SCHOTT
glass made of ideas

Technical Glasses

Physical and Technical Properties

SCHOTT is a leading international technology group in the areas of specialty glass and glass-ceramics. With more than 130 years of outstanding development, materials and technology expertise we offer a broad portfolio of high-quality products and intelligent solutions that contribute to our customers' success.

For 130 years, SCHOTT has been shaping the future of glass technology. The Otto Schott Research Center in Mainz is one of the world's leading glass research institutions. With our development center in Duryea, Pennsylvania (USA), and technical support centers in Asia, North America and Europe, we are present in close proximity to our customers around the globe.

Foreword

Apart from its application in optics, glass as a technical material has exerted a formative influence on the development of important technological fields such as chemistry, pharmaceutics, automotive, optics, optoelectronics and information technology. Traditional areas of technical application for glass, such as laboratory apparatuses, flat panel displays and light sources with their various requirements on chemical-physical properties, have led to the development of a great variety of special glass types. Through new fields of application, particularly in optoelectronics, this variety of glass types and their modes of application have been continually enhanced, and new forming processes have been developed. The hermetic encapsulation of electronic components has given decisive impetus to development activities. Finally, the manufacture of high-quality glass-ceramics from glass has opened entirely new dimensions, setting new standards for various technical applications.

To continuously optimize all commercial glasses and glass articles for existing applications and develop glasses and processes for new applications is the constant endeavor of SCHOTT. For such dynamic development, it is essential to be in close contact with the customers and to keep them as well informed as possible about glass.

SCHOTT Technical Glasses offers pertinent information in concise form. It contains general information for the determination and evaluation of important glass properties and also informs about specific chemical and physical characteristics and possible applications of the commercial technical glasses produced by SCHOTT. With this brochure, we hope to assist scientists, engineers, and designers in making the appropriate choice and make optimum use of SCHOTT products.

Users should keep in mind that the curves or sets of curves shown in the diagrams are not based on precision measurements but rather characterize and illustrate the typical property profiles of the respective glasses or glass types. Up-to-date characteristic values of particular glasses can be found in the tables of this brochure or in separate data sheets.

Contents

Basic physical & chemical properties of specialty glass

Application of specialty glass in select fields

Appendix

1. Types of Technical Glasses

In the following, technical glasses are understood to be special glasses manufactured in the form of tubes, rods, hollow vessels and a variety of special shapes, as well as flat glass and glass powder for use mainly in chemistry, laboratory technology, pharmaceuticals, optoelectronics, and household appliance technology.

Glasses for purely optical applications are usually distinguished from these technical glasses by their special manufacturing processes and by their special compositional ranges.

For the purposes of classification, the multitude of technical glasses can be roughly arranged in the following six groups, according to their oxide composition (in weight percent). It should be noted, however, that certain glasses fall between these groups, and others completely outside of the groups, and therefore cannot be classified as belonging to these types.

Borosilicate glasses

Characteristic of this type is the presence of substantial amounts of silica (SiO_2) and boric oxide ($B_2O_3 > 8\,\%$) as glass network formers.

The amount of boric oxide affects the glass properties in a particular way. Apart from the highly resistant varieties (B_2O_3 up to a maximum of 13 %), there are others that – due to the different way in which the boric oxide is incorporated into the structural network – have only low chemical resistance (B_2O_3 content over 15 %). Hence we differentiate between the following subtypes.

Non-alkaline earth borosilicate glass (borosilicate glass 3.3)

The B_2O_3 content for borosilicate glass is typically 12 – 13 % and the SiO_2 content over 80 %. High chemical durability and low thermal expansion (3.3×10^{-6}/K) – the lowest of all commercial glasses for large-scale technical applications – make this a multitalented glass material.

High-grade SCHOTT borosilicate flat glasses are used in a wide variety of industries, mainly for technical applications that require either good thermal resistance, excellent chemical durability, or high light transmission in combination with a pristine surface quality. Other typical applications for different forms of borosilicate glass include glass tubing, glass piping, glass containers, etc. especially for the chemical industry.

BOROFLOAT® 33, SUPREMAX® and DURAN® belong to this glass family.

Alkaline earth containing borosilicate glasses

In addition to about 75 % SiO_2 and 8 – 12 % B_2O_3, these glasses contain up to 5 % alkaline earths and alumina (Al_2O_3). To this subtype of slightly softer glasses (as compared with non-alkaline earth borosilicate glass), which have thermal expansion of between $4.0 – 5.0 \times 10^{-6}$/K, belong the chemically highly resistant varieties FIOLAX® 8412 and 8414 (“neutral glasses”), and SUPRAX® and 8488.

High-borate borosilicate glasses

Glasses containing 15 – 25 % B_2O_3, 65 – 70 % SiO_2, and smaller amounts of alkalis and Al_2O_3 as additional components, have low softening points and low thermal expansion. Sealability to metals in the expansion range of tungsten-molybdenum and high electrical insulation are their most important features. The increased B_2O_3 content reduces the chemical resistance; in this respect, high-borate borosilicate glasses differ widely from non-alkaline earth and alkaline earth borosilicate glasses.
Examples: 8245, 8250, 8337B, 8487.

Aluminosilicate glasses

Alkaline earth aluminosilicate glasses

Characteristically, these glasses are free of alkali oxides and contain 15 – 25 % Al_2O_3, 52 – 60 % SiO_2, and about 15 % alkaline earths. Very high transformation temperatures and softening points are typical features. Main fields of application are glass bulbs for halogen lamps, high-temperature thermometers, thermally and electrically highly loadable film resistors and combustion tubes.
Examples: Halogen lamp glass types 8252 and 8253.

Alkali aluminosilicate glasses

The Al_2O_3 content of alkali aluminosilicate glasses is typically 10 – 25 % and the alkali content over 10 %. The high alkali content prepares the glass for ion exchange with bigger alkali ions in order to improve the surface compressive strength. High transformation temperatures and outstanding mechanical properties, e. g. hardness and scratch behavior, are characteristic features of this glass type. Examples: Ion exchange glass types AS87 (8787) and LAS80 (8785).

Aluminoborosilicate glasses

Alkaline-free aluminoborosilicate glasses
Typically, these glasses essentially consist of 55 – 65 % SiO_2, 15 – 20 % Al_2O_3, 5 – 10 % B_2O_3 and about 10 to 15 % alkaline earth oxides, without any additions of alkali oxides. A low coefficient of thermal expansion combined with high transformation temperature and good chemical stabilities makes them especially useful as substrate glasses for flat panel displays.
Examples: substrate glasses for TFT displays AF37 (8264) and AF32 (8266).

Alkali-lead silicate glasses

Such glasses typically contain over 10 % lead oxide (PbO). Lead glasses containing 20 – 30 % PbO, 54 – 58 % SiO_2 and about 14 % alkalis are highly insulating and therefore of great importance in electrical engineering. They are used in lamp stems.

Ingredients for the production of special glasses

Lead oxide is also of great importance as an X-ray protective component in radiation shielding glasses.

Alkali alkaline earth silicate glasses (soda-lime glasses)

This is the oldest glass type. It comprises flat glasses (window glass) and container glasses, which are produced in large batches. Such glasses contain about 15 % alkali (usually Na_2O), 13 – 16 % alkaline earths (CaO + MgO), 0 – 2 % Al_2O_3 and about 71 % SiO_2.

Different versions of the basic composition can also contain significant amounts of BaO with reduced alkali and alkaline earth content. Example: 8350.

Also belonging to this group are glasses with higher BaO content for X-ray protection such as those used in technical applications requiring radiation shielding. On a broader plane, certain crystal glasses (drinking glasses) can also be included.

LAS-glass-ceramics

Due to their outstanding properties, crystallizable glasses in the Lithium-Aluminium-Silicate (LAS) system have achieved high commercial significance. Key properties are very low, even zero thermal expansion, optical transparency and high chemical resistance. Characteristically, these glasses contain 3 – 6 % Li_2O, 18 – 25 % Al_2O_3, 58 – 75 % SiO_2 (crystal constituents), 2 – 6 % $TiO_2 + ZrO_2$ (nucleating agents) and about 2 % alkaline and alkaline earths to improve glass melting (residual glass formers). MgO, ZnO and P_2O_5 can also enter the crystalline phase to form solid solution crystals. Coloration of glass-ceramics (by adding coloring oxides like V_2O_5, Fe_2O_3, CoO, NiO, MnO_2) creates black CERAN® cooktop panels. Transparent glass-ceramics are used in ROBAX® fireplace windows, CERAN CLEARTRANS® cooktop panels with underside coating, PYRAN® Platinum fire resistant glazings, ZERODUR® precision articles and a broad range of special applications under the trade name NEXTREMA®.
Examples: CERAN HIGHTRANSeco® 8712, ROBAX® 8724

2. Chemical Stability/Resistance of Glasses

Characteristically, glass is highly resistant to water, salt solutions, acids, and organic substances. In this respect, it is superior to most metals and plastics. Glass is attacked to a significant degree – particularly at higher temperatures – only by hydrofluoric acid, strong alkaline solutions, and concentrated phosphoric acid.

Chemical reactions with glass surfaces, induced by exchange, erosion or adsorption processes, can cause most diversified effects ranging from virtually invisible surface modifications to opacity, staining, thin films with interference colors, crystallization, bubbles, rough or smooth ablation, to name but a few. These changes are often limited to the glass surface, but in extreme cases they can completely destroy or dissolve the glass. Glass composition, contact medium, and operating conditions will decide to what extent such chemical attacks are technically significant.

2.1 Chemical reaction mechanisms with water, acids, and alkaline solutions

Chemical stability is to be understood as the resistance of the glass surface to chemical attack by defined agents, whereby temperature, exposure time, and the condition of the glass surface play important roles.

Every chemical attack on glass involves water or its dissociation product, i.e. H^+ or OH^- ions. For this reason, we differentiate between hydrolytic (water), acid and alkali resistance. By water or acid attacks, small amounts of (mostly mono- or divalent) cations are leached out. In resistant glasses, a very thin layer of silica-gel then forms on the surface, which normally inhibits further attack (Figure 1a, b). Hydrofluoric acid, alkaline solutions and in some cases phosphoric acid, however, gradually destroy the silica framework and thus ablate the glass surface in total (see Figure 1c). In contrast, water-free (i.e. organic) solutions do not react with glass.

Chemical reactions are often increased or decreased by the presence of other components. Alkali attack on glass is thus hindered by certain ions, particularly those of aluminum. On the other hand, complex-forming compounds such as EDTA, tartaric acid, citric acid, and others increase solubility. In general terms, the glass surface reacts with solutions which induce small-scale exchange reactions and/or adsorptions. Such phenomena are observed, for example, in high-vacuum technology when residual gases are removed, or in certain inorganic chemical operations when small amounts of adsorbed chromium, resulting from treatment with chromic acid, are removed.

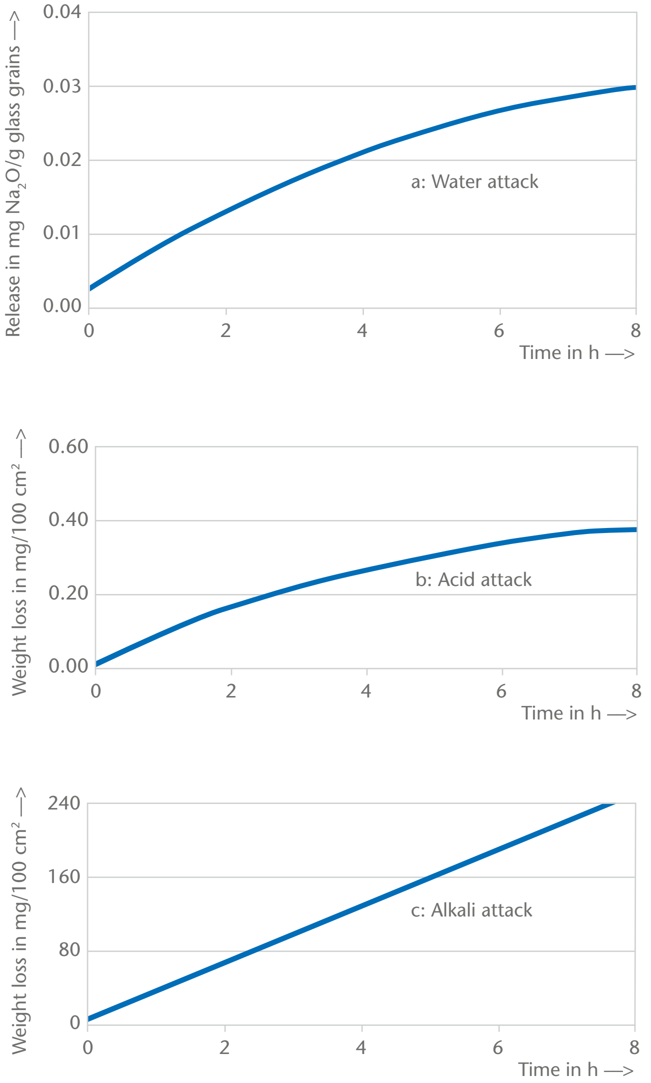

Fig. 1. Attack by water, acids and alkaline solutions on chemically resistant glass as a function of time

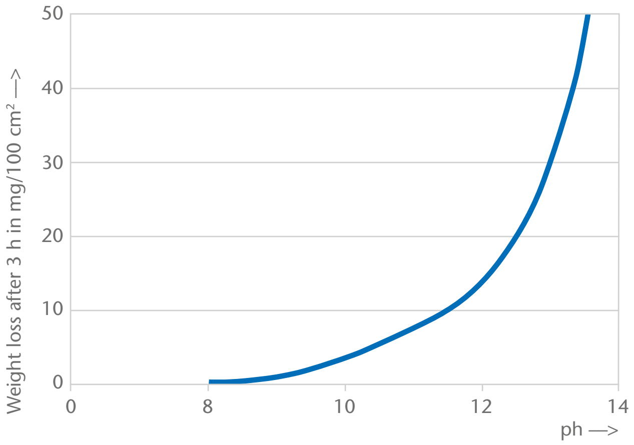

Fig. 2. Alkali attack on DURAN®/BOROFLOAT® 33/SUPREMAX® related to pH value at 100 °C

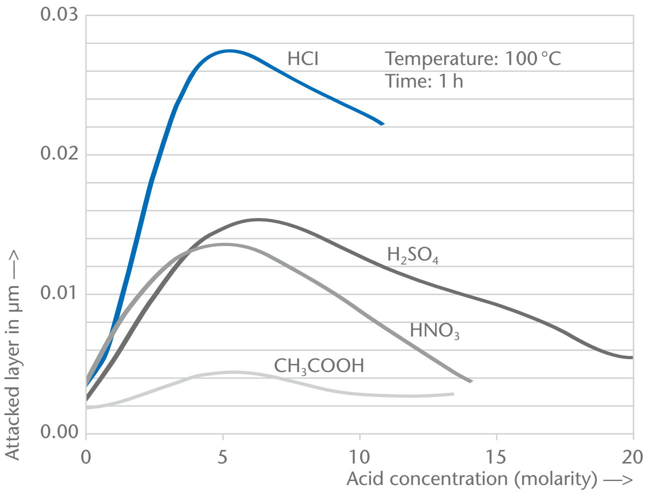

Fig. 3. Acid attack on DURAN®/BOROFLOAT® 33/SUPREMAX® as a function of concentration

Because acid and alkali attacks on glass are fundamentally different, silica-gel layers produced by acid attack obviously are not necessarily effective against alkali solutions and may be destroyed. Conversely, the presence of ions that inhibit an alkali attack does not necessarily represent protection against acids and water. The most severe chemical exposure is therefore the alternating treatment with acids and alkaline solutions. As in all chemical reactions, the intensity of interaction increases rapidly with increasing temperature (Figures 27 and 28).

In the case of truly ablative solutions such as hydrofluoric acid, alkaline solutions, or hot concentrated phosphoric acid, the rate of attack increases rapidly with increasing concentration (Figure 2). As can be seen in Figure 3, this is different for the other frequently applied acids.

2.2 Determination of chemical stability

In the course of time, many analysis methods have been suggested for determining the chemical stability of glass. In most cases, it is the glass surface that is analyzed either in its “as delivered” condition (with the original fire-polished surface) or as a basic material with its fire-polished surface removed by mechanical or chemical ablation, or after crushing.

The standardized DIN* test methods, which are universally and easily applicable, are the most reliable analysis methods. They include the determination of hydrolytic resistance (by two grain-titration methods and one surface method), of acid resistance to hydrochloric acid, and of alkali resistance to a mixture of alkaline solutions.

Hydrolytic classes	Acid consumption of 0.01 mol/l hydrocholric acid per g glass grains ml/g	Base equivalent as Na_2O per g glass grains µg/g	Possible designation
1	up to 0.10	up to 31	very highly resistant glass
2	above 0.10 up to 0.20	above 31 up to 62	highly resistant glass
3	above 0.20 up to 0.85	above 62 up to 264	medium resistant glass
4	above 0.85 up to 2.0	above 264 up to 620	low resistant glass
5	above 2.0 up to 3.5	above 620 up to 1085	very low resistant glass

Table 1. Hydrolytic classes of DIN ISO 719

* Deutsches Institut für Normung e.V. German Institute for Standardization

2.2.1 Hydrolytic resistance (water resistance)

Grain-titration method A

(after leaching at 98 °C, according to DIN ISO 719; testing of glass as a material)

An amount of 2 g of powdered glass with 300 – 500 µm (ISO) grain size is heated with 50 ml water for one hour in a boiling water bath. The extracted alkali is then titrated with hydrochloric acid, c(HCl) = 0.01 mol/l*, using methyl red sodium as an indicator. On the basis of the acid consumption (or its alkali equivalent), the glass is assigned to one of the five hydrolytic classes listed in Table 1. The hydrolytic classes shown in Table 20 (on page 68ff) were determined using the above method.

Grain-titration method B

(after leaching at 121 °C, according to DIN ISO 720; testing of glass as a material)

In this method, which originated in the USA and is particularly suitable for highly resistant glasses, 10 g of powdered glass (grain size 300 – 425 µm) is leached with 50 ml of water in an autoclave for 30 min at 121 °C. The extracted alkali is then titrated with hydrochloric acid, c(HCl) = 0.02 mol/l, using methyl red sodium as an indicator. Here, too, the acid consumption is a measure of the hydrolytic resistance. Presently, no allocation into classes exists for DIN ISO 720.

DURAN® borosilicate glass in the laboratory

Class[1]	Consumption of hydrochloric acid solution [c(HCl) = 0.02 mol/l] (4.2) per gram of glass grains ml/g	Equivalent of alkali expressed as mass of sodium oxide (Na_2O) per gram of glass grains µg/g
HGA 1	up to and including 0.10	up to and including 62
HGA 2	from 0.10 up to and including 0.85	from 62 up to and including 527
HGA 3	from 0.85 up to and including 1.50	from 527 up to and including 930

[1] "HGA" stands for the hydrolytic resistance of glass grains according to the autoclave test method.

Table 2. Limit values in the hydrolytic resistance grain test (autoclave test)

Surface test method A

(at 121 °C, according to ISO 4802-1 (2010) and current Ph. Eur. and USP)

Grain-titration methods are always carried out on crushed glass samples and the glass is tested as a material. With the surface test method, in contrast, the water resistance of the surface can be determined in its "as delivered" state. In this method, new, undamaged vessels (e.g. flasks, test tubes, vials, ampoules) are filled with water and heated for 60 min at 121 °C in an autoclave. The leaching solution is then titrated with hydrochloric acid, c(HCl) = 0.01 mol/l, using methyl red sodium as an indicator. Distinguished according to volume, the containers are classified on the basis of the amount of acid required for neutralization.

The values gained by this method indicate not only the behavior of the glass material as such, but also reflect possible modifications induced in the glass surface during hot forming. Therefore, these values are not quoted in the tables included in this publication.

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* The old term for concentration in "normal solutions N" has been replaced by "mol/l" in the SI system.

Surface test method B
(at 121 °C, according to ISO 4802-2 (2010) and current Ph. Eur.)
Grain-titration methods are always carried out on crushed glass samples and the glass is tested as a material. With the surface test method, in contrast, the water resistance of the surface can be determined in its "as delivered" state. In this method, new, undamaged vessels (e.g. flasks, test tubes, vials, ampoules) are filled with water and heated for 60 min at 121 °C in an autoclave. The leaching solution is then analyzed by using flame atomic emission or adsorption spectrometry (flame spectrometry). This is a direct and precise method for quantifying the specific leached ions in the solution. Distinguished according to volume, the containers are classified according to the mean value of the concentration of the oxides.

2.2.2 Acid resistance, according to DIN 12116

The glass surface to be tested is boiled for 6 h in 20 % hydrochloric acid [c(HCl) = 6 mol/l], and the loss in weight is determined in mg/100 cm^2. Using the half loss in weight, the glasses are then classified as follows:

Acid class	Designation	Half loss in weight after 6 h mg/100 cm^2
1	highly acid resistant	up to 0.7
2	acid resistant	above 0.7 up to 1.5
3	slight acid attack	above 1.5 up to 15
4	high acid attack	above 15

Table 3. Acid classes

Acid classes for glasses manufactured by SCHOTT are listed in Table 20, p. 68ff.

2.2.3 Alkali resistance, according to DIN ISO 695

To determine the alkali resistance, glass surfaces are subjected to a 3 h treatment in boiling aqueous solution consisting of equal volumes of sodium hydroxide, c(NaOH) = 1 mol/l and sodium carbonate, c(Na^{2}CO^3) = 0.5 mol/l. The loss in weight is then determined, and the glasses are classified as follows:

Alkali class	Designation	Loss in weight after 3 h mg/100 cm^2
1	low alkali attack	up to 75
2	slight alkali attack	above 75 up to 175
3	high alkali attack	above 175

Table 4. Alkali classes

Alkali classes for glasses manufactured by SCHOTT are listed in Table 20, p. 68ff.

The following borosilicate glasses have particularly high chemical resistance: DURAN®/BOROFLOAT® 33/ SUPREMAX® (8330), SUPRAX® (8488), FIOLAX® clear (8412), FIOLAX® amber (8414) and PYRAN® S (8341); see Table 6, p. 30.

FIOLAX® highly chemical resistant glass for save primary packaging in the pharmaceutical industry

2.3 The significance of chemical stability

2.3.1 Corrosion resistance in chemical plant applications

For such applications, the glasses must be resistant to the various chemical solutions to such a degree that manifold reactions can take place without running the risk of damaging the laboratory glass or the equipment by strong ablation. Moreover, no interfering amounts of glass components must be released into the reaction mixture. Attack by acids is of particular importance, both in laboratories and in chemical technology. Here, borosilicate glasses with their high acid resistance are superior to other materials. Up to the boiling point, their reactivity is very low; it then increases with increasing acid concentration, but decreases again at higher concentrations (Figure 3). The alkali attack, in contrast, increases exponentially with increasing alkali concentration (Figure 2).

A comparison of the effect of the alkaline mixture (concentration of alkaline components about 1 mol/l) with the effect of 6 mol/l hydrochloric acid (the most aggressive acid used in acid resistance tests) under standard conditions shows that the alkali attack increases by a factor of 1000 after extended exposure.

2.3.2 Release of glass constituents

In various processes of chemical technology, pharmaceuticals, and laboratory work, the material glass is expected to release no constituents (or a very minimum) into the reacting solutions or stored specimens.

Production of floated borosilicate glass

Because even highly resistant materials such as non-alkaline earth and alkaline earth borosilicate glasses react to a very small degree with the surrounding media, the fulfillment of this requirement is a question of quantity and detection limits. Concentrations of 10^{-6}–10^{-9} (i.e. trace amounts), which are measurable today with highly sophisticated analytical instruments, can be released even from borosilicate glasses in the form of SiO_2, B_2O_3, and Na_2O, depending on the conditions. However, solutions in contact with high-grade colorless DURAN® laboratory glass will not be contaminated by Fe, Cr, Mn, Zn, Pb, or other heavy-metal ions.

2.3.3 Undesirable glass surface changes

When an appreciable interaction between a glass surface and aqueous solutions occurs, there is an ion exchange in which the easily soluble glass components are replaced by H^+ or OH^- ions. This depletion of certain glass components in the surface leads to a corresponding enrichment in silica, which is poorly soluble, and thus to the formation of a so-called silica-gel layer. This layer proves, in most cases, to be more resistant than the base glass. When its thickness exceeds about 0.1 – 0.2 µm, interference colors caused by the different refractive indices of layer and base glass make this silica-gel layer visible to the unaided eye. With increasing layer thickness, it becomes opaque and finally peels off, destroying the glass.

In the case of technical laboratory glass, the first stages are only a question of aesthetics. The functionality of the glass is not influenced in any way. In optical glasses, however, interference colors and opacity are usually unacceptable, and in glasses for electrical engineering, applicability may be reduced. In the final stage of degradation, when the silica-gel layer peels off, the glass of course becomes useless for any application.

Between these stages there is a wide scope of possible surface modifications, some of which, although optically visible, are of no practical significance, whereas others must be considered.

In the case of less resistant glasses, small amounts of water (air moisture and condensation) in the presence of other agents such as carbon dioxide or sulfur oxides can lead to surface damage. In the case of sensitive glasses, hand perspiration or impurities left by detergents can sometimes induce strongly adhering surface defects, mostly recognizable as stains. If the contaminated glass surfaces are reheated ($>$350 – 400 °C), the contaminants or some of their components may burn in. Normal cleaning processes will then be ineffective and the whole surface layer will have to be removed (e.g. by etching).

2.3.4 Desirable chemical reactions with the glass surface (etching)

Very strong reactions between aqueous agents and glass can be used for fundamental cleaning of glass. The complete ablation of glass layers leads to the formation of a new surface.

Hydrofluoric acid reacts most strongly with glass. Because it forms poorly soluble fluorides with a great number of glass constituents, it is mostly only used in diluted form. The best etching effect is usually achieved when another acid (e.g., hydrochloric or nitric acid) is added. A mixture of seven parts by volume of water, two parts of concentrated hydrochloric acid ($c = 38\%$) and one part of hydrofluoric acid ($c = 40\%$) is recommended for a moderate surface ablation of highly resistant borosilicate glasses. When chemically less resistant glasses (e.g. 8245, 8250) are exposed for five minutes to a stirred solution at room temperature, surface layers with thicknesses of 1–10 µm are ablated, and a transparent, smooth, completely new surface is produced.

