PHOTOTHERMOACOUSTIC EFFECT IN STRESSED MEDIA

R.M. BURBELO, M.K. ZHABITENKO

National Taras Shevchenko University, Faculty of Physics
(64, Volodymyrska Str., Kyiv 01033, Ukraine; e-mail: RMB@mail.univ.kiev.ua)

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Results of experimental and theoretical investigations of the photothermoacoustic (PTA) effect in solids are presented. Influence of the stressed state of medium on the PTA-transformation process was cleared up. By immediate experiments conducted on model samples, it has been shown that the PTA effect is sensitive to elastic stresses in solids. A model of the PTA effect formation mechanism in a stressed medium is proposed.

In the recent time, there appeared scientific woks [1—3] in which PTA-effect-based methods are used for the study and control of stresses in a solid medium. The essence of these methods may be explained as the generation of thermal and acoustic waves in a solid body absorbing modulated or pulsed electromagnetic radiation. Employment of lasers as radiation sources in PTA investigations has lead to a variety of instrumental realizations of the methods such as the gas-microphone method, piezoelectric, “mirage”, probe-beam-deflection ones, and others. In many cases, the mentioned methods are beyond competition in comparision with the traditional ones as to sensitivity, set of determined parameters, and probe-accessible thickness.

At the same time, it should be noted that the mechanism of PTA effect formation in an elastically stressed area and the role of parameters of the stressed medium are still not determined. Basing upon a qualitative analysis of results obtained from the investigation of stress-involving materials, an assumption has been made that it is the field of stresses that causes the experimentally observed spatial nonhomogeneity of PTA effect manifestation. In this case, the relative variation of the PTA response is attributed to a possible dependence of the elastic and thermal parameters of material on residual stresses. At the same time, mechanisms of such an influence practically are not given, and what is more, as affirm the authors themselves, additional experiments are needed to make them clear.

Probably, in [4], it was firstly attempted, within the framework of a model experiment, to demonstrate a possibility of PTA measurement of the constant stresses, including the residual ones.

We have undertaken a set of experimental and theoretical investigations targeted at the elucidation of the PTA-effect-forming mechanism acting in a stressed medium [5]. In the experiments, a computerized PTA microscope was employed, in which the sinusoidal intensity modulation of the Ar-laser beam was used. The measurements were carried out at a modulation frequency of near 80 kHz, thus providing a thermowave visualization of the investigated materials at depths of 5 to 20 μm approximately. Immediate model experiments with employment of the pulsed PTA technique were conducted as well.

Work [6] presents the results of studying the PTA response spatial distribution for Si_3N_4-ceramic-based samples having a preliminary indented surface. Basing on this study, it was assumed that the elastic stresses resulted from the plastic deformation occurring in an indentation-undergone area, essentially influence the PTA transformation process outside this area.

A PTA-microscopic study was also conducted on a variety of Si-based semiconductor structures suspected, for some causes, to have the stressed regions. It is stated that a considerable linear size of the PTA-response-variation area, as compared to a visible defect size, is peculiar to obtained PTA images. This is determined by

Fig. 1. PTA image of a crack located under a metallic film in a diode structure (6×6 mm^2)

the influence of the stressed state, existing in the defect-adjacent region of material, on the PTA-transformation process. Basing on the results obtained, a conclusion is made that the stresses are the most probable cause of the observed variation in the PTA effect manifestation [7].

As an example, the PTA image of a typical technological defect is shown in Fig. 1, namely, cracks of a diode structure (planar $p-n$ junction) covered with a two-layer metallic 2-μm-thick Ni—Au contact. Note that the transverse size of the crack visible in an optical microscope is considerably (approximately by 3 times) less than that of the PTA response variation area in the PTA image formation zone.

Thus, proceeding from the experimental results both of ours and other authors' [8], the fact of a considerable linear size of the PTA response variation area in its comparison with the visible defect size, could be considered as being established for the obtained PTA images. And this, probably, may be determined by influence of the defect-neighbouring stressed state on the PTA transformation process.

To determine the influence of the stressed state on the PTA transformation process, a series of model experiments has been carried out with employment of the pulsed PTA technique.

Let us adduce, in particular, the results of the experiment [9] in which bar-shaped Ti samples with indented surface had been studied. Fig. 2 shows the dependence of a PTA response on coordinates (the "spatial dependence"). It is seen that the spatial variation of the PTA response extends over a considerable distance from the indentor-prick point. This distance exceeds the visible size of the defect (approximately 0.75 mm).

