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Technology of continuous high-temperature chlorination of high-purity quartz in the presence of air

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Abstract

The relevance of the work is determined by the need to obtain natural high-purity quartz (HPQ) with purity parameters that meet the criteria of the semiconductor industry. High-temperature chlorination is the final stage of purifying HPQ from a number of impurity elements (primarily heavy and alkali metals), the low content of which is critical for the semiconductor industry. Due to the high temperatures of this process, the use of aggressive processing gases and complex hardware design, the production cost of the resulting products when using traditional methods is very high.
The purpose of the work is to confirm a new, more economical and easier to industrially use, compared to previous processes, method of high-temperature chlorination of HPQ with achievement of specified quality parameters for the content of iron, copper, chromium, nickel, sodium and potassium.
Methodology. A comparative analysis of open sources, including patent ones, was carried out; a technological scheme for high-temperature chlorination of HPQ in the presence of air has been developed; an experimental chlorination installation was created; a number of experiments were carried out to determine the optimal cleaning regimes for HPQ; analyzes of the initial and finished chlorination products were carried out using the ICP-OES method.
Results. It has been confirmed that the chemical purity of HPQ has been achieved, meeting the requirements of the semiconductor industry, during high-temperature chlorination of HPQ in the presence of air. Samples of products were obtained that are not inferior in purity to the IOTA 4, IOTA 6 grades of Sibelco, the world leader in the HPQ production. Optimal purification modes using the proposed method were selected.
Conclusions. The proposed method for continuous high-temperature chlorination of HPQ in the presence of air ensures the achievement of the required purity parameters, being more simple in hardware implementation and more economical in terms of capital and production costs in comparison with traditional methods. Can be used in the industrial production of HPQ for the semiconductor industry.

Keywords: high-purity quartz, HPQ, quality criteria, high-temperature chlorination, semiconductor industry, Sibelco, UNIMIN, IOTA, Heraeus, hot chlorination.

Introduction

High temperature chlorination of quartz began to be used as a highly effective method for purifying high-purity quartz (HPQ) since the 1980s [1, 2]. Quartz chlorination is used by such well-known companies as Sibelco (formerly UNIMIN), The Quartz Corp, Heraeus and many others. Many patents have been issued for various options for carrying out chlorination processes for quartz concentrates. Various combinations of chlorination by other methods are used, in particular using microwave heating [3].

Nevertheless, the topic of chlorination of high-purity quartz still remains insufficiently clear from the point of view of the physicochemical justification of the process. This situation, in addition to the closedness of production know-how (problems of instrumentation of the process, especially continuous, selection of chlorination modes, etc.), is possibly due to the fact that the mechanisms and kinetics of the processes of chlorination of natural materials are complex and have not yet been sufficiently studied. This view is confirmed by the fact that in the deposits of fumaroles – to some extent natural analogues of chlorination plants – a large number of new minerals are discovered every year, many of which have no synthetic analogues.

In the theoretical foundations of chlorination, it is possible, with great convention, to distinguish several interconnected sections:

a) properties of crystalline chlorine-containing inorganic compounds. Relatively simple systems have been studied in great detail [4–6], in particular, the issue of balance in chloride–oxide systems, which is often used to interpret the mobility of elements during the chlorination of quartz. Complex oxychlorides are less studied, and many compounds, as indicated, may still be unknown;

b) balance in multicomponent gas mixtures, in particular, data on the oxidation reaction $2HCl + 0.5O_2 \rightarrow Cl_2. + H_2O$. Both the experimental approach [7] and theoretical modeling [8] have become widespread.

