At-wavelength characterization of DUV-radiation-induced damage in fused silica

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ABSTRACT

Fused silica is the optical material of choice for deep ultraviolet (DUV) lithographic systems. However, this material is subject to irradiation-induced compaction with ArF excimer radiation. Here we report direct, at-wavelength, wavefront measurements of DUV-laser-damaged fused silica samples performed using phase-shifting point diffraction interferometry (PS/PDI). Experimental results show that the damage anneals in the temperature range of 200 ~ 600°C. Finally, the interferometric measurements are compared to birefringence studies performed on the same samples.

Keywords: 193 nm lithography, DUV lithography, phase shifting point diffraction interferometry, irradiation –induced compaction, fused silica, birefringence measurement, optical material.

1. INTRODUCTION

The fabrication of electronic devices with ever-smaller feature sizes is an ongoing challenge for the integrated-circuit manufacturing community. Recently, the industrial standard critical dimension for integrated-circuit devices has dropped from 0.35 μm to 0.25 μm. Further progress to critical dimensions of 0.18 μm and 0.13 μm are anticipated by reducing wavelength from 248nm to 193nm.

At both 248 nm and 193 nm, the choice of optical materials is limited essentially to fused silica and CaF_2. For reasons of homogeneity, cost, and availability, the former is preferred. However, fused silica is subject to both irradiation-induced color center formation and compaction at DUV wavelengths.[5] Compaction introduces phase aberrations in lithographic optical systems owing to both the change in refractive index of the compacted area and the path-length change through the optic.[3]

DUV-radiation-induced densification in fused silica has been previously studied with stress-induced birefringence measurements and visible-light interferometers.[4-6,9-10] Isothermal annealing of the damage has been demonstrated with birefringence measurement.[3,6-7] However, the birefringence test measures the $\Delta\rho/\rho$ at 633-nm wavelength and extracts $\Delta n/n$ using fitting routines for 193-nm wavelength applications. The material properties cannot be directly interpreted from one wavelength to the other wavelength due to the dispersion relation of materials. Thus, the birefringence method could conceivably lead to errors the predicted refractive index change.

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Here we present a study of damage and annealing of DUV (λ=193nm) radiation-induced damage in fused silica using a phase-shifting point diffraction interferometer (PS/PDI)[1-2] at 193-nm wavelength. Because the method used here is a direct, at-wavelength phase measurement, it has advantages over the birefringence method.

2. EXPERIMENTS AND RESULTS

The phase measuring device employed here is a version of the PS/PDI[2] implemented at a wavelength of 193 nm and modified to test flat samples. A detailed description of the 193-nm PS/PDI can be found in the literature.[1] The illumination source is a Lambda-Physik LPX-140I pulsed ArF excimer laser operating at 193 nm. This laser provides pulse widths of approximately 18 nsec (FWHM) at 150-Hz and can be operated at repetition rates as high as 400-Hz with a maximum power output of 60 W. This laser was used for both the interferometric testing and irradiation-damage phases of the work presented here.

2.1 Testing of UV damaged fused silica samples

To see the effects of DUV-induced radiation damage and subsequent isothermal annealing, two samples of fused silica (type B, supplied by SEMATECH[3]) were characterized in the interferometer three separate times: before and after DUV-radiation-induced damage and after isothermal annealing. The samples used came from the same manufacturer and were virtually free of metallic impurities and contained approximately 1000 ppm OH. The samples had dimensions of 4 x 2 x 1 cm and were polished on all six surfaces.

The samples were interferometrically characterized over a 15-mm diameter area as depicted in Fig. 1. A hard aperture was placed on the surface to define the test area and serve as a fiducial for the three tests. Figures 2(a) and (b) show the measured wavefronts over the 10-mm sub-region in the test area for the two virgin samples (A and B).

After measuring the quality of the two virgin samples with the PS/PDI, the samples were damaged by placing them in the raw LPX-140I beam. An approximately 5-mm diameter area centered in the measurement region was exposed. The damage exposure region was significantly smaller than the 15-mm measurement region. The exposure uniformity was measured to be 33% peak-to-valley from edge to center for the two samples. The beam profile was also observed to be assymetric, which we believe leads to the damage asymmetries seen in Figs. 2(c) and (d). Sample A was exposed for 7 hours at an average power of 730 mW, which corresponds to a dose of 23.43 KJ/cm^2, and sample B was exposed for 5 hours at 760 mW, which corresponds to a dose of 17.43 KJ/cm^2. The laser repetition rate was set to 330 Hz in both cases.