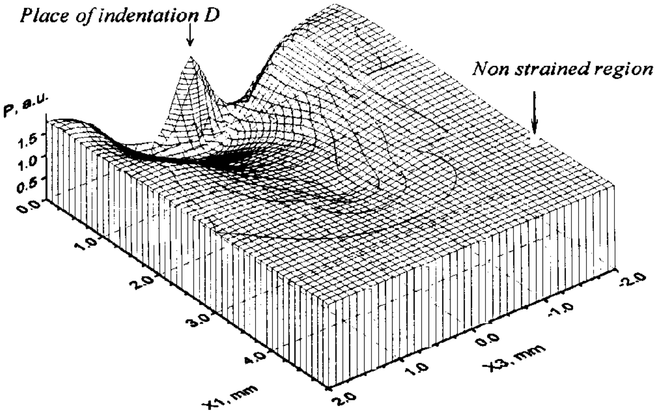

Fig. 2. Spatial pattern of a PTA signal (D is the place of indentor action)

Fig. 3 shows the dependence of the PTA response variation value on the X_1 coordinate at $X_3 = 0$. On this curve, one can distinguish several sections:

"1" is a central section that corresponds to the visible defect size. At this section, the PTA signal is of considerable value;

"2" is a region of abrupt decrease of the PTA signal down to its minimal value. This region is lying in the near-boundary zone of the visible lune of a defect;

"3" – here the PTA signal increases with its further saturation at a distance of about 4 mm.

Analysis of constant deformations and stresses arising from the indentor action, allows making a conclusion that section "1" corresponds to the existence of par excellence plastic deformations with practical absence of the constant ones. Section "2" (transitional) reflects a rise of the compression stresses ($\sigma < 0$) culminating at a certain point and then decaying in their absolute values (section "3"). Under plastic deformation a fixing of deformations on the defects along the material surface occurs. In the elastic region the stresses are not relaxed, so, residual stresses arise.

The residual stresses were calculated according to the schematic draft shown in Fig. 3,*b*, where: $0 < r < a_0$, with a_0 being the region of plastic deformations in which the residual stresses are absent; $r > a_0$ is the area of residual stresses. It was assumed that a compensating radial stress $\sigma_r\big|_{r=a_0} = \sigma_0$ exists at the boundary of the plastic deformation zone, thus causing a balanced distribution of residual stresses.

The distribution of residual stresses calculated from the obtained expression $\sigma_r = -\frac{\sigma_0 a_0^2}{r^2}$ is presented in Fig. 3,*c*. The comparison between the experimental and calculated curves has lead to the conclusion that the assumption of similarity between the dependences of $\Delta P = f(\mathrm{X}_j)$ and $\sigma = f(\mathrm{X}_j)$ is true, and that the PTA response variation in the deformed zone is connected with residual stresses existing in the subsurface region of the sample.

The above-presented experimental results have given a basis for a theoretical analysis of the influence of constant stresses on the PTA transformation process. In distinction from the traditional methods [10], we have considered a PTA excitation of elastic waves after the end of light pulses. In this case, the process of temperature variation from this point on, evolves in both the time and the space. It is the temperature variation process that forms a thermoelastic pulse detected in the experiment. In this consideration of the thermoelastic excitation of elastic waves generated due to the absorption of light energy in a stressed medium, the influence of nonlinear elastic and thermoelastic constants is taken into account for the first time.

PTA response in the stressed area of a medium was calculated by solution of the modified motion equation for a thermoelastic medium with constant stresses. To do this, the temperature distribution in a medium irradiated with short light pulses had been looked for. In accordance with the experiment conditions, it was assumed that the light absorption takes place within a rather thin layer of the medium, i.e. the heat flux is considered to be fed into the sample through its surface. In view of small size of the light spot, we have neglected the transverse thermal diffusivity, i.e. we considered the case of planar temperature field in the direction of laser beam propagation.

A model that describes the mechanism of PTA effect formation in a stressed medium after the end of short laser pulses and low-frequency detection is proposed. According to this model:

— The surface-region temperature is taken as the product of a step function of coordinates and a slow (as compared to the pulsed function of light irradiation) function of time. Such a temperature representation model allows the deformations in the PTA-formation region to be considered as quasi-static, which essentially simplifies the calculation.

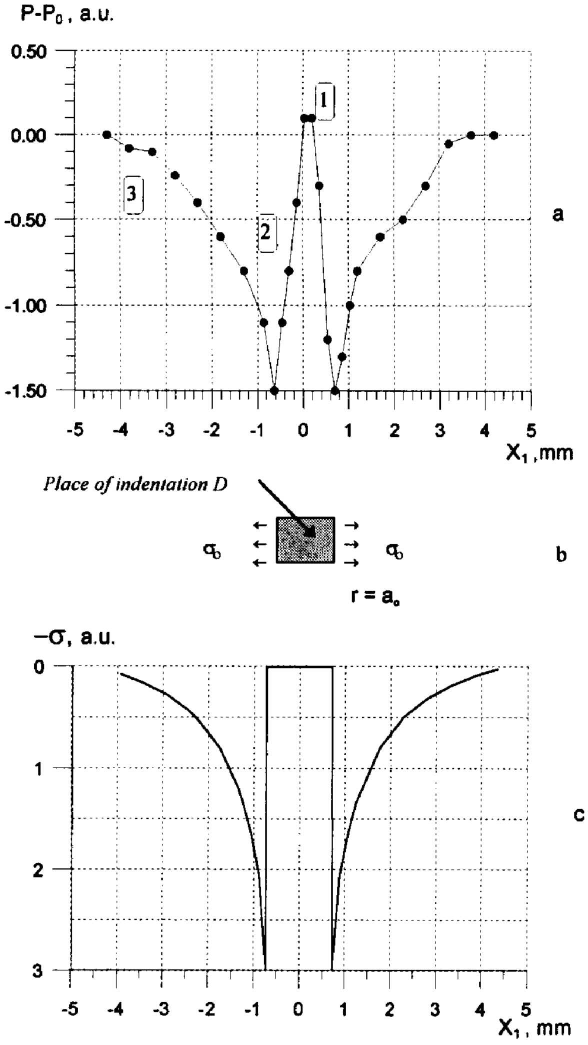

Fig. 3. Dependences of $\Delta P = P - P_0$ (*a* — experiment) and σ (*c* — calculation) on the X_1 coordinate *b* — schematic representation of the experimental situation

