ІІ. ПРОБЛЕМИ МЕТОДИКИ НАВЧАННЯ ФІЗИКИ

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STUDYING THERMAL WAVES PROPERTIES ON THE BASIS OF THERMOACOUSTIC EFFECT IN THE COURSE OF GENERAL PHYSICS

The paper presents a simplified theory of photothermoacoustic (PTA) signal generation and its dependence on the sample's optical, thermal and mechanical properties, geometric structure, etc. Both the experimental technique and the results of investigating PTA microscopy in a university laboratory are discussed. The unique ability of thermal wave microscopy for non-destroying level-by-level diagnostics of subsurface defects is analyzed. The paper describes a virtual laboratory workshop to study characteristics of thermal waves on the basis of thermoacoustic effect in the course of general physics.
Keywords: thermal wave, thermoacoustic effect, course of general physics, virtual laboratory workshop.

Introduction. One of the basic concepts in modern physics is the concept of oscillatory processes and their spreading in space in a form of waves. Along with elementary fractions of substance – atoms and molecules – the quanta of oscillation have got their place in the course of modern physics: mechanical – phonons, electromagnetic – photons, spin – magnones, etc. Moreover, when studying a lot of phenomena of the microworld we have to consider microparticles not as pieces of matter, but as quanta of de Broglie waves. Thus it is important for future teachers to shape the understanding of wave processes development, of universality of oscillation phenomena law in nature.

Studying waving process is an important part of a university Physics course. It includes carrying out laboratory workshops while studying “Mechanics”, “Electricity and Magnetics”, “Optics”, “Atomic and Nuclear Physics” [1]. Despite the variety of the researched characteristics of oscillations and phenomena, following their propagation (interference, diffraction, polarization, attenuation, dispersion, laws of photoeffect, discrecity of atoms and molecules spectra, etc.), only two types of waves are traditionally discussed at Physics lab works: mechanical and electromagnetic [1-2].

Meanwhile, other wave types, including such interesting type as thermal (heat) waves, remain beyond laboratory sessions [3, p.176-179]. Apart from enriching students’ knowledge of the waves processes, studying the waves of this type could improve teaching the section “Thermodynamics and Molecular Physics”, where experimental investigation merely comes to the use of sound waves while measuring thermal capacity [2, p.298-303].

Currently thermal waves have been attracting scientists’ attention as the unique tool for non-destroying diagnostic of microstructure of materials, in particular semiconductor microelectronic devices [4-6]. Traditional methods of research, such as optical, x-ray and electronical microscopy, have some restrictions. For example, optical and electronical microscopes are hardly suitable for research of the internal structure of high-absorbing materials; the use of x-ray microscope is connected with difficult decoding of the received images. Besides, one common fault is inherent in all listed types of microscopes – the impossibility of studying thermal properties of the samples.

Photothermoacoustic (PTA) effect is directly related to the sample's optical, thermal and mechanical properties, geometric structure, etc. Therefore, surface and subsurface features of a sample can be investigated by PTA signal detecting. Moreover, PTA microscopy has a unique ability for non-destroying level-by-level diagnostic of the sample's structure. Besides, PTA effect is well applicable in the spectral investigations of high-transparent, nontransparent and high-scattering materials, in particular in depth profiling of both transparent and nontransparent samples optical characteristics [7-8].

I. Simplified theory of PTA signal generation

Photothermoacoustic effect occurs when an investigated sample is irradiated by amplitude-modulated light. The absorbed part of light energy causes periodical heating and thermal expansion of the material. As a result, acoustic waves are generated both inside the sample, and in the environment.

Three types of waves can exist in a researched sample – optical, thermal and mechanical, and, as a result, PA signal contains information on the correspondent properties of the object. In semiconductors the generation of a PA signal is accompanied by the occurrence of electronical excitations, which have certain time of living and pass certain distance before recombination. Hence, PA signal gets information on electronical parameters: average time of life, diffusion length, spatial distribution of impurities etc.

In order to qualitatively understand the mechanism of PA signal generation, let us consider a simplified one-dimensional model. The solid isotropic infinite elastic layer by thickness d is homogeneously irradiated in a plane x=0 by modulated light.

