Appl. Phys. A 82, 325–328 (2006)
DOI: 10.1007/s00339-005-3387-x

Applied Physics A
Materials Science & Processing

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Laser backside etching of fused silica due to carbon layer ablation

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Received: 15 July 2005/Accepted: 9 August 2005
Published online: 27 September 2005 • **© Springer-Verlag 2005**

ABSTRACT The backside ablation of a absorbing carbon layer onto fused silica is studied in air and water confinement in comparison. The confinement influences the etch rate and the laser fluence dependence of the etch rate significantly while the threshold fluence is almost the same. The different confinement of the laser induced plasma results in the observed rate saturation in the case of air and in a linear growing rate in the case of water confinement at medium laser fluences. The less dense air confinement permits a faster plasma expansion of the laser plume than in the case of water confinement and effects consequently the interaction time and interaction strength of the laser plume with the fused silica surface. The differences in the laser-plasma-substrate interaction cause the observed rate saturation at weak interaction (air) and the growing etch rate at strong interaction (water). Thus, the confinement situation controls the interaction process in the case of backside ablation and should be considered in indirect material processing methods such as LIBWE and LESAL, too.

PACS 81.65.C; 81.05.K; 79.20.D; 61.80.B; 42.55.L; 68.45.D

1 Introduction

The challenge of etching inorganic transparent materials such as fused silica glass results from potential applications in micro system technology. In particular manufacturing of micro-optical and micro-fluidic devices requires the etching of manifold structures of different lateral and vertical dimension with high accuracy and flexibility combined with a low surface roughness. Direct laser ablation has been demonstrated as an important tool for microstructuring of a broad range of absorbing materials [1]. On the other hand the wide band gap, and therefore the low absorption of transparent material, causes only less surface quality and accuracy for conventional nanosecond UV-laser ablation [2]. High-quality laser ablation using VUV-wavelengths or ultra-short pulse duration (femtosecond) has been reported [3, 4].

During the past decade many investigations have been carried out of indirect laser processing techniques for micromachining transparent materials. Some methods make use of interaction processes of laser irradiated absorbing additives with the backside surface while exposure was performed through the frontside. Two representatives of indirect processing are LIBWE (laser-induced backside wet etching) [5, 6] and LESAL (laser etching at a surface adsorbed layer) [7] which make use of organic liquids and adsorbed hydrocarbon layers as absorbing additives, respectively. These methods are characterized by low threshold fluences, minimal etch rates, and minimal, nearly optical roughness at optimized experimental conditions and make the indirect approaches to promising candidates for high-quality laser processing in micro system technology.

All of these techniques have in common that the etching involves the deposition of layers on and around processed area due to decomposition of organic molecules [7, 8]. In any case a thin carbon film modifies the substrate surface that affects subsequent laser pulse.

In this work the influence of an absorbing carbon layer on the different backside etching approaches is investigated in dependence on the confinement. To study the intrinsic contribution of backside layer ablation to etching mechanisms the experiments were carried out at chemical inert and non-absorbing backside medium. Considering the kind of ambient medium both dilute gas and liquid are used.

2 Experimental

A KrF excimer laser incorporated into a laser workstation running at $\lambda = 248$ nm was applied for the experiments. A reflective objective ($\times 15$ demagnification) with an optical resolution of 1 µm was used for mask projecting. In all investigations fused silica samples cut from double side polished wafers with a thickness of about 380 µm have been used.

The absorbing carbon layers were prepared by scanning KrF excimer laser across fused silica backside surface in LESAL set-up [7]. In this configuration electric heater warms the sample, and the backside is in contact with toluene vapor. Laser irradiation occurs below the threshold for material etching [7] at a fluence of 450 mJ/cm^2 and causes the deposition of a carbon layer. Different scan speed (100 and 50 µm/s) at a constant repetition rate of 100 Hz and a mask size of 100 µm × 100 µm results in carbon layer thickness of 22 and 26 nm, respectively. Raman spectrum confirms (Fig. 1) that similar to LIBWE experiments [8] LESAL-deposited films feature properties of amorphous structure. According to Shin et al. [9] the Raman peaks at 1360 cm^{-1} and 1600 cm^{-1} can be identified as amorphous carbon.

