

Growth chamber gas dynamics in Cz silicon single crystal growth process

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Abstract

Mathematical simulation results for inert gas (argon) dynamics in the rarefied atmosphere of Redmet-10 Cz single crystal silicon growth furnace chamber have been reported. Gas flows in cold (room temperature) and hot (growth process) chambers have been analyzed. Convective gas flows have been considered for two growth chamber gas supply options: basic supply, i.e., through the top central inlet hole only, and combined, i.e., with additional gas supply through the lateral inlet hole. Gas outlet is through the growth chamber bottom outlet hole for both options. For the cold chamber option, forced convection has been studied using the incompressible ideal gas model. For hot chamber, both the non-isothermal compressible ideal gas model and the weakly compressible gas model in the Boussinesq approximation have been used for studying the vortex structure produced by a joint action of forced and thermal-gravitational convection. The effect of different gas inlet methods on the convective transport of silicon monoxide evaporating from the free melt surface has been discussed.

Keywords

Czochralski method, gas dynamics, argon, modeling, silicon monoxide

1. Introduction

Silicon single crystals are grown using the Czochralski method at a reduced pressure in an inert gas (argon) atmosphere for avoiding or minimizing the effect of accompanying chemical reactions on the process. One important chemical reaction occurs in the silicon melt due to the dissolution of the quartz crucible resulting in the formation of silicon monoxide. The vapor-gas mixture of argon with silicon and carbon monoxides produces coagulated microparticles that deposit on the inner components of the growth chamber thus reducing their service life. The concentration of silicon monoxide in the vapor-gas mixture above the melt surface affects the intensity of its

evaporation from the melt thus changing the oxygen content in the growing single crystal. Therefore studying gas dynamics in the growth chamber is important.

Publications on the topic can be divided in three groups: theoretical ones that are based on the physical representation of mass exchange during crystallization, calculations on the basis of mathematical models that may have different degrees of completeness, and technological studies the novel results of which are disclosed in patents on growth chamber gas dynamics control.

Monographs [1, 2] can be referred to the first group of reports. The former work [1] dealt with the origins of incidental (non-doping) impurity introduction into growing crystals during Cz crystallization. It was stressed that

the single crystal silicon oxygen contamination source is the quartz crucible whose walls react with the silicon melt during growth to form free atomic oxygen in the melt bulk which is trapped by the growing single crystal silicon. Quartz dissolution in silicon melt occurs by the reaction $\text{SiO}_2 + \text{Si} = 2\text{SiO}$.

The intensity of crucible dissolution and oxygen transfer to the melt depends on the crucible and melt contact surface, crucible inner surface condition and convection flows in the melt. Volatile silicon monoxide SiO forms on the free melt surface and evaporates to the growth chamber space. It is recommended to accelerate this evaporation by blowing the melt surface with an inert gas (argon). Technological problems caused by oxygen and carbon contamination of silicon single crystals were addressed in [2]. It was shown that the oxygen-rich silicon melt layer at the crucible walls is transferred to the sub-crystal region by convection. Oxygen in the form of SiO is a volatile impurity which evaporates intensely upon reaching the melt surface. The evaporation rate is the highest in the vicinity of the crucible walls and decreases closer to the sub-crystal region. Carbon sources in single crystal silicon were also discussed. They include graphite heater components and graphite screens used for developing the optimum thermal conditions of growth. Carbon monoxide CO forms as a result of chemical interaction between the graphite crucible support and the quartz crucible by the reactions $3\text{C} + \text{SiO}_2 \leftrightarrow \text{SiC} + 2\text{CO}$ and $\text{C} + \text{SiO}_2 \leftrightarrow \text{SiO} + \text{CO}$ as well as between oxygen penetrating into the chamber through the sealing and chamber fittings $2\text{C} + \text{O}_2 \leftrightarrow 2\text{CO}$ and between silicon monoxide SiO and chamber fittings $2\text{C} + \text{SiO} \leftrightarrow \text{SiC} + \text{CO}$.

The formation of a vapor-gas mixture of cold argon, hot silicon monoxide SiO, carbon monoxide CO and other volatile compounds above the melt in the chamber causes their coagulation in microparticles that deposit onto relatively cold inner chamber surfaces or are transferred by convective flows in the chamber space to the melt surface and enter the crystallization region thus interrupting the growth of dislocation-free single crystals.

The second group of works includes reports on the mathematical simulation of gas dynamics for different Cz growth chamber designs and various gas flow intake and outlet options. A growth chamber design was presented [3] delivering power and argon consumption reduction. It was noted that the pulling rate was significantly increased and the oxygen content in silicon was considerably reduced while retaining the quality of the as-grown single crystals. A review of works dealing with the calculation of melt and gas flows, oxygen transfer in the melt and SiO transfer in the growth chamber was published [4]. Numerical calculations and growth experiments were carried out for studying the effect of pulling rate and crystal and crucible rotation speed on the oxygen distribution in growing single crystal silicon. Experiments showed that the oxygen concentration in the single crystal increases with SiO partial pressure in the vapor-gas mixture. A numerical calculation was reported [5] for carbon