Glasses can also be ablated using alkaline solutions, but the alkaline etching process is much less effective.

3. Mechanical and Thermal Properties

3.1 Viscosity

Between melting temperature and room temperature, the viscosity of glasses increases by 15–20 orders of magnitude. Within this viscosity range, glasses are subject to three different thermodynamic states:

1. melting range – above liquidus temperature T_s;
2. range of the supercooled melt – between liquidus temperature T_s and transformation temperature T_g;
3. frozen-in, quasi-solid melt ("glass range"), below transformation temperature T_g.

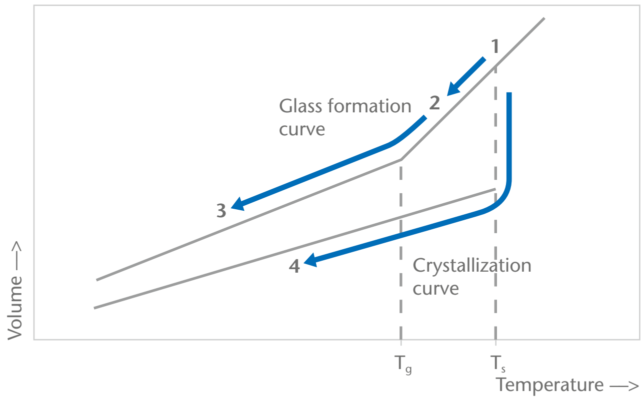


Fig. 4. Schematic volume-temperature curves for crystallization and glass formation:
1: liquid, 2: supercooled liquid, 3: glass, 4: crystal;
T_s: melting temperature, T_g: transformation temperature

The absence of any significant crystallization in the range of the supercooled melt (compare Figure 4 (2)) is of utmost importance for glass formation. Hence a basically steady and smooth change in the viscosity in all temperature regions is a fundamental characteristic of glass (Figure 5).

The temperature dependence of the viscosity (see Figure 6) is the crucial property for glass production.

Melting and fining (homogenization) must generally take place at viscosities ≤ 200 dPa · s; for glasses with low melting temperature, 1 dPa · s can be achieved.

Typical processing techniques for glasses, such as blowing, pressing, drawing and rolling, require viscosities in the range of 10^3–10^7 dPa · s. As a characteristic temperature for this "working range," generally the temperature for 10^4 dPa · s, called the **working point** (ISO 7884-1), is measured and quoted (Table 20, p. 68ff). Depending on the magnitude of the temperature interval between 10^3 dPa · s and 10^7 dPa · s, one distinguishes between "long" (large temperature difference, shallow slope) and "short" glasses.

At temperatures around the **softening point**, glass products deform rapidly under their own weight (forming by "sagging"), glass powders are sintered porously or densely, and glassblowing is carried out. The softening point is defined as the temperature at which the glass has a viscosity of $10^{7.6}$ dPa · s (method of measurement: ISO 7884-3).

Somewhat above 10^{10} dPa · s, the viscosity becomes increasingly time-dependent. With increasing viscosity (i.e. decreasing temperature), the delay in establishing structural equilibria finally becomes so large that under normal cooling conditions the glass structure at 10^{13} dPa · s can be described as solidified or "frozen-in." The low flow capability at this viscosity only suffices to compensate for internal stresses

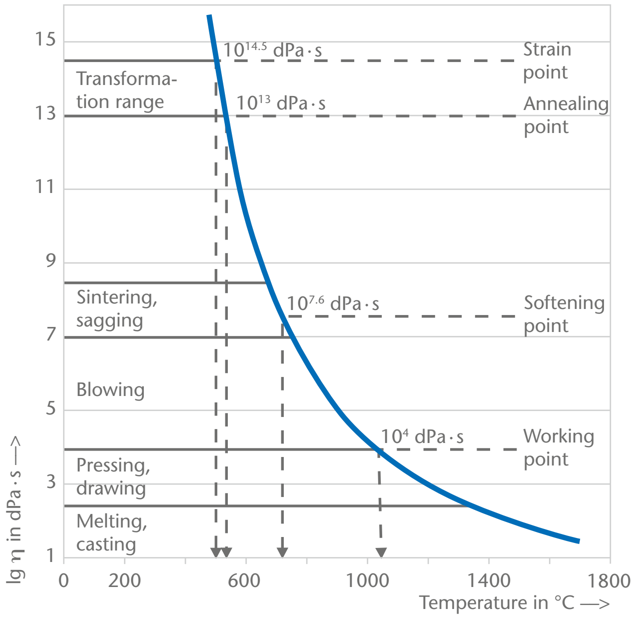


Fig. 5. Typical viscosity-temperature curve; viscosity ranges for important processing techniques and positions of fixed viscosity points

in the glass after 15 min of annealing time. On the other hand, the dimensional stability of the glass is sufficient for many purposes, and its brittleness (susceptibility to cracking) is almost fully developed. The glass is now in the transformation range, and many properties indicate this by changing the direction of their temperature dependence. Thus the change in the slope of the coefficient of linear expansion is used to define the transformation range by way of the so-called **transformation temperature** T_g according to ISO 7884-8.

At this transformation temperature, most glasses show viscosities in the range of 10^{12}–$10^{13.5}$ dPa·s. The "10^{13} temperature," at which the glass has a viscosity of 10^{13} dPa·s (method of measurement: ISO 7884-4), is called the **annealing point**. It is of crucial importance for stress relaxation after the hot forming of glasses, indicating the upper temperature limit of the so-called annealing range, at which internal stress is released within minutes. The lower limit of the annealing range is expressed by the **strain point**, at which the glass has a viscosity of $10^{14.5}$ dPa·s (determination: extrapolation from the viscosity-temperature curve). For most glasses, the strain point lies about 30–40 K below the annealing point. Relaxation of internal stresses here already takes 3–5 hours. Therefore faster cooling is possible at temperatures below the strain point without freezing in new stresses. On the other hand, the strain point marks the maximum value for short-term heat load. Thermally prestressed glasses, in contrast, show significant stress relaxation already at 200–300 K below T_g. For glasses with precisely defined dimensions (e.g. etalons or gauge blocks) and in case of extreme demands on the stability of certain glass properties, application temperatures of 100–200 °C can already be the upper limit.

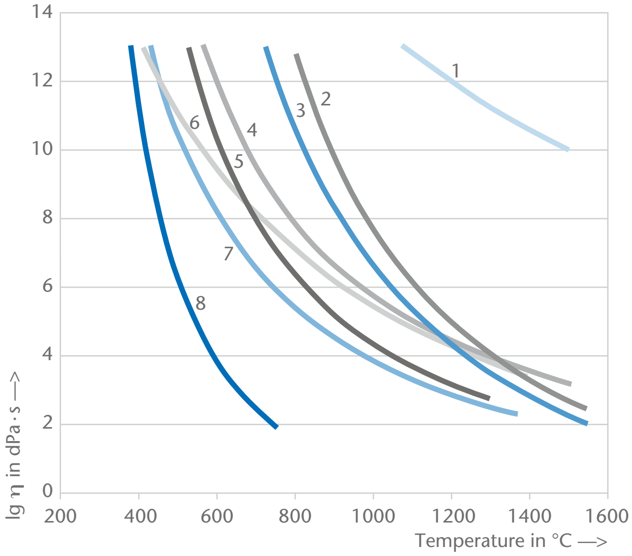


Fig. 6. Viscosity-temperature curves for some important technical glasses. 1: fused silica, 2: 8253, 3: 8252, 4: 8330, 5: 8350, 6: 8248, 7: 8095, 8: 8465. Glasses with steep gradients (8) are called "short" glasses and those with relatively shallow gradients (6) are "long" glasses

3.2 Strength

The high structural (= theoretical) strength of glasses and glass-ceramics (> 10^4 MPa) cannot be used in practice since the strength of glass articles is actually determined by surface defects induced by wear. Contact with hard materials often causes damages in the surfaces of glass and glass-ceramic articles in the form of tiny chips and cracks, at whose tips critical stress concentrations may be induced by mechanical load, causing breakage of the articles.

In ductile materials such as metals, these stress concentrations are relieved by plastic flow. Glasses and glass-ceramics, in contrast, behave as brittle as ceramics. At typical application-specific temperatures and load times, they show no plastic flow by which the stress concentrations at the chip and crack tips could be relieved.

Regarding strength, surface damages are therefore particularly important for glass and glass-ceramic articles.

Surface Condition

As a result of wear-induced surface defects, glass and glass-ceramic articles have practical tensile strengths of 20–200 MPa, depending on the surface condition (Figure 7) and exposure conditions. Only a slight – as a rule negligible – dependence on the chemical composition is found for silicate glasses.

Time and size dependence

For testing and applying tensile strength values, the time dependence of the load and the size of the surface area exposed to the stress are particulary important.

As a result of subcritical crack growth due to stress corrosion, a long lasting tensile stress may boost critical surface flaws, thus reducing the residual strength with time. Hence the strength of glass and glass-ceramics is time-dependent!

Stress corrosion causes the dependence of the measured fracture probability on the stress rate as depicted in Figure 8.

Static fatique

Fracture analyses of broken specimens for the initial flaw, its origin and growth kinetics yield further information about the time dependence of the strength of glasses and glass-ceramics. Some rules are established for estimating the strength for a permanent load from fast tests with a constant load rate, see Figure 9 for example. As a simple rule, the permanent strength (for years of loading) will only amount to about 1/2 to 1/3 of the strength measured in fast experiments.

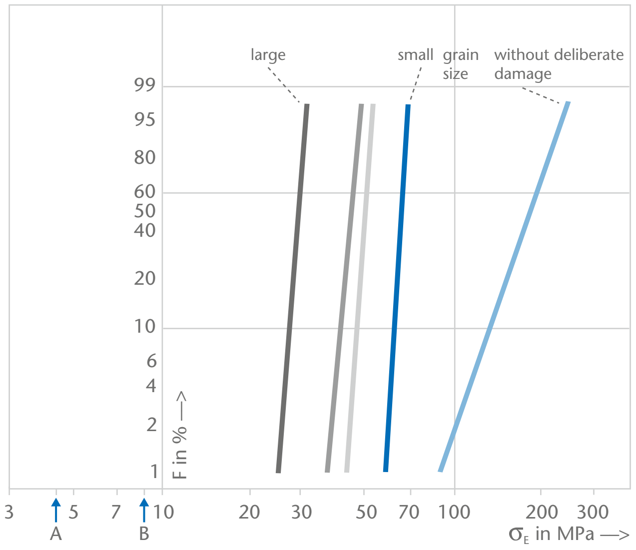
Size dependence

Increasing the stressed area increases the probability of low strength flaws within this area. This relationship is important for converting of experimental strengths, which are mostly determined using small test specimens, to large glass articles such as pipelines, where many square meters of glass may be loaded (Figure 10).

Strengthening

The defects that reduce the strength of the surfaces become ineffective if the glass surface ist subjected to compressive stress. The resulting strength of a glass article may be so high that it virtually sets no limits to technical applications. In glass articles with simple geometries, for example flat glass, the entire surface of the article can be put under compressive stress.

The toughening can be caused by rapid cooling (quenching) of the softened glass (Figure 11) or, in suitable glasses, by an ion exchange in an approximately 50 – 200 µm thick surface layer. In subsequent external loading (tensile or bending), the externally induced stress adds to the internal stress. Up to the value of the compressive surface stress,



A: nominal strength values for chem. techn. large-scale units
B: … and for normal glass constructions

Fig. 7. Failure probability F for samples abraded by various size grains; predamaged surface area: 100 mm², rate of stress increase $\dot{\sigma}$ = 10 MPa/s

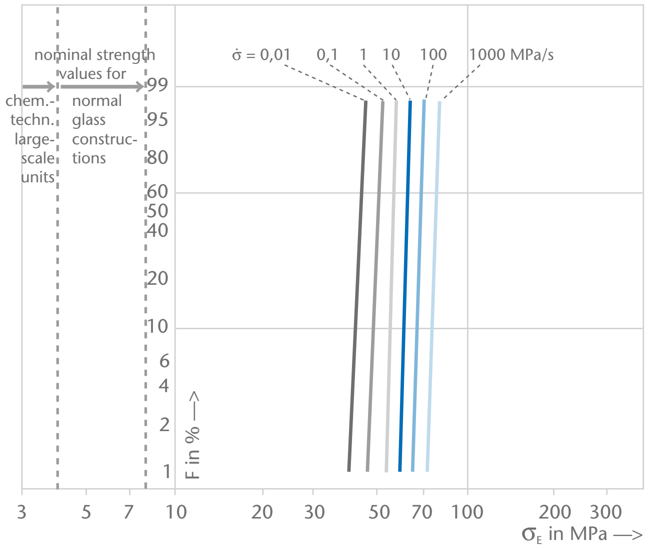


Fig. 8. Failure probability F of a predamaged surface for various rates of stress increase $\dot{\sigma}$. (predamaged area: 100 mm², grain size: 600)

a superimposed tensile stress keeps the surface under total compressive load. Thus, surface condition, loading rate, and loading time do not influence the strength.

3.3 Elasticity

The ideal brittleness of glasses and glass-ceramics is matched by an equally ideal elastic behavior up to the breaking point. The elastic moduli for most technical glasses is within the range of 50 – 90 GPa. The mean value of 70 GPa is about equal to Young's modulus of aluminum. Poisson's ratio of most glasses is in the range 0.21 to 0.25 and is lower than for metals or plastics.

3.4 Coefficient of linear thermal expansion

With few exceptions, the length and the volume of glasses increase with increasing temperature (positive coefficient).

The typical curve begins with a zero gradient at absolute zero (Figure 12) and increases slowly. At about room temperature (section A), the curve shows a distinct bend and then gradually increases up to the beginning of the experimentally detectable plastic behavior (section B = quasi-linear region). A distinct bend in the extension curve characterizes the transition from the predominantly elastic to the more visco elastic behavior of the glass (section C = transformation range). As a result of increasing structural mobility, the temperature dependencies of almost all glass properties are distinctly changed. This transformation range is characterized by the transformation temperature T_g according to ISO 7884-8. Figure 13 shows the linear thermal expansion curves of five glasses; 8330 and 4210 roughly define the normal range of technical glasses, with expansion coefficients $\alpha_{(20\,°C;\,300\,°C)} = 3.3 - 12 \times 10^{-6}$/K. The linear thermal expansion is an essential variable for the sealability of glasses with other materials and for thermally induced stress formation, and is therefore of prime importance for glass applications.

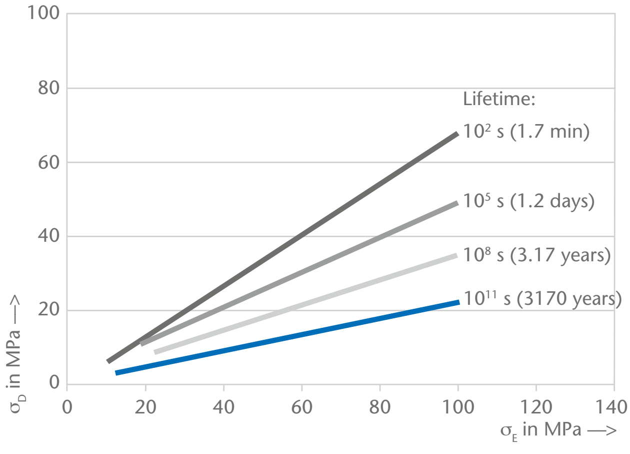


Fig. 9. Time-related strength σ_D (strength under constant loading) compared to experimental strength $\dot{\sigma}_E$ at 10 MPa/s stress increase with lifetime t_L, in normally humid atmosphere (soda-lime glass).

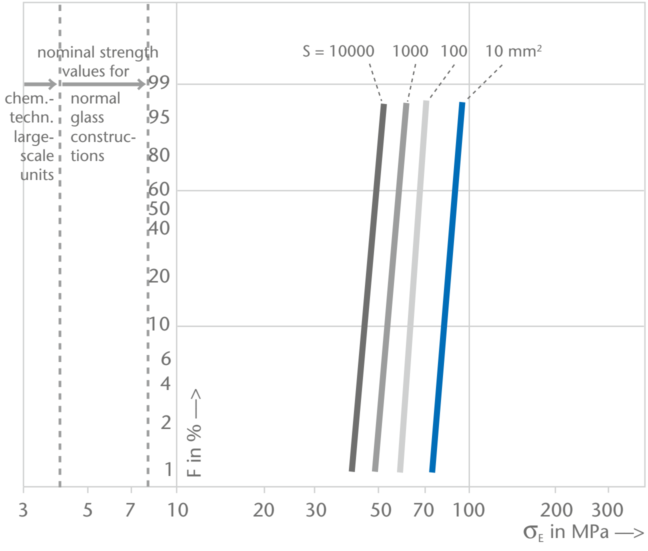


Fig. 10. Failure probability F for differently sized stressed areas S; all samples abraded with 600 mesh grit, stress rate $\dot{\sigma}$ = 10 MPa/s

Sealability

In fusion sealing with other materials, the decisive glass property is the linear contraction. As Figure 14 shows, the experimental setting point T_E lies in the already sharply bent section of the glass curve, and the experimental setting temperature increases with increasing cooling rate. Predicting the linear contraction is only possible if the shape of the glass curve and the setting point T_E for the respective cooling rate are known. The stress-optical measurement of stresses in test fusions with practice-oriented cooling rates (ISO 4790) is a simpler and much more accurate method of testing the sealability.

Thermal stresses

Owing to the low thermal conductivity of glass (typically 0.9 – 1.2 W/(m · K) at 90 °C, or a minimum of 0.6 W/(m · K) for high-lead-containing glasses), temperature changes produce relatively high temperature differences ΔT between the surface and the interior, which, depending on the elastic properties E (Young's modulus) and μ (Poisson's ratio), and on the coefficient of linear thermal expansion α, can result in stresses

$$\sigma = \frac{\Delta T \, \alpha \, E}{(1 - \mu)} \text{ [MPa].}$$

In addition to the geometric factors (shape and wall thickness), the material properties α, E and μ decisively influence the thermal strength of glasses subjected to temperature variations and/or thermal shock. Thermal loads of similar articles made from different glasses are easily compared by means of the characteristic material value

$$\varphi = \frac{\sigma}{\Delta T} = \frac{\alpha \, E}{1 - \mu} \text{ [MPaK}^{-1}\text{],}$$

which indicates the maximum thermally induced stress to be expected in a flex-resistant piece of glass for a local temperature difference of 1 K. Because cracking originates almost exclusively from the glass surface and is caused there by tensile stress alone, cooling processes are usually much more critical than the continuous rapid heating of glass articles.

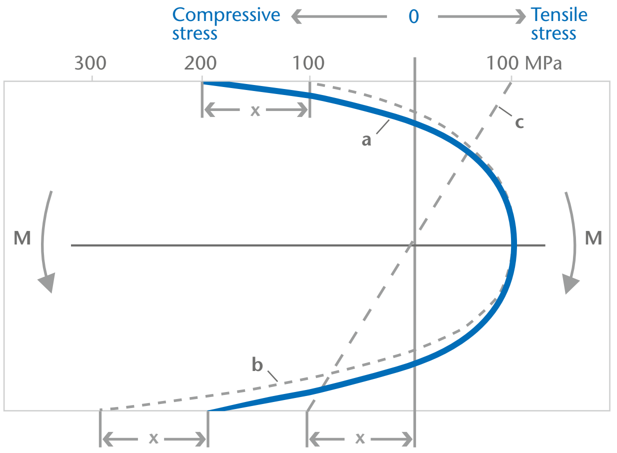


Fig. 11. Stress distribution across the thickness of thermally prestressed flat glass (a) without, (b) with additional bending M; (c) stress distribution in bending without prestressing

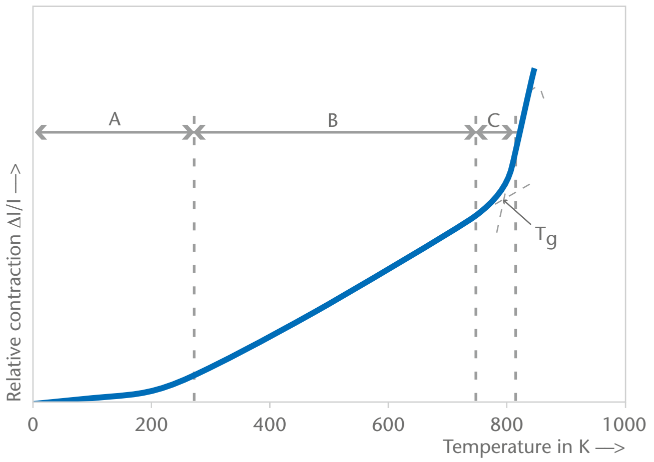


Fig. 12. Typical thermal expansion – temperature curve for glasses

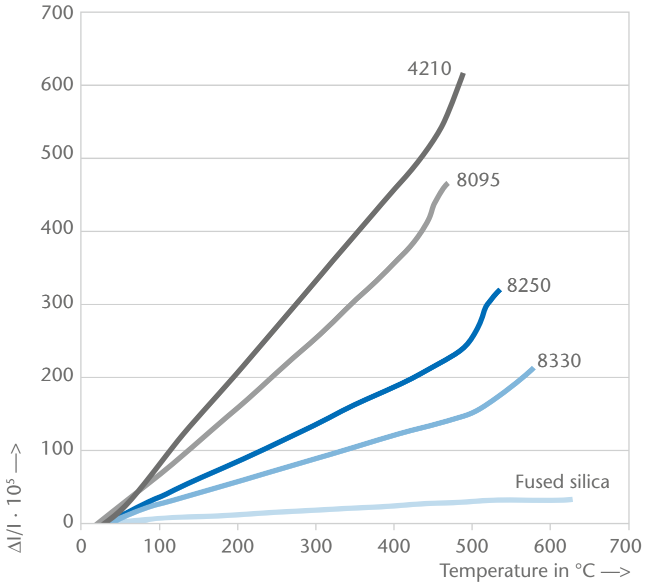


Fig. 13. Linear thermal expansion of various technical glasses and of fused silica

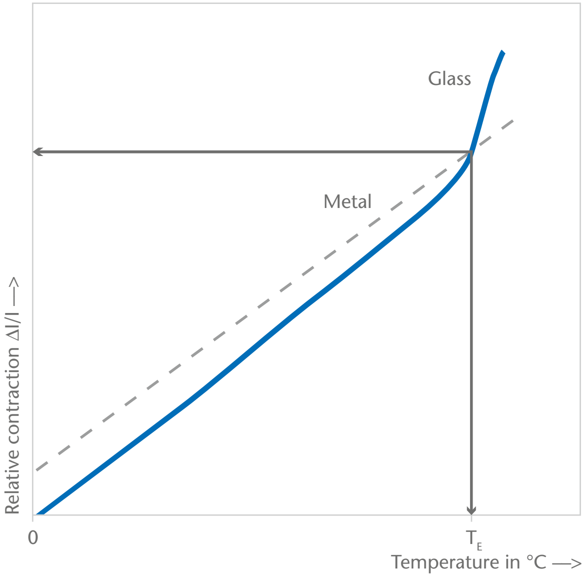


Fig. 14. Contraction/expansion curves of two fusion partners which are shifted so that they intersect at setting temperature T_E. The vertical difference thus describes the contraction difference with the correct sign.

PYRAN® Platinum fire-rated glass-ceramic resists fire without fracturing.

4. Electrical Properties

For more than 70 years, SCHOTT has been developing vacuum-tight assemblies of glass and metal that enable electrical signals to pass through the walls of hermetically sealed packages, relays, for example.

As electrically highly insulating materials, glasses are used in electrical engineering and electronics for the production of high-vacuum tubes, lamps, electrode seals, hermetically encapsulated components, high-voltage insulators, etc. Moreover, glasses may be used as insulating substrates of electrically conducting surface layers (surface heating elements and data displays).

4.1 Volume resistivity

Electrical conductivity in technical silicate glasses is, in general, a result of the migration of ions – mostly alkali ions. At room temperature, the mobility of these ions is usually so small that the volume resistivities with values above 10^{15} Ω cm (10^{13} Ω m) are beyond the range of measurement. The ion mobility increases with increasing temperature. Besides the number and nature of the charge carriers, structural effects of other components also influence the volume resistivity and its temperature relationship. An Arrhenius law which is used in glass science sometimes also called Rasch-Hinrichsen law applies to this relationship at temperatures below the transformation range:

$$\lg \rho = A - B/T$$

ρ = electrical volume resistivity
A, B = specific glass constants
T = absolute temperature

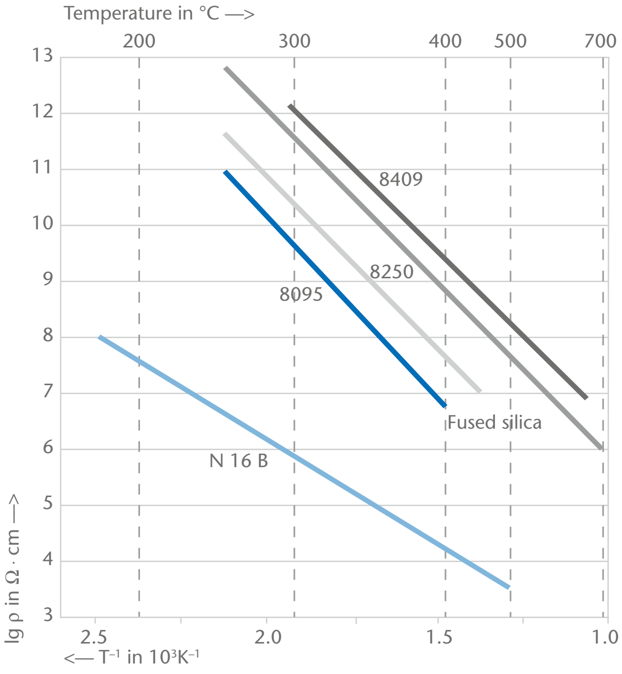


Fig. 15. Electrical volume resistivity of various technical glasses and fused silica related to the reciprocal of absolute temperature

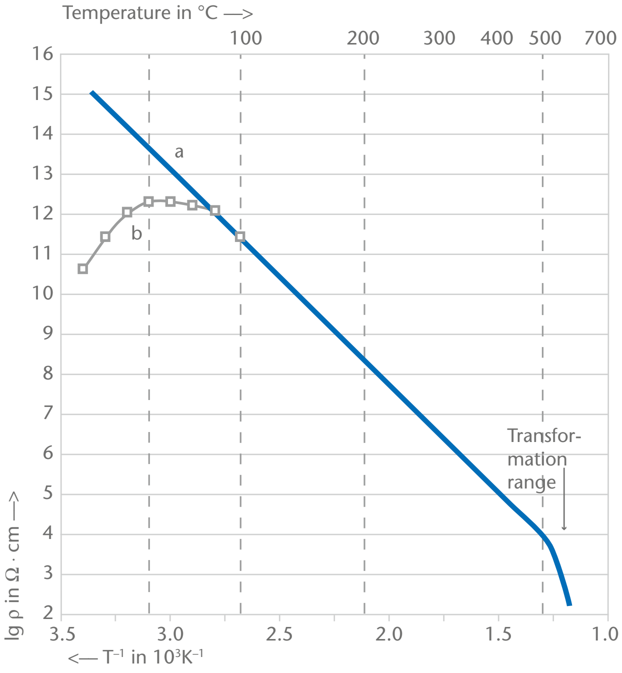


Fig. 16. Electrical resistance r of a soda-lime glass related to temperature (a) without, and (b) with a hydrated layer

The plot of lg ρ = f (1/T) thus yields straight lines (Figure 15). Because of the relatively small gradient differences for most glasses, the electrical insulation of glasses is often defined only by the temperature for 10^8 Ω cm (= 10^6 Ω m). According to DIN 52326, this temperature is denoted as T_{k100}. The international convention is to quote volume resistivities for 250 °C and 350 °C, from which the constants A and B and various other values below T_g can be calculated.