The equation of the intensity modulation is

$$I = I_0(1+\cos(\omega t))/2 \quad (1)$$

where I_0 is the incident laser intensity, ω – is the modulation angular frequency. For simplification of accounts we shall solve a model in complex recording.

Assuming that all absorbed light energy is transformed into the thermal one, we can describe the thermal field in the sample by the thermal conductivity equation:

$$c\rho \frac{\partial T}{\partial t} - \chi \frac{\partial^2 T}{\partial x^2} = \alpha \frac{I_0}{2} e^{-\alpha x} e^{i\omega t} \qquad (2)$$

where c, ρ, χ, α are the specific heat, the density, the thermal conductivity and the optical absorption coefficient of the sample correspondingly, T – the harmonic component of the temperature on the .depth x

Neglecting transfer of heat to the environment and considering thermal thick sample (l<<d), we shall write down a boundary conditions as:

$$\left(\chi \frac{\partial T}{\partial x}\right)_{x=0} = C, \qquad (3a)$$

$$T(d,t) = 0 \qquad (3b)$$

whence the result T(x,t) can be written as:

[illegible] (4)

The first component in (8) describes the temperature fluctuations caused by the modulated light absorption in this region, and another one – the heating that has come from other areas of the sample. It is the second component, which represents thermal wave. Thermal diffusion length $l = \sqrt{2\chi / c\rho\omega}$ corresponds to the distance, on which thermal wave is attenuated *e* times. Its wavelength is $\lambda_T = 2\pi l = 2\pi\sqrt{2\chi / c\rho\omega}$. It is seen that the thermal wave is attenuated for the distance λ_T in $e^{2\pi}$ = 534 times

For example in Table 1 the thermal diffusion length for some materials are shown.

Table 1 The thermal diffusion length for some materials

Material	Density g/sm^3	Specific heat, kal/g·K	Thermal conductivity, kal/s·ms·K	Thermal diffusion length at different frequencies				
				ν=10 Hz	ν=10^2 Hz	ν=10^3 Hz	ν =10^4 Hz	ν=10^5 Hz
Al	2,7	0,216	0,48	1870	590	187	59	18,7
Si	2,33	0,168	0,45	1900	610	190	61	19,0
Ge	5,32	0,167	0,167	3670	1160	367	116	36,7

Strong attenuation makes direct registration of thermal waves (for example, by pyroelectric transducer) practically impossible, that, on the first sight, makes it difficult to study their properties in a laboratory. Therefore in the most cases phenomena accompanying the thermal wave propagation are recorded.

II. Methods of PA signal detection

Methods of PA signal detection can be divided into two groups. The first group is connected with detection of sample's surface mechanical fluctuations arising due PA effect (thermomechanical methods). The second group includes investigation of phenomena accompanying the thermal wave (photothermal methods), which are not connected to sample's mechanical fluctuations. Among photomechanical (PM) methods we can specify:

1. piezodetector method – detection of sample's surface mechanical fluctuations by piezoelectric detector;
2. photodisplacement method – detection of periodic change of the reflection angle of probing optical beam due to sample's surface mechanical fluctuations;
3. photointerferention method – detection of periodic change of the way of a reflected probing optical beam by interferometer.

The group of the photothermal methods is more numerous:

4. gas-microphone method – detection of the acoustic waves generated due to the transfer of heat to environmental gas by a microphone;
5. photodeflection method – detection of the periodical deflection of probing optical beam passing through the region heated by the surface of the sample;
6. thermo-lens method – detection of probing optical beam extension in the field of modulated heating;
7. refraction-interferention method – detection of the periodical change of probing optical beam phase shift in the field of modulated heating;
8. photothermal radiometry – – detection of the modulated optical radiation of the sample's surface caused by modulated heating (IR radiation);

9. contact methods – direct detection of the sample's surface temperature (pyroelectric transducer, bolometer, etc.);
10. photoreflection method – detection of the periodical change of the sample's optical reflection coefficient by probing light beam.

Most of PA investigations are based on piezodetector and gas-microphone methods due to their high sensitivity and simplicity. It is rather easy to detect, for example, acoustic waves, which arise inside the sample due to thermal expansion in the region of a thermal wave passage. It is necessary to note that as in a sound range acoustic wave on some orders longer than the thermal one, it in this case serves only as a passive carrier of the information obtained by the thermal wave.

