Micro-drilling of alkali-silicate glass with ultraviolet picosecond laser

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Для увеличения низкой эффективности УФ-лазерной абляции прозрачного щелочно-силикатного стекла его облучали γ-квантами ^{60}Co до доз 10^4–10^7 Гр с целью индуцирования интенсивного окрашивания в УФ-видимой области. Варьируя энергию пикосекундных импульсов Nd:YAG-лазера на 4-й гармонике 266 нм в пределах 1-9 мДж и число импульсов, сверлили линейки и решетки сквозных отверстий диаметром от 9 до 40 μм на площади до 1×1 см^2. При плотности энергии сфокусированного импульса >10^8 Дж/м^2 вокруг этих отверстий генерировались ударные волны 4-5 μм от расширяющейся плазмы и происходила наноразмерная кристаллизация. Также в стороне от центрального микронного отверстия образуется субмикронная дырка за счет генерации вакуумных УФ-гармоник. Комбинированное воздействие γ-облучения с последующим сверлением УФ-лазером привело к уменьшению содержания кремния и кислорода и образованию фтора, что может быть вызвано фотоядерными реакциями $^{28}Si_{14}\rightarrow{}^{19}F_9+3^3T_1$; $^{16}O_8\rightarrow4^4He_2$; $^{16}O_8+^3T_1\rightarrow{}^{19}F_9$. Из-за вязкости стекла и релаксации в течение 2 месяцев при 300 К выходной диаметр просверленных отверстий увеличился до размера на входе. Такие микрорешетки могут быть использованы для сепарации жидких смесей или очистки воды.

Ключевые слова: гамма-индуцированное окрашивание, лазерное сверление стекла, ударная волна плазмы, фотоядерная реакция.

The low efficiency of UV-laser ablation of transparent alkali-silicate glass has been increased by means of irradiation by ^{60}Co γ-quanta to doses 10^4–10^7 Gy to induce intensive UV-visible coloration. Varying the picosecond pulse energy of Nd:YAG laser at 4-harmonics 266 nm within 1–9 mJ and pulse number, arrays and grids of holes were drilled with diameters from 9 to 40 μm on area up to 1×1 cm^2. Shock waves of 4–5 μm were generated by expanding plasma around ablated holes at focused pulse energy density >10^8 J/m^2 and nanoscale crystallization occurred there. Besides, a submicron hole was drilled aside the central micron hole due to generation of vacuum UV harmonics. The combined effect of γ-irradiation followed by UV laser drilling has resulted in decrease of silicon and oxygen contents, and generation of fluorine that may be caused by photonuclear reactions $^{28}Si_{14}\rightarrow{}^{19}F_9+ 3^3T_1$; $^{16}O_8\rightarrow4^4He_2$; $^{16}O_8+^3T_1\rightarrow{}^{19}F_9$. Because of glass viscosity and relaxation during 2 months at 300 K, the exit diameter of drilled holes has increased up to the entry one. Such micro-scale grids can be used for separating liquid mixtures or cleaning water.

Keywords: gamma-induced coloration, laser drilling of glass, plasma shock wave, photonuclear reaction

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I. Introduction

The earliest report on nanosecond and femtosecond excimer laser ablation of fused silica under condition of intensive UV-absorption was in 1992 [1].

Then femtosecond (fs) optical breakdown in dielectrics was discussed in [2]. Some years later commercial applications of micromachining of fused silica with 1 picosecond laser were reported in [3]. Particular morphology of surfaces of borosilicate glass and other transparent materials ablated with fs-laser was found in [4-6]. Then nanogratings were fabricated in fused silica with the morphology depending on fs-pulse duration [7]. The fs-laser induced changes in the refraction index n of boron-silica, alumina-silica and glasses doped with heavy metal oxides were examined in details in [8]. One should mention that local Δn=0.01 is enough for application in 3D-optical memory of high density. The laser-induced near-subwavelength ripples were attributed to interference between surface plasmons and incident laser wave [9]. Femtosecond laser-induced periodic surface structures were found in [10]. Micro-holes were drilled in silicon above the forbidden gap E_g with 355 nm picosecond and nanosecond pulses, and threshold for plasma generation was about 3×10^8 Wt/cm^2 [11]. Generation of higher harmonics due to non-linear processes at high power density conditions was considered in details in the review [12]. Ultrafast laser pulses of a μJ energy tightly focused inside the bulk of a transparent solid have the MJ/cm^3 energy density within a micro-scale focal volume significantly above the threshold for optical breakdown and material ablation, and are used for micro-patterning (grooves) of surface of glass substrates [13]. UV fs-lasers are used also for extruding glass fibers of nano- and submicron diameters [14]. Excimer laser (193 nm) illumination through a mask allows parallel drilling of 1000 through holes in 30–100 μm thin glass interposers for 2.5D and 3D packaging small consumer electronics [15]. Multilayer dielectric gratings were made with picosecond laser in vacuum [16]. Few-cycle pulse laser induced damage threshold was determined in ultra-broadband optics [17]. Collimated relativistic electron transport was detected in dielectric BK7 glass, which was driven by high intensity contrast $>10^{18}$ Wt/cm^2 of fs and picoseconds (ps) laser pulses, followed by plasma expansion in vacuum for tens picoseconds [18].

This literature analysis has shown that just a few paper deal with ps-laser micromachining of glasses, although ps pulses have much higher energies (~mJ) than fs ones (~μJ) [3, 11, 13, 16, 18]. The available papers do not mention about relaxation of the drilled or micro-patterned glass, which is quite possible due to the well known viscosity of glass. New phases and new materials are formed in strongly non-equilibrium conditions of confined micro explosion. Glass materials can exist in two different states (amorphous and polycrystalline) and transit between them. Besides microscopic control, any laser drilling glass technology should be monitored with structure sensitive analyses.

The aim of this research was to study mechanisms of drilling micro- and nano-size holes in optical-transparent alkali silica glass with picosecond UV-laser and (for the first time) the effects of γ-irradiation induced coloration of the glass before drilling and the following time relaxation of the drilled holes.