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The actual course of processes is strongly influenced by the presence of certain components even in very small quantities, for example, the catalytic effect of Fe_2O_3. Calculation of balance in a multicomponent system by the method of minimizing the Gibbs free energy is now widely used to predict the behavior of various elements in chlorine-containing gaseous atmosphere, but sometimes the calculation results differ by more than an order of magnitude from the observed contents of components in fumarole gases [9];

c) study of real mechanisms of processes at the gas–solid interface and, in a more complicated version, *gas–liquid–solid*;

d) kinetic aspects of chlorination processes and, above all, the rate of diffusion of components in a solid. To a rough approximation, we can say that the diffusion rate increases exponentially with temperature, and the diffusion time at constant temperature is proportional to the square of the distance. The practical implementation of chlorination of quartz at temperatures above 1200 °C is hampered by the complexity of choosing materials for the manufacture of equipment. Estimates of the rates of diffusion of components in quartz grains encounter difficulties in taking into account the real anatomy of natural quartz grains containing various kinds of defects, twin boundaries, pores, etc., while taking into account the role of the polymorphic transition of quartz from a low-temperature modification to a high-temperature one and vice versa;

e) study of the forms of occurrence of elements in natural quartz. The division of impurities into structural and non-structural has become generally accepted, for example, in the now classic works [10]. The flow of works devoted to this aspect is growing like an avalanche, but is not always accompanied by new experimental material. The forms of occurrence of elements in quartz play a large role, for example, when interpreting the more complex removal during chlorination of Li, compared to Na and K (this is often explained by the participation of lithium in charge compensation mechanisms during the isomorphic replacement of silicon with aluminum and the appearance of Al groups –O(Li), a large role is played by $[TiO_4/Li]$, $[GeO_4/Li]$, etc.). In quartz from different objects, and often in quartz from different parts of the same body, the forms of occurrence of certain impurity elements can vary significantly [1].

One more mechanism that can be noted is the purification of quartz during chlorination, the role of which has been poorly studied and, apparently, is underestimated. This is the decripitation of part of the fluid inclusions and the entrainment in the form of an aerosol by the gas flow of the contents of the inclusions, the conversion into volatile chlorides of compounds from salt efflorescences that could have formed during the opening of the inclusions or during acid (HF) treatment (films, accumulations in caverns and cracks) at previous stages of enrichment of quartz grains, especially if it was calcined before chlorination. The reality of such a mechanism of component transfer has been convincingly proven [11, 12].

Currently, high-tech industries, especially the semiconductor industry, are tightening the requirements for the chemical purity of HPQ. The contents of such impurity elements in HPQ as Na, K, Fe should not exceed 0.1 ppm, and in some cases Cr, Ni, Cu, Mn – 0.01 ppm (preferably 0.001 ppm). Achieving such a level of purity in natural quartz is only possible using high-temperature chlorination.

The purpose of the work is to conduct research confirming the possibility of a new method of high-temperature chlorination of HPQ, providing the necessary efficiency of cleaning HPQ and its cost-effectiveness, as well as minimal impact on the environment and the safety of production operations.

Choice of chlorinating gas. Traditionally, industrial chlorination of high-purity quartz is carried out in an atmosphere containing chlorine and (or) hydrogen chloride as a compound that removes impurities.

Both of these gases are toxic and corrosive, but the industrial use of chlorine is subject to much more stringent requirements than the use of hydrogen chloride gas. Studies on the chlorination of high-purity quartz have shown that the use of chlorine as a chlorinating compound does not provide any advantages. Moreover, a comparison of the results of chlorination in an atmosphere of pure chlorine and in an atmosphere of pure hydrogen chloride shows that hydrogen chloride is more effective in removing impurities than chlorine, especially for Fe and Na, for the content of which in high-purity quartz consumers have very stringent requirement. Treatment in a mixture of Cl_2 and HCl shows in a number of experiments slightly higher efficiency than in pure HCl, but the difference in the results obtained is insignificant [13].