Let us calculate the acoustic response of a sample (mechanical fluctuations of its non-irradiated surface) neglecting generation of heat at its deformation. Let us write down the thermal elasticity equation:

$$\frac{\partial^2 U}{\partial x^2} - \frac{1}{V^2}\frac{\partial^2 U}{\partial t^2} = \xi a_T \frac{\partial \theta}{\partial x}, \quad (5)$$

where U is the elastic displacement, V is the acoustic waves speed, a_T is the thermal expansion coefficient, $\xi = \dfrac{\alpha + \frac{2}{3}\mu}{\lambda + 2\mu}$, λ and μ are Lame constants.

If the surfaces of the sample are free, we can obtain the result elastic displacement of the bottom side of the sample:

$U_{x=d} =$ [illegible], (6)

where k is the acoustic wave vector.

It is seen that the PA signal depends on the sample's optical (α), thermal and mechanical (η, ξ, k) properties and geometric structure (d). Therefore the spatial distribution of the optical, thermal and mechanical features can be investigated by detecting PA signal. According to the features contribution three modes of PA microscopy are separated: optical, thermal-wave and acoustic.

We can see that thermal-wave microscopy provides a unique capability for non-destroying detection of nontransparent solid subsurface structure. The visualization is caused by the thermal wave dispersion on the regions with variations of the specific heat, the density, and the thermal conductivity (such as microcracs, delaminations, voids, inclusions, lack of bonding etc.).

Due to the thermal wave strong attenuation, the harmonic component of the temperature creates "thermal probe" with a diameter about the thermal diffusion length. It is apparent that we can change the depth of visualization by the frequency.

III. Simplified installation for PTA investigation

Block diagram of the simplified mounting for PTA investigations is shown in Fig.1. The radiation of the pumping optical source 1 (He-Ne laser or power lamp with monochromator) is modulated on intensity by the modulator 3-6. The modulator consists of mechanical chopper 3-4 and low-frequency generator 5 with amplifier 6.

Generator's signal supplies motor 4, which rotates disk 3. That disk has periodically situated holes and interrupts the laser beam. The modulator provides frequency range from 100 to 2000 Hz.

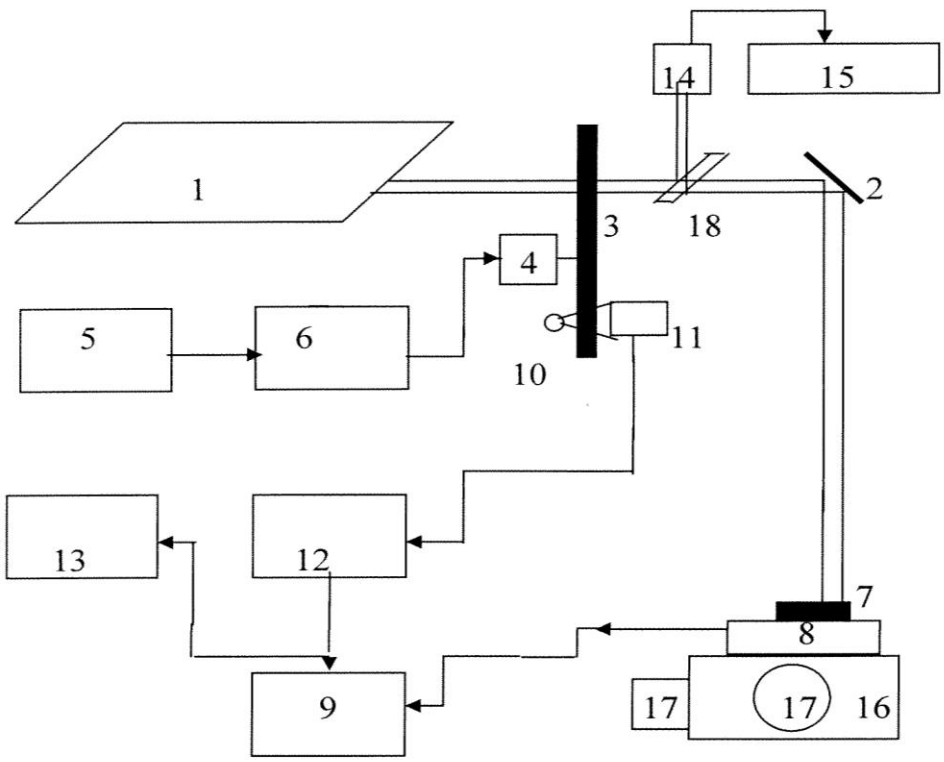


Fig.1. Block diagram of the simplified mounting for PA investigations:

1 – pumping optical source (He-Ne laser or power lamp with monochromator);
2 – mirror;
3 – disk with periodically situated holes (chopper);
4 – the chopper's motor;
5 – low-frequency generator;
6, 12 – amplifiers;
7 – sample;
8 – PA signal detector 8 (piezodetector or gas-microphone cell);
9 – main amplifier with a synchronous detector (lock-in amplifier);
10 – lamp;
11, 14 – photodiodes;
15 – voltmeter;
16 – two-coordinate platform;
17 – micrometric screws;
18 – glass plate.

The laser beam by a mirror 2 is directed on a surface of the sample 7, which is in contact with the detector 8. The main amplifier 9 registers the result PTA signal. As the level of the result signal is low and comparable with the level of the environmental noise (□V), the main amplifier has a synchronous detector (lock-in amplifier). In this case the amplifier separates only signals identical in the form with the reference signal. Lamp 10 and photodiode 11 create the reference signal, which through the additional amplifier 12 goes to the main amplifier. The part of the reference signal goes to the frequency controller 13. The PTA signal detector 8 is situated on the two-coordinate platform 16. With the help of the micrometric screws 17 we can move the sample in relation to the falling beam at two perpendicular directions. The glass plate 18, the photodiode 14 and the voltmeter 15 help to carry out the laser beam intensity control.

IV. Testing experiment

A model sample was aluminum plate (5 μm thickness), in which at different depths cavities were created. In the first case the modulation frequency was 30 Hz (low frequency), and hence the thermal diffusion length (0,9 mm) was about cavities depth. As a result the thermal wave reached the cavities. Experiment showed that in that case the PA signal from the cavities region was stronger (Fig.2,a).

