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THE EFFECT OF ISOMORPHOUS SUBSTITUTIONS ON THE MELTING OF QUARTZ AND ITS TRANSFORMATION TO CRISTOBALITE

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Abstract. Taking as an example two commercial varieties of rock crystal used for the manufacture of transparent silica glass, the effect of the total content of isomorphous substitutions on the melting rate of quartz and the rate of its transformation to cristobalite has been determined. Quartz that contains more than 100 ppm of these impurities melts more rapidly than pure quartz. More rapid is also the rate of its transformation to cristobalite, yet the optical properties of silica glass formed from cristobalite are worse than those of glass obtained from quartz. Therefore, quartz should be heated to its melting point at a rate preventing its change into cristobalite.

INTRODUCTION

Phase transformations of SiO_2 have been a subject of extensive studies. The temperature of polymorphic changes, their mechanism and kinetics, as well as the factors determining these changes, have been investigated in detail. Relatively little known, however, is the process of melting of quartz. The course of this process is of primary importance for the manufacture of transparent silica glass as it determines the quality of this glass, particularly its homogeneity, force of crystallization and transmission of ultraviolet light.

It is now generally held that the two thermodynamically stable polymorphs of SiO_2 are quartz and cristobalite, each of them having a high- (α) and low-temperature (β) modification. The transformation of quartz to cristobalite has been a subject of extensive studies (Chaklader 1963; Chaklader, Roberts 1958; Roberts, Chaklader 1961). As appears from these studies, cristobalite forms from quartz at about 1450°C. This change, however, does not take place directly but through a transient phase, metacristobalite, the exact nature of which is not yet known. It is thought to be either an amorphous substance (Pranishnikov 1971) or cristobalite with a poorly ordered structure (Chaklader 1963).

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Pure quartz heated at a sufficiently rapid rate melts at 1600–1650°C, changing into a melt without the transformation to cristobalite. Upon cooling, the melt becomes silica glass. The high-temperature modification of SiO₂, α -cristobalite, which is stable above 1470°C, melts at 1713°C.

As appears from earlier investigations (Stoch, Łączka, Kucharski 1980), samples of coarse-crystalline quartz (rock crystal) of different origin melt at different rates. Heated in the same way, they change directly into a melt or their melting is preceded by the formation of varying amounts of cristobalite. The latter has the form of fine-grained powder which is hard to sinter and melts at a much higher temperature than quartz.

The rate of phase transformations of silica is appreciably affected by mineralizers. They are substances containing alkalis, as well as CaO, MgO, Fe₂O₃, Al₂O₃, in their composition. The addition of substantial amounts of mineralizers causes quartz to pass to tridymite. Tridymite is not pure silica as it contains alkalis and alkaline earth metals, as well as iron and aluminium, in its structure, their total content running up to a few per cent. It is feasible that the behaviour of quartz in the process of melting, and especially the amount of cristobalite being formed, may also depend on the content of impurities, including isomorphous substitutions in the structure, as well as on the imperfection of its crystals, such as lattice defects, gas and liquid inclusions, etc.

The effect of structural impurities on the formation of cristobalite in the process of melting of rock crystal is the subject of this paper. Studies have been made of the behaviour of rock crystal in the process of manufacture of silica glass by the method developed by Thermal Syndicate Company Ltd. The method involves the melting of raw material at 1950°C in an electric vacuum rotary furnace with a graphite electrode. Rock crystal used in this method is reduced to a grain-size of 0.3–0.5 mm. To facilitate the grinding, its crystals are heated to 900°C and subjected to thermal shock.

EXPERIMENTAL

Investigations were carried out on quartz used for the large-scale production of silica glass. It was African rock crystal of the trade name of "Angola" and the "Telequartz" rock crystal from Brazil, differing in the degree of chemical purity. The total content of impurities in the Brazilian quartz was twice as high as in the African rock crystal (Table 1).

The quartz crystals to be investigated were carefully purified and ground to a grain-size of 0.1–0.5 mm. They were preheated in an electric furnace in an atmosphere of air at 1500°C for two and four hours to induce the change into cristobalite.

Quartz in natural state and samples subjected to thermal pretreatment were melted at 1650°C and 1750°C in a Baltzers vacuum furnace installed at the Research and Development Centre POLAM in Ożarów near Warsaw. The samples were held in graphite crucibles at the melting temperature for 0.5 hr. The heating rate was: 50–60°C/min. over the temperature range from 20 to 1300°C, 4°C/min. from 1300 to 1500°C, and 6°C/min. above 1550°C.