II. Experiment

Pure quartz glass (KI, KU) does not absorb UV harmonics (266 nm) of short-pulse solid Nd:YAG lasers. Therefore optical alkali silicate K8 glass was chosen, which contains the network of 51% O and 29% Si, and 11% of Na modifier (and 1% of Mg, Ca, Al) responsible for strong UV absorption band below 270 nm. Optically polished slabs had 1 mm thickness and roughness <1 μm comparable with a laser wavelength. The UV laser source was diode pumped Nd:YAG laser (PL2231-50, Ekspla, Litvania) operating at the 4-th harmonic (line at 266 nm) within 20 ps pulse energy range 0.1–9 mJ (5 pulses in each train) at the repetition rate 50 Hz. Achromatic quartz lens with the focal length 75 mm was used for focusing UV laser beam to 4 μm diameter on the glass target surface. This focusing provides an energy density $>10^8$ J/m^2 enough for evaporating enthalpy and igniting dense plasma, so as to drill cylindrical holes in the percussive pulse mode [3, 11]. This complicated process includes a sequence of interconnected stages: non-linear optical absorption of a few photons of laser beam in the focal spot, avalanche ionization and energy transfer from electrons to ions, conversion of solid material into plasma, melting and evaporation by the extra heat conduction, hydrodynamic dense plasma expansion, generation of strong shockwave propagating into the surrounding cold material [13]. Surface morphology of the obtained micro- and nano-structures was investigated with scanning electron microscope (SEM-EVO-MA10, Zeiss, Germany) and X-ray diffraction with phase analysis (Empyrean, PAnalytical). Possible changes of local chemical composition of the laser affected volume were studied with energy dispersion system Aztec INCA at the SEM. In order to increase the absorption of laser

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emission at 266 nm the optical transparent glass samples were irradiated with ^{60}Co gamma quanta at the Institute of Nuclear Physics to deposited doses from 4×10^4 Gy to 10^7 Gy so as to induce coloration due to saturated UV absorption up to optical density OD>6, which is related to charge transfer between alkali metal and oxygen ligand. Optical absorption spectra of glass prior and after the γ-irradiation were measured at double beam spectrophotometer (UV3600, Shimadzu, Japan) in the wavelength range of 200–1000 nm. Infra-red spectra were scanned at FTIR spectrometer (iS50 Nicolet, Thermoscientific) in the attenuated total reflection (ATR) mode from 10 micron subsurface layer and in the transmission mode (mst) from the whole thickness1 mm within the wave number range of 4000–400 cm^{-1}. The program transforms reflection and transmission to the absorptionin OD scale up to 6.

III. Results and discussion

Figure 1 shows optical absorption spectra of glass prior and after γ-irradiation to 10^7 Gy.

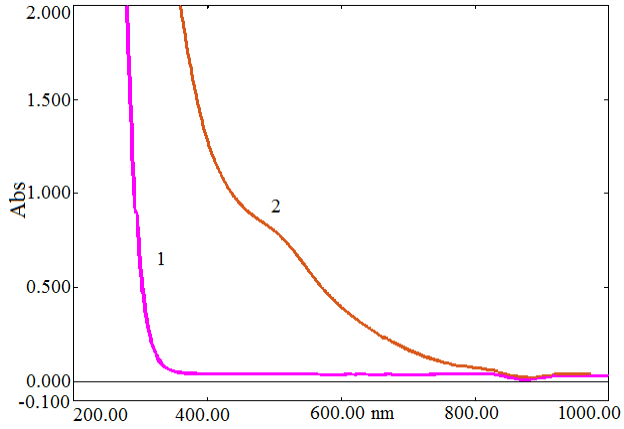


Figure 1. Optical absorption spectra of K8 glass: curve 1 – non-irradiated, curve 2 – after ^{60}Co γ-irradiation to the dose 10^7 Gy.

The absorption edge of non-irradiated glass is at 270 nm, which is the same as the 4-harmonics of laser. After γ-irradiation to 10^7 Gy the absorption edge-shifts to 350 nm, the refraction index *n* increases and there appears intensive brown color. The broad band with the maximum near 500 nm overlapped with the shifted absorption edge looks like the extinction spectra of spherical metal nanoparticles inalkali halide crystals (Na nanocolloids in NaCl), glass or dielectric solution, which size is estimated by simplified G. Mie formula $L \cong 0.1\lambda/\pi$ as ~16 nm [19]. The γ-irradiation causes metallization of the modifier ions by trapping electrons and self-assembling inside cages of silica carcass. Therefore the laser line at 266 nm becomes more effective for ablation of γ-irradiated glass with the induced color centers absorbing this line and also the increased refraction index *n* causing a better light focusing with higher numeral aperture NA=*n*sinθ.

Nanoparticles made from low absorbing dielectrics having large permittivity values [13, 14], and also alkali metal nanocolloids with very high absorbance [19] and surface plasmons [9] can be resonantly excited by external electromagnetic fields.

E′-centers absorbing at 215 nm appear in pure silica glass KU-1 after irradiation to γ-dose 10^4 Gy and neutron fluency 10^{17} cm^{-2} [20]. They are generated in the alkali glass too and can absorb the Nd-laser emission at the 5-th harmonics at 215 nm. When the glass is irradiated with ^{60}Co γ-quanta at 670 R/s (6×10^{12} q/cm^{2}s) to doses within 10^4–10^8 Gy, the concentration of E′ centers saturates at the dose 10^7 Gy (6×10^{21} q/cm^2) [21].

The most intensive γ-excited luminescence band at 460 nm saturates in KU-1 glass after ^{60}Co-γ-dose 10^7-10^8 Gy or neutron fluency 10^{19} cm^{-2} in WWR-SM reactor [21]. It can also be induced by 2 MeV electrons and ascribed to Cl impurity [22, 23], by fast neutrons of DT-generator and attributed to self trapped exciton emission at oxygen vacancies [24], and by neutron+gamma spectra of pulse nuclear reactor and related to e-h recombination at oxygen vacancies [25].

Figure 2 shows FTIR absorption spectra (measured in transmission and reflection modes) of alkali glass prior and after γ-irradiation to 4×10^4 Gy.

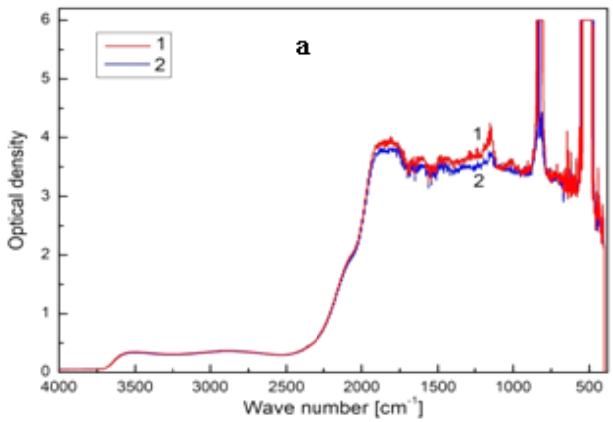


Figure 2. FTIR absorption spectra of K8 glass scanned in transmission (a) mode: curve1 – non-irradiated, curve 2 – after^{60}Co γ-irradiation to the dose4×10^4 Gy.

