PRECURSORES POLIMÉRICOS PARA A CRIAÇÃO DE UMA CÂMARA DE DESCARGA DE GÁS DO MOTOR DE FOGUETE ELÉTRICO**POLYMER PRECURSORS FOR CREATING GAS DISCHARGE CHAMBER FOR ELECTRIC ROCKET ENGINE****ПОЛИМЕРНЫЕ ПРЕКУРСОРЫ ДЛЯ СОЗДАНИЯ ГАЗОРАЗРЯДНОЙ КАМЕРЫ ЭЛЕКТРИЧЕСКОГО РАКЕТНОГО ДВИГАТЕЛЯ**

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RESUMO

Motores de foguete elétricos são amplamente utilizados em tecnologia espacial. Além disso, atualmente, os motores de propulsão elétricos também são usados como motores de propulsão principais para voos no espaço interplanetário. Nas naves espaciais modernas, os seguintes tipos dos motores de propulsão elétricos são usados principalmente: motores de plasma estacionários e motores de íons com grades. Ao usar esses motores como motores de propulsão principais, é importante aumentar a potência total para obter a tração necessária e o impulso específico. Com o aumento da potência total, o volume da câmara de descarga aumenta, o que leva a dificuldades tecnológicas na fabricação de câmaras de descarga a partir de materiais cerâmicos. Portanto, a tarefa de encontrar alternativas aos materiais cerâmicos é relevante e necessária no desenvolvimento de motores de íons de alta frequência. O artigo discute a criação de um material compósito à base de materiais de tecido de quartzo e um aglutinante de silício orgânico como precursor preenchido com nitreto de silício para a fabricação de uma câmara de descarga de gás do motor de íons de alta frequência. Por análise termogravimétrica, selecionamos um aglutinante termo-reativo que atende aos requisitos de resistência à vibração e permeabilidade eletromagnética da câmara de descarga de gás na faixa de megahertz. Com base nesse aglutinante, preenchido com pó de nitreto de silício, reforçado com material de tecido de quartzo, foi feita a câmara de descarga de gás. O produto resultante foi testado como parte do motor de propulsão elétrico de laboratório com um diâmetro de 100 mm e uma potência de 200W.

Palavras-chave: *cerâmica, resinas de silício orgânico, materiais compósitos, motores de foguetes elétricos, câmara de descarga de gás.*

ABSTRACT

Electric rocket engines are widely used in space technology. Furthermore, at present, electric propulsion engines are also used as mid-flight engines for flights in interplanetary space. On modern spacecraft, the following types of electric propulsion are mostly used: SPT and grid ion thruster. When using these engines as sustainers, it is important is to increase the total power for obtaining the required thrust and specific impulse. With an increase in total power, the volume of the discharge chamber increases, which leads to technological difficulties in the manufacture of discharge chambers from ceramic materials. Thus, the task of finding alternative ceramic materials is relevant and necessary in the development of high-frequency ion thrusters. The article discusses the issues of creating a composite material based on woven quartz materials and organosilicon binder as a precursor

filled with silicon nitride for the manufacture of gas discharge chamber (GDC) of high-frequency ion thruster (RFIT). By thermos-gravimetric analysis, a thermosetting binder, which meets the requirements of vibration resistance and electromagnetic permeability of GDC in the megahertz range, was selected. Based on the binder filled with silicon nitride powder, reinforced by quartz woven fabrics, manufactured GDC. The resulting product was tested as part of the laboratory electric propulsion device with a diameter of 100 mm and power of 200W.

