INTERNATIONAL SEMINAR ON ELECTRON DEVICES DESIGN AND PRODUCTION

PROCEEDINGS

SED

APRIL 23-24, 2019
PRAGUE, CZECH REPUBLIC

International Seminar on Electron Devices Design and Production
(SED-2019)

April 23–24, 2019
Prague, Czech Republic
sed.diag.ru

Seminar schedule

April 23, Tuesday		
9:00 – 10:00	Registration of participants	
10:00 – 13:00	PLENARY OPEN SESSION	
13:00 – 14:00	Coffee Break (Lunch)	
14:00 – 17:30	**Computer-Aided Design and Production of Electron Devices**	**Ensuring the Quality and Reliability of Electronics Devices**
17:30 – 19:30	Get Together Party	
April 24, Wednesday		
10:00 – 13:00	**Electronics Manufacturing Services**	
13:00 – 14:00	Coffee Break (Lunch)	
14:00 – 17:30	**Electronics Manufacturing Services**	
April 25, Thursday		
Social Program		

Organized by

- MIREA - Russian Technological University (RTU MIREA)
- Russian Centre of Science and Culture in Prague
- Russian Section of the Institute of Electrical and Electronics Engineers (IEEE);
- The IEEE Tomsk Chapter & Student Branch.

Sponsors

- Experimental laboratory NaukaSoft

Location:

Seminar will be carried out at the Russian Science and Culture Centre (RSCC) in Prague (Praha 6, ul. NaZátorce 16)

Russian science and culture centre (created in 1971) is one of the Rossotrudnichestvo foreign representations (Federal Agency for the Commonwealth of Independent States, Compatriots Living Abroad and International Humanitarian Cooperation).

The preparation and realization programs of the sphere of science, culture and education, Russian language advancement, outreach of Russian achievements in these spheres are the major RSCC activities.

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Key objectives of the seminar:

1. Computer-Aided Design and Production of Electronic Devices
2. Electronics Manufacturing Services
3. Ensuring the Quality and Reliability of Electronic Devices

Guidelines for Oral Presentations

Please note that the overall time available for your presentation is limited to 10 minutes allowed for the actual presentation and 5 minutes for discussion. You should plan your presentation carefully. You should select your vocabulary to address as wide an audience as possible and avoid unfamiliar abbreviations or expressions. Your oral presentation should be performed in the way of answers the following questions:

Why was the project undertaken?

What was done?

What was learned?

What does it mean?

Remember, the three rules for an effective presentation are:

- Tell them what you are going to say (spend a few moments introducing your topic and what you intend to speak about).
- Tell them (deliver your talk, including the methods, results and conclusions)
- Tell them what you said (summarize the most important points of your lecture).

Please remember that the responsibility of having your paper ready for Presentation at the scheduled time is primarily in your hands as the presenter. Check the readability, completeness and order of your slides before your presentation. Arrive well in advance of the session, and acquaint yourself with the operation of the podium and location of the equipment. Seminar staff will be present to assist you. There are no scheduled breaks in the agenda so it is mandatory that the presentations be loaded before the beginning of each session.

Be careful to speak in accordance with the sequence of your slides. Avoid making major modifications to your transparencies during your presentation. Do not use more than 1 slide per minute. Please stay within the time limit allocated for your presentation.

Technical equipment provided in the Conference room are:

- Multimedia video projector;
- Projection screen;
- Standard multimedia PC with CD-ROM drive.

The operating system for session computers is Microsoft Windows XP. The available software is Microsoft Office 7 (or newer) that includes Word, Excel, PowerPoint, Adobe Acrobat Reader, and Windows Media Player. Therefore, all presentations must be compatible with these packages. Slide and overhead projectors will not be available!

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Plenary session (I^2T and SED)

1. Atanas Kostadinov
   Technical University - Sofia, Bulgaria
   About Marie Curie Alumni Association

2. Yasuto Hijikata
   Saitama University, Japan
   Room temperature electronic-driven quantum devices using single defects in silicon carbide semiconductors

3. Zhuravlev V.Ph. Perelyaev S.E.
   Ishlinsky Institute for Problems in Mechanics of the Russian Academy of Sciences
   3-D MICROMACHINED SPHERICAL SHELL RESONATORS: IMPLEMENTATION VISION

4. Perelyaev S.E., Zhuravlev V. Ph.
   Ishlinsky Institute for Problems in Mechanics of the Russian Academy of Sciences
   MEMS Integrating gyroscope and angular velocity sensor (AVS) based on 2D micro-wineglasses and 3D micro-spheres

5. Alla G. Kravets, Natalia A. Salnikova, Ilya P. Mikhnev, Nazim Y. Orudjev, Olga V. Poplavskaya
   Volgograd State Technical University
   Web Portal for Project Management in Electronics Design Software Development

