Femtosecond laser-induced formation of low-dimensional thin-films elements

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Abstract The work is devoted to the problem of precision laser micromachining of thin films. Examples of thin-film materials processing by laser radiation sources with different pulse duration are presented. The causes of defects formation in the obtained structures are described, methods for their elimination are proposed. The physical mechanisms of ultrashort laser pulses interaction with thin-film coatings, the influence of radiation parameters on the processing result, and the field of the technological approach application are considered.

1. Introduction
Laser processing of materials and processes occurring in the interaction and propagation of laser radiation, especially ultrashort duration (USP), determine the breadth of use of techniques and techniques for the creation, formation and control of the properties of the formed micro- and nanostructures. With its high peak power combined with ultra-short duration, pulsed laser radiation can achieve local conditions in the field of exposure sufficient to remove the material, change the structure and its properties. Selective laser ablation by USP allows high-precision processing of thin-film coatings of various nature, excluding the occurrence of thermal and mechanical stresses.

2. Thin films laser processing
The characteristic features of the action of ultrashort laser pulses of femtosecond order of duration on the material surface is the process of ultrafast energy transfer, which occurs due to the interaction of radiation with the electron shells of the material atoms. The extremely low duration of a single laser pulse provides a significant reduction of the thermal mechanism contribution in the process of material destruction, which suggests a relaxation nature of the impact. Despite the fact that the thermal mode of laser radiation energy transfer to the processed material is characteristic for systems having the pulse duration of the order of a few tens of nanoseconds [1], when carrying out the laser micromachining of materials by USP, excessive heating of the treatment areas should be avoided.

Excessive thermal load brings a lot of undesirable consequences: the formation of the melt of the processed material, the presence of splashes on the treated surface, the melting of materials located under the treated layer, the violation of the structural and phase state of the material as a result of thermal action, the formation of alloys of the treated coating and the substrate material, including the deformation of the entire part [2]. With intensive heating of the metal forming the film, a significant deterioration of its physical and chemical properties is possible, up to local delamination (in the case of a multilayer thin-film coating) and partial separation of the coating from the substrate. In addition to
the thin films processing problems, there are also defects associated with changes in the morphology of the substrate, the formation of cracks, craters, and melting areas.

The main task during the precision processing of thin-film materials is to obtain the maximum contrast of the formed structures, the absence of processing defects of edges and the surface of the substrate. Figure 1 shows the SEM image reflecting the characteristic defects of excessive thermal radiation exposure: low contrast of edges of the formed structures, violation of the geometry of the thin-film element, the formation of transition zones at the boundary of the laser radiation exposure area, peeling and swelling of the coating.

The image of the surface is obtained by processing a thin-film nickel coating using a nanosecond setup with a pulse duration of 100 ns. Despite the fact that the use of this laser source for micromachining tasks is not quite correct, there are applications where its use is appropriate and economically feasible. The nanosecond processing mode is conditionally threshold. As a result of the pulse impact, free molecules, atoms and ions are scattering, and a liquid phase at which the material is sprayed is forming [3], which is clearly reflected in the presented image.

![Figure 1. Defect of a thin-film structure treated with nanosecond laser radiation.](image)

The reduction of the temperature effect achieves by creating conditions that allow to transfer the maximum amount of laser energy to the process of material removal from the impact area [4]. In processing by ultrashort laser pulses, thermal effect on the material is possible both as a result of relaxation of the material electronic system, and as a result of laser-induced plasma exposure. A large energy contribution to the treatment process leads to intensive plasma formation. Laser-induced plasma has a good shielding effect, including disperses and absorbs laser radiation. It is quite difficult to avoid plasma exposure, since focusing of intense radiation in the gas environment leads to an optical breakdown with the formation of a plasma cloud. Thus, the processing of the material acquires not so much a laser as a laser-plasma character. The proportion of laser radiation passing through the formed plasma cloud depends both on the medium in which the processing takes place and on the presence of the processed material particles. The material ablated as a result of laser action significantly increases the lifetime of the plasma plume, its reflecting properties, and, accordingly, the temperature effect on the processed material. Additional material heating is also possible as a result of the impact of laser radiation reflected from the plasma plume, the intensity of which is below the ablation threshold, which leads not to the removal of the material, but to the heating and melting outside the laser exposure zone.

The minimization of the thermal mechanism of influence is achieved by selecting the pulse repetition frequency and laser power in such a way that the process becomes «cold» in nature. The optimal parameters are those at which each subsequent impulse comes after the cooling of the laser-induced plasma [5], however, an excessive decrease in the frequency and average power negatively affects the performance of the operation. The use of ultrashort laser pulses with a power of about several tens of nanjoules makes it possible to work in modes that exclude the formation of plasma, since it is impossible to form optical breakdown in air. This is characterized by minimal ablative
removal of the surface layer (about several nanometers) [6-7]. The described properties allow the effective formation of the thin-film elements topology by selective laser ablation by ultrashort pulses, possibly due to the high locality and predictability of the effect. These conditions allow the use of a much lower average radiation power and pulse energy for the removal of material areas and to localize the radiation energy in a strictly limited area of the laser spot.

3. Low-dimensional thin-films elements formation technology

The experiments of thin-film elements formation were carried out using the pulsed femtosecond Yb:KGW laser system with the wavelenght $\lambda = 1030$ nm, the energy of the pulse $E_{\text{max}} \approx 150 \mu$J, the pulse duration $\tau \approx 280$ fs. The pulse repetition rate was set to 10 kHz. Processing was performed using a 50x microobjective with a NA of 0.46, with an average power of 1.9 mW. Selective laser removal of film areas was carried out by moving the sample relative to a stationary laser beam with a given speed (Figure 2).

![Figure 2. Experimental scheme of the thin-films elements geometry formation.](image)

Figure 2. Experimental scheme of the thin-films elements geometry formation.

Figure 3 shows the result of surface treatment of a transparent quartz substrate coated with a thin nickel film. The formed element is a planar inductor. The micrograph is taken in reflected light, so only light areas contain a metallic coating. The optical image demonstrates the possibility of forming a stencil of microelectronic devices on the surface of a dielectric substrate covered with a thin film.

![Figure 3. Optical image of the square-type planar inductor formed by the selective laser ablation of a thin metal coating.](image)

4. Conclusion

Thus, the main task during the precision processing of thin-film materials is to reduce the influence of parasitic heat, which can be achieved by optimizing the processing mode, selecting the optimal power of radiation exposure and pulse repetition rate. Femtosecond laser radiation is a universal tool for
processing of almost all types of materials. Modern laser systems allow to control not only the parameters of radiation power and frequency, but also the pulse duration. The mechanism of interaction of ultrashort laser pulses with the material, in conjunction with high-precision positioning and competent technological selection of the processed materials, probably in the near future, will allow to create a complete cycle setups of optoelectronic and nanophotonic components formation.

References
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