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Area Measurement Crystals Grown from the Liquid Melt Using the Czochralski Method, Based on the Control-Circuit Conditions Contact Sensor Liquid Level

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For crystals grown from the liquid melt using the Czochralski method, the mathematical model of the current control chip area by controlling the conditions of the contact sensor circuit level of the melt in the crucible, which allows to calculate the control signal, as the difference between the current and the target area grown crystals.

Keywords: crucible, growing crystals, the level sen.

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Измерение площади кристаллов, выращиваемых из жидкого расплава по способу Чохральского, на основе управления условиями замыкания контактного датчика уровня расплава

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Для кристаллов, выращиваемых из жидкого расплава по способу Чохральского, разработана математическая модель контроля текущей площади кристалла на основе управления условиями замыкания контактного датчика уровня расплава в тигле, позволяющая вычислить сигнал управления как разность текущей и заданной площади выращиваемых кристаллов.

Ключевые слова: тигель, выращивание, кристаллы, датчик уровня.

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Introduction

For growing single crystals of semiconductor material from the crucible to melt using the Czochralski method, developed by the contact method of measurement and control [14] of the current area of the crystal.

The basis of the method of measurement is that the crucible which performs rotational movement around its own axis with a speed of rotation $W_{\text{т}}$, and has an inner diameter D, the molten metal to be molten (Fig. 1) from which the growing crystal diameter d, with the growing speed (drawing) $V_{\text{з}}$ and a rotation speed $W_{\text{з}}$ crystal. Grown crystal is placed in heat sealed to provide the necessary snap-temperature growth conditions. The entire process occurs in the growing chamber with an inert gas or in vacuo. The melt temperature is controlled by controlling heater power using temperature $T_{\text{з}}$, the side surface of the heater. Floats on the surface of the melt conductive graphite screen, the function of which is closing and opening of the graphite isolated melt level sensor is fed to the control system signal H to change the level of the melt in the crucible. This signal is required to control the formation of the crucible lifting speed $V_{\text{т}}$ that provides stabilization of the melt level in the crucible and the conditions of constant opening and closing of the contact level sensor.

An important basis for the contact method of monitoring and control of crystal growth is to control the current area (or diameter with round shape) of the growing crystal, according to the control signal y, calculated as a function of the current deviation from a given chip area, using the movements of the crystal $X_{\text{зц}}$ and the crucible $X_{\text{тц}}$ for the period $T_{\text{ц}}$ evaluating the control signal y.

The rate of decrease of the melt in the crucible $V_{\text{р}}$, as well as the accelerated rate of rise of the crucible after breaking up $V_{\text{тм}}$ contact sensor and the slow rate of rise of the crucible after the closure

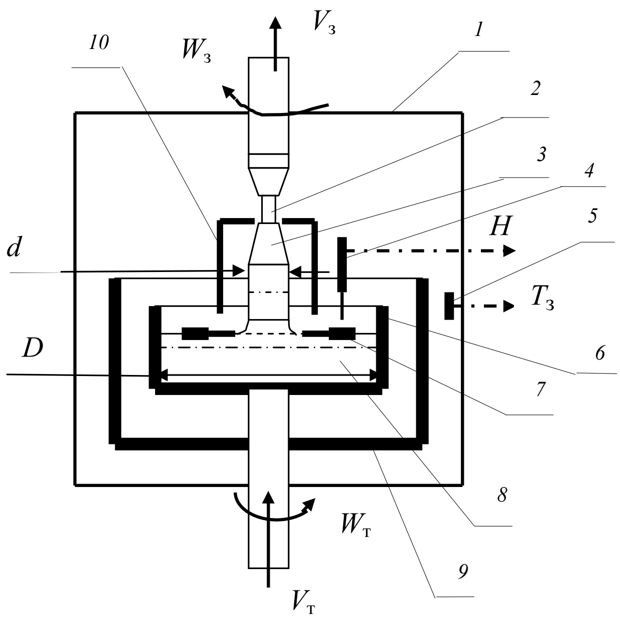

Fig. 1. Schematic of a contact measurement method: 1 – camera; 2 – seed; 3 – crystal; 4 – pin level sensor; 5 – temperature sensor; 6 – crucible; 7 – conductive screen; 8 – molten metal; 9 – heater; 10 – thermal accessories

of the contact sensor $V_{тм}/M$ determined by the expression (1) – (5), which introduced the coefficients increase the speed (C = 4) and the crucible lifting speed reduction (M = 4).

This control provides a crystal growth process periodic opening and closing of the contact sensor in the range of changes in the level of the melt about 1-2 microns.

$$V_р = V_з \cdot \frac{\rho_т}{\rho_ж} \cdot \left[\frac{d}{D}\right]^2, \tag{1}$$

$$V_{тм} = V_р \cdot \left[\frac{d_{max}}{d}\right]^2 = V_з \cdot \frac{\rho_т}{\rho_ж} \cdot \left[\frac{d_{max}}{D}\right]^2, \tag{2}$$

$$d_{max} = d_1 \cdot \frac{1}{\sqrt{1 - 1/C}}, \tag{3}$$

$$\frac{V_{тм}}{M} = V_р \cdot \left[\frac{d_{min}}{d}\right]^2 = V_з \cdot \frac{\rho_т}{\rho_ж} \cdot \left[\frac{d_{min}}{D}\right]^2, \tag{4}$$

$$d_{min} = d_{max} \cdot \frac{1}{\sqrt{M}}, \tag{5}$$

where $V_р$ – the rate of decrease of the melt in the crucible; $V_з$ – the rate of crystal growth; d – the current diameter of the crystal; D – inner diameter of the crucible; $\rho_т$ – beats. the density of the solid material; $\rho_ж$ – beats. density of the liquid material; d_1 – the nominal diameter of the crystal grown on the cylindrical part; d_{max} – maximum diameter of the growing crystal, in compliance with which the basic condition under which the sensor and the screen closeness after opening; d_{min} – the minimum allowable value of the diameter of the crystal, where the conditions of the backlog of the screen from the sensor after it has closed.