An analysis of patent solutions for the chlorination of high-purity quartz, including patents from the world's leading manufacturers of high-purity quartz (Heraeus [14], Feldspar Corporation [15], Unimin [16]), showed that preference for

Table 1. Content of impurity elements in the starting material and product after heat treatment in atmospheres containing Cl_2 and HCl
Таблица 1. Содержание элементов-примесей в исходном материале и продукте после термообработки в атмосферах, содержащих Cl_2 и HCl

Product	Impurity elements, ppm												
	Al	B	Ca	Cr	Cu	Fe	K	Li	Mg	Mn	Na	Ni	Ti
Original RQ-2K	3.5	0.07	0.4	0.04	< 0.01	0.32	0.17	0.25	0.10	< 0.01	0.40	< 0.01	2.6
After chlorination in atmosphere $Cl_2 + N_2$	3.5	0.09	0.4	0.02	< 0.01	0.20	0.02	0.24	0.09	< 0.01	0.15	< 0.01	2.8
After chlorination in an atmosphere of $HCl + N_2$	3.3	0.09	0.3	< 0.01	< 0.01	0.15	0.02	0.20	0.06	< 0.01	0.05	< 0.01	2.6

Note: in this table and below, the contents of trace elements are given based on the results of analyzes of quartz grains using the ICP-OES method after acid opening.

Table 2. Chlorination results depending on the dry air content in the gas mixture [16]
Таблица 2. Результаты хлорирования в зависимости от содержания сухого воздуха в газовой смеси [16]

HCl content, %	Dry air content, %	Fe content, ppm	Na content, ppm	K content, ppm	Li content, ppm
25	75	0.2	0.08	0.29	0.4
50	50	0.2	0.08	0.27	0.4
75	25	0.2	0.06	0.21	0.3
100	0	0.2	0.05	0.18	0.3
Content of impurity elements in the original quartz		***0.4***	***1.00***	***0.70***	***0.4***

industrial cleaning is given to hydrogen chloride, but not chlorine or a gas mixture of Cl_2 and HCl.

Presumably, such a greater efficiency of hydrogen chloride compared to chlorine is due to the fact that dissociated H+ protons penetrate the quartz crystal lattice to maintain neutrality and replace positive metal ions, preventing their reverse diffusion.

An experiment on the chlorination of quartz concentrate grade RQ-2K produced by Russian Quartz LLC in an atmosphere of Cl_2, HCl and neutral gas (nitrogen) also confirmed the greater efficiency of hydrogen chloride (Table 1).

Taking into account the above, gaseous hydrogen chloride was chosen as a chlorinating agent, the most effective in terms of cleaning and industrial use.

Selection of the gas composition of the atmosphere in which chlorination is carried out. One of the key issues addressed in this work is the possibility of effectively reducing impurity elements during chlorination in the presence of air.

The presence of air in the gas mixture during the industrial chlorination of high-purity quartz allows one to significantly simplify the design of the equipment used, reduce its cost and operating costs and, accordingly, reduce the cost of the final product.

Gas mixtures used in industry and pilot plants for the chlorination of high-purity quartz assume the absence of air/oxygen [13–18]. It was assumed that the presence of oxygen sharply reduces the efficiency of the process, in particular, due to this, the formation of stable contaminant compounds in the form of nitrides or oxides, which can then no longer be removed using a treatment gas [14].

At the same time, analysis of data from previous experiments showed that the efficiency of purification in the presence of air in a gaseous environment is quite high, at least in relation to such elements as Fe, Na, K (Table 2).

From the data in table 2, it is clear that the presence of air does not affect the decrease in Fe content. At the same time, although the efficiency of removing alkaline elements is somewhat lower in the presence of air, nevertheless, the decrease in the content of K and especially Na is very significant. It should be noted that traditional chlorination in an oxygen-free atmosphere also does not provide significant results in terms of reducing the Li content.

Thus, gaseous hydrogen chloride in the presence of air was chosen as the gas composition of the mixture in which high-purity quartz is chlorinated.

Experimental hot chlorination pilot line. The studies were carried out in a specially designed experimental hot chlorination pilot line (Fig. 1).