4.2 Surface resistivity

The generally very high volume resistivities of glasses at room temperature are superposed in normal atmosphere by surface resistivities which are several orders of magnitude lower (Figure 16). The all-important factor is the adsorption of water on the glass surface. Depending on the glass composition, surface resistivities of 10^{13}–10^{15} Ω per square occur at low relative humidities, or 10^8–10^{10} Ω per square at high relative humidities. Above 100 °C, the effect of this hydrated layer disappears almost completely. Treatment with silicones also considerably reduces this effect.

Electrically conducting and transparent layers can be produced on glass by using semi-conducting oxides (e.g., of tin and indium). The surface resistance range is 1–100 Ω per square.

4.3 Dielectric properties

The dielectric constant ε_r describes the relative increase in capacitance by introducing a polarizable dielectric into e.g a plate capacitor previously in vacuum.

Although ε_r is not a constant but varies e.g. with material, frequency range and temperature, the term “dielectric constant” is misleading but still widely used instead of the correct term “relative permittivity.” In this brochure, we stay with the old term “dielectric constant.”

With dielectric constants generally between 4.5 and 8, technical glasses behave like other electrically insulating materials. The highest values are obtained for lead glasses such as 8531 (ε_r = 9.5) and for ultra-high lead-containing solder glasses (ε_r = ~20). The dependence of the dielectric constants ε_r on frequency and temperature is relatively small (Figure 17). For a frequency range of $50-10^9$ Hz, ε_r values will generally not vary by more than 10 %.

Reversing the polarity and shifting the dipoles of a dielectric situated in an alternating electrical field will cause heating and hence dissipation of energy as compared to ideal loss-free reactive power. The ratio of practical performance to ideal loss-free performance, which is dependent on the type of material as well as on frequency and temperature, is called the dielectric dissipation factor tanδ.

Due to the diverse mechanisms which cause such losses in glasses, there is a strong relationship with frequency, which shows minimum tanδ values in the region of 10^6-10^8 Hz and increasing values for lower and higher frequencies (Figure 18).

At 10^6 Hz, the dissipation factor tanδ for different glasses lies between $10^{-2}-10^{-3}$; fused silica, with 10^{-5}, has the lowest dissipation factor of all glasses. The special glass 8248 has relatively low losses and tanδ increases only slightly up to 5.5 GHz (tanδ = 3 x 10^{-3}).

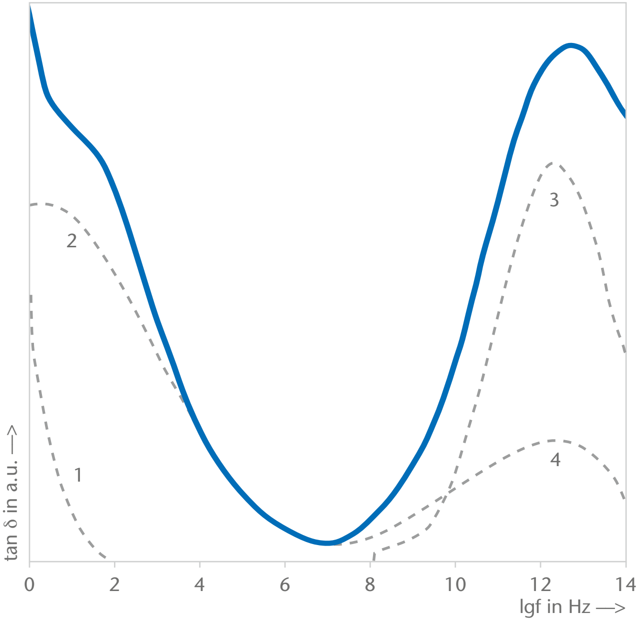


Fig. 18. Schematic representation of the frequency spectrum of dielectric losses in glass at room temperature (Stevels). The solid curve shows the total losses built-up from: 1. conduction losses, 2. relaxation losses, 3. vibration losses, and 4. deformation losses.

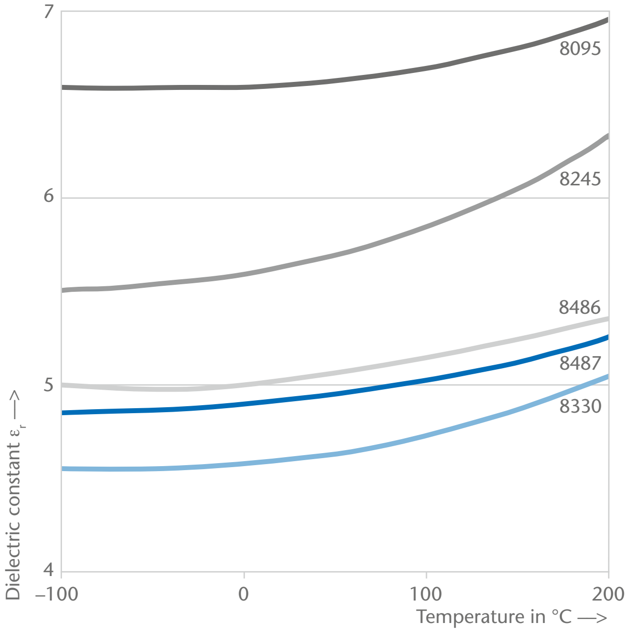


Fig. 17. Dielectric constant ε_r of electro-technical glasses related to temperature, measured at 1 MHz

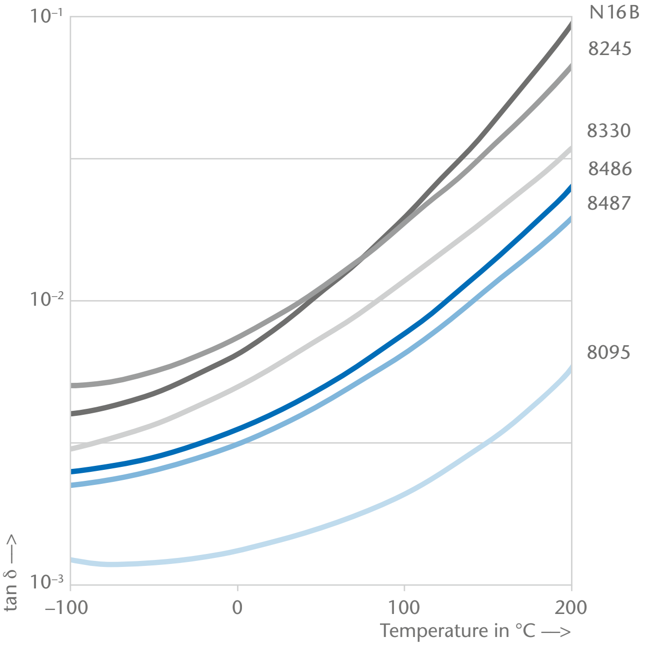


Fig. 19. Dissipation factor tanδ as a function of temperature in the range –100 to +200 °C, measured at 1 MHz

Several glasses, especially glasses with low or close to zero alkaline content are good dielectrics with low loss in the GHz range. Examples are AF32, BF33, 8253. In Tab. 5, we show the dielectric loss of AF32 in the GHz range. In microwave electronics the loss if often characterized with the Q-factor Q = 1/tanδ or with Q*f (unit GHz) which is the product of the Q factor and the frequency.

The steep increase in dielectric losses with increasing temperature (Figure 19) can lead to instability, i.e. to overheating of the glass due to dielectric loss energy in the case of restricted heat dissipation and corresponding electrical power.

4.4 Dielectric strength

Glasses that are free of inhomogeneities such as bubbles and impurities are dielectrically very stable and often outperform porous electro-ceramics.

The dielectric strength of glasses depends on the frequency, the rate of increase in voltage, the temperature, the glass composition, and the external test conditions. Furthermore, the breakdown field strength increases substantially with decreasing glass thickness, indicating heat breakdown (interrelated increase in temperature and electrical conductivity) as the preferred breakdown mechanism. For ultra-thin glasses, the dielectric breakdown strength can show extremely large values. With an alkaline free glass, breakdown strength of 1200 kV/mm has been measured on 12 µm thick samples. In Figure 20 we schematically show the thickness dependence of the dielectric breakdown strength of AF32. “Cold” breakdown caused by the sudden formation of an electron avalanche is technically unimportant.

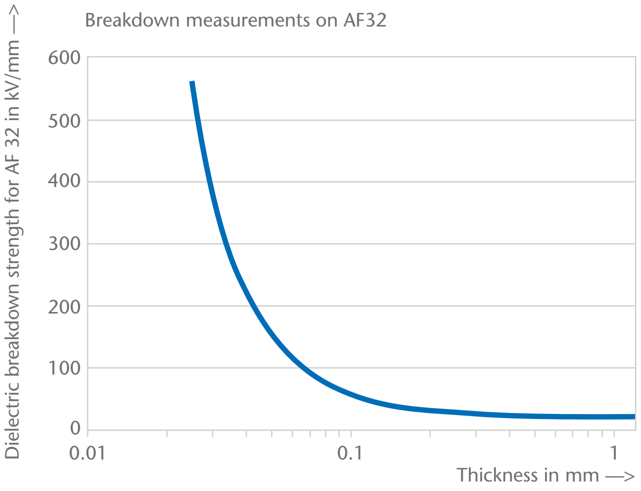


Fig. 20. Thickness dependence of the dielectric breakdown strength of AF32

Approximate values for the dielectric strength of glass are field strengths of 20 – 40 kV/mm for glass thicknesses of 1 mm at 50 Hz at 20 °C, and 10 – 20 kV/mm for greater thinknesses. Decreasing values can be expected at higher temperatures and frequencies.

f [GHz]	tanδ	error ±	Q	error ±	Qf [GHz]	error ±
2	0.003	0.0005	372	18	744	37
5	0.004	0.0006	283	17	1416	86
10	0.005	0.0006	219	16	2195	155
20	0.006	0.0008	159	13	3175	258
30	0.008	0.0009	125	11	3740	328
50	0.012	0.0015	83	10	4161	512
70	0.018	0.0026	57	11	3977	748
77	0.020	0.0034	49	12	3809	913

Table 5. Dielectric loss of AF32 in the GHz range

Close-up of the front of an ozonizer, inside

5. Optical Properties

High homogeneity glass

5.1 Refraction of light

The ratio of the speed of light in vacuum to that in a defined material is called the refractive index n_λ of that material. The refractive index of glass is dependent on the wavelength (dispersion). This is a decisive factor in purely optical applications.

The refractive indices n_d of technical glasses are valid for $\lambda_d = 587.6$ nm and generally lie within the range of 1.47 – 1.57. Exceptions to this rule are lead glasses with PbO contents of over 35 % (glass type 8531 : $n_d = 1.7$). The principal dispersion $n_F - n_c$ ($\lambda_F = 486.1$ nm, $\lambda_c = 656.3$ nm) of technical glasses lies between 0.007 bis 0.013.

5.2 Reflection of light

At the boundary glass surface – air, the incident light is partly reflected. At perpendicular incidence, the reflectance $R(\lambda)$ at wavelength λ is expressed as follows

$$R(\lambda) = \left(\frac{n(\lambda) - 1}{n(\lambda) + 1}\right)^2$$

For technical glasses $R(\lambda = 587.6 \text{ nm}) = R_d$ lies within 3.6 % to 4.9 % per interface.

The transmittance τ_d and the reflectance ρ_d of a non-absorbing plane-parallel glass plate with two glass-air surfaces, with multiple reflections taken into account, are expressed as follows

$$\tau_d = \frac{(1 - R_d)^2}{1 - R_d^2} = \frac{1 - R_d}{1 + R_d} = \frac{2n_d}{n_d^2 + 1}$$

and

$$\rho_d = \frac{2R_d}{1 + R_d} = \frac{(n_d - 1)^2}{n_d^2 + 1} \ .$$

The transmittance τ_d at perpendicular incidence decreases correspondingly to values between 93.1 % and 90.6 %.

The reflection r_d of a parallel glass plate can be reduced (and its total transmittance τ_d can be increased) by using so-called anti-reflective (AR) coatings. In its simplest form, a transparent layer on each surface with $n_{layer} = \sqrt{n_{glass}}$ and a thickness of $\lambda/4/n_{layer}$ will reduce the reflection for perpendicular incidence and wavelength λ completely. For other wavelengths close to λ, the reflection is reduced but not canceled. With more complex multy-layer AR coatings, reflections in the visible range can be reduced to less than 1 % per surface.

5.3 Transmittance

Normally, glass is transparent to visible light and certain regions of UV and IR radiation. Losses in transmittance occur due to internal absorption and reflection, as indicated above. The so-called internal transmittance τ_i can be modified by using coloring agents (oxides of transition elements or colloids) or fine particles in the glass, which have different refractive indices (light scattering).

The internal transmittance τ_i of an absorbing glass is a function of the thickness d:
$\tau_i = e^{-\alpha d}$, where α is the spectral absorption coefficient.

The relation between spectral transmittance τ and spectral internal transmittance τ_i is:

$$\tau(\lambda) = \left(\frac{2n(\lambda)}{n(\lambda)^2 + 1}\right) \tau_i(\lambda)$$

The dependence of the factor $\left(\frac{2n(\lambda)}{n(\lambda)^2 + 1}\right)$

on wavelength is usually small, thus, a constant reflection factor P

$$P_d = \frac{2n_d}{n_d^2 + 1}$$

is sufficient for use in most cases.

The best UV transmission is achieved with pure fused silica (UV cut-off for 1 mm thickness is in the region of 160–180 nm); particularly good UV-transmitting multicomponent glasses have cut-offs of up to 220 nm wavelength (Figure 21); normal technical glasses (Figure 22) already absorb considerably at 300 nm.

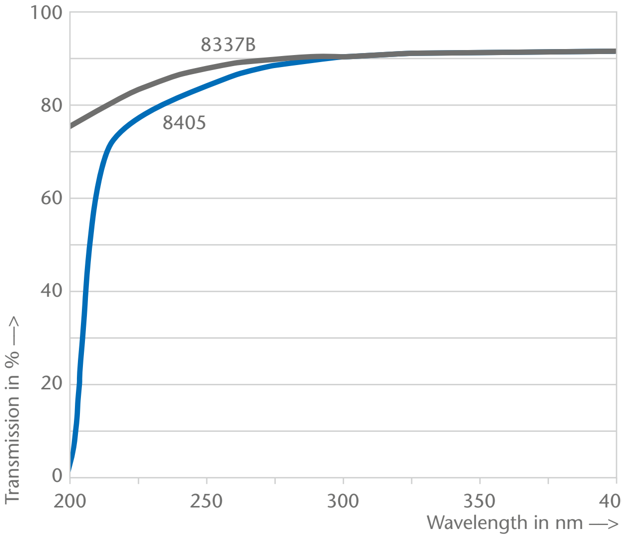


Fig. 21. UV transmission of highly UV-transparent technical glass types 8337B and 8405 at 0.5 mm glass thickness

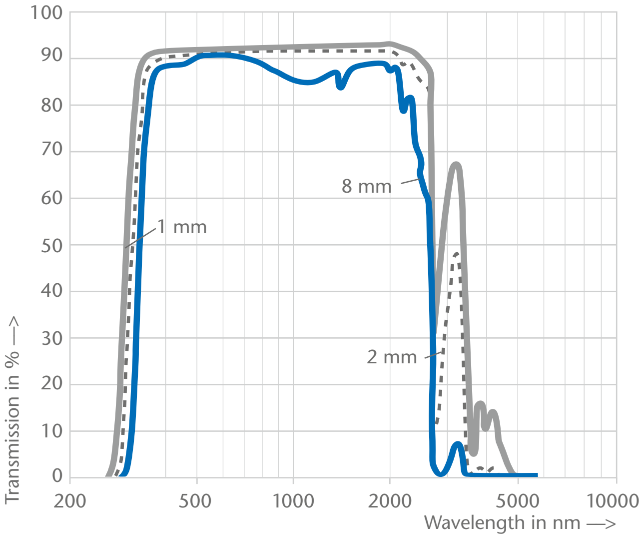


Fig. 22. Transmission of DURAN® 8330 for thicknesses 1, 2 and 8 mm

Optical glass

The term “optical glass” is used in distinction to “technical glass” for a specific group of glasses mainly for optical applications like imaging in the UV, visible, and infrared wavelength range. These applications require a broad set of glasses with high transmission and well defined refractive index and specific dispersion properties (described by Abbe-numbers). Combinations of these glasses allow for the construction of high-performance optical systems.

Up to 17 or more different raw materials with the lowest level of impurities to avoid absorption by coloring elements are used to achieve the desired specifications. Each optical glass is described (beside others) by its coordinates in the so-called “Abbe-Diagram” (see Figure 23).

Optical filter glass

Optical filter glass is known for its selective absorption in certain wavelength ranges. The absorption within the glasses is caused either by ions of heavy metals or of rare earths or it is caused by nano crystals within the glass matrix. By combining different coloring agents a wide range of different filter functions (neutral density filters, longpass filters, short pass filters and bandpass filters) can be obtained. Figure 25 depicts special UV bandpass filters that have a region of high internal transmittance in the UV and high absorption for visible light.

As an alternative to bulk filter glasses, coated interference filters are used. Here a transparent glass substrate is coated with a set of thin transparent layers of e.g. oxidic materials with different refractive indices. The spectral properties of these filters are defined by interference effects.

Optical filter glass and inteference filters are optimized for industrial applications, thus the main focus is the reproducibility of spectral transmittance. However, these glasses appear to be colored if their filter effect lies within the visible light spectrum.

Chalcogenide glass

In most known glass types, oxides of e.g. silicon, phosphorous, lanthanum and borate are building the glass forming network. Though some oxidic glass types with special compositions melted under very dry conditions show transmittance until 4–5 microns, the absorption of the cation-O-bond in the network sets a limit to the (mid – far) infrared (IR) transmission of these glasses. The main characteristic of chalcogenide glasses is the complete replacement of the element oxygen by other elements of the chalcogenide group like sulfur, selenium or tellurium to extend transmittance further into the mid to far IR. For instance, SCHOTT IR chalcogenide glasses (IRG) exhibit high transmission from the visible range to beyond 12 µm into the far infrared (see. Figure 24).

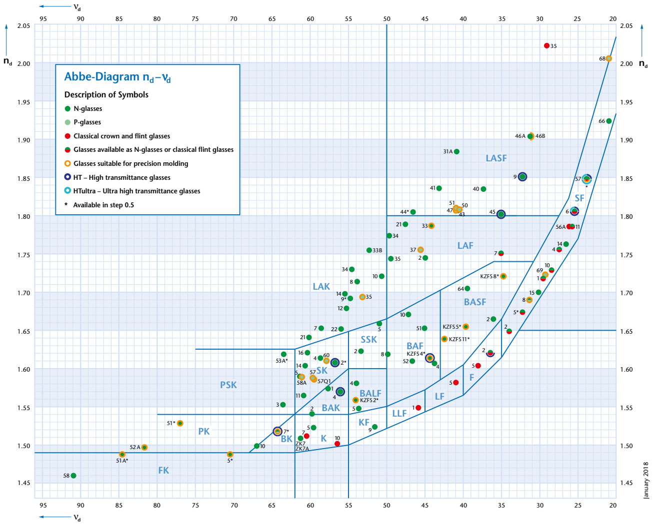


Fig. 23. SCHOTT Advanced Optics Abbe-Diagram that gives an overview of SCHOTT’s optical glass types

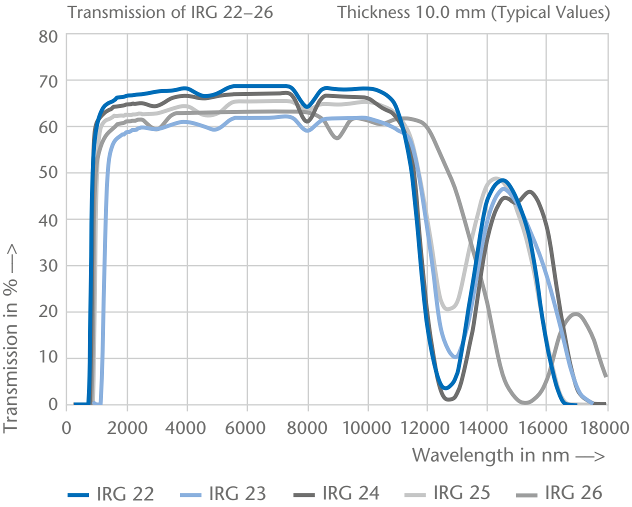


Fig. 24. Transmission of IRG 22–26

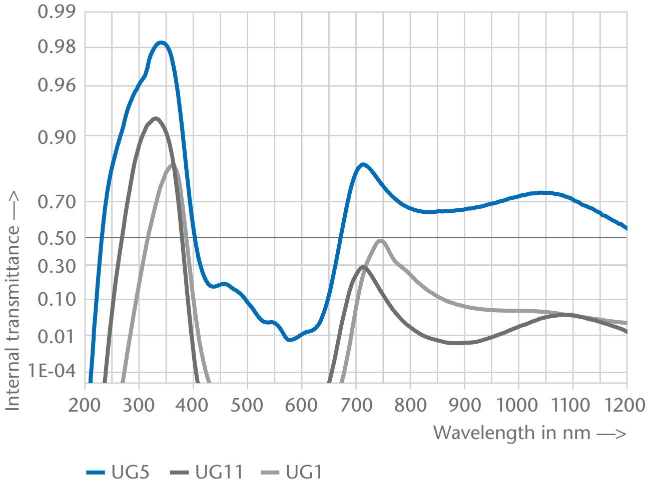


Fig. 25. UV bandpass filter for a glass thickness of 1 mm

5.4 Color of glass

Color is a sensation perceived by the human eye when observing an illuminated filter glass or incandescent object. The color of glass is a function of its spectral transmission and the spectral energy distribution of the illuminating light source. Color stimulus is measurable and is defined by three numerical values (X, Y, Z) in accordance with color metric conventions set forth by the CIE (see publication CIE N° 15.2 (1986)). The first value is its brightness (standard tristimulus value) Y and the other two values define the color locus. There are two possibilities to define the color locus F (see Figure 26): Either the chromaticity coordinates x and y, or the dominant wavelength λ_d (at S) and the excitation purity Pe = DF : DS.

5.5 Stress birefringence

Owing to its very structure, glass is an isotropic material. Mechanical stress causes anisotropy which manifests itself as stress-induced birefringence. A ray of light impinging on glass will be resolved into two components vibrating in planes perpendicular to each other and having different phase velocities. After passing through a plate of thickness d which is subjected to a principal stress difference $\Delta\sigma$, an optical path difference Δs exists between the two components. This path difference can either be estimated by means of the birefringence colors or measured with compensators:

$$\Delta s = K \cdot d \cdot \Delta\sigma \text{ [nm]}.$$

K is the stress-optical coefficient of the glass (determination according to DIN 52314).

$$K = \frac{\Delta s}{d} \frac{1}{\Delta\sigma} \text{ [MPa}^{-1}\text{]}$$

Many glasses have stress-optical coefficients of about 3×10^{-6} MPa^{-1}, and borosilicate glasses of up to 4×10^{-6} MPa^{-1}. High-lead content glasses can have values down to nil or even negative.

Stress-optical measurements permit the determination of permanent stress in glass (state of annealing) as well as of reactive stress caused as a reaction to exterior forces. Stress-optical measurements for the evaluation of glass seals with other glasses, metals, or ceramics are of particular importance. These offer a sensitive method of determining thermal expansion and contraction differences.

