

# ON A PHYSICO-MATHEMATICAL MODEL FOR CONTROLLED FORMATION OF PERIODIC NANOSTRUCTURES AT SOLID SURFACES IRRADIATED BY FEMTOSECOND LASER PULSES

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**Abstract:** In this paper, we propose a physico-mathematical 3D model to study some of the basic features of the interaction of radiation with solid materials (metals, semiconductors, insulators) under the action of femtosecond laser pulses. The constructed model is a parametric model that, in particular, takes into account the dependence of the physical and chemical characteristics of the periodic nano-surface structures controlled laser irradiation parameters the polarization, angle of incidence, the energy density, wavelength, etc. The developed model is meant for the excitation of periodic nano-surface structures by electric waves which are in the process of irradiation and periodically amplified and attenuated, i.e. it holds periodic interference.

**Keywords:** PERIODIC NANOSTRUCTURE, LASER PULSE, MATHEMATICAL MODEL, STABLE SOLUTION

## 1. Introduction

The synthesis of periodic nanostructures on various solid surfaces together with femtosecond laser impulses is one of the most perspective methods in the field of laser ablation on the metal surfaces, metal-like materials and dielectrics. In particular, the use of femtosecond lasers has several advantages. First of all, the effect of these impulses on the target leads to ultra-fast heating, which then reaches a very high quality of material processing. Second of all, the next two very crucial aspects provide unique conditions for the ablation of material together with the femtosecond laser impulses (see, for instance, [1]-[3]). Now it is vital to observe that the amount of time it takes after the laser impulse from the heated zone is negligible so that the laser energy is absorbed in the targeted and localized area that can be controlled.

Currently the laser synthesis of periodic nano-surface structures is successfully applied in increasing the ultra-thin materials that are often used in the microelectronics and aerospace materials, for colour coding, for local chemical modification of surfaces, to excite Raman light scattering, and to improve the strength of ultra-thin materials (see, for instance, [4], [5] and the corresponding references therein). Nevertheless, there are no adequate complex physical and mathematical models that are based on rigorous theoretical calculations; no strictly mathematically based concept can make accurate predictions in the evolution of both the geometry and characteristics of the synthesized periodic nano-surface structures on surfaces of various metals and metal-like materials under the influence of femtosecond laser impulses with different physical and technological conditions.

For an accurate description of the mechanism of synthesis of periodic nanostructures on the surface of semiconductors by the femtosecond laser impulses, there appears different approaches that mostly use the same method of studying the analysis of various surface instabilities. Notice that such analysis is not able to fully identify the particular nano-surface periodic structures (see, for instance, [6], [7]), as the absorption of the femtosecond pulse geometry on the surface of the material hardly changes. Thus, this is considered as a problem of the non-uniform distribution of the laser energy on the treated nano-surfaces; optical properties are instantly changed in the course of photoexcitation and the melting of the electronic subsystem.

Simultaneously, the developed methods for solving this problem apply only to a perfectly flat or rough surface with very low relief modulation amplitude ([9], [8]). In particular, when the ratio between the relief modulation and the laser wavelength is negligible, and in both cases, the following restrictions apply: the number of laser impulses must not exceed 10 and the periodic values of the nano-surface structures should be in the range 1÷1.1 (see, for instance, [9], [10]).

The authors of this work have built from scratch 1D-3D mathematical models for the study of some of the main features of the interaction of radiation with solid materials (taking as an example copper) under the action of femtosecond laser pulses. The models follow the parametric model, which incorporates the dependence of physical and chemical characteristics of the periodic nano-surface structures (periodic nanoscale particles) from the controlled parameters of laser ablation: from polarization, the angle of incidence, the energy density, of the wave length, etc. All the new models are expressed in the form of linear and non-linear non-stationary partial differential equations with linear and nonlinear boundary conditions of mixed type (the Neumann-type and Newton-Robin type).

Furthermore, the authors of this paper developed an analytical and numerical algorithm for finding stable solutions in 1D approximation for constructed 3D model. However, due to restrictions on the presented volume of this work, we will skip the output constructed 1D-3D physical and mathematical models and give only the setting of the "ready-made" 3D model. Therefore, we will present the developed analytical and numerical algorithm.

