more than 5000 h without substantial degradation of the emission characteristics. This is illustrated in Fig. 6, which shows the results of measurements made by Busta et al. [9] with an electron emission current density of about 1 A cm^{-2}.

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Development of new-generation equipment for crystal growth from melt. The RAS Experimental Factory of Scientific Engineering in the novel economic conditions

V A Borodin

1. Introduction

The present report discusses the results in developing technologies for growing crystals of a specified shape and equipment for single-crystal growth by the Czochralski and Stepanov methods and by modifications of the Stepanov method developed at the Institute of Solid-State Physics of the Russian Academy of Sciences (Chernogolovka). In addition, the main areas of development of the Experimental Factory of Scientific Engineering (EFSE) of the Russian Academy of Sciences are covered.

2. Shaping of crystals from melt and the equipment for crystal growth

The standard Stepanov growth allows the production of profiled crystals with a given shape of cross section along the growth axis. However, various technical applications also require crystals with more complicated shapes that could have been grown directly from melt if a technology for changing the shape of the cross section of the growing crystal directly during growth existed.

The research conducted at the Institute of Solid-State Physics, RAS since 1982 has led to two main technologies in this field. The first, which became known as variational shaping [1, 2], ensures discrete changes in the shape of the cross section of the pulled profile. The second technology, known as local dynamic shaping, makes it possible to grow complex crystalline products with the shape of the lateral surface of the crystal changing continuously according to a program [3–7]. Previous papers (see Refs [1, 2, 4, 6, 7]) discussed complex sapphire products grown by these methods, including products of hemispherical shape, in the shape of hollow cones, etc. This research made it possible to build new growth equipment that has no analogs, a crystallization center, so to say, that permits the following [4, 6]:

(a) growth of crystal with a constant cross section (the common Stepanov growth);

(b) discrete changes in the shape of crystals during growth (variational shaping);

(c) continuous changes (according to a given program) in the shape of the lateral surface of solid and hollow bodies of revolution (local dynamic shaping), and

(d) growth of crystals with a helical relief on the lateral surface.

Growing crystals of complex shapes using variational shaping and local dynamic shaping has shown that it is possible to construct a new promising technology that ensures three-dimensional changes in the shape of the growing crystal during its growth.

The experience in growing single crystals by the Czochralski, Stepanov, variational shaping, and local dynamic shaping methods has revealed that raising the quality of the crystals, increasing the productivity of manufacturing crystals by increasing the yield of acceptable crystals, and introducing new crystallization-center type technologies have no meaning without building new equipment for crystal growth. On the one hand, the new-generation equipment must be precise so as to allow for active investigations in growing various types of crystals and profiles and must provide the possibility of establishing the effect of various parameters of the growth process on the quality of the crystal. On the other hand, such equipment must comply, in reliability and operating characteristics, with commercially produced equipment. One of the main criteria for compliance with this dual requirement is the presence in the growth facility of a modern hardware–software complex (HSC), which incorporates data acquisition, computational, and controlling functions.

The data acquisition and computational functions of the HSC in the newly developed ROSTOKS-01 facility amount to acquiring and initial processing of the analog and digital data, displaying and recording the data for the operating staff, generating technological signals, detecting potential emergencies, recording events, storing data in an archive, and keeping a log of all the data.

The controlling functions of the HSC amount to automatic control, logical control, and the possibility of remote control. The control program NIKA2000 is written in Microsoft Visual C++ 6.0 language and operates in Windows95/98/NT. The block construction of the program ensures its rapid adaptation to different methods of crystal growth from melt and to new peripherals. The program consists of the following separate blocks: the block for forming the influx of data from the crystal growth process, the block responsible for manually controlling the growth process and for controlling the peripherals according to fixed regimes, and the block responsible for the computer simulation of the growth process and the automatic control through the power channel.

The automated system with negative feedback incorporates the algorithms needed to estimate the state of the object and control the temperature of the heater and the pulling rate (the control channels). The control parameter is the transverse size of the pulled crystal, which is usually determined, via simple calculations, from the signal of the weight cell measuring the total force acting on the pulled crystal. The computational device (or the program block) calculates the value of the force corresponding to the supported value of the ingot radius. The main regulator records the reading from the gauge and the calculated value of the force, determines their mismatch, and generates the signal for controlling the power of the heater according to the values set in the tuning stage. The magnitude of the programmed force is calculated via the weight-cell equation in which the phase variables (the crystal's radius and the meniscus height) remain constant or change in accordance with preset functions.