Section meeting

	Computer-Aided Design and Production of Electronic Devices April 23, Tuesday, 14:00 – 17:30	
c101	Pavel N. Anisimov, Denis A. Kuzin	Application of Experiment Planning Methods for Building a Network of Digital Television Broadcasting of DVB-T2 Standard
c102	Vadim A. Zhmud, Lyubomir V. Dimitrov, Oleg V. Stukach	Investigation of the Numerical Optimization Toolkit for Control of the Oscillatory Unstable Object
c103	Yury Shornikov, Evgeny Popov	Modeling and Simulation of Electronic Devices in the ISMA Environment
c104	Elena P. Dogadina, Yuriy A. Kropotov, Aleksander Y. Proskuryakov	A model of simultaneous optimization of production planning
c105	Viktor M. Kureychik, Irina B. Safronenkova	Ontology-based approach to design problem formalization
c106	N.V. Butyrlagin, N.V. Chernov, N.V. Prokopenko, A.V. Bugakova	Current Digital Logical Elements' Synthesis and Circuitry: Linear Threshold Approach

c107	Yury N. Kofanov, Svetlana Y. Sotnikova	The Foresight Modeling in Ensuring High Quality of Space Electronic Equipment
c108	Irina Safonova, Elizaveta Dmitrieva, Boris Zhelenkov, Yakov Goldovsky	Taking Project Decisions in Computer Aided Design of Electronic Computing Equipment Modules
c109	Elmar Kuliev, Vladimir Kureichik, Vladimir Kureichik Jr.	Mechanisms of swarm intelligence and evolutionary adaptation for solving PCB design tasks
c110	A.G. Kravets, N. A. Salnikova, I.P. Mikhnev, N.Y. Orudjev, O.V. Poplavskaya	Web Portal for Project Management in Electronics Design Software Development
c111	Dmitry Bulakh, Sergey Zhestkov	Logic gates placement algorithm for visualization of integrated circuits netlists
c112	Kiya Bushmeleva, Svetlana Uvaysova, Aida Uvaysova, Oksana Avdeuk	The System of Automated Circuit Simulation of Electronic Devices
c113	Fedor Polishchuk	Development and research methods of calculation induced interference in the onboard network of spacecraft
c114	Daria Zaruba, Dmitriy Zaporozhets, Nina Kulieva	Glowworm Swarm Optimization Algorithm for Computer Equipment Partitioning
c115	Vladimir Kureichik Jr., Victoria Bova, Vladimir Kureichik	Hybryd Approach for Computer-Aided Design Problems
c116	Alina Kulgina, Darya Sharova, Aleksandr Vostrikov, Ekaterina Prokofeva	Development of software module for the analysis of electrical circuits
c117	Y.N. Kofanov, Y.A. Vinokurov, S.Y. Sotnikova	Optoelectronic Devices' Thermal Working Modes Providing Method
c118	V.V. Martynov, E.S. Zakieva, A.A.Petunin	Modeling the Initial Shape in the Tasks of Automating the Design of Electronic Means Placement on a Flat Material
f250	Daniil E. Shumakher, Galina V. Nikonova, Liia V. Shchapova	Radiosignal Identification System For The Software-Defined Radio

	Ensuring the Quality and Reliability of Electronic Devices **April 23, Tuesday, 14:00 – 17:30**	
q301	Dmitry Lovtsov, Dmitry Gavrilov	Automated special purpose optical electronic system's functional diagnosis, quality and informational performance index estimation
q302	Oleg V. Stukach, Raushan Zh.	Model of the Yield Loss Factors Based on Survey Analysis for the Integrated Circuits Manufacturing

	Aimagambetova	
q303	Farkhad A. Abdullin, Valeriy E. Pautkin, Ekaterina A. Pecherskaya, Anatoliy V. Pecherskiy, Dmitriy V.Artamonov, Kirill O. Nikolaev	Application of the Selective Silicon Etching Methods for Estimation of the Wafers Quality in the Micromechanical Sensors
q304	Alexey A. Shamin, Ekaterina A. Pecherskaya, Kirill O. Nikolaev, Timur O. Zinchenko, Yuliya V. Shepeleva, Aleksei A. Golovyashkin	Quality Control of Technological Processes of Manufacturing Functional Solar Cells Layers Based on Hybrid Organic-Inorganic Perovskites
q305	Yulia Logunova, Viktor Kureichik	Algorithm of Graph Planarity Defenition for Improving the Quality of the Very Large Scale Integrations Circuits Tracking.
q306	I.Makarova, E.Mukhametdinov, L. Gabsalikhova, R.Garipov, A.Pashkevich, K.Shubenkova	Justification of the Possibility to Use Vibration Measuring Sensors in Onboard Diagnostic Devices
q307	K. Palaguta, V. Bebenin, A. Kuznecov	Testing of the device of the help to visually impaired people for positioning in space
q308	Lysenko A.V., Trusov V.A., Tankov G.V., Kochegarov I.I., Danilova E.A.	An Algorithm for the Implementation of an Adaptive Vibration Testing System of Onboard Radio-Electronic Equipment
q309	Lysenko A.V., Yurkov N.K., Goryachev N.V., Danilova E.A., Lapshin E.V.	An Adaptive Vibration Testing System of Structural Elements of Radio-Electronic Equipment
q310	Igor Lushpa, Konstantin Novikov, Sergey Polesskiy	The Reliability Characteristics of the Data Processing Centers Cooling Systems
q311	Ishkov Anton, Solodimova Galina	Measuring complex for testing pulsed thermoelectronic training of electronic components
q312	Chesalin A.N., Grodzenskiy S.Ya.	The Algorithm Of Calculating The Refined Boundaries Of Sequential Criteria Based On The Likelyhood Ratio
q313	S.Polesskiy, P.Korolev, K.Sedov, I.Ivanov	Development of methods for identifying factors affecting the electronic tools reliability in the design
q314	B.Kenzhaliyev, K.Ozhikenov, A.Ozhikenova, O.Bodin, L.Krivonogov, D.Papshev	Improving the Interference Tolerant Noise Immunity of Ambulatory Telemetry ECG Diagnostics Systems

