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МОДИФІКАЦІЯ РСГР СПЕКТРОМЕТРА ДЛЯ ОТРИМАННЯ ЧАСОВИХ ЗАЛЕЖНОСТЕЙ РЕЛАКСАЦІЇ

Запропоновано принципові апаратні зміни до існуючих автоматизованих релаксаційних спектрометрів глибоких рівнів у напівпровідниках для отримання повних релаксаційних кривих. Отримані результати продемонстровано на діоді серії Д231А.

Ключові слова: РСГР, спектрометр, релаксація ємності, глибокі рівні.

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МОДИФИКАЦИЯ РСГУ СПЕКТРОМЕТРА ДЛЯ ПОЛУЧЕНИЯ ВРЕМЕННЫХ ЗАВИСИМОСТЕЙ РЕЛАКСАЦИИ

Предложены принципиальные аппаратные изменения к существующим автоматизированным релаксационным спектрометрам глубоких уровней в полупроводниках для получения полных релаксационных кривых. Полученные результаты продемонстрированно на диоде серии Д231А.

Ключевые слова: РСГУ, спектрометр, релаксация емкости, глубокие уровни.

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LASER ABSORPTION SPECTROSCOPY OF ELECTRIC ARC DISCHARGE PLASMA WITH COPPER IMPURITIES

Technique of laser absorption spectroscopy was applied for diagnostics of electric arc plasma between composite Cu-Mo electrodes. Spatial brightness distributions of laser emission were registered by CCD-matrix in realized experimental scheme. The graphical user interface for experimental data treatment was developed. Expected experimental errors are estimated. Obtained spatial distributions of copper atomic energy level $^5D_{5/2}$ population were used for calculation of plasma composition in assumption of local thermodynamic equilibrium.

Keywords: optical emission spectroscopy, plasma of electric arc discharge.

Introduction. Diagnostic of plasma is important part of numerous scientific investigations and industrial applications. The optical emission spectroscopy is the most widely used method for arc plasma diagnostic [7]. It is well known, that laser based techniques can significantly expand capabilities of plasma diagnostics.

Different approaches of laser based techniques were applied for arc plasma diagnostics. In work [6] distribution of tungsten impurities in atmospheric arc was obtained by techniques of laser-induced fluorescence. Thomson scattering of laser emission were used in work [8] for obtaining of electron density, gaseous and electron temperature distributions. Two dimensional distribution of electron density was obtained by Shack-Hartman method in work [5]. This method provides determination of refractive indexes, which depends on electron density in plasma.

Methods based on absorption of laser emission by plasma components also can be applied for arc plasma diagnostics. Particularly, method of linear laser absorption spectroscopy (LAS) provides simultaneous registration of plasma properties in different spatial points [1, 9].

Applications of copper based composite materials in the electrical engineering industry stimulate the interest in studying of the arc discharge plasma between such electrodes. It is reasonable to investigate such plasma by LAS with using of copper vapor laser.

The main aim of this work is determination of spatial distribution of copper atoms in the plasma of electric arc discharge between Cu-Mo electrodes by LAS. Analysis of obtained results is carried by specially developed graphical user interface. Obtained results are discussed as well as occurred errors.

Experimental setup. The arc was ignited between non-cooled electrodes in argon flow 6.4 slpm. The discharge gap was 8 mm and arc current was 3.5 A. Cu-Mo composite electrodes fabricated by electron beam evaporation and following condensation in vacuum were used. These electrodes have layered structure, content of molybdenum changes from layer to layer in range 1%–20%; average content of molybdenum was 12%.

Copper vapor laser "Kriostat 1" was used as source of probing emission on wavelength 510.5 nm, which is absorbed by copper atoms in arc plasma volume. Grade of laser emission absorption depends on population of copper atomic energy level $^2D_{5/2}$. As diameter of laser beam exceeds dimensions of arc plasma, so absorption distribution for different spatial points can be simultaneously registered by CCD-matrix (Fig.1).

