PHOTOTHERMOACOUSTIC EFFECT IN A PIEZOELECTRIC–SEMICONDUCTOR LAYERED STRUCTURE

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The results of theoretical and experimental studies of the photothermoacoustic effect in a layered piezoelectric–semiconductor plate are reported. To avoid the influence of optical irradiation on the physical properties of a semiconductor, thermal waves were excited in a piezoelectric. An expression describing the dependence of the potential difference across the piezoelectric layer on the physical and geometrical parameters of the structure under study is derived. The amplitude-frequency dependence of an information-bearing signal was experimentally studied, by using a layered x-cut quartz–silicon plate. The fitting of experimental data within the theoretical model allowed us to determine the reduced Young modulus of silicon.

When studying a substance by photothermoacoustic (PTA) methods, thermal waves are excited directly in the substance [1]. As a rule, they are excited by irradiating a specimen with a modulated light beam. The physical (optical and thermoelastic) properties of some classes of solids such as semiconductors, polymers, and others are known to change under photoirradiation [2–4]. At the same time, the results of researches of such substances within PTA methods depend, as a rule, on experimental conditions, which does not allow one to comprehensively study the physical picture of the phenomenon. To overcome this shortcoming, thermal waves have to be excited outside of the substance under study. In the case of a solid, such an opportunity exists, if a piezoelectric measuring device in the form of a layered solid–piezoelectric plate is used [5]. In this case, the thermal wave should be excited in the piezoelectric rather than in the solid, i.e. it is the piezoelectric rather than the solid that should be irradiated with a modulated light beam. This work aimed at solving this problem.

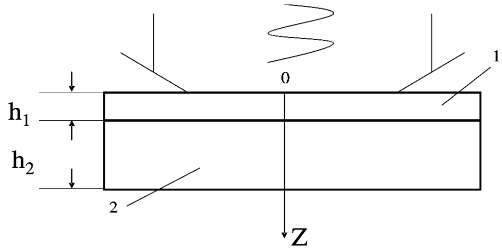

Fig. 1. Geometry of the problem

Consider (see Fig. 1) a layered plate composed of a piezoelectric of the class $6mm$ (*1*) and an isotropic solid (*2*). Let the thickness of the piezoelectric be h_1, and let its thermomechanical properties be isotropic. The thickness of the solid is h_2. The polar axis of the piezoelectric coincides with the Z axis. The piezoelectric surface $z = 0$ is uniformly illuminated with a light flux modulated with the frequency ω,

$$P = \frac{1}{2}P_0(1 + \cos(\omega t)), \qquad (1)$$

where P_0 is the light intensity.

Light is absorbed by the piezoelectric, heats it, and changes its temperature. As a result, thermal waves which propagate along the Z axis are excited. Consider the near-surface absorption of light (actually, the piezoelectric surfaces are metallized). Owing to the thermoelastic effect, the temperature field induced by thermal waves excites acoustic vibrations in the layered plate. In the piezoelectric, there emerges the electric polarization. A potential difference appears between the piezoelectric surfaces $z = 0$ and $z = h_2$, which is a measure of PTA vibrations in the structure concerned. Let us determine this potential difference

$$\hat{U} = -\int\limits_0^{h_1} E_z dz. \qquad (2)$$

In the analyzed geometry of the problem, the normal component of the electric field induction is determined by the formula (the pyroelectric effect is neglected)

$$D_z = \varepsilon_{33}E_z + 2d_{31}T_p, \qquad (3)$$

where ε_{33} and d_{31} are the dielectric permittivity and the piezoelectric constant of the piezoelectric, respectively, and T_p are elastic strains in the piezoelectric. External electric fields are absent and, in the absence of free charges, the electric induction is continuous. Therefore, we have $D_z = 0$. Then Eq. (3) yields

$$E_z = -\frac{2d_{31}}{\varepsilon_{33}} T_p. \quad (4)$$

Let the modulation frequencies of light flux be low enough, i.e. the length of acoustic waves is much longer than the linear dimensions of the layered plate (it is the quasistatic approximation). In this case, the elastic stresses are described by the formula [6]

$$T = E_r(C_1 - C_2 z - \alpha\Theta), \quad (5)$$

where $E_r = E/(1-\sigma)$ is the reduced Young modulus, E is the Young modulus, σ is Poisson's ratio, Θ is the varying temperature component, α is the coefficient of linear thermal expansion of the piezoelectric (the solid), and C_1 and C_2 are constants.

