Thin film elements design: software and possibilities of femtosecond laser techniques

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Abstract. In this paper we consider the possibilities of thin-film coatings micromachining by femtosecond laser radiation (wavelength \( \lambda = 1030 \) nm, pulse repetition frequency \( f = 10 \) kHz, Emax pulse energy \( \approx 150 \) \( \mu \)J, pulse duration \( \tau \approx 280 \) fs) for elements of microelectronics and optoelectronics. Using self-developed software the thin film elements with a given geometry were designed and formed on a surface of the quartz substrate. Examples of the microelements formation by selective laser ablation of a samples with deposited metal coating are shown.

1. Introduction
There are many methods of micro- and nanoscale technologies for the production and processing of thin-film elements, which are used in microelectronics and micromechanics [1]. The great advantage of thin-film technologies is their flexibility, which is expressed in the possibility of selecting materials with optimal characteristics and obtaining virtually any desired configuration of passive elements. At the same time, the tolerances with which certain parameters are maintained can reach 1-2%, which is especially important in cases where the exact nominal value and the stability of the microcomponents characteristics are crucial.

To form the topology of the conductive, resistive or dielectric layers of thin-film elements, the following methods are used: masking (the corresponding materials are deposited onto the substrate through removable masks); photolithography (the film is applied to the entire surface of the substrate, after which it is etched from certain areas); electron-beam lithography (some parts of the film are removed from the substrate by evaporation under the action of an electron beam) [2-4], etc. Despite the rather high efficiency of traditional methods, with the development of the miniaturization process, the technological problems of these approaches are becoming increasingly significant. The main drawback is the problem of templates using. The complexity and long duration of the photomasks manufacturing, the multistage processing and the inability to control the operation lead to the inevitability of the defects formation, and as a result, the yield of acceptable elements is reduced and their cost increases.

In view of these shortcomings, the technology of selective laser ablation (SLA) with ultrashort pulses offers an excellent solution for precision micromachining of thin-film coatings, including both restoration and correction of templates, and production of optoelectronic components.
2. Experimental setup

2.1. Hardware configuration

The experiments of thin-film elements formation were carried out using the developed hardware-software complex of femtosecond laser micromachining (figure 1). The setup uses a pulsed femtosecond Yb:KGW laser system TETA-10 as a radiation source. The system characteristics: \( \lambda = 1030 \text{ nm} \) (with the ability to work on the second \( (\lambda = 515 \text{ nm}) \) and the fourth \( (\lambda = 257 \text{ nm}) \) harmonics), pulse repetition rate \( f = 10 \text{ kHz} \), the energy of the pulse is \( E_{\text{max}} \approx 150 \mu\text{J} \), the pulse duration \( \tau \approx 280 \text{ fs} \).

![Figure 1. Femtosecond laser micromachining complex: 1 – high-speed camera, 2 – light filter, 3 – beam splitter, 4 – dichroic mirror, 5 – focusing lens, 6 – kinematic mount with a sample/cuvette, 7 – XYZ-coordinate stages system, 8 – backlight, 9 – femtosecond laser, 10 – variable attenuator, 11 – joystick.](image1)

Spatial positioning of the samples is carried out by using a combined motion system including the Aerotech ANT130-XY nanopositional two-axis platform (XY axes, 110 mm displacement range, 1 nm minimum increment, positioning accuracy \( \pm 300 \text{ nm} \)), and the motorized linear translator Standa 8MT167-25LS (Z-axis, 25 mm displacement range, full-resolution resolution 1.25 \( \mu\text{m} \)). To correct the angular deviation of the sample plane the ultra-stable kinematic mount Standa 5VDOM-1 (tip/tilt range \( \pm 2.5^\circ \), sensitivity 2 arcsec) is used. The system is controlled in two modes: manual, in which the positioning of the sample and the activation of laser radiation are performed by the operator using a joystick or keyboard, and programmatically by writing a set of executable commands.