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Plato 3600–2400 cm^{-1} relates with single M-O-M vibrations M^{1+} alkali ion impurities. More intense absorption bands in the range 2400–1100 cm^{-1} are attributed to double Me=O vibrations in Me^{2+} and Me^{3+} oxides. No significant change was found in the range of basic vibrations of silica network in the transmission (A), while there observed decrease in the magnitude of stretching Si-O bonds at 1050 and 800 cm^{-1} and O-Si-O bending angle at 700–500 cm^{-1} in thethin subsurface layer. However, narrow impurity peaks at 1200, 850, 650, 550 and 470 cm^{-1} have increased after the irradiation because of metallization of the modifier ions (Na^{1+}, Mg^{2+}, Al^{3+}, Ca^{2+}) by trapping electrons followed by aggregation in nanocolloids. Thus, the radiation induced changes in optical (Fig. 1) and infrared (Fig. 2) spectra agree each to other and can be attributed to nanocolloids of modifier metals (major Na colloids in this glass).

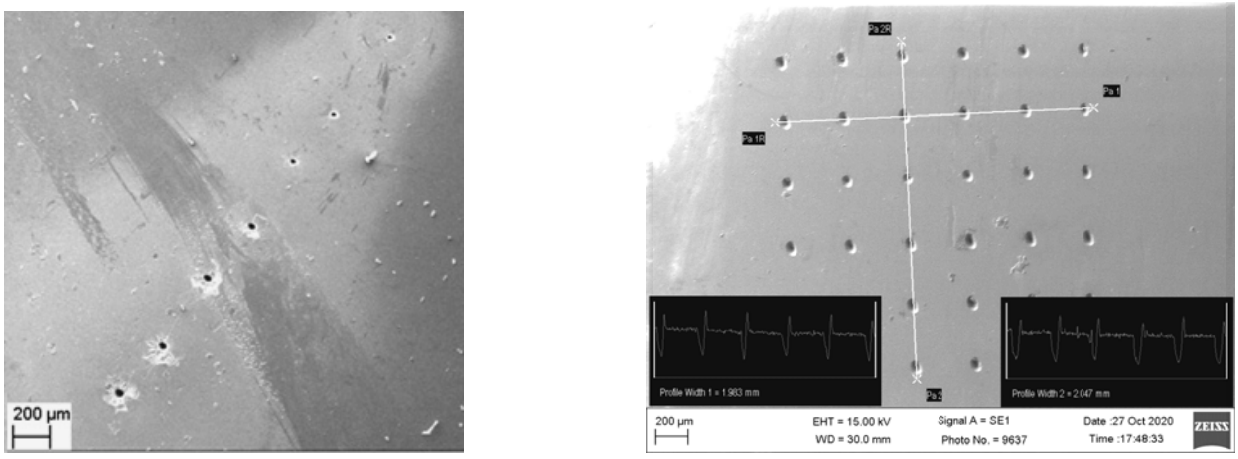


Figure 3. SEM images: (left) 7 holes drilled in K8 glass after γ-irradiation to 4×10^4 R with 400 laser pulses at the 4-th harmonics (266 nm) by increasing pulse energy from 0.45 to 4.05 mJ (5–45% of power); (right) grid of 36 holes. Insets show the total profile of the drilled membrane.

Figure 3 shows 7 holes drilled in the glass after γ-irradiation to 4×10^4 Gy with up to 400 laser pulses of energy increasing from 0.45 to 4.05 mJ, which are from 5 to 45% of maximal pulse energy. Light halo around each hole is due to ignited plasma and its area is proportional to the total pulse energy [26]. Besides, at pulse energy ~2 mJ focused to 4×10^8 Wt/cm^2 that is above the threshold of igniting hot plasma [12, 13, 26], radial shock waves appear around the drilled holes, which were called as periodic structures (patterning) in earlier papers [3, 4, 10]. Provided the same laser pulse energy and focusing lens, after γ-irradiation the hole diameter is less than one in non-irradiated glass. It can be attributed mainly to increasing in the refraction index n at the γ-induced absorption band 200–300 nm and the related narrowing the focal area $d=4\lambda f/\pi D$ [12, 13].

Figure 4 show several holes in the gamma-irradiated glass at higher magnification to reveal details of laser induced damage.

The common features are: all holes are elongated along the laser E polarization, nano-droplets around them are caused by laser evaporation mechanism, rather than by melting. Fig. 4a shows the through hole (exit size 9 µm) of triangle shape drilled at the pulse energy 0.9 mJ. In the same conditions of non-irradiated glass the hole has the diameter 13.5 µm. Drilling at 1.35 mJ the hole diameter is 34 µm with hexagonal cross-section (Fig. 4b). This γ-induced narrowing of the hole diameter was discussed above and ascribed to increasing in the refraction index. While at 2.25 mJ there appeared radial shock waves with the period of 5 µm (70 THz) directed normally to the electric polarization, which move radial till ~100 µm from the hole (Fig. 4c).

According to [12, 13, 17, 18, 26], shock waves appear above the threshold of higher harmonics generation by means of the multiphoton absorption and emission of relativistic electrons from hot plasma. It was detected during the drilling a few cm aside the glass target by Radioscan-701A as β-radiation and γ-radiation. In the case of higher contrast fs-laser, long (~1 mm) relativistic fast electron streaks are obtained at early times (~few ps) inside the target, while the plasma expansion in vacuum becomes observable much later (~30 ps) [18].