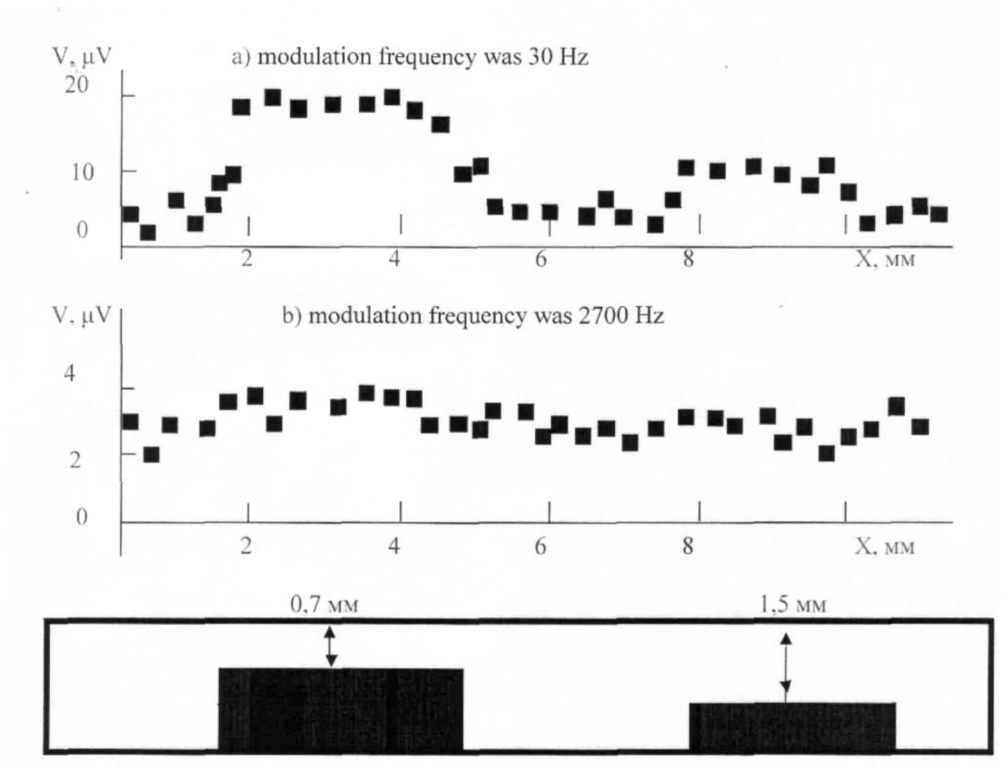


Fig.2. PA topogram of the aluminum plate with cavities

In the second case the modulation frequency was 2700 Hz (high frequency), and hence the thermal diffusion length (0,3 mm) was three times shorter than cavities depth. As a result the thermal wave practically did not reach the cavities. The experiment showed small increase of the PA signal from only the first cavity region.

We can see that thermal-wave microscopy provides a unique capability for non-destroying level-by-level detection of nontransparent solid subsurface structures. The visualization is caused by the thermal wave dispersion on the regions with variations of the density, and the thermal conductivity.

Acoustic waves are about 100 times longer than thermal waves at these frequencies. That is why acoustic waves serve only as a passive carrier of the information obtained due to thermal waves dispersion on the defects.

V. Virtual lab workshop for thermal wave investigation by thermoacoustic effect

Though the method of piezoelectric detector is one of the simplest in photoacoustics, in practice one should use rather powerful laser and high-sensitive measuring apparatus to gain acceptable level of acoustic signal. It doesn't seem easy to exercise amplitude modulation of laser emission with the possibility to modify it in the required frequency range. Moreover, rather few educational establishments can afford to create such device in their study laboratories. A pleasant exception is the department of Physics of Kyiv National University, which has constructed and is currently using the former in its training process [9].

This article suggests to use virtual laboratory workshop that can help modulate the experiment on the properties of thermal waves. The paper surveys strongly damped character of thermal waves and the dependence of damping depth on frequency.

Model samples include plates of different materials (aluminium, silicon, germanium), which have a number of voids, generated at different depths. The model surface itself is polished to gain maximum homogeneity.

At the first stage after starting the program and getting familiar with the block diagram of the apparatus, students are suggested to set the experiment parameters: model material, bedding topology of the areas with disturbed thermal peculiarities, modulation frequency (Fig.3).

This is followed by launching the scanning of the surface model with a focused laser beam and automatic computer plotting of the diagram of piezoelectric detector signal dependence on the position of the probing bean. In the model areas where the heat wave is beginning to disperse at the subsurface defect, piezoelectric detector signal is changing.

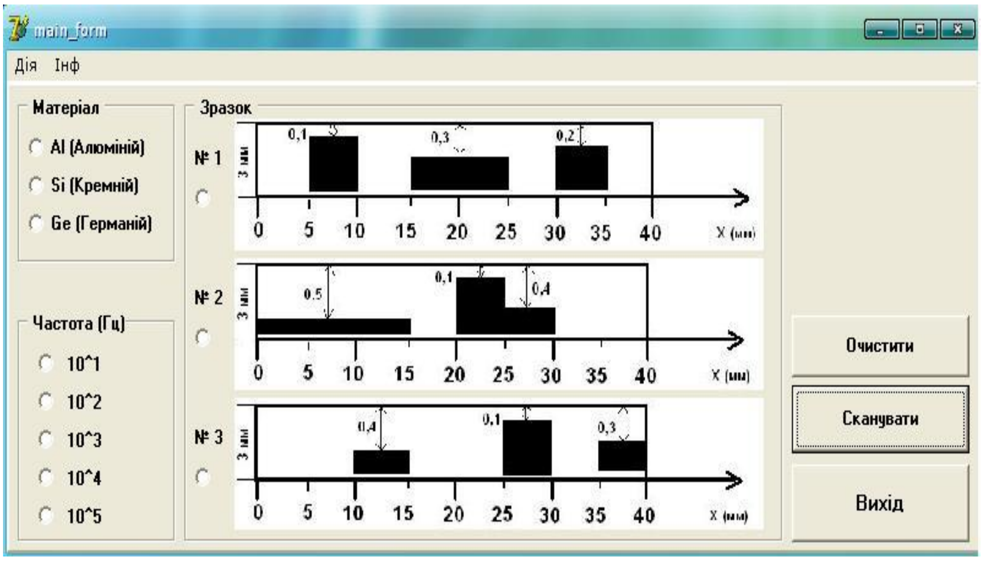
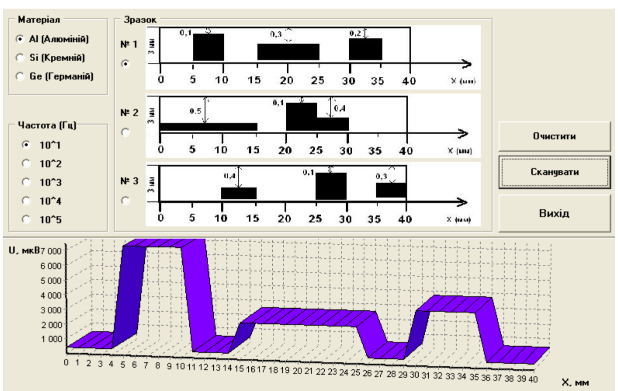


