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USE OF SOLAR FURNACES UNDER ORBITAL-FLIGHT CONDITIONS

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Use of direct solar heating under space conditions for the production of materials with prescribed properties has a number of advantages over resistance and optical heaters used earlier for these purposes. Using SP-1.0 and Zenit SP-01-5 furnaces designed for the Alpha international space station as examples, the author analyzed the technical capabilities of solar furnaces as compared to resistance and optical heaters under space conditions in the production and investigation of: disilicides of transition metals of high purity; compositions based on the Al–Pb system, which is an antifriction material; photostimulated epitaxial films; crystals of CdTe and Bi_2Te_3 from melts; tantalum disilicide; single crystals of high-temperature superconductors and other materials.

1. State of the Art of the Problem. Solar furnaces – environmentally safe and renewable energy sources – are promising installations that, working in a prescribed gas system without energy consumption, ensure high-quality high-temperature technological regimes for various purposes. Solar ground furnaces were widely used by the country's leading organizations in the field of solar engineering for the production and testing of heatproof materials with prescribed properties.

In the mid-Seventies, in Katsiveli (the Crimea), a proving ground of automated solar furnaces equipped with solar precision-guidance systems and systems for controlling temperature regimes at powers of 1.0, 1.5, 2, and 5 kW to process technological processes was put into operation (responsible for the execution of the work is the Moscow Power Institute) [1, 2].

A 20-kilowatt automated heliostat solar furnace with pumping of radiant energy into the pressure chamber has been put into operation in Makhachkala (Daghestan). In Europe, there is only one similar installation in Almeria (Spain), which ranks below the Russian one in power.

It is necessary to note the functioning full-size models of 1-kW SP-1.0 and 5-kW Zenit SP-01-05 solar orbital furnaces installed in Katsiveli (responsible for the execution of the work is the Moscow Energy Institute) [3, 4].

As a result of the work performed on creating solar-engineering complexes there has been accumulated extensive experience in the development and creation of highly efficient mirror solar-energy concentrators, solar precision-guidance systems, and methods and means for monitoring and control of thermal regimes of treatment of materials [5, 6].

In the process of ground materials-science work on the indicated installations, there arose scientific and commercial interest in high-temperature technological processes that occur under zero-gravity conditions. In this case, the physics of the processes of melting and crystallization of materials differs significantly from the processes realized under ground conditions, which provides new wide possibilities of producing unique materials with prescribed properties. Classical laws of mechanics constitute the basis for the principles of realization of technological processes under zero-gravity conditions. One of the principles is associated with the law of statics and dynamics of interfaces. Under zero-gravity conditions, intermolecular surface-tension forces prevail over gravity, which is the basis for producing ingots of large dimensions and accurate composition. The second principle is associated with the possibility of altering gravitational mechanisms of convection (heat, concentration) in melts and mixtures. Under the earth's conditions, gravitational convection has most frequently a tran-

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sition or turbulent character in processes at the stage preceding crystallization, and therefore it is difficult to monitor. Melt-temperature fluctuations lead to banded inhomogeneity of a material. The quality of crystallization of materials under the earth's conditions is degraded by the inhomogeneity of the composition. The main reasons for the inhomogeneity of crystallized material are somehow or other associated with convection. Under zero gravity, gravitational convection can either be totally suppressed or be laminarized, which will permit the production of ingots and the growth of crystals with a prescribed structure throughout the volume [7].

Various directions of materials science and technology that are promising for realization under zero-gravity conditions are currently being developed. One of them is the production of crystals for integrated circuits, solid-state lasers and infrared engineering, and superconducting materials with special physical properties.

2. Basic Technological Directions in Work under Zero-Gravity Conditions. *2.1. Production of disilicides of transition metals of high purity. Investigation of the structure, phase composition, and physical properties of thin films.* In recent years, high requirements on the degree of integration, speed of response, supersensitivity, etc. have been imposed in connection with the creation of large and superlarge integrated circuits. For this purpose, in metallization technology it is necessary to produce current-conducting compounds with a low specific electrical resistance, high resistance to corrosion, and controlled parameters of pressure drop at the semiconductor-metal boundary. Metallization based on films of the series of disilicides of high-purity transition metals (Co, Nb, Ti, Hf, W, Ta, Cr, and Fe) meets these requirements to a great extent [8]. Realization and adoption of a fundamentally new technology of production of disilicides will make it possible to produce massive specimens of higher purity than powder specimens produced earlier since high-purity single crystals of metals produced by zone melting and single-crystalline silicon of high purity are used as the charge, and they are melted together by the method of crucible-free melting.

