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Laser Ultrasound Methods for Investigation of Thermal Properties of Semiconductors Plate with Modified Surface Layer

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In the article the results of analyze of laser ultrasound generation in inhomogeneous semiconductors plate is presented. The case of strong absorption of electromagnetic fields is considered. It is shown that in this case submicron surface layer thermal properties influence on thermal distribution evolution. The case of thin infinite plate considered. Peculiarities of excitation and propagation of elastic waves in such media regarding gives the possibility to obtain dispersive equation for laser ultrasound wave-vectors. It is shown that such processes in 1D case can be described.

Keywords: Laser Ultrasound, Photoacoustic and Photothermal Phenomena, Inhomogeneous Semiconductors Structures.

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1. INTRODUCTION

The basis of modern high-tech materials research is the structures in which the properties of surface layer are modified (for example ion-doped structures). Traditional methods for investigation of such structures are contact and (or) require certain distinct sizes and parameters of sample.

Ultrasonic techniques are perspective methods for the study of such materials because they are nondestructive. Usage of laser irradiation for ultrasound excitation makes such methods also non-contact.

It is traditionally considered that the first usage of a laser beam for ultrasound generation was proposed in [1] in which detailed analysis of acoustic wave excitation in one-dimensional case was presented. In [2] laser generated ultrasound by laser pulse length of the order of 10 ns was experimentally studied. In this paper was shown that in addition to generated longitudinal there is shear wave, to describe the presence of which in one-dimensional case [1] is impossible. In [2] presented semi-phenomenology model of laser ultrasonic response generation, which subsequently was more strictly proved in [3].

In the data works were fully described ultrasound excitation by laser irradiation in semi-infinite environment, but without features of radiation absorption and the presence of diffusion of heat – the volume energy absorption and thermal diffusion was neglected. Effect of heat diffusion on the ultrasonic signal shape was first observed in [2], and it manifested itself in the appearance of a small dipole component of the signal. More detailed effects of heat conduction in semi-infinite samples experimentally investigated in [4] and in [5] described theoretically.

Effect of heat diffusion on the shape of the ultrasonic response gives the possibility not only to use laser radiation for excitation of ultrasound, but also use it as additional information about the material properties. Especially it is important for materials with modified surface layer, since modification leads to significant changes in the heat transfer processes in such structures [6]. The aim of this paper is to investigate the properties and parameters of laser ultrasound response generated in inhomogeneous semiconductor plate under its irradiation by short laser pulse.

2. MODELING OF LASER ULTRASOUND GENERATION

Accordingly to the aim let us consider forming of laser ultrasound signal in plate with thickness d (see Fig. 1) and infinite in other directions.

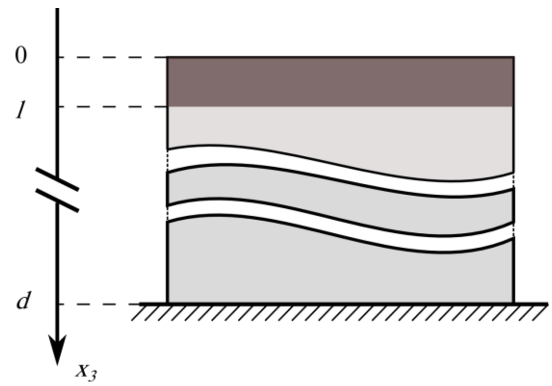

Fig. 1 – Schematic illustration of investigation structure. [0-l] – modified surface layer, [l, d] – unmodified region of material (substrate)

The main mechanism of laser ultrasound generation is photothermal transformation – when radiation is absorbing by environment, its energy transforms into thermal energy by non-radiation relaxation.

2.1 Thermal Distribution Formation

Let us consider formation of nonequillibrium thermal distribution in investigation structure under its radiations by laser pulse with intensity I_0, which is small, i.e. which doesn't lead to structure modification of the material.