After the damage exposures, the samples were retested in the PS/PDI over the same region. Figures 2(c) and (d) show the resulting wavefronts obtained from averaging 80 measurements over the 10-mm sub-region in the test area for the two samples (A and B). To remove the systematic effects and isolate the effect of the UV damage, the difference wavefront between the before and after damage results is calculated and displayed in Figs. 2(e) and (f). Figures 3(a) and (b) show wavefront cross-sections plots through the center of the difference wavefronts, in Figs. 2(e) and (f), respectively. As evidenced by Figs. 2 and 3, the UV radiation changes the optical path length of the material, indicating changes in index of refraction and/or reduction in volume.

The damaged spot geometry can be analyzed by using a three-region stress model,[11] which is depicted in Fig. 4. The three regions are defined by the ideal UV beam geometry: for $r < r_i$, the intensity is approximately uniform and induces uniform compaction, between r_i and r_o, the intensity drops to zero and causes a transition area where stress develops (beyond the range of irradiation).[3]

The OPD changes seen in Figs. 2 and 3 are due to two effects: i) the index of refraction change in the compaction region and ii) a surface indentation due to volume contraction which extends beyond the compacted region. These two effects cause changes of opposite sign to the OPD; increase in refractive index yields a positive OPD while volume compaction generates a negative OPD. In the region within r_i, compacted area region 1, the dominant effect on the OPD change is the increase in refractive index making the OPD positive, whereas for $r>r_i$, stressed region 2, the OPD drops rapidly to zero, indicating the increase importance of the surface-depression effect on the OPD. Also, it is clear that the wavefronts are zero outside of the damaged area, indicating uncompacted region 3. In order to isolate the effects from the radiation damage, the before and after damage wavefronts are subtracted. The zero-phase-change plane can be established by using the data from the region 3, as in this area no phase change is expected.
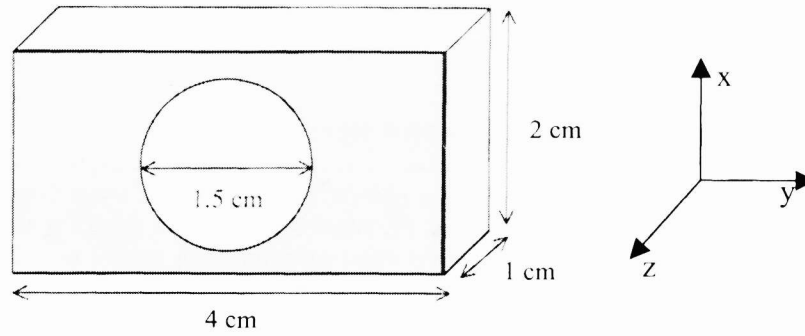
Figure 1. Geometry of the fused silica sample under test. All six surfaces are polished, and the sample was tested with the illumination propagating in the z-direction with the x-y plane surface being imaged onto the CCD. A hard aperture of diameter 15 mm was placed on the sample.
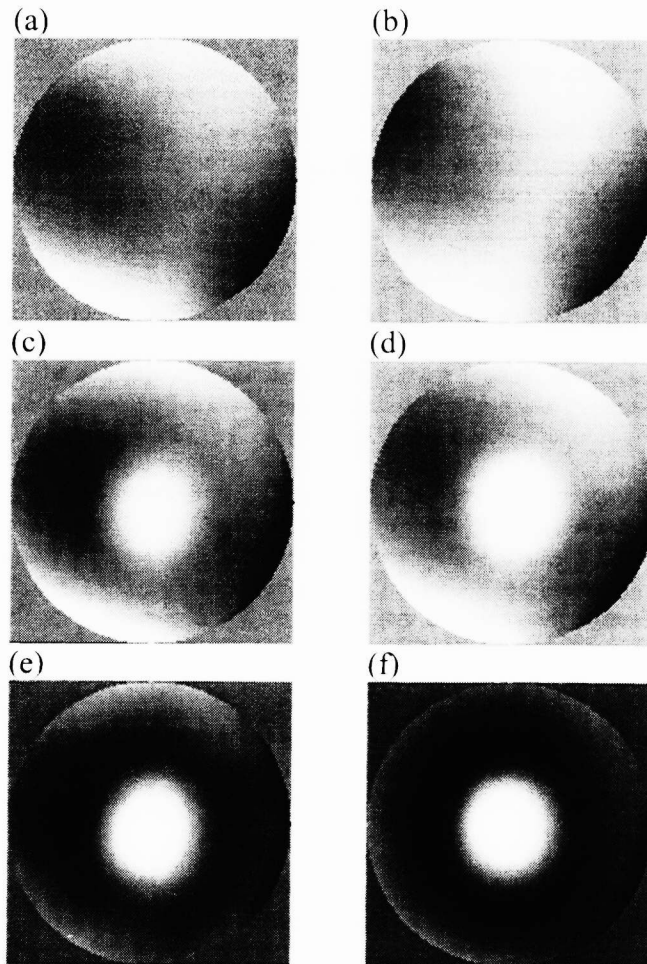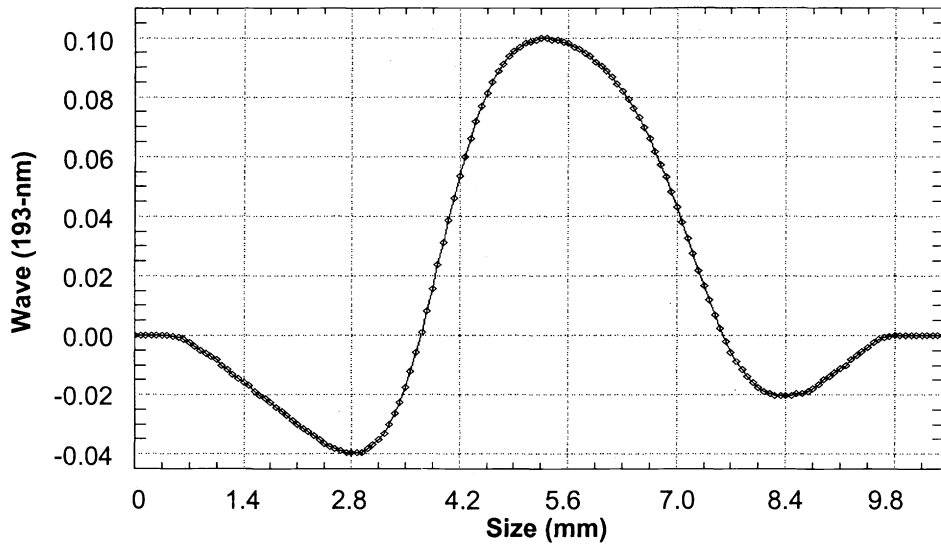