Registered brightness distributions of reference laser beam and absorbed emission were used for determination of plasma properties. Reference image of spatial distribution of brightness in laser beam without arc is shown in Fig.2, *a*. The image obtained in presence of the arc is shown in Fig.2, *b*. These images were registered at the same operation conditions. CCD-matrix dynamic range selection was realized by changing of exposure time.

Graphical user interface for treatment of brightness spatial distribution (images) was specially developed. It allows:

- visualization of obtained brightness distributions;
- interactive selection of studied cross-section;
- determination of absorption characteristics for selected cross-section;
- determination of local values of absorption coefficient by Abel transformation.

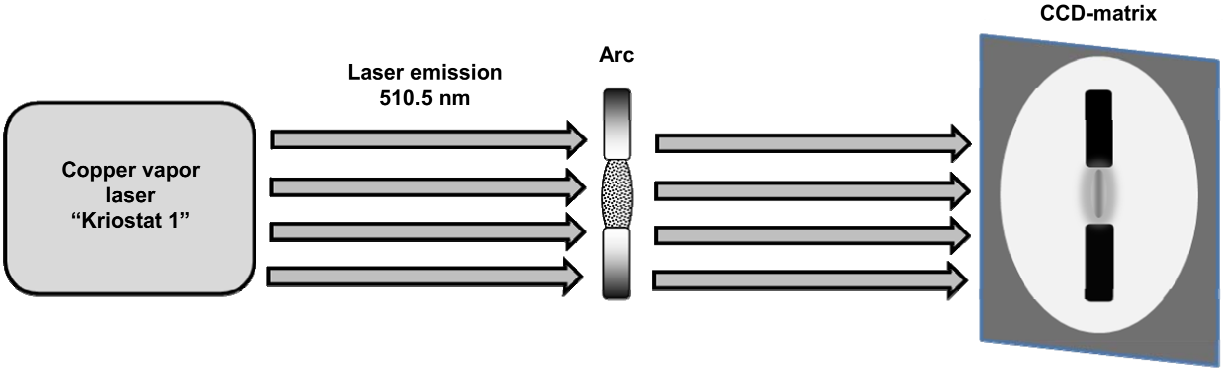

Fig. 1. Optical scheme of linear laser absorption spectroscopy

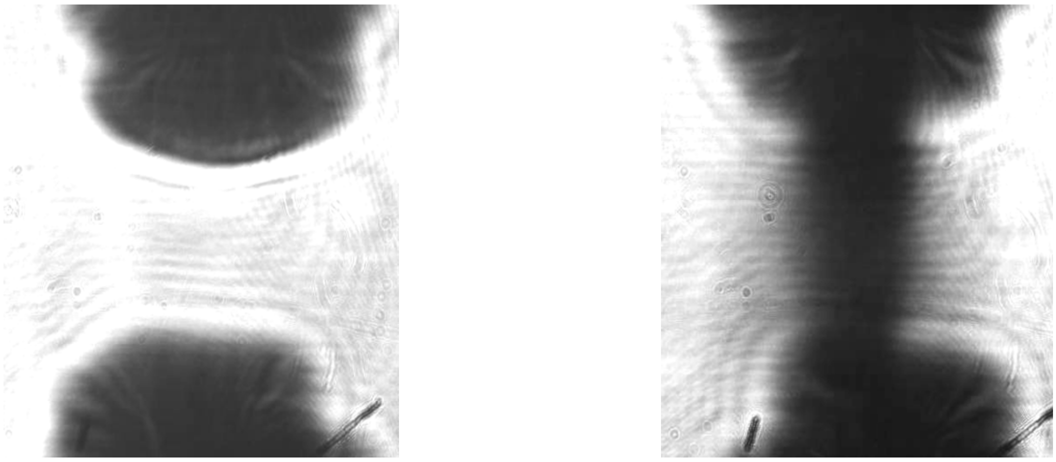
a) b)

Fig. 2. Spatial distributions of brightness in reference laser beam (a) and in presence of the arc (b)

Optical thickness τ at fixed wavelength and at every spatial point can be given as:

$$\tau = \ln\frac{b_{ref}}{b_{absorbed} - b_{arc}} \;\rightarrow\; \tau = \ln\frac{b_{ref}}{b_{absorbed}},\; \text{if } b_{arc} = 0,$$

where b_{ref} and $b_{absorbed}$ are brightness of reference and absorbed by plasma laser emission; b_{arc} is brightness of own arc emission. It has been experimentally found that influence of own arc emission is negligible in studied experimental conditions. Absorption characteristics were calculated for middle cross-section of the arc column; radial profile of optical thickness τ is shown in Fig.3, *a*.