The phase composition of samples heated at different temperatures was determined using a variety of research methods. Thermal analysis was made with a MOM Budapest Derivatograph apparatus. Quartz content was determined from the peak of DTA curve of β -quartz \rightleftharpoons α -quartz polymorphic transformation at 573°C, and cristobalite content from the peak of β -cristobalite \rightleftharpoons α -cristobalite transformation, appearing at 240–265°C.

Table 1

The content of impurities in "Telequartz" and "Angola" quartz

Quartz	Impurities ppm									
	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	Li ₂ O	MnO	CuO	TiO ₂
Angola	42.6	2.3	2.8	1.0	5.0	1.5	3.5	1.0	1.0	2.0
Telequartz	69.7	2.8	21.8	3.2	14.0	6.0	6.5	0.6	0.6	1.5
										Total
										60.7
										126.7

To determine the content of cristobalite, infrared absorption spectroscopy was also used. Infrared spectra were obtained with a Zeiss UR-10 spectrometer. Cristobalite content was estimated from the intensity of the 620–622 cm⁻¹ band, characteristic of β -cristobalite.

Raman spectra were recorded for some samples with a Varian Carry 82 spectrometer. This method was used to confirm the presence of vitreous phase. According to Görlich *et al.* (1980), silica glass displays bands at 604, 444 and 490 cm⁻¹, permitting one to detect its presence besides crystalline forms of silica when its content is as low as 1 wt. %. The phase composition was also controlled by X-ray method, using a DRON-3 diffractometer. Ultraviolet spectra of silica glass melted from the rock crystals studied were obtained with a Zeiss UVIS spectrometer.

RESULTS AND DISCUSSION

Quartz heated at 1500°C changes progressively into α -cristobalite. From DTA curves (Fig. 1) it is evident that the degree of this change is different for the two rock crystals under study. As the heating time is prolonged, the peak of the low-high quartz transformation at 573°C diminishes and simultaneously there appears a peak of the polymorphic transformation of cristobalite (263°C). The "Telequartz" quartz changes rapidly into cristobalite. After 4-hour heating the peak of quartz disappears, which indicates that its content has decreased to less than 10 wt. %. The degree of transformation for the "Angola" quartz, which shows higher purity, is less. After 4-hour heating the bulk of quartz has not changed, and a weak peak of quartz is still visible (Fig. 1, curve 6).

As a result of heating of the "Angola" quartz at 1500°C, the doublet at 780–798 cm⁻¹, typical of quartz, becomes less pronounced in its infrared absorption spectrum (Fig. 2). After 4-hour heating, a single band of cristobalite appears in its place at 790 cm⁻¹. This phase also displays a characteristic band at 623 cm⁻¹. At the same time a change has been noted in the shapes of quartz bands occurring between 400 and 600 cm⁻¹ and between 900 and 1300 cm⁻¹.

In the case of the "Telequartz" quartz, cristobalite bands attain considerable intensity already after 2-hour heating (Fig. 3, curve b). This fact confirms the earlier statement that this quartz changes more rapidly into cristobalite than the "Angola" quartz. The degree of transformation of "Telequartz" after 4 hours, determined from its infrared spectrum, is 80 wt. % compared with 35 wt. % for the "Angola" quartz (Table 2).

X-ray investigation has confirmed the presence of cristobalite and unchanged quartz alone in the two quartz samples heated at 1500°C. The determined content of quartz, however, is relatively low. It follows therefore that besides cristobalite