The known weight-cell equation for the Czochralski method, derived by Bardsley [8] from an analysis of the forces acting on the crystal, has the following form

$$W(t) = \int_0^t \rho_S g\pi r^2 V(\tau)\,\mathrm{d}\tau + \pi r^2 \rho_L gh + 2\pi r\sigma_{LG}\cos\varepsilon\,, \quad (1)$$

where $W(t)$ is the modelled value of the reading taken from the weight cell, ρ_S and ρ_L are the densities of the crystal and melt, r is the radius of the crystal, σ_{LG} is the surface tension coefficient of the melt, ε is the growth angle, V is the crystal pulling speed, and h is the height of the meniscus. The first term on the right-hand side is the weight of the crystal grown in time t, the second term is the weight of the meniscus of height h, and the third term is the surface tension force acting on the crystal.

However, the above equation cannot be applied to the Stepanov growth and to its variants that employ shaping devices. The experimental studies of the effect of the process parameters on the readings of the force sensor in the growth of profiled crystals [9] and computer simulations of the heat and mass transfer processes in the crystal – melt system [10] have shown that deviations from the steady-state growth regime change the hydrodynamic pressure in the melt meniscus, which accordingly leads to changes in the force acting on the crystal. As a result, the weight-cell equation for crystals grown with shaping devices takes the form

$$W(t) = \int_0^t \rho_S gS(t)V_0\,\mathrm{d}t + S(t)\rho_L gh + \Gamma(t)\sigma_{LG}\cos\varepsilon + H_{\mathrm{eff}}(t)\rho_L S(t) + K_R V_0 + \int_S p(h, V_0)\,\mathrm{d}s\,. \quad (2)$$

Here, $S(t)$ and $\Gamma(t)$ are the surface area and the perimeter of the crystal, V_0 is the crystal pulling speed, h is the height of the meniscus, K_R is the resistance coefficient of the shaping channel to the flow of melt, and $p(h, V_0)$ is the hydrodynamic pressure under the crystallization front.

Temperature fluctuations near the crystallization front and the mechanical noise generated by the different devices are the cause of oscillations in the position of the crystallization front. Analysis of the new observation equation (2) has shown that a decrease in the meniscus height is accompanied by an increase in the amplitude of oscillations in the force sensor readings. Indeed, attempts to automatically grow profiled crystals using classical PID controllers have revealed that supercooling of the melt accompanied by a decrease in the meniscus height caused a rise in the level of the measured noise. Numerical differentiation of the deviation of the weight cell readings from the modelled value of the force made it possible to substantially expose the effect. When the oscillation amplitude $\Delta\dot{W}$ exceeded a certain value, the control lost its stability and the operator was forced to interfere. Usually the stable regime was manually maintained by the operator, who rapidly increased the heating power or corrected the programmed value of the force.

The most simple and effective method in automatic control, which became known as the combined method, is described in Ref. [11]. The above implies that to ensure continuity of the process of automatic control with a constant adjustment of the controller, the dynamic characteristics of the controlled object must be maintained constant, i.e. in our case the meniscus height must be kept within certain limits. The experimental data and the results of simulation revealed that the amplitude $\Delta\dot{W}$ is a parameter of indirect information about the meniscus height. If the value of this parameter exceeds a certain critical value found experimentally, the program blocks the PID controller and increases the heating power until the amplitude $\Delta\dot{W}$ is brought back into its prescribed range. The decrease of $\Delta\dot{W}$ to a given value is a signal that switched the PID controller on, which then 'leads' the growth process up to the moment when $\Delta\dot{W}$ again exceeds the established value. The combined control method has been successfully used for growing a group of 15 sapphire rods with a rectangular cross section and a packet of 10 ribbons in batch production.

To grow crystals using the Czochralski, Stepanov, variational shaping, and local dynamic shaping methods, the ROSTOKS-01 facility was designed and is currently manufactured in batches at the RAS Experimental Factory of Scientific Engineering (Chernogolovka). This facility makes it possible to grow crystals from congruently melting substances with melting points up to 2200 °C. The facility consists of a growth module, mechanisms for rotating and translating the upper and lower shafts, vacuum pumps (5×10^{-5} mm Hg) and a system for controlling the influx of technological gases (Ar, N_2, and O_2), an HSC, a computerized control system, and a high-frequency thyristor converter.

The diameter of the cylindrical growth chamber measures 600 mm, and the height of the chamber is 750 mm. There is also an auxiliary upper chamber for receiving the growing crystal. The working stroke of the upper shaft is 600 mm, and the operating pulling speed is 0.6 – 120 mm per hour. The rated speed of translation of the upper shaft is 0.5 – 150 mm per minute. The range of controlling the rate of rotation of the upper shaft varied from 5 to 100 rotations per minute. The working stroke of the lower shaft is 200 mm. Its translation and rotation velocities also vary over a broad range. The output power of the thyristor frequency converter amounts to 50 kW at 8000 Hz. The facility is fairly compact, with the different modules having the following dimensions (width × length × height in mm): 1125 × 1160 × 3500 for the growth module, 600 × 600 × 2000 for the thyristor frequency converter, and 500 × 500 × 500 for the automatization and control module.