To contact method for measuring the control signal y, the amount of movement of the crucible $X_{тц}$ and the seed $X_{зц}$ for the evaluation of $T_ц$ can be represented in the form of expressions (6)(10):

$$y = X_{итц} \cdot \frac{K_у}{A \cdot B} - \frac{X_{изц}}{A}, \tag{6}$$

$$K_у = B \cdot \frac{x_т \cdot \rho_ж}{x_з \cdot \rho_т} \cdot \left[\frac{D}{d_1}\right]^2, \tag{7}$$

$$y = \frac{X_{изц}}{A} \cdot \left(\left[\frac{d}{d_1}\right]^2 - 1\right), \tag{8}$$

$$X_{зц} = X_{изц} \cdot x_з, \tag{9}$$

$$X_{тц} = X_{итц} \cdot x_т, \tag{10}$$

where A, B – scaling factors; $K_у$ – the setting of a given diameter (area) of the growing crystal; $X_{изц}$ – moving from seed sampled $x_з$; $X_{итц}$ – moving the crucible with discrete samples $x_т$; $x_з$ – sampled move seed; $x_т$ – sampled move the crucible.

Equation (8) shows the direct connection of the control signal y from the current deviation from a given chip area. During the evaluation cycle control $T_ц$ signal y is calculated in the control system for the expression (6). With the entry into the control system installation drawing setpoint diameter $K_у$ on the cylindrical part of the growing crystal is defined by a given area of cultivation.

As the hoist crucible to control the speed climbing up used open stepper drive stepper motor, which provides multiple process changes ascent rate of the crucible, at a signal from the contact level sensor.

Specifying fast $V_{тм}$ and slow $V_{тм}/M$ crucible lifting speed at the time of open and closed states of the contact sensor is produced by the expressions (11)(12):

$$X_{изрр} = P \cdot \frac{\left(1 - \frac{1}{C}\right) \cdot K_у}{B}, \tag{11}$$

$$X_{изрм} = P \cdot M \cdot \frac{\left(1 - \frac{1}{C}\right) \cdot K_у}{B}, \tag{12}$$

where $X_{изрр}$ – number of pulses seed is produced through the issuance of P pulses move the crucible with open contact sensors; $X_{изрм}$ – number of pulses seed, which is issued by P pulses move the crucible with closed contact sensors; P – the number of pulses issued by lifting the crucible to the stepper drive.

The above expressions for rate control of the crucible moving upwards as valid crucible provided movement at slow speed in the contact points of the sensor circuit of the melt (M = 4) and provided to stop raising of the crucible of the closed state of the sensor points of the melt (M = ∞).

Expression for the momentum moving $X_{изц}$ seed, the crucible $X_{итц}$ time $T_ц$ and evaluation of the control signal y can be represented as expressions (13)(14):

$$X_{изц} = \frac{X_{итц} \cdot K_у}{B}, \tag{13}$$

$$T_ц = \frac{X_{изц} \cdot x_з}{V_з} = \frac{X_{зц}}{V_з} = \frac{X_{итц} \cdot K_у \cdot x_з}{B \cdot V_з}, \tag{14}$$

where $T_ц$ – the evaluation period of the control signal (the time of processing a predetermined number of pulses $X_{итц}$).

Total movement time t in the process of closing the contact sensor in slow motion and time of the total traffic at an accelerated speed of the crucible after the opening of the sensor $t_д$, as well as the number of cycles $K_ц$ on opening and closing sensor for the evaluation period signal control $T_ц$ can be represented as expressions (15)(16):

$$t_д(d) = t \cdot \frac{\left[1 - \left(\frac{d_{min}}{d}\right)^2\right]}{\left[\left(\frac{d_{max}}{d}\right)^2 - 1\right]}, \tag{15}$$

$$K_ц = \frac{T_ц}{(t_д + t)}, \tag{16}$$

where t – while driving at slow speed crucible $V_{тм}/M$ after closing sensor for the assessment period signal management; $t_д$ – the movement of the crucible at an accelerated pace $V_{тм}$ after opening sensor for the evaluation period signal management; $K_ц$ – number of cycles of opening and closing the sensor during $T_ц$.

Schedule crucible lifting drive in accordance with the expression (15) shown in Fig. 2. Automatic control system provides a range of changes in the diameter according to the expressions (17)(19):

$$d \subset d_{mp} \ldots d_{pp}, \tag{17}$$

$$d_{pp} = d_1 \cdot \frac{1}{\sqrt{1 - \frac{1}{C \cdot \alpha}}}, \tag{18}$$

$$d_{mp} = d_{\max} \cdot \frac{\sqrt{\beta}}{\sqrt{M}} = d_1 \cdot \frac{\sqrt{\beta}}{\sqrt{M \cdot \left(1 - \frac{1}{C}\right)}}, \tag{19}$$

where d – the current diameter of the crystal; d_{pp} – maximum diameter; d_{mp} – minimum diameter; α – coefficient of maximum diameter; β – coefficient of the minimum diameter.