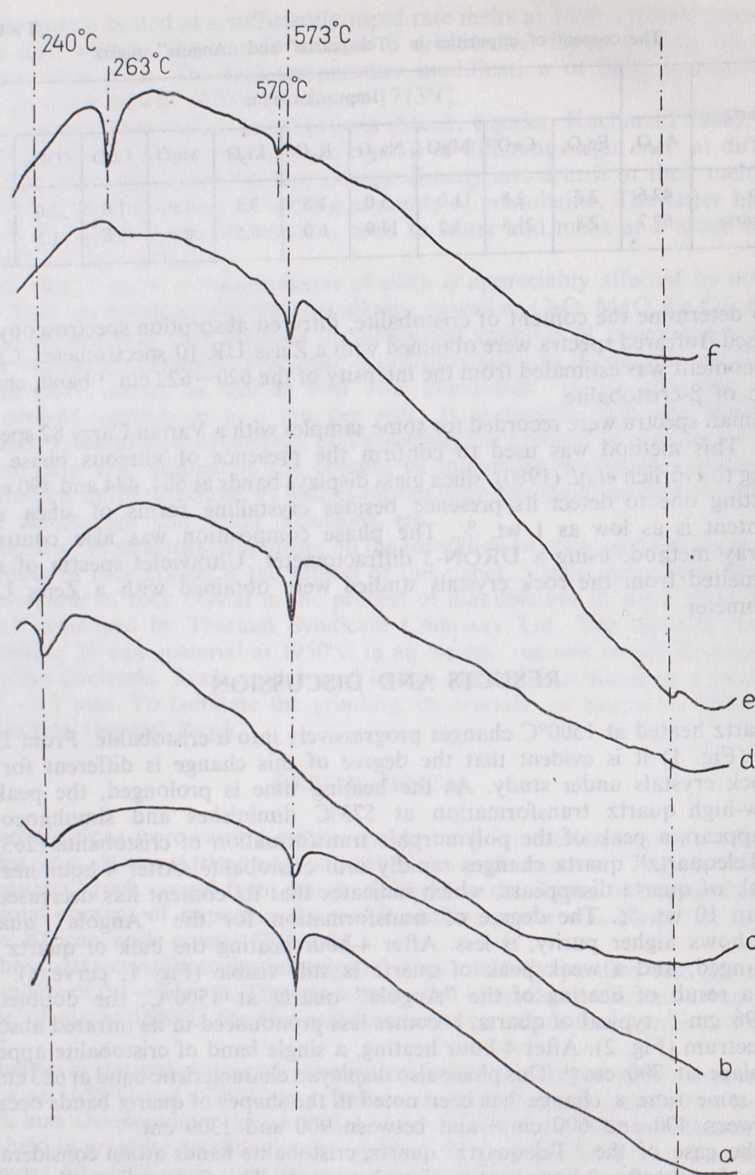


Fig. 1. DTA curves: *a* — untreated „Telequartz”, *b* — „Telequartz” preheated at 1500°C for 2 hours, *c* — „Telequartz” preheated at 1500°C for 4 hours, *d* — untreated „Angola” quartz, *e* — „Angola” quartz preheated at 1500°C for 2 hours, *f* — „Angola” quartz preheated at 1500°C for 4 hours

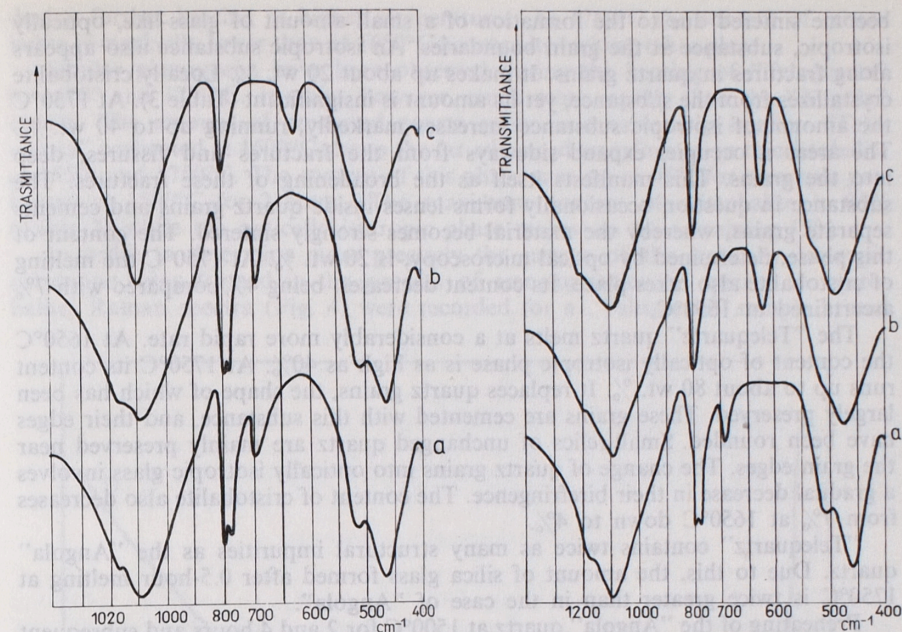


Fig. 2. Infrared absorption spectra: *a* — untreated „Angola” quartz, *b* — „Angola” quartz heated at 1500°C for 2 hours, *c* — „Angola” quartz heated at 1500°C for 4 hours

Fig. 3. Infrared spectra: *a* — untreated „Telequartz”, *b* — „Telequartz” heated at 1500°C for 2 hours, *c* — „Telequartz” heated at 1500°C for 4 hours

and quartz, a substance is present that completes the content of these two crystalline phases to 100%. It failed, however, to be detected by X-ray method or infrared absorption spectroscopy.