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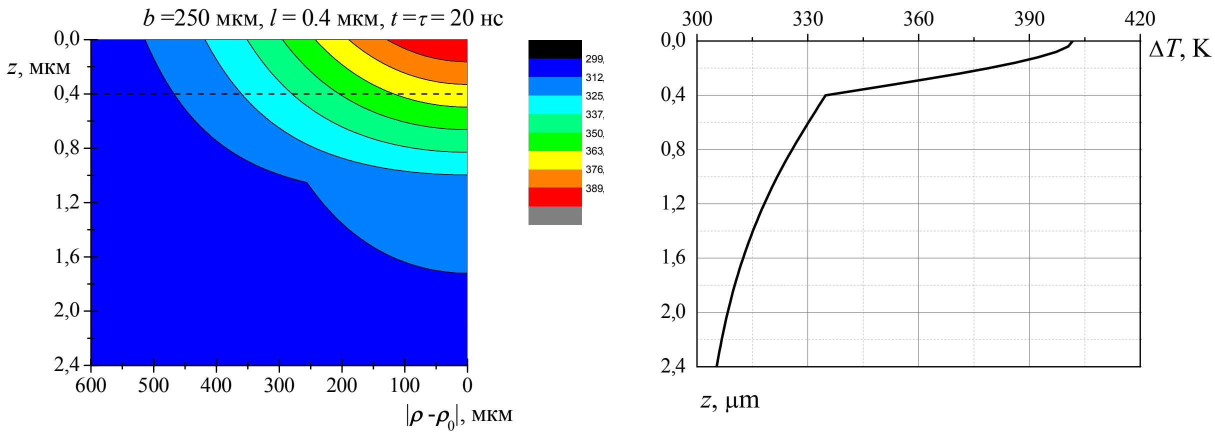
For definiteness let us suppose, that intensity of radiation in cross-section of laser beam is distributed by Gaussian function with radius b. Coefficient of absorption is finite and equals α with $\alpha^{-1} < d$ та $b >> \alpha^{-1}$ – radiation absolutely absorbs in surface layer – and focusing radius of the beam is much greater than absorption depth of the light. Also for definiteness let us suppose that layer of investigation sample differ only by thermal conductivity K. In such case equation that describes time evolution of the thermal distribution T (r, t) is

$$\frac{\partial T}{\partial t} = \vec{\nabla}\left(D(T,z)\vec{\nabla}T\right) + I_0(1-R)\alpha\exp\left(-\alpha z\right)g(t)\exp\left(-\frac{\left(\vec{\rho}-\vec{\rho}_0\right)^2}{b^2}\right) \quad (1)$$

here R is a reflection coefficient of radiation from the surface of the sample, $g(t)$ is a function, that characterize time distribution of intensity. Let us consider approximation by which

$$g(t) = \begin{cases} 1 & \text{when} \quad t < \tau \\ 0 & \text{when} \quad t > \tau \end{cases},$$

$D = K/c\rho$ – is a coefficient of thermal diffusivity, c and ρ – thermal capacity and density, respectively; $\rho = x_1, x_2$ – radius-vector of a point in the cross section of laser beam, ρ_0 – epicenter of laser excitation. Attached thermal distributions, which can be described by Eq. (1) are shown in Fig. 2. Here the absence of heat outflow from environment has been chosen as boundary condition.



a) b)

Fig. 2 – Spatial thermal distribution (a) and temperature distribution (b) along the depth at the epicenter of laser excitation (**ρ= ρ_0**) of laser beam in the moment $t = \tau = 0$ ns at the end of laser pulse ($t = \tau$)

2.2 Field of Elastic Displacement Formation

For calculation of elastic displacement, which occurred in a structure through the existence of nonequilibrium thermal distribution, let us use equations of motion of infinitesimal volume with regard of thermoelastic forces [7] (equation of thermoelasticity):

$$\rho\frac{\partial^2 u_i}{\partial t^2} = C_{ijkl}\frac{\partial^2 u_l}{\partial x_k \partial x_j} - \alpha_T C_{ijkl}\delta_{kl}\frac{\partial T}{\partial x_j}, \quad (2)$$

C_{ijkl} – stiffness tensor, α_T – coefficient of thermal expansion, δ_{kl} – Kronecker delta.

Let us use boundary conditions, which are the most often take place in practice:

- $\left.\left(\sigma_{ij}n_j\right)\right|_{z=0} = 0 \quad n_j = \delta_{j3}$ – free upper surface(i);
- $\left.u_i\right|_{z=d} = 0$ – rigidly fixed lower surface (ii).

From the last boundary condition (ii) the elastic displacement can been found in the kind

$$\vec{u}(\vec{r},t) = \sum_{n=0}^{\infty}\int_{-\infty}^{+\infty}\vec{u}_0^n(\vec{k}_{||},t)e^{-i\vec{k}_{||}\vec{\rho}}d\vec{k}_{||}\sin\left(k_3^n(z-d)\right), \quad (3)$$

here $\vec{k}_{||} = (k_1, k_2)$.

