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KRZYSZTOF PIESZYŃSKI

Institute of Physics, Technical University of Lodz
Wólczańska 219/223, 90-924 Łódź, Poland

SOME OF THE PHOTOTHERMAL PROPERTIES OF ONE – AND TWO-LAYER STRUCTURES

The results of numerical calculations of temperature on a multi-layer structures' surface illuminated with intensity periodically-modulated beam of light are presented. In fact the influence of some geometrical and thermal properties such structures on the amplitude of time-dependant temperature component is shown. Moreover, only one- and two-layer structures are taken into account.

Keywords: Photothermal effect, multi-layer system.

1. INTRODUCTION

Phototermal methods are widely used in the investigations of the thermal materials properties and their geometrical structure. Especially interesting objects for such investigations are multi-layer structures [1-4].

Employment of intensity periodically-modulated beam of light for illuminating the sample as well as analysis of the thermal response of the sample characterize photothermal examination methods. Mostly the laser is exploited for such illumination due to profitable parameters of laser beam.

When light beam illuminates the sample its energy is absorbed and turns into heat and then the heat is conducted to further areas of sample as well as to the ambient. The conducted energy modifies physical parameters of the sample and the ambient. Some parameters modified in this way can be specified, for example: temperature, density, refractive index, stress and strain of material etc. Various photothermal examination methods differ from one another in the measurement technique of the chosen physical parameter which varies due to absorption energy of light.

Fundamentally, the magnitudes of physical parameters mentioned above depend on one another, but when the absorbed energy flux is not too big we may accept that variations some of them are insignificant. In this paper it is assumed that absorption of light affects the variation of sample's temperature but such physical constants of materials as density, thermal conductivity and specific heat do not change considerably. Thus, calculated below, the temperature amplitude of the time dependent component of total temperature on the sample's surface can be applied to measurement of the geometrical parameters of the sample [5] (e.g. thickness of sample's layer) as well as some physical constants of sample's layer [1].

2. THEORETICAL FOUNDATIONS OF NUMERICAL CALCULATIONS

Let us assume [6] that plane light wave travels in the – x direction of Cartesian coordinate system and illuminates the examined sample. The 1st layer of the sample is in contact with gas on the left side and with substrate on the right. Such system is called one-layer structure. It is illustrated on Fig. 1a. Two-layer structure is very similar to one-layer structure but the 2nd layer is placed between the 1st layer and the substrate. It is illustrated on Fig. 1b. For both types of structures it is assumed that transverse size of each sample's constituent is much greater than its size in the – x direction so it is one-dimensional problem. The sizes of each sample's constituents are exaggerated for clarity of the schemes on Fig. 1.

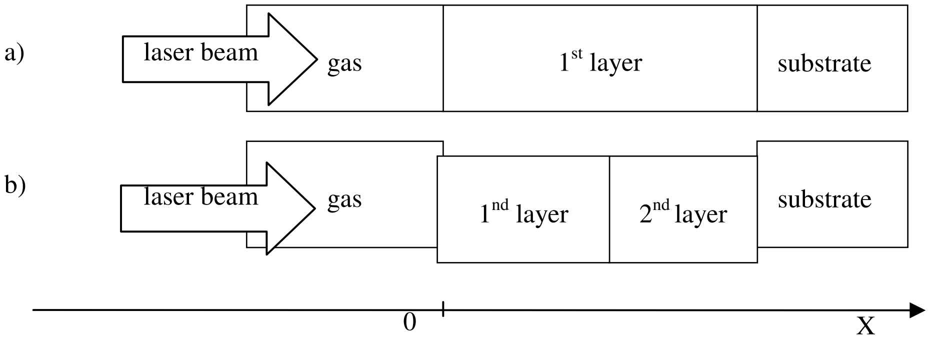

Fig. 1. Scheme of: a) one-layer structure, b) two-layer structure

Let us assume that on the gas side intensity periodically-modulated beam of light enters the 1st layer and that absorption of light energy takes place only in the 1st layer. The flux of heat caused by the absorption of light is described by Eq. (2).

$$I = \frac{I_0}{2}\left(1+\cos(\omega\cdot t)\right) \tag{1}$$

$$\frac{I_0\cdot\beta_1}{2}\exp(-\beta_1\cdot x)\cdot\left(1+\cos(\omega\cdot t)\right) \tag{2}$$

where I (described by Eq. (1)) is light intensity, I_0 is its amplitude, ω is angular frequency modulation of light intensity and β_1 is absorption coefficient of light. According to what was written above heat diffusion equation, with the term describing the internal heat source (3), expresses the temperature T_1 in 1st layer.

$$\frac{\partial^2 T_1}{\partial x^2} = \frac{1}{\alpha_1}\frac{\partial T_1}{\partial t} - \frac{I_0\cdot\beta_1}{2}\exp(-\beta_1\cdot x)\cdot\left(1+\exp(i\omega\cdot t)\right) \tag{3}$$

where $\alpha_1 = \frac{k_1}{\rho_1\cdot c_1}$ – thermal diffusivity,
k – thermal conductivity, ρ – density of material, c – specific heat.
The temperature T is a function of time t and x coordinate. Subscript 1 denotes that physical quantities in Eq. (3) pertain to 1st layer.