To find the distribution of the varying temperature component Θ in the structure concerned, it is necessary to solve the heat equation for the piezoelectric and the solid, together with the corresponding boundary conditions.

Let us write down the heat equation in the complex form for the piezoelectric and the solid, as well as the corresponding boundary conditions (the continuity of the thermal flux and the temperature) [1]. The heat equation reads

$$\frac{\partial^2\Theta_p}{\partial z^2} - \frac{c_p\rho_p}{\chi_p}\frac{\partial\Theta_p}{\partial t} = -\frac{\beta P_0}{2\chi_p}\exp(-\beta z)\exp(i\omega t) \quad (6)$$

for the piezoelectric and

$$\frac{\partial^2\Theta_s}{\partial z^2} - \frac{c_s\rho_s}{\chi_s}\frac{\partial\Theta_s}{\partial t} = 0. \quad (7)$$

for the solid. The thermal flux into the surrounding medium is neglected, so the boundary conditions can be written down as follows:

$$\chi_p\frac{\partial\Theta_p}{\partial z}\Big|_{z=0} = 0, \quad \chi_s\frac{\partial\Theta_s}{\partial z}\Big|_{z=h_1+h_2} = 0,$$

$$\chi_p\frac{\partial\Theta_p}{\partial z}\Big|_{z=h_1} = \chi_s\frac{\partial\Theta_s}{\partial z}\Big|_{z=h_1}, \quad \Theta_p\big|_{z=h_1} = \Theta_s\big|_{z=h_1}, \quad (8)$$

where c_p, ρ_p, χ_p and c_s, ρ_s, χ_s are the specific heats, densities, and heat conduction coefficients of the piezoelectric and the solid, respectively; β is the coefficient of optical absorption by the piezoelectric, and Θ_p and Θ_s are the varying temperature components in the piezoelectric and the solid, respectively. Below, we assume that the total light energy absorbed by the piezoelectric is spent on its heating.

Consider a case where the thermal wave decays completely in the layered plate and does not reach the surface $z = h_1 + h_2$. Finding the relevant temperature distribution in the layered plate and substituting Eqs. (4) and (5) into Eq. (2), we obtain

$$\hat{U} = \frac{2d_{31}E_{rs}}{\varepsilon_{33}}\left(\left(C_1 - \frac{1}{2}C_2 h_1\right)h_1 - \frac{\alpha_p}{\gamma_p}\Theta_0(s-b)\right), \quad (9)$$

$$s = \mathrm{sh}(\gamma_p h_1) + b\,\mathrm{ch}(\gamma_p h_1), \quad b = \frac{\chi_s\gamma_s}{\chi_p\gamma_p}, \quad \Theta_0 = \frac{P_0}{2\chi_p\gamma_p s},$$

$$\gamma_p = \sqrt{\frac{c_p\rho_p\omega}{2\chi_p}}(i+1), \quad \gamma_s = \sqrt{\frac{c_s\rho_s\omega}{2\chi_s}}(i+1).$$

The constants C_1 and C_2 are determined from the following boundary conditions: the resultant force and the resultant force momentum per unit length of the contour of the structure concerned must be equal to zero [6]:

$$\int_0^h T dz, \quad \int_0^h Tz dz, \quad h = h_1 + h_2. \quad (10)$$

From Eqs. (10), we find

$$C_1 = \frac{\alpha_p\Theta_0}{\gamma_p h Z_0}\left(\xi Z_t - \frac{g}{\gamma_p h}\right), \quad (11)$$

$$C_2 = \frac{\alpha_p\Theta_0}{\gamma_p h^2 Z_0 Z_f}\left(\xi Z_f - \frac{g}{\gamma_p h}\right),$$

where

$$\xi = \eta(s-b) + \alpha_0\gamma_0,$$

$$g = \eta(\mathrm{ch}(\gamma_p h_1) - 1 + b(\mathrm{ch}(\gamma_p h_1) - \gamma_p h_1) +$$

$$+\alpha_0\gamma_0^2(\gamma_s h_1 + 1)),$$

$$Z_0 = (Z_t - Z_f)(1 + (\eta - 1)H_1), \quad H_1 = h_1/h,$$

$$\eta = E_{rp}/E_{rs}, \quad \alpha_0 = \alpha_s/\alpha_p, \quad \gamma_0 = \gamma_p/\gamma_s,$$