Fig. 3.

As an example, figure 4 shows thermowave topograms of the aluminium sample 4 at various modulation frequencies, acquired with the help of the described program. The plate demonstrates generated mechanical defects – holes of different depth, as the conventional sample section shows.

On the topograms, shot at the frequencies of 10 and 100 Hz (fig. a, b) one can observe that the signal strongly increases where the laser beam is probing the areas with disturbed conditions of heat removal (subsurface void). The temperature gradient is dramatically increasing in these areas, and thus, the amplitude of the acoustic wave, generated due to the thermal expansion.



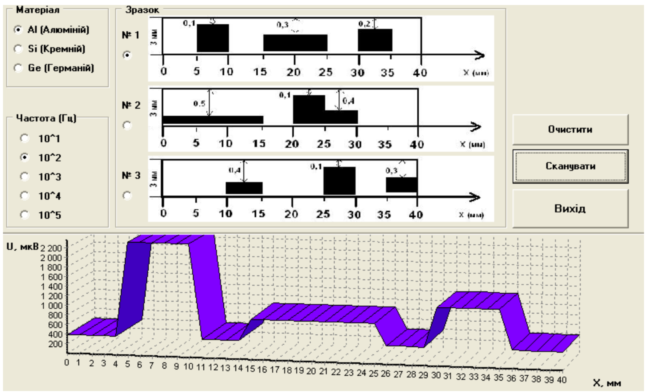


Fig. 4 (a) Modulation frequency 10 Hz Fig. 4 (b) Modulation frequency 100 Hz

The topograms at the frequencies of 10 and 100 Hz of the abovementioned sample (fig. 4 c, d) demonstrate that at high frequencies the "heat probe" almost fails to reach the defect area and doesn't "feel" disturbances of the sample structure. In this case the depth of heat wave penetration is less than the depth of defects bedding. The figure proves that the signal from all the areas is almost identical, and that means that the "heat probe" almost fails to reach the defect area and doesn't "feel" disturbances of the sample structure.