Keywords: *ceramics, organosilicon resins, composite materials, electric rocket engines, gas discharge chamber.*

АННОТАЦИЯ

Электрические ракетные двигатели нашли широкое применение в космической технике. Также в настоящее время, ЭРД применяются и как маршевые двигатели для полетов в межпланетном пространстве. На современных космических аппаратах в основном используются следующие типы ЭРД: СПД и сеточные ионные двигатели. При использовании данных двигателей в качестве маршевых, важным является увеличение суммарной мощности для получения необходимой тяги и удельного импульса. При увеличении суммарной мощности объем разрядной камеры увеличивается, что приводит к технологическим трудностям при изготовлении разрядных камер из керамических материалов. Поэтому задача поиска альтернативных керамическим материалам является актуальной и необходимой при разработке высокочастотных ионных двигателей. В работе обсуждаются вопросы по созданию композиционного материала на основе тканых кварцевых материалов и кремнийорганического связующего в качестве прекурсора наполненного нитридом кремния, для изготовления газоразрядной камеры (ГРК) высокочастотного ионного двигателя (ВЧИД). Путем термогравиметрического анализа подобрали термореактивное связующее, отвечающее требованиям вибростойкости и электромагнитной проницаемости ГРК в мегагерцовом диапазоне. На основе данного связующего, наполненного порошком нитрида кремния, армированного кварцевым тканым материалом, изготовили ГРК. Полученное изделие прошло испытания в составе лабораторного ЭРД диаметром 100 мм, мощностью 200Вт.

Ключевые слова: *керамика, кремнийорганические смолы, композиционные материалы, электроракетные двигатели, газоразрядная камера.*

1. INTRODUCTION:

Electric rocket engines are extensively used in space technology. These types of engines, the main principle of which is ionization and acceleration of working substance, are used to stabilize and correct the position of spacecraft in orbit (Antropov *et al.*, 2002; Gorshkov *et al.*, 2008; Khartov *et al.*, 2013; Loeb, 2015; Orlov *et al.*, 2001; Rabinsky *et al.*, 2016a; Sitnikov, 2017). Also, at present, the electric propulsion engines are used as mid-flight engines for flights in interplanetary space.

On modern spacecraft, the following types of electric propulsion are mainly used: SPT and grid ion engines. The principles of their work and the design of these types are different. The acceleration and ionization of the working fluid in the SPT is carried out in the discharge channel, while the processes of ionization and acceleration are separated in grid ion thruster. Separation of the processes of ionization and acceleration makes it possible to obtain a specific impulse of up to 50,000 s, which exceeds the maximum specific impulse of SPT (about 20,000 s).

One of the types of grid ion thrusters is RFIT. The principle of operation of this engine is

based on ionization by the electromagnetic field of the working fluid (xenon) in the discharge chamber of the engine. The acceleration of ions occurs in the ion-optical system. The schematic diagram of the engine is presented in Figure 1.

For this kind of engine, the electromagnetic properties of the material of the walls of the discharge chamber are important. Presently, alumina-based ceramics are used as the material, and silicon nitride-based ceramics are also used in laboratory samples. These ceramic materials provide required radio transparency at frequencies from 500 kHz to 2 MHz and higher. The diameter of present experimental chambers reaches 500 mm, with wall thicknesses up to 8 mm (Lurie *et al.*, 2011; Formalev *et al.*, 2015; Pogodin *et al.*, 2016; Poliakov *et al.*, 2016; Ripetsky *et al.*, 2016; Rabinsky *et al.*, 2016b; Skvortsov and Karizin, 2012; Pogodin *et al.*, 2019). It is worth noting that when using ceramic materials, the question arises about their strength qualities, especially at the stage of launching a spacecraft into operational orbit.

It is also worth mentioning that when using these engines as marching, it is important to increase the total power to obtain the necessary

thrust and specific impulse. With an increase in the total power, the volume of the discharge chamber increases, which leads to technological difficulties in the manufacture of discharge chambers from ceramic materials. All this, together, makes the task of finding alternatives to ceramic materials appropriate and necessary in the development of high-frequency ion engines.