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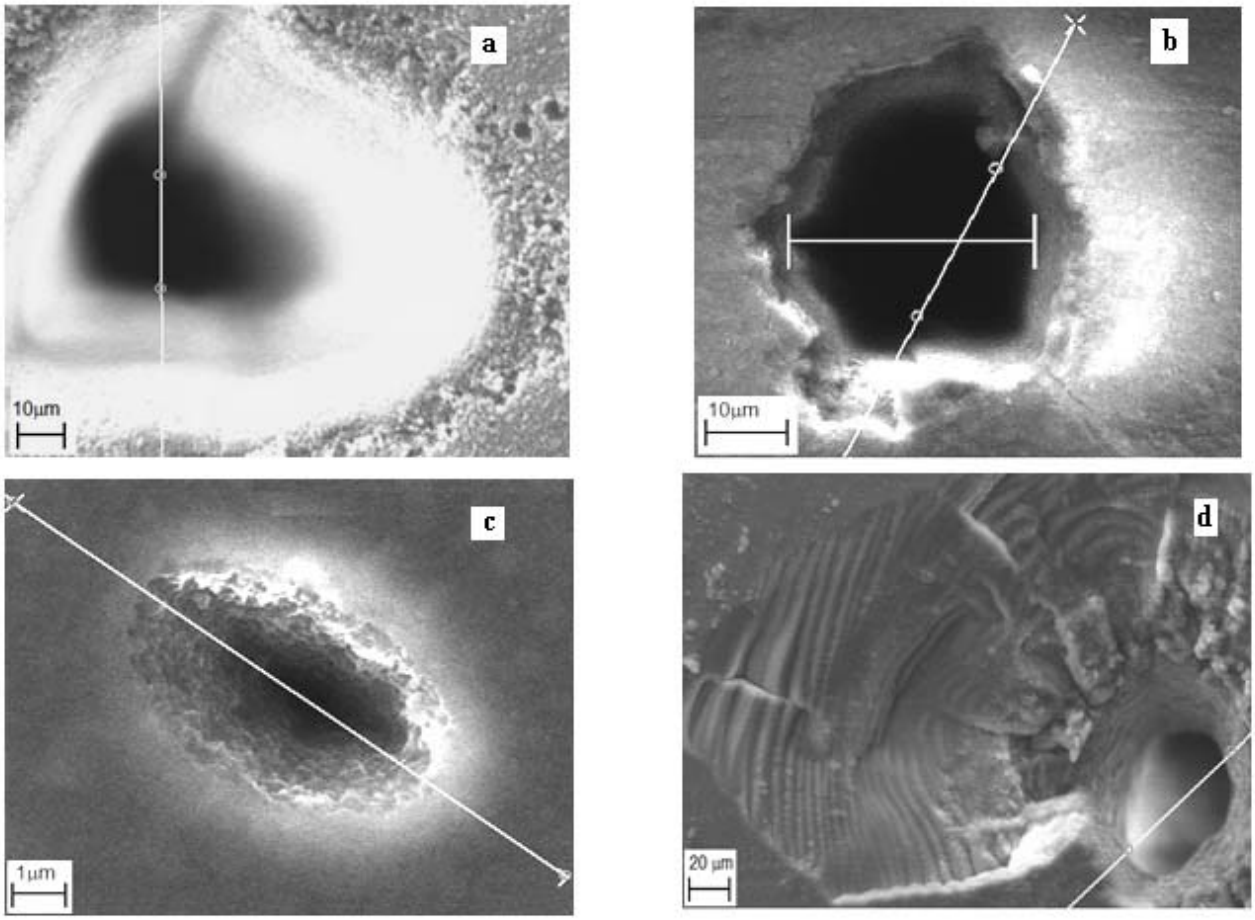


Figure 4. SEM images of several holes in the γ-irradiated glass drilled by varying the average pulseenergy: *a* – 0.9 mJ, *b* – 1.35 mJ, *c* and *d* – 2.25 mJ. White lines show electric polarization vector for the laser beam.Circles show the exit diameter of holes and a bar marks the entry size.

The motion of a flux of charged particles inside dielectrics is limited by space charge. But due to the ionization by the strong space charge field itself (breakdown field ~5×10^{10} V/m) and the collision-ionization processes, a lateral expansion of the plasma was finally registered on-line with fast camera at the distance ~200 μm from the laser-glass interface [18].

However the scanning electron microscopy shows only "frozen" post-effect of shock waves propagating in the hot soft glass during ~30 ps of plasma existence.

Fig. 4d shows the minimal conical nano-hole of elliptic shape (2 and 0.5 μm) and many nano-crystals around it at 10 times higher magnification. Since the theoretical minimum for the focal area of the 4-th harmonic is ~3×3 μm, this nanosized hole could be produced by vacuum UV-harmonics (50-100 nm) focused in submicron area 0.5×0.5 μm [12]. Dominating mechanisms of ionization here are multiphoton transitions through the band gap followed by heating of free electrons, ending up, in some beneficial cases, in their impact multiplication at high frequency of electron collisions with atoms [13, 18, 26]. One should emphasis, that detecting β- and γ-radiation in our case can not be attributed just to ionization, since it is caused by nuclear excitation and photonuclear reaction.

Figure 5 show front (a) and back (b) views of the hole drilled at 0.9 mJ in *non-irradiated* glass. Entry size is ~30 μm and exit one is 13 μm. An average size of droplets is 2–3 μm.

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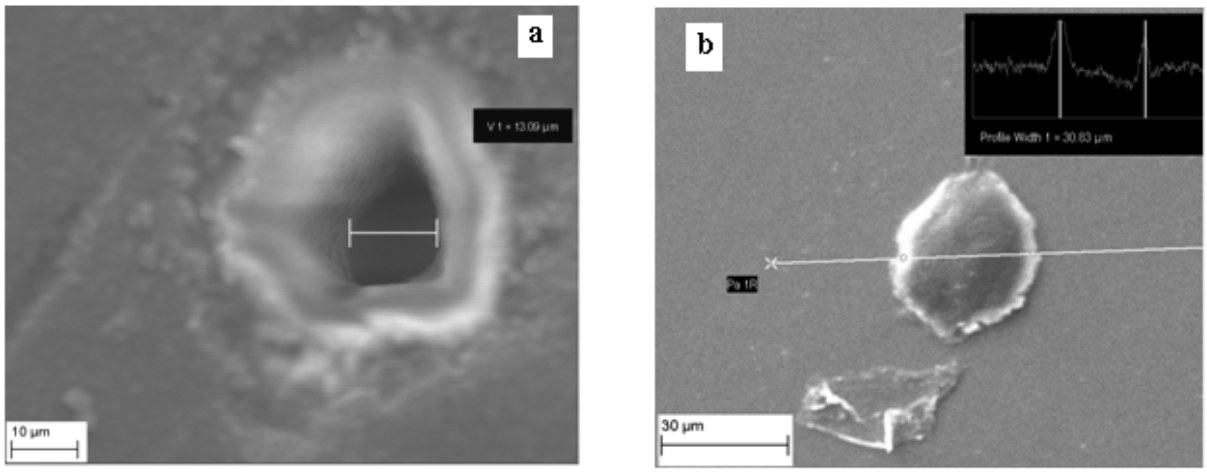


Figure 5. SEM images of the hole drilled at the pulse energy 0.9 mJ in the non-irradiated glass: front (a) and back (b) views.

In one week relaxation (b) one can see hollow hexagonal tube profile of the exit hole surrounded by a crater with the same size and shape as the entry one. They are the same holes in the same sample studied again and again in a month and in 2 months later (we showed only the first and last scan). This evidences about laser induced nano-crystallization of non-irradiated glass into the SiO_2 crystal phase with hexagonal symmetry.

Figure 6 shows the relaxation of holes drilled at the same conditions 0.9 mJ but in the glass γ-irradiated to the dose 4×10^4 Gy, measured in 2 days after drilling (a) and in 2 months (b). Indeed, alkali silica glass has a high viscosity (like honey), and the deformations, caused by intensive gamma-irradiation and laser drilling, relax slowly so as to release the induced stress.

Here the hole size is a little smaller than in non-irradiated glass and the droplets are of submicron size. The higher temperature of ablation, the smaller droplets are, as it is stated in [13]. Besides, in the left upper corner (a) a submicron hole appears similar to Fig. 4d after drilling at >2 mJ. It can be explained by more effective absorption of the laser beam at 266 nm by γ-irradiated glass with the defect color centers and also by better focusing due to increasing of the refraction index near the radiation induced color centers. Some of these centers may be related to metal colloids emitting surface plasmons, which interact to the laser beam [9].