	Electronics Manufacturing Services April 24, Tuesday, 10:00 – 17:30	
m201	U.A. Konstantinov, E.D. Pozhidaev, S.R. Tumkovskiy	Investigation of Electrostatic Discharge Effect on High-power Mosfet-Transistors Considering the Influence of PCB
m202	Atanas Kostadinov, Vitali Guitberg, Morten Olavsbraten, Guennadi Kouzaev	Multi-Logics Gates
m203	Abaturov Vladimir Vladimirovich, Savelyev Igor Ivanovich, Skopin Constantin Alexandrovich	Thermal model of Zeeman ring laser
m204	A.R. Bestugin, O.M. Filonov, I.A. Kirshina, N.A. Ovchinnikova	Design of micro – and nanoelectromechanical resonators taking into account internal temperature fields
m205	Aleksandr F. Kryachko, Yuliana A. Novikova, Maksim B. Ryzhikov, Elizaveta V. Kucherova	Research of perspective materials for thin optical films for the mid-IR
m206	Yelizarov A.A., Nazarov I.V., Skuridin A.A.	Application of a Cylindrical Resonator for Measuring the Parameters of Dielectric Materials
m207	Alexandra V. Salnikova, Vladimir P. Litvinenko, Boris V. Matveev, Alexey N. Glushkov, Yuliya V. Litvinenko, Alexander A. Makarov	The Fast Digital Algorithm for Measuring the Parameters of the Random Processes
m208	Maxim Yu. Shtern, Maxim S. Rogachev, Yury I. Shtern, Alexey A. Sherchenkov, Alexander O. Kozlov	Creation of multisectional thermoelements for increasing of the efficiency of thermoelectric devices
m209	S.E. Perelyaev, V. Ph. Zhuravlev	MEMS Integrating gyroscope and angular velocity sensor (AVS) based on 2D micro-wineglasses and 3D micro-spheres
m210	Ibrahim Ibrahim Nizar	Investigation of Inverse kinematics Solution for a Human-like Aerial Manipulator Based on The Metaheuristic Algorithms
m211	Chernyshov N.N., Belousov A.V., Grebenik A.G.	Spin-Dependent Tunneling in Semiconductor Structures Without an Inversion Center
m212	N.N. Chernyshov, A.V. Belousov, I.N.	Spin Resonance in a Semiconductor Structure in Quantizing Magnetic Field

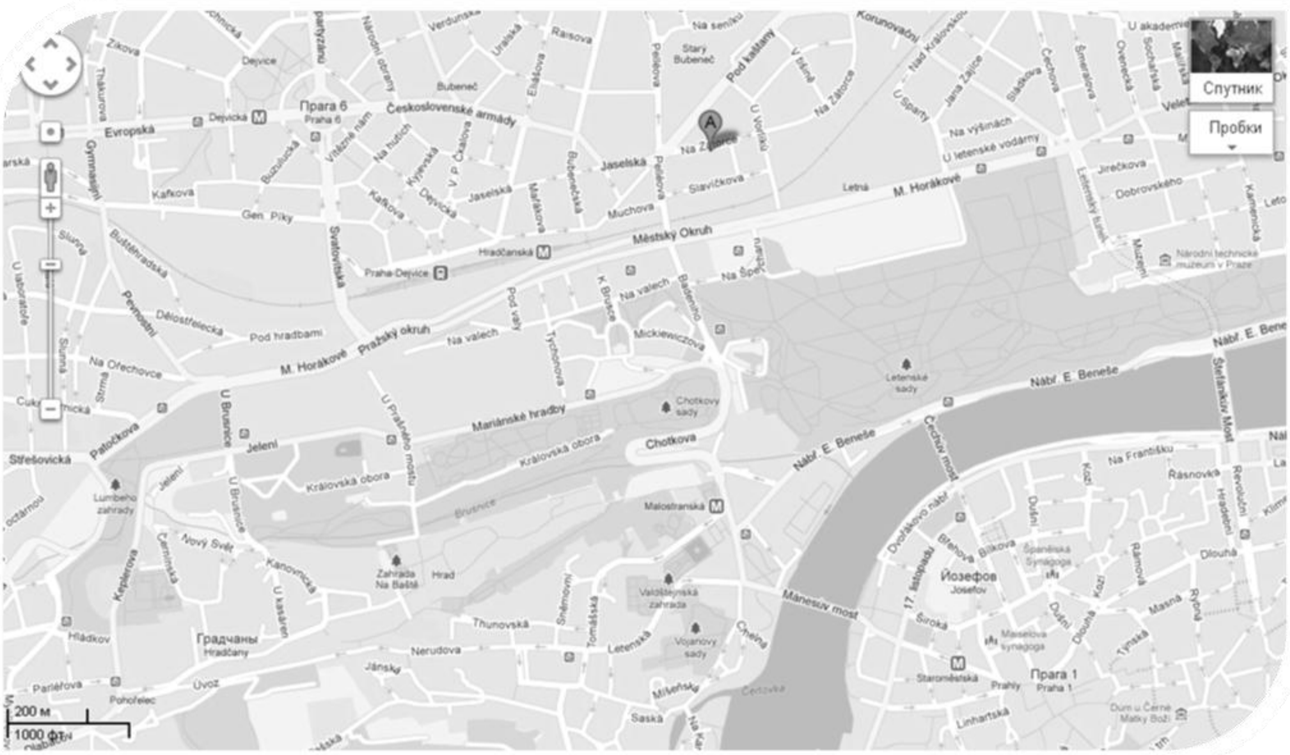
	Gvozdevskiy, N.I. Slipchenko, M.A.F. Alkhawaldeh	
m213	Valentin Ashmarin, Yevgeniya Tyryshkina	Conductivity of Fiberglass after Long-Term Exposure to Vacuum
m214	Ilya Agapov, Margarita Afanasyeva	Experimental Determination of the Electric Field Gain Coefficient on the Top of the Spherical Electrode on Air
m215	Vladimir Petrosyan, Alexander Belousov, Artem Grebenik	Solution of the Stefan problem during radiation-conductive heat transfer in the process of growing sapphire single crystals by a modified Kyropoulos method
m216	Riabyshenkov Andrei, Karakeyan Valery, Zaharov Artem, Larionnov Nikolay	Exergy analysis of the recirculation scheme for air preparation of clean rooms based on a system approach
m217	Bagdaulet K. Kenzhaliyev , Kassymbek A. Ozhikenov, Aiman K. Ozhikenova, Oleg N. Bodin, Mikhail N. Kramm, Fahim K. Rahmatullov	Reconstruction of Equivalent Electric Heart Generator
m218	Boloznev V.V., Zastela M.Yu., Chabdarov Sh.M., Yurkov N.K., Bannv V.Y.	To the Problem of Vibration Resistance Ensuring of Microwave Radio Receivers
m219	F.R. Ismagilov, V.E. Vavilov, I.F. Sayakhov	The electromagnetic and thermal analysis of electrical machines from composite materials
m220	Tychkov Alexander, Kochegarov Igor, Goryachev Nickolay	Design Of An Instrumentation Amplifier For A Mobile Electrocardiogram Recorder With Autonomous Power Supply
m221	Vasiliy Berdnikov, Valeriy Lokhin, Saygid Uvaysov	Determination of Guaranteed Stability Regions of Systems with a PID Controller and a Parametrically Perturbed Control Object
m222	Victor E. Voitovich, Alexander I. Gordeev, Nikolay N. Prokopenko, Anna V. Bugakova	Prospects for Development of Fast Recovery Power GaAs SBD on the basis of LPE-Technology
m223	Victor E. Voitovich, Alexander I. Gordeev, Ahmet B. Saytiev, Igor A. Sysoev	Extreme, based on new physical principles, high-bandwidth, high-efficiency photovoltaics and hyper-speed power electronics on LPE GaAs single crystals
m224	Trofimov A. A., Bezborodova O. E., Gromkov N. V., Polosin V. G., Spirkin	Magnetodiode-Based Speed-of-Rotation Transducers