The pilot line includes the following main components:

– a horizontally located rotating reactor made of quartz glass, which is a quartz tube with quartz blades placed inside to mix the flow of quartz grains, through which a flow of quartz grains continuously passes. The reactor is placed in a tubular electric heating furnace with adjustable temperature, adjustable reactor rotation speed and adjustable reactor inclination angle. The rotation speed of the reactor and its angle of inclination make it possible to determine the residence time of quartz grains in the reactor. Quartz blades inside the rotating reactor continuously mix the flow of quartz grains, ensuring uniform and homogeneous contact of quartz particles in the material flow with hydrogen chloride for purification;

– loading unit made of quartz glass, performing two functions – supply of material and removal of gaseous chlorination products;

– an unloading unit made of quartz glass, which performs two functions – unloading the material after cleaning and supplying pure hydrogen chloride to the reactor.

The process of cleaning quartz grains is carried out in a horizontally located rotating single-chamber quartz reactor heated to a temperature of 1200 °C, through which a continuous flow of quartz grains is directed. Gaseous hydrogen chloride is supplied to the reactor through a discharge unit at a controlled speed depending on the processing mode. The gas-air mixture formed in the reactor is forcibly drawn out of the reactor at a speed of at least 2500 l/h through the loading unit. In this case, the hydrogen chloride present in the reactor at a time is sufficient to carry out the necessary reactions, and forced gas-mixture removal ensures the rapid removal of gaseous reaction products of hydrogen chloride and contaminants from the reactor. In addition, rapid drawdown of the gas-air mixture ensures a continuous supply of unreacted hydrogen chloride to the surface of the quartz grains, which significantly accelerates the purification reactions.

The selected cleaning temperature is due to the fact that the effective reaction of contaminant elements with gas begins at a minimum temperature of 1000 °C. The higher the temperature, the more efficient the reaction, however, at temperatures above 1200 °C, the service life of the quartz reactor is reduced, so the optimal temperature is determined to be 1200 °C.

Experiments carried out at an experimental chlorination pilot line. A series of tests of high-temperature chlorination modes of quartz concentrate of the RQ-2K brand produced by Russian Quartz LLC was carried out on an experimental setup.

The experimental conditions were dictated by ideas about the kinetics of the process, the need to achieve the specified

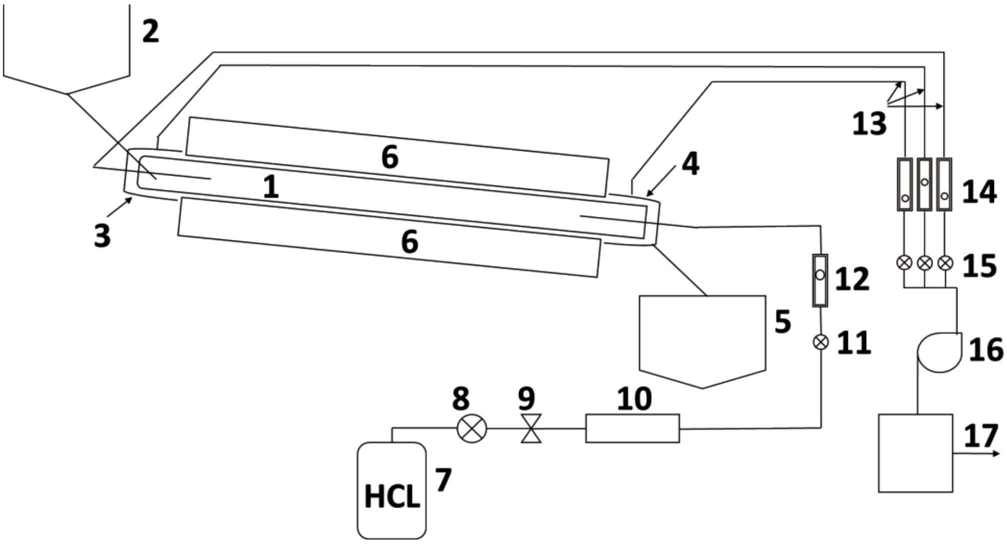

Figure 1. Diagram of a laboratory chlorination pilot line: *1* – rotating reactor; *2* – container with the original quartz grain; *3* – loading unit for purified quartz grains; *4* – unloading unit for original quartz grains; *5* – container with the finished product; *6* – tubular electric heating furnace with adjustable temperature, adjustable reactor rotation speed and adjustable reactor inclination angle; *7* – tanks with hydrogen chloride; *8* – gas reducer; *9* – shut-off valve; *10* – filter for additional purification of hydrogen chloride; *11* – gas flow regulator; *12* – gas flow meter; *13* – pipelines for removing the gas mixture; *14* – meters of removed gas flows; *15* – regulators of removed gas flows; *16* – vacuum pump; *17* – scrubber for neutralizing gaseous chlorination products

