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Formation of nanostructures at laser ablation under the action of ultrashort laser impulses on a surface of solid states


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Abstract

One of the most popular methods for producing nanostructures on solid surface is laser ablation. The experimental results of ultrashort pulses laser interaction with metals and carbon are presented. Our femtosecond laser system generates pulse trains with $E_{\text{pulse}}=1$ mJ, pulse duration $T_{\text{pulse}}=50$ fs and repetition rate $f_{\text{rep}}=1$ kHz. Under vacuum condition in chamber (pressure $p=10^{-4}$ Torr) atomic vapors condensate on cold substrate surface. Scanning electron and atomic-force microscopy were used for sample investigation. The nanostructured films of nickel, titanium and carbon with the minimum characteristic size of nanostructures 30 nm are obtained.

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Keywords: Laser ablation; ultrashort laser pulses; nanostructures; carbon materials; metals

1. Introduction

The given work is devoted to experimental research of the nanostructures arising at laser ablation of metal and carbon targets and deposition of products of ablation on a substrate.

The geometry of our experiment is similar to the scheme offered in work [1]. However, in our experiments radiation of femtosecond Ti:Sapphire laser system (Fig. 1) had different parameters: frequency of repetition of pulses $f_{\text{rep}}=1$ kHz, radiation pulse duration $T_{\text{pulse}}=50$ fs and energy $E_{\text{pulse}}=1$ mJ. In our system we used the autocorrelation method and method of spectral phase interferometry (SPIIDER) for control of duration of femtosecond laser pulse. Thus, measurements by two independent methods allow to control laser pulse duration and to regulate system at necessity. The radiation was focused by a single lens on a surface of the target which is in the vacuum chamber (see Fig. 2). Diameter of a spot of the focused radiation was 250 microns. The chamber was pumped out by a turbo-molecular pump station to pressure $10^{-4}$ Torr (Fig. 3).

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2. The experiment

The laser radiation focused on a target located under a corner 45° to surface. During action of a laser impulse energy of laser radiation is absorbed by an electron subsystem of substance, of which the target consists. Then, in time approximately equal to several picoseconds energy is transferred to an ionic subsystem of substance of a target, the ablation of substance occurs. In the course of ablation there is an adiabatic expansion of substance. This process occurs during an order of 1 ns, thus substance steams are cooled to condensation temperature. The liquid and steam mix in which processes of formation of nanoparticles are possible is formed.

The distance from a target on which there is a formation of nanoparticles should be \( l = c \cdot \tau \), where \( c \) – sonic speed, \( \tau = l \times \text{uc} \). It is possible to show that \( l = 100 \ \mu \text{m} \) [1]. We selected thermodynamic conditions of formation of nanoparticles experimentally, varying parameters of laser pulses, frequency of repetition, and also distance from a target to a substrate. The sprayed material of a target scatters in volume of the vacuum chamber and deposits on a cold substrate. Depending on adjustable parameters of experiment on a substrate sufficiently compound structures are formed [2].

Metal targets were made of nickel and the titanium. Carbon targets were made of amorphous glasscarbon. As substrates the polished plates of quartz glass were used.
In the course of influence on a target the characteristic craters are formed (presented on Fig. 4).

Time of influence for nickel targets is approximately 6 seconds. The zone structure of evaporation is well visible on a substrate (see Fig. 5). The raised dust material has small adhesion with a substrate and is unstable to external influence.
Typical SEM-images of nanoparticles of nickel which deposits on a surface of a substrate from quartz glass are shown on Fig. 6. Corresponding distributions of nanoparticles show, that the characteristic size of particles in the central zone $I$ is 100 nm, in an average zone $II$ - 60 nm, in a regional zone $III$ - 40 nm.

![SEM images of nanoparticles](image1)

![Graph](image2)

Fig. 6. (a) Evaporation of nickel SEM images and corresponding distribution of particles: (a) in the central zone $I$; (b) an average zone $II$; (c) in a regional zone $III$.

The nanoparticles with the smaller characteristic size of 17 nm, have been received at influence of laser radiation on a surface of a titanium target. The typical images of nanoparticles which deposit on a surface of a cold substrate from quartz glass are presented on Fig. 7.
The nanoparticles at influence of laser radiation on a titanium target are received at the same geometry of experiment, as in experiments with targets from nickel. However, under some conditions of experiment a layer of nanoparticles after experiment (in air atmosphere) was transformed (itself was organized), forming almost regular structures which are shown on Fig. 8.

At the analysis of optical images of a surface the impression that there is a formation of microcracks (see Fig. 8, 9) can be made. In the central zone the regular or periodic distribution of structures is distinctly observed. Thus, at a distance from the central zone is closer to edge, there is an exhausting of the given microcracks and allocation of separate strips is observed. In the most remote zone of evaporation of microcracks it is not observed.
Fig. 9. SEM images of evaporation central zone of the titanium

However, measurements executed on AFM have shown, that enough sharp cambers (folds) are formatted on surface which represents a layer of nanoparticles. Distribution of nanoparticles by the sizes is presented on Fig. 10. Further, at increase in distance from a target to a substrate, the effect of microstructurization disappears and nanoparticles with the characteristic size 100-200 nanometers are formed.

Fig. 10. Zone structure and distribution of nanoparticles by the sizes of titanium target

It is possible to assume, that the given effect is due to intensive interaction of nanoparticles of the titanium with atmospheric oxygen with formation of oxide TiO$_2$ and self-organising of nanoparticles in the course of such interaction. However, more detailed understanding of the physical mechanism of microstructurization of a surface of evaporation of the titanium layer in atmospheric air demands further experimental research.
The nanostructures received at ablation of glasscarbon by ultrashort laser pulses on a surface of a substrate from quartz glass are presented on Fig. 11. The most typical AFM-images are shown. The main difference from similar images for nickel and the titan consists that for carbon separate nanoparticles are not formed, and there is a formation of nanostructures enough the difficult form. The area shown on Fig. 11(b) is a increased part of Fig. 11(a). On Fig. 10(b) it is possible to see difficult labyrinth structure of nanotubes with the characteristic cross-section size of an order 10 nm and ring structures in diameter of an order of 30 nm, height of structures of an order of 15 nm that will be agreed with researches of other authors and our earlier work [1-3].

3. Conclusion

The research carried out by means of AFM and SEM show that the deposition area of carbon and metal targets under the influence of femtosecond laser impulses consists of several zones with different structure. Each zone is characterised by the one's own scale of the formed nanostructures. There are the central, average and regional zones, with the characteristic sizes 100 nm, 80 nm, 60 nm. The evaporation has uniform enough structure. Typical diameter of nanostructures of glasscarbon samples is 30 nm and 15 nm in height.

The effect of microstructurization of the received titanium evaporation in atmospheric air can be explained by interaction with atmospheric oxygen with formation of oxides of the titanium, and is also found out by processes of self-organising of nanoparticles.

References