Similar equations to Eq. (3), but without the term describing the internal heat source Eq. (4), express the temperature in other parts of depicted on Fig. 1 sample.

$$\frac{\partial^2 T_j}{\partial x^2} = \frac{1}{\alpha_j}\frac{\partial T_j}{\partial t} \tag{4}$$

Subscript j beside temperature T_j and thermal diffusivity α_j points at the area of the sample in which the parameters and equation are valid: j = g – gas, j = 2 – 2nd layer, j = s – substrate.

In all calculations, the same boundary conditions are used:

1) The outer sides of the gas and substrate are in ambient temperature.
2) The temperature on all internal interfaces of the sample's constituents is continuous.

3. RESULTS OF NUMERICAL CALCULATIONS

The solution of equations (3) and (4) with above described boundary conditions give temperature T = T(x,t) in all parts of the sample. It is true for sample depicted on Fig. 1a as well as on Fig. 1b. This temperature consists of time-dependant and time-independent components.

The time-dependant component of the Eq. (3,4) solution was extracted because the time-independent component has no important significance in most problems occurring in photothermal techniques. The time-dependent component obviously oscillates with frequency equal to frequency of light modulation and also depends on x coordinate.

Below we will present only the amplitude of time-dependant component of the surface's temperature. We can do this because all samples made of opaque materials are considered.

Due to the fact that 1st layer of the sample always consists of metal, the value of absorption coefficient of light which is taken into calculation is so large that one may acknowledge that the absorption of light takes place only on the sample's surface. Instead of layer's thickness L, the reduced thickness L/μ is used; where $\mu = \sqrt{2 \cdot \alpha / \omega}$. The intensity amplitude of the light which enters the 1st layer equals $I_0 = 10^4 W/m^2$.

Using the theory which was briefly presented above, the temperature amplitude on sample's surface was numerically obtained and the results for one-layer structure are presented on Fig. 1 and Fig. 2.

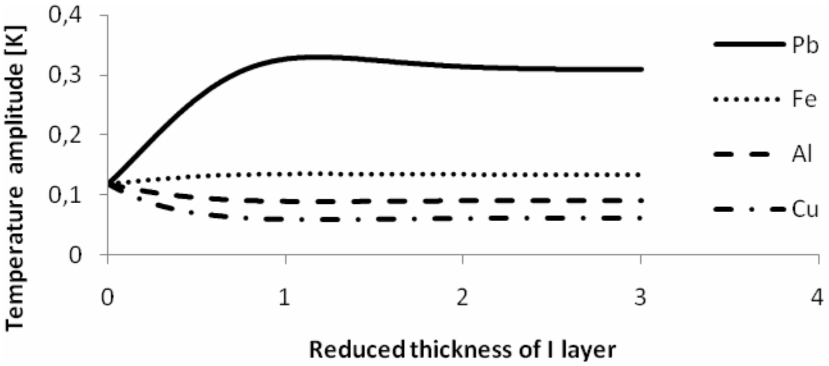

Fig. 1. Temperature amplitude on sample's surface as a function of reduced thickness of 1st layer. Different curves represent sort of material what the 1st layer of sample was made of. Pb – lead, Fe – iron, Al – aluminium, Cu – copper. In all cases substrate is made of Ni – nickel

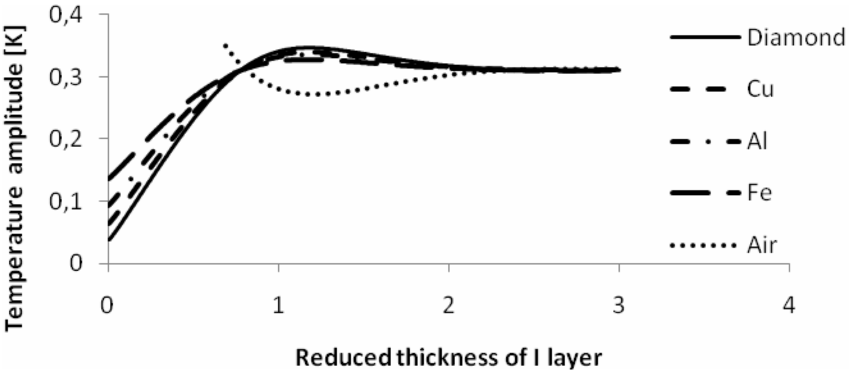

Fig. 2. Temperature amplitude on sample's surface as a function of reduced thickness of 1st layer. Different curves represent sort of material what the substrate is made of. Diamond, Cu – copper, Al – aluminium, Fe – iron, air. In all cases 1st layer is made of Pb – lead