As soon as side-on (lateral) registration of intensity distribution has place in proposed experimental setup, therefore local values of absorption coefficient κ can be obtained from τ by solving of Abel equation:

$$\kappa = -\frac{1}{\pi}\int_{r}^{r_0}\frac{\tau'}{\left(x^2 - r^2\right)^{\frac{1}{2}}}\,dx,$$

where r_0 is radius of visible arc region, τ' is spatial derivative of optical thickness.

Generally it is complicated problem, which can be significantly simplified in case of axisymmetric arc configuration. The method [4] of Abel transformation was applied:

$$\kappa_j = \frac{1}{r_0}\sum\nolimits_k a_{jk}\cdot\tau_k,$$

where j and k are indexes of local and observed characteristics, a_{jk} are appropriate transformation coefficients. Obtained in this way local values of absorption coefficient κ are shown in Fig.3, *b*.

As far as half width of laser spectral line is narrower than absorption line of plasma, so κ can be assumed as absorption in the center of spectral line. Population of absorbing atomic level $^2D_{5/2}$ was calculated with regard to spectral line contour. Since, Doppler broadening dominates for this line at 3.5 A current, so its profile can be described by Gaussian function with half width $\Delta\lambda_D$.

$$\Delta\lambda_D = 7.16\cdot10^{-7}\cdot\lambda\cdot\sqrt{\frac{T}{M}},$$

where M is atomic weight, T is previously measured plasma temperature [3].

So, population N_k (Fig.4) of lower energy level can be given as:

$$N_k = \frac{\kappa\cdot\Delta\lambda_D}{8.19\cdot10^{-20}\cdot f_{ki}\cdot\lambda^2},$$

where f_{ki} and λ are oscillator strength and wavelength of the absorbing spectral transition.

It must be noted, that these population values are independent on local thermodynamic equilibrium assumption.

Calculation of plasma composition. Distribution of copper atom concentration N_{Cu} (Fig.5) can be calculated according to Boltzmann law with using of previously obtained temperature profile:

$$N_{Cu} = \frac{N_k\cdot\Sigma_{Cu}}{g_i\cdot\exp\left(-\frac{E_i}{kT}\right)},$$

where Σ_{Cu} is partition function of copper atom, g_i and E_i statistical weight and energy of absorbing level.

