Application of Femtosecond Laser pulses for Nanometer Accuracy Profiling of Quartz and Diamond Substrates and for Multi-Layered Targets and Thin-Film Conductors Processing

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Abstract**—**Research results and optimal parameters investigation of laser cut and profiling of diamond and quartz substrates by femtosecond laser pulses are presented. Profiles 10 μm in width, ~25 μm in depth and several millimeters long were made. Investigation of boundaries quality has been carried out with the use of AFM «Vecco». Possibility of technological formation of profiles and micro-holes in diamond and quartz substrates with nanometer-scale boundaries is shown. Experimental results of multilayer dielectric cover treatment are also presented. Possibility of precise upper layer (thickness of 70–140 nm) removal is demonstrated. Processes of thin metal film (60 nm and 350 nm thick) treatment are considered. Isolation tracks (conductance ~ 10^{-11} S) 1.6–2.5 μm in width in conductive metal layers are formed.

Keywords**—**Femtosecond laser ablation, microhole and nano-profile formation, micromachining

I. INTRODUCTION

THERE is a plenty of papers concerning interaction of laser radiation with semiconductor and dielectric targets. Fundamental investigations of target exposure to nano-, pico-, and femtosecond laser pulses have been carried out by leading scientific laboratories all over the world [1]–[4]. At, present, there are also theoretical models describing the mechanisms of absorption of laser radiation, electron-phonon relaxation, melting and ablation of the substance [5]–[9]. Large volume of fundamental knowledge accumulated creates favorable background for applied investigations in precise treatment of target material. There are some papers reporting a successful application of femtosecond laser systems for profiles and microholes formation in silicon and quartz substrates [10]–[13].

II. EXPERIMENTAL SETUP

Fig. 1 demonstrates the experimental setup for laser micromachining. There are two laser systems applied in this scheme. The first one is based on Ti:sapphire crystal. Parameters of which are: radiation wavelength λ = 800 nm, pulse duration τ = 40 fs, repetition rate 1000 Hz, pulse energy up to 2 mJ. The second one is a femtosecond fiber laser system with the following parameters: radiation wavelength λ = 1060 nm (530 nm for second harmonic), pulse duration τ = 270 fs, repetition rate 5000 Hz, pulse energy up to 100 μJ. In order to adjust the laser pulse energy, an attenuator, consisting of combination of half-wavelength plate with Glan-Thompson prism is applied. Some portion of radiation is reflected from optical surface of a wedge and is directed to laser energy measurement unit. Laser beam focusing is performed by a micro-objective ($3.5^{\times}$, $8^{\times}$ or $20^{\times}$); laser spot ~ 1.5 – 10 μm in diameter is formed on a target surface.

Radiation of white LED is used to highlight the laser interaction area. Because the target surface is placed in the vicinity of front focal plane of micro-objective (or coincide with the one), a 4F optical system is applied for image transfer; it consists of a micro-objective and the long-focus objective. Image detection is performed by a CCD-camera and is represented on PC monitor in real-time mode. Optical system magnification is determined by the focal length ratio of both of objectives. Image scale (reduced to the pixel size of CCD-array for $8^{\times}$ objective) is β = 0.68 μm/pixel. Resolution of the optical system is on the order 1 μm. Sample is mounted on a 3D motorized stage ensemble, which provides 1 μm positioning accuracy, and which is controlled by specially developed software.

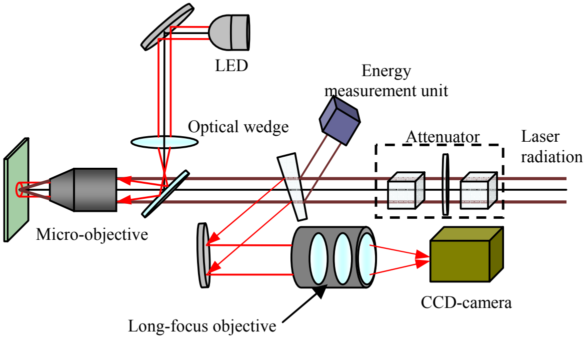

Fig. 1 Experimental setup

Two-dimensional laser intensity distribution on a target surface is presented in Fig. 2 (a). For $8^{\times}$ objective laser spot size is ~5 μm at $1/e^2$ level (where about 90% of laser energy is

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concentrated); and on the order of 1.5 μm for 20$^{\times}$ one. The radius of ablation crater on target surface is determined by the ratio of laser fluence in the center of the spot to the threshold ablation value, as well as the laser spot diameter. Thus, the size of ablation crater, which defines the width of the profile to be formed, can be less than a laser spot size at 1/e^2 level (Fig.2 (b)). As it is seen, the minimum excess of the laser fluence F_0 over the ablation threshold level in the center of the spot should be provided. It is application of femtosecond laser pulses that makes the boundaries of the crater not to extend due to heat transfer. Thus the area of ablation is close in size with the area of laser-target interaction.

