Regularities of influence of electron beam technology on heat resistance of optical elements in precision instrument-making

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Abstract: *Existing experimental researches show that in order to prevent the destruction of optical elements of modern opto-electronic devices (discs as the light filter linings for IR devices, the input protective windows of laser sighting systems for observation in IR areas of the spectrum, semispherical fairings of IR devices for homing and observation of objects, lightguides for laser medical devices, etc.), electron beam method becomes promising, as it provides cleaning of surfaces, increases their microhardness, makes them more resistant to external influences. The results of experimental studies to improve the properties of the surface layers of elements from optical ceramics after their processing with a moving electron beam with a heat density* $F_n = 10^6...1.6 \cdot 10^7$ *W/m*^{2} *and moving speed* $V = 10^{-3}...10^{-1}$ *m/s (increase in the surface microhardness from 1.2 ... 2.9 GPa (raw elements) to 5.7 ... 6.4 GPa (processed elements), the occurrence of hardened layers with a thickness of 210... 230 microns). It has been established that the improvement of these properties leads to an increase in the resistance of elements to external thermal effects: an increase of 1.3...1.7 times the critical values of external heat flows and their exposure times, exceeding which leads to the destruction of elements and the failure of devices for the studied range of change of external pressure is* $10^5...10^7$ *Pa; increasing the maximum allowable values of thermoelastic stresses in elements from 50...140 MPa to 160...370 MPa at heating temperatures of 300...1200 K.*

Keywords: Precise instrument making, Optical ceramics, Electron beam, Microstructure, Hardness, Thermoelastic stresses.

1. INTRODUCTION

Modern opto-electronic devices with elements from optical ceramics (KO1, KO2, KO3, KO5, KO12, etc.) (discs as the light filter linings for IR devices, the input protective windows of laser sighting systems for observation in IR areas of the spectrum, semispherical fairings of IR devices for homing and observation of objects, lightguides for laser medical devices, etc. [1 – 4]), under the conditions of their operation, can be subjected to intense external thermoactions (elevated heating temperatures and external pressures, shock thermal actions under shot and flight conditions, etc.).

Under these conditions there is a significant change in the properties of surface layers of optical elements up to their destruction (the emergence of cracks, chips, and other. defects), which leads to a significant deterioration in the technical and operational characteristics of the devices (reliability, service life, etc.) and their failure.

Therefore, prevention of these non-desirable phenomena is relevant at the stage of design and manufacturing of devices with the concerned fairings.

Existing experimental researches [5 – 9] show that in order to prevent the destruction of optical elements, electron beam method becomes promising, as it provides cleaning of surfaces, increases their microhardness, makes them more resistant to external influences.

Now the researches on prevention of possible destruction of optical elements of precise instrument making under the conditions of their operation, taking into account the influence of external thermoactions, are absent. In addition, the issue of influence of the thermal action of an electronic beam on the surface of optical elements for their resistance to external thermoactions is not studied enough: optimal change ranges of electronic beam parameters (density of thermal effect, movement velocity), within which there is a significant improvement of the properties of surface layer of elements, increasing their resistance to heat loads and, ultimately, the improvement of the technical and operational characteristics of the devices.

Thus, the purpose of the work is to prevent the destruction of elements from optical ceramics of optical-electronic devices by improving the properties of surface layers of elements and increasing their resistance to external thermoactions by means of finishing electron-beam processing.

2. METHODOLOGY AND SETTINGS FOR CONDUCTING THE RESEARCHES

In order to study the influence of electronic beam parameters on the properties of surface layers of elements from optical ceramics (KO1, KO2, KO3, KO5, KO12) the discs were used with diameter of $3 \cdot 10^{-2}…5 \cdot 10^{-2}$ m and thickness of $4 \cdot 10^{-3}…6 \cdot 10^{-3}$ m, semi-spherical fairings with diameter of $4 \cdot 10^{-2}…8 \cdot 10^{-2}$ m [1, 5]. For researching thermal actions of the movable electronic beam on the element from optical ceramics the following equipment was used developed by the authors. This is specialized specialized electron-beam equipment, which is protected by the patent of Ukraine, which allows to implement tape electronic beam with the width of $5 \cdot 10^{-4}…5 \cdot 10^{-3}$ m, length of $6 \cdot 10^{-2}…8 \cdot 10^{-2}$ m, density of thermal action $F_n = 5 \cdot 10^6…9 \cdot 10^8$ W/m^2 and movement speed $V = 5 \cdot 10^{-3}…10^{-1}$ m/s.