	A. N.	
s230	Tatyana Murashkina, Tatyana Istomina, Anna Shcherbakova, Pavel Tsarev	The Energetic Estimate of Optical Fiber Measuring System for Determination of the Fluid Composition
s231	Ekaterina A. Polyakova, Tatiana I. Murashkina, Elena A. Badeeva, Sergey I. Torgashin, Natalya N. Yankina	Principles of Reliability Improvement of Fiber-Optic Sensors for Rocket and Space Equipment and Aeronautical Engineering
s232	Alexander Chernodarov, Olga Khalyutina, Andrew Patrikeev	Monitoring and Optimization of the Structure of a Navigation System on a Set of MEMS Sensors
s233	E.A. Badeeva, T.I. Murashkina, D.I. Serebryakov, T.Yu. Brostilova, I.E. Slavkin	Fiber-optic pressure sensors with an open optical channel for rocket-space and aviation engineering
s234	Maxim Yu. Shtern, Ivan S. Karavaev, Yury I. Shtern, Sergey. P. Timoshenkov, Artem V. Makshakov	The structurally-technological principles of creation for smart sensors of thermodynamic parameters
s235	A.Sh. Rakhmatulin, V.D. Popov	Integral microaccelerometer based on GaAs / InAs
s236	Alina M. Esimkhanova, Galina V. Nikonova, Olga A. Nikonova	Fiber And Optical Sensors Of Information And Measuring Systems
i240	Nikita Chuvaldin, Bogdan Belogurov, Alexey Rolich, Ilya Motajlenko	Study of energy harvesting using high-frequency emitting for IoT
i241	Tatyana Istomina, Anatoly Nikolsky, Elena Petrunina, Anatoly Svetlov, Elmin Bayramov, Boris Chuvykin	Car Internet cyberbiological system for persons with disabilities
i242	Igor Lvovich, Yuriy Preobrazhenskiy, Yakov Lvovich, Oleg Choporov, Andrey Preobrazhenskiy	Managing developing Internet of things systems based on models and algorithms of multi-alternative aggregation
i243	Grishko A.K., Buts V.P., Rybakov I.M., Dolotin A.I., Brostilov S.A.	Principles of Mathematical Logic for Multi-Agent Control of Intellectual Mobile Objects and Systems In the Dynamic Environment
i244	Valery A. Kokovin,	Intelligent Power Electronic Converter For Wired and

	Vladimir I. Diagilev, Jaroslav Halík, Svetlana S. Uvaysova	Wireless Distributed Applications
f250	Daniil E. Shumakher, Galina V. Nikonova, Liia V. Shchapova	Radiosignal Identification System For The Software-Defined Radio
f251	Konstatntin S. Kalashnikov, Yury N. Bugaev, Vladimir A. Ivanov, Alexandra V. Salnikova, Oleg V. Chernoyarov,	The Phase Measurements Disambiguation by Means of the Two Paths Similarity Method
f252	Artyushenko Vladimir Mikhaylovich, Volovach Vladimir Ivanovich	Permissible interference power from earth station equipment within 3400-4200 MHz band
f253	Artyushenko Vladimir Mikhaylovich, Volovach Vladimir Ivanovich	Evaluation of electromagnetic compatibility between earth stations and network of wireless access in the band 3400-4200 MHz
f254	Il'ya Boykov, Pavel Aikashev	To the numerical method for synthesis of fractal antennas
f255	Egor Gurov , Aida Uvaysova, Saygid Uvaysov, Ilya Ivanov	Analysis of the Parasitic Parameters Influence on the Analog Filters Frequency Response
f256	Konstantin Klimov, Kirill Konov	Modification of the Integration Variable Selection Method in Numerical Simulation of Electromagnetic Wave Propagation in the Time Domain
f257	Vladimir P. Kulagin, Yuri M. Kuznetsov	Directions of development and creation of receiving demodulation modules for digital signal processing in communication systems