— The PTA response is formed due to radial forces (F_x, F_y) in the case of free surface and by normal forces (F_z) in the case of dumped one.

Basing on the proposed model, the expressions for displacements (u_z) outside the PTA excitation zone under different boundary conditions (the damped or free surface) are obtained:

a) the damped surface case (d):

$$u_z^d = \frac{\gamma_3^+ \theta_0}{C_{33}^+} h_0 f(t)\,, \tag{1}$$

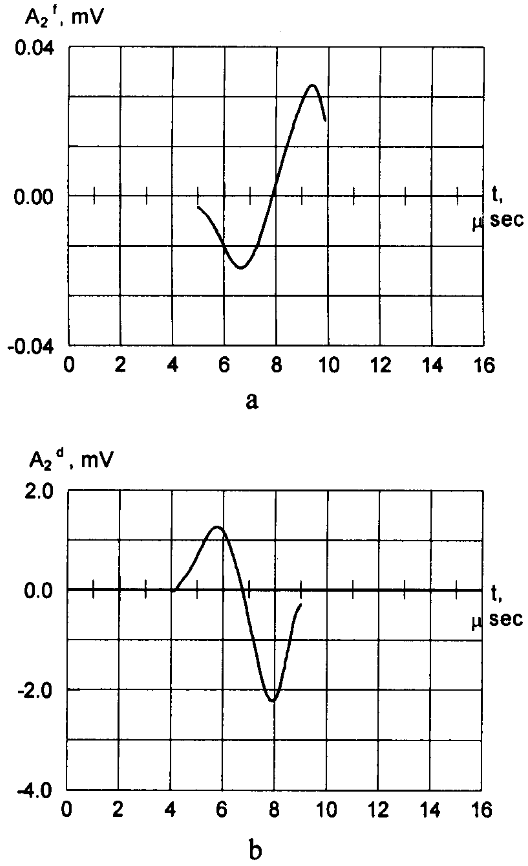

Fig. 4. Oscillograms of a PTA response signal on piezotransducer A_2 under different boundary conditions: *a* – free surface; *b* – damped surface

b) the free surface case (*f*):

$$u_z^f = -\Pi \frac{\gamma_1^+ \theta_0}{C_{33}^+} V \int_0^t f(t)\, dt \quad , \tag{2}$$

where C_{33}^+, $\gamma_{1,3}^+$ are effective elastic and thermoelastic constants, correspondingly; θ_0 is a temperature of the h_o-thick layer of material; $f(t)$ is a certain known function of time that is slow as compared to the rise time of a light pulse; V is the propagation velosity of a thermoelastic wave; Π is the coefficient of transformation of the transversal stresses into the excitation forces along the Z axis.

It was established experimentally that the PTA response function for a damped surface is a time derivative of the free-surface PTA-response function (Fig. 4), and the PTA-response variations themselves possess opposite signs under different boundary conditions [11]. This agrees with theoretical results and confirms a validity of the proposed model of thermal field and elastic forces.

The dependence of the relative PTA response variation $\Delta P/P$ on the values of constant surface stresses (σ_{0x}) for damped and free surfaces was calculated as

$$\left(\frac{\Delta P}{P}\right)_d = -\left[\left(\frac{\gamma_{12}}{\gamma}\right) - \frac{C_{112}}{C_{11}}\right]\left(\frac{\sigma_{0x}}{C_{11}}\right),$$

$$\left(\frac{\Delta P}{P}\right)_f = -\left[\left(\frac{\gamma_{11}}{\gamma}\right) - \frac{C_{112}}{C_{11}}\right]\left(\frac{\sigma_{0x}}{C_{11}}\right). \tag{3}$$

As seen from (3), this variation inside the stressed area of the medium is determined by the linear and nonlinear, elastic C and thermoelastic γ constants of the substance.

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ФОТОТЕРМОАКУСТИЧНИЙ ЕФЕКТ В НАПРУЖЕНОМУ СЕРЕДОВИЩІ

Р.М. Бурбело, М.К. Жабітенко

Резюме

Наведено результати експериментальних та теоретичних досліджень фототермоакустичниго (ФТА) ефекту в твердих тілах. З'ясовано вплив напруженого стану середовища на процес ФТА-перетворення. Прямими експериментами на модельних зразках показано, що ФТА-ефект чутливий до наявності пружних напружень у твердому тілі. Запропоновано модель механізму формування ФТА-ефекту в напруженому середовищі.