Earlier, GDC was obtained based on polymethylphenylsiloxane rubber modified with terminal vinyl groups and filled with silicon nitride by molding. The main drawback of the material used was its low heat resistance, limited by the temperature of 370°C at a residual pressure of 10-5 Pa. Taking into account the requirements for heat resistance, the binder was advanced by using MQ resins and stabilising the main polymer chain. Hence, it was possible to increase the heat resistance of the GDC material to 410°C. As a result of the tests, and it was found that with a diameter of GDC 100 mm, the material of the chamber fully met all the requirements for nodes RFIT. Nonetheless, an increase in specific capacities during optimization of RFIT design leads to the appearance of local sections of short-term heating of the gas distribution system to a value of 450°C and higher. As a result, there was a need to create a radio transparent, vibration-resistant material for GDC with increased (up to 600 °C) heat resistance.

To accomplish this task, the authors revised the concept of composite material for the manufacture of gas distribution systems for promising RFIT (Golushko and Semisalov, 2015; Pintossi *et al.*, 2019). Despite the high resistance of silicones to heat, among other polymers, it is limited by temperatures of the order of 400-420 °C. Organic-silicon polymers in the composition of GRC, compensated for vibration loads at low temperatures, due to the low glass transition temperature. Stiff requirements for heat resistance to the binder forced to continue the search for an alternative material from the class of organic-silicon polymers operating at temperatures up to 800 °C . With complete loss of elasticity, some organosilicon polymers (for example, thermostable net siloxanes (Voronkov *et al.*, 1976; Sevryukova *et al.*, 2012; Andrianov and Sokolov, 1995) allow the GDC material to retain its electrical insulating properties, dielectric constant, and low dielectric loss tangent at temperatures up to 800 °C and higher. The densely reticulated structure of polyorganosiloxanes is characterized by low mass loss after pyrolysis of the binder and high yield of ceramo-forming residue. Therefore, composite materials based on them are characterized by high

heat resistance and can withstand repeated heating in an oxidizing environment up to 550 ... 600 °C. Composite materials based on them can work up to 1000 °C. For cross-linked polymers, the main proportion falls on the main polymer chain, represented by silicon and oxygen atoms. Correspondingly, the proportion of organic framing can be less than 20% of the mass.

The most optimal compound is methylphenylcyclospiroxiloxane (Figure 2). A distinctive feature of this oligomer is the curing mechanism by the polycondensation reaction without the release of low molecular weight substances. The use of this product is difficult due to the complexity of its synthesis by heterocondensation of silicon tetrachloride and methyl phenylsilandiol in the presence of pyridine (Andrianov *et al.*, 1978; Tkachev *et al.*, 2018).

An alternative way to obtain methylphenylcyclospiroxiloxane is the cohydrolysis of tetramethoxysilane and methylphenyl dimethoxysilane (Efremova *et al.*, 2014). Though, as a result, a low molecular weight product is formed with terminal methoxyl groups, and, as is typical for the polycondensation reaction, further molecular weight growth is difficult due to the loss of reactivity of terminal functional groups. If dysfunctional methylphenyldimethoxysilane is replaced by trifunctional vinyltrimethoxysilane, the molecular weight will increase while preserving solubility according to the critical point and Flory gelation (Florry, 1953). To increase the conversion rate by functional groups is desirable to use a polycondensation catalyst when curing the composition. Similar results were given in (Antufev *et al.*, 2019; Alekseev *et al.*, 2019; Nikitin *et al.*, 2019a; Rabinskiy and Tushavina, 2019; Umbetov *et al.*, 2017; Nikitin *et al.*, 2019b).

Since cross-linked polyorganosiloxanes, thermostable materials, are not characterized by good elastic deformation, reinforcement with woven materials is used to maintain vibration stability. According to the principle, the similar is combined with the similar, the most suitable are quartz fibers, which are characterized by a low value of the coefficient of thermal expansion, high dielectric properties and heat resistance up to 1200 °C.