Electron beam equipment and its basic elements The equipment is created on the basis of universal vacuum installation УВН-74П3 [1]. Vacuum system consists of a vacuum chamber and a vacuum installation post УВН-74П3, steam-oil diffusion pump НП-400, forvacuum pump АВЗ-20, vacuometers ВИТ-3, and ВМБ-8, vacuum sensors (Thermocouple ТП-1, ionic ИП-1, magnetic-blocking М-2) located in the vacuum volume. In the vacuum chamber of the installation there is a special technological equipment for electronic processing, namely: quartz infrared furnace of previous heating and final cooling, electronic gun with Pierce optics for forming of tape electron flow, mechanism of optical elements moving. Provide the work of special technological equipment the following external devices, namely: high-voltage power supply of electronic gun based on the unit УЭЛИ-1, quartz furnace control unit based on the thermal sensor-thermostat РИФ-101, he automated processing control system is developed.

To simulate thermal influences on the investigated elements under normal conditions (T_0 = 293 K, P = 10^5 Pa) and find the critical values of their parameters (heat flow q_n^* and the time of its effect t^*), exceeding of which led to the destruction of optical elements, they used guided IR heating by quartz lightbulbs КГТ-220-1000-1, by using the thermal sensors РИФ-101 to control the surface temperature of the elements in the range 300... 1900 K and heat flows that come to them.

To simulate the effects of elevated heating temperatures (up to 1500 K) and external pressures (up to 10^7 Pa) the standard installation was used, where the tests were carried out by methods worked out at "Zavod Arsenal" (Plant Arsenal) (Kyiv) and at

Cherkassy State Technological University within the framework of joint state budget and state contractual research works [1].

To determine the properties of optical elements before and after electron beam processing (microhardness of the surface (H_v, MPa), the magnitudes of residual thermal stresses ((σ, MPa) and thickness of strengthened layers (Δ,microns) they used the known methods of physicochemical analysis (microidention by Vikers method, optical microscopy and microdiffraction analysis, which include raster and scanning microscopy (REM) and transmission electron microscopy (TEM), general-duty diffractometers ДРОН-0,5, ДРОН-2,0, ДРОН-3,0 with special consoles for measuring the microvoltages in surface layers, etc. [1]. The hardness boundary of the optical elements σ^*(T) before and after electron-beam processing were found by the central-ring bend (CRB) [5].

The relative error was not higher than 5... 10% in the conducted studies, aimed to determine the above-mentioned properties of the surface layer of optical elements and critical values of the external influences parameters.

3. RESEARCH RESULTS AND THEIR ANALYSIS

It has been established that for the parameters of an electronic beam change ($F_n = 10^6…1.6·10^7$ W/m^2, $V = 10^{-3}…10^{-1}$ m/s) surface element microhardness varies from 1.2…2.9 GPa (for raw items) to 5.7…6.4 GPa (for the processed items). In this case, an increase of F_n of 10^6 W/m^2 до $1.6·10^7$ W/m^2 leads to an increase of the microhardness of the ceramic surface by 1.5…1.7 times, and an increase of V from 10^{-3} to 10^{-1} m/s leads to a reduction of microhardness of the ceramic surface by 1.3…1.4 timess (Fig. 1).

The results of the research on changes of microhardness at the depth of elements from optical ceramics, which are processed by electron beam, are presented in Fig. 2. From this data it follows that the material microhardness of all types of considered ceramics is rapidly decreasing, heading to its value for the raw material. The thickness of the strengthened layer (Δ), where there are basic structural changes and the microhardness of the processed material increases for the considered parameters of the electronic beam changes in the range from 70...90 microns to 210... 230 microns at the thicknesses of the processed items of $4...6·10^{-3}$ m. Value Δ significantly depends on the nature of ceramics, as well as the parameters of electronic beam (fig. 3): F_n increase from 10^6 W/m^2 м^2 to $2·10^7$ W/m^2 leads to an increase in the thickness of the strengthened layer by 1.8...2.6 times, and increase of beam flow velocity from $1.5·10^{-3}$ m/s to $2·10^{-2}$ m/s leads to a decrease in the thickness of the strengthened layer by 1.7...2.5 times.