Seminar venue

Russian Science and Culture Centre in Prague,
Address : Na Zátorce str., 16



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2019 International Seminar on Electron Devices Design and Production (SED)

Solution of the Stefan Problem During Radiation-Conductive Heat Transfer in the Process of Growing Sapphire Single Crystals by a Modified Kyropoulos Method

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***Abstract*— In the present article, the Stefan problem for the process of growing sapphire single crystals by the modified Kyropoulos method (GOI method) has been posed and solved. The problem was solved under the condition of the cylindrical symmetry of the thermal field in the quasistationary approximation, taking into account the transparency of the crystal and the different functional dependence of the thermal conductivity on temperature in different ranges. The exact analytical solutions of the heat equation in different temperature ranges are found. The model was verified and semi-empirical formulas were obtained for calculating the temperature distribution in a growing crystal with a moving phase transition front. Taking into account the calculated temperature gradients, analytical expressions are obtained for calculating the thermal stresses, the density of dislocations and velocity of crystal growth.**

***Keywords*— sapphire single crystals, the modified method of Kyropoulos, crystal temperature distribution, solutions of the heat equation, crystal growth rate.**

I. INTRODUCTION

Artificial sapphire is a solid single crystal transparent material obtained from a melt of aluminum oxide (Al_2O_3). By its chemical composition, synthetic sapphire single crystal is identical to the natural one, which is a blue or blue variety of corundum and used in jewelry production. Artificial sapphire does not contain substances that give it a variety of shades and is of great interest in various fields of science, technology, medicine and biology.

The rapid development of micro-electron technology, precise optics component and infrared equipment has made a higher request for sapphire cristal's quality and size. Therefore, very strict requirements are imposed to the technological process of growing sapphire single crystals on the stability of the thermal regime over time. Controlling such a process requires a detailed study of the formation of the temperature field and the dynamics of the phase transition front under the conditions of predominance of radiation in the heat transfer for a transparent crystal [1].

Numerous experiments conducted by Techsapphire LLC (Belgorod), as well as the experience of other companies, have shown that the shape and direction of natural convection flows (not including forced convection during crystal rotation) determine the shape of the growth front of sapphire crystals. In addition, impurities and micron bubbles create in the growing crystal a scattering and absorption region at wavelengths corresponding to the IR range, which leads to a decrease in the radiation heat sink through the grown part of the crystal. With fluctuations in the concentration of impurities and gas saturation of the melt in a growing crystal, the shape of the crystallization front may change with a change in the angle of solution of the growth cone. In turn, it is known that a change in the angle at the apex of the growth cone can change the nature of growth from stratified, when small bubbles repel from the front to normal, when there is a change in the morphology of the crystallization front, which causes the capture of bubbles by the growing crystallization front. It has been established experimentally that in the steady-state growth regime, the optimal cone angle at the apex ranges from 70 to 95 degrees.

As a rule, the boundaries of the sections saturated with gas inclusions have increased internal stresses. Therefore, an abrupt change in the sign of the stresses associated with the fluctuation of the temperature gradient in the growing part of the crystal and at the crystallization front can lead to the appearance of blocks in the conical part of the crystal or on the edge of the growing crystal. This is especially important at the stages of seeding and growing the upper part of the crystal. It is important to note that during the growth process, the temperature distribution in the grown part of the crystal changes and, accordingly, the temperature gradient at the boundary of the phase transition front.

Thus, the knowledge and control of thermal conditions in the growth chamber when growing sapphire single crystals from the melt is essential for the synthesis of single crystals of high optical quality.

Since translucent media have high transparency for thermal radiation in certain regions of the spectrum, an experimental study of temperature fields in the bulk of a semitransparent material at high temperature presents considerable difficulties. These difficulties are associated both with the design features of the growth plants, in which the observation area is limited, and with the unsuitability of traditional contact measurement methods. Non-contact methods allow to measure the temperature values on the sample surface. Therefore, the problem of calculating temperature fields and heat fluxes during the crystallization and cooling of a semitransparent material in the coverage of the melt-crystal system is of a particular relevance.

To establish the relationship between the technological parameters of the crystallization process, the size of the growing crystal and the position of the crystallization front, a joint consideration of the heat fluxes in the crystal-melt system is required, that is, the joint solution of the convective heat equation and the Navier-Stokes equation, which takes into account the melt crystallization flows and convection. However, when analyzing the stability of the crystallization process, it is sufficient to know the signs of the derivatives of temperature gradients at the crystallization front by the relevant parameters [2], and the effect of melt convection on transfer can be taken into account by formally introducing effective thermal conductivity and heat transfer coefficients from the crystal surface.

We note that due to the presence of a large number of factors that must be taken into account in the thermal problem, for example, the complex dependence of the thermal characteristics of various substances on temperature, there is currently no complete mathematical description of thermal phenomena of the growth of single crystals.

Closed solution is usually achieved by using some simplifications, for example, by specifying a certain dependence of the transfer coefficients on temperature. Thus, in [3], the thermal conductivity coefficient is applied proportional to $\approx 1/T$, and in T^3, in the linearization of the law of radiation from the crystal surface is proposed.