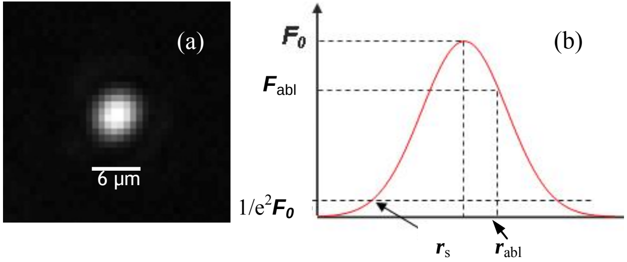

Fig. 2 (a) Two-dimensional laser intensity distribution at the target surface for 8× objective; (b) beam profile at target surface, F0 is the laser fluence in the center of the spot , Fabl is the ablation threshold, rs is the laser spot radius, rabl is the ablation crater radius

Because of the size of laser spot is from several unites to several tens of micrometers, this makes it possible to engrave the sample with thin lines. In order to form a "well" of several hundreds of micrometers in size, formation of special equidistant line pattern is required. The distance between the lines is defined by (having regard to laser pulse energy and the diameter of laser beam waist) the width of the groove formed at the target surface. Combination of the lines is called a "layer".

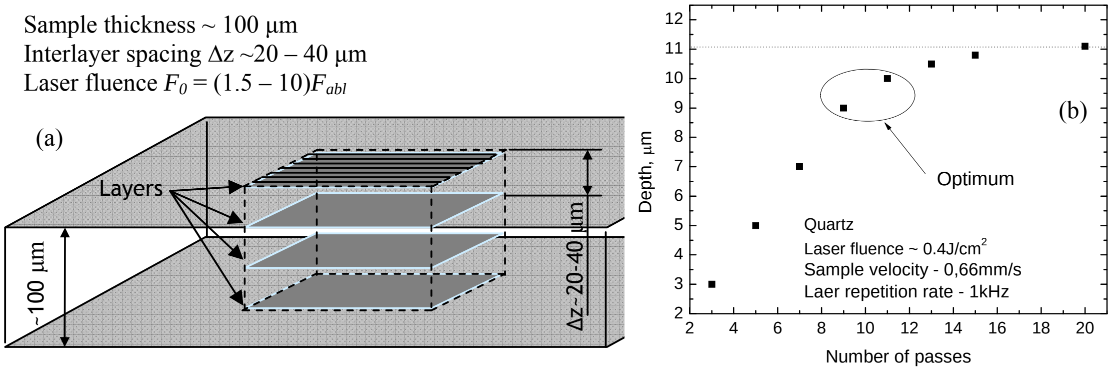

Fig. 3 (a) Scheme of layer-by-layer "well" formation; (b) "well" depth as a function of number of passes

Experimental investigations have demonstrated that the optimal laser treatment conditions of transparent media are achieved in the region of 1.5 – 10 laser ablation thresholds. Small crater depth at the target surface caused by a single laser pulse exposure (on the order of several tens of nanometers, depending on the substance) requires application of multiple laser shots on the treated area. In this connection, application of laser systems with high repetition rate is preferred. Reducing the target movement velocity solves the problem only partially, because of a considerable time growth for a large scale crater to be formed. Thus, target movement along the set trajectory is cyclically performed with given number of passes.

There is a preparatory stage, preceding the treatment, during which the optimal number of cycles is investigated. For this purpose a depth of the "well" as a function of number of repetitions is investigated. According to analysis results, a number of passes along the trajectory is chosen. It is associated with a certain value of "well" depth (Δz ~ 25 μm typically). The following layer (a set of equidistant lines filling the area of the "well" to be formed) is placed at the distance Δz deeper relative to a previous layer (Fig. 3 (a)).