It was established that the influence of an electronic beam on the surface of elements from optical ceramics leads to an increase of mosaic blocks and reduction of micro-deformation of the crystalline lattice: the size of mosaic blocks from the output to processed by electron beam of optical elements increases by 3.9 times for elements of optical ceramics КО1, by 5.5 times for elements of optical ceramics КО2, by 3.3 times for elements of optical ceramics КО12, by 4.7 times for elements of optical ceramics КО3 and by 7.7 times for elements of optical ceramics КО5, and the magnitude of microdeformation decreases by 3.7 times for elements of optical ceramics КО1 , by 5.4 times for elements of optical ceramics КО2, by 4.2 times for elements of optical ceramics КО12, by 5.5 times for elements of optical ceramics КО3 and by 5.9 times for elements of optical ceramics КО5.

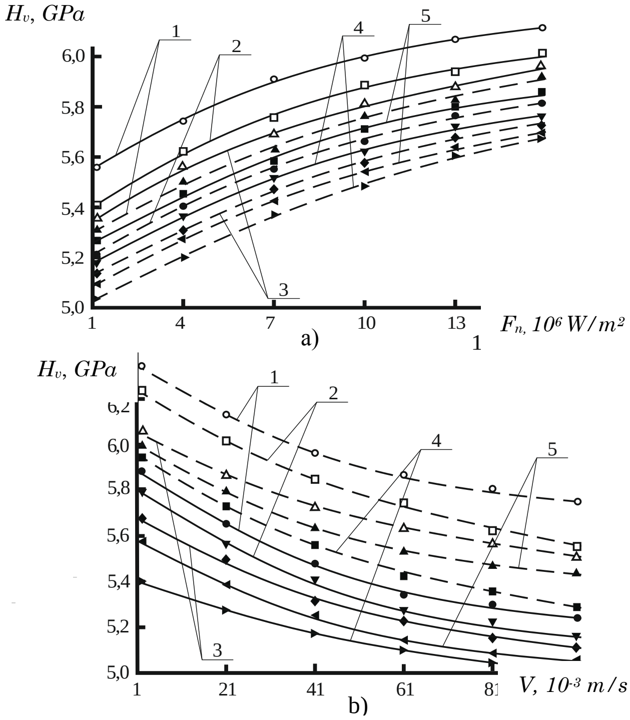

Fig. 1 *- Dependencies of element surface microhardness of optical ceramics КО12 (1), КО2 (2), КО1 (3), КО5 (4) and КО3 (5) that are processed by electron beam: a) – from the density of its thermal effect (——— – $V = 7·10^{-3}$ m/s; – – – – $V = 1.5·10^{-2}$ m/s); b) from the speed of its movement (——— – $F_n = 2.3·10^6$ W/m^2; – – – – $F_n = 1.4·10^7$ W/m^2); Δ, ○, □, ▲, ■, ♦, ▼, ●, ►,◄ – experimental data.*