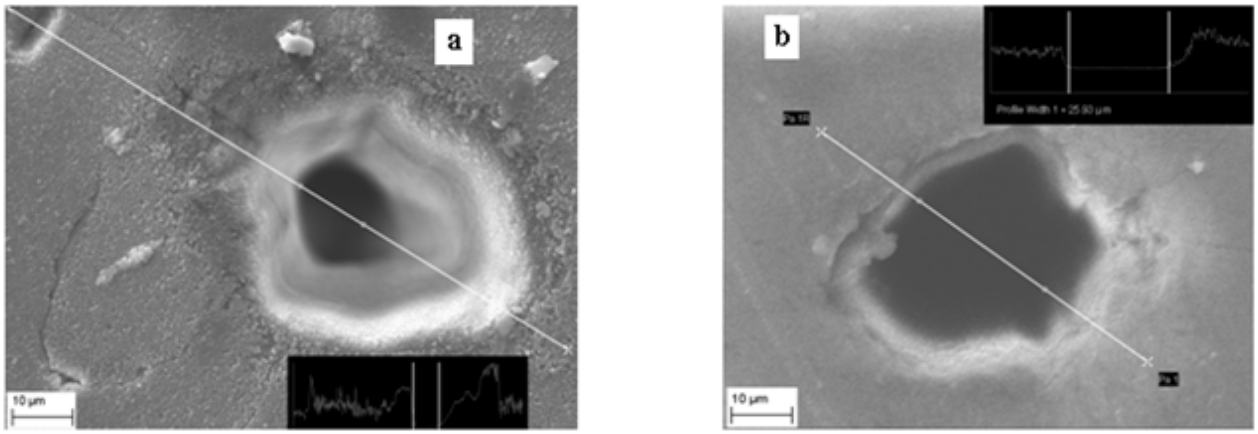


Figure 6. SEM images of holes vias drilled at the pulse energy 0.9 mJ in the glass γ-irradiated to the dose 4×10^4 Gy: *a* – measured in 2 days after drilling, *b* – in 2 months of the glass relaxation.

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Figure 7 show holes in glass irradiated to 4×10^4 Gy and drilled with 3 pulses of 4 harmonics at 2.7 mJ/pulse 2 days later and in 2 months of relaxation at 300 K.

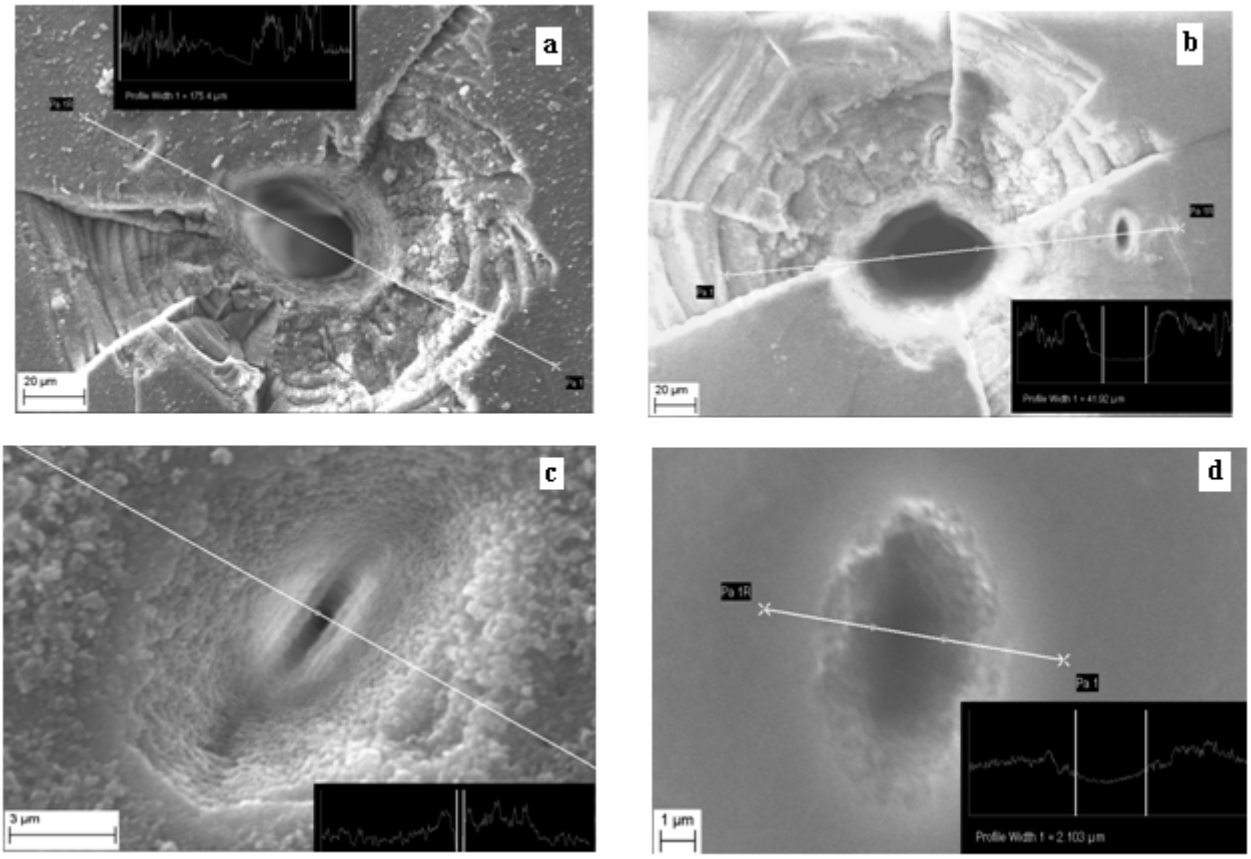


Figure 7. SEM images of holes drilled with 3 pulses of 4 harmonics at 2 mJ/pulsein glass γ-irradiated to 4×10^4 Gy: *a*, *c* – 2 days after drilling; *b*, *d* – in 2 months of relaxation at 300 K.

One can see (Fig. 7a,b) anisotropic shock waves relative to E-polarization vector. Similar behavior was observed above in Fig. 4c and attributed to ablation with hot plasma [13]. Small hole (c,d) is surrounded by nanosized crystallites, a part of which disappeared during the glass relaxation for 2 months at 300 K.The walls of spherical, hexagonal and conical holes looked like interlaced wires of 1–5 μm with plenty submicron pores. Formation of hexagonal vias may be due to recrystallization (devitrification) of the silica glass into the crystal lattice of quartz or crystobalite with the hexagonal symmetry, which is induced by intensive laser beam.