2.2. Photostimulated growth of epitaxial films. For creating ultralarge integrated circuits and infrared detectors, the method of photostimulated epitaxy in space seems promising: using short-duration focusing of the sun to the substrate surface, the substrate surface is cleaned and is recrystallized, then the substrate temperature is brought to the optimum temperature of photostimulated epitaxy, the substance of the grown film in the gaseous state is supplied to the substrate, and epitaxial films are grown.

A combination of heating the substrate by solar radiation and the absence of gravitation also permits high-speed crystallization of semiconductor materials from the melt.

2.3. Production and investigation of an antifriction composition based on the Al–Pb system. The development of a composition based on the Al–Pb system, which is a promising antifriction material, is urgent. The use of antifriction materials based on aluminum with an increased content of lead for bearings enhances significantly their antiscoring properties. Aluminum-lead alloys must contain no less than 10% of finely divided lead. However, their use in industry was retarded by the impossibility of obtaining a uniform distribution of more than 1% of lead in the aluminum matrix by traditional methods of casting because of the lead's low solubility. Technological difficulties emerge in producing these alloys (of a "frozen-emulsion" type). These systems are characterized by a wide region of stratification in the liquid state. Because of the difference in specific weights and gravitation conditions, separation into two layers occurs: the heavy layer is at the bottom and the light layer is at the top. It is assumed that in outer space, under microgravitation conditions, there will be no similar separation. Space zero gravity makes it possible to produce compositions with a uniform distribution of finely divided inclusions of the second phase throughout the ingot volume [9].

2.4. Growth of cadmium telluride (CdTe) single crystals from the melt. The aim of the experiment is to investigate the method of CdTe crystallization in axial heating that can ensure a convex crystallization front. These conditions must contribute to the elimination of "parasitic" crystallization and the improvement of the crystal structure. In standard airborne equipment with resistance heating, the conditions of formation of a convex crystallization front are not attained in spite of a number of technical improvements of the heaters [10].

The material is used as substrates in the production of matrix photodetectors of the infrared range.

The experimental conditions were tested earlier on Korund-IM equipment and agree with the technical capabilities of the SP-1.0 solar furnace [7, 8].

The experimental regulations are:

attaining the prescribed temperature regime, 10–15 min;

growth of the crystal, 45–50 min;

cooling of the crystal, 6–8 h.

A series of 12–16 processes is required to determine the optimum conditions for producing high-quality material. The expected results are specimens of CdTe crystals up to 25 mm in diameter.

2.5. Melt growth of single crystals of bismuth telluride Bi_2Te_3. The aim of the experiment is to improve the coefficient of thermal emf and mechanical characteristics of the crystals by altering the form of crystallization that contributes to the improvement of the crystal structure. The expected results are specimens of Bi_2Te_3 crystals up to 25 mm in diameter.

2.6. Production of germanium single crystals. The production method is ultra-high-speed directed crystallization. The temperature interval is 850–1250°C.

2.7. Production of gallium (indium, antimony) arsenide single crystals. The production method is directed melt crystallization. The temperature interval is up to 1250°C, where the temperature in the cold part of the ampule is maintained at the level of 700–800°C, accurate within 0.5°C. The duration of the process is from 10 min to 100 h. The diameter of the specimen is to 20 mm.

2.8. Other technologies. In addition to the technological processes considered above, in the Zenit SP-01-5 solar orbital furnace it is planned to produce the following materials:

single-crystalline silicon with diameter 30 mm and length up to 150 mm;

silicon composites and tantalum silicide with diameter 30 mm and length 150 mm;

crystals for jewelry;

single crystals of high-temperature superconductors with volume up to 4 cm^3 [8].

3. Methods and Technology of Direct Solar Heating under Orbital-Flight Conditions. Most of the processes considered above were realized on astronaut-inhabited space stations with the use of resistance heaters: Kristall, Splav, Magma, Korund, Gallar, Krater-V, Zona-02, Zona-03, and others [7, 10]. Use was also made of Optizon-1-type optical heaters [7, 10].

Under the conditions of constant energy deficiency on various orbital stations, the use of direct solar heating installations for the purpose of producing heat appears preferable compared to installations employed earlier where multiple energy conversion occurred: radiant – electric – chemical – electric – thermal – radiant. The illogicality of the chain of transformations from radiant energy back to radiant energy is obvious. In this connection, the experiments on using directly concentrated solar energy to produce heat in technical processes of creation of materials became topical [10].

By focusing solar radiation using mirror concentrating systems in near-earth orbits one can obtain radiant fluxes up to 1.5×10^4 kW/m^2 and, accordingly, heating temperatures up to 3000–3500°C. Theoretically, the heating temperature attained by calculation is 5800°C.