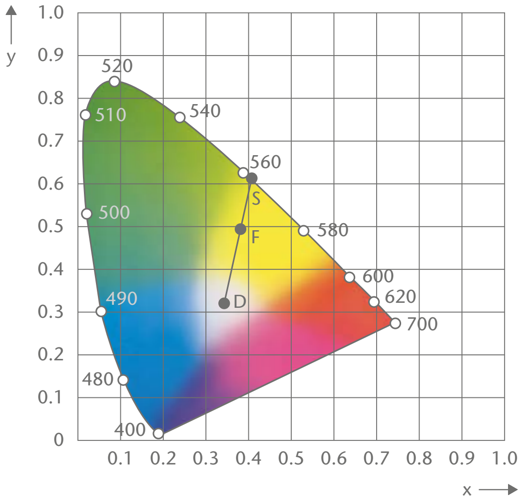
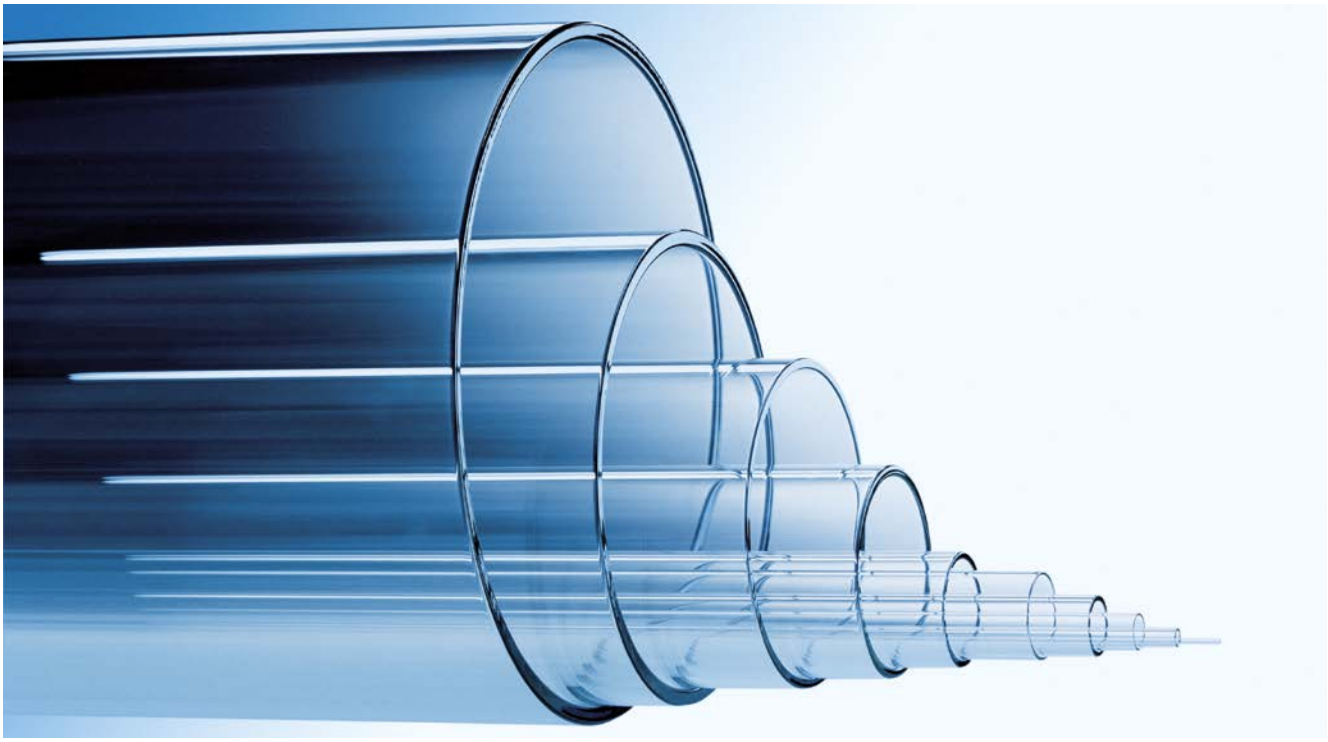


Fig. 26. The color of optical filter glasses according to the definition of CIE 1931
D: Color locus of the radiation source, for example D65
S: Point at which the extension $\overline{DF}$ intersects the spectrum locus at λ_d

6. Highly Resistant Glasses for Laboratory, Pharma and ...



DURAN® tubing for a wide range of applications

The chemically resistant glasses categorized as “borosilicate glasses” contain a high percentage of silica (70 – 80 %), considerable amounts of boric oxide (7 – 13 %), as well as alkali oxides (Na_2O, K_2O, 4 – 8 %), alumina (2 – 7 %), and sometimes alkaline earth oxides (CaO, BaO, 0 – 5 %). Characteristically, they have high chemical durability (hydrolytic class 1, acid class 1) and relatively low thermal expansion, giving high thermal resistance and enabling the manufacture of large, thick-walled components from these glasses.

These exceptional properties of borosilicate glasses were recognized by Otto Schott, and large-scale melts were first put to use in 1892.

Chemically durable borosilicate glasses have such a high acid resistance that even for surface areas as large as 400 cm^2, exposed to a six-hour boiling in 20 % hydrochloric acid, only very small weight losses can be measured. Because the measurement accuracy in determining the variation in the weight of glasses that have large surface areas is roughly equivalent with the weight losses themselves, a sound comparison between the different glasses of this group is impossible. The values simply indicate high acid resistance.

On the other hand, silicate glasses with higher boric oxide contents (> 15 %) are generally not classified as chemically resistant. Examples are electro-technical sealing glasses such as 8245 or 8250, which fall into acid class 4 and 3, respectively.

6.1 DURAN®

The coefficient of linear thermal expansion of 3.3×10^{-6}/K is the lowest of all the large-scale mass-produced technical glasses with high chemical resistance. The low specific thermal stress $\varphi = 0.24$ N/(mm^2 K) indicates its exceptional resistance to thermal shock and temperature variations. These properties allow the production and hot forming of large, thick-walled articles which can be exposed to application temperatures of up to max. 200 °C.

Its thermal properties coupled with outstanding water and acid resistance make DURAN® a highly suitable material for use in laboratories and large-scale chemical plants, for example as pipelines, reaction vessels, heat exchangers, and so on.

For thin-walled DURAN® items, application temperatures can lie considerably above 200 °C. To guarantee shape stability, a maximum of 500 °C should not be exceeded.

DURAN® is made into tubes of up to 450 mm in diameter and pressed and blown glassware. Processed as flat glass, it is available as a floated product under the tradename BOROFLOAT® 33 and as a rolled sheet glass under the tradename SUPREMAX® for applications in home appliances, lighting, chemical engineering, safety, optics, precision engineering and photovoltaics. Figures 27 and 28 illustrate the chemical resistance.

DURAN® is also available in different shapes and called CONTURAX®.

CONTURAX® Pro profile glass tubing

6.2 FIOLAX®

These highly resistant borosilicate glasses are particularly suited for pharmaceutical parenteral packaging such as syringes, ampoules and vials for high-grade injection solutions. Their manufacturing, exclusively in the form of tubes, is today possible with exceptionally tight diameter and wall thickness tolerances. Therefore, the production of syringes, ampoules and vials and their filling on the high-speed filling lines of the pharmaceutical industry are unproblematic. Because the wall thickness of the tubes is comparatively small,

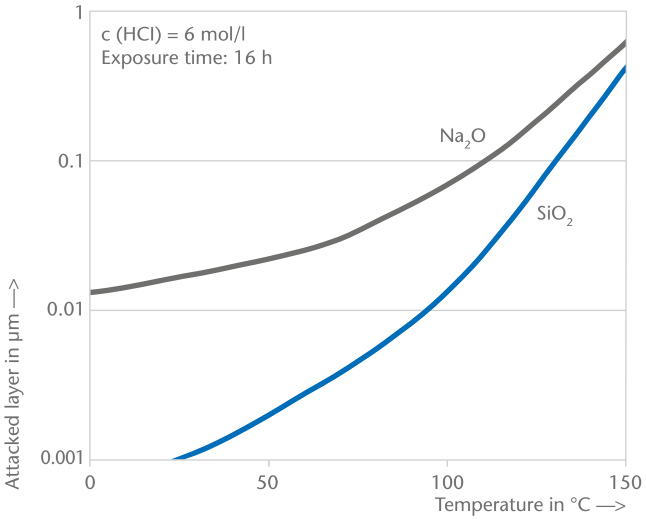


Fig. 27. Acid attack on DURAN®/BOROFLOAT® 33/SUPREMAX® 8330 as a function of temperature and calculated from leached amounts of Na_2O and SiO_2

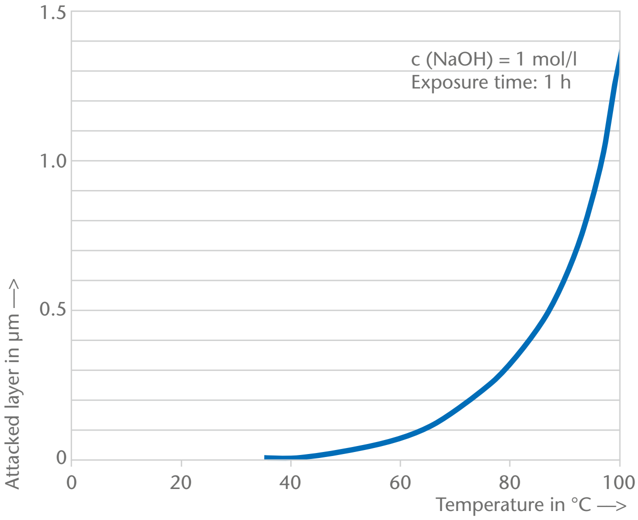


Fig. 28. Alkali attack on DURAN®/BOROFLOAT® 33/SUPREMAX® 8330 as a function of temperature and calculated from the weight losses

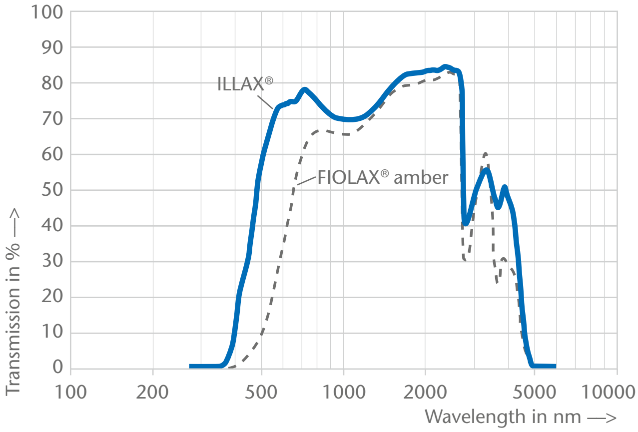


Fig. 29. Spectral transmittance of FIOLAX® amber and ILLAX® for 1 mm glass thickness

Syringes made from FIOLAX® neutral glass tubes

thermal stresses in subsequent processing are not critical, despite thermal expansions of 4.9×10^{-6}/K and 5.4×10^{-6}/K, respectively.

FIOLAX® tubes guarantee highest quality and outstanding chemical stability. Containers made from these glasses, sometimes also called “neutral glasses,” fulfill all the specifications listed in the European Pharmacopoeia and in the various pharmacopoeia of other nations.

Glass type	**Hydrolytic resistance DIN ISO 719**	**Hydrolytic resistance DIN ISO 720**	**Acid resistance DIN 12 116**	**Alkali resistance DIN ISO 695**
	Consumption of 0.01 mol/l HCl ml/g glass	**Consumption of 0.02 mol/l H_2SO_4 ml/g glass**	**Weight loss mg/dm²**	**Weight loss mg/dm²**
DURAN®/BOROFLOAT® 33/ SUPREMAX® 8330	0.030	0.02	0.4	136
SUPRAX® 8488	0.029	0.03	0.3*	92
FIOLAX® clear 8412	0.030	0.04	0.4	110
FIOLAX® amber 8414	0.030	0.04	0.6	115
PYRAN® S 8341	0.033	n.n.	0.3	130

* DIN ISO 1776

Table 6. Values of chemical stability

FIOLAX® clear, 8412
This glass belongs to the chemically resistant alkaline earth containing borosilicate glass type. Its water and acid resistance correspond to those of DURAN®, and its alkali resistance is even higher. Alkaline preparations up to pH values of 12 can be stored and autoclaved in FIOLAX® clear.

FIOLAX® amber, 8414
Due to additions of iron and titanium oxides, this borosilicate glass exhibits high light absorption in the blue and UV spectral regions (see Figure 29). Sensitive pharmaceutical preparations can therefore be effectively protected from light in the critical wavelength region.

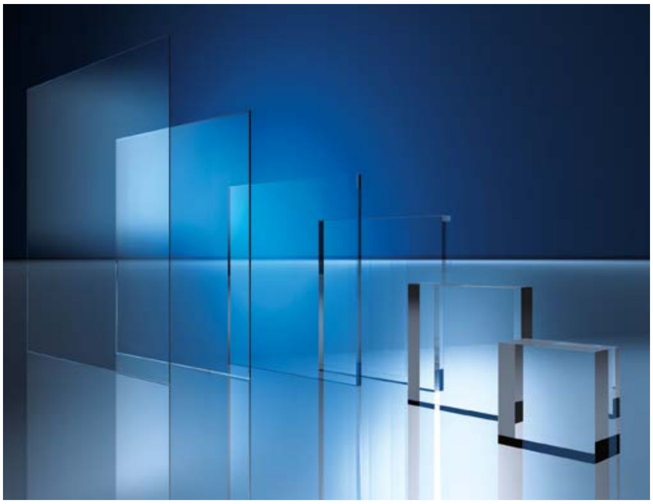
AR-GLAS®
AR-GLAS® with a CTE of 9.1 x 10^{-6}/K belongs to the so-called soda-lime glass family. The hydrolytical resistance is lower compared to the neutral glasses FIOLAX® and DURAN® but the glass is still stable enough to be used as a packaging material for non-parental drugs i.e. pipets, vials for tablets, and test tubes. An advantage is good workability and the good price/performance ratio.

6.3 BOROFLOAT® 33/SUPREMAX®

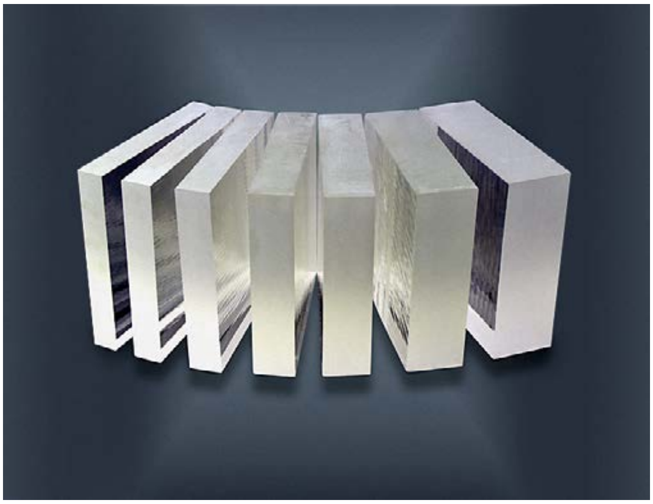
BOROFLOAT® 33 is a high-quality borosilicate glass with impressive properties that make it suitable for a wide range of applications. BOROFLOAT® 33 is manufactured using the microfloat process. SUPREMAX® is a rolled borosilicate glass that utilizes SCHOTT's unique rolled sheet glass technology to offer thicknesses that cannot be produced via the microfloat process.

The chemical composition of BOROFLOAT® 33/SUPREMAX® complies with the requirements for a typical borosilicate glass according to DIN ISO 3585 and EN 1748 Pt. 1 respectively. Like all borosilicate glasses, BOROFLOAT® 33/SUPREMAX® demonstrate high resistance to water, many alkalis and acids as well as organic substances. Its chemical resistance is superior to that of most metals, even during long-term use and at temperatures in excess of 100 °C (as used as sight glasses in the chemical industry). Exposure to water and acids only results in the leaching out of small amounts of ions from the glass (as used in medicine and analytical engineering).

BOROFLOAT® 33/SUPREMAX® are produced using only the finest natural raw materials and are therefore harmless to human beings and the environment in accordance with the requirements of the European guideline ROHS/2002/95. The glass can be recycled for further use.



BOROFLOAT® 33 is a highly versatile high-tech material suitable for manifold applications in industry, engineering and research



SUPREMAX® is available in a broad range of thicknesses

7. Flat Glasses for Home Appliances, Architecture and Safety

Amiran® anti-reflective glass

7.1 AMIRAN®

SCHOTT AMIRAN® – A clear view of what counts: AMIRAN® anti-reflective glass offers low reflection, superb color fidelity and is nearly invisible – even when there are significant differences in the brightness in front and behind the glass. It reduces reflections to only a fraction compared to conventional glass. This makes AMIRAN® anti-reflective glass the material of choice for display windows and showrooms, museums and glass cabinets, luxury box seating in stadiums and panorama restaurants, television and recording studios, façades and balustrades, lobbies and foyers. The boundaries between the outside and inside disappear. This creates the highest possible freedom of design. Canopies or other constructive measures designed to avoid reflections are no longer necessary.

7.2 MIRONA®

SCHOTT MIRONA® – From sight to insight: One glass, two purposes: one moment, MIRONA® translucent, mirrored glass is a stylish, shimmering mirror of silver, and the next, it offers unimpeded views in and out. It's an amazing effect, and unlike other switchable glass products, this effect is produced solely by the coatings applied to MIRONA® mirrored glass. The light level behind the glass determines what you see.

MIRONA® translucent, mirrored glass is a mineral glass that has been coated on both sides. It has low absorption losses and is extremely homogeneous with respect to reflection and transmission. Thanks to its optical interference layer, it has precisely defined states of reflection and transmission. This purely physical principle makes MIRONA® glass an ideal choice to create eye-catching effects.

7.3 MIROGARD®

SCHOTT MIROGARD® – Masterful picture glazing: Museums, collections and galleries all over the world have been relying on MIROGARD® anti-reflective glass for decades. This practically invisible glass that features an anti-reflective optical interference coating protects valuable works of art. Without detracting from art enjoyment. Conventional glass reflects approximately eight percent of incident light. And results in undesirable reflections. MIROGARD® glass reduces reflections in the visible spectrum to under one percent and thus allows for an unadulterated view of art. At the same time, MIROGARD® anti-reflective glass is completely neutral in color. This means the brilliance of the glazed artwork remains true to the original and is rendered in its natural colors.

7.4 PYRAN®, PYRANOVA®, NOVOLAY® secure & PYRANOVA® secure

Fire resistant glazing solutions from SCHOTT act as a barrier against the spread of fire, smoke and heat radiation in the event of fire.

PYRAN® S is manufactured using the micro-float process and clearly outperforms soda-lime glass. Its special physical properties allow for large formats and long fire resistance times.

PYRANOVA® fire resistant glass with heat protection consists of two components: glass and a transparent protective layer between the panes. The layer reacts at approximately 100 °C and foams up to form an opaque heat shield.

Fire resistant glass can also be used for the protection of people and property as an attack-resistant glazing. With NOVOLAY® secure and PYRANOVA® secure, SCHOTT has developed highly effective and compact multifunctional laminates, fulfilling the additional requirements of protection against impact, burglary and bullet penetration.

7.5 Processed flat glass for home appliances

SCHOTT® Flat Glass is a thermally toughened (tempered) float glass produced from a variety of raw materials. Due to its particular resistance to thermal shock, temperature gradients and mechanical loads (e.g. bending and impact), SCHOTT® Flat Glass is an ideal component in many applications such as home appliances and commercial refrigeration applications.

7.6 Special solutions for home appliances

Easy-to-clean coating SCHOTT® CleanPlus
SCHOTT® CleanPlus is the industry leading easy-to-clean coating in the market for inner oven door glasses for baking ovens. The coating is resistant against high temperatures as well as mechanical and chemical stress. SCHOTT® CleanPlus is made of a fully tempered, heat-reflective glass and an advanced, easy-to-clean surface. The powerful self-cleaning capability is based on a system that consists of inorganic and hybrid layers. This results in the combined advantages of the inorganic matrix and the functional organic components. Whereas the inorganic, glassy network delivers high mechanical stability, the organic components help make it easy to clean. This state-of-the-art treatment repels spills and dirt away from the inner window surface, allowing it to be cleaned with minimum effort.

SCHOTT® Hydro Barrier
SCHOTT® Hydro Barrier is a transparent coating that repels liquids and stops liquids from passing over the edge of the glass, i.e. on a refrigerator shelf. It is extremely durable and withstands mechanical stress and temperatures up to 120 °C. SCHOTT® Hydro Barrier is an optically clear hydrophobic coating developed to protect glass. The thin coating (5–15 nanometers) is chemically bound to the substrate (glass) to create a durable protective seal.

Features of glass in combination with electronic components
SCHOTT offers special printing technologies such as heating circuits and capacitive printing to integrate functionality into the glass.

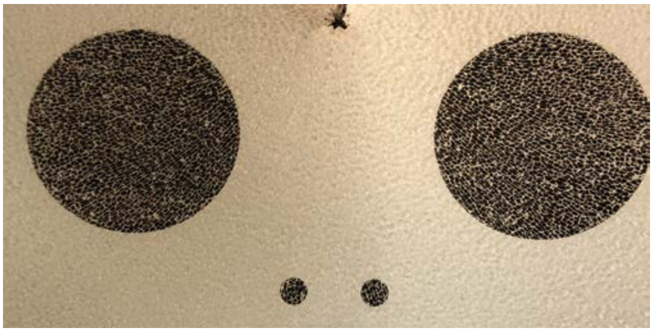
Heating circuits are high current circuits which are printed onto the glass. It is a conductive layer which transmits and can be used to apply power circuits onto the glass.

Capacitive printing is used for electrical circuits to conduct electricity and can be used for touches on control panels. The conductive layer is printed on the rear side of the glass as an interface for capacitive switches to avoid the assembly of a capacitive foil.

In addition, SCHOTT offers the following features for glasses compatible with electronics: IR transparent printing which lets through infrared waves, haptic printing effect and dead front effect printing.

Conductive layer front side

Conductive layer rearside



Fragmentation test for a tempered glass

Refrigerator shelf

Assembly solutions
SCHOTT offers a broad range of assembly solutions to the home appliance industry including encapsulation and a broad range of assembly solutions combining glass with plastics and metal parts (i.e. for refrigerator shelves, washing machine lids and doors). Solutions to combine glass with lighting are also available.

7.7 Insulated glass doors for commercial refrigeration

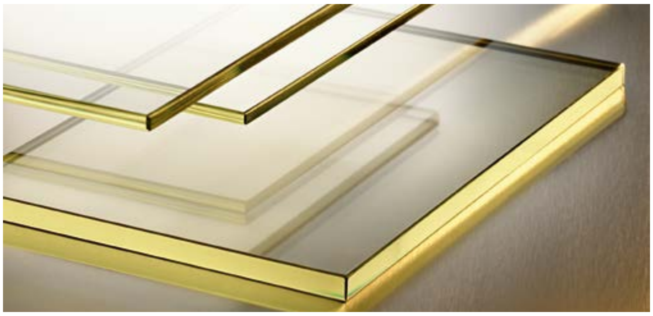
SCHOTT Termofrost® insulated glass door systems are used in a broad range of applications for commercial refrigeration to display and store chilled products down to +2 °C, and frozen goods down to –25 °C. The glass doors typically contain double or triple glazed insulated glass units, the front and rear panes are made of tempered safety glass. Self-closing, condensation-free door systems are essential to display food and beverages at the right temperature, while incurring the lowest possible energy costs.

7.8 Radiation shielding glasses

RD 30 protective clear glass filters are used against X-scattered rays at mammography work stations. Therefore, the lead equivalent is 0.5 mm Pb. RD 30 can also be used for all other applications in the X-ray area if 0.5 mm Pb is required. RD 30 is a drawn flat glass. The lead oxide content is more than 22 percent by weight. Therefore, a density of above 3.13 g/cm³ is reached, so that 6 mm glass thickness fulfill all legal safety regulations.

Radiation shielding glass RD 50® protects against X-rays and gamma rays in the medical and technical field. RD 50® is an extra dense flint glass. Its protective effect is based on its high content of heavy metallic oxides of nearly 70 percent by weight. The lead oxide content alone is more than 65 percent by weight. Therefore, a density of above 5.05 g/cm³ is reached, so that relatively small glass thicknesses fulfill all legal safety regulations. Radiation shielding glass RD 50® meets the requirements of DIN EN 61331-2.

SCHOTT Termofrost® insulated glass door system



SCHOTT radiation shielding glass offers various levels of protection

8. Thin Glasses/Ultra-Thin Glasses for Electronics and More

8.1 BOROFLOAT® 33

BOROFLOAT® 33 is a premium quality, floated borosilicate glass from SCHOTT. It is recognized worldwide for its outstanding material properties and has become established as one of the key materials used in the electronics and semiconductor industry.

Thin BOROFLOAT® is the glass substrate of choice for a high number of technically challenging applications. With a premium-grade surface quality, a very tight thickness tolerance, an extremely low level of defects and an outstanding level of transparency, BOROFLOAT®'s unique performance characteristics are often decisive in fulfilling the requirements of modern thin glass applications.

BOROFLOAT® 33's coefficient of linear thermal expansion (CTE) matches perfectly with that of Silicon, making it the material of choice for anodic bonding and temporary bonding technologies.

8.2 Xensation® Cover

Xensation® Cover is a floated aluminosilicate glass that offers an outstanding level of mechanical impact and bending strength, as well as high resistance to scratches. This specialty glass has been designed for highly efficient chemical strengthening to achieve strength performance levels ideally suited for cover glass protecting touch screen devices, as well as protective and ruggedized light-weight glazing solutions.

The unique glass composition of Xensation® Cover results in the most robust and reliable cover glass available on the market today.

Xensation® Cover: Aluminosilicate glass for capacitive touch technologies

8.3 Thin glasses

Manufactured in proprietary down-draw and up-draw processes, SCHOTT offers a choice of technical thin glasses with outstanding material properties and pristine surface qualities.

AF 32® eco is an alkali-free flat glass available in a thickness range from 0.03 mm to 1.1 mm. Its fire-polished surface has a roughness value below 1 nm. The coefficient of thermal expansion of AF 32® eco matches silicon, therefore it is the perfect choice as optical packaging material in semiconductor related applications. Due to its high transformation temperature, it can be used for high temperature applications up to approx. 600 °C. AF 32® eco is supplied in wafer formats and is manufactured with eco-friendly refining agents.

D 263® T eco thin glass is a clear borosilicate glass that has high chemical resistance. It is available in a variety of thicknesses ranging from 0.03 mm to 1.1 mm. D 263® T eco borosilicate glass is available in standard stock size sheets or can be custom cut into round or square shapes. D 263® T eco thin glass is used as substrate glass for coatings in optical interference filters and in touch panel applications in the automotive and electronics industries. D 263® T eco is manufactured with eco-friendly refining agents.

MEMpax® is a borosilicate glass which has similar chemical and physical characteristics as the well-known product SCHOTT Borofloat® 33.

At the same time, MEMpax® is produced as wafers in much lower thicknesses of 0.1 – 0.7 mm and offers thin wafers that no longer need to be ground and polished, thanks to its excellent surface quality.

The coefficient of linear thermal expansion of MEMpax® corresponds with that of silicon, therefore this glass is perfectly suited for use in anodic bonding.

Its low fluorescence, combined with its excellent surface quality, flatness and homogeneity, opens up numerous application possibilities for SCHOTT MEMpax® in MEMS and biotechnology.

