Ablation-induced stresses in fused silica by 157-nm F₂-laser irradiation

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ABSTRACT

The F₂ laser is a promising source for direct etching of microstructures and the precise shaping of optical-grade surfaces on wide bandgap materials such as fused silica. We report here on residual tensile stresses induced in fused silica (Corning 7940, UV grade) by 157-nm laser ablation. Plastic strain of 160-mm thick rectangular strips, monitored with an optical interferometric microscope, revealed the presence of residual tensile stresses in the near-ablated surface. HF chemical thinning of the sample showed the thickness of ablation-affected layer provoking strain was ~275 nm, a value independent of laser fluence (1.9-4.7 J/cm²) and scanning speed (94 - 220 μm/s). A near-surface mean residual tensile stress of ~80 MPa was inferred from a thin film-substrate approximation.

INTRODUCTION

Thin-film devices and systems consisting of dissimilar materials or layers frequently exhibit substantial residual stresses as noted in numerous studies of thin films [1]. Large residual stresses can also develop during surface treatment involving ion, electron, or laser beams. While such treatments offer improved surface properties, the residual stresses become increasingly important in microsystems where feature sizes are shrinking to the dimensions of the affected surface layer. Residual stresses can hinder the operation of microelectronic, photonic or biological components and can lead to bending or buckling of micro-electromechanical devices (MEMs).

In laser material processing, a field of widespread commercial significance, residual stresses arise in the shaping and machining of materials and in the texturing and modification of surfaces. Laser-induced residual stresses can grossly affect the macroscopic properties of materials, when using ultraviolet lasers such as excimers to define feature sizes on the scale of 100's of nanometers. This paper examines the stresses formed by laser ablation of fused silica, a high-quality material widely used in optical and photonic applications.

Laser damage and laser ablation of fused silica has been extensively studied using conventional sources such as CO₂, YAG, visible, and excimer [2-7]. Several kinds of damage related to residual stresses have been noted for fluences below the ablation threshold. Material densification and concomitant refractive index changes lead to residual tensile stresses in irradiated glasses [13]. Another form of damage includes the generation of surface or internal cracks, and the manifestation of residual tensile-stress fields around the crack [14-15]. Microcrack formation is common for fluences above the ablation threshold. In these cases, residual stresses increase with increasing fluence or number of laser pulses.

For a special class of short wavelength sources such as the vacuum-ultraviolet Raman laser [6-9] and the 157-nm F₂ laser [10-12], precise etch-rate control and smooth morphology

are available over a wide fluence range without deleterious effects such as microcracking or bulk coloration. While prospects for shaping optical materials and fabricating photonic components are highly promising, bending and distortion of small fused silica samples has been noted in our laboratory during 157-nm laser ablation. Laser ablation provides rapid heating of thin melt zones and glassy-temperature zones that generally supports stress relaxation. This is followed by residual tensile stress formation during the cooling cycle to ambient temperature [16]. The purpose of this paper is to evaluate residual stress formed during crack-free ablation of fused silica with a 157-nm laser. A ~275-nm thick laser-affected layer was noted, which together with a thin-film-on-substrate model [17] of sample bending, yielded an average tensile stress of ~80 MPa.

ABLATION EXPERIMENTS

A F₂-laser (Lambda Physik model LPF 220i) provided 15-ns pulses at 157-nm wavelength. A CaF₂-lens pair (18-cm and 7-cm focal lengths) demagnified the 22-mm x 7-mm beam to provide uniform exposure of a rectangular mask at ~45 mJ/cm² fluence. The mask was imaged by a MgF₂ lens (5-cm focal length) using ~15x demagnification to provide spatially uniform fluence ($\pm 5\%$) in the range of 1.9 - 4.7 J/cm² on target samples. These fluences exceed the 1.0 J/cm² ablation threshold of fused silica [11]. The beam line and target chamber was evacuated of air and flushed with argon (500 mTorr) to provide transparency at 157-nm. Details of the optical system have been described previously [11-12].