Figure 2. Measured wavefront from (a) sample A and (b) sample B, before UV radiation damage. Reconstructed wavefront from (c) sample A and (d) sample B, after UV radiation damage. Difference between the before and after damage wavefronts for (e) sample A and (f) sample B.
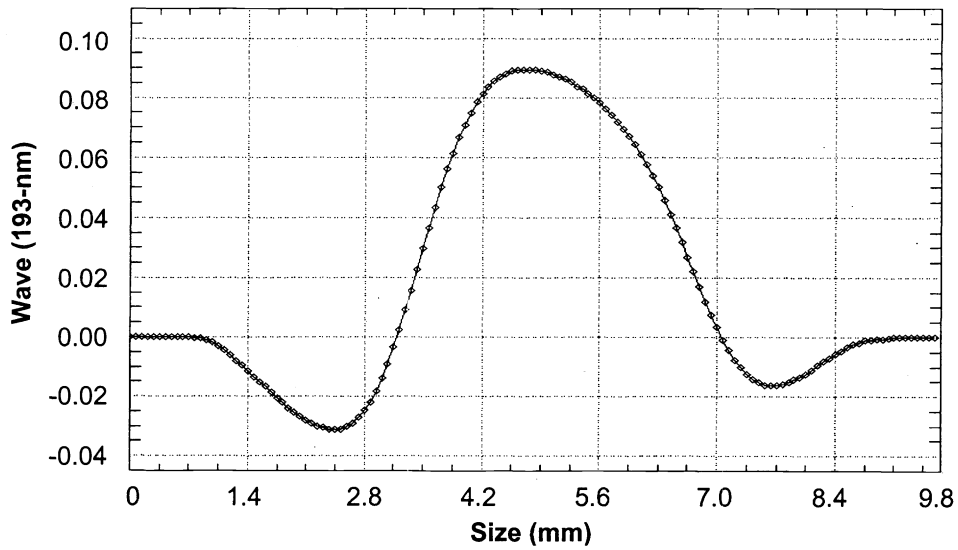
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(a)

