The grating pitch is chosen to accommodate the sample size and the radiation wavelength. The radius of curvature is likewise chosen to accommodate the sample size. For the current configuration, the minimum center to center sample spacing could be 45 mm. This accommodates a 2.7 degree diffraction angle generated by a 4 micron pitch grating. The grating was generated using direct writing electron beam lithography onto a chrome coated quartz substrate.

The grating was translated on a micrometer stage driven by an electrostrictive actuator powered by a high voltage ramp generator. The amplitude of the deflection was approximately 20 microns, resulting in a fringe shift of approximately 10 fringes at the detector. The ramp interval was 1 s. Because the electrostrictive actuator was somewhat non-linear in its response, adjustments had to be made in order to locate a reasonably linear region of grating displacement vs. time.

3.3 Signal Detection

Detection of the interference signals was accomplished with two silicon detectors optimized for UV operation. The laser was operated at a 50 Hz pulse rate. The pulsed signals were amplified and routed into sample and hold circuitry that converted the train of short pulses into a continuous waveform. Because the pulse to pulse intensity from an excimer laser can vary by as much as 10 percent, the signals were averaged and smoothed using a digital signal processing oscilloscope. The signal was averaged and filtered over a sliding 30 second measurement window, resulting in a uniform sinusoidal signal over the measurement range. Phase calculations were based upon zero crossing measurements of the measurement and reference signals relative to the linear ramp. Figure 3 shows the grating phase shifter hardware, as well as a representative oscilloscope screen trace.

3.4 Thermal design

Each sample was placed in a temperature controlled oven which could regulate the temperature to better than 0.01 °C over a period of one hour. The oven consists of a break-apart copper jacket with a wall thickness of at least 5 mm thick around the sample. Two 15 mm diameter holes centered on opposite faces provide optical access along the 10 mm dimension of the sample. A thermoelectric module (TEM) on a side face heated or cooled the sample oven. Temperature error sensing was provided by a precision thermistor inserted in a hole in the jacket near the TEM. The thermistor was placed close to the TEM in order to reduce oscillatory behavior of the control circuit due to thermal lag. Temperature control was then maintained by a commercially available proportional integrating differential (PID) analog temperature control circuit designed for laser diode temperature control or other precision temperature control applications.

Actual temperature monitoring was performed by a second thermistor placed in contact with the sample surface as close as possible to the optical interferometer probe beam. All sample surfaces in contact with the copper jacket were coated with a high thermal conductivity silicone-based grease. Likewise, the sample thermistor was in thermal contact with the sample surface via the thermal grease. Foam insulation surrounded each oven to help stabilize temperature.

Thermal analysis of the jacket shows that radiative losses through the windows would cause the surface temperature at the center of each window to drop a maximum of 4 percent below the temperature at the window edge. (Figure 4). Thus, a correction could be applied to the temperature measured. Actual position of the thermistor relative to the beam was close enough that this correction proved unnecessary. Figure 5 shows the three sample ovens, as well as the phase/wedge compensator assemblies and the spherical retro mirror. During measurement cycles a foam box to stabilize the temperature and reduce turbulent air currents enclosed the entire interferometer.

3.5 Data acquisition

The initial plan was to allow the sample to stabilize to a given temperature, after which a phase shift and corresponding temperature readings would be manually taken. However, inconclusive results were obtained with this approach because the system took too long to achieve thermal equilibrium with each new temperature setting. Instead, a digital PID controller was developed using the LabView™ instrumentation program⁹ to provide a near linear ramp of the sample oven temperature. The temperature was linearly cycled over a 3 °C temperature range. All the while, the temperatures of all three sample ovens, as well as the phase difference between the two detected signals were recorded under LabView. Measurements of all of these parameters were recorded every 10 seconds and averaged in a running measurement window. Data was then analyzed using a computer spreadsheet program.

4. Measurement Results

Measurements were made for several grades of fused silica from a number of manufacturers. In some cases disassembling and reassembling an oven using the same sample checked the repeatability of the instrument. The raw results from a typical fused silica measurement are shown in figures 6 and 7. Figure 6 shows a representative data set plotted against acquisition time. Figure 7 is a parametric plot of the total effective optical path change vs. temperature change for the same measurement. In these two plots, the reference, measurement (uncorrected), and measurement minus reference (drift corrected) channels are all plotted simultaneously to demonstrate that the interferometer corrects for drift.

The optical path change is expressed as an effective index change by dividing by the optical path length change by the total sample thickness. The best-fit slope as established by linear regression is then the effective dn/dT .

However, this plot does not account for the effect of linear expansion that also contributes an optical phase change to the measurement, as shown in eqn. 8. This may be accounted for by subtracting out the value $(n-1)\alpha$ from the effective dn/dT to yield the corrected value. The value of α for fused silica is 0.56 ppm/°C and $n(193\text{ nm})=1.56$. Then, the dn/dT measurement is reduced by an amount 0.31 ppm/°C.

Note, too, that there is a hysteresis-like loop in the data due to thermal lag in the sample when the temperature cycle is reversed and temperature transients exist in the sample. Individual slopes were then calculated over a temperature range that avoids the endpoints of the temperature cycle.