Expression (15) for the time of accelerated growth crucible $t_д$, for different values of the operating range of the diameter of the crystal can be represented in the form of expressions (20)(22):

$$t_д(d_{pp}) = t \cdot \frac{\left(C \cdot \alpha - \alpha - \frac{C \cdot \alpha}{M}\right)}{(\alpha - 1)}, \tag{20}$$

$$t_д(d_1) = t \cdot \left(C - 1 - \frac{C}{M}\right), \tag{21}$$

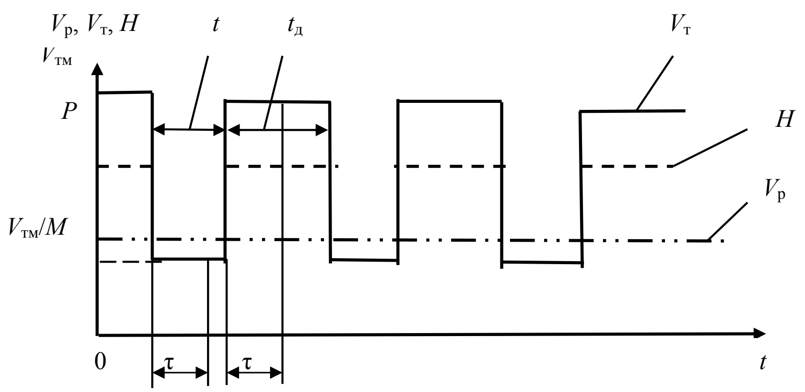

Fig. 2. Graph of formation of the crucible lifting speed: $V_р$ – the rate of decrease of the melt in the crucible; $V_т$ – the rate of rise of the crucible; H – the contact level sensor (P – sensor open)

$$t_д(d_{тр}) = t \cdot \frac{(\beta - 1)}{(M - 1)}. \tag{22}$$

If you specify a condition for the maximum reduction of the melt in contact mode control $L_р$ (1-2 microns), the expression of time delayed recovery crucible $t(d)$ will take the form of (23):

$$t(d) = \frac{L_р}{\left(V_р(d) - \frac{V_{тм}}{M}\right)} = L_р \cdot T_ц \cdot \frac{\left[\frac{d_1}{d}\right]^2}{X_{тц} \cdot \left(1 - \frac{\left[\frac{d_1}{d}\right]^2}{M \cdot \left(1 - \frac{1}{C}\right)}\right)}, \tag{23}$$

where $L_р$ – the maximum reduction in the melt; $T_ц$ – the period of the signal evaluation.

Slow ascent graph crucible $t(d)$, in accordance with the expression (23) shown in Fig. 3. Here, the estimate of the slow motion of the crucible corresponds to an extreme minimum value of the range of diameter $t(d_{mp})$ is defined as the expression (24):

$$t(d_{тр}) = \tau = \frac{L_р \cdot T_ц}{X_{тц} \cdot E}, \tag{24}$$

where $E = \frac{(\beta - 1)}{M \cdot \left(1 - \frac{1}{C}\right)}$.

The number of cycles of opening and closing $K_ц$ sensor can be represented as the expression (25), the schedule of opening and closing cycles $K_ц$ is shown in Fig. 4.

$$K_ц = \frac{X_{тц} \cdot E}{\left[\frac{L_р \cdot \left\{\left(1 - \frac{1}{C}\right) - \left[\frac{d_1}{d}\right]^2 \cdot \frac{1}{M}\right\}}{\left\{\left[\frac{d_1}{d}\right]^2 - \left(1 - \frac{1}{C}\right) + \left(C - 1 - \frac{C}{M}\right)\right\}}\right]}. \tag{25}$$

In accordance with the expressions (15) – (25) a control signal y can be represented as equations (26) – (27). In this case, at the time of closing and opening of the contact sensor in the program to pause τ, is calculated by the expression (24), during which the state of a contact sensor is not analyzed and there is a software time delay to the simultaneous movement with slow and fast speed recovery crucible. Graph signal y, in accordance with the expression (27) for different diameters of germanium crystals is shown in Fig. 5.

$$y = t_д(d) - t_д(d_1) = t_д(d) - \tau \cdot \left(C - 1 - \frac{C}{M}\right), \tag{26}$$

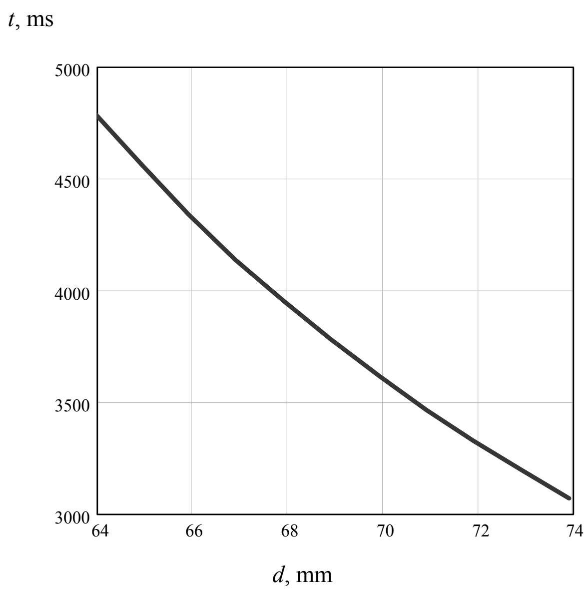

Fig. 3. Diagram of time slow motion speed when lifting the crucible t: d_1 = 70 mm; d_{pp} = 74 mm; d_{mp} = 64 mm; $L_р$ = 2 microns ; $T_ц$ = 120 000 ms; $X_{тц}$ = 100 microns