3.1. Advantages of the method of direct solar heating. Direct solar heating has a number of features and advantages:

direct use of solar energy for heating of materials without its conversion to other kinds makes it possible to practically eliminate the energy consumption from the airborne power supply and to reduce the total mass of the technological system and operating costs;

energy is supplied to the material in a noncontact manner, possibly through transparent windows, ensuring the sterility of heating, isolation of the technological volume from the ambient medium, and any other gas medium;

production is removed from the pressurized compartment to the exterior part of the orbital station, into vacuum, which makes it possible to reduce the load on the thermal control system of the pressurized compartment and to increase the living space of the astronauts;

there are no external electromagnetic fields that disturb the melt;

low inertia of the thermal control makes it possible to realize accelerated regimes of heating and cooling of materials;

flexibility in selecting the shape and overall dimensions of the specimens of materials;

wide range of working temperatures;

possibility of concentrating the energy collected from large reflecting surfaces 12–15 m in diameter and with small losses (approximately 5–10%);

possibility of container-free processes both with free liquid zones and spherical specimens;

visual monitoring of the thermal regimes of treatment of the materials under study via telecameras, which is relatively simple technically.

3.2. Disadvantages of the method of direct solar heating. Periodic transmission by the region darkened by the earth with a duration of about 30 min limits the time of a heating session from 60 min to 120 h, depending on the orbit of the station. Consideration is given to the variants for further improvement of the thermal modules of solar furnaces on accumulating thermal energy and supplying it to the specimen of material in the darkened part of the orbit with the aim of increasing the heating time.

4. Basic Types of Orbital Solar Furnaces. *4.1. SP–1.0 solar furnace.* Intended for finishing off prototype elements and assemblies in flight tests when experiments on producing materials by the method of container-free and accelerated directed crystallization are conducted.

The installation incorporates:

a solar-energy concentrator (sectioned);

a solar precision-guidance system;

a radiation-flux power regulator;

a thermal module;

a magazine – storage of specimens;

a manipulator for feeding ingots to the working zone of the furnace;

an automatic-control system;

an automatic-monitoring system;

a telemonitoring system.

The basic technical characteristics are [6, 7]:

power of the concentrated radiation flux in the working zone, W	up to 800
density of the radiation flux on the specimen, W/cm^2	up to 180
range of control of the radiation-flux power relative to the maximum power	0–1.0
range of measured temperatures, ^{o}C	300–1500
root-mean-square error of maintaining the prescribed temperature on the specimen, ^{o}C	0.5
limiting heating rate, ^{o}C/sec	10
limiting cooling rate, ^{o}C/sec	1
maximum time of continuous heating of the specimen, h	120
linear microaccelerations of the specimen in the process of heating, m/sec^2	$5 \cdot 10^{-5}$–10^{-4}
pressure of the medium, mm Hg	10^{-6}–10^{-4}
diameter of the specimens, mm	up to 25
length of the specimens, mm	up to 150
capacity of the changeable magazine with the specimens,	24
overall dimensions, mm	1600 × 1600 × 1100
mass, kg	60
average total electric power consumption, W	no higher than 80
service life under operating conditions, years	5

4.2. Zenit SP–01–5 solar furnace.

Indended for producing materials with prescribed properties under space conditions by the methods of crucible-free zone melting and container-free crystallization.

In addition to the devices and systems of the SP-1.0 solar furnace enumerated in Sec. 4.1, the installation incorporates additionally electric drives for:

independent movement of the ingot;

independent movement of the seed;

rotation of the seed;

positioning of the ingot to the focal zone.

The basic technical characteristics are [6, 7]:

power of the concentrated radiation flux in the working zone, kW	up to 5
density of the radiation flux on the specimen, W/cm^2	up to 250
range of control of the radiation-flux power relative to the maximum power	0–1.0
working range of heating temperatures, $^{\circ}$C	1100–1800
root-mean-square error of maintaining the prescribed temperature on the specimen, $^{\circ}$C	1
limiting heating rate, $^{\circ}$C/sec	10
limiting cooling rate, $^{\circ}$C/sec	1
maximum time of continuous heating of the specimen, h	120
linear microaccelerations of the specimen in the process of heating, m/sec^2	$5\cdot10^{-5}$–10^{-4}
pressure of the medium, mm Hg	10^{-6}–10^{-4}
diameter of the ingots, mm	up to 30
length of the ingots, mm	up to 200
length of the seeds, mm	30–40
capacity of the magazine-storage,	40
drawing rate, mm	no lower than 150
overall dimensions, mm	3100 × 3100 × 1800
mass, kg	350
average total electric power consumption, W	no higher than 200
service life under operating conditions, years	5

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