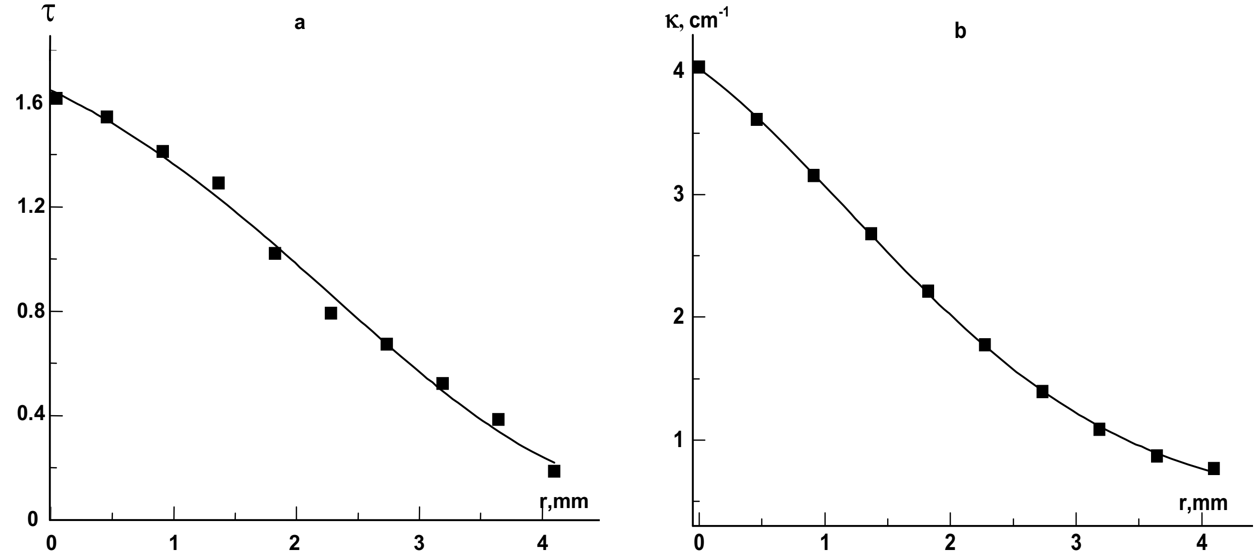

Fig. 3. Radial profiles of optical thickness τ (a) and local values of absorption coefficient κ (b)

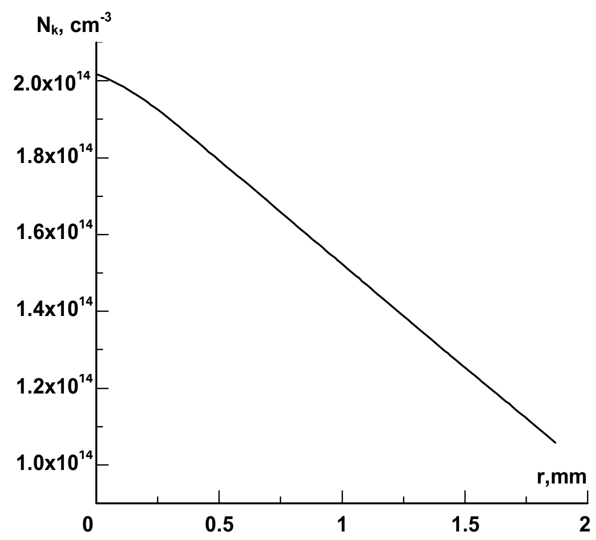

Fig. 4. Radial profiles of population of lower energy level N_k

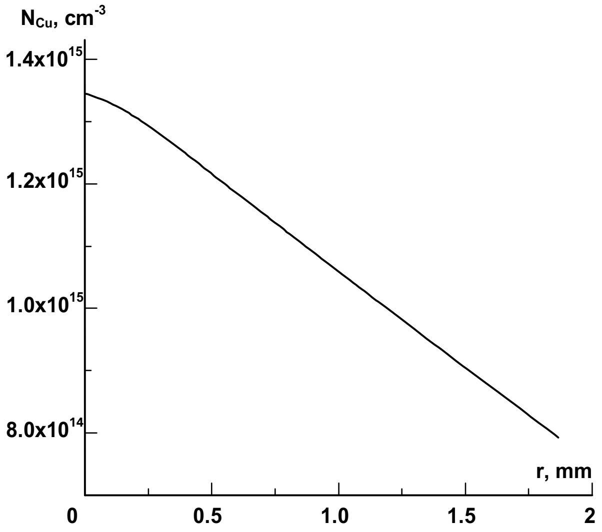

Fig. 5 Radial profiles of concentration of copper atoms

Plasma of electric arc discharge between Cu-Mo in argon flow generally contains atoms and ions of copper, molybdenum and argon. Plasma in state of local thermodynamic equilibrium can be described by equations set [2], which consist of Saha equations for each plasma component, equation of charge neutrality, perfect gas law. Additionally, expression for ratio of Cu and Mo atoms' concentration in plasma volume were included into equations set. This expression can be obtained from ratio of CuI 510.5 and MoI 550.6 nm spectral lines intensities:

$$\frac{N_{Cu}}{N_{Mo}}=\frac{I_{Cu}\cdot\Sigma_{Cu}\cdot\lambda_{Cu}^{2}\cdot(gf)_{Mo}\cdot e^{\frac{E_{Cu}}{kT}}}{I_{Mo}\cdot\Sigma_{Mo}\cdot\lambda_{Mo}^{2}\cdot(gf)_{Cu}\cdot e^{\frac{E_{Mo}}{kT}}}$$

where Σ_{Cu} are Σ_{Mo} are partition functions of copper and molybdenum atoms, $(gf)_{Cu}$, $(gf)_{Mo}$ and E_{Cu}, E_{Mo} are oscillator strengths and energies of appropriate spectral lines. I_{Cu} and I_{Mo}, λ_{Cu} and λ_{Mo} are intensities and wavelengths.

Calculated in this way plasma composition is shown in Fig. 6. One can see that atomic argon is dominant plasma component.

Electric conductivity of plasma channel mainly supports by ionization of copper. Contribution of molybdenum ions in plasma conductivity is relatively low, because amount of molybdenum vapors is lower than copper one. However, ionization degree of molybdenum is high, the main reason of that is low ionization potential of molybdenum in comparison with copper and argon.

It would be interesting to follow influence of initial electrodes' composition and structure on plasma properties.

In work [2] were performed investigations of Cu-Mo composite electrodes composed of 50 % copper and 50 % molybdenum (by mass), which was fabricated by methods of powder metallurgy. Contents of metallic vapor for powder metallurgy technology (curve 1) and for electron beam evaporation and following condensation in vacuum (curve 2) are shown in Fig. 7. One can see that in case of the last technology the content of metallic vapor is lower. So, erosion properties of these electrodes are better at conditions of experiment.

Content of metallic vapor were calculated as:

$$X_{Me}=\frac{N_{Cu}+N_{Cu+}+N_{Mo}+N_{Mo+}}{N_{Cu}+N_{Cu+}+N_{Mo}+N_{Mo+}+N_{Ar}+N_{Ar+}}\cdot 100\%,$$

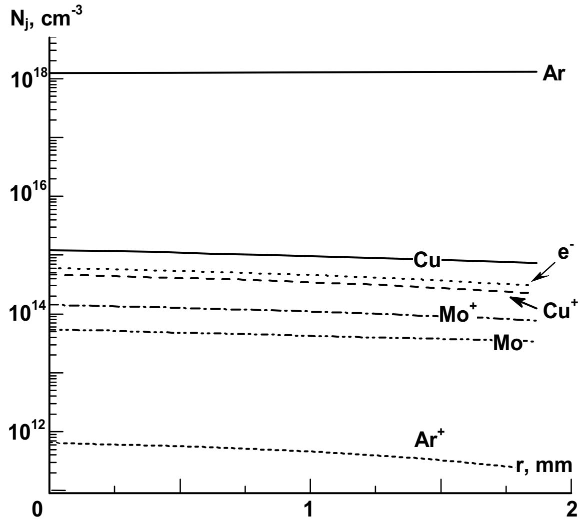

Fig. 6. Calculated plasma composition

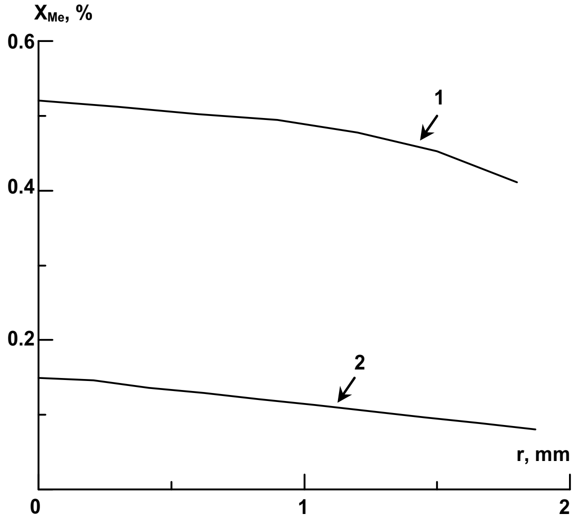

Fig. 7. Content of metallic vapor in plasma of electric arc discharge between Cu-Mo electrodes fabricated by different technology