2. MATERIALS AND METHODS:

The starting polymer was obtained by partial cohydrolysis of tetramethoxysilane methyltrimethoxysilane, vinyltrimethoxysilane, and γ-

aminopropyltrimethoxysilane, the finished product was 22-25% solution in acetonitrile, with medium viscosity molecular weight of 2700-3500 g/mol. As a reinforcing filler, quartz fabric material of TS-8/3-K brand, manufactured by NPO Fiberglass, was used (Fouquet *et al.*, 2015; Herbert *et al.*, 2009).

Silicon nitride for the filling was obtained in the SHS process by nitriding silicon powder, and the material was characterized by a specific surface of 10 m²/g. The fibrous structure of the α and β phases of silicon nitride crystals. Crystal size $D_{50} = 5 \mu\text{m}$.

The pre-preg was prepared by mixing a colloidal solution of the raw polymer and silicon nitride powder; the proportion of silicon nitride was 60 wt%, relative to the binder and subsequent impregnation of silica fiber" (Dimitrakellis and Gogolides, 2018; Mansour *et al.*, 2019). The composite material was solidified at 200 °C and residual pressure of 1–3 mm Hg., tetrabutoxy titanium was used as a curing catalyst, the curing process was carried out for 2 hours. The final processing of the composite GDC material was carried out at 800°C in argon (Andrianov and Sokolov, 1995). The pyrolysis process was carried out in argon by heating to 800 degrees. Celsius at a speed of 10 degrees per minute.

The structural transformations occurring during heating of materials were studied by synchronous thermal analysis using the STA 449 F3 Jupiter device from NETZSCH (Germany) (Figure 3) in differential scanning calorimetry (DSC) mode together with thermogravimetric analysis (TGA) mode.

The samples were heated to 900°C in open crucibles from Al₂O₃ with a volume of 0.085 ml at linearly increasing furnace temperature at a rate of 10°C/min. The crucibles were placed in cylindrical recesses of the upper part of the DSC/TG sensor made of Pt-Rh alloy. The argon flow rate through the measuring cell (sample and standard) during the experiment remained constant at 50 ml/min. A vacant crucible was used as a standard. The sample and reference temperatures were measured using built-in S-type thermocouples made of Pt-Rh alloys. The temperature measurement accuracy was ± 0.3 °C. The sample weight change was recorded with precision of 1 μg . The isothermal balance drift over the entire temperature range was not greater than 10 $\mu\text{g/h}$. Data collection and calculations, as well as device operation control, were made using the NETZSCH Proteus Software (Germany) software operating under the MS-Windows system.

Operational tests of prototypes of RFIT gas

distribution system with a diameter of 100 mm were carried out on a 0.4 m³ vacuum test bench (Figure 4). The pumping system of the stand provided a dynamic vacuum of 10 –3 Pa at xenon flow rates of up to 0.65 mg/s.

3. RESULTS AND DISCUSSION:

The pyrolysis process was accompanied by the thermolysis of methyl, vinyl, substituents at silicon atom. As a result of pyrolysis, amorphous silicon oxide was formed. The yield of pyrolysis residue was about 80%. Losses of mass up to 400°C can be associated with the condensation of terminal methoxyl groups, with the release of methanol. In this area, the molecular weight increased slightly. The loss of mass above 400°C was due to the initiation of the process of thermal degradation of framing of the main polymer chain, primarily aminopropyl and vinyl substituents at silicon atom. Hence, processes that proceed up to 400°C can be associated with the progress of reaction along with unreached functional groups, the telomerization reaction, the intramolecular rearrangement of macromolecules, and removal of low boiling substances. Figure 5 displays graphs of DTA polymer filled with Si₃N₄ 60% by weight in argon.

The heat resistance of the obtained composite material filled with Si₃N₄ 60 wt% was somewhat higher. As can be seen from the diagram in Figure 6, a slight drift of the mass loss curve on the isotherm at 800°C is observed, which is associated with the hydrolysis of the filler, silicon nitride, and the release of ammonia, which was experimentally established. During the hydrolysis of silicon nitride, an amorphous oxynitride phase forms, which reacts with the pyrolysis residue of polymer binder (Figure 7).