It is clearly seen from Fig. 1 that the temperature amplitude on sample's surface depend on the sort of material what the 1st layer is made of but on condition that 1st layer is sufficiently thick or the modulation frequency of the illuminating light is high enough. Moreover, the statement that the temperature amplitude mentioned above is proportional to I_0 is so clear that it was not shown on any chart. On no chart it was also illustrated that the temperature amplitude on sample's surface does not depend on the thickness of the substrate. Although, it may be very useful information in photothermal investigations.

The curves on Fig. 2 show that when the reduced thickness of 1st layer is thin enough the sort of material, what the substrate is made of, affects the temperature amplitude on sample's surface. This property can be practically exploited for controlling the temperature amplitude on sample's surface i.e. this temperature amplitude can be amplified or reduced in the way mentioned above.

Data shown in Fig. 3 were calculated in a similar way to those in Fig. 1 but between 1st layer and substrate the 2nd layer, made of metal, was inserted.

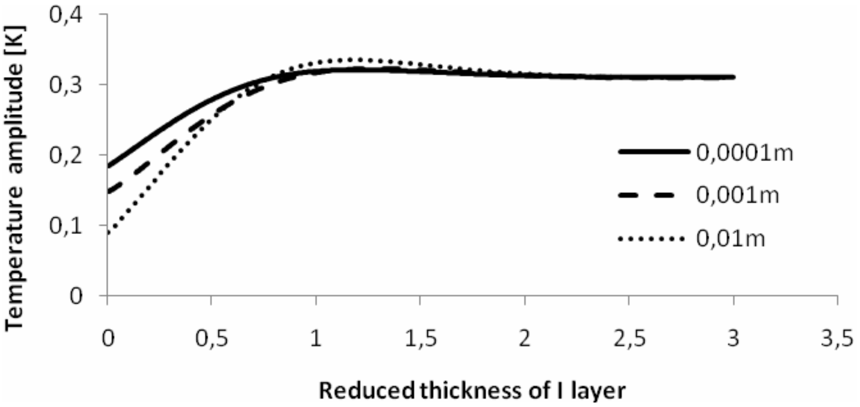

Fig. 3. Temperature amplitude on sample's surface as a function of reduced thickness of 1st layer. Different curves represent the thickness of the 2nd layer. In all cases 1st layer, the 2nd layer and the substrate are made of Pb – lead, Al – aluminium and Al_2O_3 – aluminium oxide respectively

Earlier was mentioned that for one-layer structures the temperature amplitude on sample's surface does not depend on the thickness of the substrate but when between 1st layer and substrate the 2nd layer, made of metal, was inserted the thickness of such additional layer affects discussed temperature amplitude. Although, it plays similar role as substrate. Above statement is true when the reduced thickness of 1st layer is thin enough as it is shown on Fig. 3.

4. CONCLUSIONS

For one-layer structures it was shown that when one use the substrate which is made of relevant material the expected temperature amplitude on sample's surface can be obtained on condition that reduced thickness of 1st layer is thin enough. Similarly, but less effectively, the control of temperature amplitude on sample's can be achieved when the reduced thickness of 1st layer change is employed.

A little shift of discussed temperature amplitude can be also achieved for two-layer structures when the thickness of 2nd layer is being changed on condition that the reduced thickness of 1st layer is sufficiently thin.

The temperature amplitude on sample's surface was analyzed as a function of reduced thickness μ but not real physical measure of thickness L because reduced thickness can be changed by changing frequency modulation of the illuminating light as well as by changing the real thickness which is very convenient. Such analysis also makes easy the understanding of the heat transfer of time-dependent component of energy [7].

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WYBRANE WŁASNOŚCI FOTOTERMICZNE STRUKTUR JEDNO- I DWUWARSTWOWYCH

Streszczenie

Praca przedstawia wyniki obliczeń numerycznych temperatury na powierzchni struktur wielowarstwowych oświetlanych modulowaną wiązką światła. W szczególności pokazano jak na amplitudę zależnej od czasu składowej temperatury wpływają niektóre parametry geometryczne i cieplne takiej struktury. W pracy rozważano struktury jedno- i dwuwarstwowe.