The automated system incorporates a channel for monitoring and controlling the power of the thyristor oscillator, a channel for translating and rotating the shafts, and a channel for monitoring the weight of the growing crystal and other forces acting on the crystal during growth. In the automatic regime, monitoring and controlling the thyristor oscillator power is done by a control program. The processing of the current information, the storing of this information, and the control of the process are done by a commercially available computer, which makes the operation of the facility more reliable.

The facility is also shipped to other countries. At present, a production prototype (based on the above-described facility) that will be used for local dynamic shaping is being built. Another production prototype will be fabricated to ensure three-dimensional control of the crystal shape in the growth process.

3. The main areas of development of the Experimental Factory of Scientific Engineering (EFSE) of the Russian Academy of Sciences

Today the main areas of the EFSE practical activities are as follows:

(1) the production of modern telecommunications equipment;

(2) the design and production of modern engineering facilities for automated systems used in controlling technological processes, facilities for use in industrial and special purpose electronics, and HSCs for industrial units, including atomic power stations;

(3) the design and production of automated facilities for single-crystal growth and of analytical instruments for studying the structure and chemically analyzing substances, and

(4) the design and production of facilities for special projects.

Work to launch serial production of telecommunications equipment of plesiochronous digital hierarchy (PDH) and synchronous digital hierarchy (SDH) began in 1994. The equipment of NEC Corporation (Japan) was taken as the basic equipment. In 1997, EFSE bought the technology and licence from NEC to produce on its own the above equipment. Since April 1998, EFSE has been producing telecommunications equipment of PDH and SDH according to a complete manufacturing cycle. In 1999, EFSE commercially produced SDH equipment of the STM-16 level with a data transmission rate of 2500 Mbps. Several dozen Russian communications companies, among which are the biggest companies such as RosTeleKom and the St. Petersburg Telephone Company, the Russian Ministry of Transportation, and the Moscow Region Elektrosvyaz' Company have become EFSE's clients.

The RAS Experimental Factory of Scientific Engineering is the first Russian plant to master the production of SDH equipment. The equipment produced by EFSE and NEC and shipped to various parts of Russia is serviced during and after the guarantee period at the Service Center at EFSE (Chernogolovka).

The special design office of EFSE has designed and manufactured a batch of Evromekhanika constructs of various sizes in accordance with the IEC 297 standard and a series of hardware devices based on the open dataway–modular standards VME and PCI, including a wide range of communication-with-object modules and programmed controllers with built-in commercial processors.

In order to solve the problems that challenge the creators of automatic control systems for technological processes of the upper and lower levels as applied to specific industrial units, the hardware–software complex TURBOKOM-4011 developed in cooperation with the TEKHNOKOM-micro Company has been employed. This complex is intended for designing multilevel distributed systems used in the automation of technological processes. EFSE has received a licence from the State Atomic Inspection Committee to design and produce automation equipment for atomic energy stations.

During recent years, in order to retain the high technological standards in manufacturing analytical instruments and producing high vacuum and also taking into account the growing market for instruments involved in such activities, EFSE has developed, in cooperation with the Institute for Analytical Instrument Making of the Russian Academy of Sciences, and assembles the chromato-mass-spectrometer MSD-650. The latter is intended for qualitative and quantitative analysis of toxic components of mixtures of organic compounds and their identification. This is the first Russian-made top-grade instrument that allows the identification of supertoxicants, including dioxins. The instrument has been certified by the State Standards Committee of the Russian Federation in the State Registry for Measuring Devices (Certificate No. 1297). The MSD-650 spectrometer is used to develop new instruments, in particular, mass spectrometers with a glow discharge for the analysis of inorganic substances.

The implementation of the program of developing high technologies, the production and delivery of knowledge-intensive products to various parts of Russia and abroad have made it possible to transform the plant into a profitable and competitive enterprise.

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Femtosecond photoelectronics — past, present, and future

M Ya Shchelev¶

1. Introduction

Among the diagnostic methods and techniques used in experimental physics to study fast processes (FP), high-speed electron-optical photography is distinguished by its record-high speed (the theoretical limit of the time resolution is 10 fs $= 10^{-14}$ s), the large volume of spatial data recorded simultaneously (up to 10^6-10^8 resolvable elements), an extremely high sensitivity (each electron emitted by the input

¶ The author is also known by the name M Ya Schelev. The name used here is a transliteration under the BSI/ANSI scheme adopted by this journal.