Using tensor expression of Hooke's law and Voigt notation expression (i) can been presented in the kind

$$\begin{cases} \left.\sigma_{13}\right|_{z=0} = C_{44}\left(\frac{\partial u_1}{\partial x_3} + \frac{\partial u_3}{\partial x_1}\right) = 0 \\ \left.\sigma_{23}\right|_{z=0} = C_{44}\left(\frac{\partial u_2}{\partial x_3} + \frac{\partial u_3}{\partial x_2}\right) = 0 \\ \left.\sigma_{33}\right|_{z=0} = C_{11}\frac{\partial u_1}{\partial x_1} + C_{12}\left(\frac{\partial u_2}{\partial x_2} + \frac{\partial u_3}{\partial x_3}\right) = 0 \end{cases}.$$

Substituting in this conditions expression (3) the system of equations relative to u_{i0}^n can been obtained. This system is homogeneous and there are three unknowns ($i = 1\ldots3$). Searching for nontrivial solutions of the system transcendent equation for determination of k_3^n can been received

$$\cos^2\left(k_3^n d\right) = \frac{c_{12}k_{||}^2}{c_{11}\left(k_3^n\right)^2 + c_{12}k_{||}^2}$$

approximate solution of which can be obtained in numerical form. For simplification let us do an estimate, since the structure is finite by direction x_3: $k_3^n > 1/d$, $k_{||}$ may take arbitral values, but in consideration of excitation of elastic waves by beam, which has a Gaussian distributions of intensity in cross-section, $k_{||} > b^{-1}$. Thus in case of great radius of laser beam ($b >> d$) Eq. (4) can be written in following form:

$$\cos\left(k_3^n d\right) = 0$$

From this equation it is possible to determinate

$$k_3^n = \left(\pi/2 + \pi n\right)/d ,$$

which correspond to wave vectors in one-dimensional case [8]. Hence for simplification of analysis solution of one-dimensional thermoelastic equation can be used [9]:

$$u = \exp\left(-\frac{\left(\vec{\rho}-\vec{\rho}_0\right)^2}{b^2}\right)\cdot\frac{\beta}{\upsilon_L}\sum_{m=0}^{\infty}\sum_{n=0}^{\infty} c_{nm}\frac{k_3^n}{k_3^m}\int_0^t \sin\left(\upsilon_L k_3^m\left(s-t\right)\right) b_n(s)ds \times \cos\left(k_3^m z\right), \quad (4)$$

here

$$b_n(t) = \frac{2}{d}\int_0^d T(z,t)\cos(k_3^n z)dz ,$$

υ_L – velocity of longitudinal sound wave, β – some constant, that depend on elastic parameters and thermal expansion.

Time dependence of surface displacement for modified structure, which have been calculated by formula (6) are presented in Fig. 3

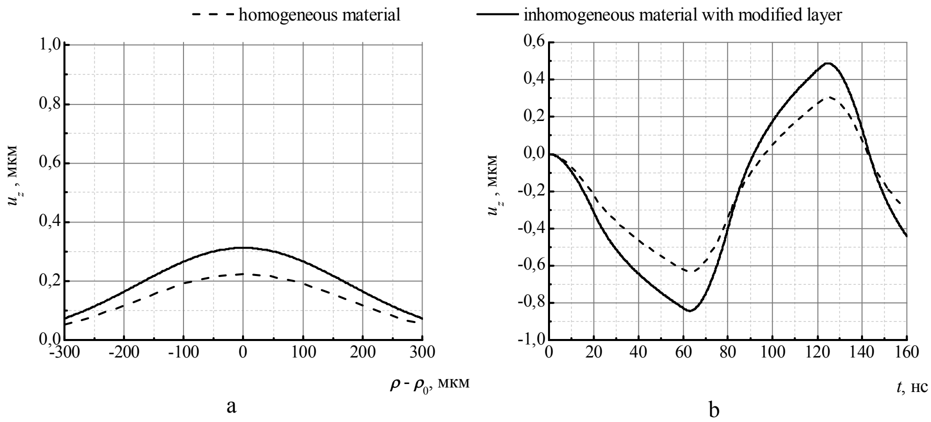


Fig. 3 – Surface displacement (a) in homogeneous material (solid line) and in material with modified surface layer (dash line) and time evolution of surface displacement (b) at epicenter of irradiation

3. CONCLUSIONS

In the paper processes of laser ultrasound response formation in semiconductors plate with modified properties of submicron surface layer is considered. The influence of thermal properties of modified layer on formation of temperature distribution in such structures under its irradiation by a laser pulse is analyzed. The dispersion relation for the wave vectors of laser ultrasound in semiconductors plate in 3D case was obtained. Analyse of this relation gives the possibility to make correct transition in 1D case.

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