Рисунок 1. Схема лабораторной установки хлорирования: *1* – вращающийся реактор; *2* – емкость с исходным кварцевым зерном; *3* – узел загрузки очищаемых кварцевых зерен; *4* – узел разгрузки очищенных кварцевых зерен; *5* – емкость с готовым продуктом; *6* – трубчатая печь электрического нагрева с регулируемой температурой, регулируемой скоростью вращения реактора и регулируемым углом наклона реактора; *7* – баллоны с хлористым водородом; *8* – газовый редуктор; *9* – запорный вентиль; *10* – фильтр дополнительной очистки хлористого водорода; *11* – регулятор подаваемого потока газа; *12* – измеритель подаваемого потока газа; *13* – трубопроводы для удаления газовой смеси; *14* – измерители удаляемых потоков газов; *15* – регуляторы удаляемых потоков газа; *16* – вакуумный насос; *17* – скруббер для нейтрализации газообразных продуктов хлорирования

quality and productivity of the process, and the stability of the production of pilot line as a whole. The process temperature did not vary during the cycle of experiments and was set as 1200 °C. The residence time of the material in the reactor is determined by the speed of rotation of the reactor and the angle of inclination. The lowest rotation speed for the safety of the reactor was chosen to be about 4 rpm. One of the most important parameters for the successful and safe implementation of the process is the rate of removal gas mixture from the reactor, since insufficient removal of gas mixture will lead to leakage of hydrogen chloride into the working area of the pilot line, and excessive suction will lead to the supply of additional air into the reactor volume and additional dilution of the reaction mixture. Experimentally, the most effective and safe gas mixture removal speed was established at 3.2 m^3/h. The variable parameters that varied from experiment to experiment were the rate of supply of hydrogen chloride and loading of the starting material into the reactor. The conditions and results of the experiments are given in table 3.

According to the results of experiments, the optimal mode for industrial cleaning can be adopted at a HCl flow rate of 100–150 l/h and a starting material load of about 10 kg/h.

For example, the method of continuous high-temperature chlorination, according to the patent of the Unimin company, provides for the supply of gaseous HCl in a volume of 1650 l/h with a loading of the starting material of 2.4 kg/h [16].

To evaluate the efficiency of purification in comparison with traditional oxygen-free methods, chlorination of the RQ-2K concentrate was carried out in an independent laboratory, Germany (Table 4).

The result of chlorination in an independent laboratory showed that the efficiency of chlorination of HPQ according to the proposed method is not inferior to methods using an oxygen-free gas mixture and allows for purification according to standardized impurity elements (Fe, Cr, Cu, Ni, Na, K), which are the target when carrying out chlorination, to the level of the most purified grades of HPQ from Sibelco, USA, used in the semiconductor industry (Table 5).

To evaluate the proposed method for purifying other types of high-purity quartz materials, chlorination of quartz grains produced from artificial quartz crystals (IQC) grown hydrothermally, produced by Quartz Technologies , Shilovo, was carried out (Table 6).

The results of AQC chlorination show that the degree of purification from target impurity elements (Fe, Cr, Cu, Ni, Na, K) for this type of high-purity quartz materials is even higher than for natural high-purity quartz, which allows reaching a level of 0.01 ppm and less than 0.01 ppm for Na, K, Cr, Cu, Ni in one purification stage.