When studying the evolution of impurities, point defects (interstices, vacancies) and dislocations, when a thermal history of the process (including cooling) is required, non-stationary modeling is necessary.

II. METHOD

When sapphire crystals are grown by the GOI method, the characteristic time of changing the crystal shape is long compared to hydrodynamic parameters. Therefore, we use a quasistationary approach, solving a number of stationary problems corresponding to different functional dependences of the thermal conductivity coefficient on temperature in the temperature range up to 1973 K°, as well as near the phase transition temperature of 2303 K°.

This greatly simplifies the modeling and allows one to obtain exact analytical solutions of the heat equation under the appropriate boundary conditions. It is necessary to take into account the reflection of radiation from the outer opaque boundaries (the inner surface of the tungsten crucible and the covering tungsten disk), from the inner boundaries due to different refractive indices and the dependence of the optical properties of the crystal on the radiation wavelength.

Let us consider the heat conduction equation for the temperature field in a growing crystal, which is of a general nature and is true both for the case of growth of the weft on seeding and for the growing crystal.

$$\chi\rho_S \frac{\partial T(r,x,t)}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(K_S(T)\, r \frac{\partial T(r,x,t)}{\partial t}\right) + \frac{\partial}{\partial x}\left(K_S(T)\frac{\partial T(r,x,t)}{\partial t}\right) \qquad (1)$$

where $0<r<r_0$, $0<x<l$, r_0- the radius of the crystal, l - is the length of the crystal, ρ_S - density, χ – heat capacity, $K_S(T)$ - thermal conductivity, T - temperature.

Radiation occurs from the surface of the grown part of the crystal located above the surface of the melt. Schematically, the crucible with the melt and the grown part of the crystal is shown in Fig.1.

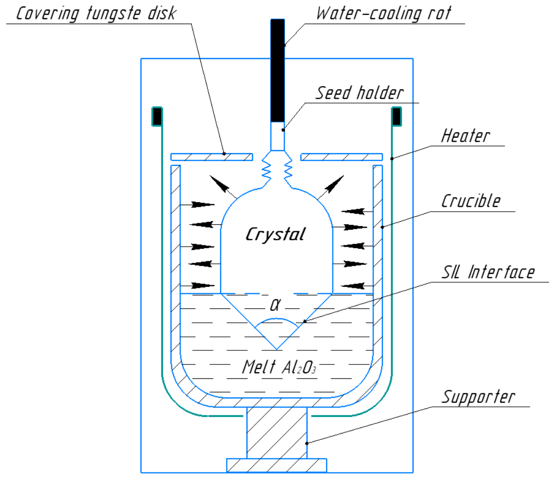

Fig.1 - Schematic diagram of crystal growth by GOI method

On the surface of the crystal radiation condition takes place:

$$-K_S(T)(\mathrm{grad}T)_{\vec{n}} = \sigma\varepsilon_S T^4 - Q_B(M) \qquad (2)$$

where ε_S – the degree of blackness of the crystal, $\vec{n}$ - the external normal at some point *M* on the surface of the crystal, $Q_B(M)$ - heat flux incident on the crystal at point *M*, radiated by the heated internal surfaces (the inner surface of the crucible and the covering disk), σ - Boltzmann constant.

It is possible to determine the temperature in a stream of radiation incident on a crystal as follows:

$$Q_B(M) = \varepsilon_T\, \sigma\, T_B^4(M) \qquad (3)$$

wher ε_T - the amissivity coefficient of the inner surface of the crucible and the covering disk.

Before continuing further calculations, we note that the growth cone of a crystal in the melt is formed by convective melt flows and the crystallization front is located along the melt isotherm on this boundary.

Figure 2 shows the real cone of monocrystal sapphire growth after the seeding is completed, extracted from the melt, and further cooled. In a real process, as experiments have shown, the angle at the apex of the cone increases to approximately 90-95° at the exit to the cylindrical growth zone.

Fig.2 - Growth cone of sapphire monocrystal

Variation in the growth angle, with the same crystal diameter, leads to a change in the heat flux from the melt through the boundary of the crystallization front. Given that the surface area of a cone can be defined as

$$S_{con}=\pi(r_0^{eff})^2 \qquad (4)$$

where $r_0^{eff}=\frac{r_0}{\sqrt{\sin\left(\frac{\alpha}{2}\right)}}$ – effective radius.

Therefore, to get the equation for average temperature $\overline{T_S}(x,t)$, let us integrate equation (1) by r_0^{eff} and take into account relations (2) and (3).

Then we get

$$\chi\rho\frac{\partial\overline{T_S}}{\partial t}=-\frac{2}{r_0^{eff}}\left[\sigma\varepsilon_S\overline{T_S}^4(x,t)-\sigma\varepsilon_T T_B^4(x,t)\right]+ +K_S(\overline{T})\frac{\partial^2\overline{T_S}}{\partial x^2} \qquad (5)$$

Let us introduce some empirical parameter ξ and imagine the temperature in the radiation flux falling on the growing part of the crystal from the inner surface of the crucible and the covering disk as follows:

$$\chi T_B^4(x,t)\varepsilon_T=\overline{T}_S{}^4(x,t)\varepsilon_S\xi \qquad (6)$$

Then, in the stationary case from (5) and taking into account (6), we obtain a second-order nonlinear differential equation

$$\frac{d^2\overline{T_S}(x)}{dx^2}-\frac{2\sigma\varepsilon_{eff}}{r_0^{eff}K_S(\overline{T_S})}\overline{T}_S{}^4=0 \qquad (7)$$

where the designation is entered $\varepsilon_{eff}=\varepsilon_S(1-\xi)$ - effective coefficient of crystal blackness. The parameter «ξ» is found from the experiment for each installation separately.