## 2. Mathematical Models

### 3D model for temperature distribution and electric field in metallic materials

The proposed 3D mathematical model consists of determining the temperature distribution  $T = T(x, t)$  and the electric field  $\vec{E} = \vec{E}(x, t)$  in the region  $\bar{D} \stackrel{\text{def}}{=} \{x = (x_1, x_2, x_3) \in \square^3 : x_i \in [0, L_i], i = \overline{1,3}\}$  during any moment of time  $t \in [0, t_{\max}]$  with the following equations as well as the initial and boundary conditions:

- dual-temperature heating dynamics for electron ( $T^e(x, t)$ ) and lattice ( $T^\ell(x, t)$ ) subsystem of metal materials (taking as an example copper) with femtosecond laser pulse:

$$\left[ c_v \cdot \frac{\partial T}{\partial t} \right]^{e,\ell} + \tau \cdot \left[ \frac{\partial^2 T}{\partial t^2} \right]^{e,\ell} = \text{div} \left( \chi_v^e(x, t; T^e, T^\ell) \cdot \nabla T^e \right) + F(x, t; T^e), (x, t) \in D \times [0, t_{\max}]; \quad (1)$$

- electric field distribution on the periodically structured surface of the metallic material:

$$\frac{4 \cdot \pi \cdot \sigma \cdot \mu}{c^2} \cdot \frac{\partial \bar{E}}{\partial t} + \frac{\varepsilon \cdot \mu}{c^2} \cdot \frac{\partial^2 \bar{E}}{\partial t^2} = \Delta_{x_j, x_k} E_{x_i} - \sigma \cdot |\bar{E}|^2 - \frac{\partial}{\partial x_i} \left( \frac{\partial E_{x_j}}{\partial x_j} - \frac{\partial E_{x_k}}{\partial x_k} \right), (x, t) \in D \times [0, t_{\max}], \quad (2)$$

$$\forall (i, j, k) = \overline{1, 3}: j \neq k \neq i;$$

- the following initial conditions:

$$T^e(x, t) \Big|_{t=0+0} = T_s^e(x), x \in \bar{D}, \quad (3)$$

$$\frac{\partial T^e(x, t)}{\partial t} \Big|_{t=0+0} = 0, x \in \bar{D}, \quad (4)$$

$$T^\ell(x, t) \Big|_{t=0+0} = T_s^\ell(x), x \in \bar{D}, \quad (5)$$

$$\frac{\partial T^\ell(x, t)}{\partial t} \Big|_{t=0+0} = 0, x \in \bar{D}, \quad (6)$$

$$\bar{E}(x, t) \Big|_{t=0+0} = \bar{E}_0(x), x \in \bar{D}; \quad (7)$$

$$\frac{\partial \bar{E}(x, t)}{\partial t} \Big|_{t=0+0} = 0, x \in \bar{D}; \quad (8)$$

- and the following boundary conditions:

$$\left\{ T^e(x, t) - k_1 \cdot \frac{\partial T^e(x, t)}{\partial x_i} \right\} \Big|_{x_i=0+0} = T_{0,i}^e(x/\{x_i\}, t), \quad (9)$$

$$x \in \bar{D}, t \in [0, t_{\max}], \forall i = \overline{1, 3};$$

$$\left\{ T^\ell(x, t) - k_2 \cdot \frac{\partial T^\ell(x, t)}{\partial x_i} \right\} \Big|_{x_i=0+0} = T_{0,i}^\ell(x/\{x_i\}, t), \quad (10)$$

$$x \in \bar{D}, t \in [0, t_{\max}], \forall i = \overline{1, 3};$$

$$\frac{\partial T^e(x, t)}{\partial x_i} \Big|_{x_i=L_i-0} = T_{L,i}^e(x/\{x_i\}, t), \quad (11)$$

$$x \in \bar{D}, t \in [0, t_{\max}], \forall i = \overline{1, 3};$$

$$\frac{\partial T^\ell(x, t)}{\partial x_i} \Big|_{x_i=L_i-0} = T_{L,i}^\ell(x/\{x_i\}, t), \quad (12)$$

$$x \in \bar{D}, t \in [0, t_{\max}], \forall i = \overline{1, 3};$$

$$\bar{E}(x, t) \Big|_{x_i=0+0} = \bar{E}_{0,i}(x/\{x_i\}, t), \quad (13)$$

$$x \in \bar{D}, t \in [0, t_{\max}], \forall i = \overline{1, 3};$$

$$\bar{E}(x, t) \Big|_{x_i=L_i-0} = \bar{E}_{L,i}(x/\{x_i\}, t), \quad (14)$$

$$x \in \bar{D}, t \in [0, t_{\max}], \forall i = \overline{1, 3}.$$

Furthermore, we assume compliance with the relevant consistency conditions of the initial and boundary conditions.