and silicon oxide deposition on the screen and heater surfaces during growth. Chemical reactions on the screen and heater surfaces were analyzed depending on the argon consumption and growth chamber pressure. The calculation results were confirmed by growth experiments. Numerical simulation allowed optimizing the heating unit design. Another numerical calculation [6] dealt with the effect of argon flow rate on the oxygen concentration in large diameter silicon single crystals (200 mm). The effect of argon flow rate on the structure of melt flows and oxygen concentration at the crystallization front was studied. It was shown that oxygen transfer depends on convective flows in the melt. The oxygen concentration at the crystallization front was shown to decrease with an increase in argon consumption. Optimum argon consumption for minimizing the oxygen concentration in the melt was recommended. Conjugated heat exchange in the top part of the growth chamber was studied using a simplified model for the Czochralski process [7]. It was shown that crystal rotation makes the convective flows unstable and produces secondary vortices that effectively cool the growing crystal. A review of numerical simulation works dealing with impurity transfer in the growth chamber for Cz silicon single crystal growth was reported [8]. Among other problems, chamber top central gas inlet and chamber bottom central gas outlet options were considered. CO concentrations above the melt and in the outlet hole were reported depending on the growth chamber gas pressure. It was shown that the CO concentrations increase with pressure and that the CO concentration is higher in the outlet hole than above the melt. It was stressed that the CO concentrations at both those points decrease with an increase of gas blowing rate.

The third group of works includes patents and technical reports describing design and gas inlet/outlet novelties and changes in growth chamber fittings and materials.

The latter group includes US Patents [9, 10] disclosing novelties in foreign Cz growth chambers having conventional chamber top central gas inlet holes and bottom central gas outlet holes but differing in specific shapes of heat screens near the crystal that control gas flows and therefore require special simulation.

RU Patent [11] suggested a new growth chamber inert gas supply method from the bottom and removal of established gas flow with the vapor-gas mixture forming above the melt. The inert gas flow supplied to the chamber from the bottom under the crucible is directed upwards along the crucible walls through a porous fine-grained heat insulating material filling layer that heats the gas and increases its volume. As a result, the overall gas consumption is lower. The authors state that the gas flow provides for heat removal from the heat insulating filling layer thus reducing cooling water consumption in the chamber sheath and heater power consumption.

Technical publication [12] described in detail the Cz single crystal silicon growth process for Redmet-10 industrial growth furnaces which was improved by using two instead of one argon gas flows in the heating unit. The

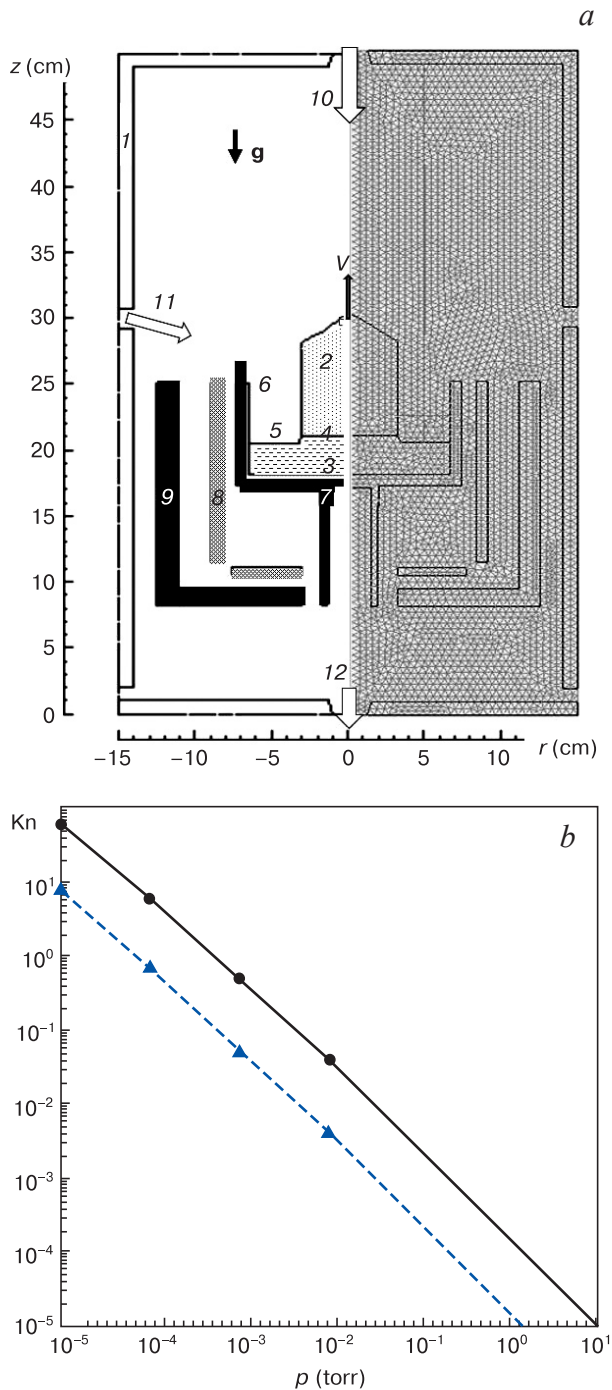


Figure 1. (a) To the left of the axis: Redmet-10 furnace growth chamber components. (1) water-cooled steel shell, (2) silicon single crystal, (3) silicon melt, (4) crystallization front, (5) melt free surface, (6) quartz crucible, (7) graphite crucible support, (8) resistive heater, (9) graphite screen, (10) top central gas inlet port, (11) additional lateral gas inlet hole, (12) bottom central gas outlet hole. White arrows show gas inlet and outlet directions, black arrow shows crystal pulling direction from melt at speed V . To the right of the axis: triangle components calculation grid; (b) Knudsen number (Kn) for argon as a function of static pressure (p , torr). Symbols show earlier data [14] (triangles) for $T = 300$ K and (circles) for $T = 2400$ K.