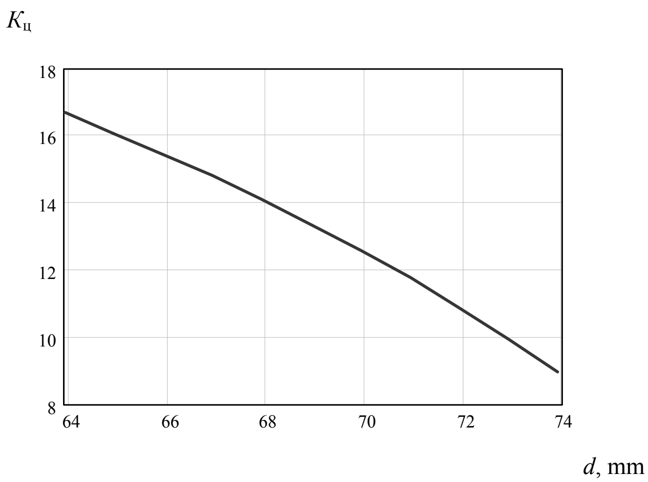

Fig. 4. Diagram of the number of cycles of opening and closing sensor $K_ц$ at: d_1 = 70 mm; d_{pp} = 74 mm; d_{mp} = 64 mm; $L_р$ = 2 microns; $X_{тц}$ = 100 microns; M = 4; C = 4

$$y = \tau \cdot \left[\frac{\left\{ \left(1 - \frac{1}{C}\right) - \left[\frac{d_1}{d}\right]^2 \cdot \frac{1}{M} \right\}}{\left\{ \left[\frac{d_1}{d}\right]^2 - \left(1 - \frac{1}{C}\right) \right\}} - \left(C - 1 - \frac{C}{M}\right) \right]. \tag{27}$$

To program the control signal in the plant stretching germanium applied timing chart control shown in Fig. 13. The proposed algorithm is that the control system at the time of closing the contact

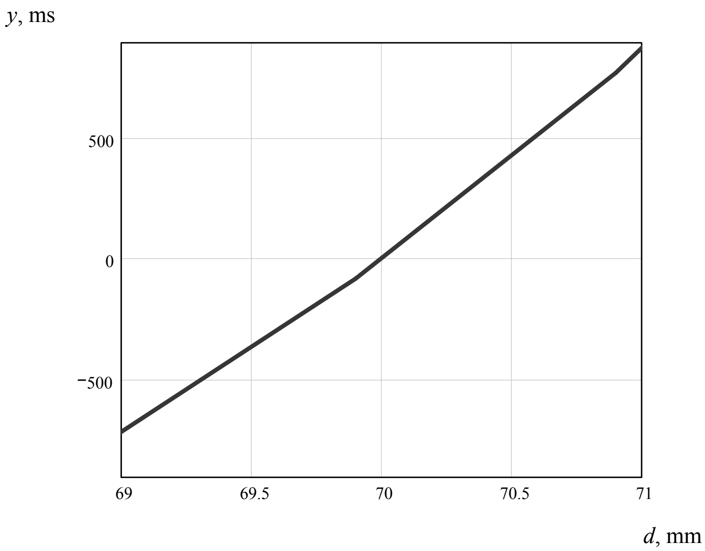

Fig. 5. Diagram of the control signal y for: d_1 = 70 mm; d_{pp} = 74 mm; d_{mp} = 64 mm; τ = 3052 ms, M = 4, C = 4

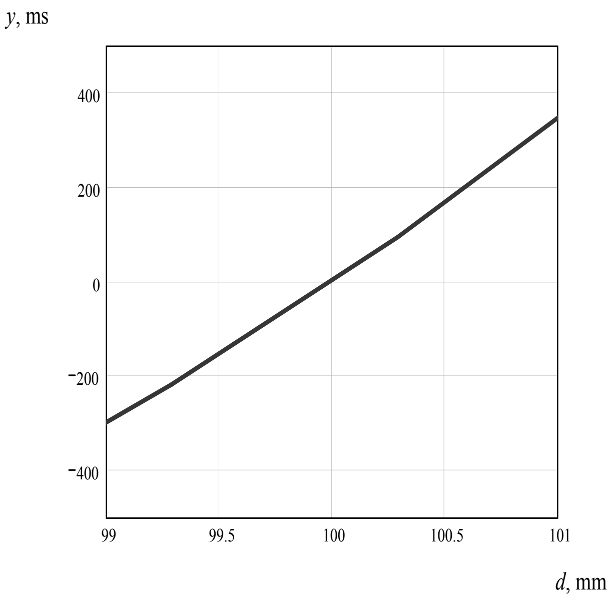

Fig. 6. Diagram of the control signal y for: d_1 = 100 mm; d_{pp} = 92 mm; d_{mp} = 106 mm; τ = 1 782 ms, M = 4, C = 4

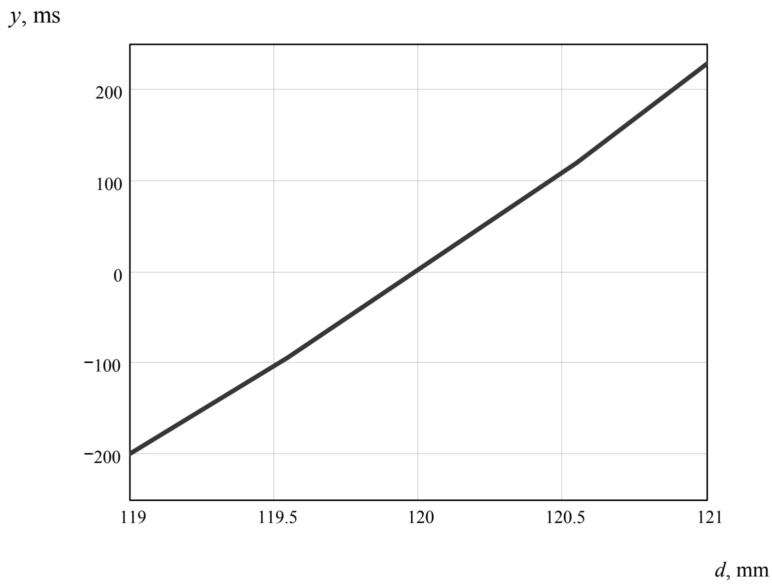

Fig. 7. Diagram of the control signal *y* for: d_1 = 120 mm; d_{pp} = 110 mm; d_{mp} = 128 mm; τ = 1 419 ms, M = 4, C = 4