Despite the loss of flexibility inherent in elastomers, the tested material did not significantly affect the performance of GDC. The introduction of quartz fibers made it possible to increase the vibration resistance of the obtained chamber by 50% compared to the ceramic counterpart.

The resulting composite material is characterized by the following properties:

- Shore hardness –85 to 90 (scale D);
- density –1.65 to 1.67 g / cm³;
- stress rupture at elongation for fibers – based on tissue 1000 kgf;
- tensile strength for fibers – Warp and weft 550 kgf;
- volumetric shrinkage after curing: 3 to 4%;

- the temperature coefficient of linear expansion: 1.0 to $1 \cdot 10^{-3} \text{K}^{-1}$;
- electrical strength: 15 to 20 kV / mm ;
- dielectric loss tangent: 0.2% to 0.02% .

4. CONCLUSIONS:

In the outline of the work carried out, the vacuum temperature stability of densely cross-linked polyorganosilaxane obtained by the cohydrolysis of tetramethoxysilane, vinyltrimethoxysilane, γ -aminopropyltrimethoxysilane was studied to create a polymer-ceramic composite. The resulting material, combined with the filling of quartz fibers and silicon nitride, ensured the required electrophysical and operational characteristics for RFIT (radio transparency, manufacturability, vibration resistance and other).

It was demonstrated that the studied material is characterized by high heat resistance. Silicon nitride obtained by SHS is characterized by a small fraction of free nitrogen, which is replaced by a hydroxyl group during hydrolysis. Therefore, during heating, the formation of a mixed oxynitride phase can be observed due to the interaction of silicon nitride and amorphous silicon oxide.

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6. REFERENCES:

1. Alekseev, A. N., Alekseev, S. A., Zabashta, Y. F., Hnatiuk, K. I., Dinzhos, R. V., Lazarenko, M. M., Grabovskii, Y. E., and Bulavin, L. A. (2019). Two-dimensional ordered crystal structure formed by chain molecules in the pores of solid matrix. *Springer Proceedings in Physics*, 221, 387-395.
2. Andrianov, K. A., and Sokolov, N. N. (1995). The chemistry of the formation of organopolysiloxanes. *DAN USSR*, 101(1), 81-84.
3. Andrianov, K. A., Zachernyuk, A. B., and Solomatin, G. V. (1978). *Patent SU 603 645 A1. Organopolyspirocyclosiloxanes and method for their preparation*. Moscow: Organization of the Order of Lenin Institute of Organoelement Compounds of the USSR Academy of Sciences.
4. Antropov, N. N., Dyakonov, G. A., Pokryshkin, A. I., Popov, G. A., Kazeev, M. N., and Hodnenko, V. P. (2002). Pulse plasma engines in spacecraft control systems. *Applied Physics*, 2002, 1. Retrieved from <http://applphys.orion-ir.ru/appl-02/02-1/02-1-5r.htm>.
5. Antufev, B. A., Egorova, O. V., and Rabinskiy, L. N. (2019). Dynamics of a cylindrical shell with a collapsing elastic base under the action of a pressure wave. *INCAS Bulletin*, 11, 17-24.
6. Dimitrakellis, P., and Gogolides, E. (2018). Hydrophobic and superhydrophobic surfaces fabricated using atmospheric pressure cold plasma technology. *Advances in Colloid and Interface Science*, 254, 1-21.
7. Efremova, N. V., Ivanov, P. V., and Majorova, N. G. (2014). *Patent RU 2507217 C1. The method of obtaining polyelementorganospirocyclosiloxanes*. Moscow: Limited Liability Company "Research and Production Firm" MIX "(LLC" NPF "MIX")
8. Florry, P.J. (1953). *Principles of Polymer Chemistry*. New York: Cornell University Press.
9. Formalev, V. F., Kuznetsova, E. L., and Rabinskiy, L. N. (2015). Localization of thermal disturbances in nonlinear anisotropic media with absorption. *High Temperature*, 53(4), 548-553.
10. Fouquet, T., Mertz, G., Delmée, M., Fetzer, L., and Becker, C. (2015). Thermal analysis goes with mass spectrometry to evaluate the molecular weight of a fluorinated plasma polymer. *Plasma Processes and Polymers*, 12(9), 980-990.
11. Golushko, S. K., and Semisalov, B. V. (2015). Numerical modeling of deformation of anisogrid structures using high-precision schemes without saturation. *Mathematical Modeling and Numerical Methods*, 2(6), 23-45.
12. Gorshkov, A. S., Muravyov, V. A., and Shagayda, A. A. (2008). *Hall and ion plasma engines for spacecraft*. Moscow: Mechanical Engineering.
13. Herbert, P. A. F., O'Neill, L., and Jaroszyńska-Wolińska, J. (2009). Soft Plasma Polymerization of Gas State