main flow (15–20 sl/min) is supplied from the top central hole downwards to circumvent the growing crystal. The second additional flow (1.5–2 sl/min) is supplied from inlet holes arranged inside the heating unit so that their nozzles are located close to the melt at a 45 deg angle to the melt surface. The nozzles are evenly spaced at the melt perimeter, their number being seven for providing axially symmetrical gas supply. The chamber pressure during growth was maintained at 10 mm hg (1.33 kPa). The additional gas flows were shown to provide for more intense evaporated oxygen removal from the melt in the form of SiO .

This work deals with the innovative additional lateral gas supply method suggested in the above-cited earlier work [12]. Numerical simulation of growth chamber gas dynamics was carried out for the Redmet-10 growth furnace. The methodical approach to a conjugate simulation of heat and mass transfer processes for Cz silicon single crystal growth [13] was added with growth chamber low pressure inert gas flow simulation tools.

2. Mathematical model

The growth chamber design of the Redmet-10 industrial growth furnace for Cz silicon single crystal growth is shown in Fig. 1. The chamber is deemed to be axially symmetrical and have a 28.2 cm inner diameter, a 0.8 cm wall thickness and a 50 cm height. The crucible has a 25.9 cm inner diameter, the melt height being 2.5 cm. The total crystal length is 9 cm, the crystal diameter is 6 cm and the pulling rate is 1 mm/min.

The crystal is grown in a rarefied atmosphere at 14 torr. The argon is blown downwards (main supply) and in combination with lateral inlet (additional supply). The gas flow rate is substantially below the speed of sound (e.g. the speed of sound in argon gas is 319 m/s at 273 K). For rarefied gas dynamics, it is of fundamental importance to know the ratio of the free path length of gas molecules between collisions l and the effective flow size L , i.e., the Knudsen number: $Kn = l/L$.

Classical gas dynamics rules hold for $Kn \ll 1$ since in this case the gas parameters change but slightly within the free path length, and collisions between molecules produce, in the vicinity of each collision point, a local close-to-equilibrium state that can be described by the macroscopic parameters of density, speed and temperature. One can therefore represent the gas as a continuous media having the thermophysical properties of viscosity, heat conductivity, diffusion etc. According to earlier data [14], the Knudsen number at $P = 10$ torr is quite low: $Kn = 10^{-6}$ at $T = 300$ K and $Kn = 10^{-5}$ at $T = 2400$ K (Fig. 1b), allowing one to consider argon gas in the growth chamber as a continuous media obeying the equations of continuity and the transfer of moment of motion, heat and impurities. The model takes into account the “condition of sticking” of gas to walls and solid components of the growth chamber.

The mathematical simulation of heat and mass transfer for the Cz process was carried out using the *Crystmo/Marc* software package [15] and included 2 stages.

At the first stage, the conjugate heat exchange in the crystal-melt system and at the solid components of the growth chamber was calculated in accordance with an earlier method [13]. The calculation took into account the heat convection in the melt, melt crystallization, conductive heat transfer in the solid bodies (the crystal, the heater, the heat screens etc.) and thermal radiation between their open surfaces that were considered to be diffusive grey. The melt was considered as a Newton liquid, its free surface deformation being ignored. Melt motion was described with the Navier–Stokes equations for a viscous incompressible liquid having temperature-dependent thermophysical properties, i.e., viscosity, heat conductivity and heat capacity. Melt crystallization was taken into account in the assumption that there is a transient fraction between the crystal (the solid fraction) and the melt (the liquid fraction). The transient fraction was taken to be the crystallization region the temperature of which is slightly above the solidus temperature but lower than the liquidus temperature. The convective oxygen diffusion equation was solved taking into account the calculated velocity field in the melt.

At the second stage the *Crystmo/Marc* software package was added with two transient equation solution modules describing the flow and heat exchange on the basis of the ideal gas model [16] with the equation of state in which the density ρ is determined as follows: $\rho = pm/RT$, where $R = 8.314 \cdot 10^7$ erg/(mole·K) is the gas constant and $m = 39.948$ g/mole is the molecular weight of argon. Since gas flow consideration changed the thermal balance in the growth chamber calculated at the first stage, final thermal balance was achieved by means of corrective iterations of the radiation and conduction heat exchange in the growth chamber.