Fused silica cover slips (Corning 7940, UV grade) of 160- μ m thickness were cut with a diamond scribe into 0.25-mm by 10-mm rectangles, a geometry offering pronounced bending when laser ablated. Samples were dipped in HF acid (50%) for 90 s to relieve stresses induced by the scribing process. Samples were cleaned with alcohol solvent and mounted onto an x-y translation stage inside the target chamber in the orientation shown in Fig. 1. The laser beam overfilled the sample width and the sample was scanned vertically at speeds of 94 or 220 μ m/s. The laser repetition rate was 10 Hz. Vertical and horizontal surface profiles of a static fused silica sample are shown on the left in Fig. 1 for ablation with 25 pulses at 4.7-J/cm² fluence. A moderately uniform excision of 2.2- μ m depth is noted. Ablation depths for scanned samples varied from 0.15 to 1.0 μ m. Ablation debris of 10 to 20 nm thickness typically accumulated over the scanned surface sample for these scanning speeds. Thicker coatings can affect the sample bending but were not thought to influence the observations in the present case.

Sample surface profiles and shapes were characterized with a WYKO optical surface profiler (white-light vertical-scanning interferometry mode) before and after laser ablation. One end of the sample was clamped to stabilize the interferometric fringes without distorting the sample. A stylus profilometer (Tencor) was used for short-range surface morphological measurements.

The thickness of the laser-affected layer was evaluated by etching bent samples (10's of seconds) in hydrofluoric acid (50%) and noting the bending radius as a function of the chemical etch depth. Chemical etching increased the surface roughness slightly to <10 nm (rms).

RESULTS AND DISCUSSION

All ablated samples bent toward the same direction – opposite to the laser beam direction – indicating the development of tensile stresses immediately below the ablation

Figure 1. Horizontal (a) and vertical (b) ablation beam profiles (Tencor stylus profilometer) for 157-nm ablation of fused silica (left) ablated with 25 pulses at 4.7 J/cm^2 . Schematic (right) showing the orientation of the laser-ablation beam relative to scanning fused silica sample. See text for further details.

surface. Material compaction is anticipated in this layer. Compaction of fused silica is observed when below-ablation fluence irradiates surfaces. Figure 2 (left) shows the convex back surface of an ablated sample with a center deflection of 180 nm across a 4.7-mm span. Surprisingly, a center deflection of $195 \pm 15 \text{ nm}$ was noted for all irradiated samples irrespective of the fluence ($1.9 - 4.7 \text{ J/cm}^2$), the scanning speed (94 or $220 \text{ } \mu\text{m/s}$), or the ablation depth ($0.15 - 1.0 \text{ } \mu\text{m}$) applied to the samples. This consistency suggests the formation of a fixed thickness of laser-affected material. Each additional laser ablation pulse must therefore remove and generate an equal thickness of tensile material in the laser-affected layer.

Single-pulse ablation rates (depth D) for fused silica follow [11] a logarithmic fluence dependence characteristic of strongly absorbing polymers and dielectrics:

$$D = (1 / \alpha) \ln (F / F_{th}) \quad (1)$$

Here, $\alpha = 1.7 \times 10^5 \text{ cm}^{-1}$ is the effective absorption coefficient, F is the laser ablation fluence, and $F_{th} = 1.0 \text{ J/cm}^2$ is the ablation fluence threshold. This relation suggests that a fixed fluence, F_{th} , will penetrate to the ablation-melt interface (at depth D) irrespective of the incident laser fluence. Larger fluence values are balanced by removal of thicker layers of material.

Figure 2. Left figure shows a typical surface profile (WYKO) of F_2 -laser ablated fused silica recorded along the vertical axis (see Fig. 1) of the non-radiated side. A 500-nm deep surface layer was excised at 4.0 J/cm^2 fluence and $220\text{-}\mu\text{m/s}$ scanning speed. The center is deflected by 180-nm over a 4.7-mm span. Right figure shows the front surface of this sample following chemical etching to $\sim 300 \text{ nm}$ depth. The sample is flat with a rms surface roughness of 20 nm.