(b)

Figure 3. Wavefront-center cross section for difference wavefronts shown in (a) Fig. 6(e) (sample A) and (b) Fig. 6(f) (sample B). X-axis indicates the size of the damaged region in mm and y-axis indicates the OPD in waves at 193 nm.
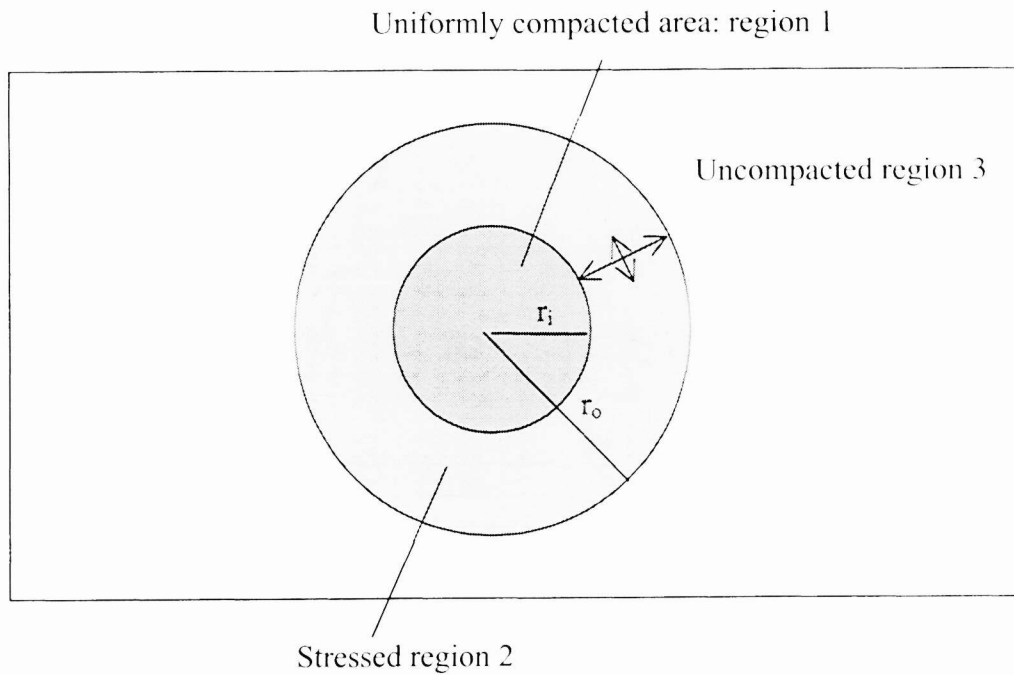
Figure 4. Schematic drawing of the damaged spot geometry on the samples. Region 1 is approximated to be uniformly compacted, while the transition region (region 2) suffers from stress.
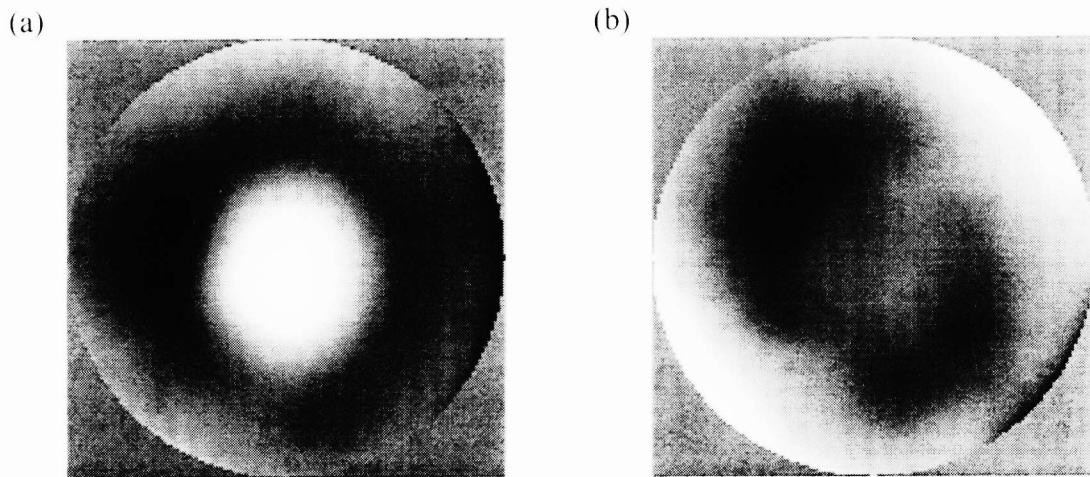