Optical examination under the polarizing microscope has revealed the presence of isotropic substance besides quartz and cristobalite grains which are anisotropic in polarized light. This substance fills up fractures and fissures in quartz grains and corresponds to the so-called metacristobalite, described in several papers. It is held that it is a substance with the structure of cristobalite which is so defect that it does not show optical anisotropy.

As a next step, the behaviour of quartz heated at 1650° and 1750°C in a Baltzers furnace was investigated. It is known that quartz begins to melt at these temperatures. After heating at 1650°C for 0.5 hr the „Angola” quartz grains

Table 2
Phase composition of quartz heated at 1500°C

Quartz	Heating time (hrs)	Phase composition
Angola	2	Quartz, ca 4% of cristobalite
Angola	4	Quartz, ca 35% of cristobalite
Telequartz	2	Quartz, ca 20% of cristobalite
Telequartz	4	Quartz, ca 80% of cristobalite

become sintered due to the formation of a small amount of glass-like, optically isotropic, substance at the grain boundaries. An isotropic substance also appears along fractures in quartz grains. It makes up about 20 wt. %. Locally cristobalite crystallizes from the substance, yet its amount is insignificant (Table 3). At 1750°C the amount of isotropic substance increases markedly, running up to 40 wt. %. The areas it occupies expand sideways from the fractures and fissures, deep into the grains. This manifests itself as the broadening of these fractures. The substance in question occasionally forms lenses inside quartz grains and cements separate grains, whereby the material becomes strongly sintered. The content of this phase, determined by optical microscopy, is 20 wt. %. At 1750°C the melting of cristobalite also takes place. Its content decreases, being 4% compared with 7% ascertained at 1650°C.

The "Telequartz" quartz melts at a considerably more rapid rate. At 1650°C the content of optically isotropic phase is as high as 40%. At 1750°C its content runs up to about 80 wt. %. It replaces quartz grains, the shape of which has been largely preserved. These grains are cemented with this substance, and their edges have been rounded. Small relics of unchanged quartz are mainly preserved near the grain edges. The change of quartz grains into optically isotropic glass involves a gradual decrease in their birefringence. The content of cristobalite also decreases from 7% at 1650°C down to 4%.

"Telequartz" contains twice as many structural impurities as the "Angola" quartz. Due to this, the amount of silica glass formed after 0.5-hour melting at 1750°C is twice greater than in the case of "Angola".

Preheating of the "Angola" quartz at 1500°C for 2 and 4 hours and subsequent heating to 1650° and 1750°C enhances the rate of its transformation to cristobalite. The content of this phase increases respectively from 4 and 7% to 17 and 35%. It appears therefore that the transformation initiated by the longer heating of quartz at a temperature favouring the formation of cristobalite takes place rapidly

during further heating at higher temperatures. At 1750°C the content of cristobalite is markedly lower than at 1650°C because its melting takes place.

Similar phenomena have been observed during the heating of "Telequartz" to 1650° and 1750°C. It melts, however, much more rapidly than the "Angola" quartz. The amount of preserved quartz grains is considerably smaller. "Telequartz" preheated at 1500°C shows the far-advanced transformation to cristobalite at 1650° and 1750°C. The content of this phase runs up to 45% for a sample preheated at 1500°C for 2 hours. The maximum content of cristobalite is 85% (Table 3) while the optically isotropic phase makes up the remaining 15%.