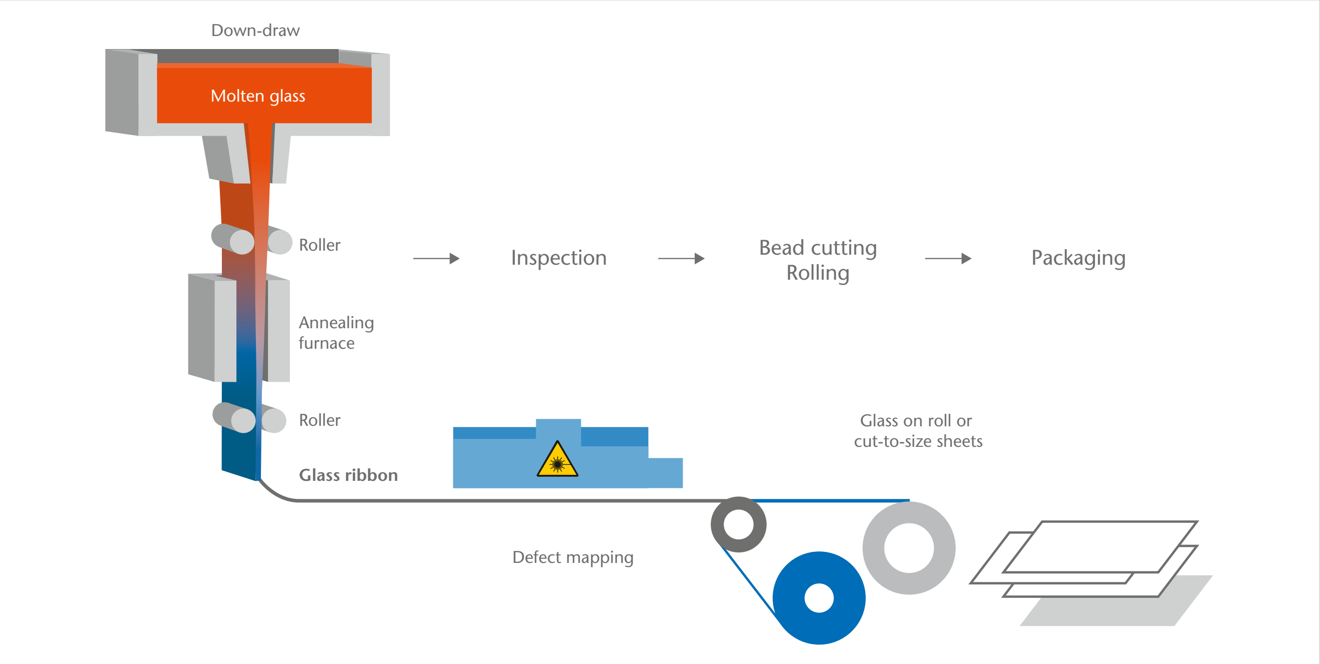


Fig. 30. Schematic representation of the production up to the finalized sheet

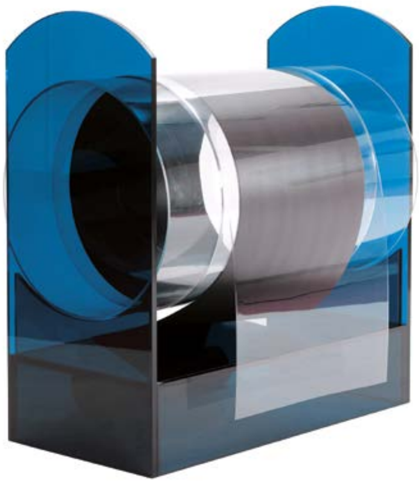
Thanks to its low alkali content, MEMpax® acts as a high-quality insulator. For this reason, MEMpax® is an extremely appropriate material for applications that require electrical insulation at high temperatures (up to 450 °C). It is manufactured with eco-friendly refining agents.

D 263® M is a colorless borosilicate glass for microscopy cover slip applications. It is available in different stock sheet sizes with thicknesses ranging from 0.1 mm to 0.21 mm. D 263® M is a perfect choice as cover glass for microscopic analysis and meets the requirements specified in ISO 8255-1 and DIN ISO 8255-1.

The chemical composition of D 263® M ensures valid and reliable research results due to its low fluorescence and high chemical resistance.

B 270i®, is an ultra white low-iron glass manufactured in an up-draw process. It offers high stability with respect to solarization in combination with high transmission in the visible wavelength range. It has a fire-polished surface and high chemical stability. B 270i® is available in a wide range of thicknesses and various in-stock formats. Customized formats (e.g. rounds) and processing can be offered upon request.

Ultra-thin glass – the flexibility of the down-draw process technology in terms of thicknesses has recently introduced the possibility to manufacture ultra-thin glass in the range of 100 down to 25 µm from some of the well established glass types mentioned above. Glass of that thickness can be rolled up on a core similar to polymer film.



Ultra-thin glass on roll

The material properties – especially the gas barrier properties – are by far superior to polymer films:

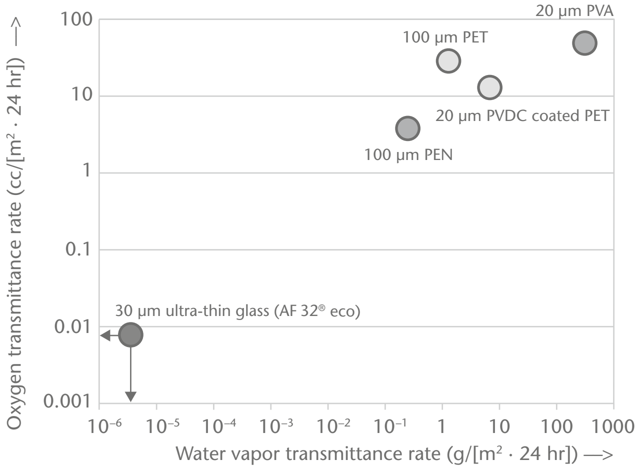


Fig. 31. Gas barrier properties of ultra-thin glass

Further material properties of the ultra-thin glass types which are available either on roll or as cut-to-size sheets

property	D 263 T eco	AF 32® eco
CTE	7.2 ppm/K	3.2 ppm/K
alkaline content	low	no
transformation point	557 °C	715 °C
refractive index	1.5231	1.5255
transmission λ = 550 nm, d = 1 MHz	91.7 %	91.9 %
dielectric constant (at 1 MHz and 20 °C)	6.7	5.1
loss tangent (tan δ) (at 1 MHz and 20 °C)	0.0061	0.0009
thermal conductivity (90 °C)	1.06 W/(m · K)	1.06 W/(m · K)
glass type	borosilicate	alumin-borosilicate

Table 7. Technical data of relevant materials

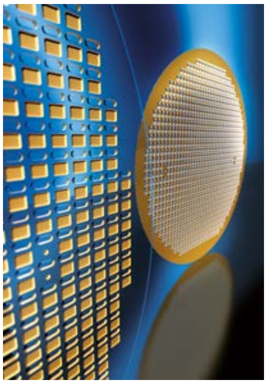
Sample inspection of a thin glass wafer after processing

8.4 Thin glass processing

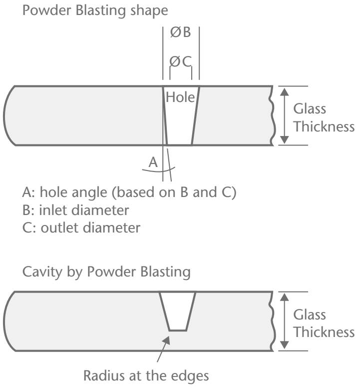
SCHOTT offers an entire portfolio of technologies for processing of thin glass, e.g.

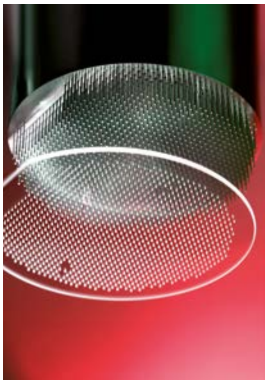
- Cut-to-size for a wide range of wafer and substrate sizes
- Surface refinement by polishing and/or coating
- Structuring of holes or cavities
- Edge treatment options
- Ultrasonic washing
- Clean room packaging

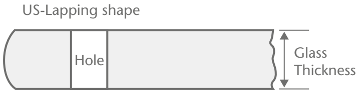
SCHOTT thin glass from a down-draw process does not require any polishing for typical wafer applications due to its inherently pristine surface quality, low roughness and excellent geometry like low total thickness variation. Wafers are directly CNC cut from the mothersheet. Depending on customer requirements, only edge grinding and ultrasonic washing are subsequent processing steps. These wafers are used in high volumes as semiconductor cover glass in wafer level packaging processes of CMOS image sensors for camera modules.



Structured glass wafer







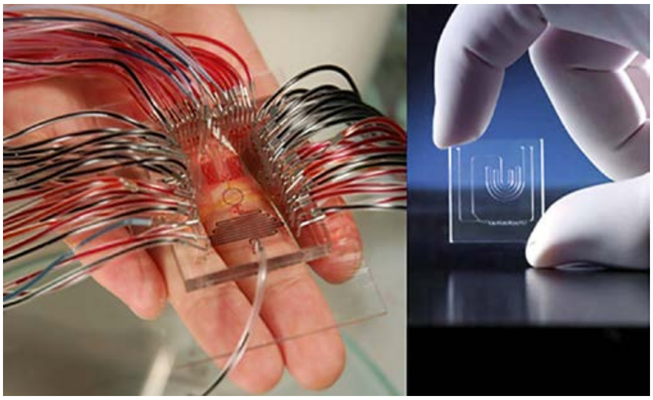
Applications of structured glass wafers and substrates with holes and cavities are in the electronics industry, e.g. for MEMS capping wafers and in the biotech industry, e.g. for flow cells for blood analysis. The two major technologies currently applied by SCHOTT for structuring and their technical capabilities are:

	Ultrasonic lapping	**Powder blasting**
Size	100 mm to 200 mm	Max. 400 mm x 400 mm
Thickness range	0.4 mm up to 3 mm	0.05 mm up to 3 mm
Different hole configurations	Round holes	Round, rectangular holes and caverns
Positioning tolerances	± 65 µm*	± 65 µm*
Min. hole diameter	0.4 mm	0.1 mm

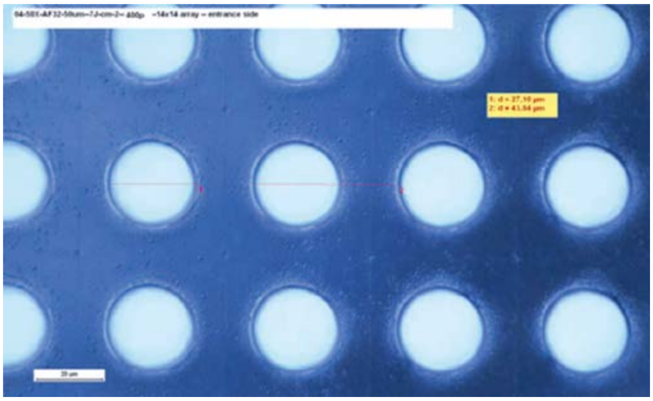
*Tighter tolerances upon request

Table 8. Structured technologies and technical capabilities

For processing of ultra-thin glass, new laser-based processes are under design to cut the glass but also to generate a high number of holes with diameters around 50 microns as TGVs (through glass vias) in printed circuit board and interposer applications.



Flow cell for DNA analysis, structured into SCHOTT thin glass



TGV technology with SCHOTT AF 32® eco 100 µm ultra-thin glass processed by excimer laser at 193 nm wavelength

8.5 Anti-reflective glasses for technical applications (CONTURAN®/DARO)

8.5.1. CONTURAN®

CONTURAN® is an anti-reflective coating on both surfaces based on optical interference coatings, which can be used for technical applications i.e. front panels of visual display units, televisions, display panels, public displays.

The multilayer coating is applied by way of a sol gel process that uses dip coating technology. As shown in Fig. 32a, three different layers are subsequently formed simultaneously on both surfaces of the glass. The refractive index of the layers is varied by the composition of the sol gel solution. SiO_2 is used as a low index material and TiO_2 for the high refractive index. In standard float glass, without an interference coating, about 8 % of light is reflected backwards to the observer (Fig. 32b, lower picture). The interference coating creates a design, which reduces reflecting light waves significantly. As shown in Fig. 32b, less than 1 % of light is now reflected. This reduction of the reflection leads to an enhanced contrast for pictures or displays behind CONTURAN® cover plates.

The coating is designed to reduce the reflection in the visual wavelength region of approximately 400 to 700 nm. Fig. 33 shows the reflection curve for two distinctive coating designs used in the CONTURAN® product portfolio. The "green hue" coating is a design used in standard optics. The "blue hue" coating yields a distinct residual blue reflection often desired in technical, design-oriented applications.

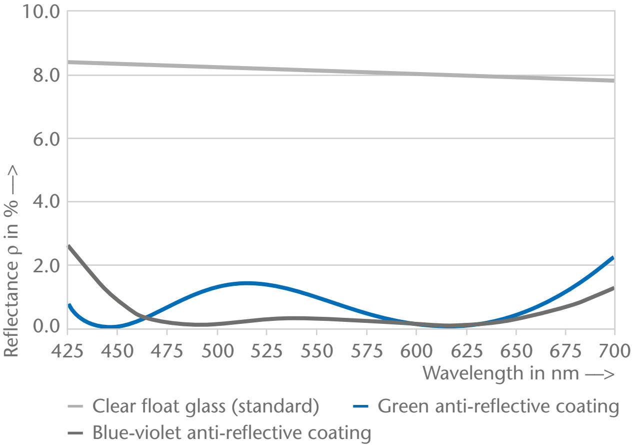


Fig. 33. Reflection spectrum of CONTURAN®: Comparison of "blue hue" and "green hue" reflection

8.5.2. Applications of CONTURAN®

Mineral-based cover plates are often used in display applications to protect the display from mechanical damage. However, the reflection of light on the glass reduces the contrast of the display, especially when used outdoors. One of the most obvious examples is the usage of smartphone outdoors, where the excellent display performance often is completely wiped out by the sunlight. CONTURAN® with its low reflection is exactly designed to maintain the contrast of the display by reducing undesired reflections. Popular examples for applications are automotive displays, public displays and professional displays used for automatization.

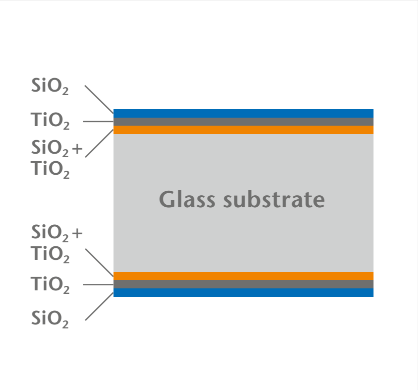


Fig. 32a. Three layer coating design

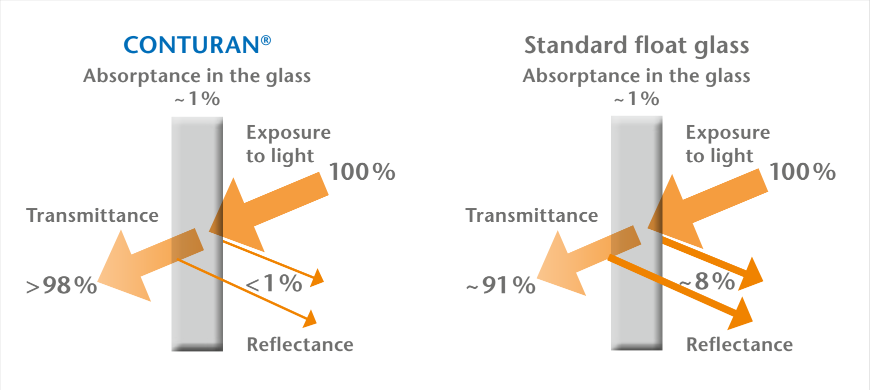


Fig. 32b. Effect of anti-reflective coatings on the reflection of light

Applications of CONTURAN®: Public displays, machine automatization and automotive displays

Since CONTURAN® can be processed in the same way as regular flat glass, all design opportunities can be applied. Different shapes, edge processing and even complex contours can be achieved. Safety standards for automotive and building standards are fulfilled using tempered or laminated CONTURAN®.

8.5.3. CONTURAN® DARO

In order to use an AR coating in a touch application, it must have an oleophobic coating that can stand up to hundreds of thousands of finger touches and rubs. CONTURAN® DARO keeps its properties such as reduced visibility of finger prints, easy-to-clean properties and good haptics even if subjected to harsh chemical stress.

DARO is a new coating family designed to enhance the user experience of anti-reflective coated displays by eliminating the disturbing visual impression of finger prints. **DARO** stands for **D**urable **A**nti **R**eflective **O**leophobic coating and yields an organic coating on top of CONTURAN® with unique, long lasting anti finger print (AFP) behavior.

Unique advantages created by the DARO coating:

Reduced visibility of finger prints: The oleophobic nature of the coating repels the fatty substances of a finger print and hence leaves less material on the surface: This yields a dramatic reduction of the visibility of the finger prints as shown in the comparison in Figure 34.

Fig. 34. Visual appearance of a finger print on **CONTURAN®** (right) and on **CONTURAN® DARO** (left)

Easy to clean properties: The hydrophobic behavior of DARO, which can be seen in the Figure 34 as a round water droplet, leads to an easy-to-clean effect. Dry wiping of the surface is normally sufficient to remove dirt and traces of finger prints.

Using a dry cheesecloth rub test according to MIL-C-675C (3/8 inch pad of dry laundered cheesecloth, load 1.5 lbs., cheesecloth exchanged after 10,000 cycles each), the coating proves to be durable in excess of 450,000 rubs and still maintains its high contact angle, as shown in Fig. 35, well surpassing the result of a standard AFP coating on the market today. In addition, a **neutral salt water spray test** reflects the typical chemical challenge imposed by the sodium content of finger prints. DARO has proven to be extremely long lasting and can withstand more than 90 days in a salt water spray test according to ASTM B117-73 and EN ISO 9227-NSS (Temperature 35 °C +/–2 °C, salt concentration 5 % +/–1 %). Fig. 36 shows the result of the contact angle, which still is above 90 ° after 90 days of test duration.

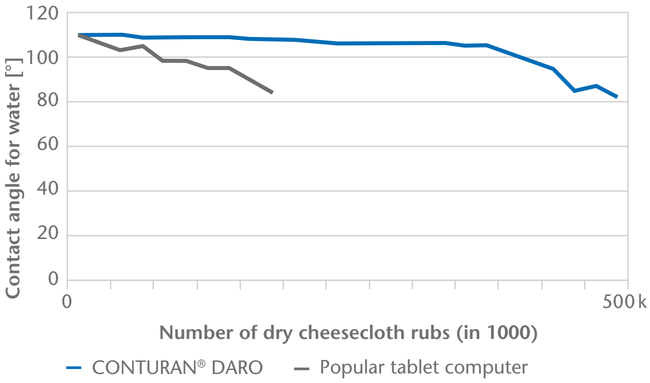


Fig. 35. Contact angle of DARO after multiple cheese cloth wipes

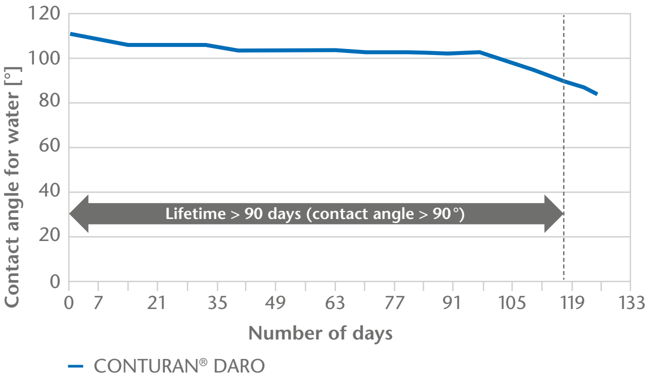
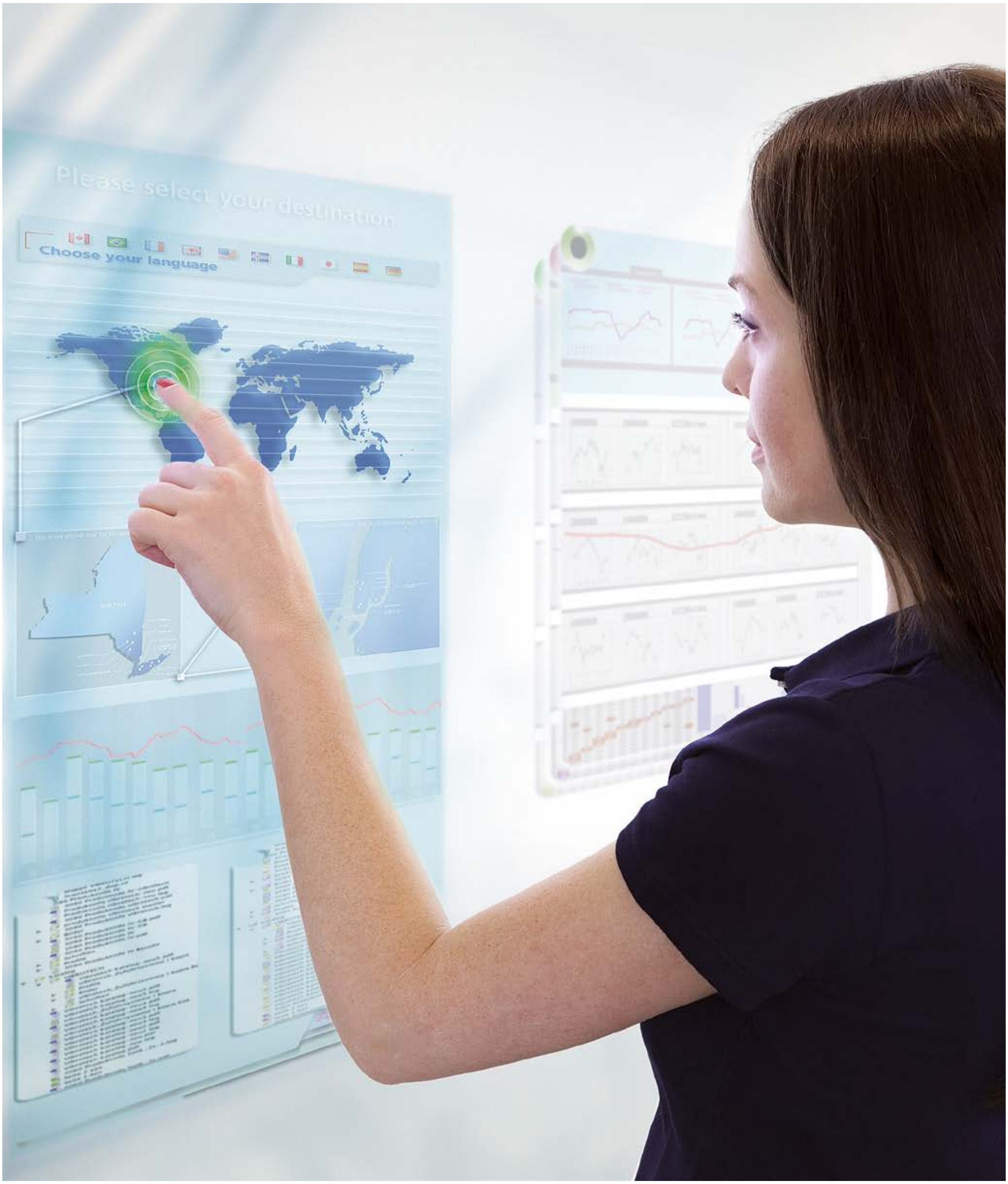


Fig. 36. Contact angle of DARO after long term exposure in EN ISO 9227-NSS test



Applications of CONTURAN® Daro: public displays

9. Glasses for Joinings

9.1 Sealing glasses

9.1.1 General information

Glasses are best suited for the production of mechanically reliable and vacuum-tight fusion seals with metals and ceramics. Particularly favored properties are the viscosity behavior of glass and the direct wettability of many crystalline materials by glasses.

A necessary condition for the stability and mechanical strength of glass seals is the limitation of mechanical stress in the glass component for temperatures encountered during production and use. To ensure “sealability” (which means that the thermal contractions of the two sealing components match each other below the transformation temperature of the glass), glasses of a special composition, so-called sealing glasses, are often developed. Apart from sealability, such glasses must very often fulfill other requirements such as high electrical insulation, special optical properties, etc. The sealability can be tested and evaluated with sufficient accuracy and certainty by stress-optical measurements in the glass portion of a test seal (ISO 4790).

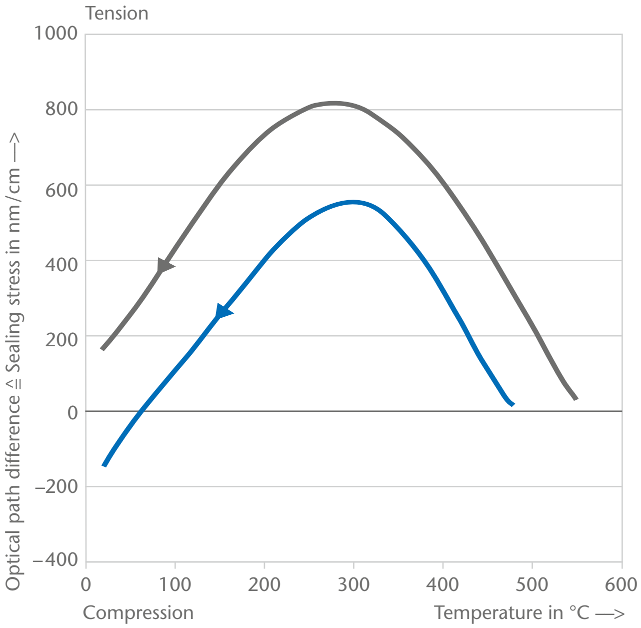


Fig. 37. Influence of cooling rate on the temperature–sealing stress relationship in a 8516–52 Ni/Fe combination; blue curve: low cooling rate, black curve: high cooling rate

Reed switches encapsulated in SCHOTT glass type 8516

Apart from characteristic material values such as coefficient of linear thermal expansion, transformation temperature, and elastic properties, the cooling rate (Figure 37) and the shape can also have considerable influence on the degree and distribution of seal stresses.