The experiments carried out at the experimental pilot line for high-temperature chlorination allow us to draw the following conclusions:

– continuous high-temperature chlorination of high-purity quartz materials in a gas atmosphere with the presence of air/oxygen has been successfully carried out. The quality of the resulting products in terms of the content of standardized impurity elements corresponds to the parameters required by the semiconductor industry;

– the experimental pilot line is suitable for scaling for the purpose of industrial organization of HPQ production;

Table 3. Examples of the results of chlorination of quartz concentrate RQ-2K, ppm (ICP-OES method) at various parameters of supply of chlorinating gas and starting material
Таблица 3. Примеры результатов хлорирования кварцевого концентрата RQ-2K, г/т (метод ICP-OES) при различных параметрах подачи хлорирующего газа и исходного материала

HCl supply, l/h	Loading RQ-2K, kg/h	Impurity elements, ppm										
		Al	Ca	Cr	Cu	Fe	K	Li	Mg	Na	Ni	Ti
Original RQ-2K		***4.0***	***0.19***	***0.008***	***0.002***	***0.18***	***0.16***	***0.29***	***0.03***	***0.41***	***0.001***	***3.4***
60	2.4	3.5	0.15	< 0.001	0.001	0.07	0.06	0.28	< 0.01	0.04	< 0.001	3.3
100	0.5	3.4	0.15	< 0.010	< 0.010	0.09	0.07	0.30	0.06	0.07	< 0.010	3.4
100	0.5	3.6	0.17	< 0.010	< 0.010	0.09	0.08	0.30	0.06	0.06	< 0.010	3.2
120	5.0	3.6	0.15	0.002	0.001	0.08	0.07	0.27	0.01	0.04	< 0.001	3.4
120	6.8	3.8	0.13	0.001	0.001	0.08	0.07	0.27	0.01	0.07	< 0.001	3.4
150	0.5	3.8	0.14	0.001	< 0.001	0.08	0.07	0.29	< 0.01	0.05	< 0.001	3.4
180	13.7	3.5	0.14	0.001	0.001	0.07	0.07	0.27	< 0.01	0.07	< 0.001	3.3
250	1.0	3.6	0.15	0.001	< 0.001	0.09	0.08	0.26	< 0.01	0.05	< 0.001	3.3
260	2.4	3.6	0.12	< 0.001	< 0.001	0.07	0.05	0.26	< 0.01	0.04	< 0.001	3.4

Table 4. Results of chlorination of quartz concentrate RQ-2K, ppm, in an independent laboratory (Germany)
Таблица 4. Результаты хлорирования кварцевого концентрата RQ-2K, г/т, в независимой лаборатории (Германия)

Product	Impurity elements, ppm										
	Al	Ca	Cr	Cu	Fe	K	Li	Mg	Na	Ni	Ti
Original RQ-2K	3.9	0.23	0.020	< 0.010	0.18	0.13	0.25	0.02	0.33	0.020	3.2
Chlorinated RQ-2K (Germany)	4.0	0.32	< 0.010	< 0.010	0.08	0.04	0.26	0.04	0.04	< 0.010	3.2
Chlorinated RQ-2K (HCl supply 260 l/h, loading 2.4 kg/h according to the method in the presence of air)	3.6	0.12	< 0.001	< 0.001	0.07	0.05	0.26	< 0.01	0.04	< 0.001	3.4

Table 5. Comparison of the results of chlorination of quartz concentrate RQ-2K, ppm, with HPQ grades from Sibelco, USA
Таблица 5. Сравнение результатов хлорирования кварцевого концентрата RQ-2K, г/т, с сортами ВЧК компании Sibelco, США

Product	Impurity elements, ppm					
	Cr	Cu	Fe	K	Na	Ni
IOTA STD-SV	0.004	0.003	0.10	< 0.10	< 0.05	0.001
IOTA 4	0.007	0.004	0.30	0.40	1.00	0.002
IOTA 6	0.003	0.001	0.20	0.10	< 0.10	0.002
IOTA 6-SV	0.002	0.001	0,.0	< 0.10	< 0.05	0.001
IOTA 8	0.001	< 0.001	< 0.05	< 0.05	< 0.05	< 0.001
Chlorinated RQ-2K (HCl supply 260 l/h, loading 2.4 kg/h according to the air method)	< 0.001	< 0.001	0.07	0.05	0.04	< 0.001