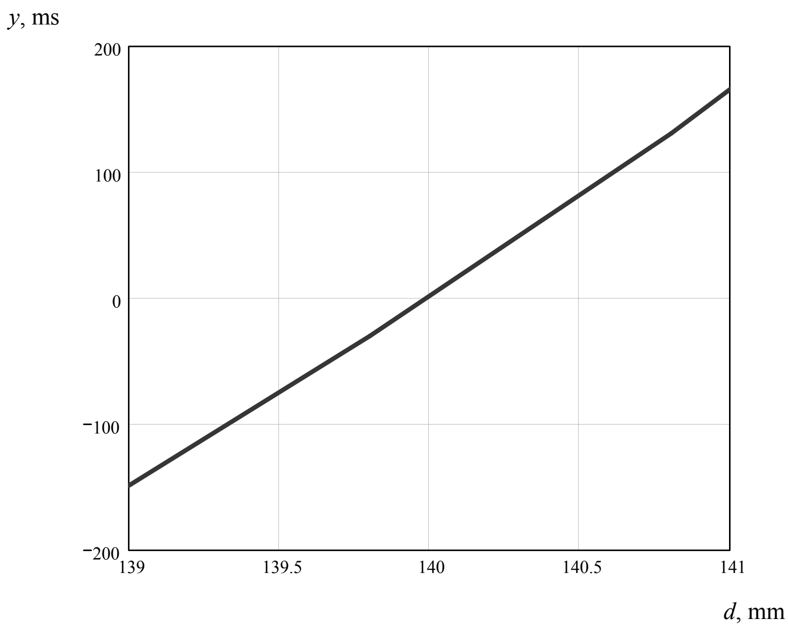

Fig. 8. Diagram of the control signal *y* for: d_1 = 140 mm; d_{pp} = 127 mm; d_{mp} = 149 mm; τ = 1 221 ms, M = 4, C = 4

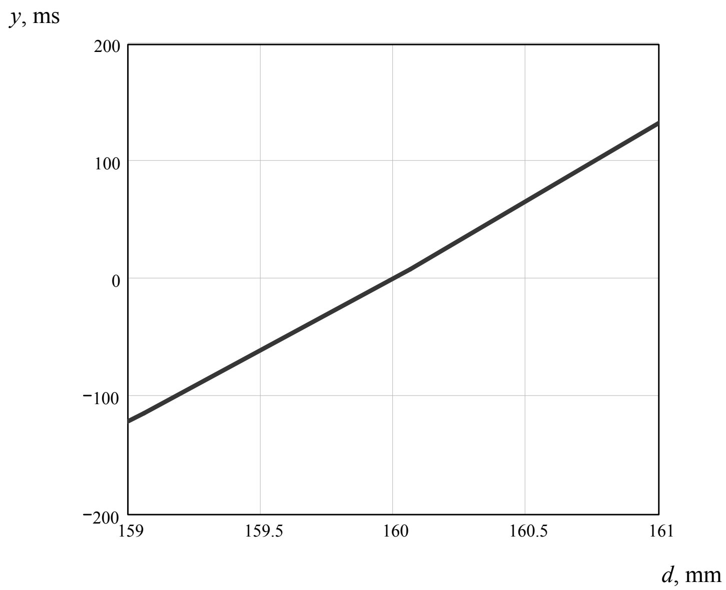

Fig. 9. Diagram of the control signal y for: d_1 = 160 mm; d_{pp} = 146 mm; d_{mp} = 171 mm; τ = 1 128 ms, M = 4, C = 4

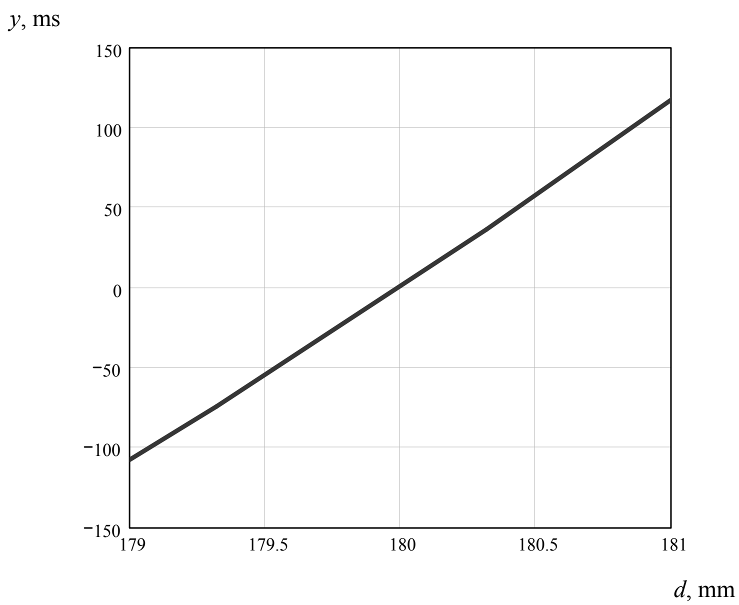

Fig. 10. Diagram of the control signal y for: d_1 = 180 mm; d_{pp} = 165 mm; d_{mp} = 192 mm; τ = 1 124 ms, M = 4, C = 4

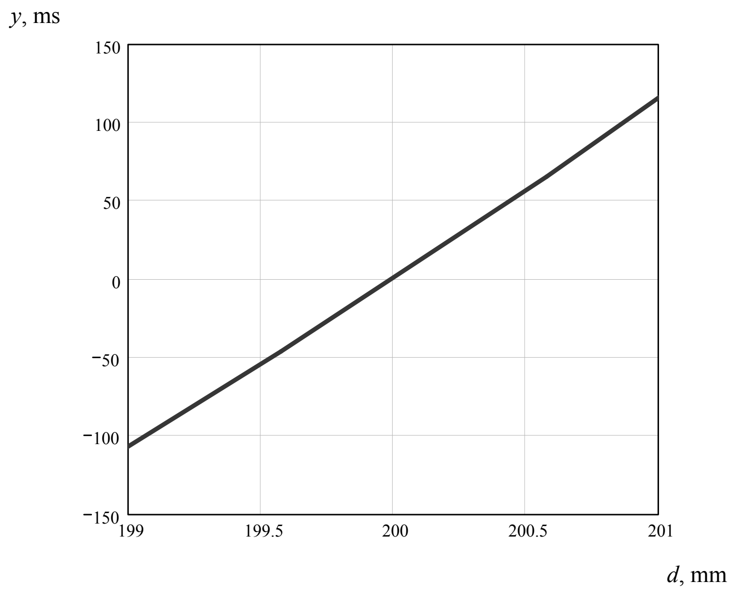

Fig. 11. Diagram of the control signal y for: d_1 = 200 mm; d_{pp} = 183 mm; d_{mp} = 213 mm; τ = 1 232 ms, M = 4, C = 4