The complex equipped with a video registration system, the high-speed camera Point-Gray Flea3 Color Vision (60 frames per second image transmission rate at a resolution of 2080x1552 pixels). The camera allows monitoring the process of laser exposure on the sample in a real time and evaluating the quality of the processing.

2.2. Software

The presented laser complex operates under the control of specialized developed software, which purpose is to combine individual technical devices into a single organized and controlled system (figure 2).
Figure 2. The structure of the components management of the laser micromachining complex.

Interaction with the setup is carried out through a graphical user interface of the program. The software has a number of functions intended both to simplify the process of materials microprocessing and to carry out preparatory operations.

In order to ensure the normal incidence of the laser beam on the sample surface, the system uses an iterative algorithm for angular correction of the X-Y plane deflection based on analysis of the microrelief images recorded by the camera. This operation automates the process of the sample positioning in the plane of the beam focus and ensures the constancy of the diameter of the laser spot on the entire surface of the sample (figure 3).

Figure 3. Schematic view of the angular correction unit.
Designing the topology of the developed thin-film elements is carried out by CAD systems. The resulting drawings in DXF-file format can be loaded into the complex software, which allows to convert the contained data into a set of commands for the setup, and also to scale the drawing and perform its spatial positioning in the absolute coordinate system of the platform working area (figure 4).

![Figure 4](image)

**Figure 4.** Thin-film element of a given geometry processed in accordance with the dxf-drawing.

### 3. Thin film selective laser ablation

The characteristic features of ultrashort laser pulses with a duration of less than picoseconds are ultrafast transfer of laser radiation energy to the treated material and extremely low heat removal from the affected area. These conditions make it possible to use significantly lower average radiation power and pulse energy to remove material areas. The radiation energy is localized in a strictly limited area of the laser spot [5,6].

Unlike pulses of longer duration, where the main mechanisms are thermal evaporation and explosive boiling, for femtosecond radiation, desorption of excited particles from the target surface, nonlinear absorption, development of avalanche ionization, nonequilibrium electronic and vibrational excitation of the target substance, as well as effects associated with overheating of the substance above the thermodynamic point are important components [7-9]. Despite the relatively short exposure time (for the present system pulse duration $\tau \approx 280$ fs), the thermal contribution, although of a small order, takes place. During the processing by ultrashort laser pulses, the thermal effect on the material is carried out as a result of relaxation of the electronic structure of the material, as a result of the action of laser-induced plasma formed both in the process of laser ablation and in the interaction of radiation with the medium in which the treatment is performed in the caustic region.

In any case, the accuracy and quality of laser processing of thin films is directly related to the magnitude and nature of the thermal impact on the sample. As a result of the outflow of heat from the irradiated region, material melts outside the laser-affected zone. Thermal distortions lead to the following consequences: smoothing the edges of the formed structures, breaking the geometry of the thin elements of the formed structure, the formation of transition zones at the boundary of the region of laser radiation. In addition to the problems of processing thin films, there are also problems associated with changes in the morphology of the substrate, the formation of cracks, craters, melting as a result of exposure to ultrashort laser pulses. The main objective of the precision processing of thin-film materials is to reduce the influence of parasitic heat. Reduction of heat exposure can be achieved by optimizing the processing mode, selection of the optimal power of radiation exposure and pulse repetition rate. Figure 5 schematically shows the main phenomena that arise during the action of laser radiation on a transparent material.
Figure 5. Scheme of processes occurring under the influence of a single laser pulse on the sample: 1 – glass substrate, 2 – multilayer thin-film metal coating, 3 – laser radiation, 4 – ablated particles of the material leaving the laser radiation exposure area, 5 – particles of the material contributing to the plasma plume development, 6 – plasma formed as a result of optical breakdown in the air on the processed material particles, 7 – the front of the heat propagation in the volume of the quartz substrate, 8 – the front of the heat propagation of the plasma plume, 9 – the melting area of the glass substrate, 10 – external environment.