The mass conservation equation and the moment, heat and impurity transfer equations for gases are written as follows:

- the mass conservation equation:

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \mathbf{v}) = 0; \quad (1)$$

- the moment transfer equation for ideal gas:

$$\frac{\partial}{\partial t}(\rho \mathbf{v}) + \nabla(\rho \mathbf{v} \mathbf{v}) = -\nabla p + \nabla \tau + \rho \mathbf{g}; \quad (2)$$

– the moment transfer equation in the Boussinesq approximation for which the constant gas density ρ_0 is set in accordance with the gas rarefaction level and the local temperature change is low in comparison with the reference value T_0 from which local temperature is counted, i.e., $(T - T_0) \ll T_0$:

$$\frac{\partial \mathbf{v}}{\partial t} + \nabla(\mathbf{v} \mathbf{v}) = -\frac{1}{\rho_0} \nabla p + \nabla \tau + \mathbf{g} \beta_T (T - T_0), \quad (3)$$

where τ is the tensor of stress which is deemed to be uniform and spatially isotropic, and there is a linear dependence between the tensor of stress and the tensor of strain rate:

$$\tau = \mu \left[(\nabla \mathbf{v} + \nabla \mathbf{v}^T) - \frac{2}{3} \nabla \mathbf{v} I \right];$$

- the heat transfer equation:

$$\frac{\partial}{\partial t}(\rho c_p T) + \nabla(\rho c_p \mathbf{v} T) = \nabla(\lambda \nabla T); \quad (4)$$

- the impurity transfer equation:

$$\frac{\partial}{\partial t}(\rho C) + \nabla(\rho \mathbf{v} C) = \nabla(D \nabla C). \quad (5)$$

Here $\mathbf{v}$ is the velocity, $\rho \mathbf{g}$ is the gravity force, μ is the dynamic viscosity coefficient, λ is the heat conductivity coefficient, c_p is the heat capacity coefficient, I is a unity tensor, $\mathbf{g}$ is the gravity vector, C is the molecular concentration and D is the molecular diffusion coefficient of SiO in the gas.

For Eqs. (1)–(3) the velocity boundary conditions corresponded to the condition of gas sticking to solid surfaces and the inlet/outlet flow rates at the inlet and outlet holes. The temperature boundary conditions in Eq. (4) were set as described above, i.e., based on the solution of the conjugate thermal task without account for gas dynamics, and then corrected by iteration until establishment.

For the oxygen impurity transfer model in silicon melt, it was assumed that the quartz crucible is dissolved: in the melt, released molecular oxygen is trapped by the growing crystal at the crystallization front, and on the free melt surface, oxygen in the form of silicon monoxide evaporates to the gas atmosphere. For studying the effect of different gas flow convection modes on silicon monoxide transfer in the growth chamber, it is accepted that, as a result of inner processes in the melt, the silicon monoxide concentration on the melt surface reaches C_0 [18]. This value is used as a scale unit for dimensionless concentration, and therefore for practical calculations using Eq. (5) the dimensionless concentration value $C = 1$ was set for the melt surface and $C = 0$ was accepted for the gas inlet holes. For the gas outlet hole, the silicon monoxide convective outlet condition was set.

The calculations were carried out in this work both for the ideal gas model and for the Boussinesq model. Comparison between the respective calculation results did not reveal any qualitative differences in the gas flow structure, isotherm distributions and silicon monoxide transfer in the growth chamber. Below is a detailed discussion of the Boussinesq model calculation results.

The physical parameters of argon gas were assumed to be linearly dependent on temperature, i.e., $\mu = \mu(T)$, $\lambda = \lambda(T)$, $c_p = c_p(T)$. Note that the equation of state for ideal gas is applied to an equilibrium condition of a system of non-interacting particles, although the heat conductivity coefficient describes the non-equilibrium process of

Table 1. Parameters of argon at $T = 1000$ K and $p = 14$ torr

Density	Heat capacity coefficient	Heat conductivity coefficient	Dynamic viscosity coefficient	Heat expansion coefficient	SiO diffusion coefficient
ρ (g/cm ³)	c_p (erg/(g·K))	λ (erg/(cm·s·K))	μ (P)	β_T (1/K)	D (cm ² /s)
$8.94 \cdot 10^{-6}$	$5.2 \cdot 10^6$	2500	$5.02 \cdot 10^{-4}$	10^{-3}	7.73

thermal balance establishment and viscosity describes molecular interactions. Viscosity and heat conductivity are described using the Chapman–Enskog kinetic theory of gases based on the Leonard–Jones molecular interaction potentials. The heat conductivity, dynamic viscosity and specific heat capacity coefficients were set linearly dependent on temperature in accordance with reference data on thermophysical values [19, 20].

For the Boussinesq model, it is important to know the volume heat expansion coefficient of the gas. Its value is calculated by substituting the ideal gas equation of state into the definition of the volume heat expansion coefficient:

$$\beta_T = \frac{1}{V} \left(\frac{\partial V}{\partial T} \right)_p = \frac{1}{V} \left(\frac{R}{p} \right) = \frac{1}{T}.$$

For example, at $T = 1000$ K, the following value is obtained: $\beta_T = 1/T = 10^{-3}$ 1/K. The density of argon at $p = 14$ torr and $T = 1000$ K can also be evaluated from the equation of state:

$$\rho = \frac{pm}{RT} = 8.94 \cdot 10^{-6} \text{ g/cm}^3.$$

In accordance with the kinetic theory, the temperature and pressure dependences of the silicon monoxide diffusion coefficient can be written as follows:

$$D = aT^{1.5}/p,$$

where $a = 3.42 \cdot 10^{-3}$ torr·cm²/(s·K^{1.5}) and $D = 7.73$ cm²/s at $T = 1000$ K and $p = 14$ torr. Note that the SiO diffusion coefficient in argon was set using the following expression [4]:

$$D = bT^{1.75}/p,$$

where $b = 8.626 \cdot 10^{-2}$ torr·cm²/(s·K^{1.5}), which at $T = 1000$ K and $p = 14$ torr yields a value close to the above one: $D = 2.09$ cm²/s.