Another effect that requires correction is heating of the air path near the sample oven. This is the largest systematic error in the measurement. The dn/dT of air at 193 nm in a standard laboratory environment is calculated to be -1.1 ppm/°C, based upon modeling by Barrell and Sears¹⁰. Thermocouples placed near the optical path near the oven in measured locations show that the air temperature tracked the sample temperature, decreasing in effect as the distance from the sample increases. The

individual thermocouple measurements in air and the resulting effective calculated integrated optical path variation are plotted in figures 8 and 9. From this data the effective optical path was estimated to contribute an effective dn/dT error on the order of $-2.3 \text{ ppm}/^\circ\text{C}$. A calculation based upon the thermal model of the oven showed a contribution on the order of $-1.5 \text{ ppm}/^\circ\text{C}$. The thermocouple-based correction (figure 9) was chosen as being more realistic. Therefore a correction of $+2.3 \text{ ppm}/^\circ\text{C}$ is added to the measurements.

The average value for dn/dT of SiO_2 is then $+22.3 \pm 1.11 \text{ ppm}/^\circ\text{C}$ for all but one material sample type tested (Sample "B"). This sample had a value of 24.15 ± 0.77 , and is believed to be of a significantly different composition than the other samples of SiO_2 tested.

Measurements for calcium fluoride samples were also made. One sample each, from two suppliers, were tested, for a total of 22 separate measurements. A correction of $-9.5 \text{ ppm}/^\circ\text{C}$ was applied to the data to account for a material α of $19 \text{ ppm}/^\circ\text{C}$ and an index of 1.501, as well as the air heating correction. The average value of dn/dT for CaF_2 is $-5.9 \pm 0.78 \text{ ppm}/^\circ\text{C}$. The complete results for SiO_2 and CaF_2 are summarized in Table 1.

5. Conclusions

The change in index of refraction vs. temperature of two materials critical for 193 nm lithography has been successfully performed using an interferometric method.

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7. References

1. S. E. Gianoulakis, "Modeling Software to Predict the Performance of Optical Materials in 193 nm Systems", presented at Second International Symposium on 193 nm Lithography, Colorado Springs, CO, Jul 30-Aug 2, 1996.
2. I. H. Malitson, "Interspecimen Comparison of the Refractive Index of Fused Silica," *J. Opt. Soc. Am.* **55**, pp. 1205-1209 (1965).
3. G. Gosh, "Temperature Dispersion of Refractive Indexes in Some Silicate Fiber Glasses", *IEEE Photonics Technology Letters*, **6** (3), pp 431-433 (1994).
4. G. E. Fishter, "Refractometry", in *Applied Optics and Optical Engineering IV*, R. Kingslake, Ed., p. 378 (Academic Press, 1968).
5. J. M. Jewell, C. Askins, and I. D. Aggarwal, "Interferometric method for concurrent measurement of thermo-optic and thermal expansion coefficients," *Appl. Opt.* **30**, pp. 3656-3660 (1991).
6. J. E. Grievenkamp and J.H. Bruning "Phase Shifting Interferometers" in *Optical Shop Testing*, 2nd Ed., Daniel Malacara, ed. p501, John Wiley & Sons, 1992.
7. J. C. Wyant, "Use of an ac heterodyne lateral shear interferometer with real-time wavefront correction systems," *Appl. Opt.* **14**, 2622 (1975).
8. ZEMAX is a product of Focus Software, Tucson, AZ.
9. LabView is a product of National Instruments Corp., Austin, TX.
10. H. Barrell and J.E. Sears, *Trans Roy. Soc A* **238**, 1 (1939).

8. Tables

Table 1 Summary results for fused silica—various manufacturers

Sample ID	dn/dT (ppm/ $^{\circ}$ C) (Corrected)	Std. Dev.	No. of Measurements
SiO ₂ Results: A	22.40	1.14	30
B	24.15	0.79	12
C-1	22.24	0.54	6
C-2	22.19	0.77	12
D	21.99	1.52	12
Overall Average SiO ₂	22.57	1.27	
Overall Average SiO ₂ (excluding Sample B)	22.28	1.11	
CaF ₂ Results F	-5.82	0.88	16
G	-6.02	0.38	6
Overall Average (Both samples)	-5.89	0.78	

9. Figures

Figure 1 Interferometer concept (unfolded schematic)

Figure 2 Interferometer schematic as implemented

Figure 3 Grating phase shifter assembly and signal display

Figure 4 Thermal model showing temperature distribution around sample window

Figure 5 Sample Ovens, Phase/wedge adjust assembly and spherical retromirror

Figure 6 Representative data set—change in effective index, temperature vs time Fused Silica Sample. Note that the middle two channels (sample and reference) show drift, while the top trace has been corrected for interferometer drift

Figure 7 Index change vs temperature variation before air path index correction—representative data—fused silica

Figure 8 Representative temperature, calculated air optical path variation over measurement path for correction of dN/dT of air.

Figure 9: Computed equivalent index of refraction variation over air path as a function of sample temperature

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