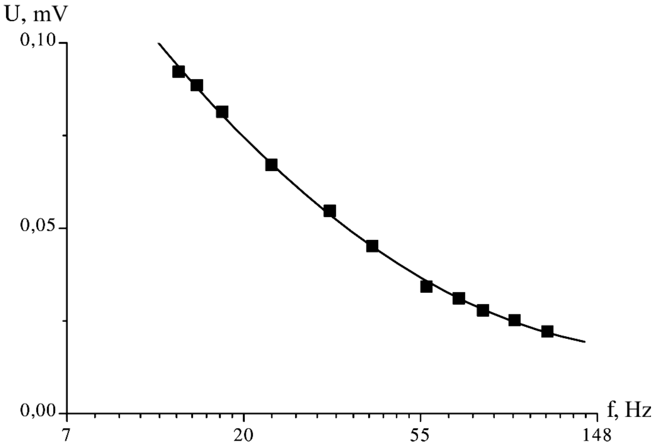

Fig. 2. Amplitude-frequency dependence of the voltage across the piezoelectric layer

$$Z_t = \frac{2}{3}\frac{1+(\eta-1)H_1^3}{1+(\eta-1)H_1^2}, \quad Z_f = \frac{1}{2}\frac{1+(\eta-1)H_1^2}{1+(\eta-1)H_1},$$

E_{rp} and E_{rs} are the reduced Young moduli, α_p and α_s are the coefficients of linear thermal expansion of the piezoelectric and the solid, respectively. At last, for the potential difference across the piezoelectric, we obtain

$$\hat{U} = \frac{d_{31}\alpha_p E_{rp} P_0}{\varepsilon_{33}\chi_p s Z_0 \gamma_p^2}\left(\left(\frac{H_1}{2} - Z_t\right) \times\right.$$

$$\left.\times \left(\frac{gm}{\gamma_p h} - \xi\right) H_1 - Z_0(s-b)\right),$$

$$m = \frac{Z_1 - Z_f}{Z_f(Z_1 - Z_t)}. \qquad (12)$$

The analysis of formula (12) testifies that the information-bearing signal depends on the physical properties and the geometrical parameters of both the solid and the piezoelectric, as well as on the modulation frequency of a light beam, in rather a complicated manner. If heat does not reach the solid (the case of relatively high frequencies), expression (12) becomes substantially simpler,

$$\hat{U} = \frac{d_{31}\alpha_p E_{rp} P_0}{\varepsilon_{33}\chi_p \gamma_p^2}\left(\left(\frac{H_1}{2} - Z_t\right)\left(\frac{m}{\gamma_p h} - 1\right)\frac{\eta}{Z_0}H_1 - 1\right). \qquad (13)$$

The analysis of expression (13) shows that the amplitude-frequency dependence of information-bearing signals can be used to determine the reduced Young modulus of the solid.

The experimental researches were carried out using the layered structure x-cut crystalline quartz–silicon fabricated in the form of a thin plate. The quartz layer had the sputtered copper electrodes. The researches were carried out in the frequency range (13–112) Hz. We studied the dependences of the amplitude of a PTA signal which was registered across the piezoelectric layer on the light modulation frequency. The results of experimental researches are depicted by points in Fig. 2. The experimental data were approximated by expression (13) to determine the reduced Young modulus for silicon, $E_{rs} = (14 \pm 3) \times 10^{10}$ N/m^2. The SiO_2 parameters which were used for those calculations were taken from work [7].

It should be noted that a layered piezoelectric–solid plate can also be used to study thermoelastic properties of piezoelectric materials, provided that a solid with known thermoelastic parameters is used.

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ФОТОТЕРМОАКУСТИЧНИЙ ЕФЕКТ В ШАРУВАТІЙ СТРУКТУРІ П'ЄЗОЕЛЕКТРИК–НАПІВПРОВІДНИК

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Р е з ю м е

Наведено результати теоретичних і експериментальних досліджень фототермоакустичного ефекту в шаруватій пластині п'єзоелектрик–напівпровідник, в якій з метою усунення впливу оптичного опромінення на фізичні властивості досліджуваного напівпровідника теплові хвилі збуджуються у п'єзоелектрику. Отримано вираз для різниці потенціалів на шарі п'єзоелектрика залежно від фізичних та геометричних параметрів досліджуваної структури. Експеримент проведено на шаруватій пластині кварц x-зрізу–кремній. Досліджено амплітудно-частотну залежність інформативного сигналу. Апроксимація експериментальних даних теоретичною моделлю дозволила визначити зведений модуль Юнга кремнію.