In order to determine more precisely the nature of the optically isotropic substance being formed in the process of transformation of quartz to cristobalite, Raman spectra (Fig. 4) were recorded for a "Telequartz" sample heated

Table 3
The content of cristobalite in samples heated at 1650 and 1750°C

Quartz	Heating temperature (°C)	Approximate content of cristobalite
Angola	1650	7
Angola	1750	4
Angola preheated at 1500°C for 2 hrs	—	4
Angola preheated at 1500°C for 2 hrs	1650	17
Angola preheated at 1500°C for 2 hrs	1750	12
Angola preheated at 1500°C for 4 hrs	—	35
Angola preheated at 1500°C for 4 hrs	1650	65
Angola preheated at 1500°C for 4 hrs	1750	45
Telequartz	1650	7
Telequartz	1750	4
Telequartz preheated at 1500°C for 2 hrs	—	20
Telequartz preheated at 1500°C for 2 hrs	1650	45
Telequartz preheated at 1500°C for 2 hrs	1750	60
Telequartz preheated at 1500°C for 4 hrs	—	80
Telequartz preheated at 1500°C for 4 hrs	1650	85
Telequartz preheated at 1500°C for 4 hrs	1750	55

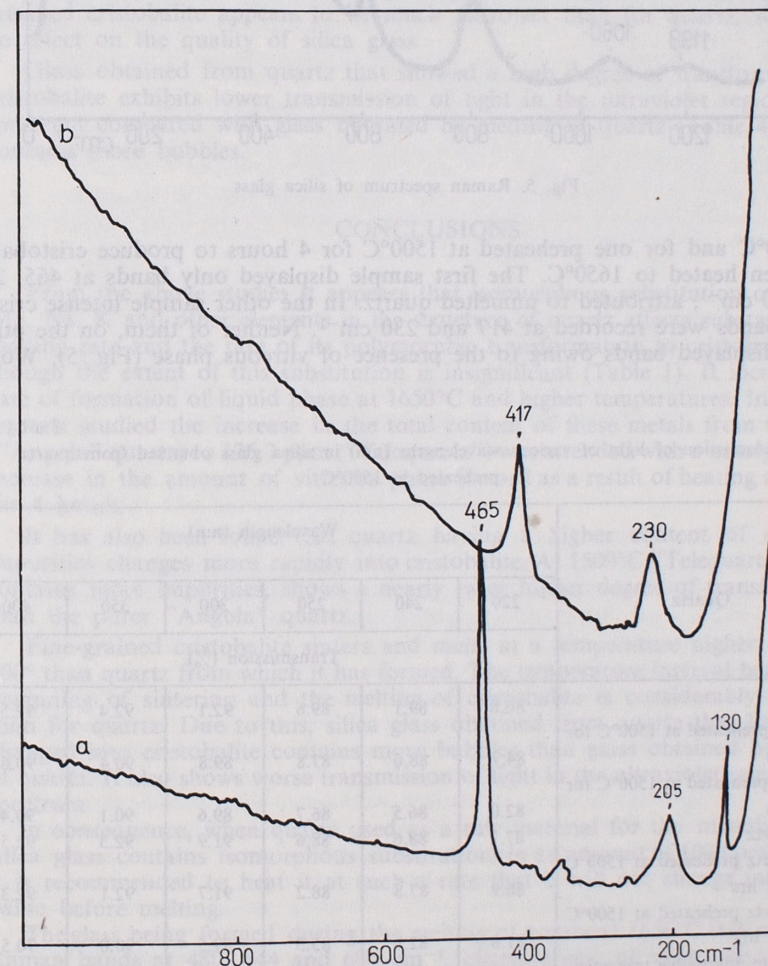


Fig. 4. Raman spectra of quartz: a — "Telequartz" heated at 1650°C for 0.5 hr, b — "Telequartz" heated at 1500°C for 4 hrs and then at 1650°C at 0.5 hr