Table 6. Results of IQC chlorination
Таблица 6. Результаты хлорирования ИКК

Product	Trace elements										
	Al	Ca	Cr	Cu	Fe	K	Li	Mg	Na	Ni	Ti
Original IQC	4.1	0.08	0.05	< 0.01	0.38	0.03	1.00	0.47	1.20	0.02	0.01
IQC after chlorination 2K (HCl supply 100 l/h, loading 10 kg/h according to the method in the presence of air)	4.0	0.01	< 0.01	< 0.01	0.07	< 0.01	0.83	0.10	< 0.01	< 0.01	0.01

– experiments have shown the possibility of significantly lower consumption of gaseous hydrogen chloride in comparison with traditional methods. There is also a small dependence of the quality of the final product on the consumption of hydrogen chloride in the range of 100–300 l/h;

– under the experimental conditions, a significant decrease in the concentrations of Na, K, Fe and less pronounced Mg in HPQ is observed. The behavior of Al during chlorination is less clear – a slight decrease in its concentration is observed, but differences with the initial content may be within the limits of analytical error. If this occurs, then a likely explanation may be the chlorination of aluminum fluoride residues that are formed during the treatment of HPQ at the previous stages of purification with hydrofluoric acid;

– based on the results of successful tests, the method of high-temperature chlorination in the presence of air was patented according to patent RU2691344 [19].

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Технология непрерывного высокотемпературного хлорирования высокочистого кварца в присутствии воздуха

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Аннотация

Актуальность работы определяется необходимостью получения природного высокочистого кварца (ВЧК) с параметрами чистоты, удовлетворяющими критериям полупроводниковой промышленности. Высокотемпературное хлорирование является заключительной операцией очистки ВЧК от ряда элементов-примесей (прежде всего это тяжелые и щелочные металлы), низкое содержание которых является критически важным для полупроводниковой промышленности. В связи с высокими температурами этого процесса, использованием агрессивных обрабатывающих газов и сложным аппаратным оформлением производственная себестоимость получаемой продукции при использовании традиционных методов очень высока.

Цель работы – подтверждение нового, более экономичного и простого в промышленном использовании, по сравнению с предыдущими процессами, способа высокотемпературного хлорирования ВЧК с достижением заданных параметров качества по содержанию железа, меди, хрома, никеля, натрия и калия.

Методология. Проведен сравнительный анализ открытых источников, в том числе патентных; разработана технологическая схема высокотемпературного хлорирования ВЧК в присутствии воздуха; создана экспериментальная установка хлорирования; проведен ряд экспериментов для определения оптимальных режимов очистки ВЧК; проведены анализы исходных и готовых продуктов хлорирования с помощью метода ICP-OES.

Результаты. Подтверждено достижение параметров химической чистоты ВЧК, удовлетворяющих требованиям полупроводниковой промышленности, при высокотемпературном хлорировании ВЧК в присутствии воздуха. Получены образцы продукции, не уступающие по чистоте сортам IOTA 4, IOTA 6 компании Sibelco, мирового лидера в производстве ВЧК. Подобраны оптимальные режимы очистки с использованием предлагаемого способа.

Выводы. Предлагаемый способ непрерывного высокотемпературного хлорирования ВЧК в присутствии воздуха обеспечивает достижение необходимых параметров чистоты, являясь более простым в аппаратной реализации и более экономичным с точки зрения капитальных и производственных затрат в сравнении с традиционными способами. Может быть использован в промышленном производстве ВЧК для полупроводниковой промышленности.

***Ключевые слова*:** высокочистый кварц, ВЧК, критерии качества, высокотемпературное хлорирование, полупроводниковая промышленность, HPQ, Sibelco, UNIMIN, IOTA, Heraeus, hot chlorination, semiconductor industry.

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