By way of example, Table 1 shows the calculated thermophysical parameters for constant temperature and pressure.

3. Calculation results

Below two gas flow cases are considered: (1) in a cold growth chamber (at room temperature) and (2) in a heated growth chamber (under conditions of growing a silicon single crystal). Calculation results for silicon monoxide concentration are analyzed for the second case. The gas

flow in the growth chamber is calculated for both options in the assumption of gas inlet only from the top central inlet hole at a 200 cm/s flow rate (38 sl/min) and for additional gas inlet from the lateral chamber inlet hole at the rate $V_{\text{in-lat}} = 10$ cm/s.

3.1. Gas flow in cold growth chamber

The main gas supply through a small (2 cm diam.) top central inlet hole for cold growth chamber (Fig. 2a) is in the form of a high-velocity axial jet ($V_{\text{in}} = 200$ cm/s). The gas jet flows downwards along the conical part of the growing crystal and changes direction from vertical (downwards) to tilted depending on the crystal cone angle. The gas jet produces a secondary vortex with the same rotation direction in the lateral part of the top chamber section. There is an inner cavity between the crucible

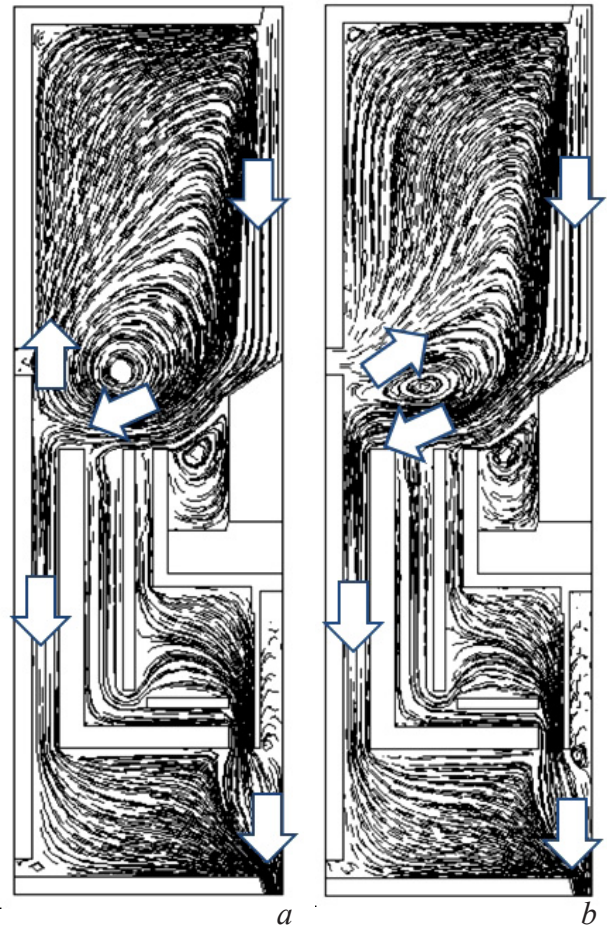


Figure 2. Gas flow in cold growth chamber: (a) central gas inlet only, $V_{\text{in}} = 200$ cm/s and (b) combined central and lateral gas inlet at $V_{\text{in}} = 200$ cm/s and $V_{\text{in-lat}} = 10$ cm/s

side wall and the crystal side surface. The gas jet circumvents that cavity in the top part of the chamber without penetrating inside it but causing the formation of a weak secondary vortex, i.e., gas flow downwards along the crucible side wall and gas flow upwards along the crystal side wall. Then the gas flows downwards in the gaps between the graphite crucible support, the heater and the lateral and bottom screen assemblies and is outlet through the central gas outlet port in the growth chamber bottom.

If gas is additionally supplied through 0.9 cm diam. lateral inlet holes (Fig. 2b) at $V_{\text{in-lat}} = 10$ cm/s, the main jet flow undergoes changes, e.g. in the flow structure near the lateral gas inlet hole. However, the general gas flow remains substantially the same.

3.2. Gas flow in hot growth chamber and its effect on silicon monoxide transfer

Heat release from the heater causes heat radiation towards other growth chamber components: the crystal, the crucible assembly with melt, the heat screens, the chamber walls etc. Thermal-gravitational convection occurs in the gravity field of the melt and the gas atmosphere. We consider the effect of that convection on the forced gas flow as described in the previous section.

It is of interest to make a criterion-based estimation of the effects of thermal-gravitational and forced (gas inlet) convection. In accordance with the Table 1 and given the gas inlet flow rate through the top central gas inlet hole $V_{\text{in}} = 200$ cm/s, one can provide a preliminary estimate of the identity criteria: $Gr = \rho^2 g \beta_T \Delta T L^3 / \mu^2 = 1.5 \times 10^3$ is the Grashof number, $Pr = \mu c_p / \lambda = 2.6$ is the Prandtl number and $Re = \rho V L / \mu = 7.2$ is the Reynolds number. The parameter γ is used for estimating the ratio between the thermal-gravitational and forced convection. Its next estimate indicates a greater contribution from thermal-gravitational convection: $\gamma = Gr/Re^2 = 7.5 > 1$. Considered below are numerical simulation results.