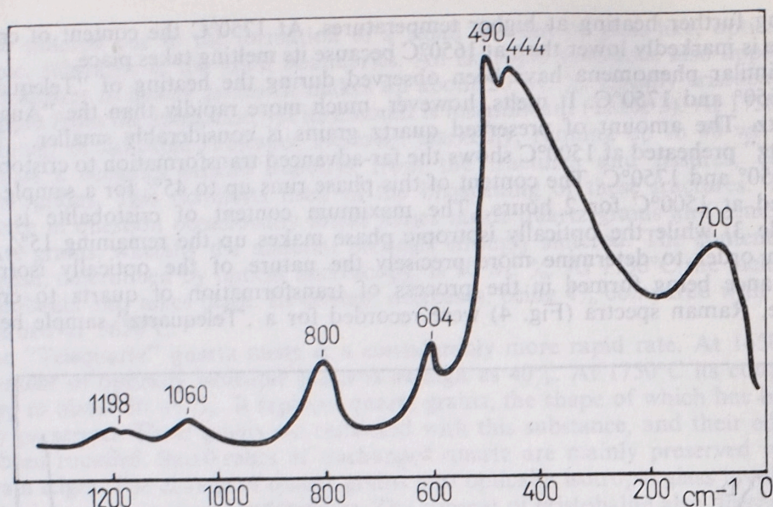


Fig. 5. Raman spectrum of silica glass

to 1650°C and for one preheated at 1500°C for 4 hours to produce cristobalite and then heated to 1650°C. The first sample displayed only bands at 465, 205 and 130 cm^{-1} , attributed to unmelted quartz. In the other sample intense cristobalite bands were recorded at 417 and 230 cm^{-1} . Neither of them, on the other hand, displayed bands owing to the presence of vitreous phase (Fig. 5). Worth

Table 4

Transmission of light of various wavelengths (nm) in silica glass obtained from quartz preheated at 1500°C

Quartz	Wavelength (nm)					
	220	240	250	300	350	400
	Transmission (%)					
Angola	86.8	89.1	89.6	92.1	92.4	92.5
Angola preheated at 1500°C for 2 hrs	84.7	88.0	87.8	89.8	90.4	90.6
Angola preheated at 1500°C for 4 hrs	82.0	86.5	86.7	89.6	90.1	90.4
Telequartz	87.1	88.6	88.6	91.9	92.3	92.5
Telequartz preheated at 1500°C for 2 hrs	86.9	87.8	88.2	91.7	92.1	92.3
Telequartz preheated at 1500°C for 4 hrs	81.8	82.0	85.5	89.5	90.0	90.5
Minimum admissible transmission	82.0	82.0	85.5	88.5	90.5	90.5

noting is the fact that X-ray diffraction patterns of these samples do not show a broad band at 0.4 nm that is typical of silica glass.

Pure quartz and quartz that has largely changed into cristobalite behave differently in the process of melting. The melting of quartz proceeds progressively, beginning with the sintering of the raw material throughout its volume. It is noticeable already at 1650°C and causes a small amount of liquid phase to appear at this temperature. At 1750°C the charge has the form of solid, partly vitrified sinter.

Quartz that has been largely transformed to cristobalite by preheating at 1500°C sinters only at temperatures higher than 1700°C. Pellets of vitrified sinter form at 1750°C, the bulk of material remaining in the form of powder. The temperature interval between the beginning of sintering and the melting of fine-grained cristobalite appears to be much narrower than for quartz, which has an effect on the quality of silica glass.

Glass obtained from quartz that showed a high degree of transformation to cristobalite exhibits lower transmission of light in the ultraviolet region of the spectrum compared with glass obtained by melting of quartz (Table 4). It also contains more bubbles.

CONCLUSIONS

From the above studies it appears that isomorphous substitution of Al, Ca, Mg, Na, K and other elements in the structure of quartz affects substantially its melting rate and the rate of its polymorphic transformation to cristobalite, even though the extent of this substitution is insignificant (Table 1). It increases the rate of formation of liquid phase at 1650°C and higher temperatures. In the rock crystals studied the increase in the total content of these metals from 60.7 ppm ("Angola" quartz) to 126.7 ppm ("Telequartz") was attended with a nearly fourfold increase in the amount of vitreous phase formed as a result of heating at 1650°C for 4 hours.

It has also been found that quartz having a higher content of structural impurities changes more rapidly into cristobalite. At 1500°C "Telequartz", which contains more impurities, shows a nearly twice higher degree of transformation than the purer "Angola" quartz.

Fine-grained cristobalite sinters and melts at a temperature higher by about 100° than quartz from which it has formed. The temperature interval between the beginning of sintering and the melting of cristobalite is considerably narrower than for quartz. Due to this, silica glass obtained from quartz that has largely changed into cristobalite contains more bubbles than glass obtained by melting of quartz. It also shows worse transmission of light in the ultraviolet region of the spectrum.

In consequence, when quartz used as a raw material for the manufacture of silica glass contains isomorphous substitutions in an amount of 100 ppm or more, it is recommended to heat it at such a rate that it will not change into cristobalite before melting.

The glass being formed during the melting of quartz at 1650°C fails to display Raman bands at 480, 444 and 604 cm^{-1} , characteristic of silica glass. Neither does the 0.4 nm band, typical of silica glass, appear in X-ray diffraction patterns. It can be inferred from these facts that while melting, quartz forms initially a melt in which the structural elements of quartz are preserved. Upon cooling,

it changes into silica glass with the structure closer to that of quartz than to the structure of cristobalite, and therefore it does not display the bands in question.