In the formulated problem (1)-(14) the following definitions and designations occur:

- $[A]^{e, \ell} \stackrel{\text{def}}{=} A^e - A^\ell;$

- $\text{div} A \stackrel{\text{def}}{=} \sum_{i=1}^3 \frac{\partial A_{x_i}}{\partial x_i};$

- $\nabla A \stackrel{\text{def}}{=} \left( \frac{\partial A}{\partial x_1}, \frac{\partial A}{\partial x_2}, \frac{\partial A}{\partial x_3} \right)^T;$

- $D$  denotes the interior field  $\bar{D}$ , i.e.

$$D \stackrel{\text{def}}{=} \text{int}(\bar{D}) = \{x = (x_1, x_2, x_3) \in \square^3: x_i \in (0, L_i), i = \overline{1, 3}\};$$

- $c_V^e$  and  $c_V^\ell$  are respectively the electron gas and heat capacities per unit volume  $V$ ;

- $\tau \square 1$  and  $k_i$  ( $i = 1, 2$ ) are positive constants;

- the function  $\chi_V^e(x, t; T^e, T^\ell)$  describes the electron thermal conductivity, which plays a pivotal role in the metals, semimetals, as well as certain semiconductors and superconductors. The electron thermal conductivity provides information on the carrier scattering mechanism, on the peculiarities of the band structure of the material, as well as information about the magnitude and temperature dependence of the bandgap (energy gap) of the material. It is important to note that the electron conductivity at low temperatures is determined by the scattering of electrons by impurities and defects and also increases with temperature. However, at high temperatures the process is determined by scattering on phonons and decreases with increasing temperature and therefore, at a certain temperature the electron thermal conductivity reaches a maximum, higher than that of a perfect crystal. The conductors in electron thermal conductivity are related to the conductivity of the Wiedemann-Franz Law; in superconductors electrons are combined into Cooper pairs, not involving in the transfer of heat. Furthermore, when the temperature falls below the transition temperature to the superconducting state, the electron thermal conductivity is determined by the normal (unpaired) electrons and decreases exponentially as it approaches zero. In bipolar semiconductors and semimetals, there is an additional mechanism called a bipolar component, namely, electron-hole pairs generated at the hot end of the target and diffusing towards the temperature gradient and recombining at the cold end to produce heat;

- the function  $F(x, t; T^s)$ , calculated by the Beer-Lambert-Bouguer Law:

$$F(x, t; T^s) \stackrel{\text{def}}{=} \left(1 - \Phi(T^s)\right) \cdot I \cdot e^{-\sum_{i=1}^3 \beta_i \cdot x_i} \times e^{-\delta(t-t_{\text{laser pulse}}) \cdot \frac{\gamma(x, t)}{b} dV_x}, \forall t_{\text{laser pulse}} \in [0, t_{\text{max}}^{\text{laser pulse}}] \quad (15)$$

describes the attenuation/absorption of laser radiation on the feeding surface of the target "flow" of free electrons due to the inverse scattering brake; in Equation (15) the function  $\Phi$ , depending on the temperature  $T^s$ , the surface of the metal material at the initial moment of time, is the reflectance of the target material;  $I$  denotes the intensity of the incident laser beam on the target;  $\beta_i$  ( $i = \overline{1, 3}$ ) is the absorption coefficient of the target material in the direction of the coordinate axis  $\overline{OX}_i$ ;  $\delta(\cdot)$  is the Dirac Delta Function; the function  $\gamma(x, t)$  is the coefficient absorption in the resulting plasma laser flare;  $t_{\text{max}}^{\text{laser pulse}} \square t_{\text{max}}$  denotes the end of the laser radiation;

- ◆ the scalar function  $E_{x_i}(x, t)$  is the  $i$ -th ( $i = \overline{1, 3}$ ) component (corresponding axis  $\overline{OX_i}$ ) of the electric vector field  $\vec{E}(x, t)$ ;
- ◆  $\varepsilon$  and  $\mu$  mean respectively dielectric and magnetic permeability of the metal material (in our situation copper);
- ◆  $\sigma$  is a specific conductivity of the material;
- ◆  $c$  is the speed of light. Here it should be noted that for the simulation of the femtosecond laser radiation, the nested (embedded) laser energy distribution may exclude relief modulation over time  $t_{\max}^{\text{laser pulse}}$ , however, it is crucial to consider that in the photoexcitation process, the copper surface for heating ultrafast electronic subsystem of the material to the temperature  $T^e$  of the order of several electron volts, can significantly affect the optical properties of copper. It is easy to show at a specific wavelength (for example,  $\lambda = 700$  nm) the femtosecond laser pulse by calculating the dependence  $\text{Re}(\varepsilon)$  and  $\text{Im}(\varepsilon)$  to  $T^e$ ; consequently from the Drude Model considering the contribution of the lattice  $\varepsilon^\ell$  we can apply the following formula to determine the dielectric constant  $\varepsilon$ :