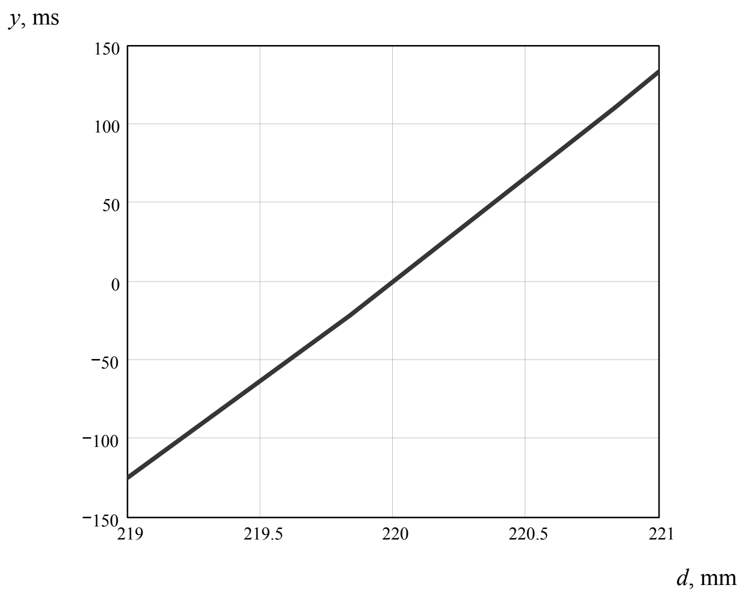

Fig. 12. Diagram of the control signal y for:d_1 = 220 mm; d_{pp} = 201 mm; d_{mp} = 235 mm; τ = 1 573 ms, M = 4, C = 4

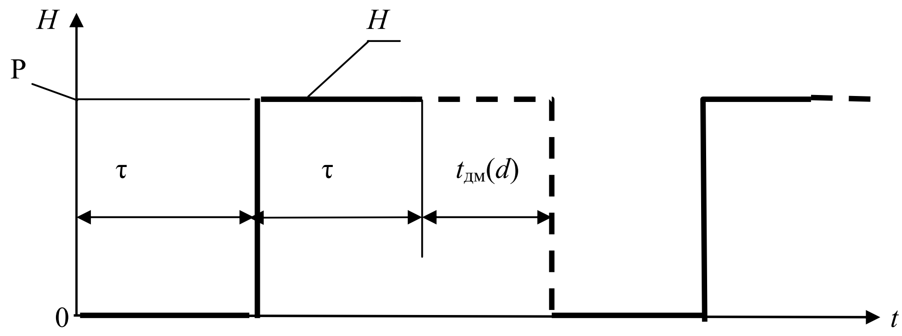

Fig. 13. Timing diagram of the sensor level: *H* – the contact level sensor (*P* – sensor open)

of the sensor should be kept soft pause τ closed and the subsequent pause τ open state level sensor. In moments of silence τ value of the state of the contact sensor control system does not analyze and manage the rise of the crucible occurs with slow and fast speed of recovery in the crucible moments "conditionally" closed and "conditional" open state level sensor.

After holding two pauses is evaluated control signal y by the expression (28) based on counting the length of the pause $t_{дм}(d)$ until the first closed state of the sensor. This control lifting up the crucible eliminates the "extra" trigger level sensor and the reaction to them in the control system, which improves noise immunity of the method of measurement.

$$y = t_{дм}(d) - \tau \cdot \{C - 2\}. \tag{28}$$

Further control signal in each y_i^* measurement cycle is subjected to averaging, during its cycle by evaluating $T_ц$ number of measurements $K_ц$ in accordance with the expression (29):

$$y_i^* = \frac{1}{K_ц} \sum_{1}^{K_ц} \left[t_{дм}(d) - \tau \cdot \{C - 2\} \right]. \tag{29}$$

The algorithm for calculation of the control signal from the expressions (28)(29), provided control without stopping the crucible at a level sensor closing the contact (when M = 4; C = 4) is applied on the cylindrical part of the growing crystal (for control and stabilization of the current chip area), due to the introduction of an integrated management system and the proportional component of the control signal on channels of temperature and the crystal growth rate, respectively.

Growing on the plot of the direct and inverse cone crystals used algorithm for calculating a control signal by the expression (6) with the complete stop of lifting of the crucible in the closed condition of the sensor points of the melt (at M = ∞, C = 4). A control signal at the same time use only as the control information on the current area of the growing crystal, and of the shape of farmed cones made indirectly, through input from the memory of the control of the controller software by scheduling the change in temperature and the rate of crystal growth.

Basic principles of setting temperature and rate of growth of semiconductor crystals, based on the geometry of the crystal, its thermal properties and thermal conditions of crystal growth (axial gradient in the solid part of the crystal during growth) are given in [5].

Schedule change control signal, which is calculated based on the above given measurement model, drawing on the installation of a single crystal of germanium is shown in Fig. 14, and Fig. 15 and Figure 16 shows the form of graphite floating screen, a level sensor and melt grown crystals of germanium.