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WPLYW PODSTAWIEŃ IZOMORFICZNYCH NA PRZEMIANĘ W KRYSOTALIT I TOPIENIE KWARCU

Streszczenie

Na przykładzie dwóch handlowych gatunków kryształu górskiego „Angola” i „telequartz” (Brazylia), używanych do wytwarzania przezroczystego szkła krzemionkowego, określono wpływ sumarycznej zawartości podstawień izomorficznych na szybkość topienia i przemiany kwarcu w krystobalit.

Z przeprowadzonych badań wynika, że podstawienia izomorficzne Al, Ca, Na, K i innych pierwiastków w strukturze kwarcu mają istotny wpływ na szybkość jego topienia oraz przemianę polimorficzną w krystobalit, mimo że występują one w nieznacznych ilościach (tab. 1). Zwiększają one szybkość tworzenia się fazy ciekłej w temperaturze 1650°C i wyższych. W przypadku badanych kwarców zwiększeniu sumarycznej zawartości tych metali z 60,7 ppm (kwarc „Angola”) do 126,7 ppm („telequartz”) towarzyszył około czterokrotny wzrost ilości fazy szklistej, powstałej w wyniku ogrzewania w 1650°C przez 4 godziny. Równocześnie kwarc o większej ilości zanieczyszczeń strukturalnych szybciej przechodzi w krystobalit. W temperaturze 1500°C spośród dwu badanych kwarców, „telequartz” zawierający więcej zanieczyszczeń wykazywał około dwukrotnie większy stopień przemiany w porównaniu z czystym kwarcem „Angola”.

Drobnoziarnisty krystobalit spieka się i topi w temperaturze około 100°C wyższej w porównaniu z kwarcem, z którego powstał. Przedział temperatur pomiędzy początkiem spiekania a topieniem krystobalitu jest znacznie krótszy niż kwarcu. Powoduje to, że szkło krzemionkowe otrzymane z kwarcu, który w znacznym

stopniu przeszedł wcześniej w krystobalit, zawiera więcej pęcherzy niż uzyskane przez stopienie kwarcu. Wykazuje ono też gorszą przepuszczalność w ultrafioletowej części widma. W konsekwencji używając do wytwarzania szkła krzemionkowego surowca w postaci kwarców, które zawierają podstawienia izomorficzne w ilości około 100 ppm lub więcej, zalecane jest grzać je z taką szybkością, aby przed ich stopieniem nie zaszła przemiana w krystobalit.

Szkło powstające w czasie topienia kwarcu w temperaturze 1650°C nie daje ramanowskich pasm 480, 444 i 604 cm^{-1} , charakterystycznych dla szkła krzemionkowego. Na dyfraktogramie rentgenowskim nie pojawia się też pasmo około 0,4 nm, typowe dla szkła krzemionkowego.

Nasuwa się przypuszczenie, że kwarc topiąc się tworzy w pierwszej chwili stop, w którym zachowane są elementy struktury kwarcu. Ostudzony przechodzi on w szkło krzemionkowe, którego struktura bliższa jest strukturze kwarcu niż krystobalitu i stąd brak wspomnianych linii.

OBJAŚNIENIA FIGUR

- Fig. 1. Krzywe DTA: a — „Telequartz” w stanie naturalnym, b — „Telequartz” po wstępnej obróbce termicznej w temperaturze 1500°C przez 2 h, c — „Telequartz” po wstępnej obróbce termicznej w temperaturze 1500°C przez 4 h, d — kwarc „Angola” w stanie naturalnym, e — kwarc „Angola” po wstępnej obróbce termicznej w temperaturze 1500°C przez 2 h, f — kwarc „Angola” po wstępnej obróbce termicznej w temperaturze 1500°C przez 4 h
- Fig. 2. Widma w podczerwieni: a — kwarc „Angola” w stanie naturalnym, b — kwarc „Angola” ogrzewany w temperaturze 1500°C przez 2 h, c — kwarc „Angola” ogrzewany w temperaturze 1500°C przez 4 h
- Fig. 3. Widma w podczerwieni: a — „Telequartz” w stanie naturalnym, b — „Telequartz” ogrzewany w temperaturze 1500°C przez 2 h, c — „Telequartz” ogrzewany w temperaturze 1500°C przez 4 h
- Fig. 4. Widma ramanowskie kwarcu: a — „Telequartz” ogrzewany w temperaturze 1650°C przez 0,5 h, b — „Telequartz” ogrzewany w temperaturze 1500°C przez 4 h, a następnie w temperaturze 1650°C przez 0,5 h
- Fig. 5. Widmo ramanowskie szkła krzemionkowego