Note that the thermal conductivity coefficient in equation (7) has a different functional dependence on temperature in different temperature ranges from 293 K° to 1973 K° and from 1973 K° to 2303 K° and above [4].

It is known [5] that for dielectric crystals the value of co thermal conductivity coefficient depends on the molecular weight M_S, interatomic distance Λ, Debye temperature Θ_D and Gruneisen constant γ.

In the framework of the microscopic theory of thermal properties of crystals, the coefficient of thermal conductivity is described by the Leibfried-Shleiman formula [5]:

$$K_S=\frac{M_S\Lambda\Theta_D^2}{\gamma^2 T_S} \qquad (8)$$

For sapphire $\Theta_D=1000K°$, $\gamma\approx 2$, $\Lambda=12$ angstrom, $M_S=101{,}96$.

Taking into account (8), it's obvious that equation (7) has a fifth degree of nonlinearity in temperature.

However, for sapphire at high temperatures from a crystallization temperature of 2303 K° to a melting point of 2323 K° and higher, both cubic and quadratic dependence of the coefficient of thermal conductivity on temperature is possible.

Consider the case when $K_S\approx\bar{T}_S{}^3$.

In a fairly narrow temperature range of 2173 - 2303 K°, we write the ratio

$$K_S=K_{SL}\frac{\bar{T}_S^3}{T_{SL}^3} \qquad (9)$$

Substituting (9) into (7), we obtain a second-order linear differential equation:

$$\frac{d^2\overline{T_S}(x)}{dx^2}-\frac{2\sigma\varepsilon_{eff}T_{SL}^3}{r_0^{eff}K_{SL}(T_{SL})}\overline{T_S}(x)=0 \qquad (10)$$

The general solution of equation (10) is

$$\overline{T_S}(x)=\sqrt{A}\left[C_1\exp(x\sqrt{A})-C_2\exp(-x\sqrt{A})\right] \qquad (11)$$

where the designation is entered: $A=\frac{2\sigma\varepsilon_{eff}T_{SL}^3}{r_0^{eff}K_{SL}(T_{SL})}$.

To find the independent constants C_1 and C_2, we use the boundary conditions:

$$\begin{cases}\overline{T_S}(x)=T_{SL}, x\to 0 & (12)\\ \overline{T_S}(x)=T_S^l, x\to l & (13)\end{cases}$$

where l is the length of the crystal, T_S^l- temperature in the upper part of the grown crystal at x = l.

Taking into account (12) and (13) from (11) we find:

$$C_1=\frac{T_S^l-T_{SL}\exp(-l\sqrt{A})}{2\sqrt{A}\cdot sh(l\sqrt{A})} \qquad (14)$$

$$C_2=\frac{T_S^l-T_{SL}\exp(l\sqrt{A})}{2\sqrt{A}\cdot sh(l\sqrt{A})} \qquad (15)$$

where $sh(l\sqrt{A})$ - hyperbolic sine.

Then the solution of equation (10) is obtained in the form:

$$\overline{T_S}(x)=\frac{1}{2\cdot sh(l\sqrt{A})}\left\{\left[T_S^l-\exp(-l\sqrt{A})\right]\exp(x\sqrt{A})- -\left[T_S^l-T_{SL}\exp(l\sqrt{A})\right]\exp(-x\sqrt{A})\right\} \qquad (16)$$

Since the temperature at the top of the crystal, as it grows, decreases from T_{SL} to T_S^l, can accept

$$T_S^l=T_{SL}\cdot b \qquad (17)$$

where $0<b\le 1$.

Then (16) will be rewritten as:

$$\overline{T_S}(x)=\frac{T_{SL}}{2\cdot sh\left(l\sqrt{A}\right)}\left[b-\exp(-l\sqrt{A})\right]\exp(x\sqrt{A})- -\left[b-\exp(l\sqrt{A})\right]\exp(-x\sqrt{A})\} \quad (18)$$

or

$$\overline{T_S}(x)=\frac{T_{SL}}{2\cdot sh(l\sqrt{A})}\left\{b\cdot sh(x\sqrt{A})+sh\left[(l-x)\sqrt{A}\right]\right\} \quad (19)$$

If we assume that the upper part of the crystal cools down exponentially, then we can take:

$$b=\exp(-l\sqrt{A}) \text{ или } T_S^l=T_{SL}\exp(-l\sqrt{A}) \quad (20)$$

Then from (18) or (19) we can finally get, taking into account the true values for A and r_0^{eff}:

$$\overline{T_S}(x)=T_{SL}\exp\left(-x\sqrt{\frac{4\sigma\varepsilon_{eff}T_{SL}^3\sqrt{\sin\left(\frac{\alpha}{2}\right)}}{K_{SL}D_S}}\right) \quad (21)$$

where $D_S=2r_0$ - crystal diameter.