Graphite sensor working growth vessel for growing a crystal of germanium is an insulating quartz tube and closes relative floating on the melt surface in a crucible of graphite of the screen to the housing

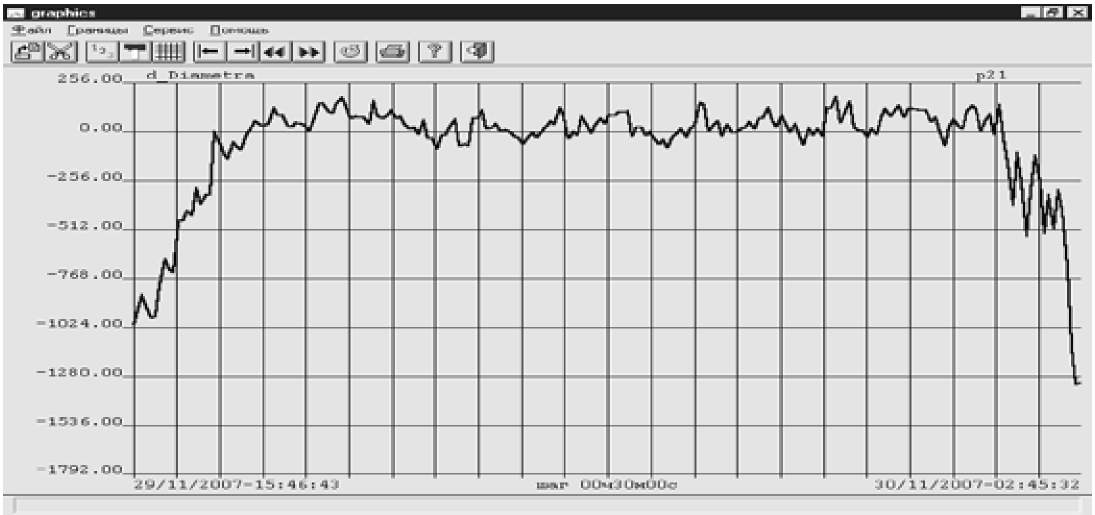

Fig. 14. Diagram of the control signal y (d_Diametra)

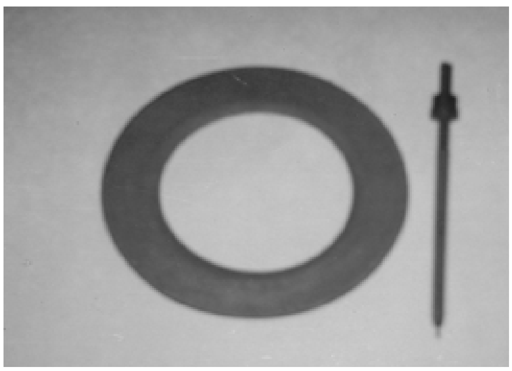

Fig. 15. Floating screen graphite graphite melt level sensor

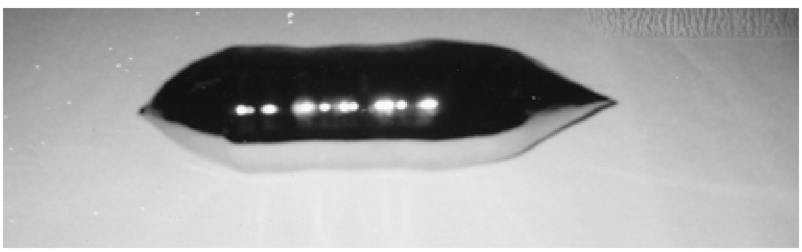

Fig. 16. Cast germanium diameter 104 mm

unit. Analyze the contact sensor circuit conditions of the melt on the installation housing is possible due to the fact that the germanium melt in the crucible has a significant conductivity.

An additional condition in this method of measurement is the condition of continuous rotation floating graphite screen that is provided by fabricating ultra-light graphite needles at the end of the sensor (Fig. 15), which is tapered in a free state under its own weight goes down in one and the the same point of tangency, and upon touching the sensor screen, the screen can rotate freely in the crucible with a speed of rotation of the crucible.

Test check of the control system on the installation drawing germanium was performed through a special program mode of the control system and was intended to test the functioning of the measuring system, with an open chamber furnace (no mode crystal pulling from the melt). The algorithm for calculation of the control signal thus asked by the expression (6) with the complete stop of lifting of the crucible in the closed condition of the sensor points of the melt.

The scheme of the test checks the installation is shown in Fig. 17. The test system microprocessor control checks on the plant consists in the fact that the system without metal open chamber at a complete stop of rotation of the crucible and a seed sensor graphite layer through the insulator fixedly secured to the rod and the seed is introduced into contact with the bottom of the crucible for receiving the housing of the sensor circuit unit.

After that, the control system of the program set out a number of test setpoint diameter $K_{у}$ (16, 18, 20, 22), with a period of change jobs every 30 minutes, and then include the step drive crucible lift up and set the test speed of crystal growth $V_{з} = 0{,}2$ мм/мин.

With proper operation of all control systems takes delivery of graphs (Fig. 18) shows the change of the control signal y, calculated by the expression (6).