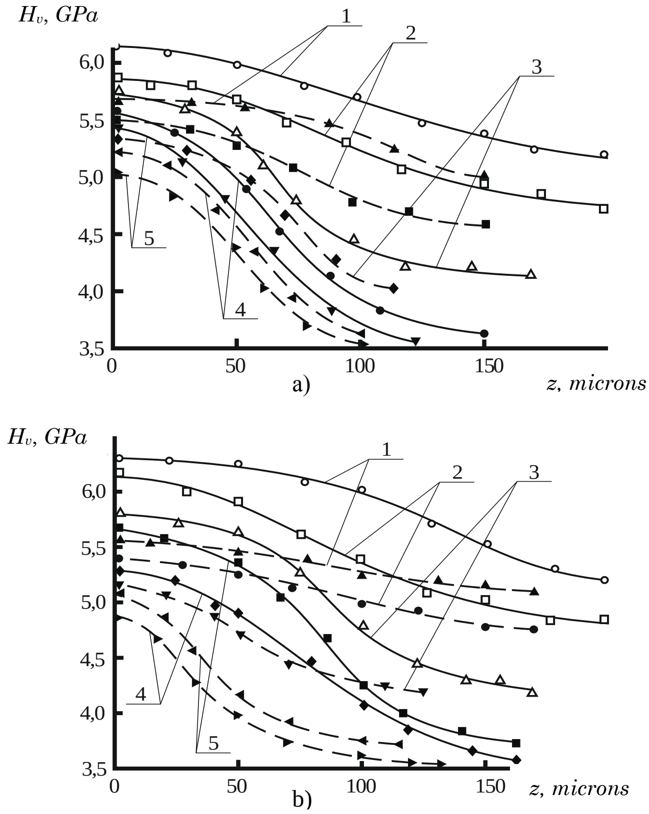

Fig. 2 *– Dependencies of microhardness at the depth of elements of optical ceramics КО12 (1), КО2 (2), КО1 (3), КО3 (4) and КО5 (5), processed by electron beam: a) - for different speeds of movement (——— – $V = 7·10^{-3}$ м/с; – – – – $V = 1.5·10^{-2}$ м/с) та $F_n = 1.5·10^7$ Вт/м^2; b) - for different values of its thermal effect density (——— – $F_n = 1.5·10^7$ Вт/м^2; – – – – $F_n = 5·10^6$ W/m^2)*

ma $V = 7 \cdot 10^{-3}$ *m/s*; Δ, ○, □, ▲, ■, ♦, ▼, ●, ▶,◀ – *experimental data.*

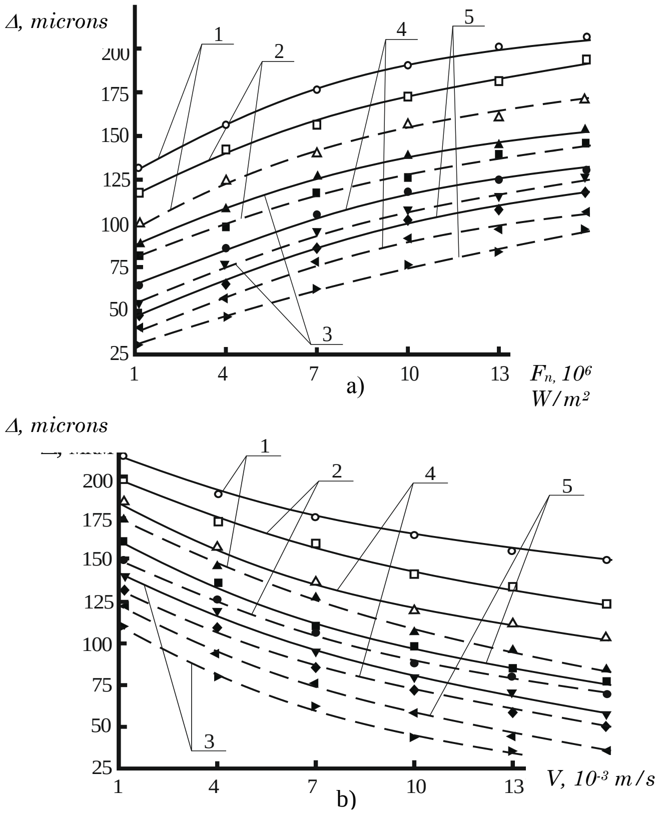

Fig. 3 *– Dependencies of thickness in strengthened layers of elements of optical ceramics (1), KO2 (2), KO1 (3), KO3 (4) and KO5 (5), processed by electron beam: a) - from the density of its thermal effect (——— –* $V = 7 \cdot 10^{-3}$ *m/s; – – – –* $V = 1.5 \cdot 10^{-2}$ *m/s); b) – from the speed of its movement (——— –* $F_n = 1.6 \cdot 10^7$ *Вт/м²; – – – –* $F_n = 2 \cdot 10^6$ *Вт/м²);* Δ, ○, □, ▲, ■, ♦, ▼, ●, ▶,◀ *– experimental data.*

Analysis of the obtained changes of parameters of the crystalline lattices of elements after the electronic processing according with the known methods of data calculation of X-ray patterns [1, 5] based on direct analytical dependence between residual stress, acting on the surface of the element and changing the period of the crystalline lattice of the main components of the considered ceramics, showed the presence of compressive stresses in the thin surface layers of the elements at depth of 40...60 microns for the central part of the processed areas (size of the sections $4 \cdot 10^{-2}$...$5 \cdot 10^{-2}$ m) in the observed parameter ranges of electronic beam changes: for elements of optical ceramics KO2 by 60…70 MPa; for elements of optical ceramics KO2 by 60... 70 MPa; for elements of optical ceramics KO3 by 25... 30 MPa; for elements of optical ceramics KO5 by 55... 65 MPa; for the elements of optical ceramics KO12 by 75... 90 MPa.