Estimation of errors. As far as technique of linear laser absorption spectroscopy based on measurement of brightness b_{ref} and $b_{absorbed}$, so standard deviation of optical thickness $\Delta\tau$ can be estimated as:

$$\Delta\tau = \left(\left(\frac{\partial\tau}{\partial b_{ref}} \cdot \Delta b_{ref} \right)^2 + \left(\frac{\partial\tau}{\partial b_{absorbed}} \cdot \Delta b_{absorbed} \right)^2 \right)^{1/2},$$

or in explicit form:

$$\Delta\tau = \left(\left(\frac{\Delta b_{ref}}{b_{ref}} \right)^2 + \left(\frac{\Delta b_{absorbed}}{b_{absorbed}} \right)^2 \right)^{1/2}.$$

Error in determination of local values of absorption coefficient κ caused by Abel transformation, according to method [4], it can be estimated as

$$\Delta\kappa = \Delta\tau \sqrt{\sum_k a_{jk}^2},$$

where a_{jk} is appropriate Bockasten's coefficients.

Population of absorption level N_k linearly depends on κ, therefore:

$$\Delta N_k = N_k \cdot \frac{\Delta\kappa}{\kappa}.$$

As N_{Cu} depends on population of absorbing level N_k and plasma temperature T, so standard deviation can be estimated as:

$$\Delta N_{Cu} = \left(\left(\frac{\partial N_{Cu}}{\partial N_k} \cdot \Delta N_k \right)^2 + \left(\frac{\partial N_{Cu}}{\partial T} \cdot \Delta T \right)^2 \right)^{1/2}.$$

After substitution and simplifying it can be given as:

$$\frac{\Delta N_{Cu}}{N_{Cu}} = \left(\left(\frac{\Delta\kappa}{\kappa} \right)^2 + \left(\frac{E_i}{kT} \right)^2 \cdot \left(\frac{\Delta T}{T} \right)^2 \right)^{1/2}.$$

In assumption of typical inaccuracy of brightness measurements $\Delta I / I = 0.1$ or 10% and acceptable inaccuracy of plasma temperature determination no more than 10%, relative error of copper concentration N_{Cu} does not exceed 27%.

Conclusions. Technique of laser absorption spectroscopy was applied for diagnostics of electric arc discharge between Cu-Mo composite electrodes. Experimental setup and graphical user interface for data acquisition and treatment are developed.

Proposed technique allows determination of copper atoms concentration profiles, which were used in calculation of plasma composition in assumption of local thermodynamic equilibrium.

Obtained results indicate, that atomic argon is dominant plasma component, while electric conductivity of plasma channel mainly supports by ionization of copper and in smaller degree by molybdenum ionization.

Content of metallic vapors in plasma of electric arc discharge between composite electrodes fabricated by electron beam evaporation and following condensation in vacuum are significantly lower than for electrodes fabricated by powder metallurgy.

Occurred errors are estimated with regards to uncertainty of registration and treatment. Relative error of copper concentration N_{Cu} does not exceed 27% in the worst case.

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ЛАЗЕРНА АБСОРБЦІЙНА СПЕКТРОСКОПІЯ ПЛАЗМИ ЕЛЕКТРОДУГОВОГО РОЗРЯДУ З ДОМІШКАМИ МІДІ

Для діагностики плазми електродугового розряду між композитними Cu-Mo електродами застосовано методику лінійної лазерної абсорбційної спектроскопії. Реалізовано експериментальну схему реєстрації просторових розподілів інтенсивності лазерного випромінювання за допомогою ПЗЗ-матриці. Розроблено програмний інтерфейс користувача для обробки експериментальних даних, визначено ймовірну експериментальну похибку. Отримані просторові розподіли заселеності $^5D_{5/2}$ рівня атомів міді використано для розрахунку складу плазми у припущенні локальної термодинамічної рівноваги.