There are papers on nanocrystal growth under fs-laser beam: crystallization of amosphous Si nanoclusters in SiO_x films using laser pulse annealing [27]; structuring materials at micro/nano scale from wave guides to super hydrophobic surfaces [28]. Possible mechanism of nanograin growth is ultrafast crystallization in shock-compressed SiO_2 [29]. Crystallization of glasses in the $BaO\text{-}B_2O_3\text{-}SiO_2$ system under laser beam pulses 2–4 ns at intensity 7×10^{11} W/cm^2 is non-isothermal [30]. Thus it is not spontaneous thermodynamical crystallization, because it was caused by a sequence of intensive ps-laser pulses.This morphology of laser modified surface layer can be described asquite fast non-equilibrium sitall growth. The layer is thin because of short laser pulses and very low heat conductivity of the dielectrics.

Figure 8 shows the local chemical composition of glass surface near the hole determined by the energy dispersion system at SEM, as characteristic X-ray spectra.

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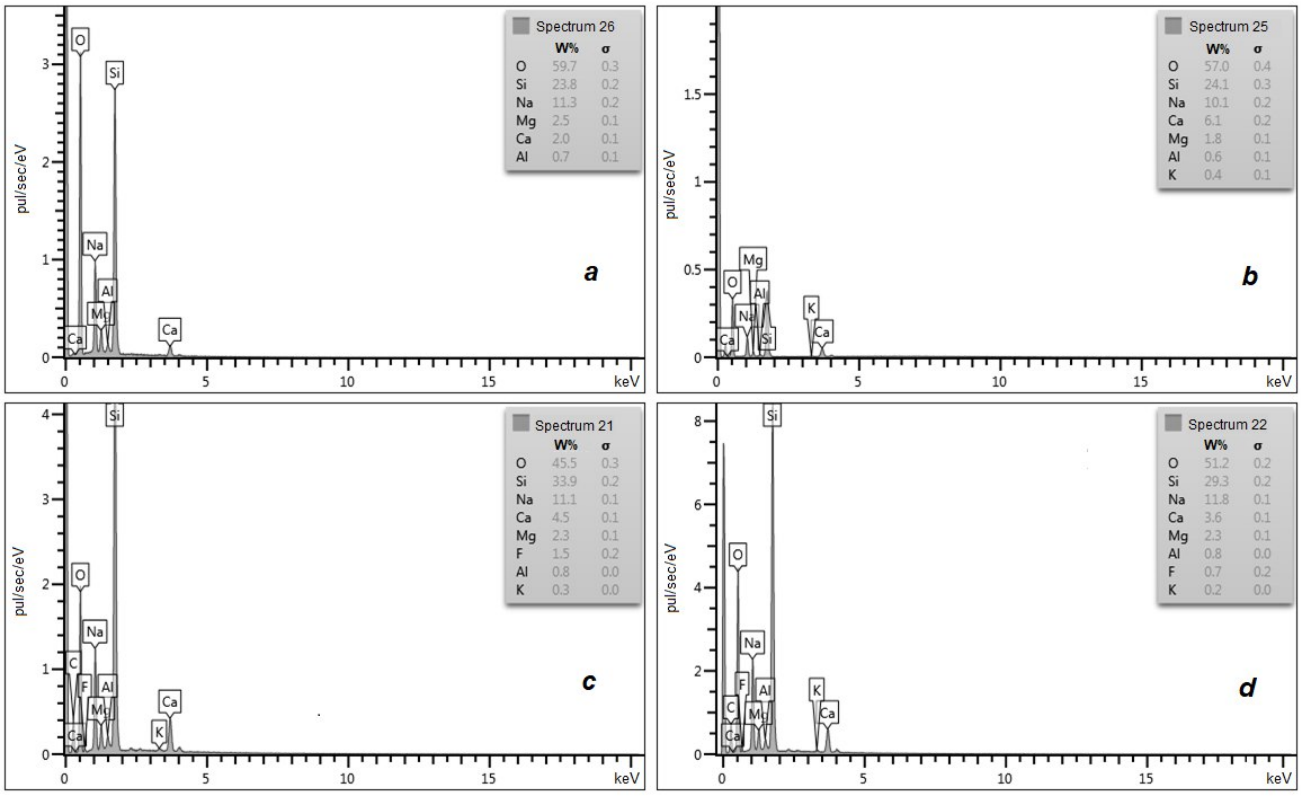


Figure 8. Characteristic X-spectra of non-irradiated glass drilled at 4.05 mJ: *a* – at 300 μm from the hole, *b* – at the hole edge; after γ-irradiation to 4×10^4 Gy drilled at 1.35 mJ: *c* – at 50 μm from the hole, *d* – at the hole edge 300 K.

The peak of carbon is attributed to nano-film of graphene deposited on the glass surface to avoid charge accumulation while electron microscopy. Spectrum (a) taken far from the laser spot confirms the composition of K8 type alkali silica glass. Spectrum (b) taken at the drilled hole edge does not correspond to the normal composition of SiO_2. It has substoichiometric deficit of oxygen and surplus of calcium, which is indicative of radial emission of light and heavy ions to long and short distances from expanding plasma. Spectra (c, d) show that preliminary γ-irradiation of glass followed by UV laser drilling at pulse energies >1 mJ resulted in decreasing silicon and oxygen contents, and fluorine generation, that may be caused only by photonuclear reactions and other nuclear transmutations:

$$^{28}Si_{14}\rightarrow {}^{19}F_9+ 3{}^3T_1;\ {}^{16}O_8+{}^3T_1\rightarrow {}^{19}F_9;\ {}^{16}O_8\rightarrow 4{}^4He_2.$$

Fluorine was found under these conditions for the first time. The fluorine concentration at the hole edge is 0.7%, and at the distance of 50 μm it has increased 2 times, because of increasing kinetic energy of F ions from expanding plasma [12, 13, 18, 31-33]. There was not any source of fluorine around the sample prior irradiation, during and after gamma-irradiation and laser drilling in air to contaminate it.

Since the concentration of fluorine decreases with the distance from the laser drilled place, it is caused by laser plasma impact and can't be contamination. All the rest minor impurities (Na, K, Al, Ca) have the same mass% independent on the local place of (21-26) spectra measurements X-ray diffraction analyses of initial and irradiated glass samples are shown in Fig. 9.

Wide diffused bands at low angles (8 and 22 gradus) correspond to SiO_2 glass network, made from cages of 1 and 2 nm diameter. There are also two sets of narrow reflections, which identify nanocrystal phases of SiO_2 and Na ($AlSiO_4$), the ratio of which has changed after gamma-irradiation and laser drilling. Thus, irradiation and grilling affects on the main SiO_2 network, since alkali modifiers are inside the nanometer cages.