Thermal-gravitational convection has a penetrating nature. It generates a vortex above the top heater surface and the crucible assembly between which radiation heat exchange is established. This vortex propagates upwards, covers the entire top part of the chamber adjacent to the chamber side wall and changes the direction of the jet from the top central inlet hole (Fig. 3a). The vortex hovers above the inner cavity between the crucible side wall and the crystal side surface in which the weaker secondary vortex rotates in the direction opposite to that for cold chamber, i.e., when gas flows downwards along the crystal side surface and upwards along the crucible side wall.

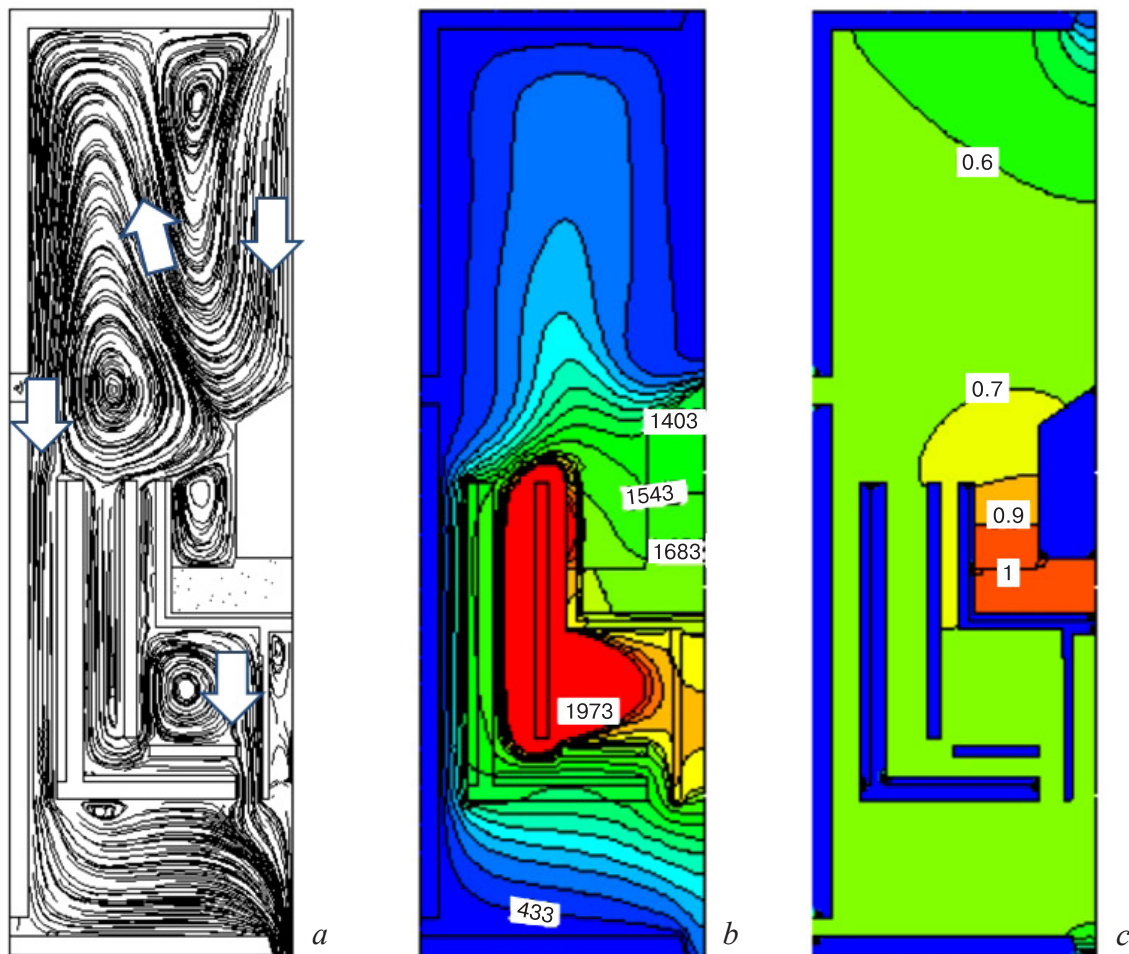


Figure 3. Central gas inlet in hot growth chamber at $V_{\text{in}} = 200$ cm/s: (a) gas flow, (b) isotherms and (c) silicon monoxide concentration contourlines (C/C_0)