Laser generation of tensile stress layers are also manifested in 157-nm laser cutting of fused silica cantilevers. Fig. 3a shows the schematic outline of a $200\text{-}\mu\text{m}$ wide by 10-mm long slot laser-cut in $160\text{-}\mu\text{m}$ thick fused silica. When one end of the slot was broken (Fig. 3b), the cantilever arms moved 10% closer together ($180\text{-}\mu\text{m}$ separation) as shown in Fig. 3d compared with the original $200\text{-}\mu\text{m}$ gap shown in Fig. 3c. This inward direction is further evidence for the formation of tensile stresses in the laser-ablated walls of fused silica. Such bending with ablation-induced stresses limits the precision available in laser machining of 3-dimensional silica microstructures.

The material compaction and concomitant tensile stress generation as evidenced in Figures 2 and 3 must occur in thin layers. Thermal diffusion suggests a $\sim 100\text{-}\mu\text{m}$ thick heating zone in fused silica during the 15-ns laser-heating pulse while the effective-absorption coefficient (Equation 1) provides a 59-nm value for the optical penetration depth (during laser ablation). To better assess the laser-affected layer thickness, strained samples were thinned by wet chemical etching until stress relief was noted. Figure 2 (right) shows a sample flattened after etching 300-nm of the sample surface. A slight increase in surface roughness to 20 nm (rms) is noted. The radius of curvature was doubled (deflection halved) when only a 100-nm thick surface layer was chemically removed. These values only slightly exceed the thermal transport and optical penetration depth associated with 157-nm laser ablation, and is much smaller than the $160\text{-}\mu\text{m}$ thickness of the fused silica sample. More precise chemical etching data is one future goal of this group to determine tensile stress relief below the ablated surface.

A thin film having uniform stress, σ , will deflect a long thin substrate to radius, r , according to [17]

$$\sigma = Ed^2 / 6rt. \quad (2)$$

Here, E is Young's modulus for the substrate, d is the substrate thickness, and t is the thickness of the film. Strain associated with tensile stress in the film yields a concave shape on the thin film side, similar to the deflection caused by tensile stresses in the laser-affected layer of the

present fused silica strips. If we assume the stress profile in the laser-affect layers of fused silica is

Figure 3. Schematic and photos of fused silica with a laser-cut trough: (a) drawing of sample with trough before breaking along section B; (b) photo of the sample showing the broken end near B; (c) magnification of 100- μm trough at section A; (d) tensile stresses on laser cut surface is revealed by reduced width (180- μm) of trough at section B after breaking. The optical microscope was imaged on the top surface of the sample.

uniform across a 275-nm thickness, then the tabulated value of $E = 72$ GPa [18] yields an average residual stress of 80 MPa directly below the laser-ablated surface. Larger stresses are anticipated at the ablated surface, yielding stresses well above the 50 MPa tensile strength of bulk-fused silica [18, 19].

Such a large tensile stress may be stable if 157-nm laser ablation strengthens the near-surface layer (200-300 nm) of fused silica. Tensile strengths up to 6 GPa have been reported [22, 23] in undamaged fused-silica fibers. However, for the bulk samples studied here, much lower strengths are anticipated. Further, optical polishing is widely known to induce surface defect states and stresses that weaken the surface. Laser-damage studies of glass windows also demonstrate the importance of surface treatments and underlying stresses on the value of the damage threshold – typically noted as the onset of microcrack formation. For example, the 325-nm laser-damage threshold for thermally treated glasses (fused silica and BK-7) is 2–4 factors less than untreated samples [20], while cleaved fused silica generally offers comparably higher damage threshold [21]. Such surface treatment does not appear to play a significant role in 157-nm laser ablation of fused silica [10, 11]. Surface damage and microcracks are rarely observed with this source suggesting a different mechanism that possibly strengthens the underlying ablated surface. Laser treatments that strengthen optical glasses are highly desirable and deserve further study.

CONCLUSIONS

F₂-laser ablation of fused silica generates localized tensile stresses in a thin ~275-nm surface layer that is independent of fluence (1.9- 4.7 J/cm²) and ablation depth (150-1000 nm). An inferred tensile stress of ~80 MPa was found to exceed the tensile strength of polished fused silica, suggesting the a possible laser ablation mechanism that strengthens the fused silica surface.

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