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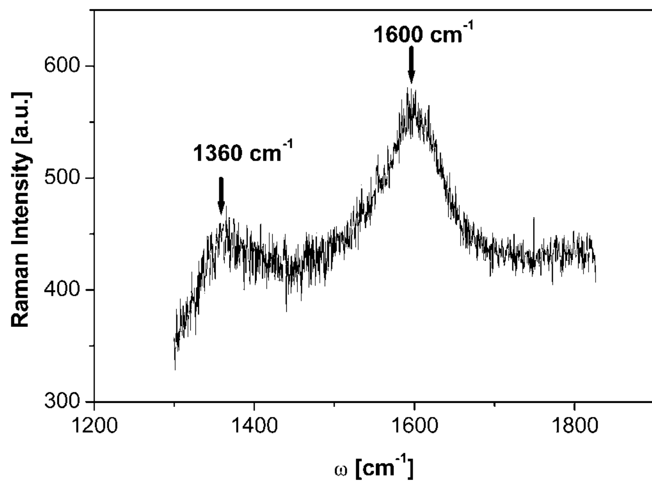

FIGURE 1 Raman spectrum of LESAL-deposited amorphous carbon layer

The experimental set-up for backside layer ablation is similar to LESAL and LIBWE technique [6, 7] and is sketched in the insets of Figs. 2 and 3, respectively. Laser irradiation is performed through the frontside of the sample. The backside, covered with the prepared carbon layer, is in contact with air (low density medium) or distilled water (high density medium) at normal pressure and room temperature causing different confinement (air and water) situations. In all of the experiments, the carbon film is irradiated with one laser pulse using a beam size of 100 μm × 100 μm. The etch depth was measured with white light interference microscope after removing the carbon layer selectively.

3 Results

The backside ablation of carbon layers on fused silica with air and water confinement results in an etching of the transparent fused silica sample that does not have a relevant absorption at low laser fluences. Without the absorbing layer no etching occurs in air and water confinement up to fluences of about 10 000 mJ/cm^2 at one laser pulse. This correlates with the findings for direct front side ablation of fused silica in air [2] and with water film [10].

The measured etch depth of fused silica in dependence on the laser fluence after one-pulse-treatment in air and water confinement is shown in Figs. 2 and 3, respectively. The threshold fluences for etching of the fused silica surface in air and water were determined to about 500 mJ/cm^2 and differ not significantly for the two ambient mediums. Between 300 and 500 mJ/cm^2 only ablation of the carbon layer occurs without influence on the fused silica and below 300 mJ/cm^2 carbon film withstands laser irradiation.

For backside ablation of carbon layers in air confinement (Fig. 2) the etch depth first tends to saturate for fluences between 600 and 2200 mJ/cm^2 and shows a heavy increase for higher fluences. An etch depth exceeding 60 and 150 nm at 3100 and 4800 mJ/cm^2, respectively, is reached. At these fluences, the ablation depth resembles the rate of thermal ablation [2]. The etch depth at saturation depends on the thickness of the carbon layer and amounts for $d_l = 26$ nm (○) and $d_l = 22$ nm (□) about 20 nm and 12 nm, respectively.

In contrast to air the etch depth in water confinement after one pulse treatment (Fig. 3) grows continuously with increasing laser fluence. Otherwise similar to backside ablation on air the etch depth behaviour can be separated roughly into two fluence ranges with an almost linear slope of the etch depth and transition fluence between 2500 and 3100 mJ/cm^2.