$$\varepsilon = \varepsilon^\ell - \frac{\omega_{\text{plasma}} \cdot t_{\text{electron collision}}^2}{(\omega \cdot t_{\text{electron collision}})^2 + 1} \cdot \frac{i \cdot \omega \cdot t_{\text{electron collision}} + 1}{i \cdot \omega \cdot t_{\text{electron collision}}}, \quad (16)$$

where  $\omega$  is the frequency of the femtosecond laser pulses;

$$\omega_{\text{plasma}} = \sqrt{\frac{\rho_{\text{electron density}} \cdot e^2}{\varepsilon_0 \cdot m_{\text{effective mass}}}} \quad (17)$$

has a plasma frequency when the effective mass of the electron  $m_{\text{effective mass}} \approx \frac{3}{2} \cdot m$  and the electron density  $\rho_{\text{electron density}}$  for copper;

- ◆  $t_{\text{electron collision}}$  is a collision of electrons within the random phase approximation (see, for instance, [11]), and it is determined by the following formula:

$$t_{\text{electron collision}} = t_{\text{electron collision}}(T^e) \approx \frac{1}{K_{\text{electron-electron scattering}}} \times \frac{1 + e^{-\frac{\hbar \cdot \omega}{T^e}}}{(\pi \cdot T^e)^2 + (\hbar \cdot \omega)^2}, \quad (18)$$

with respect to  $K_{\text{electron-electron scattering}}$ , which for the investigation of the material (in our situation copper) can be determined by tabular dependence approximation  $\varepsilon(\omega)$  at  $T^e = 0$ .

Thus, under certain assumptions the foregoing non-linear 3D model (1)-(18) describes the evolution of the temperature field and the electric field distribution on the surface of metals (taking as an example copper) under the action (irradiation) of femtosecond laser pulses. Since dielectrics with a forbidden gap in the beginning of laser radiation's exposure there is no absorption of the radiation pulse due to reverse brake dissipation; hence, most dielectrics with relative moderate intensities of laser radiation can be considered as transparent. It is important to observe that the mechanism of interaction of femtosecond laser pulses with insulators is significantly different from the above-described mechanism for metals.

When the threshold of intensity, depending on the characteristics of the particular dielectric surface structure, begins to break down, the changing of the reflectance and absorbance of the surface is followed by the melting and ablation of the dielectrics (with a further increase in the intensity of radiation).

Following the outline of monograph [1] below, the main process leading to the synthesis of nano-sized particles is the influence of femtosecond laser pulses in the dielectric materials. At the initial stage of the action of a femtosecond laser pulse on a dielectric surface (we neglect the presence of impurities and defects in the original) the multiphoton absorption mechanism forms a free primeval / seeding electrons, and these electrons efficiently absorb laser energy by dissipating the reverse braking process, with energy  $E^e$  beginning to increase rapidly and reaching the critical value, while developing process of ionization by electron impact (the so-called avalanche / cumulative ionization). For laser pulse durations of the order of hundreds of femtoseconds with a capacity in the range of  $10^{10} \div 10^{14}$  W/cm<sup>2</sup>, the tunnel ionization mechanism can be neglected. Then the dynamics of the electron density in the conduction band can be described by the following simplified equations:

$$\begin{cases} \frac{\partial \rho^e}{\partial t} = (\mathcal{G}^{\text{m.i.}})^n \cdot I^n(t) + \mathcal{G}^{\text{c.i.}} \cdot I(t) \cdot \rho^h; \\ \frac{\partial \rho^h}{\partial t} = (\mathcal{G}^{\text{m.i.}})^n \cdot I^n(t) + \mathcal{G}^{\text{c.i.}} \cdot I(t) \cdot \rho^h, \end{cases} \quad (19)$$

where the superscripts  $e$  and  $h$  refer, respectively, to the electrons and the holes;  $\mathcal{G}^{\text{m.i.}}$  and  $\mathcal{G}^{\text{c.i.}}$  mean respectively multiphoton ionization rates (multiphoton ionization) and avalanche ionization (cumulative ionization);  $I(t)$  indicates the intensity of the radiation incident on the target; and  $n$  is the number of photons required for the excitation of electrons at the transition from the valence band to the conduction band.

