Thermoelastic Deformations of Composites Based on Porous Silicon in Terms of Periodic Heating

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Abstract. In this work photoacoustic conversion efficiency was analyzed in the porous silicon (PSi) and in the composite based on it, such as the “porous matrix–liquid” was analyzed. The minimum of phase on frequency dependence was observed experimentally and theoretically. This minimum is caused by summation of the different species of PA signal—thermal piston and thermoelastic bending (drum effect). Experiments showed that the effective dynamic (rapid changes on temperature) coefficient of the thermal expansion of the “PSi-liquid” composite exceeds the thermal expansion coefficient of the porous silicon more than in 40 times as proved by experiments conducted.

Introduction

PA methods are an effective research way to observe thermophysical characteristics of materials and complex structures [1], in particular, it relates to the porous materials and composites on its bases [2]. It is seen that PA techniques are noncontact methods which is important for porous materials. The main mechanism of PA effect is photothermal conversion efficiency which is why thermal parameters affect strongly on the PA signal. In “porous matrix–liquid” composites PA conversion efficiency features connected with the significant distinction of the substance (that are the components of a such composite) characteristics can be expected. Porous and nanostructure materials are in perspective for use due to the sensitive elements of sensor devices [3], as the electrodes of power supply elements [4], and in other technical devices, in which exactly thermal characteristics are important.

There are [5,6,7] two main mechanism of PA signal generation at the open photoacoustic cell (OPC) geometry [8] of the experiment. The first one is a heat diffusion mechanism (Thermal Piston), the main idea of which is based on the heating of the gas surrounding a sample. Due to the thermal expansion of the gas, the pressure in a PA cell has been changed. This pressure variation is registered by the electrical microphone (Fig. 1a). The second mechanism is a thermoelastic bending (Drum Effect) that is depicted in Fig. 1b. The effect is shown in the following: inhomogeneous temperature distribution in a sample creates thermoelastic stresses that cause bending of the sample.

The pressure components in a cell are determined by the following expressions [2]:

\[ P_{TP} = \frac{\gamma P_0 I_0 (\alpha_g \alpha_s)^{1/2}}{2 \pi l f \kappa f} \cdot e^{-\pi^2/2} \cdot \text{sh}(\sigma h) \]

\[ P_{DE} = \frac{3 \alpha_s \rho c^2}{h^2} \cdot \frac{\gamma P_0 I_0}{l k \alpha_s^2} \cdot \frac{\text{ch}(\sigma h) - 1}{\sigma h \cdot \text{sh}(\sigma h)} - 1/2 \]

where: where: \( P_{TP} \)—PA signal component is related with mechanism of thermal piston, \( P_{DE} \)—drum effect, \( I_0 \)—light intensity, \( l_{TG} \), \( l_{TR} \)—length of thermal diffusivity of gas (TG) and material (T), \( \alpha_r \)—thermal expansion coefficient of a sample, \( g = \frac{(l+i)/l_r}{l} = \frac{\sqrt{2 \chi / c \rho \omega}}{l_r} \), where \( c, r, \omega \)—heat capacity, density and thermal conductivity, \( w \)—modulation frequency, \( i \)—imaginary unit.

Experimental Result

Two sample types were experimentally observed:

- the first one is the original sample of the porous silicon with porosity 60%, thickness 270 mkm;
- the second one is the composite sample that had been prepared through injection of the technical oil in the pores of the original sample.
In this report we propose a microphone detection version for the OPC geometry [5]. The schematic cross section of the proposed OPC configuration is shown in Fig. 1. It consists of mounting the sample directly onto a circular electrets microphone.

The periodical heating of a sample surface through the modulated light of light-emitting diode (LED) was performed. Luminous flux intensity made 1 mW/mm². The variable pressure in the cell was registered with the electrical microphone.

For numerical simulation of PA signals phase and amplitude equations (1) and (2) was used. The simulation was made according to the geometry that corresponded to the experiment. Dependencies of the phase and the amplitude on frequency for porous silicon in Fig. 3a and for the composite in Fig. 3b are shown.

Theoretical dependencies for the total PA signal (curve 1) and for the signal component connected with the thermal piston mechanism (curve 2) and with the mechanism of the drum effect (curve 3) are shown. Experimental data are shown with dots.

The results of the numerical simulation and the experimental data correlates with each other, this proves the accuracy of the experiment results interpretation. The minimum of phase on frequency dependence has been observed. The position and the depth of this minimum depend on the thermal parameters of the material.

In Fig. 4 the amplitudes of PA signal for PSi (circular dots) and for composite “PSi-liquid” (trigonal dots) are shown.

The PA signal amplitude for the composite is more than the amplitude for the PSi sample in the frequency region above 200 Hz (where the composite sample is “thermally thick”) in about 20 times.

The amplitude dependences of the PA signal for the “Psi-liquid” shows that in this case PA is caused only by the drum effect. The increase of the PA signal amplitude has an effect a significant increase of $\alpha_T$ of the composite.
Figure 3. The dependence of the PA signal parameters on frequency: upper graphs—amplitude, the bottom graphs—phase shift in relation to the modulation of light; (a) the dependencies for the porous silicon, (b) the dependencies for the composite.

Figure 4. Comparison of the amplitudes for the PSi and the composite “PSi-liquid.”

**Conclusion**

It is evident that the PA signal in the OPC geometry from the PSi samples is a result of the act of two mechanisms: thermal piston and drum effect. The minimum of the phase dependence has been observed experimentally and theoretically. The amplitude of PA signal increase is due to the composite induced by the increase of the thermal expansion coefficient in about 40 times in comparison to the porous silicon without the liquid.
References