- Precursors from an Atmospheric Pressure Corona Plasma Discharge. *Chemistry of Materials*, 21(19), 4401–4407.
14. Khartov, S. A., Balashov, V. V., Sitnikov, S. A. (2013). The choice of structural materials for high-frequency ion engines. *Proceedings of the Moscow Aviation Institute*, 63. Retrieved from <http://trudymai.ru>.
 15. Loeb, H. W. (2015). A realistic concept of a manned Mars mission with nuclear-electric propulsion. *Acta Astronautica*, 116, 299-306
 16. Lurie, S. A., Belov, P. A., Rabinsky, L. N., and Zhavoronok, S. I. (2011). *Large-scale effects in the mechanics of continuous media. materials with microstructure and nanostructure*. Moscow: MAI-Print Publishing House (Moscow).
 17. Mansour, A., Poncin-Epaillard, F., and Debarnot, D. (2019). Affinity and distribution of silver nanoparticles within plasma polymer matrices. *Journal of Materials Science*, 54(19), 12972-12987.
 18. Nikitin, P. V., Rabinskiy, L. N., and Tushavina, O. V. (2019a). Features of heat transfer in dissociated air supersonic flows. *Asia Life Sciences*, 2, 645-655.
 19. Nikitin, P. V., Tushavina, O. V., and Shkuratenko, A. A. (2019b). Calculation of heat transfer on the catalytically active surface of high-speed aircraft. *INCAS Bulletin*, 11(SI), 191-201.
 20. Orlov, A. M., Skvortsov, A. A., and Gonchar, L. I. (2001). Magnetically stimulated variation of dislocation mobility in plastically deformed n-silicon. *Physics of the Solid State*, 43(7), 1252-1256.
 21. Pintossi, D., Saakes, M., Borneman, Z., and Nijmeijer, K. (2019). Electrochemical impedance spectroscopy of a reverse electrodialysis stack: A new approach to monitoring fouling and cleaning. *Journal of Power Sources*, 444, Article number 227302.
 22. Pogodin, V. A., Rabinsky, L. N., and Sitnikov, S. A. (2019). Technological aspects of 3D-printing of parts of a gas-discharge chamber of an electric rocket engine. *STIN*, 4, 20-21.
 23. Pogodin, V. A., Sitnikov, S. A., and Solyaev, Yu. O. (2016). The study of porous ceramics based on silicon nitride obtained using three-dimensional printing technology. *New Refractories*, 11, 33-37.
 24. Poliakov, P. O., Soliayev, Y. O., and Sitnikov, S. A. (2016). Numerical modeling of residual thermal stresses in Si₃N₄ based high-porous fibrous ceramics. *International Journal of Pure and Applied Mathematics*, 111(2), 319-330.
 25. Rabinskiy, L. N., and Tushavina, O. V. (2019). Problems of land reclamation and heat protection of biological objects against contamination by the aviation and rocket launch site. *Journal of Environmental Management and Tourism*, 10(5), 967-973.
 26. Rabinsky, L. N., Sitnikov, S. A., and Khartov, S. A. (2016a). Creation of working prototypes of ceramic gas-discharge chambers of high-frequency ion engines resistant to ion-plasma spraying by the method of layer-by-layer modeling. In *Abstracts of the V international scientific seminar "Dynamic deformation and contact interaction of thin-walled structures when exposed to fields of various physical nature"* (pp. 159-160). Moscow: Publishing House "TR-Print" LLC.
 27. Rabinsky, L. N., Sitnikov, S. A., and Solyaev, Yu. O. (2016b). Comparative assessment and choice of a solution to the problem of developing a technology for the manufacture of samples and structural elements from composite nitride-silicon ceramics. In *Materials of the XXII International Symposium "Dynamic and Technological Problems of Mechanics of Structures and Continuous Media" named after A.G. Gorshkov* (pp. 108-109). Moscow: Publishing House "TR-print" LLC.
 28. Ripetsky, A., Sitnikov, S., and Rabinskiy, L. (2016). Fabrication of porous silicon nitride ceramics using binder jetting technology. *IOP Conference Series: Materials Science and Engineering*, 1-6. Retrieved from <http://iopscience.iop.org/article/10.1088/1757-899X/140/1/012023/pdf>.
 29. Sevryukova, M. M., Piryatinski, Y. P., Vasylyuk, S. V., Yashchuk, V. M., Viniychuk, O. O., Gerasov, A. O., Slominskii, Y. L., and Kachkovsky, O. D. (2012). Cyanine-like and polyenic relaxation paths of merocyanine derivatives of malonodinitrile in the excited state detecting by low temperature time-resolved fluorescence. *Ukrainian Journal of Physics*, 57(8), 812-823.
 30. Sitnikov, S. A. (2017). *Development of ion erosion-resistant materials based on silicon nitride for discharge chambers of electric*