The appearance of a large number of electrons in the conduction band of the dielectric leads to metallization of the dielectric surface layer. Therefore, it increases the absorption and reflection coefficients. However, unlike the metals, the density of electrons in the conduction band of dielectrics depends strongly on the time and distance target depth. Furthermore, it is possible to describe the electron- lattice relaxation dielectric process, by analogy with the description of metals. In addition, at the end of femtosecond laser pulses, with the passage of time, there are processes of recombination of electrons and three-body recombination (Auger recombination / three-body recombination), from which there is a gradual return of the target dielectric properties. Typically, after the irradiation in the process of recombination of electrons are formed various defective state whose lifetime depending on the type of the dielectric ranges from microseconds to days. Repeated action of femtosecond laser pulses lead to a more efficient heating by priority field defects with larger absorption cross section compared with the electrons of the valence band.

### 1D model for metallic materials

In conclusion, this paper presents the basic equations in 1D approximation describing the mechanism of action of femtosecond laser pulses in the dielectric materials based on photoemission and electric fields.

- The first equation is a modification (towards complexity – a detailed description) of the simple equations (19):

$$\frac{\partial \rho^e}{\partial t} = \theta \cdot \frac{\partial^2 \rho^e}{\partial x^2} + \mu \cdot E \cdot \frac{\partial \rho^e}{\partial x} + \frac{\mu}{\varepsilon \cdot \varepsilon_0} \cdot \rho^e \cdot [\rho]^{e,h} + (\mathcal{G}^{\text{m.i.}} + V^{\text{c.i.}}) \cdot \frac{\rho^{\text{n.a.}}}{\rho^{\text{n.a.}} + \rho^h} - \mathcal{G}^{\text{e.r.}} - F^{\text{ph.e.}}; \quad (20)$$

- The Poisson's equation:

$$\frac{\partial \vec{E}}{\partial x} = - \frac{|e|}{\varepsilon \cdot \varepsilon_0} \cdot [\rho]^{e,h}; \quad (21)$$

- The following is a formula for calculating the intensity of femtosecond laser radiation onto a target Gaussian time profile:

$$I(t) = \sqrt{\frac{\ln 2}{\pi}} \cdot (1 - \Phi(t)) \cdot \frac{2 \cdot f}{t_f} \cdot e^{-4 \ln 2 \left(\frac{t}{t_f}\right)^2}; \quad (22)$$

- The radiation intensity equation inside the dielectric depending on the time and distance of the target depth considering the multi-photon absorption and absorption by free electrons:

$$\frac{\partial I(x,t)}{\partial x} + a(x,t) \cdot I(x,t) = -g^{m.i.} \cdot \frac{\rho^{n.a.} \cdot m \cdot \hbar \cdot \mu}{\rho^{n.a.} + \rho^h}; \quad (23)$$

- The following formula calculates the absorption coefficient of a free electron:

$$a(x,t) = \frac{4 \cdot \pi \cdot k(x,t)}{\lambda}; \quad (24)$$

- The Fresnel's formula for the estimation of the reflection coefficient:

$$\Phi(t) = \frac{\left( \sqrt{\frac{\operatorname{Re}(\varepsilon) + \sqrt{(\operatorname{Re}(\varepsilon))^2 + (\operatorname{Im}(\varepsilon))^2}}{2}} - 1 \right)^2 + k^2}{\left( \sqrt{\frac{\operatorname{Re}(\varepsilon) + \sqrt{(\operatorname{Re}(\varepsilon))^2 + (\operatorname{Im}(\varepsilon))^2}}{2}} + 1 \right)^2 + k^2}; \quad (25)$$

- The Einstein's formula for the diffusion coefficient:

$$\theta = \frac{k \cdot T^e \cdot \mu}{|e|}; \quad (26)$$

- Formula estimation for the photoemission:

$$F^{ph.e.} = \frac{(g^{m.i.})^n \cdot I^n + g^{c.i.} \cdot \rho^e \cdot I \cdot \rho^{n.a.} \cdot e^{-\frac{x}{\xi}}}{2 \cdot (\rho^{n.a.} + \rho^h)}. \quad (27)$$

In the equations (20)-(27) there are the following designations (the designations that occurred earlier below are not listed):

- ♦  $V^{m.i.} = g^{m.i.} \cdot I \cdot \rho^e$  the acceleration/development of cumulative ionization;
- ♦  $g^{e.r.} = \frac{\rho^e}{\tau_r}$  the recombination velocity electron capture of the coupled state;
- ♦  $\rho^{n.a.}$  the neutral atoms;
- ♦  $\xi \approx 1 \text{ nm}$  the characteristic depth of the target, which photoemission depth (maximum photoemission takes place on the surface of the dielectric material) decreases exponentially.