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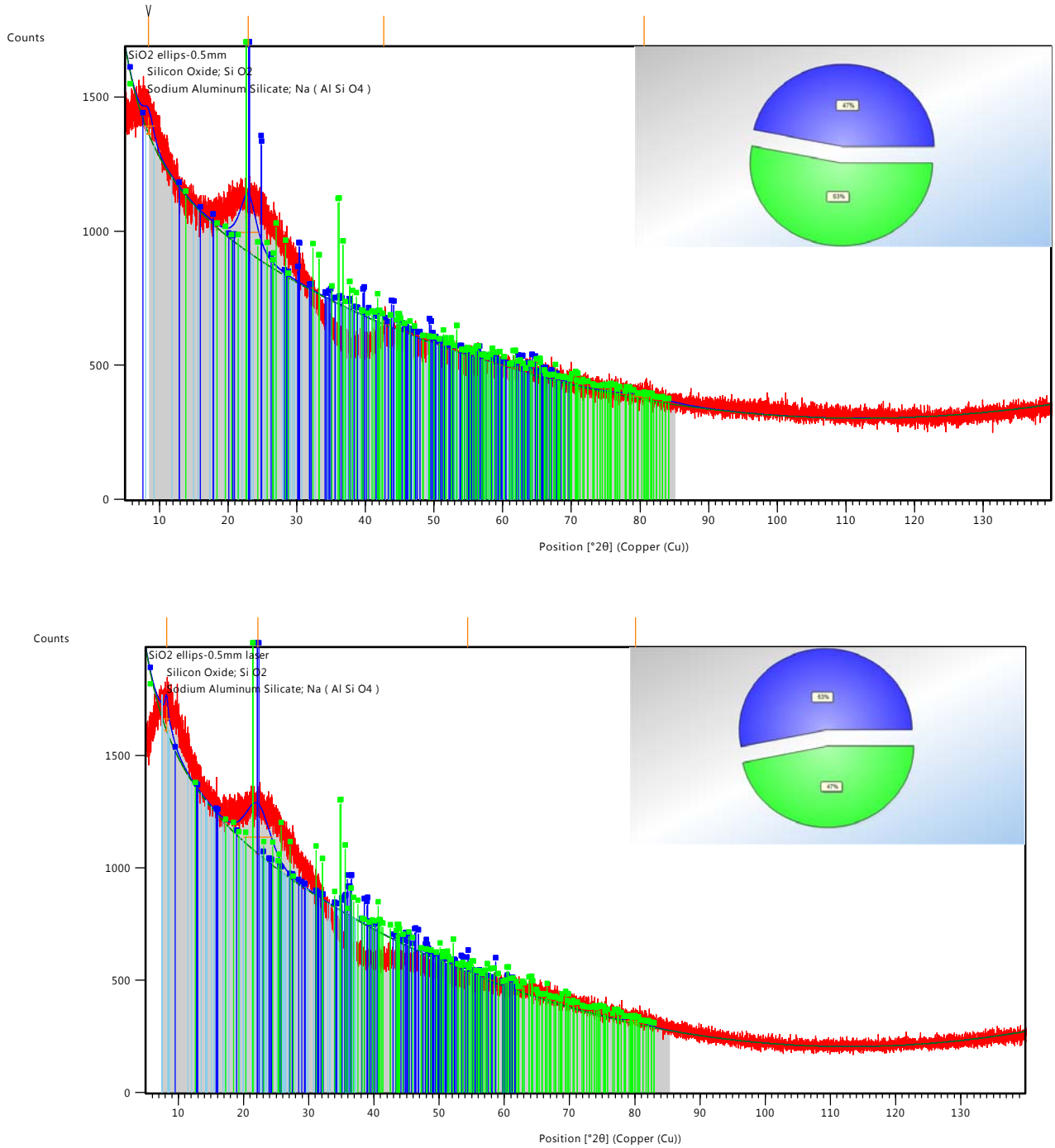


Figure 9. X-ray diffraction spectra of alkali silicate glass prior (top) and after γ-irradiation for laser drilling (bottom).

IV. Conclusions

Laser drilling of glass in its transparency window was found ineffective, while drilling with UV laser harmonics at 266 nm (at the basic absorption) resulted to energy losses by means of intensive luminescence. For the first time before laser drilling the alkali silicate glass was irradiated with gamma-quanta of ~1.25 MeV ^{60}Co so as to increase the absorption at 266 nm, instead of increasing the laser

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power or shortening the laser wavelength, like other authors did [1-8, 13-18]. Preliminary irradiation of glass with ^{60}Co generates intensive coloration and removes luminescence centers thereby increase the efficiency of UV-laser beam absorption for drilling-holes 5–25 μm without cracking. Scanning electron microscopy showed microholes and nanodroplets made by 28 picosecond laser pulses at 266 nm in glass K8 at the pulse energies 1–3 mJ. The obtained microholes have diameter within 9–30 μm depending on the deposited laser energy and the refraction index. Additional holes of ~1–2 μm size, which is less than the theoretical focal diameter 5 μm for the laser wavelength 266 nm, may be drilled with the 5-th harmonics generated by non-linear process in the γ-irradiated glass. Linear polarization of laser beam is good for crystallization, but not proper for obtaining round holes. Because of quite low thermal conductivity of glass and high viscosity, the laser induced shock waves are spread radial till ~60 μm. It requires additional experiments for improving technology of laser drilling of 1 mm thick glass.

For the first time the long term relaxation of glass network after laser drilling was examined taking into account the effect of gamma-irradiation. It was found that conical holes are transformed into cylindrical with hexagonal profile close to the entrance size which is required for filter membrane. Final stabilization of laser drilled holes is provided only by completed nano-micro-crystallization of alkali silicate glass around the holes within ~20 ps pulse length. The fs-pulse has 10^{-3} times weaker energy than the picoseconds pulse and is too short for completing glass-crystal phase transformation.

Glass micromembranes with 2–40 μm holes are in demand for filtering liquid from suspended microparticlesor separating liquid mixtures.