As a result of the studies, it was found that after the electron-beam processing of optical elements there is an increase in the critical values of external heat flows q_n^* and the time of their action t^* by 2...4 times (Fig. 4). Thus, the increase in external pressure up to 10^7 Pa, which can be implemented, for example, in the front of the shock wave at a supersonic air flow of the IR device fairings under the conditions of shot and flight, leads to an increase in the values of q_n^* та t^* only by 1.3…1.7 times (Fig. 5).

In addition, it has also been shown that the maximum permissible values of thermoelastic stresses σ^* at different heating temperatures of *T* for optical elements, processed by an electronic beam, are 1.8…2. 7 times higher than for raw elements (fig. 6).

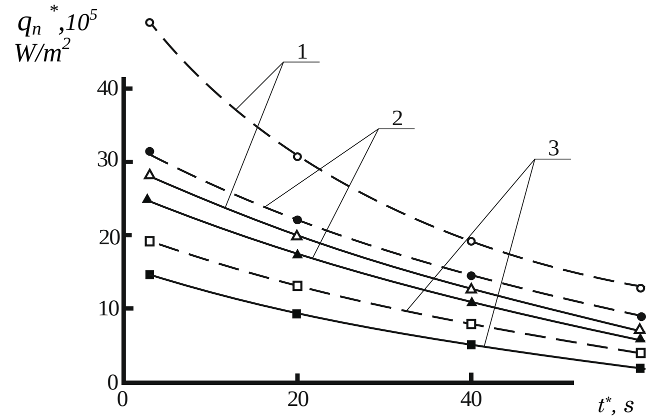

Fig. 4 *– Critical value dependencies of external heat flows* q_n^* *from the time of their action* t^* *on the optical elements processed and unprocessed by electron beam (element thickness* $H = 4 \cdot 10^{-3}$ *m,* $T_0 = 300$ *К,* $P = 10^5$ *Pa) : ——— – unprocessed elements;– – – – processed elements (*$F_n = 1.6 \cdot 10^7$ *W/m²,* $V = 10^{-3}$ *m/s); elements of optical ceramics KO5 (1), KO1 (2) and KO12 (3);* Δ, ○, □, ▲, ■, ● *– experimental data.*

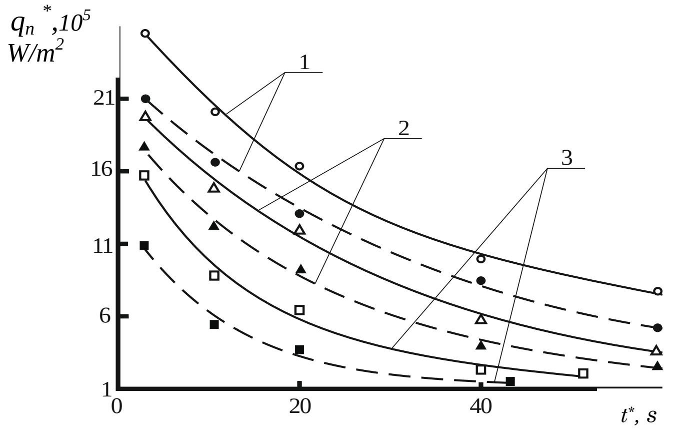

Fig. 5 – Critical value dependencies of external heat flows q_n^* from the time of their action t^* on the optical elements processed and unprocessed by electron beam (element thickness $H = 6 \cdot 10^{-3}$ m, $F_n = 1.6 \cdot 10^7$ W/m², $V = 10^{-3}$ m/s): ——— – $P = 10^5$ Pa; – – — $P = 10^7$ Pa; elements of optical ceramics KO5 (1), KO1 (2) and KO12 (3); Δ, ○, □, ▲, ■, ● – experimental data.

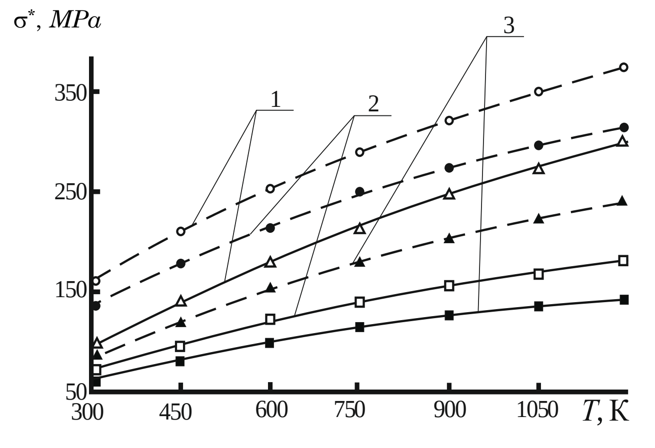

Fig. 6 – Dependencies of values of maximum thermoelastic stresses in the elements of optical ceramics KO1 (1), KO2 (2), KO3 (3) from the heating temperature ($P = 10^5$ Pa, thickness of the element $H = 4 \cdot 10^{-3}$ m, $F_n = 1.6 \cdot 10^7$ W/m², $V = 10^{-3}$ m/s): ——— – elements unprocessed by electron beam; – – – – processed elements; Δ, ○, □, ▲, ■, ● – experimental data.