Figure 5. (a) The resulting difference wavefront, subtracting the wavefront of the virgin sample from the wavefront of the thermally annealed *sample A*, annealed at 200 degrees C for 35 minutes at atmospheric pressure. (b) The resulting difference wavefront, subtracting the wavefront of the virgin sample from the wavefront of the thermally annealed *sample B*, annealed at 600 degrees C for 60 minutes at atmospheric pressure.

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The overall OPD before and after the damage can be described by the following equation;

$$OPD = \Delta L(n_{air} - n_{fused\ silica}) + \Delta n(L - \Delta L) \qquad\qquad Eq.\ (1)$$

where ΔL, Δn, and L indicate the surface indentation, refractive index change, and the sample thickness respectively. Knowledge of ΔL is required to calculate $\Delta n/n$ as indicated in Eq. (1) and can be obtained directly from Fig 3.

The minimum magnitude points in Fig. 3 indicate the positions where the surface indentation effect and refractive index effect are balanced. By choosing this balanced point as the cut-off line between region 1 and region 2 shown in Fig. 4, ΔL can be extracted by assuming only surface depression exist in region 2, and it is calculated to be 10.32 nm. This balance point is found to be 28.5% of the peak OPD due to refractive index change. With this approximation, the peak $\Delta n/n$ is found to be 1.61 ppm and 1.42 ppm for samples A and B, respectively.

The role of the surface indentation effect, ΔL, on the OPD has been studied in detail using finite element simulations[11,12] and found to be approximately 30% of the OPD due to refractive index change for similar sample and irradiation geometry as described here. This is in good agreement with the 28.5% value found above. The surface indentation effect has also been shown to a strong function of sample geometry and damage area. It tends to increase as the damage area increases and the thickness decreases.[12] More complete study of the surface indentation would require reflection interferometry, which could be performed by replacing mirror M1 in the PS/PDI with sample surface. Alternatively, the surface indentation value could be determined using conventional (visible light) interferometry as has been discussed in the literature.[4] The at-wavelength characteristics of the PS/PDI presented here are less important for reflection studies.

Because of its high sensitivity, birefringence has been widely used to measure the refractive index change from material densification.[3,6-9,11-12] For comparison purposes, birefringence tests were also performed on the two samples. Spatial distributions of the stress-induced birefringence were recorded for the two samples by scanning the damaged fused silica samples through an initially linearly polarized HeNe laser beam and measuring polarization shifts in and around the irradiated region. This test resulted in $\Delta n/n$ of 1.4 ppm and 1.2 ppm for samples A and B, respectively, in reasonable agreement with the direct PS/PDI measurement results. The differences stem from calibration of the birefringence measurement and complication in extracting refractive index change from fitting routine, experimental errors, and our over simplified approach to division of OPD between compaction and geometrical effects.

## 2.2 Isothermal annealing of UV-induced compaction

Earlier birefringence studies of the temperature dependent UV compaction rate in fused silica have shown that damage in fused silica can be annealed at rather low temperature in the range 200 ~ 600 °C.[3,6-7] The two samples studied here were isothermally annealed at different temperatures and remeasured in the PS/PDI. Sample A was annealed at 200 °C for 35 minutes and sample B at 600 °C for 60 minutes.