Ключові слова: лазерна абсорбційна спектроскопія, плазма електродугового розряду.

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ЛАЗЕРНАЯ АБСОРБЦИОННАЯ СПЕКТРОСКОПИЯ ПЛАЗМЫ ЭЛЕКТРОДУГОВОГО РАЗРЯДА С ПРИМЕСЬЮ МЕДИ

Для диагностики плазмы электродугового разряда между композитными Cu-Mo электродами применена методика лазерной абсорбционной спектроскопии. Реализована экспериментальная схема регистрации пространственных распределений интенсивности лазерного излучения с помощью ПЗС-матрицы. Разработан программный интерфейс пользователя для обработки экспериментальных данных и определена ожидаемая ошибка эксперимента. Полученные пространственные распределения заселенности энергетического уровня $^5D_{5/2}$ атомов меди использованы для расчета компонентного состава плазмы в предположении локального термодинамического равновесия.

Ключевые слова: лазерная абсорбционная спектроскопия, плазма электродугового разряда.

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PROPAGATION OF TEMPERATURE WAVES IN MEDIUM WITH INTERNAL THERMAL RELAXATION

In this article the wave solutions of heat transfer equations, for classical model and for two alternative non-stationary models (hyperbolic and model with a time delay) have been studied. Modeling of temperature impulse propagation was performed according to dispersion relations obtained from heat transfer equations. It was shown that propagation of temperature impulse in non-stationary models could significantly differ from temperature diffusion in classical model. This can be used for signal transmission and that temperature waves could be used for delay line construction.

Keywords: wave heat transfer, non-stationer models of heat transfer, temperature impulse propagation, undumped temperature waves, dispersion of temperature waves.

Introduction. For the long time the heat transfer problems were regarded using only a classical Fourier's hypothesis that heat flux is proportional to a module of temperature gradient and have opposite direction. In the 50th of the last century first attempt to regard non-stationary heat transfer processes were made by Cattaneo and Vernotte, what leads to a hyperbolic equation for temperature field [2, 12]. Since then the hyperbolic and non-linear parabolic heat transfer models were intensively studied and a big amount of new heat transfer regimes were established, such as traveling waves, blow-up regimes and some others [7–11]. Hypothesis of finite velocity of thermal signal propagation became especially popular in last two decades. Also the non-stationary solutions, such as the temperature waves, started to attract attention of researchers, especially for application in the scanning thermo wave microscopy (STWM), which is one of the method to investigate the under layers of surface for the purpose to determine heat conductivity [1, 5, 6]. In present work we regard thermal wave solutions not only for a classical heat transfer model but also for non-stationary models: hyperbolic and with time delay. Obtained relations of dispersion were used for modeling of temperature impulse propagation, regarding the possibility to use temperature field for signals transmission.

Wave solutions of heat transfer equations. General form of classical heat transfer equation is

$$\rho c\frac{\partial T(x,t)}{\partial t}=\lambda\Delta T(x,t) \tag{1}$$

where ρ is density, c is heat capacity and λ is heat conductivity. Suppose that:

$$T=T_0e^{i(\omega t-kx)} \tag{2}$$

From (1) and (2) and regarding that k is a complex value $k=k_1+ik_2$ dispersion relation could be obtained:

$$i\rho c\omega=-\lambda\left(k_1^2-k_2^2\right)-i2\lambda k_1k_2 \tag{3}$$

It gives the system of equations:

$$\begin{cases}\lambda\left(k_1^2-k_2^2\right)=0\\ \rho c\omega+2\lambda k_1k_2=0\end{cases} \tag{4}$$

In a second half of twenty century the hyperbolic heat transfer equation became more common, especially in the problems of laser impulse interaction with matter. Since the duration of laser impulses could be very short, it yields to non-stationary problems of heat transfer [6]. Hyperbolic heat transfer equation is as follows:

$$\rho c\frac{\partial T(x,t)}{\partial t}+\tau\rho c\frac{\partial^2T(x,t)}{\partial t^2}=\lambda\Delta T(x,t) \tag{8}$$