In former studies it was noted that dry laser cleaning of glass surfaces covered with non-transparent particles results in surface damage ("hot spots") of the substrate at fluences below intrinsic ablation threshold of glass due to transfer of kinetic and thermal energy or material incorporation into the glass surface [11]. In contrast to loosely bonded particles it is obvious that the deposited, highly adherent carbon backside layer accomplishes a more efficient mechanical and thermal coupling between transparent material and absorbing film. Therefore the fast laser heating of the layer results in a considerable heat flux from layer to surface that initially causes the generation of structural transitions [12] of the glass material near the surface, shock waves [13], and stress [14].

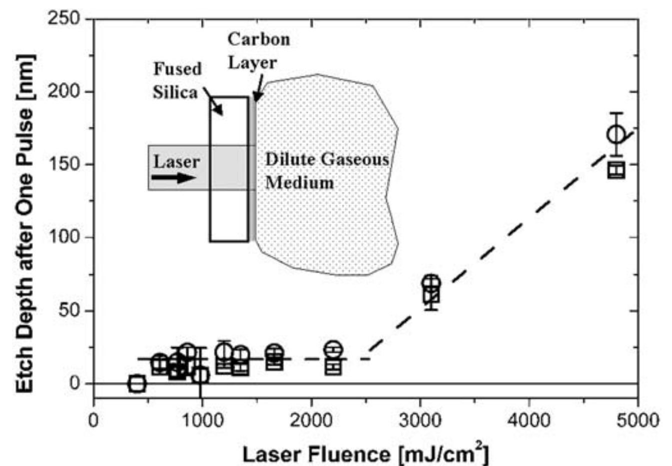

FIGURE 2 Etch depth in dependence on the laser fluence after one-pulse-treatment of solid/layer interface in air confinement. The thickness of carbon layers is 26 nm (○) and 22 nm (□). *Dashed lines* are linear fits and point the separation into two fluence ranges out

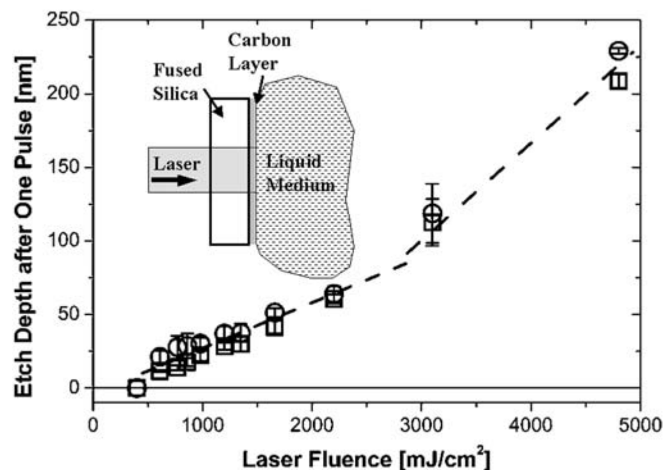

FIGURE 3 Etch depth in dependence on the laser fluence after one-pulse-treatment of solid/layer interface in water confinement. The thickness of carbon layers is 26 nm (○) and 22 nm (□). *Dashed lines* are linear fits and point the separation into two fluence ranges out

Further laser irradiation induces the laser backside ablation of the carbon layer and ionisation and plasma formation in the vapourised layer. It is known from plasma diagnostics of laser plumes that ion kinetic energy ranges from a few to several hundred electron volts [15]. The plasma interaction with the fused silica surface leads to the transfer of kinetic energy of plasma species and causes a further heating (plasma heating) of the sample. Both the direct laser heating via the carbon layer and the plasma heating originates from the laser-induced thermal treatment that results in material etching after exceeding a critical temperature, e.g., softening or melting point of fused silica. Additionally, the charged particle bombardment, e.g., ions and electrons, to the fused silica surface generates impurities, defects, or defect-trapped and free electrons. Furthermore, laser-induced carbon plasmas cause emission spectra from visible to extreme ultra-violet wavelength region [16–18]. In consideration of the band gap of fused silica of 9.0 eV and the absorption edge of around 7.3 eV (ascribed to impurities and defects) the energy of laser plasma photons is already high enough that electrons can be excited directly from valence band to defect [19] or vacuum level. The enhancement of laser ablation of transparent materials by simultaneous irradiation with electrons [20], plasma [21], or high-energy photons [19, 22] from separate sources was already described. Dependent on the laser plasma-induced defect generation, the absorption of the sample surface at the applied UV-laser wavelength increases and may lead to efficient ablation of the fused silica itself by the still acting laser pulse. In contrast to front side ablation backside ablation does not suffer from plasma shielding so that the interaction of the laser beam with the plasma-modified surface is efficient.