When checking a test without pulling the metal due to the “conditional” equality ($\rho_{ж} = \rho_{т}$) setpoint $K_{у}$ for germanium crystals can be represented as:

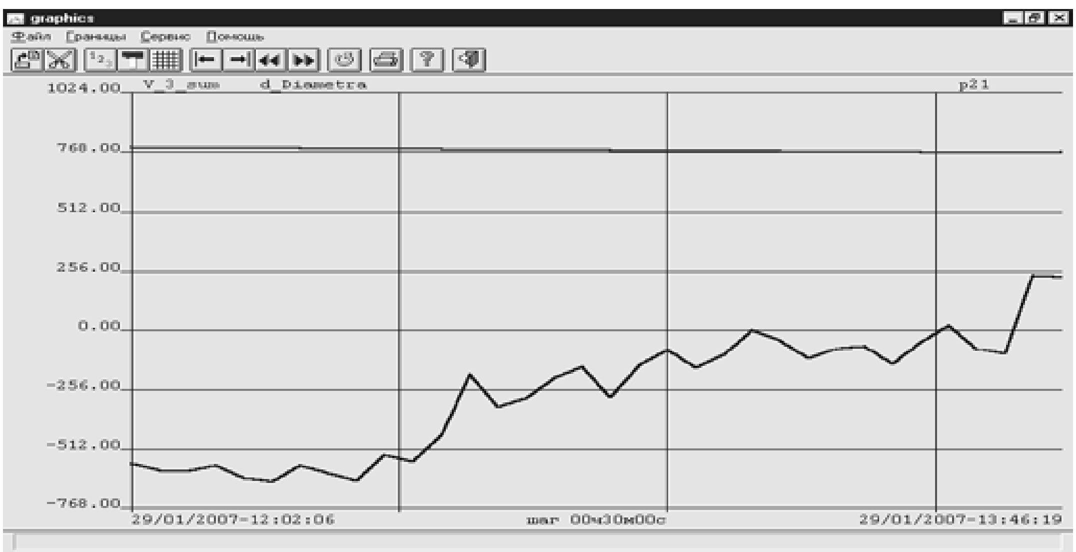

Fig. 17. Scheme of the test setup: 1 – camera; 2 – insulator melt level sensor; 3 – pin level sensor; 4 – crucible; 5 – rod crucible; 6 – seed stock

$K_{y=} 20 [D/d_1]^2$,

where d_1 – diameter of the cylindrical part of the grown crystal.

When growing crystals of germanium melt on the existing installation (due to inequality $\rho_ж \neq \rho_т$) setpoint Ku will be given in the form:

$K_{y=} 19 [D/d_1]^2$.

Zero control signal ($y = 0$) is fixed on the chart by setting the value equal to the setpoint K_y 20 (at $D = d_1$). Thus, the growth rate of the crystal and the crucible lifting is equal, and the process of validation testing takes to open and close a level sensor for the amount of movement L_p = 1-2 microns.

Testing allows you to test the functionality of the control system in the open position the camera without installing metal and crystal pulling mode.

Advantage of this method of control area for the growing crystal germanium material is the fact that during the growth of single crystals of many brands in the insulated (low gradient conditions) in the section of the crystal is not that round shape, so crystallographic direction of Germany “111” brings him closer to the triangle in cross-section, and the direction of the “100” to square. All this leads to great difficulties in controlling crystal diameter grown by conventional optical process monitoring and control of the crystal diameter, processing the digital camera of the crystal shape of the meniscus, which is due to reflection of illumination at the meniscus of the growing crystal brighter regions oven chamber and having a complex geometric shape, virtually all types of materials grown using the Czochralski method.

For ultrapure materials in the production are widely followed as an additional method of cultivation of the liquid melt in the growth vessel Czochralski method. For the cultivation of ultrapure materials of copper and aluminum has been successfully applied this method for monitoring and control of the current area of the crystal, with a contact sensor liquid level in the form of a floating screen and isolated

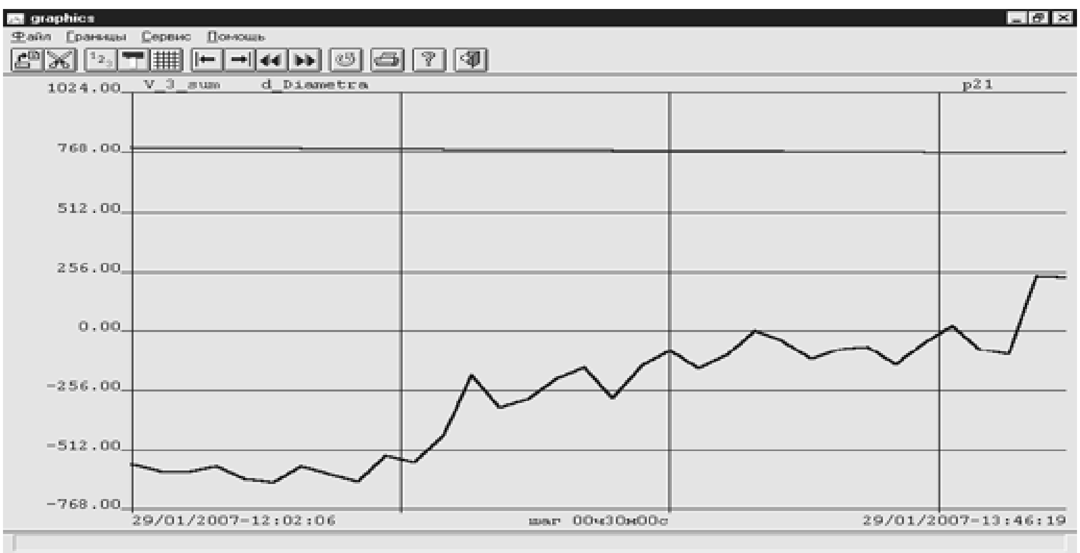

Fig. 18. Testing the Installation Schedule: $V_з$ – drawing speed; K_y – setting the diameter; y (d Diametr) – control signal

graphite rod with a needle. Given the very low luminosity halo meniscus materials for copper and aluminum, the use of them controls the optical diameter of the crystal has become almost impossible.

Findings

For grown from molten liquid crystals using the Czochralski method, the mathematical model of the current control chip area, based on the control-circuit conditions contact sensor melt level in the crucible.

The model allows, through programmable intervals closed and open states of the level sensor to calculate the control signal, as the difference in time to first closed state of the melt level sensor and the previous time delay, allowing you to determine the accuracy of the current deviation from the given chip area better than 1%.

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