rocket engines: thesis of the candidate of technical sciences. Moscow: Moscow Aviation Institute (National Research University).

31. Skvortsov, A. A., and Karizin, A. V. (2012). Magnetoplasticity and diffusion in silicon single crystals. *Journal of Experimental and Theoretical Physics*, 114(1), 85-88.
32. Tkachev, S. Y., Alekseev, O. M., Lazarenko, M. M., Lazarenko, M. V., Kovalov, K. M., Bokhvan, S. I., Grabovskii, Y. E., and Hoshlyk, N. V. (2018). Topological solitons in branched aliphatic molecules. *Molecular*

Crystals and Liquid Crystals, 665(1), 166-180.

33. Umbetov, A., Kozhahmet, M., Sabitbekova, G., Amirov, M., Hamit, A., Alieva, G., Karimova, D., and Uspanova, V. (2017). Interference of coherent radiation in a crystalline two-component lens. *Far East Journal of Electronics and Communications*, 17(5), 923-939.
34. Voronkov, M. G., Mileshekevich, V. P., and Yuzhelevsky, Yu. A. (1976). *Siloxane bond*. Novosibirsk: Nauka.

Figure 1. Schematic diagram of RFIT operation

Figure 2. Methylphenylcyclospirosiloxane

Figure 3. STA 449 F3 Jupiter device from NETZSCH (Germany)

Figure 4. The prototype GDC mounted on RFIT layout (left) and general view of the vacuum test bench for RFIT (right)

Figure 5. Dependence of mass loss on temperature during DTA of the product of partial hydrolysis of $\text{Si}(\text{OMe})_4$, $\text{MeSi}(\text{OMe})_3$, $\text{ViSi}(\text{OMe})_3\text{NH}_2\text{PrSi}(\text{OMe})$ in air

Figure 6. Dependence of mass loss on the temperature of GDC material in the air

Figure 7. Radiograph of a sample of GDC material