### 3. Conclusions

In the present paper, 3D model (1)-(18) as well as 1D model (only main equations without any initial or boundary conditions) (20)-(27) are proposed. The model (1)-(18) describes evolution of temperature field (scalar quantity) and electric field (vector quantity) in the case when femtosecond laser pulses act on the metallic materials; the model (20)-(27) contains the basic equations describing the simplified mechanism of action of femtosecond laser pulses on the dielectric materials.

In the future, the authors of this paper intend to: firstly, to develop an algorithm for finding a stable solution of the constructed 3D model (1)-(18); secondly, to complicate the model (1)-(18) by adding other equations and conditions (which were not considered in this model) that can be occurred in the mechanism of femtosecond laser pulses action on the metallic materials; thirdly, to analytically solve the proposed 1D model and to carry out the deeply analyse of the obtained results.

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### References

- [1] Bäuerle D. Laser processing and Chemistry. – Berlin, Heidelberg: Springer-Verlag, 2000, 649 p.
- [2] Korte F., S. Nolte, B.N. Chichkov, T. Bauer, G. Kamlage, T. Wagner, C. Fallnich, H. Welling. Far-field and near-field material processing with femtosecond laser pulses. – Journal of Applied Physics A, Volume 69, Issue 1 Supplemen, 1999, pp. 7-11.
- [3] Wellershoff S.-S., J. Hohlfeld, J. Güdde, E. Matthias. The role of electron-phonon coupling in femtosecond laser damage of metals. – Journal of Applied Physics A, Volume 69, Issue 1 Supplemen, 1999, pp. 99-107.
- [4] Dusser B., Z. Sagan, H. Soder, N. Faure, J.P. Colombier, M. Jourlin, E. Audouard. Controlled nanostructures formation by ultra-fast laser pulses for color marking. – Journal of Optics Express, Volume 18, Issue 3, 2010, pp. 2913-2924.
- [5] Ionin A.A., Y.M. Klimachev, A.Y. Kozlov, S.I. Kudryashov, A.E.Ligachev, S.V.Makarov, L.V.Seleznev, D.V. Sinitsyn, A.A. Rudenko, R.A. Khmel'nitsky. Direct femtosecond laser fabrication of antireflective layer on GaAs surface. – Journal of Applied Physics B, Volume 111, Issue 3, 2013, pp. 419-423.
- [6] Reif J., O. Varlamova, S. Uhlig, S. Varlamov, M. Bestehorn. On the physics of self-organized nanostructure formation upon femtosecond laser ablation. – Journal of Applied Physics A, Volume 117, Issue 1, 2014, pp. 179-184.
- [7] Gurevich E.L. Self-organized nanopatterns in thin layers of superheated liquid metals. – Journal of Physical Review E, Volume 83, Issue 3, 2011, pp. 031604\_1-031604\_5.
- [8] Sipe J.E., J.F. Young, J.S. Preston, H.M. van Driel. Laser-induced periodic surface structure. I: Theory. – Journal of Physical Review B, Volume 27, Number 2, 1983, pp. 1141-1154.
- [9] Bonse J., A. Rosenfeld, J. Krüger. On the role of surface plasmon polaritons in the formation of laser-induced periodic surface structures upon irradiation of silicon by femtosecond-laser pulses. – Journal of Applied Physics, Volume 106, Issue 10, 2009, pp. 104910\_1-104910\_5
- [10] Ionin A.A., S.I. Kudryashov, S.V. Makarov, L.V. Seleznev, D.V. Sinitsyn, E.V. Golosov, O.A. Golosova, Yu.R. Kolobov, A.E. Ligachev. Femtosecond laser color marking of metal and semiconductor surfaces. – Journal of Applied Physics A, Volume 107, Issue 2, 2012, pp. 301-305.
- [11] Groeneveld R.H.M., R. Sprik, A. Lagendijk. Femtosecond spectroscopy of electron-electron and electron-phonon energy relaxation in Ag and Au. – Journal of Physical Review B, Volume 51, Number 17, 1995, pp. 11433-11445.