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ВЛИЯНИЕ ИЗОМОРФНЫХ ЗАМЕЩЕНИЙ НА ПРЕВРАЩЕНИЕ В КРИСТОБАЛИТ И ПЛАВЛЕНИЕ КВАРЦА

Резюме

На примере двух коммерческих видов горного хрусталя — „Ангولا” и „Телекварц” (Бразилия), применяемых для получения прозрачного силикатного стекла, определено влияние суммарного содержания изоморфных замещений на скорость плавления кварца и его превращения в кристобалит.

Исследования показали, что изоморфные замещения Al, Ca, Na, K и других элементов, несмотря на их незначительное количество (табл. 1) в структуре кварца, оказывают существенное влияние на скорость его плавления и полиморфное превращение в кристобалит. Они ускоряют возникновение жидкой фазы при температурах 1650°C и выше. В исследованных видах кварца увеличение общего количества указанных металлов с 60,7 ppm (кварц „Ангولا”) до 126,7 ppm („Телекварц”) сопровождалось почти четырехкратным ростом количества стекловатой фазы, образующейся при нагреве при 1650°C в течение 4 часов.

В то же время кварц с повышенным содержанием структурных загрязнений быстрее превращается в кристобалит. При температуре 1500°C „Телекварц” содержащий больше загрязнений в сравнении с видом „Ангола”, проявлял почти в два раза большую степень превращения.

Мелкозернистый кристобалит спекается и плавится при температуре почти на 100°C выше температуры плавления кварца, за счет которого он образовался. Температурный интервал между началом спекания и плавлением кристобалита значительно уже, чем у кварца. В связи с этим силикатное стекло, полученное из кварца, который ранее в значительной степени превратился в кристобалит, содержит больше пузырьков, чем стекло, полученное путем плавления кварца. Кроме того, оно отличается более слабой проницаемостью в ультрафиолетовом интервале спектра.

Отсюда следует, что при производстве силикатного стекла из кварцевого сырья, содержащего изоморфные примеси в количестве 100 ppm и более, рекомендуется производить нагрев с такой скоростью, чтобы до момента плавления кварца не произошло его превращение в кристобалит.

Стекло, образующееся во время плавления кварца при 1650°C, не дает рамановских полос 480, 444 и 604 см⁻¹, которые характерны для силикатного стекла. На рентгеновской диффрактограмме не появляется также типичная для силикатного стекла полоса 0,4 nm.

Возникает предположение, что при плавлении кварца в первоначальный момент возникает сплав, сохраняющий элементы структуры кварца. При остывании он переходит в силикатное стекло, структура которого более близка структуре кварца, чем кристобалита, и по этому отсутствуют упомянутые спектральные линии.

ОБЪЯСНЕНИЯ К ФИГУРАМ

- Фиг. 1. Кривые ДТА: *a* — „Телекварц” в натуральном виде, *b* — „Телекварц” после предварительной термической обработки при 1500°C, в течение 2 часов, *c* — „Телекварц” после предварительной термической обработки при 1500°C, в течение 4 часов, *d* — кварц „Ангола” в натуральном виде, *e* — кварц „Ангола” после предварительной термической обработки при 1500°C, в течение 2 часов, *f* — кварц „Ангола” после предварительной термической обработки при 1500°C, в течение 4 часов
- Фиг. 2. Инфракрасные спектры: *a* — кварц „Ангола” в натуральном виде, *b* — кварц „Ангола” прокаленный при 1500°C в течение 2 часов, *c* — кварц „Ангола”, прокаленный при 1500°C в течение 4 часов
- Фиг. 3. Инфракрасные спектры: *a* — „Телекварц” в натуральном виде, *b* — „Телекварц”, прокаленный при 1500°C в течение 2 часов, *c* — „Телекварц”, прокаленный при 1500°C в течение 4 часов
- Фиг. 4. Рамановские спектры кварца: *a* — „Телекварц”, прокаленный при 1650°C в течение 0,5 часа, *b* — „Телекварц”, прокаленный при 1500°C в течение 4 часов, а затем при 1650°C в течение 0,5 часа
- Фиг. 5. Рамановский спектр силикатного стекла