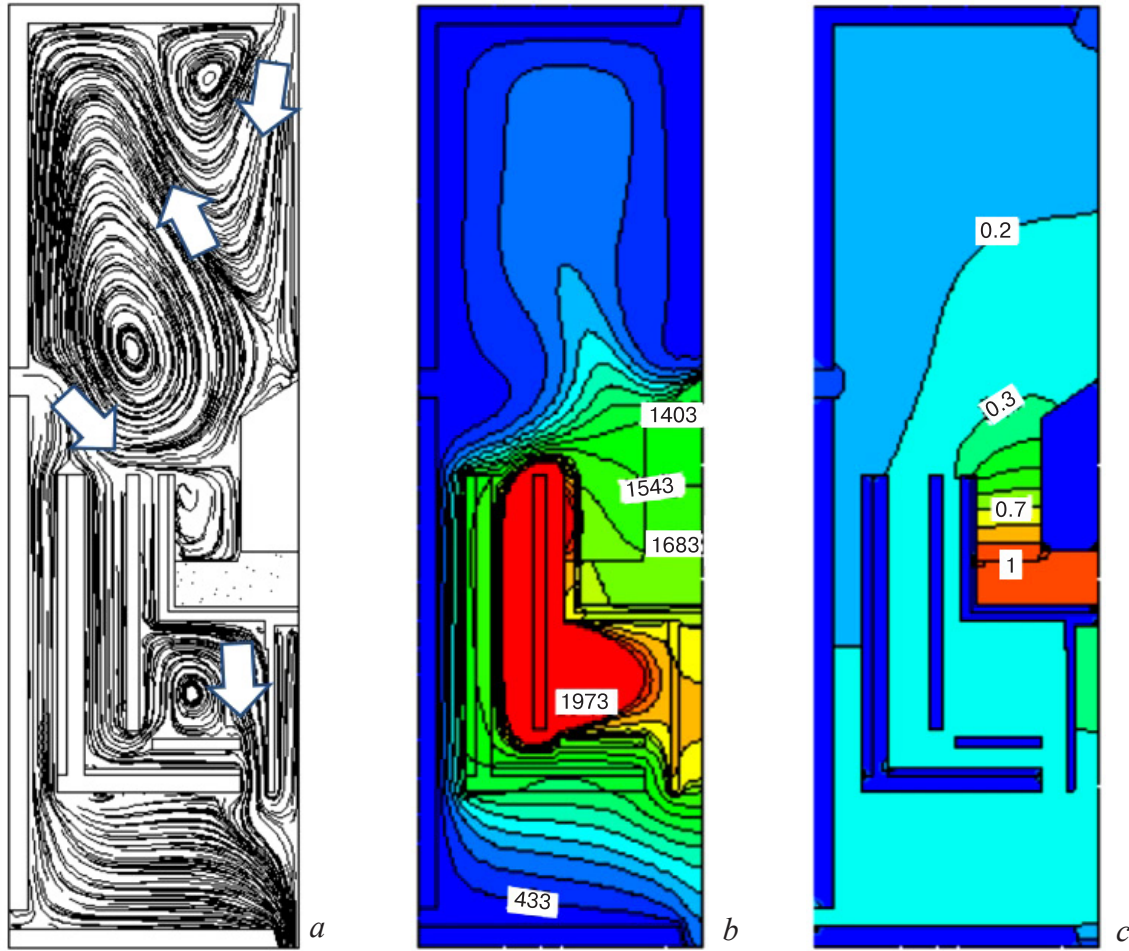


Figure 4. Central and lateral gas inlet in hot growth chamber at $V_{in} = 200$ cm/s: (a) gas flow, (b) isotherms and (c) silicon monoxide concentration contourlines (C/C_0)

By and large, one can conclude that thermal-gravitational convection dramatically changes the gas jet flow direction from the top central gas inlet hole, in accordance with the above criterion-based estimate. Then, in the bottom part of the chamber, the gas flows downwards in the gaps between the graphite crucible support, the heater and the lateral and bottom screen assemblies and is outlet through the central gas outlet hole in the growth chamber bottom. The difference from the cold chamber case is the vortex near the bottom part of the heater under the crucible assembly. The elongated pattern of the isotherms shown in Fig. 3b characterizes the intensity and direction of gas flow in different parts of the growth chamber. The described above gas flow produces a specific pattern of silicon monoxide concentration contourlines (Fig. 3c). Their analysis suggests a high concentration of silicon monoxide impurity in the growth chamber due to the above described influence of thermal-gravitational convection on the gas flow and hence on the transfer of the entrained impurity.

Figure 4 a–c shows calculation results for additional lateral gas inlet to the chamber. Then, provided the top central gas inlet at $V_{in} = 200$ cm/s is active, the thermal-gravitational convection generated vortex is affected

by the lateral inlet flow at $V_{in-lat} = 10$ cm/s. It can be seen that the lateral inlet direction coincides with the direction of that vortex, thus intensifying it along with the secondary vortex in the inner cavity between the crucible side wall and the crystal side surface. As a result, the downward gas flow along the crystal side surface and the upward gas flow along the crucible side wall are intensified. In the bottom part of the chamber the gas also flows downwards in the gaps circumventing the heat screen and the heater. A local vortex is also generated by thermal-gravitational convection above the heater bottom horizontal heat screen (Fig. 4a). The isothermal pattern (Fig. 4b) illustrates the most heated spaces in the chamber, suggesting that the resultant structure of the thermal-gravitational flow is controlled by the joint effects of the lateral (from the vertical walls) and bottom (from the butt-end surfaces) heating of the surrounding gas atmosphere. Additional lateral pure gas inlet favors a substantial reduction in the silicon monoxide concentration above the melt surface in the inner cavity between the crucible side wall and the crystal side surface (Fig. 4c).