During the processing by ultrashort laser pulses, it is almost impossible to avoid plasma exposure, since the focusing of intense femtosecond laser radiation in the gas medium causes an optical breakdown with the formation of a plasma cloud. Thus, the processing of the material acquire not so much laser as laser-plasma character. The proportion of laser radiation passing through the formed plasma cloud depends both on the medium in which the treatment takes place and on the presence of processed material particles in it. 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 exerted on the processed material. Additional heating of the material is also possible as a result of the action of the laser radiation reflected from the plasma plume, whose intensity of impact is below the ablation threshold. Thus, not the removal but the heating of the coating material occurs. Volumetric heating of the film leads to a significant deterioration of its physical and chemical properties, up to local delamination and partial separation of the coating from the substrate (figure 6). This phenomenon is achieved by the sorption of atmospheric gases in which the treatment is carried out, and the interaction of the heated metal with the substrate material.

Figure 6. A quartz substrate with a thin-film metal coating treated by a different number of femtosecond pulses.
Figure 6 shows a microphotography of the sample surface coated with a composite thin metal film obtained by thermal vacuum deposition. The coating consists of 6 layers with a total thickness of about 180 nm. Processing was performed using a 50x microobjective with a NA of 0.46, with an average power of 2 mW. The pulse repetition rate was 10 kHz. The matrix of the points represented in figure N is formed by increasing the number of pulses sent to the point (left to right, top to bottom), from 2 to 200. As a result of the action of a large number of pulses, the processing area has a pronounced fusion, which is typical for intense temperature action. Since this energy is not enough to melt the clean surface of quartz glass in the presence of a metal film absorbing laser radiation, conditions for local temperature growth are created. The photomicrograph is made in reflected light with the use of additional illumination located behind the sample to increase the informativeness of the obtained images. Areas subjected to significant thermal effects have pronounced color distortions, indicating a deep change in the relief of the impact area caused by the melting of the glass substrate.

Nevertheless, after determining the optimal treatment regime that excludes the appearance of the heat accumulation effect, femtosecond laser radiation becomes quite a versatile and high-precision tool for performing laser microprocessing of various materials. Laser processing and effects of interaction and propagation of laser radiation, especially of ultrashort duration, determine the breadth of application of methods and techniques for creating and controlling the properties of the obtained micro- and nanostructures. High-intensity pulsed laser radiation allows achieving local conditions in the field of influence, sufficient for changing the material and its properties, which opens up a new possibilities for precision processing of a wide range of materials, including dielectrics, semiconductors and metals [10-11].

The presented optical image shows the possibility of forming a stencil of a microelectronic devices on the surface of a quartz substrate containing a thin-film metal coating along a given trajectory in accordance with the drawing (figure 7). As an example, an illustration of the electrode layer for selective chemical sensors, whose working principle is based on changes in the ohmic resistance of chemoresistive material under the influence of the analyzed gas, is given.

![Figure 7. Optical image of the chemiresistor electrode layer formed by the selective laser ablation of a thin metal coating.](image)

If the processing area is placed in the focal plane of the objective, the coating material is ablated accompanied by the formation of a laser-induced plasma plume which entails damage to the surface of the quartz substrate. To eliminate negative effects associated with the violation of the substrate morphology, the microobjective focal plane was located above the surface of the processed sample. The optical system of the complex was adjusted to obtain a clear picture directly from the processing.
area to control the micromachining. Thus, it was possible to remove the metal coating from the surface of the quartz substrate. In this case, the minimum width of the processed track without damaging the substrate surface for a given focusing system is of the order of 3 μm.

4. Conclusion
Femtosecond laser radiation is a fairly versatile instrument for the formation and processing of microstructures. Ultra-short laser pulses make it possible to process virtually any kind of thin films, regardless of the transparency at the wavelength of the radiation, the conductive and the heat-conducting properties of the material. Despite the obvious advantages of the technology, the main problem with the use of selective laser ablation for the formation of the topology of microelements is relatively lower productivity, which currently limits the scope of the method to a small-scale production. A significant increase in efficiency can be facilitated by a deeper integration of laser and information technologies in the development of specialized equipment and tools for micromachining.

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