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References

[1] J. Ihlemann, B. Wolff, P. Simon. Appl. Phys. A **54**, 363 (1992).
[2] M. Lenzner, J. Krüger, S. Sartania, Z. Cheng, Ch. Spielmann, G. Mourou, W. Kautek, and F. Krausz. Phys. Rev. Lett. **80**, 4076 (1998).
[3] P. Herman, A. Oettl, K. Chen, R. Marjoribanks. SPIE Conf. Commercial and biomedical applications of ultrafast lasers. **3516**, p.148 (San Jose, CA USA, 1999).
[4] A. Ben Yakar, R. Byer, A. Harkin, J. Ashmore, H. Stone, M. Sheen, E. Mazur. Appl. Phys. Lett. **83**, 3030 (2003).
[5] R. Gattass, L. Cerami, E. Mazur. Optic Express. **14**, 5279 (2006).
[6] R. Gattas, E. Mazur. Nat. Photonics **2**, 219 (2008).
[7] C. Hnatovsky, R.S. Taylor, P.P. Rajeev, E. Simova, V.R. Bhardwaj, D.M. Rayner, and P.B. Corkum. Appl. Phys. Lett. **87**, 014104 (2005).
[8] V.R. Bhardwaj, E. Simova, P.B. Corkum, D.M. Rayner, C. Hnatovsky, R S. Taylor, B. Schreder, M. Kluge, J. Zimmer. J. Appl. Phys. **97**, 083102 (2005).
[9] M. Huang, F. Zhao, Y. Cheng, N. Xu, and Z. Xu. ACS Nano **3**, 4062 (2009).
[10] D.A. Alessi, C.W. Carr, R.P. Hackel, R.A. Negres, K. Stanion, J.E. Fair, D.A. Cross, J. Nissen, R. Luthi, G. Guss, J. Bonse, J. Krüger, S. Höhm, and A. Rosenfeld. J. Laser Appl. **24**, 042006 (2012).
[11] H. Pantsar, H. Herfurth, S. Heinemann, P. Laakso, R. Penttila, Y. Liu, G. Newaz. Laser Microprocessing Conf. (2008), p.278; JLMN-Journal of Laser Micro/Nanoengineering Vol. 14, No. 3, 2019
[12] R.A. Ganeev. Uspekhi Phys. Nauk **183**, 815 (2013).
[13] V.P. Veiko, V.I. Konov, Ed. Fundamentals of laser-assisted micro- and nanotechnologies. **195** (Springer Series in materials science, 2014).
[14] A.A. Petrov, V.A. Kochetova, A.D. Kochetov, D.A. Sinev, A.A. Yakusheva. Izvestiya VUZ: Device design. **57**/6, 36 (2014).
[15] R. Delmdahl, R. Paetzel. J. Microelectron. Packag. Soc. **21**, 53 (2014).
[16] J.A. Britten, W.H. Gourdin, C. Haefner. Optics Express **23**, 15532 (2015).
[17] K.R.P. Kafka, N. Talisa, G. Tempea, D.R. Austin, C. Neacsu, and E.A. Chowdhury. Optics Express **24**, 28858 (2016) .
[18] I. Dey, A. Adak, P.K. Singh, M. Shaikh, G. Chatterjee, D. Sarkar, A.D. Lad, G.R. Kumar. Optics Express **24**, 28422 (2016).
[19] G. Mie. Ann. Phys. **25**, 377 (1908). In: M. Born, E. Wolf. Principles of Optics. 2nd ed. (Pergamon Press, Oxford, 1968), p.585.
[20] A.V. Amosov. Phys. Chem. Glass **6**, 218 (1980).
[21] A.Kh. Islamov, E.M. Ibragimova, I. Nuritdinov. J. Nucl. Mater. **362**, 222-226 (2007).
[22] A. Morono, E.R. Hodgson, J. Nucl. Mater. **224**, 216 (1995).
[23] A. Morono, E.R. Hodgson, J. Nucl. Mater. **249**, 128 (1997).
[24] F. Sato, T. Iida, Y. Oyama, F. Mackawa, Y. Ikeda. J. Nucl. Mater. **258-263**, 1897 (1998).
[25] A. Gorshkov, D. Orlinski, V, Sannikov, K. Vukolov, S. Goncharov, Yu. Sadovnikov, A. Kirillov, J. Nucl. Mater. **273**, 271 (1999).
[26] Dieter Bäuerle. Laser Processing and Chemistry. 4th ed. (Springer, Heidelberg, 2011), p.874.
[27] T.T. Korchagina, A.K. Gutakovsky, L.I. Fedina, M.A. Neklyudova, V.A. Volodin. J. Nanosci. Nanotechnol. **12**, 8694-8699 (2012).
[28] D.S. Correa, J.M.P. Almeida, G.E.B. Almeida, M.R. Cardoso, L. De Boni, C.R. Mendonca. Photonics **4**, 8 (2017).

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[29] A.E. Gleason, C.A.Bolme, H.J. Lee, B. Nagler, E.Galtier, D. Milathianaki, J. Hawreliak, R.G. Kraus, J.H. Eggert, D.E. Fratanduono, G.W. Collins, R. Sandberg,W. Yang, and W.L. Mao. Nature Commun. **6**, 8191 (2015); Science Advances **5,** 8044 (2019)..
[30] A. Aronne, S. Esposito, P. Pernice. Phys. Chem. Glasses **39**, 4-8 (1998).
[31] E.G. Gamaly, B. Luther-Davies, L. Hallo, and V.T. Tikhonchuk. Phys. Rev. B **73**,214101 (2006).
[32] T. Brabec. In: Strong field laser physics. Springer Series in optical sciences **519** (2008).
[33] S. Glasstone and R.H. Lowberg. Plasma production by laser controlled thermonuclear reactions. (1960

Ультрабинафша пикосекунд лазери ёрдамида ишқорий силикат шишада микро-тирқишлар ҳосил қилиш

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Шаффоф ишқорий-силикат шишанинг УФ-лазер абляция самарадорлигини ошириш ва УФ-кўриниш соҳасида интенсив ранг бериш мақсадида ^{60}Co γ-квантлари билан 10^4–10^7 Гр гача нурлантирилди. Пикосекундли Nd:YAG лазерининг 4-гармоникаси, 266 нм тўлқин узунликдаги импулсларнинг сони ва энергиясини 1–9 мДж оралиқда ўзгартириб, диаметри 9 дан 40 микронгача бўлган чизиқли ва пажара шаклидаги тирқишлар очилди. Энергия зичлиғи $>10^8$ Дж/м^2 бўлган лазер нурланиши билан тирқиш очиш мобайнида 4–5 мкм ўлчамдаги тўлқин зарбалари ва наноўлчамдаги кристалланиш ҳосил бўлди. Бундан ташқари, вакуум УБ гармоникасининг генерация туфайли марказий микронли тирқиш яқинида субмикронли тирқиш ҳосил бўлди. γ–нурланишнинг комбинацион таъсири ва УБ-лазер нурланиши билан тирқиш очилгандан сўнг кислороднинг камайиб кетиши ва фторнинг ҳосил бўлиши содир бўлди, бунга сабаб фотоядровий реакциялар $^{28}Si_{14}\rightarrow{}^{19}F_9+3^3T_1$; $^{16}O_8\rightarrow 4^4He_2$; $^{16}O_8+{}^3T_1\rightarrow{}^{19}F_9$ бўлиши мумкин. Шишанинг қайишқоқлиги ва релаксацияси туфайли 300 К хароратда 2 ой давомида тирқишларнинг чиқиш диаметрини катталашди. Бундай микро-панжаралардан суюқлик аралашмаларини ажратишда ва сувни тозалашда фойдаланиш мумкин.

Калит сўзлар: гамма-индукцияли ранг бериш, шишада лазер билан тирқиш очиш, плазманинг зарба тўлқини, фотоядровий реакция.

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