A more detailed illustration of the gas dynamic parameters for the two options of chamber (Fig. 5) is provided by graphs of gas flow rate and silicon monoxide

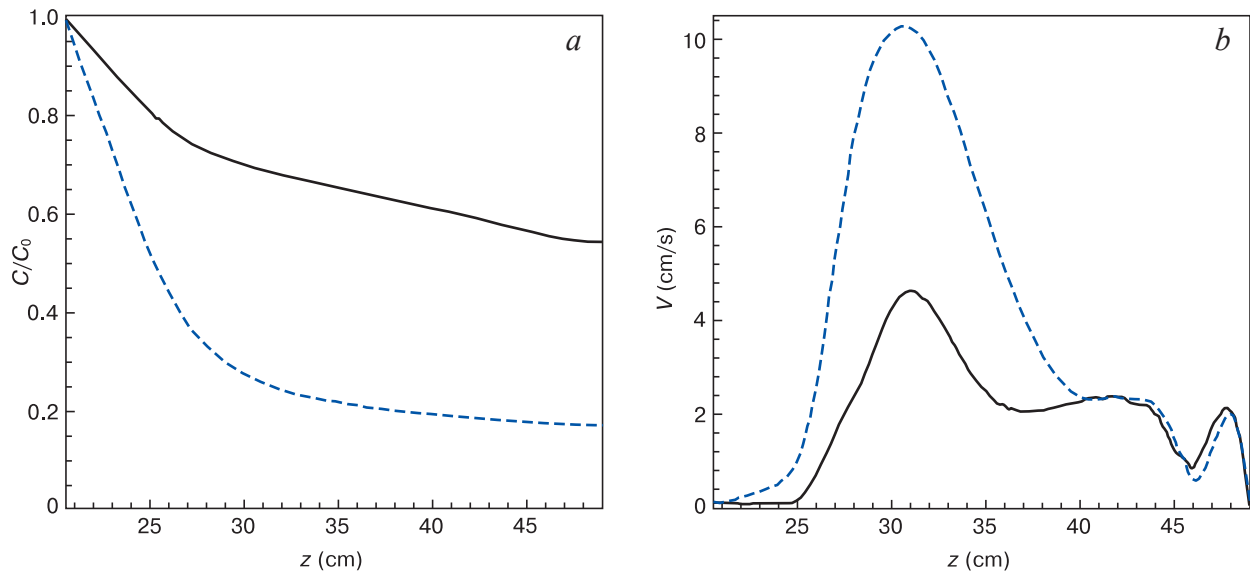


Figure 5. Silicon monoxide concentration (a) and gas velocity modulus (b) distributions in $r = 4$ cm section of hot growth chamber for two gas inlet options: (solid curves) sole central gas inlet at $V_{in} = 200$ cm/s and (dashed curves) combined (central and lateral) gas inlet at $V_{in} = 200$ cm/s and $V_{in-lat} = 10$ cm/s

concentration for the $r = 4.7$ cm section, with the axial coordinate from the melt surface to the top chamber wall changing in the range $z = 20.5\text{--}49$ cm. It can be seen that the greatest modulus of gas velocity for sole top central gas inlet is 4 cm/s (at $z = 30$ cm), being further increased at that point by additional lateral gas inlet at $V_{in-lat} = 10$ cm/s. Moreover, additional lateral gas inlet more effectively reduces the silicon monoxide concentration by approx. 60% of its maximum level.

4. Conclusion

The above presented review suggests that the gas dynamics problem for Cz single crystal silicon growth is actual and practically important. Along with theoretical analysis of the physicochemical processes in the growth chamber gas atmosphere, mathematical simulation taking into account the main features of the physical processes and the growth chamber design is also important. One should however point out that conjugate simulations carried out in foreign publications deal with foreign growth furnaces (EKZ-1300 or newer) having specific arrangement and assembly of the heat screens, gas inlet and outlet holes etc. For example, the space above the heater can be covered with a horizontal screen that potentially suppresses the effect of thermal-gravitational convection. That is probably why the cited foreign publications do not contain analysis of the effect of thermal-gravitational convection on the gas flow, although gas flows through high temperature gradient regions. The review presented herein also shows that some RU Patents and technical publications are based on quite simplified and sometimes inadequate understanding of gas flows.

This publication gives way to expand the knowledge of gas dynamic processes for the example of the domestic

Redmet-10 furnace growth chamber. Analysis of publications devoted to the calculation of gas dynamics with gas inlet in the upper dome of the growth chamber [22] showed that at high inlet speeds (100–200 cm/s) on small dome sizes corresponding to the considered Redmet-10 installation, there is no blurring of the inflowing gas stream. The methodical novelty of this review is addition of conjugation with a gas dynamic model to the Cz process mathematical model [13]. Two gas dynamic options were analyzed: (1) isothermal ideal gas in a cold growth chamber and (2) non-isothermal ideal gas in a hot growth chamber when thermal-gravitational convection has a significant contribution to vortex formation. Two gas inlet methods were calculated for each option: conventional, i.e., only through the growth chamber top central gas inlet hole, and innovative, i.e., with additional gas inlet through the growth chamber lateral gas inlet hole [12]. The expedience of using additional lateral argon gas inlet for reducing silicon monoxide concentration in the growth chamber was confirmed by numerical data.

The advantages of introducing gas into the growth chamber from the bottom up are discussed in the Russian patent [11] and in the article on mathematical modeling [3], where it is stated that the main advantage is the reduction of energy costs for the growth process. The results will be useful at the next stage, i.e., gas dynamic simulation for large capacity domestic Redmet-90 growth furnace [21].

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