9.1.2 Matching glasses

In reference to the expansion coefficients of technically applied sealing metals (e.g. tungsten and molybdenum) and alloys (of Ni-Fe-Co, Ni-Fe-Cr, and other special materials), the corresponding sealing glasses are grouped and designated as “tungsten sealing glasses,” “Kovar glasses,” etc. (see Table 9).

Alkaline earth borosilicate glasses (8412) and aluminosilicate glasses (8252, 8253) have the necessary sealability and thermal resistance to be particularly suitable for tungsten and molybdenum sealings frequently used in heavy-duty lamps.

Tungsten is very often used as a metal wire for highly developed and highly stressed seals. For this, a group of glass types with additional properties are available (8487).

Ni-Fe-Co (Kovar) alloys are of great importance as substitutes for molybdenum. Suitable glasses (8245 and 8250) characteristically contain relatively high amounts of B_2O_3. These glasses have additional special properties, such as high electrical insulation, low dielectric loss and low X-ray absorption, and meet the most stringent requirements for vacuum tube technology and electronic applications.

Metal ($\alpha_{20/300}$ in 10^{-6}/K)	Glass no.	Glass characteristics	Main applications
Tungsten (4.4)	8337B	borosilicate glass, highly UV-transmitting	photomultiplier, UV-detectors
	8487	high boron content, low melting temperature	flash lamps, lamp bulbs, exhaust and flare tubes, discharge lamps
	8689	borosilicate glass, high UV-blocked, stabilized against solarization	backlights
Molybdenum (5.2)	8252	alkaline earth aluminosilicate glass, free from alkali	halogen lamps
	8253	alkaline earth aluminosilicate glass, free from alkali, high temperature resistance	halogen lamps
Molybdenum and 28 Ni/18 Co/Fe (5.1)	8242	Borosilicate glass, electricity highly insulating	clad tube for optical fibers
	8245	high boron content, low melting temperature, low x-ray absorption	x-ray tubes, photomultiplier
	8250	high boron content, low melting temperature, high electric insulation, low dieelectric losses	transmitting tubes, image converters clad tubes for optical fibers, x-ray tubes, glass-to-metal seal packages
	8270	high boron content, stabilized against Tyndall	backlight beads
28 Ni/23 Co/Fe (7.7)	8436	alkali alkaline earth silicate, sealable with sapphire, resistant to Na vapor and alkalis	
51 Ni/1Cr/Fe (10.2)	8350	soda-lime silicate glass, AR-GLAS®	
Cu-sheathed ($\alpha_{20/400}$ radial 99) ($\alpha_{20/400}$ axial 72)	8531 8532 8360	dense-lead silicate, Na- and Li-free, low melting temp., high electrical insulation	low-temperature encapsulation of diodes
52–53 Ni/Fe (10.2.–10.5.)	8516	containing FeO for hot forming by IR, low volatilization, lead-free	reed switches

Table 9. Special properties and principal applications of technically important sealing glasses, arranged according to their respective sealing partners

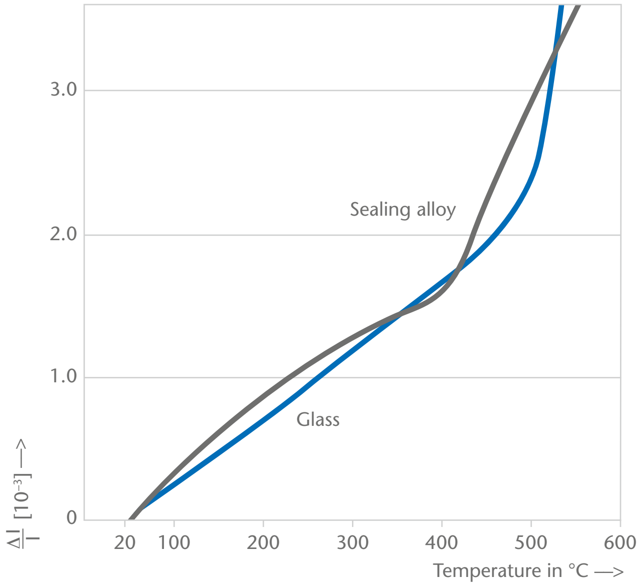


Fig. 38. Relative thermal expansion of the components of a matched glass-to-metal seal (glass 8250 – NiCo 2918)

For Ni-Fe-(Cr) alloys, which are frequently used in technical applications, but also for copper-sheathed wire, glass groups belonging to the soft glass category are recommended. Such glasses usually meet certain special requirements, such as high electrical insulation (alkali-lead silicate 8095), exceptionally low working temperature (dense-lead glasses 8531, 8532), etc.

FeO-containing glass (8516) is frequently used for hermetic encapsulation of electrical switches and electronic components in inert gas. Hot forming and sealing are easily achieved by absorption of IR radiation having its maximum intensity at 1.1 µm wavelength (Figure 39). The presence of a portion of Fe_2O_3 makes these glasses appear green. At appropriately high IR intensities, they require considerably shorter processing times than flame-heated clear glasses.

9.1.3 Intermediate sealing glasses

Glasses whose thermal expansion differs so widely from that of the partner component that direct sealing is impossible for stress reasons, must be sealed with intermediate sealing glasses. These glasses are designed for the recommended seal transitions in such a way that the sealing stresses do not exceed 20 N/mm² at room temperature.

Glass no.	Sealing partners	$\alpha_{20/300}$	Transformation temperature	Glass temperature at viscosities			Density	t_{k100}
				10^{13} dPa·s	$10^{7.6}$ dPa·s	10^{4} dPa·s		
		[10^{-6}/K]	[°C]	[°C]	[°C]	[°C]	[g/cm³]	[°C]
8228	Fused silica–8228–8229	1.3	700	726	1200	1705	2.15	355
8229	8228–8229–8230	2.0	630	637	930	1480	2.17	350
8230	8229–8230–8330	2.7	570	592	915	1520	2.19	257
8447	8412–8447–Vacon 10	4.8	480	505	720	1035	2.27	271
8448	8330–8448–8449, 8486, 8487	3.7	510	560	800	1205	2.25	263
8449	8486 } –8449– 8412 8487 } 8447	4.5	535	550	785	1150	2.29	348
8450	8412–8450–KER 220 8436	5.4	570	575	778	1130	2.44	200
8454	KER 221 }–8454–Vacon 70 Al_2O_3 }	6.4	565	575	750	1070	2.49	210
8455	8436 –8455– 8456 8454	6.7	565	–	740	1030	2.44	–
8456	8455–8456–8350	7.4	445	–	685	1145	2.49	–

Note: type designation of the ceramics to DIN 40685;
manufacturer of Vacon-alloys: Vacuumschmelze Hanau (VAC)

Table 10. Sealing and intermediate sealing glasses

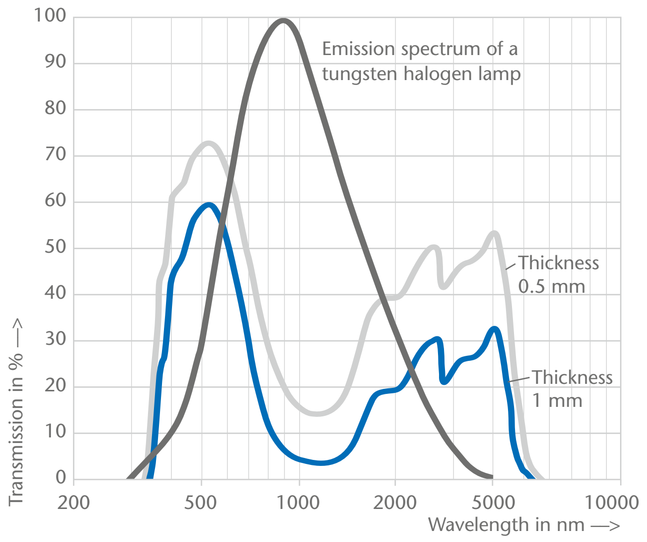


Fig. 39. IR absorption of Fe-doped glasses compared to the emission of halogen lamps. Transmission of reed glass 8516, thicknesses 0.5 mm and 1 mm, and emission of a tungsten halogen lamp (3000 K, rel. unit)

Glass-to-metal sealed housings and feedthroughs reliably protect sensitive electronics in harsh conditions such as humidity, temperature fluctuations, pressure or aggressive chemicals.

9.1.4 Compression seals

A common feature of all compression seals is that the coefficient of thermal expansion of the external metal part is considerably higher than the thermal expansion coefficients of the sealing glass and the metallic inner conductors. As a result, the glass body is under overall radial pressure after the sealing. This prestressing protects the glass body against dangerous mechanical loads and guarantees robust, mechanically insensitive seals. Because the compressive stress of the glass is compensated by tensile stress in the jacket, the jacket wall must be sufficiently thick (at least 0.5 mm even for small seals) in order to be able to absorb such tensions permanently. Like adapted seals, compression seals can be produced as hard glass or soft glass seals. If the difference of the thermal expansion of the metallic jacket and the sealing glass is significantly higher than 5 ppm/K, an additional prestressing of the glass body results ("reinforced compression seal"); see Figure 40.

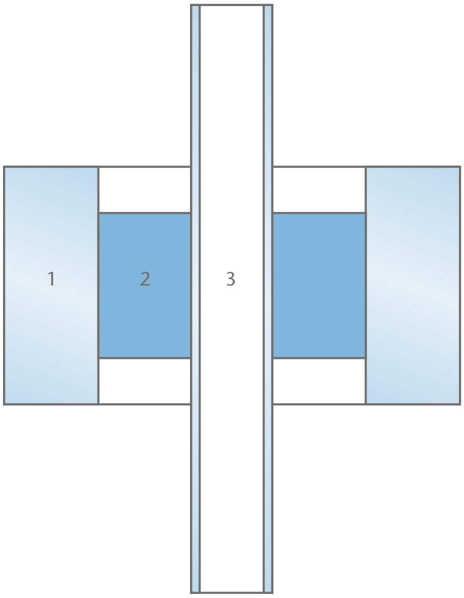


Fig. 40. Schematic representation of a compression glass-to-metal seal
1 = external lead, 2 = glass, 3 = internal tubular lead

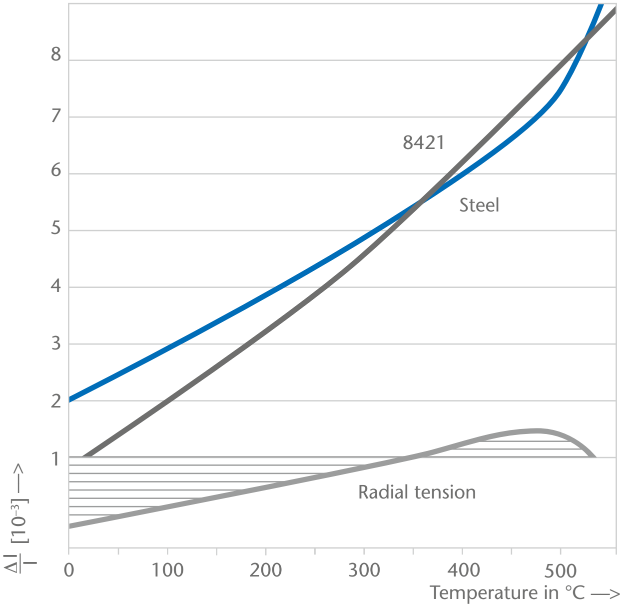


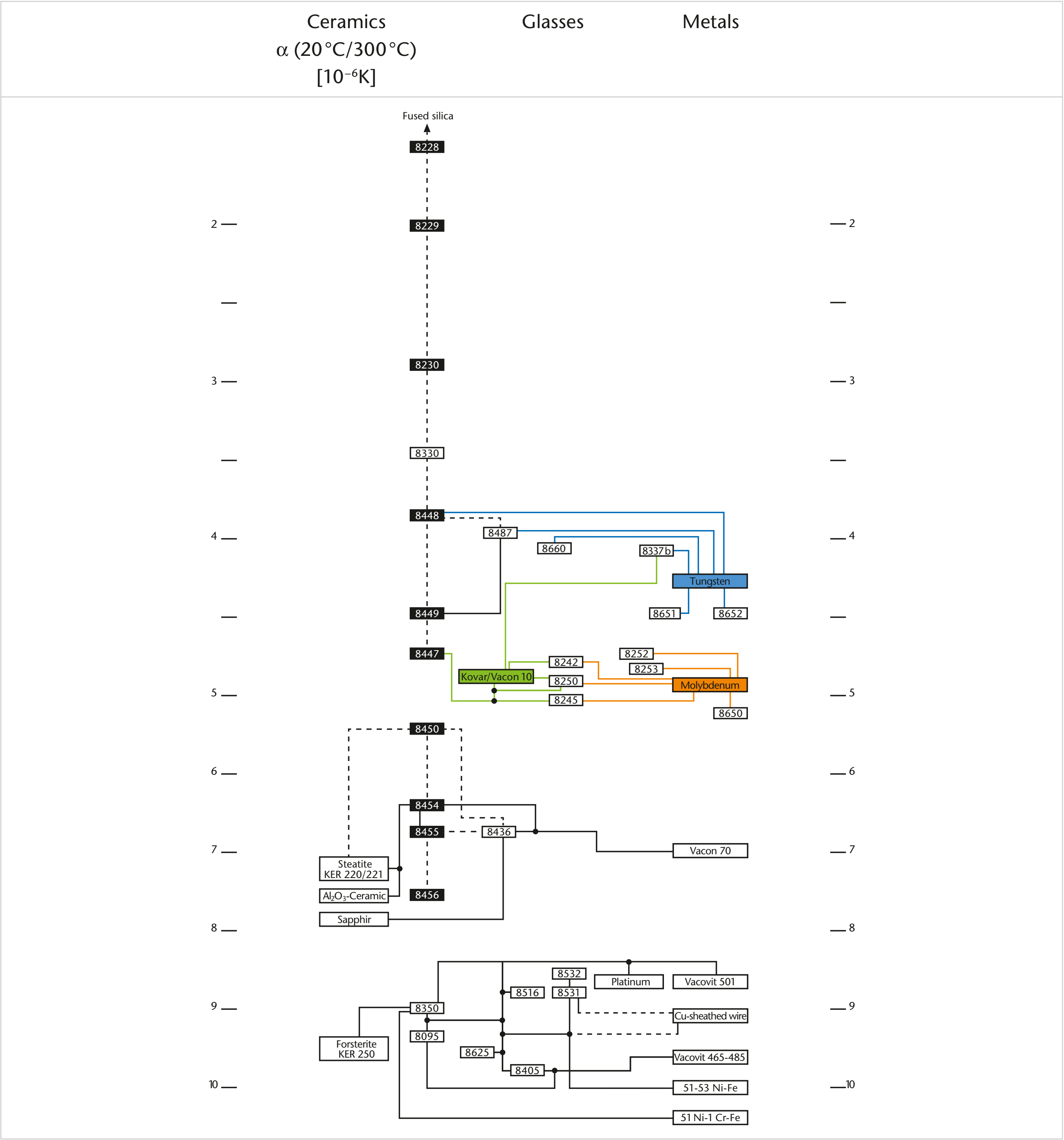
Fig. 41. Relative thermal expansion of the glass and metal (compression ring) of a compression glass-to-metal seal

	$\alpha_{(20/300)}$ [10^{-6} K^{-1}]		
Designation	**Compression ring**	**Glass**	**Interior lead**
Standard compression glass-to-metal seals	13	9	9
Low-expansion standard compression glass-to-metal seals	9	5	5
Reinforced compression glass-to-metal seals	18 13	9 5–7	9 5

Table 11. Expansion coefficients of common material combinations for compression glass-to-metal seals

Glass no.	Main applications	$\alpha_{(20/300)}$	Transformation temperature Tg	Glass temperatures in °C at viscosities dPas		Density	t_{k100}	log of the electric volume-resistivity in Ω cm at		Dielectric properties at 25 °C for 1 MHz		Chemical resistance classes		
		[10^{-6} 1K]	[°C]	$10^{7.6}$	10^4	[g/cm³]	[°C]	250 °C	350 °C	DZ	tanδ [10^{-4}]	W	S	L
8350	Compression seals Seals with steels and NiFe alloys	9.0	520	708	1035	2.52	198	7.1	5.7	7.2	70	3	1	2
8421	Compression seals Seals with steels and NiFe alloys	9.6	525	721	1000	2.59	253	8.1	6.4	7.4	43	3	3	2
8422	Compression seals Seals with steels and NiFe alloys	8.6	540	722	1027	2.46	212	7.3	5.8	7.3	60	2	3	3
8629	Compression seals Seals with steels and NiCo 2918	7.6	529	720	1020	2.52	267	8.3	6.7	6.4	26	1	3	2
8630	Compression seals Seals with steels and NiFe alloys, increased requirements for electrolytic resistance and temperature stability	9.1	440	660	975	2.53	317	9.3	7.6	6.5	21	3	1/2	2

Table 12. Sealing glasses for compression seals



☐ Technical glasses

■ Intermediate sealing glasses

- - - - Producible seals, limited with regard to size and geometry, with stresses between 8 N/mm² and 20 N/mm² at room temperature

—— Tried-out, unrestricted seals with stresses ≤ 8 N/mm² at room temperature

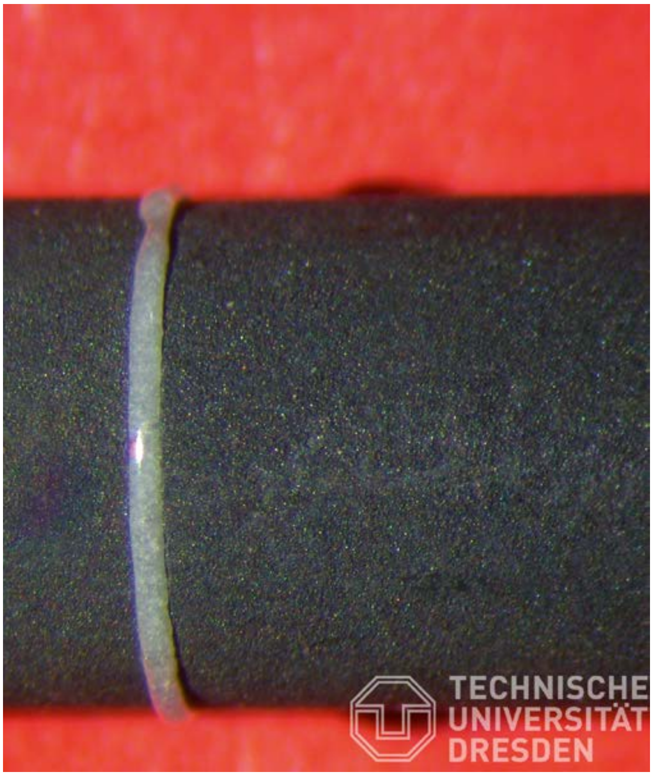
Table 13. Graded seals

9.2 Glass and glass-ceramic sealants for technical ceramics

Dielectrically superior and highly insulating ceramics such as hard porcelain, steatite, Al_2O_3 ceramics, and forsterite exhaust almost the complete expansion range offered by technical glasses. Hard porcelain can generally be sealed with alkaline earth borosilicate glasses, which are also compatible with tungsten. Glass seals with Al_2O_3 ceramics and steatite are possible with special glasses such as 8436, which will also seal with 28 Ni/18 Co/Fe alloy. Soft glasses with thermal expansions around 9 x 10^{-6}/K are suitable for sealing to forsterite.

Aluminum oxide, zirconium oxide and silicon carbide have high temperature resistance. Hence, these ceramics are commonly used in high-temperature sensor applications such as in the combustion chamber or exhaust track of automobiles.

SCHOTT has developed special glasses and glass-ceramics for the joining of these technical ceramics. The sealants are stable at elevated temperatures and are chemically resistant, thereby contributing to the stability of the ceramic applications over an extended period of time.



Joining of SiC ceramic with SCHOTT sealing glass

Advantages

- CTE-matched sealing glasses for Al_2O_3, ZrO_2 and SiC substrates
- Sealing glasses are available for operating temperatures in the range 530–1040 °C and CTE in the range 4.6–9.8 x 10^{-6}/K
- Seals can be achieved through conventional heating (in a furnace) as well as through laser welding
- Glass sealants have excellent electrical insulation
- Sealants are available in powder, paste and preform formats

Sealing partner	SCHOTT glass number	CTE* (10^{-6}/K for 20–300 °C)	T_g (°C)	Sealing temperature (°C)	Maximum operating temperature (°C)
SiC	8253	4.6	785	1320	735
AlN	G018-200	4.6	557	665	550
Al_2O_3	G018-266	6.9	585	770	530
	G018-346	7.3	720	1270	670
	G018-358	8.5 8.8**	658	940	600 1040**
	G018-385	8.4**	992	950	950 °C (1000)
ZrO_2	G018-339	9.2**	627	990	760**
	G018-311	9.1 9.9**	622	850	560 880**

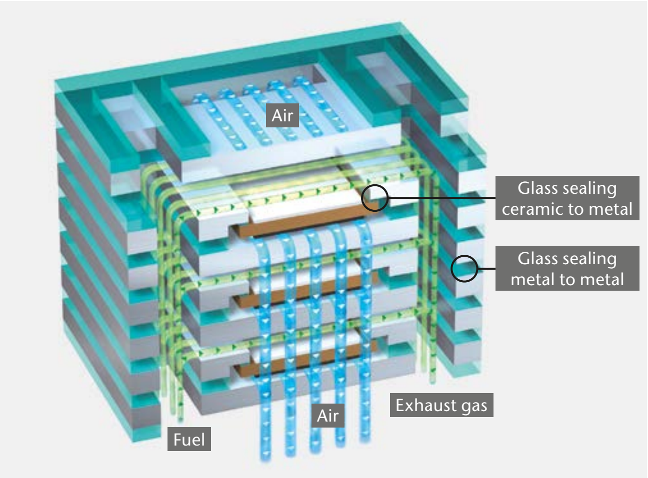
*CTE = coefficient of thermal expansion **p.c. = partially crystalline

Table 14. Sealing glasses for high-temperature applications

9.3 Glass and glass-ceramic sealants for solid oxide fuel cells (SOFC) / sold elecholyzer cells / SO EC

SOFC sealing materials are specially formulated glasses and glass-ceramics that withstand the harsh environments and high operating temperatures of SOFCs. Sealing glass pastes made of glass powder and an organic binding agent are applied to the interconnects through dispensing or screen printing. Green sheets are also available upon request.

Besides providing hermetic sealing, i.e. inhibiting fuel-oxidant mixing, the sealing material also serves as electrical insulation with high electrical resistance at operating temperatures. Moreover, they feature chemical stability under reducing and oxidizing atmospheres and have a matched coefficient of thermal expansion (CTE) to prevent material stress within the structure.



Glass and glass-ceramic sealants

Advantages

- Ideal thermal cycling achieved by perfectly matched CTE to the interconnects and ceramic components
- Crystallizing glasses and glass-ceramic composites with a stable structure for constant long-lasting properties
- High amorphous glass phase for “self-healing” characteristics
- Usage of materials with a broad range of sealing temperatures available
- Excellent electrical insulation
- Alkaline free

Glass no.	$\alpha_{(20-300)}$ [ppm/K] *	T_g [°C]*	Dil. Ew [°C]*	p [g/cm^3]	Sealing temperature [°C]	Sealing partners
GM31107	9.8	543	592	3.70	700	Crofer, ITM, StS
G018-281	12.1	639	>850	2.70	1000	CFY
G018-311	9.9	612	686	3.80	850	Crofer, ITM, StS
G018-354	9.2	637	711	3.90	850	Crofer, ITM, StS
G018-381	12.1	652	>850	2.30	950	CFY
G018-385	8.4	992	>1000	3.14	1000	CFY

*partially crystalline

Table 15. SOFC sealing glasses

9.4 Solder glasses

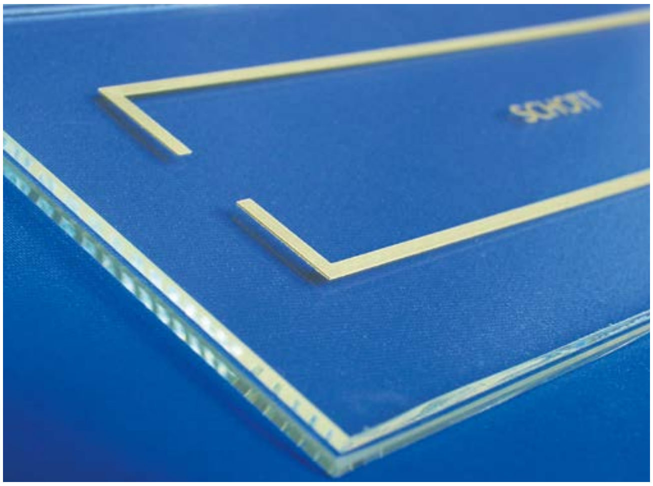
Solder glasses are special glasses with a particularly low softening point. They are used to join glass to other glasses, ceramics, or metals without thermally damaging the materials to be joined. Soldering is carried out in the viscosity range $\eta = 10^4 - 10^6$ dPa·s of the solder glass (Figure 42); this usually corresponds to a temperature range $T_{solder} = 350 - 700\,°C$.

We distinguish between vitreous solder glasses and devitrifying solder glasses, according to their behavior during the soldering process.

Vitreous solder glasses behave like traditional glasses. Their properties do not change during soldering; upon reheating the solder joint, the temperature dependence of the softening is the same as in the preceding soldering process.

Unlike vitreous solder glasses, **devitrifying solder glasses** have an increased tendency to crystallize. They change into a ceramic-like polycrystalline state during soldering. The viscosity increases by several orders of magnitude during crystallization so that further flowing is suppressed. This time-dependent viscosity behavior is exemplarily shown in Figure 43 for a devitrifying solder glass processed by a specific temperature-time program.

On the other hand, crystallization allows a stronger thermal reload of the solder joint, normally up to the temperature range of the soldering process itself. Devitrifying glasses are available upon request.



Panes of flat glass AF 45 bonded with composite solder glass

The development of solder glasses with very low soldering temperatures is limited by the fact that reducing the temperature generally means increasing the coefficient of thermal expansion. This effect is less pronounced in devitrifying solder glasses. It can be even more effectively avoided by adding inert (non-reacting) fillers with low or negative coefficients of thermal expansion (e.g. $ZrSiO_4$ or β-eucryptite). Such **composite solder glasses** are preferably used to produce stable glass solders.

