Photoacoustic thermal conductivity determination of layered structures PS-Si: piezoelectric detection

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Abstracts. Based on bending vibrations model method and also construction of multilayer transducer, which allow the measurements of thermal conductivity for porous layer on Si wafer is proposed. Time dependence of photoacoustic signal under rectangular modulation of exciting light was numerical modeling. The experimental tests were done on the samples of porous silicon on Si wafers as well as for the porous silicon free standing layers, obtained under the same anodization regime. The value of thermal diffusivity of the porous silicon layer correlates well with the value of thermal diffusivity of the porous silicon free layer, determined by TDC method.

1. Introduction

Photoacoustic (PA) methods are successfully applied to determine the values of thermophysical parameters of porous silicon (PS) [1,2]. An important advantage of these techniques is the simplicity of its experimental realization. In particular, the problem of insuring the reliable thermal contact to the porous layer characteristic for classical methods of thermal conductivity measurements eliminates easily in PA methods.

The gas-microphone PA methods are the most frequently used to measure the thermal conductivity $k$ (thermal diffusivity $D = k/cp$, where $c$ is thermal capacity, $\rho$ - density) of the PS. These methods have the solid theoretical background; they are highly sensitive to variable component of the surface temperature. We'll distinguish here the method of TDC (transmission detection configuration [1] method) and the PA spectroscopy (PAS) method [2]. The TDC method is based on the transmission of thermal waves through the sample. In the case of supported layers the TDC method allows to determinate effective parameters of entire structure and the determination of the parameters of porous layer itself comprise a problem. The PAS method is rather complicated, it is not very precise, and applies only to a narrow range of materials.

The piezoelectric method of PA signal formation has the same sensitivity the gas-microphone PA method. However, this method has no wide practical application for thermophysical measurements, due to absence of unified theory of signal generation for this method. In some particular cases at definite geometries of experimental system and different types of registered acoustic vibrations, number of rather complicated theoretical models was proposed [3, 4]. The model of excitation of low-frequency quasistatic thermoelastic bending vibrations of the system “sample-transducer” [5] should be mentioned as one of the most simple among them. For this case, the applicability of multilayer piezotransducer for measurements of thermal conductivity of highly light-absorbing samples is shown in the work [6].
In the present work we propose relatively simple and precise method based on bending vibrations model and the setup of multilayer transducer, which allow the measurements of thermal conductivity for porous layer on monolithic support. Difference of elastic properties of porous and non-porous layers, as in the case of supported PS, is crucial in this case.

2. Numerical model
From the qualitative considerations, based on the quasistatic deformations model at rectangular modulation of light, which excite the thermal wave in steady-state conditions, for the dependence of the electric potential $\mathcal{U}(t)$, taken from the electrodes of the transducer when the region of localization of thermal excitation in depth $l_t$ is much smaller than thickness of the system sample-piezoelectric transducer $h$:

$l_t << h$, at approach of isotropic layers we can write an expression:

$$
\mathcal{U}(t) = a \sum_{n=1}^{N} \frac{Q_n(t)}{c_n \rho_n} \cdot \alpha_n \hat{E}_n, \quad (1)
$$

where $\hat{E}_n = E_n / (1 - \sigma_n)$, $E_n$ - modulus of elasticity, $\sigma_n$ - Poisson coefficient, $\alpha_n, c_n, \rho_n$ corresponding thermal expansion coefficient, thermal capacity and density of material with number $n$, $a$ - constant value and $Q_n(t)$ - difference of heat quantity in the layer $n$ from its stationary value in $t$ time. Thus, the potential induced on the electrodes of a piezoelectric transducer (PA signal) is proportional to the amount of thermoelastic stresses in the layers of the system laying within the field of thermal disturbances.

The ration \( \left( \frac{\alpha_1 \cdot \hat{E}_1 \cdot c_1 \cdot \rho_1}{\alpha_2 \cdot \hat{E}_2 \cdot c_2 \cdot \rho_2} \right) \ll 1 \) for the sample where the 1st layer is porous with the porosity > 50%, and the 2nd is non-porous. That is why due to this expression in the moment when the edge of thermal agitation reaches the interface between the porous and non-porous layers, due to the redistribution of heat between the layers, significant change of rate of growth of $\mathcal{U}(t)$ should be achieved.