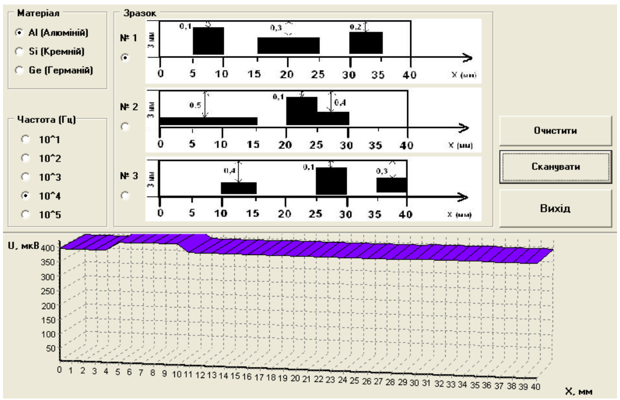


Fig. 4 (c) Modulation frequency 10 kHz

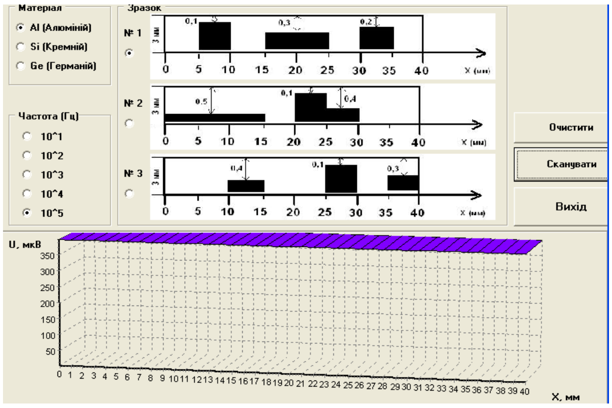


Fig. 4 (d) Modulation frequency 100 kHz

On the basis of these data the length of the heat wave at different modulation frequencies is defined and compared to the estimated. One can make a conclusion on strongly damped character of heat waves and dependence of their depth and damping length on the modulation frequency of the heating source.

Conclusions. Photoacoustic microscopy, due to its unique capabilities for non-destructive surface and subsurface structure detection is a very efficient tool for level-by-level depth profiling of opaque materials examination (for example, semiconductor microelectronic devices). By using PAM, we can "see" inside objects and locate defects and changes in material properties, such as microcracs, delaminations, voids, inclusions, lack of bonding etc., which are not evident on the outside surface.

Familiarizing students with thermal waves would permit the former to more profoundly study the peculiarities of wave processes, their universal character and to consolidate the knowledge of "Thermodynamics".

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ВИВЧЕННЯ ВЛАСТИВОСТЕЙ ТЕПЛОВИХ ХВИЛЬ НА ОСНОВІ ТЕРМОАКУСТИЧНОГО ЕФЕКТУ В КУРСІ ЗАГАЛЬНОЇ ФІЗИКИ

Пропонується спрощена теорія генерації фототермоакустичного сигналу, а також аналіз його залежності від оптичних, теплових і геометричних властивостей зразка. Обговорюються експериментальне обладнання та результати ФТА дефектоскопії оптично непрозорих обєктів. Аналізується унікальна можливість термохвильової мікроскопії проводити неруйнівну пошарову діагностику підповерхневих дефектів. Описана віртуальна лабораторна робота по вивченню властивостей теплових хвиль у курсі загальної фізики на основі термоакустичного ефекту.

Ключові слова: *теплові хвилі, термоакустичний ефект, курс загальної фізики, віртуальна лабораторна робота*

ВІДОМОСТІ ПРО АВТОРА

Волчанський Олег Володимирович – кандидат фізико-математичних наук, доцент кафедри фізики та методики її викладання Кіровоградського державного педагогічного університету імені Володимира Винниченка.

Наукові інтереси: фототермічні та фотоакустичні явища в напівпровідниках, методика викладання фізики та астрономії, реформування вищої освіти України.

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РАЗРАБОТКА АЛГОРИТМА ДЛЯ АНАЛИЗА ЭЛЕКТРИЧЕСКИХ ЦЕПЕЙ ПОСТОЯННОГО ТОКА С ОДНИМ ИСТОЧНИКОМ ЭДС

Для аналізу електричних ланцюгів постійного струму представлений алгоритм, що дозволяє спростити процес їх аналізу і застосувати комп'ютерне моделювання з використанням інтегрованого середовища розробки програмного забезпечення Borland Delphi 7.0.

Ключові слова: *електричні ланцюги, Закон Ома, правила Кирхгофа, аналіз електричних схем, еквівалентні опори, метод эквивалентного перетворення, комп'ютерне моделювання, программное забезпечення Borland Delphi 7.0*

Постановка проблемы. Реальные электротехнические устройства и системы имеют сложные электрические схемы. В электрические цепи, кроме основных элементов – источников и приемников электрической энергии, входят различные вспомогательные аппараты и приборы, предназначенные для управления, регулирования, защиты, контроля. Перед специалистами стоят задачи расчета параметров таких устройств. Процесс расчета параметров в теории электрических цепей принято называть «анализом схем». Электрические схемы любой сложности подчиняются законам Ома и правилам Кирхгофа. Теоретические расчеты таких устройств, как правило, приводят к неоправданно сложным решениям, что вызывает определенные сложности, требующие понимания сути применяемых методов и значительных временных затрат [1, 2]. С этой целью был разработан алгоритм анализа электрических цепей, упрощающий процесс расчета параметров и, позволяющий применить компьютерное моделирование для расчета этих цепей.

Основное содержание статьи. Если исследуемые устройства можно представить в