From (21) one can find the temperature gradient near the crystallization front at $x\rightarrow 0$:

$$\left|grad\overline{T_S}(x)\right|_{x\rightarrow 0}=T_{SL}\sqrt{\frac{4\sigma\varepsilon_{eff}T_{SL}^3\sqrt{\sin\left(\frac{\alpha}{2}\right)}}{K_{SL}D_S}} \quad (22)$$

If in equation (7) to substitute the expression for the thermal conductivity K_S in the high temperature region, expressed through the refractive index N for wavelengths in the infrared range and the absorption coefficient β [6, 7], that is, if

$$K_S=\frac{16N^2\sigma\bar{T}_S^3}{3\beta} \quad (23)$$

where N is the refractive index, β is the absorption coefficient, then we obtain the equation:

$$\frac{d^2\overline{T_S}(x)}{dx^2}-\frac{3\varepsilon_{eff}\beta}{8r_0^{eff}N^2}\overline{T_S}=0 \quad (24)$$

The solution of this equation with the boundary conditions for equation (7) can be written as:

$$\overline{T_S}(x)=\frac{T_{SL}}{2\cdot sh(l\sqrt{A^*})}\left\{b^*\cdot sh(x\sqrt{A^*})+sh\left[(l-x)\sqrt{A^*}\right]\right\} \quad (25)$$

where

$$A^*=\frac{3\varepsilon_{eff}\beta}{8r_0^{eff}N^2} \quad (26)$$

If by analogy with (20) it is assumed that $b^*=\exp(-l\sqrt{A^*})$, then we get

$$\overline{T_S}(x)=T_{SL}\exp\left(-\frac{x}{2N}\sqrt{\frac{3\varepsilon_{eff}\beta\sqrt{\sin\left(\frac{\alpha}{2}\right)}}{D_S}}\right) \quad (27)$$

Accordingly, the temperature gradient at the crystallization front will have the form

$$\left|grad\overline{T_S}(x)\right|_{x\rightarrow 0}=\frac{T_{SL}}{2N}\sqrt{\frac{3\varepsilon_{eff}\beta\sqrt{\sin\left(\frac{\alpha}{2}\right)}}{D_S}} \quad (28)$$

It is known that under conditions of high-temperature growth, an inhomogeneous temperature distribution in a growing crystal leads to the appearance of thermal stresses and different dislocation densities [7]. In the framework of the approach considered by us, the magnitude of the stresses arising along the axis of the growing crystal can be estimated by the formula

$$\Sigma_{xx}=\frac{\alpha_T\cdot E}{(1-\mu)}l^2\frac{d^2\overline{T_S}(x)}{dx^2} \quad (29)$$

where α_T - thermal expansion coefficient, E - Young's modulus, μ - Poisson's ratio, and l is the length of the crystal.

The relationship of stresses and deformations η_T can be written in the form:

$$\Sigma_{xx}=C_{11}\eta_T \quad (30)$$

In view of equality $\eta_T=\alpha_T\overline{T_S}(x)$ will have

$$\Sigma_{xx}=\alpha_T\overline{T_S}(x)C_{11} \quad (31)$$

where C_{11} = 497.6 GPa is the coefficient of the sapphire thermoelasticity matrix.

The density of dislocations can be estimated by the formula

$$P_D=\frac{\alpha_T}{\delta}grad\overline{T_S}(x) \quad (32)$$

where *δ* is the Burgers vector.

Thus, we obtained the exact analytical solutions of equation (7) allow us to establish the relationship of the temperature distribution in a growing crystal with thermodynamic parameters, mechanical and physical properties of sapphire.

Velocity of crystal growth throw the equation of interface transportation of thermal fluid, the maximal velocity of crystal growth V_{max} can be given as [8]:

$$V_{max}=\frac{K_S}{\rho_S H}gradT_S \quad (33)$$

where H – heat of fusion.

Equation (33) shows that the maximum growth velocity depends on the temperature gradient value of crystal. To accelerate the crystal's growth, the temperature gradient must be increased. But an excessively high temperature gradient may enlarge thermal stress and make dislocation destiny increasing, even disruption.

Considering the effect of thermal effect on the crystal disruption, the allowed maximum thermal stress Σ_{max} is [9]:

$$\Sigma_{max}=\frac{1}{4}\alpha_T r_0(hr_0)^{1/2}\left(1-\frac{1}{2}hr_0\right)^{-1}gradT_S \quad (34)$$

In equation (34): h – cooling coefficient.

Equations (33) and (34) show the relationship between the maximum thermal stress and the maximum velocity of crystal growth is proportional.

Therefore, in order to obtain crystal without disruption, the growth velocity must be lower then the maximum growth velocity. Other is, the excessively high velocity will cause a larger thermal stress, dislocation density increasing.

At the stage of iso-diameter, heat exchanger is limited in radiating efficiency and the velocity of crystal growth is mainly determined by temperature decreasing velocity.

III. CONCLUSION

Generally, GOI process control is based on reducing the heating power according to a predetermined function of time which is chosen empirically on the grounds of quality of crystal's obtained in preceding processes.

In recent years, weight sensors have been used to control the process of crystal growing by Kyropoulos method [10]. The main advantage of the crystallization process control using dynamic weighing is the ability to measure continuously and stabilize the crystallization mass rate using a feedback system. However, the signal from the crystal weight sensor is a function of two parameters — the linear crystallization rate and the shape of the crystallization front. Therefore, for example, the cause of the decrease in the derivative $\frac{dm}{dt}$ (where m – weight according to the weight sensor) can be both a decrease in the linear crystallization rate, and a decrease in the angle at the vertex of the cone of the crystallization front. This leads to a loss of reliability in managing the growth of the crystal due to incorrect operation feedback system.

The calculations presented in this article, as well as experimental studies have allowed to propose a new method of automatic control of the growth of sapphire crystals.

The method is based on experimental data and analysis of the solution of equation (7), as well as solutions in the case $K_S \sim \overline{T}^2$, and K_S=const, which lead to the solution of a nonlinear differential equation. As a result, a semi-empirical observation equation for temperature was obtained, by analogy with the W. Bardsley equation [11] for the crystal mass.

Thus, the new automatic system for controlling crystal growth by temperature allows us to avoid problems with the use of dynamic weighing. This is important to ensure the stability of the process with automatic seeding and growth of the upper part of the crystal to the maximum diameter.

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