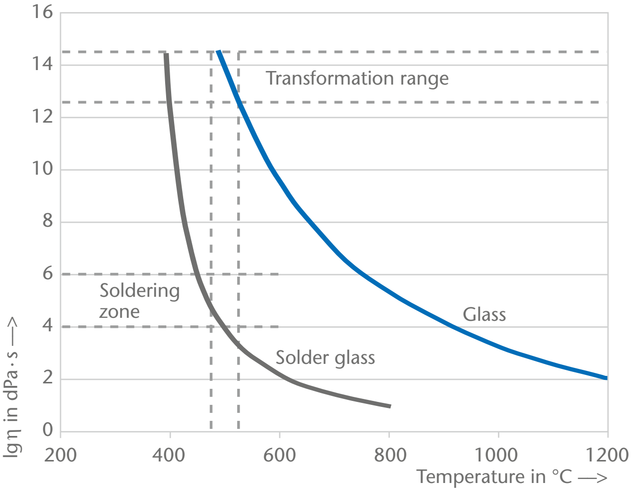


Fig. 42. Viscosities η of solder glass to be soldered

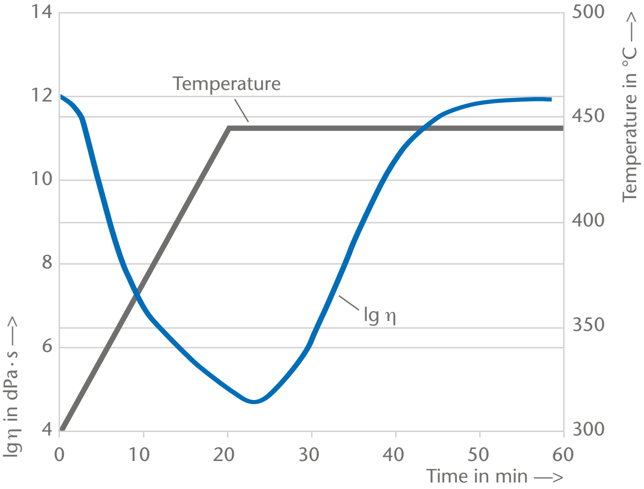


Fig. 43. Viscosity development of a crystallizing solder glass during soldering

Because fillers reduce the flow capability during the soldering process, they can be added to the batch only in limited amounts.

Taking into consideration the properties of the materials to be joined, suitable solder glasses are mainly selected under the following aspects:
1. highest permissible soldering temperature,
2. thermal expansion of the materials to be joined,
3. maximum application temperature of the solder zone,
4. chemical behavior.

Processing

To achieve satisfactory soldering, the solder glass must flow sufficiently and wet the parts to be joined well. Flow and wetting are temperature- and time-controlled; the higher the temperature, the less time is required for sufficient flow, and vice versa.

Thus, soldering at high temperatures may take only a few minutes, whereas at low temperatures (i.e. at viscosities $\geq 10^7$ dPa · s) reaching sufficient flow takes very long and usually can be achieved only under additional mechanical load.

Properties

As with all sealings involving glass, adapting the thermal expansions of the components to be joined with solder glass is a necessary prerequisite for stable, gas-/leak-tight joins. As a rule, the coefficient of thermal expansion of the solder glasses should be by $\Delta\alpha = 0.5 - 1.0 \times 10^{-6}$/K smaller than the expansion coefficients of the sealing partners.

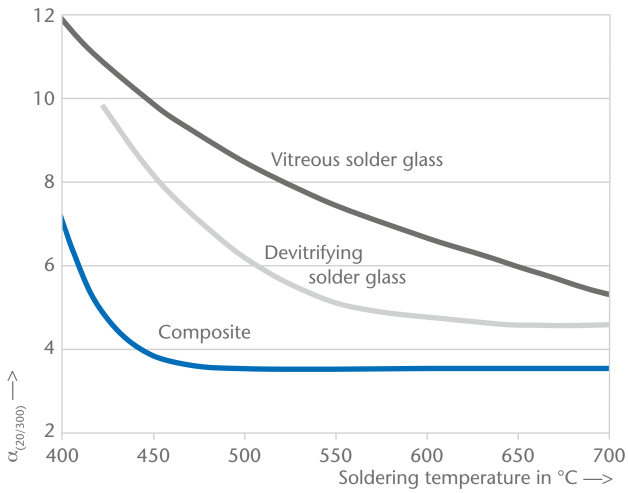
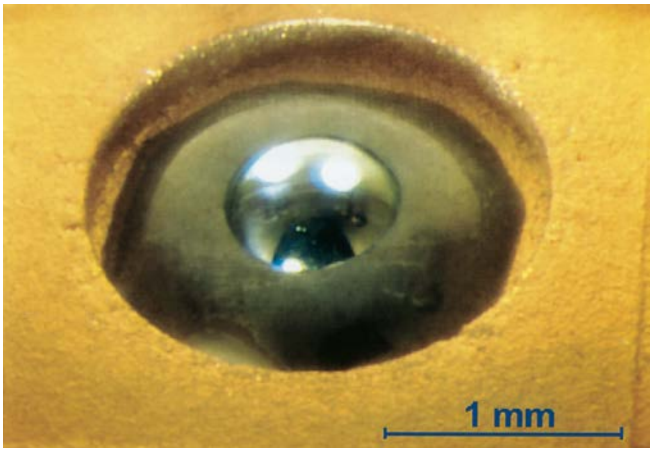


Fig. 44. Relationship between soldering temperature and linear expansion α for solder glasses. The curves describe the lowest limits for the respective solder glass types.



Spherical lense (center) sealed to a metal casing with a sintered solder glass ring

The relationship between soldering temperature and thermal expansion is schematically shown in Figure 44.

With devitrifying solder glasses, one must consider that the expansion coefficients given in the respective lists of properties are only valid on condition that the specific soldering program defined for each solder glass is complied with. Changing the soldering program, in particular the soldering temperature and the soldering time, may affect the relationship between glassy and crystalline phase and thus change the coefficient of thermal expansion, with the possible result of a mismatch.

Sealing joints produced with vitreous solder glasses can be loaded to approximately 50 K below the transformation temperature of the respective solder glass. The maximum service temperature of devitrifying solder glasses depends on the type and melting point of the precipitated crystals and on the amount and properties of the residual glass phase. Up to maximum service temperature, solder glasses are moisture- and gas-proof. Their good electric insulating property is superior to that of many standard technical glasses. They are therefore also suitable as temperature-resistant insulators. The chemical resistance of solder glasses is generally lower than that of standard technical glasses. Therefore, solder glass sealings can be exposed to chemically aggressive environments (e.g. acids, alkaline solutions) only for a limited time.

Deliverable forms and shapes
Solder glass can be supplied in the form of powder, granulate and sintered preforms (e.g. rings, rods, …), and as paste. An example of a glass-to-metal seal application is shown on page 50, Table 13.

Glass no.	$\alpha_{(20/300)}$	T_g	Sealing temperature		Density	t_{k100}	tanδ
				$t_{holding}$			
	[10^{-6} x K^{-1}]	[°C]	[°C]	[min]	[g/cm³]	[°C]	[10^{-4}]
Lead-containing							
G017-002	3.7	545	700	15	3.6	–	37
G017-339	4.7	325	510	15	4.3	11.5	19
G017-712	5.3	375	510	10	–	–	–
G017-393	6.5	320	425	15	4.8	11.6	15
G017-340	7.0	315	420	15	4.8	13.4	14
G018-228	7.6	311	400	15	5.0	–	–
8465	8.2	385	520	60	5.4	14.9	27
G018-229	8.7	310	410	15	5.4	–	–
G018-256	9.6	316	420	15	5.8	–	–
G017-052	11.7	308	410	15	6.7	–	–
Lead-free							
G018-250	7.0	380	510	15	5.7	–	–
G018-255	9.4	396	520	15	6.7	–	–
8470	10.0	440	680	60	2.8	–	–
G018-249	10.1	365	500	15	7.1	–	–

Other matched CTE available upon customer request
All solder glasses are available as K3 powder. Grain size: $d_{50} = 10 \pm \alpha_{\mu m}$, $d_{99} \leq 63_{\mu m}$

Other grain sizes available upon request

Table 16. SCHOTT solder glasses

9.5 Passivation glasses

Passivation glasses are zinc-borosilicate and lead-alumina silicate glasses used for chemical and mechanical protection of semiconductor surfaces.

Processing

To avoid distortion and crack formation, the different coefficients of thermal expansion of the passivation glass and the other semiconductor components must be taken into account. If the mismatch is too large, a network of cracks will originate in the glass layer during cooling or subsequent processing and destroy the hermetic protection of the semiconductor surfaces. Basically, there are three ways of overcoming this problem:

The thinner the passivation glass layer, the smaller is the risk of cracking. SCHOTT therefore recommends maximum thicknesses for all homogeneous passivation layers that, as a rule, should not be exceeded.

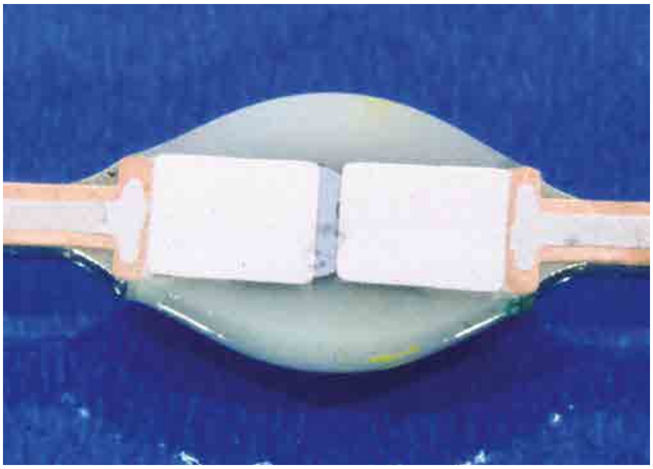
The sealing stress between glass and silicon, and thus the risk of cracking, can be reduced by slow cooling in the transformation range. As a rough rule, a cooling rate of 5 K/min is suitable for passivation layers in the temperature range $T_g \pm 50$ K.

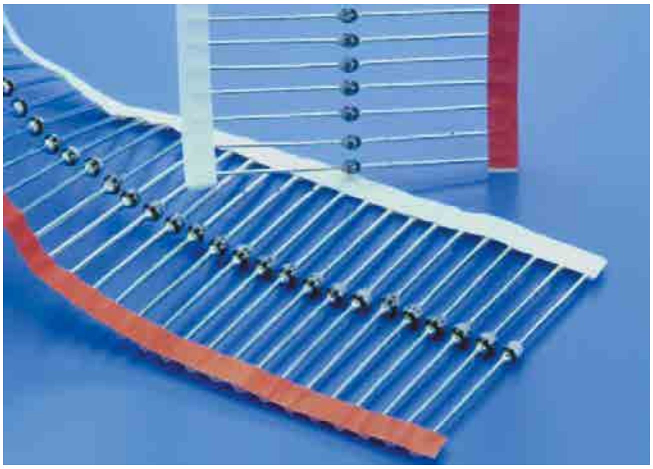
Another way of avoiding thermal expansion mismatches is using composite glasses. Composites consist of a mixture of passivation glass powder and an inert filler such as, for example, powdered ceramics with very low or negative thermal expansion. Such fillers lower the mean thermal expansion coefficient of the passivation glass and thus minimize or eliminate the risk of cracking. As a secondary effect, fillers improve the mechanical stability of the composite glass.

Different processing techniques, adjusted to the requirements of the respective applications, are employed. For the manufacturing of sintered glass diodes, usually a slurry of glass powder and deionized water is applied to the diode body, including the Mo- or W-contact studs. For wafer passivation (glass applied to the Si wafer before separating the chips), an organic suspension is applied by spinning, doctor blading, sedimentation, electrophoresis, or screen printing. The organic suspension vehicles must be completely volatile or thermally decomposable below the softening temperature of the glass.

Properties

Electrical insulation, including dielectric breakdown resistance, generally depends on the alkali content, particularly on the Na^+ content. Alkali contamination in SCHOTT passivation glasses is kept low by selecting pure raw materials and special manufacturing procedures. Contamination is tested for every batch. Typical contents are below 100 ppm for Na_2O and K_2O, and below 20 ppm for Li_2O. Some composite passivation glasses may contain fillers with slightly higher amounts of alkali; because the mobility of alkali ions is negligible, there is no risk of impairing the quality of the component.


Polished section of a glass-encapsulated silicon diode


Diodes prepared for delivery (e.g. small signal diodes)

Lead-containing	Type	Main applications	$\alpha_{(20/300)}$ 10^{-6}/K	T_g °C	Pb contents wt%	Firing temp. °C	Holding time min.	T_j °C	Layer thickness µm
G018-205	Pb-Zn-B	sinter glass diodes	4.45	541	1–5	690	10	–	–
G017-388	Zn-B-Si composite	thyristors, high-blocking rectifiers	3.6	550	1–5	700	5	180	≥ 30
G017-002	Zn-B-Si composite	sintered glass diodes	3.7	545	1–5	700	10	180	–
G017-096R	Pb-B-Si	sinter glass, planar- and mesa-diodes	4.8	456	10–50	680	5	160	–
G017-004	Pb-B-Si composite	mesa diodes	4.1	440	10–50	740	5	160	≥ 30
G017-230	Pb-B-Si composite	transistors	4.2	440	10–50	700	4	160	≥ 25
G017-725	Pb-B-Si	sinter glass diodes	4.9	468	10–50	670	10	180	–
G017-997	Pb-B-Si composite	wafer passivation	4.4	485	10–50	760	20	180	–
G018-133	Pb-B-Si composite	sinter glass diodes	4.8	463	10–50	690	30	–	–
Lead-free									
G018-200	Zn-B-Si	sinter glass diodes	4.6	557	–	665	10	–	–
G018-197	Zn-B-Si	sinter glass diodes	4.4	557	–	675	10	–	–
G018-255	Bi-Zn-B	varistors	9.4	396	–	520	15	–	–

Table 17. SCHOTT passivation glasses

Heavy metals which are incompatible with semiconductors are controlled as well. The CuO content, for example, is below 10 ppm.

Because the mobility of charge carriers increases drastically with increasing temperature, a temperature limit, called junction temperature T_j, is defined up to which glass-passivated components can be used in blocking operations.

In manufacturing, glass passivation is often followed by chemical processes (such as etching of contact windows or electrolytic deposition of contacts) which may attack the glass. The chemical resistance of the various passivation glasses differs strongly and is an important criteria in selecting the appropriate glass type. Zinc-borosilicate glasses, for instance, are highly sensitive to chemical attack by acids and alkaline solutions and therefore only recommended for use with contacts applied by sputtering.

Forms of supply

Passivation glasses are supplied as glass powders, ground iron-free and with negligible abrasion. Passivation glasses are available as tubing or sleeves for use in certain applications. They are available in various grain sizes (generally type K, see Table 17) to suit the respective application.

10. Glass-Ceramics for Industrial Applications and Home Appliances

10.1 Introduction to glass-ceramics

Glass-ceramics are distinguished from glass and ceramics by their characteristic manufacturing process (see Figure 45) and by their properties. Not classifiable as glass or as ceramic, they represent a completely new class of materials.

They are manufactured in two principal production steps. In the first step, a batch of exactly defined composition is melted (as for normal glass). The composition is determined by the desired properties of the end-product as well as by the necessary working properties of the glass. After melting, shapes are produced by pressing, blowing, rolling or casting and then annealed. In this state, the material still exhibits all the typical characteristics of glass.

In the second step, the "glassy" articles are subjected to a specific temperature-time treatment between 800 – 1200 °C (defined for each composition), by which they are ceramized, i.e. they are transformed into a mainly polycrystalline material. Apart from the crystalline phase with crystals of 0.05 – 5 µm in size, this material contains a residual glass phase of 5 – 50 %.

In the temperature range between 600 – 700 °C, small amounts of nucleating agents (e.g. TiO_2, ZrO_2 or F) induce precipitation of crystal nuclei. As the temperature increases, crystals grow on these nuclei. Their type and properties as well as their number and size are predetermined by the glass composition and the annealing program. By appropriate program selection, either transparent, slightly opaque, or highly opaque, non-transparent glass-ceramics can be produced. Unlike conventional ceramics, these glass-ceramics are absolutely dense and pore-free. To achieve controlled

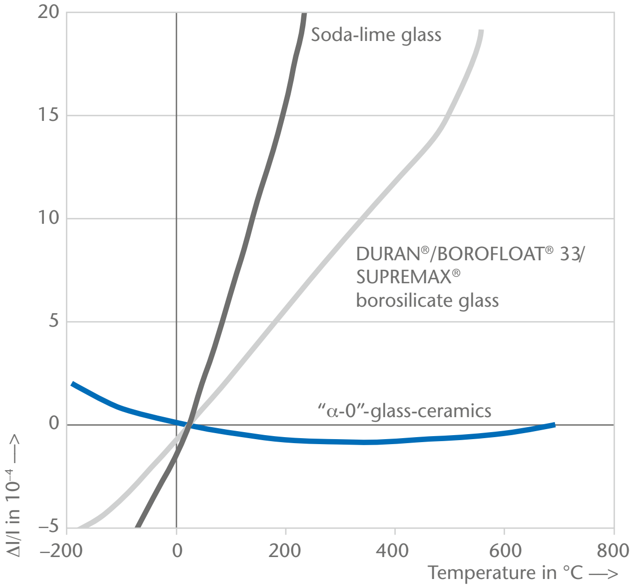


Fig. 46. Thermal expansion of "α-0"-glass-ceramics compared to borosilicate glass 3.3 and soda-lime glass

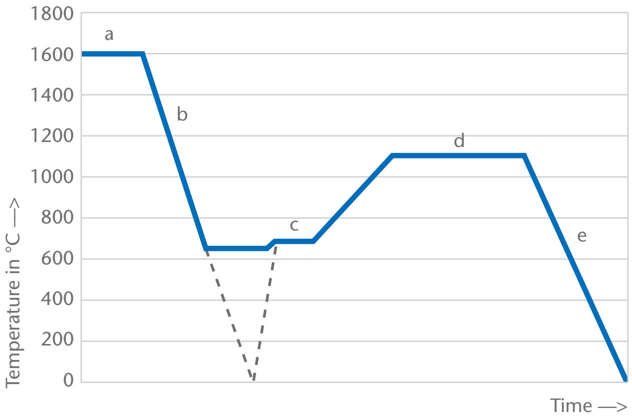


Fig. 45. Temperature-time schedule for glass-ceramic production
a: melting, b: working, c: nucleation, d: crystallization,
e: cooling to room temperature

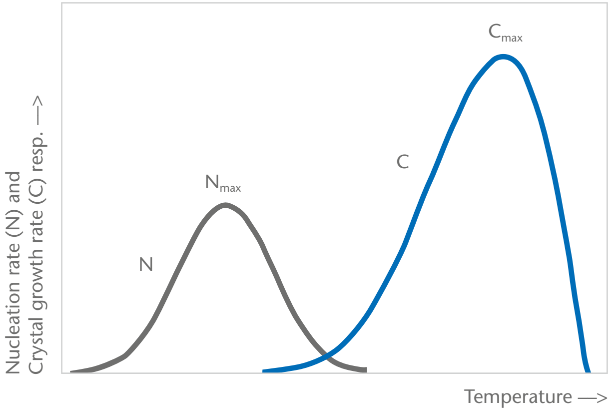


Fig. 47. Nucleation rate (N) and crystal growth rate (C) of glasses, related to temperature

crystallization in the glass, the temperature difference between the nuclei formation region and the crystal growth region must be sufficiently large (Figure 47). In this way, spontaneous crystallization during hot forming and unwanted crystal growth during nucleation can be avoided.

Like the glass composition, the composition of glass-ceramics is highly variable. Well-known compositions lie within the following systems:
$Li_2O–Al_2O_3–SiO_2$; $MgO–Al_2O_3–SiO_2$; $CaO–P_2O_5–Al_2O_3–SiO_2$.

Glass-ceramics of the $Li_2O–Al_2O_3–SiO_2$ system that contain small amounts of alkali and alkaline earth oxides as well as TiO_2 and ZrO_2 as nucleating agents have achieved great commercial significance. Based on this system, glass-ceramics with coefficients of linear thermal expansion of close to zero can be produced (Figure 46 and Table 18). This exceptional property results from the combination of crystalline constituents (such as solid solutions of h-quartz, h-eucryptite or h-spodumene), with negative coefficients of thermal expansion, and the residual glass phase of the system, with a positive coefficient of thermal expansion.

Such “α-0”-glass-ceramics can be subjected to virtually any thermal shock or temperature variation below 700 °C, whereby wall thickness, wall thickness differences, and complicated shapes are of no significance.

Another technical advantage is the exceptionally high dimensional and shape stability of objects made from these materials, even when subjected to considerable temperature variations.

An application for CERAN® glass-ceramic cooktop panels:
e.g. SCHOTT CERAN® for induction

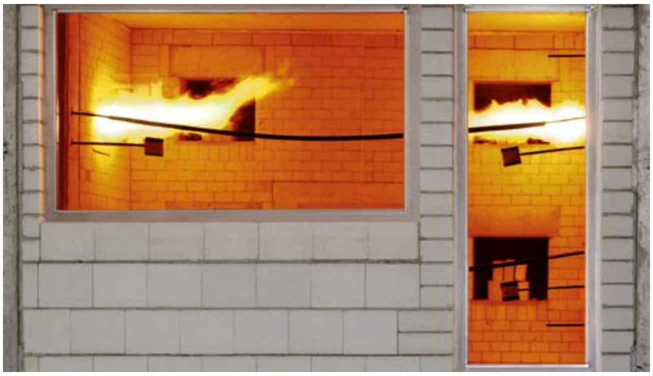
10.2 PYRAN® Platinum

PYRAN® Platinum is the world's first fire-rated glass-ceramic material manufactured using the microfloat process. It offers an outstanding surface quality and unprecedented color neutrality.

PYRAN® Platinum is the only environmentally-friendly fire-rated glass-ceramic produced without the hazardous heavy metals arsenic, antimony and barium. It is UL (Underwriters Laboratories) classified for fire-ratings up to 90 minutes and passes the required hose stream test. PYRAN® Platinum fire-rated glass-ceramic is intended for use in non-impact, safety-rated locations such as transoms and windows. The filmed and laminated PYRAN® Platinum glass-ceramic products are impact safety-rated and meet the requirements according to ANSI (Cat. I and II). They are intended for use in safety-rated locations such as door lites, transoms or sidelites, and windows.

	Unit	Product class	ZERODUR®	Glass-ceramics for cooktop panels
$\alpha_{0/50}$	10^{-6}/K	Extreme	0 ± 0.007	
		Special	0 ± 0.010	
		Exp Cl 0	0 ± 0.02	
		Exp Cl 1	0 ± 0.05	
		Exp Cl 2	0 ± 0.1	
$\alpha_{20/300}$	10^{-6}/K		+0.1	–0.2
$\alpha_{20/500}$	10^{-6}/K		–	–0.01
$\alpha_{20/600}$	10^{-6}/K		+0.2	–
$\alpha_{20/700}$	10^{-6}/K		–	+0.15
Density	g/cm³		2.53	2.56
Young's modulus E	GPa		90	92
Poisson's ratio μ			0.24	0.24

Table 18. Coefficient of linear thermal expansion α, density and elastic properties of ZERODUR® and glass-ceramics for cooktop panels



PYRAN® Platinum fire-rated glass-ceramic product lines pass the fire and hose stream tests.

10.3 ZERODUR®

ZERODUR® glass-ceramic whose coefficient of linear thermal expansion at room temperature can be kept as low as ≤ ±0.007 x 10^{-6}/K (Table 18) was originally developed for the production of large mirror substrates for astronomical telescopes. Today ZERODUR® is used in components for applications, which require the tightest control of dimensions under temperature variation such as IC and LCD lithography, precision measurement and navigation of airplanes and submarines.

To meet the highest precision requirements the production of ZERODUR® TAILORED can be adapted to achieve minimal thermal expansion at customer application temperature conditions.

Next to the extremely low values of thermal expansion, the homogeneity of this property is of crucial importance for IC lithography components. ZERODUR® blanks up to 4 m in size are frequently produced with CTE homogeneity values in the range of several parts per billions per degree K.

10.4 NEXTREMA™

Besides the well-known glass-ceramic products ROBAX® for fireplace and CERAN® for cooktop applications, SCHOTT has developed and introduced the new glass-ceramic family Nextrema™. Nextrema™ glass-ceramic panels are recommended for use in technical applications. NEXTREMA™ demonstrates what makes glass-ceramic a ground-breaking

8.2-m telescope mirror blank, ZERODUR® glass-ceramic and unique solution, particularly in high temperature environments.

The material is manufactured e.g. in sheet form and can be further processed by using a wide variety of technologies. The following different features are in principal producible – all others upon request:

- Cut to size panels, flat, and surface smooth
- Ground in random shapes and with inner cuttings
- Ground, polished, with bevelled edges or drilled holes

Nextrema™ is a type of glass-ceramic consisting of a crystalline and a residual glassy phase. The glass is obtained e.g. by a rolling process and is subsequently subjected to a heat treatment as described in the introduction before. This is called ceramization which transforms, in a controlled manner, the glass almost completely into both a fine grained crystalline phase and a residual glassy phase. Mainly different ceramization processes determine both the features and the types of Nextrema™ available. Therefore no one type of NEXTREMA™ is like another. The approach is to design glass-ceramic that corresponds to the individual and specific requirements as precisely as possible. Each product feature individually or particularly combined can lead to new technical developments and fields of application.

The ceramic types are available in 4 types, generally:

I. transparent
II. tinted
III. translucent (white colored)
IV. opaque (white or grey colored)

The technical basis of NEXTREMA™ covering a family of high-performance glass-ceramics is formed by main seven product features.