For thermal driven ablation processes of bulk materials, higher etch rates with increasing laser fluence are observed regularly due to higher heating rates and temperatures. The almost constant etch depth of fused silica from 600 to 2200 $\mathrm{mJ/cm^2}$ for backside layer ablation in air confinement (Fig. 2) does not meet this fact. In contrast to laser ablation of bulk material the absorbing volume of the thin layer is independent from the laser fluence because the optical penetration depth of the laser light is larger than the layer thickness. Although higher laser fluences might cause higher temperatures the ablation of the carbon layer starts at a certain amount of absorbed laser energies, i.e., at shorter times. Due to the fast adiabatic expansion of the plasma plume during laser pulse duration that's expansion velocity increases with raising laser fluence [15], no significant additional plasma heating occurs and etching of fused silica surface due to laser-induced thermal treatment mechanism stops causing the depth saturation at backside layer ablation in air confinement. Consequently parts of the still active laser pulse leave the sample without considerable interaction with processed fused silica surface and may interact with expanding plume away from the surface.

At laser fluences higher than 2200 $\mathrm{mJ/cm^2}$, a higher ionized carbon plasma leads to earlier ablation and stronger plasma-induced defect generation on the fused silica surface with the result that direct ablation by the same laser pulse occurs and the etch depth increases with laser fluence.

In contrast to backside ablation in air water confinement causes narrowed ablated carbon layer plasma that forms a high-pressure, high-density, and high-temperature region near the solid/liquid interface. The confinement effect is already reported for pulsed laser irradiation of water-covered aluminium, silicon, and carbon targets that results in an increased ablation efficiency [23–25].

For the backside approach the confined plasma cannot expand as easy so that the laser heating of the plasma as well as the plasma interaction with the surface is much more efficient due to the much higher temperature and pressure which depend on applied laser fluence [24]. Thus the increasing etch depth of fused silica with raising laser fluence (Fig. 3) will be a result of the enhanced laser-induced thermal treatment of the surface by the plasma due to the water confinement. Analogous to backside layer ablation in gaseous medium the etching will be affected probably, too, for fluences larger than 2200 $\mathrm{mJ/cm^2}$ by plasma-induced defect generation.

4 Conclusions

In conclusion, both, the absorbing layer and the kind of ambient medium affect etching in backside ablation basically. Comparing the etch depth behaviour of backside layer ablation of fused silica (Figs. 2 and 3) with the etch rates of the LIBWE and LESAL technique, similar characteristics are noted, i.e., separation into different fluence regions [6, 7], the saturated etch rate over wide fluence range [7] in air confinement (LESAL), and an almost linear etch rate slope with an increasing laser fluence at liquid confinement (LIBWE) [5, 6]. Hence, similar processes dominate the backside etching/ablation, i.e., both, a thin absorbing layer as well as the confinement state control the interaction process and has to be considered for the thermal etch mechanism [5, 7] proposed for backside etching methods.

ACKNOWLEDGEMENTS The authors wish to acknowledge Mrs. U. Teschner from Institut für Experimentelle Physik II, Universität Leipzig for Raman spectroscopy investigations. In parts this work was financially supported by the Deutsche Forschungsgemeinschaft Germany under contract ZI660/3.

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