The resulting difference wavefronts, subtracting the wavefront of the virgin sample from the wavefront of the thermally annealed sample, are shown in Figs. 5(a) and (b) for samples A and B, respectively. Cross sections of the wavefronts in Figs. 5(a) and 5(b) are shown in Figs. 6(a) and (b). Approximately 28% compaction recovery is observed for sample A, and almost complete recovery is observed for sample B. Small amount of negative wavefront for sample B indicates some permanent surface indentation around the damaged area even after 600 °C thermal annealing. In agreement with the PS/PDI results, birefringence measurements revealed approximately 30% recovery for sample A and almost complete recovery for sample B.[3]

3. CONCLUSION

Direct measurements of the OPD of damaged fused silica samples have been obtained with a PS/PDI operating at a wavelength of 193 nm. Refractive index changes in the 1-2 ppm range are in reasonable agreement with birefringence measurement. The surface indentation and the index of refraction change can both be measured directly in 193-nm transmission interferograms. Damage recovery by isothermal annealing has been also verified with the interferometer.
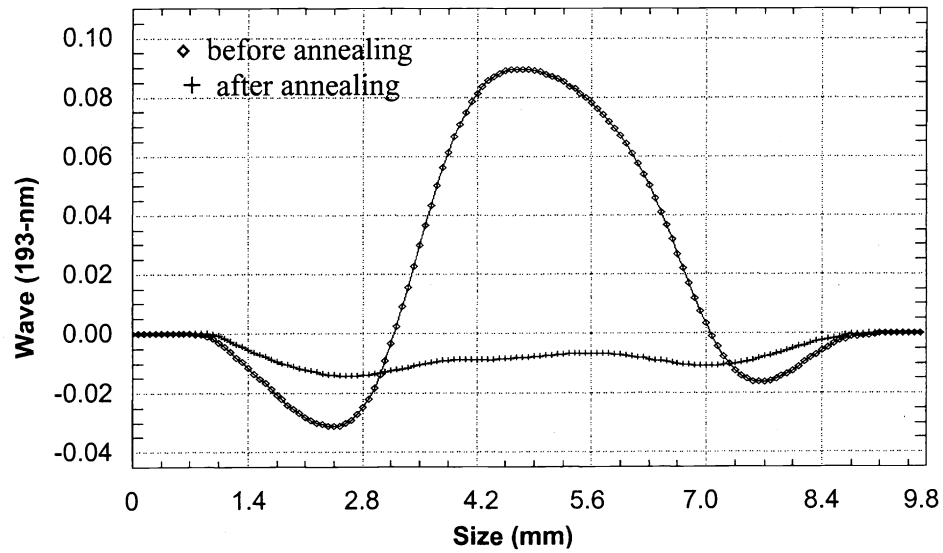
(a)
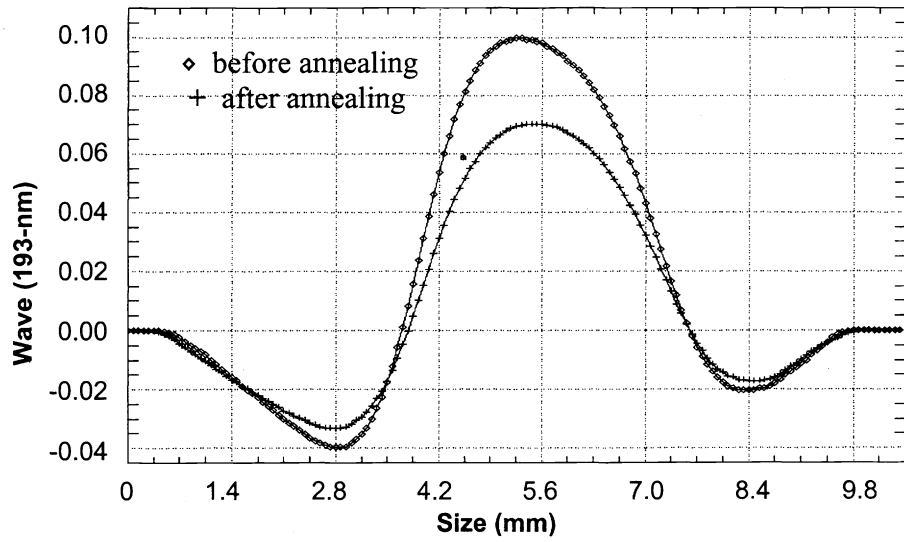
(b)

Figure 6. Cross sections of the difference wavefronts *relative to* the virgin wavefronts, before and after thermal annealing. (a) Sample A shows approximately 28% recovery in peak OPD, and (b) sample B shows almost full recovery.

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4. ACKNOWLEDGEMENT

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