4. CONCLUSION

1. It is established that after the processing of working surfaces of elements of optical ceramics (КО1, КО2, КО3, КО5, КО12) by the movable electron beam for optimum ranges of its parameter changes (density of thermal effect $F_n = 10^6 \ldots 1.6 \cdot 10^7$ W/m^{2}and its speed of movement V= $10^{-3} \ldots 10^{-1}$ m/s) there improved basic properties of their surface layers:

– surface element microhardness varies from 1,2…2,9 hPa (for raw items) to 5,7…6,4 hPa (for the processed items). In this case, an increase of F_n of 10^6 W/m^2 до $1{,}6 \cdot 10^7$ W/m^2 leads to an increase of the microhardness of the ceramic surface by 1,5…1,7 times;

– in surface layers with thickness of 40... 60 microns there appear compressive thermoelastic stresses with the value of 25... 90 MPa, which lead to the formation of strengthened layers up to 210... 230 microns thick;

– it was established that the influence of an electronic beam on the surface of elements from optical ceramics leads to an increase of mosaic blocks and reduction of micro-deformation of the crystalline lattice.

2. It is obtained that the improvement of properties in the surface layers of optical elements after their electron beam processing leads to an increase in the resistance of the elements to external thermoactions:

– the critical values of external heat flows and the time of their action increase by 2... 4 times, which lead to the destruction elements; thus, the increase of the external pressure from 10^5 Pa to 10^7 Pa decreases the specified critical values of parameters by 1.3... 1.7 time;

– the maximum allowable values of thermoelastic stresses increase by 1.8... 2.7 times in optical ele-mentah, processed by electronic beam, for the change ranges of heating temperatures 300... 1200 K.

5. REFERENCES

1. V.A. Vashchenko, I.V. Yatsenko, Y.G. Lega, O.V. Kirichenko, Osnovy elektronnoi pbrobky vyrobiv z op-tychnych materialiv [The basics of electronic processing of optical materials] (Kiev: Naukova Dumka: 2011) [In Russian].

2. A.R. Glushchenko, V.I. Gordienko, A.A. Burakovsky Lazernyye sistemy tankovykh pritselov [Laser systems for tank sights] (Cherkasy: Maclaut: 2009) [In Russian].

3. V.V. Tarasov, Yu.G. Yakushenkov, Infrakrasnyye pribory “smotryashchego” tipa [“Looking” type infrared devices] (Moscow: Logos: 2004) [In Russian].

4. M.N. Bonus, A.I. Gladkova, S.A. Gorbatyuk Sovremennyye aspekty lazernoy terapii [Modern aspects of laser therapy] (Cherkasy: Vertical: 2011) [In Russian].

5. M.A.Okatov, E.A. Antonov, A.B. Baygozhin Spravochnik optika-tekhnologa [Optician Technologist Handbook] (St. Petersburg: Polytechnic: 2004) [In Russian].

6. V. Yatsenko, V.S. Antonyuk, V.I. Gordienko, V.A. Vashchenko, O.V. Kirichenko J. Nano- Electron. Phys. 9(1), 01010 (2017).

7. I.V. Yatsenko, V.S. Antonyuk, V.I. Gordienko, V.A. Vashchenko, O.V. Kirichenko J. Nano- Electron. Phys. 10(4), 04028 (2018).

8. I.V. Yatsenko, V.S. Antonyuk, V.A. Vashchenko, O.V. Kirichenko, Tishchenko, O.M. J. Nano- Electron. Phys. 11(2), 02014 (2019).

9. H.M. Dubrovska, H.V. Kanashevych, N.I. Bozhko Prylady zastosuvannya fizychnykh metodiv doslidzhennya struktury poverkhni [Devices for the application of physical methods for surveying the structure of a surface] (Sylhet: Udon Offset Printers: 2007).