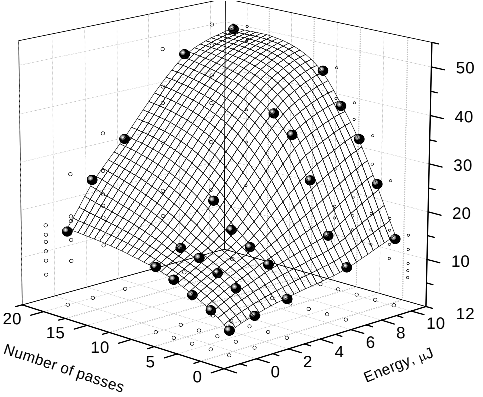

Fig. 4 Investigation results of optimal parameters of laser treatment

Fig. 3 (b) demonstrates the dependence of the "well" depth on the number of passes of laser radiation along the trajectory. Laser fluence defines (at given laser repetition rate) the depth of the groove per a single pass. 10 – 12 cycles are optimal because the depth of the groove is not significantly increased as the number of passes grows. To find the optimal conditions of laser treatment, an investigation of the "well" depth on the number of cycles for various laser energy values have been conducted. Experimental results presented in Fig. 4

demonstrate linear dependence on the parameters. Saturation of the linear dependence is observed for laser pulse energy higher than 9 μJ and for number of passes more than 10. In addition, there are some cracks and spalls observed at the "well" edges at maximum energy, which indicate unsuitability of such regime.

III. EXPERIMENTAL RESULTS

A distinctive feature of application of femtosecond laser pulses is steep edges and boundaries of microholes and grooves. At the same time, a significant drawback of laser processing technology is the conicity of the "well" walls. This influences radically on the depth and the size of the groove or "well" to be formed. The depth/width ratio of the groove is typically equals 3–5. This problem is being studied now.

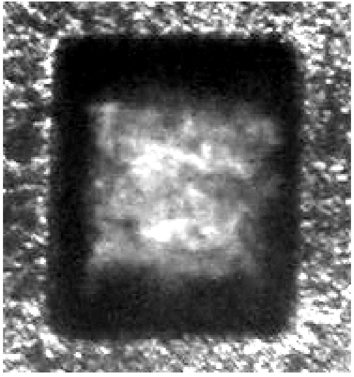

Fig. 5 Picture of a "well" in quartz substrate 100 μm ×100 μm

A picture of the "well" cut in the quartz plate is presented in Fig. 5; the walls are slightly tilted inside. To overcome this drawback a technique of sample tilting is usually applied, but it is beyond the scope of this paper. Experiments on determination of width of the boundaries at laser processing of diamond substrates have also been conducted. A femtosecond fiber laser system with radiation wavelength λ = 1060 nm (530 nm for second harmonic) have been applies for this purpose. Initial roughness of diamond plates was about several micrometers (RMS). Several cut-through grooves with the width of 15 μm are formed. Unfortunately, length of the cantilever is not enough to draw the profile of the groove. That's why the bottom of the profile in Fig. 6 is shown symbolically. Width of the boundaries is shown to be on the order of several hundreds nanometers.

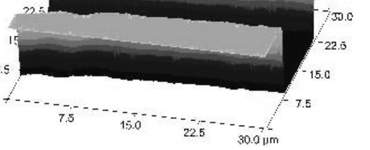

Fig. 6 AFM-scan of the profile (15 μm width) obtained by "Vecco" AFM. The bottom is shown symbolically

Surface layer removing in multilayer targets is another actual problem. Because the depth of ablation crater is on the order of several tens of nanometers (10 – 50 nm depending on the material), this feature offers the challenge of high-precision laser machining with nano-layers removal possibility. Fig. 7 demonstrates the results of laser processing of thin metal films on a glass substrate. Thicknesses of the metal layers have the thickness of ~350 nm for aluminum and ~70 nm for gold target. The purpose of the researches conducted is a removal of metal layer along the trajectory specified to obtain a minimal conductivity. The obtained width of the groove is about 1 – 2 μm; the conductivity value is ~10^{-11} S.

IV. CONCLUSIONS

Application of femtosecond laser pulses for material processing offers the challenge of high-precision laser machining with micro- and nanoaccuracy. This includes formation of microprofiles, grooves, gutters and cut-through slits. The obtained results create favorable background for development of technology of MEMS-devices fabrication.

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