Femtosecond laser micromachining of thin-film coatings in a high-voltage electrostatic field

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Abstract The work is devoted to the problem of forming micro- and nanoscale elements topologies of high-resolution by means of controlled treatment of material surface with ultrashort laser pulses. The technology of processing thin-film coatings by the method of selective laser ablation is described. The possibility of using a high-voltage electrostatic field for collecting ablation products and preventing their deposition on the surface of formed microstructures is shown.

1. Introduction
The formation of micro- and nanoscale elements by the method of selective laser ablation of thin-film coatings is a unique approach to solving problems of experimental design and rapid prototyping [1-4]. One of the most important problems arising in the thin-film structures formation by direct laser ablation is the need to minimize negative factors leading to geometry distortions of recorded structure [5-7]. The main task in carrying out precision processing of thin-film materials is to reduce the influence of parasitic heat, since the focusing of intense femtosecond laser radiation is accompanied by the appearance of optical breakdown with the formation of a plasma cloud, thereby the material processing acquires not so much a laser as a laser-plasma character (figure 1).

Fig. 1. The dynamics of plasma formation above the surface of the processed materials.
External factors, namely gas atoms, molecules, vapors of various substances, including laser ablation products, make a significant contribution to the plasma formation process. Ablated material can significantly increase the lifetime of the plasma torch, its reflective properties, and, accordingly, the temperature effect on the processed material. Additional heating of the material is also possible as a result of the action of laser radiation reflected from the plasma plume, the intensity of which is below the ablation threshold, as a result of which not removal, but heating of the coating material occurs. Thus, laser-induced plasma, although often a useful physical phenomenon inherent in the process of laser ablation, makes a negative contribution to the process of controlled micromachining [8-10].

2. Laser treatment of thin-film coatings in an electrostatic field

Figure 2 shows an optical image of the nanoantenna interface formed by selective laser ablation of a thin-film metal coating with femtosecond radiation. The structure was obtained using the following laser radiation parameters: wavelength λ = 1030 nm, radiation power P = 1.5 mW, pulse repetition rate f = 10 kHz, pulse duration τ ≈ 280 fs, laser spot diameter d ≈ 1 μm. Removal of thin-film coating areas was carried out by moving the sample relative to a stationary laser beam at a given speed, which is due to the use of a precision sample positioning system and its precise synchronization with the laser system [11-13]. The image was recorded in reflected light using additional illumination located behind the sample. As can be seen from the figure, the topology of the thin-film element is formed with a sufficiently high resolution. Nevertheless, the resulting structure geometry has pronounced defects due to the deposition of ablated coating particles near the treatment area.

![Fig. 2. Plasmonic nanoantenna interface formed by selective laser ablation of a thin-film metal coating.](image)

During laser ablation treatment, ablation products make a significant impact on the process [14-17]. The products of laser ablation during expansion can repeatedly fall under the next laser pulse, thereby causing reflection, scattering and absorption of a significant radiation part. Laser ablation products, in addition to direct interaction with laser radiation, significantly increase the lifetime and temperature of the laser-induced plasma torch, which leads to a decrease in the energy entering the treatment area. Ablated particles can be deposited on processed samples surface, which causes distortions in spatial geometry of recorded structure.

The traditional solution of this problem is the removal of ablation products using a jet of compressed gas. For the effective removal of particles from the treatment area, a high pressure gas supply is required, which leads either to a high mixture consumption or to structural changes in the experimental scheme, for example, the use of a chamber with a gas recirculation system. The development of a specialized chamber together with a gas mixture preparation unit would significantly complicate the experimental process, on the basis of which a decision was made to use the electrostatic method of removing ablation products from the treatment area (figure 3).
Removal of ablation products was carried out due to the formation of an electrostatic field with a strength of 30 kV near the treatment area (figure 4). Ablation products acquire a charge and are deposited on the negative electrode. Thus, the electrostatic field protects the surface of the thin-film coating from the deposition of ablated particles.

The use of electrostatic filters to collect ablated particles from gas streams is an effective solution. The only inconvenience is the need for periodic cleaning of the electrode surface, since with prolonged deposition of micro- and nanoparticles on the surface of the electrodes, significant build-ups can form, leading to an uneven field strength and, as a consequence, the formation of an electric arc.

3. Conclusion
Femtosecond laser radiation is a unique tool for micromachining tasks, in particular, for the controlled formation of thin-film structures topology [18-20]. The key factors that ensure high quality processing are compliance with the temperature regime of laser radiation exposure, as well as its protection against re-deposition of ablation products. The use of an electrostatic field for tasks of laser micromachining makes it possible to carry out the removal of ablation products from region of laser radiation propagation without deteriorating the surface quality, and also to reduce the negative effect of plasma torch on microstructures geometry.
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