In the more general case of dependence of the material parameters on the occurrence depth of the layer $z$ under the surface of the sample, taking to the consideration that for the ac component of the temperature $\theta(z,t)$ we can write down: $\theta(z,t) \cdot dz = dQ(z,t) / c(z,t) \cdot \rho(z,t)$ then the expression (1) takes the form:

$$
\tilde{\mathcal{U}} \sim \int_a^h \theta(z,t) \cdot \alpha(z,t) \cdot \hat{E}(z,t) \cdot dz. \quad (2)
$$

It makes possible also to model the development of PA signal through the time, by calculating the temperature distribution over the thickness of the sample.

Numerical calculations of the spatial distribution of temperature in different moments of time where realized due to the finite-element method, and the dependence $\mathcal{U}(t)$ through the numerical integration (2).

3. Experiment
The experiment was conducted with samples of mesoporous silicon in the form of a layer on the monocrystal substrate. Geometry of the experiment is shown in figure 1. The glass-ceramic layer 3 was added in the piezoelectric transducer to locate a thermal disturbance within the sample and to fulfill the conditions $l_t << h$.
Glass-ceramic has the low thermal conductivity, from whence thermal perturbation is almost completely localized in the sample due to the rapid decay in the glass ceramics. In addition, glass ceramics has a small coefficient of thermal expansion. As a result, the contribution of thermoelastic stresses in glass-ceramic layer (and the corresponding component in the expression 2) and the pyroelectric effect in the transducer to the PA signal can be neglected.

Thermal perturbations in the sample were excited in the samples by radiation of a blue LED operating at an electric power of 3 W, which was modulated by rectangular pulses (at an off/duty ratio of two). The intensity of light collected and uniformly distributed over the surface of the optical system was about 1mW/mm². The light flux was modulated by interrupting the pump current to the LED. The dependence $U(t)$ was reflected by the oscilloscope.

Figure 2 compares the experimental dependency, obtained by processing the oscillograms (curve 1), and the dependency obtained by numerical modeling (curve 2) for PA signal. By selecting the parameters of the material in the numerical model, we were pursuing the coincidence of the character of the time changes in calculated and experimental dependencies.

Figure 1. Sandwich structure comprising (1,2) composite sample where 1 - PS, 2 - Si and (3-6) piezoelectric transducer where which 3 - buffer layer, 4 and 6 - electrodes, 5 - piezoelectric ceramics.

Figure 2. The oscillogram of a half-period of heating (shade line – 1) and the dependence resulting from the numerical simulation (solid line – 2) dependence of potential on time. Graduating mark on the time scale - 2 ms / grad.
The increase in the rate of growth of potential $U(t)$ (nearly 5 times) was experimentally observed in a certain time interval (0.4 ms for the porous layer with thickness of 50 microns with a porosity of 60%) after the start of heating.

The value of thermal diffusivity of mesoporous layer of double-layer sample obtained, was compared with the experimental value of thermal diffusivity of the porous layer, grown under similar regimes of anodization, but separated from the substrate. The porosity of this sample is lower - 55%. The measure of thermal diffusivity of the layer separated from the substrate was carried out by the TDC. The results obtained by both methods are close. The results of the first case of the TDC – $0.014 \pm 0.001$ cm$^2$/s and of the second – $0.012 \pm 0.003$ cm$^2$/s.

4. Conclusion
Hence the method proposed in our work allows to precise the determination of thermal conductivity and thermal diffusivity of porous layer on the monolithic support. Although this method provides a lower accuracy than the method of TDC, it should be mentioned that it can be applied to the samples (thin layers on a substrate), where the use of other methods, including method of TDC, is problematic. It should be mentioned, that the piezoelectric registration looks most promising among the PA methods if the temperature dependencies of parameters of a material on temperature are desirable.

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