1. Near zero thermal expansion and thereby with excellent thermal strength, Nextrema™ glass-ceramic consists of a material that has an intelligent microstructure specifically designed to achieve very low thermal expansion and excellent heat resistance.
2. Robustness at high operating temperatures (up to 950 C°/1742°F) and high thermal shock resistance (up to 800 C°/1472°F).
3. High chemical resistance like multiple resistance to acids and bases and impermeability with gas.
4. Smooth, non-porous surface and process inertness NEXTREMA™ is process inert. Even under extreme conditions, the material will not have negative interactions with the process environment. There are no interfering process factors such as gas emissions from organic components.
5. Wide transmittance spectrum means high transmittance for wavelengths covering the visible and infrared range.
6. Very low transmittance for ultraviolet range.
7. High dimensional and shape stability of objects made from these ceramic materials.

These outstanding technical properties guarantee suitability for a wide range of technical applications, e.g.

- Solar processing
- LCD/OLED processing
- Heating/Lighting (e.g sauna, space heating, IR-heating/drying)
- Food processing (e.g. grills, toasters, outdoor fireplaces, microwave applications)
- Setters for firing electronic components
- Carrier plates in CVD-furnaces
- Cover panels for heating elements and burners
- Cover panels for projectors/beamers/photocopiers
- Windows for combustion furnaces
- Interior panels of oven doors
- Carrier/protection plates for food processing industries
- Linings for furnaces
- Ceramic carrier plates for sputtering and solar production

Nextrema™ high-performance glass-ceramic

11 Optical Materials

11.1 Introduction of Advanced Optics

SCHOTT Advanced Optics – Your Partner for Excellence in Optics.
Today, the Advanced Optics unit of SCHOTT offers optical materials, components and filters and has been a trailblazer for various applications.

With a product portfolio of over 120 optical glasses, special materials (e.g. active laser glass, IR-Materials, sapphire), ultra-thin glass, high-precision optical components, wafers, and optical filter glasses, Advanced Optics develops customized solutions all over the world for applications in optics, lithography, astronomy, opto-electronics, life sciences, research, and more.

Advanced Optics masters the entire value chain: from customer-specific glass development and its production all the way to high-precision optical product finishing, processing and measurement.

For more information on Advanced Optics, visit our website: www.schott.com/advanced_optics

11.2 Product overview

Optical Glass – More than 120 high-quality optical glasses
For more than 125 years, SCHOTT has been offering a large portfolio of high-quality optical glasses to meet the needs of a broad variety of optical applications as well as industrial applications, ranging from consumer products to optical systems at the leading edge of research.

Our range of optical glasses includes arsenic-free N-glasses, glasses suitable for precision molding (low Tg-Glass) as well as classical glass types with lead oxide as an essential component for outstanding optical properties. In addition, we offer special versions of our glasses, e.g. high transmission glasses (HT- & HTultra-Glasses) or our high homogeneous glasses.

Optical filter glass
Filter glasses enable applications in analytics, photography, medical technology and laser protection. Optical filter glass is known for its selective absorption in the visible wavelength range. The optical filter glasses appear to be colored if their filter effect lies within the visible light spectrum.

SCHOTT's optical filter glasses include the following filter types in the wavelength range above 200 nm:

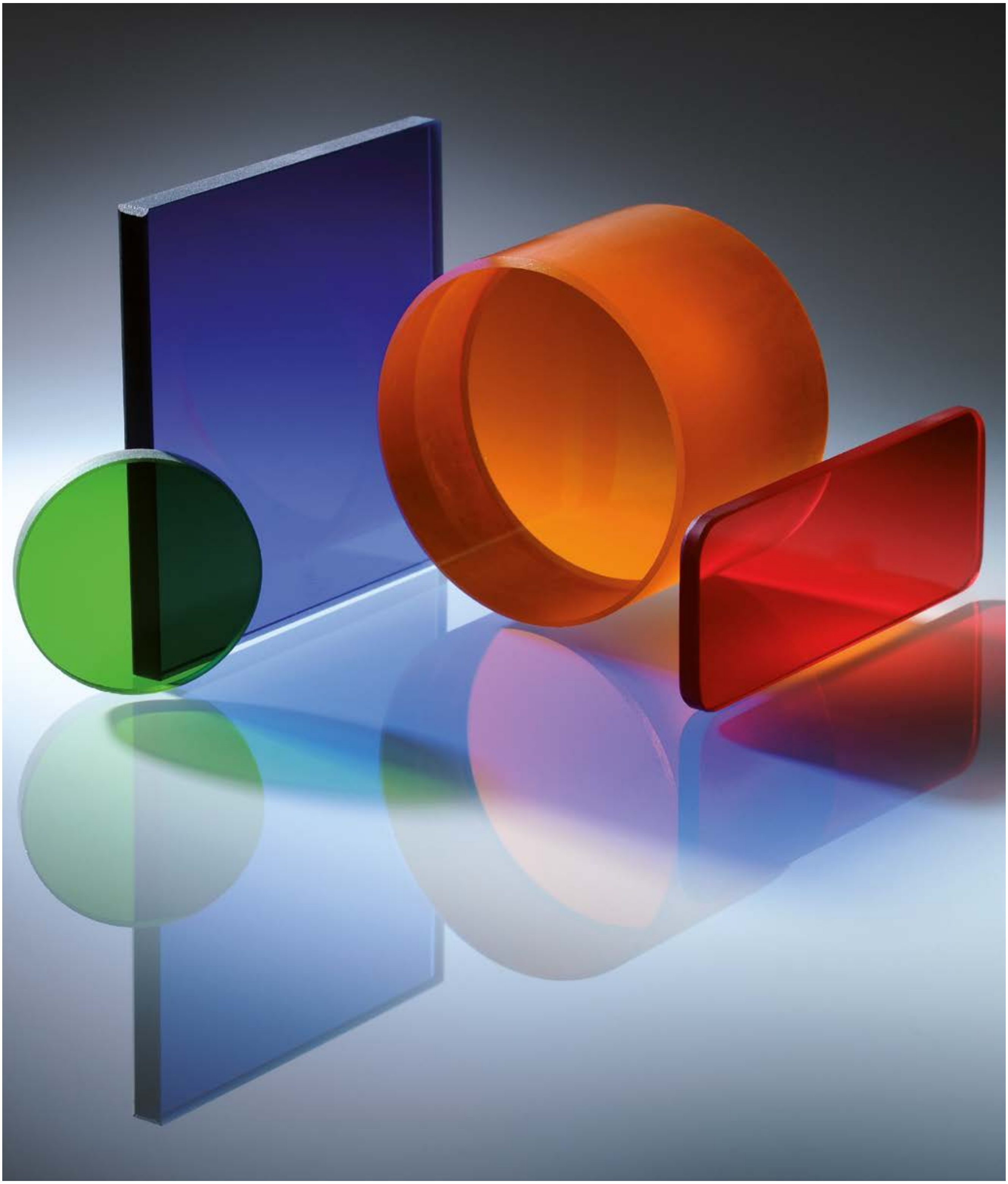
- Bandpass filters
- Longpass filters
- Shortpass filters
- Neutral density filters
- Contrast enhancement filters
- Multiband filters and
- Photo filters

Interference filters
Interference filters that use the interference effect to obtain spectral transmission are manufactured by depositing thin layers with different refractive indices onto a substrate. These filters are used for applications in medical technology, for analytics in measurements, environmental, biotech, chemical and medical, fluorescence microsopy, and more fields.

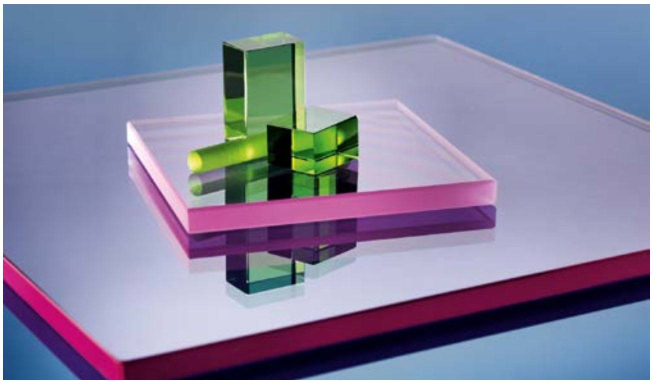
SCHOTT supplies standard and customized interference filters within the spectral range of 200 nm to 3,000 nm.

Our product range comprises various types of interference filters:

- Bandpass filters
- Edge filters
- Notch filters
- DUG 11
- Hard bandpass filters
- i-line filters
- VERIL linear variable filters
- Hard (scratch-resistant) and broadband AR coated
- Beamsplitters
- Neutral density filters
- Mirror coatings
- Black coatings



Optical filter glass



Laser glass

Interference filters

Active and passive laser glass

SCHOTT offers active & passive laser glasses from neodymium-doped laser glasses and special filter glasses for use as active laser medium and diagnostic filters to ultra-stable glass-ceramic for laser applications requiring the utmost precision.

Infrared chalcogenide glass

Infrared glasses offer excellent transmission in the shortwave, midwave, and longwave IR-range. These glasses encompass the common IR transmission bands 3 – 5 µm and 8 – 12 µm, but can transmit as low as 0.7 µm. These glasses are used for night vision systems, thermal cameras, in medical applications, and much more.

Sapphire

Sapphire offers a broad transmission range from UV to mid-infrared wavelengths (250 – 5,000 nm). This material is capable of withstanding extreme environmental conditions and fluctuations in temperature. SCHOTT offers sapphire in processed shapes according to the customer's specifications.

i-line glass

i-line glasses are optical glass types named after the i-wavelength that offer both high UV-transmittance at 365 nm and high refractive index homogeneity. These glass types can be found in lithography applications such as i-line steppers and wafer scanners.

Infrared chalcogenide glass

Sapphire

i-line glass

ZnS FLIR

Zinc Sulfide ZnS CLEAR
Polycrystalline Zinc Sulfide (FLIR – Forward Looking Infrared) is manufactured through applying a chemical vapor deposition (CVD) process. To produce ZnS CLEAR, ZnS FLIR is treated using a hot isostatic pressing process to eliminate microscopic voids and defects that occur in the regular grade-material.

ZnS CLEAR is commonly used in multispectral applications across the visible to infrared region from 0.4 µm – 12 µm. It is available in large sizes and custom shapes and formats. These can include windows, domes or lens blanks.

Zinc Sulfide ZnS FLIR
Regular (FLIR) grade ZnS is a polycrystalline optical material that offers high performance in terms of fracture strength and hardness. ZnS FLIR is often used in the 8 – 12 µm region. The material is used in applications such as IR windows for military systems.

Glass Types

The information contained in this brochure was updated in 2014.

8095	Lead glass (28 % PbO), electrically highly insulating, for general electro-technical applications
8100	Lead glass (33.5 % PbO), electrically highly insulating highly X-ray-absorbing
8228	Intermediate sealing glass
8229	Intermediate sealing glass
8230	Intermediate sealing glass
8240	Alkaline earth aluminosilicate glass for high temperature application in electrical engineering, for sealing to molybdenum, free from alkali, blue colored, defined absorption
8241	Alkaline earth aluminosilicate glass for high temperature application in electrical engineering, for sealing to molybdenum, free from alkali, blue colored, defined absorption
8242	Borosilicate glass for Fe-Ni-Co-alloys and molybdenum, electrically highly insulating
8245	Sealing glass for Fe-Ni-Co alloys and molybdenum, minimum X-ray absorption, chemically highly resistant
8250	Sealing glass for Fe-Ni-Co alloys and molybdenum, electrically highly insulating
8252	Alkaline earth aluminosilicate glass for high temperature applications, for sealing to molybdenum
8253	Alkaline earth aluminosilicate glass for higher temperature applications, for sealing to molybdenum
NEO 1730	Alkaline earth, Neodymium containing, violet color aluminosilicate glass for high temperature applications in electrical engineering, for sealing to molybdenum, free from alkali
8270	Borosilicate glass for sealing to KOVAR metal and molybdenum, electrically highly insulating, defined UV absorption, stabilized against solarization
8326	SBW glass, neutral glass tubing, chemically highly resistant
8330	DURAN®/BOROFLOAT® 33 and SUPREMAX® borosilicate glass, all-purpose glass mainly for technical applications such as apparatus for the chemical industry, pipelines and laboratories
8337B	Borosilicate glass, highly UV-transmitting, for sealing to glasses and metals of the Kovar / Vacon-10/11 range and Tungsten
8341	BOROFLOAT® 40, borosilicate floatglass adapted for thermal tougthening
8347	Colorless, highly transmitting 8330
8350	AR-GLAS®, soda-lime silicate glass
8360	Soft glass, lead-free
8405	Highly UV-transmitting soft glass
8412	FIOLAX® clear, neutral glass, chemically highly resistant, for pharmaceutical packaging
8414	FIOLAX® amber, neutral glass, chemically highly resistant, for pharmaceutical packaging
8415	ILLAX®, amber glass for pharmaceutical packaging
8436	Glass, particularly resistant to sodium vapors and alkaline solutions, suitable for sealing to sapphire
8447	Intermediate sealing glass
8448	Intermediate sealing glass
8449	Intermediate sealing glass
8450	Intermediate sealing glass
8465	Low melting lead-alumino-borosilicate solder glass. Good match to materials with thermal expansion of 8.5 … 9.5 ppm/K.
8470	Lead-free borosilicate solder glass for sealing of materials with thermal expansion of 10.5 … 11.5 ppm/K
8487	Sealing glass for Tungsten
8488	SUPRAX®, borosilicate glass, chemically and thermally resistant
8516	IR-absorbing sealing glass for Fe-Ni, lead-free, low-evaporating
8531	Soft glass, sodium-free, high lead content, for encapsulation of semiconductor components at low temperatures (diodes)
8532	Soft glass, sodium-free, highly lead-containing, for encapsulation of semiconductor components at low temperatures (diodes)
8625	IR-absorbing biocompatible glass for (implantable) transponders

8650	Alkali-free sealing glass for molybdenum, especially for implosion diodes, highly lead-containing, passivation glass
8651	Tungsten sealing glass for power and PIN diodes, passivation glass
8652	Tungsten sealing glass for power and PIN diodes, low melting passivation glass
8660	Borosilicate glass for sealing to Tungsten of high cesium content
8689	Borosilicate glass, highly UV-blocked, stabilized against solarization, sealing glass to Tungsten
8708	PYRAN® Platinum, transparent floated glass-ceramic
8800	Neutral glass, highly chemical resistant
G017-002*	Composite passivation glass, consisting of zinc-borosilicate glass and inert ceramic filler, for passivation of semiconductors
G017-004*	Lead-borosilicate glass with an inert ceramic filler for passivation of semiconductors
G017-052*	Low melting lead-borate glass
G017-096R*	Lead-borosilicate glass for passivation of semiconductors
G017-230*	Composite glass for passivation of semiconductors, especially power transistors
G017-339*	Non-crystallizing, very low melting composite solder glass, consisting of lead-borate glass and inert ceramic filler. Good match to materials with a CTE of 5…6 ppm/K.
G017-340*	Non-crystallizing, very low melting composite solder glass, consisting of lead-borate glass and inert ceramic filler
G017-388*	Passiviation glass for thyristors and high block rectifiers. Also usable as solder glass.
G017-393*	Non-crystallizing low melting composite solder glass with a lead-borate glass and an inert ceramic filler The thermal expansion coefficient is well matched to alumina.
G017-712*	Low melting composite solder glass consisting of a lead-borate based glass and inert ceramic filler
G017-725*	Lead-borosilicate glass for passivation of diodes
G017-997*	Composite glass for passivation of silicon wafers, based on a lead-silicate glass and an inert ceramic filler
G018-133*	Passivation glass for sinter glass diodes
G018-197*	Low melting, lead-free passiviation glass
G018-200*	Lead-free passivation and solder glass
G018-205*	Zinc-borate glass suitable for hermetic capsulation of diodes and general sealing glass
G018-228*	Lead-containing composite solder glass for CTE range 7–8
G018-229*	Lead-containing composite solder glass for soda-lime glass
G018-249*	Low melting lead-free solder glass
G018-250*	Low melting lead-free solder glass for the thermal expansion range of 7…8
G018-255*	Lead-free solder glass for CTE range 9…10
G018-256*	Non-crystallizing, low melting lead-borate glass
G018-266*	High temperature sealing glass for Al_2O_3
G018-281*	Glass-ceramic sealant for SOFC applications
G018-311*	Alkaline-free high temperature sealing glass for ZrO_2 ceramics
G018-339*	Alkaline-free high temperature sealing glass for ZrO_2 ceramics
G018-346*	Alkaline-free high temperature sealing glass for Al_2O_3
G018-354*	Glass-ceramic sealant for SOFC applications
G018-358*	Alkaline-free high temperature sealing glass for Al_2O_3
G018-381*	Glass-ceramic composite sealant for SOFC applications
G018-385*	SOFC sealing glass / High temperature sealing glass for Al_2O_3
GM31107*	Glass sealant for SOFC applications

***not available as tube.**

Table 19.

Glasses for the Chemical Industry and Electrical Engineering ·

1 Glass no.	2 $\alpha_{20/300}$ [10^{-6}/K]	3 Transformation temperature T_g [°C]	4 Glass temperature at viscosities			5 Density at 25 °C [g/cm³]	6 Firing conditions		7 Young's modulus [10^3N/mm²]	8 Poisson's-ratio μ
			10^{13} dPa·s [°C]	$10^{7.6}$ dPa·s [°C]	10^4 dPa·s [°C]		Firing Temp °C	Dwell time min		
8095	9.1	430	435	630	982	3.01	–	–	60	0.22
8100	9.6	465	465	655	960	3.28	–	–	–	–
8228	1.3	700	726	1200	1705	2.15	–	–	–	–
8229	2.0	630	637	930	1480	2.17	–	–	–	–
8230	2.7	570	592	915	1520	2.19	–	–	–	–
8240	4.7	790	795	1005	1305	2.67	–	–	83	0.23
8241	4.7	790	795	1005	1305	2.67	–	–	83	0.23
8242	4.8	470	480	720	1120	2.27	–	–	57.2	0.21
8245	5.1	505	515	720	1040	2.31	–	–	68	0.22
8250	5.0	490	500	720	1055	2.28	–	–	64	0.21
8252	4.6	720	725	935	1240	2.63	–	–	81	0.24
8253	4.7	790	795	1005	1305	2.7	–	–	83	0.23
NEO 1730	4.5	725	725	935	1210	2.67	–	–	–	–
8270	5.0	490	505	705	1045	2.27	–	–	64	0.21
8326	6.6	565	570	770	1125	2.45	–	–	75	0.20
8330	3.3	525	560	825	1260	2.23	–	–	63	0.20
8337B	4.1	440	465	705	1085	2.22	–	–	51	0.22
8341	4.04	577	600	840	1277	2.28	–	–	68	0.20
8347	3.3	525	560	825	1260	2.23	–	–	63	0.20
8350	9.1	525	530	720	1040	2.50	–	–	73	0.22
8360	9.1	465	470	575	745	2.66	–	–	85	0.238
8405	9.7	460	470	665	1000	2.51	–	–	65	0.21
8412	4.9	565	565	785	1165	2.34	–	–	73	0.20
8414	5.4	560	560	770	1155	2.42	–	–	71	0.19
8415	7.8	535	540	720	1050	2.50	–	–	74	0.21
8436	6.6	624	–	–	1085	2.785	–	–	–	–
8447	4.8	480	505	720	1035	2.27	–	–	–	–
8448	3.7	510	560	800	1205	2.25	–	–	–	–
8449	4.5	535	550	785	1150	2.29	–	–	–	–
8450	5.4	570	575	778	1130	2.44	–	–	–	–
8454	6.4	565	575	750	1070	2.49	–	–	–	–
8455	6.7	565	–	740	1030	2.44	–	–	–	–
8456	7.4	445	–	685	1145	2.49	–	–	–	–
8465	8.2	385	–	–	–	5.4	520	30	–	–
8470	10.0	440	–	570	748	2.80	–	–	–	–
8487	3.9	525	560	775	1135	2.25	–	–	66	0.20
8488	4.3	545	560	800	1250	2.30	–	–	67	0.20
8516	8.9	447	445	646	990	2.56	–	–	72	0.21
8531	9.1	435	430	585	820	4.31	–	–	52	0.24
8532	8.7	435	430	560	760	4.46	–	–	56	0.24
8625	9.15	514	520	703	1023	2.52	–	–	73	0.22
8650	5.1	475	475	625	885	3.57	–	–	62	0.23
8651	4.4	549	540	736	1034	2.91	–	–	59	0.24
8652	4.5	495	490	638	900	3.18	–	–	58	0.25

Sealing Glasses

9	10	11		12		13	14	15			16
Heat conductivity λ at 90 °C	t_{k100}	Logarithm of the electric volume resistance in Ω cm at		Dielectric properties for 1 MHz at 25 °C		Refractive index nd (λ_d = 587.6 nm)	Stress-optical coefficient K	Classes of chemical stability			Glass no.
[W/(m · K)]	[°C]	250 °C	350 °C	ε_r	tanδ [10^{-4}]		[10^{-6} mm²/N]	Water	Acid	Alkaline solution	
0.9	330	9.6	7.6	6.6	11	1.556	3.1	3	2	3	8095
–	–	–	–	–	–	1.595	–	3	–	–	8100
–	355	–	–	–	–	–	–	–	–	–	8228
–	350	–	–	–	–	–	–	–	–	–	8229
–	257	–	–	–	–	–	–	–	–	–	8230
1.1	630	13.0	11.0	6.6	15	1.546	2.7	–	–	–	8240
1.1	630	13.0	11.0	6.6	15	1.546	2.7	–	–	–	8241
–	–	–	–	–	–	1.480	–	2	–	–	8242
1.2	215	7.4	5.9	5.7	80	1.488	3.8	3	4	3	8245
1.2	375	10	8.3	4.9	22	1.487	3.6	3	4	3	8250
1.1	660	14.3	12	6.1	11	1.538	2.8	1	3	2	8252
1.1	630	13	11	6.6	15	1.547	2.7	1	2	2	8253
–	–	–	–	–	–	1.548	–	1	3	2	NEO 1730
1.2	377	10.3	8.4	5.3	127	1.487	3.6	3	4	3	8270
1.2	210	7.3	6.0	6.4	65	1.506	2.8	1	1	2	8326
1.2	250	8.0	6.5	4.6	37	1.473	4.0	1	1	2	8330
1.0	315	9.2	7.5	4.7	22	1.476	4.1	3	4	3	8337B
1.2	–	–	–	–	–	1.479	–	1	1	2	8341
1.2	250	8.0	6.5	4.6	37	1.473	4.0	1	1	2	8347
1.1	200	7.2	5.7	7.2	70	1.514	2.7	3	1	2	8350
–	275	8.5	6.7	7.3	24	1.566	2.9	3	4	3	8360
1.0	280	8.5	6.9	6.5	45	1.505	2.8	5	3	2	8405
1.2	215	7.4	6.0	5.7	80	1.492	3.4	1	1	2	8412
1.2	200	7.1	5.6	6.3	107	1.523	2.2	1	2	2	8414
1.1	180	6.7	5.3	7.1	113	1.521	3.2	2	2	2	8415
–	–	–	–	–	–	–	–	1	2–3	1	8436
–	271	–	–	–	–	–	–	–	–	–	8447
–	263	–	–	–	–	–	–	–	–	–	8448
–	348	–	–	–	–	–	–	–	–	–	8449
–	200	–	–	–	–	–	–	–	–	–	8450
–	210	–	–	–	–	–	–	–	–	–	8454
–	–	–	–	–	–	–	–	–	–	–	8455
–	–	–	–	–	–	–	–	–	–	–	8456
–	–	–	–	–	–	–	–	–	–	–	8465
–	295	–	–	–	–	–	3.7	1	1	2	8470
1.2	300	8.3	6.9	4.9	36	1.479	3.6	4	3	3	8487
1.2	200	7.1	5.8	5.4	96	1.484	3.2	1	1	2	8488
1.1	250	8.1	6.4	6.5	25	1.516	3.0	3	1	2	8516
0.7	450	11	9.8	9.5	9	1.700	2.2	1	4	3	8531
0.7	440	11	9.4	10.2	9	1.724	1.7	1	4	3	8532
1.1	210	7.2	5.8	7.1	68	1.525	–	3	1	2	8625
0.5	128	13.5	11.6	7.6	11	1.618	2.8	1	4	3	8650
0.9	–	11.2	10.0	6.0	31	1.552	3.6	1	4	3	8651
0.9	–	–	–	6.9	35	1.589	3.4	1	4	3	8652

1 Glass no.	2 $\alpha_{20/300}$	3 Transformation temperature T_g	4 Glass temperature at viscosities			5 Density at 25 °C	6 Firing conditions		7 Young's modulus	8 Poisson's-ratio
			10^{13} dPa·s	$10^{7.6}$ dPa·s	10^{4} dPa·s		Firing Temp	Dwell time		
	[10^{-6}/K]	[°C]	[°C]	[°C]	[°C]	[g/cm^3]	°C	min	[10^3N/mm^2]	μ
8660	4.0	555	549	830	1215	2.44	–	–	–	–
8689	3.8	515	565	770	1110	2.27	–	–	65	0.2
8708	–0.36	–	885	–	–	2.5018	–	–	92	0.254
8800	5.5	565	570	790	1175	2.34	–	–	73	–
G017-002	3.7	545	–	640	–	3.25	700	10	–	–
G017-004	4.1	440	–	660	–	3.22	740	5	–	–
G017-052	11.7	308	–	347	–	6.65	410	15	43	–
G017-096R	4.8	456	–	650	–	3.54	680	5	–	–
G017-230	4.2	440	–	650	–	3.45	700	4	62	0.224
G017-339	4.7	325	–	415	–	4.3	510	30	–	–
G017-340	7.0	315	–	360	–	4.8	420	15	60	0.281
G017-388	3.6	550	–	645	–	3.4	700	5	–	–
G017-393	6.5	320	–	370	–	4.8	420	15	58	–
G017-712	5.3	375	–	–	–	4.0	510	10	–	–
G017-725	4.9	468	–	620	874	3.59	670	10	58	0.223
G017-997	4.4	485	–	–	–	3.45	760	20	–	–
G018-133	4.8	463	–	–	–	3.47	690	30	60	0.22
G018-197	4.4	557	–	–	–	3.76	675	10	–	–
G018-200	4.6	557	–	–	–	3.63	665	10	–	–
G018-205	4.45	541	–	632	–	3.83	690	10	–	–
G018-228	7.6	311	–	–	–	5.0	400	15	–	–
G018-229	8.3	310	–	–	–	5.44	400	15	–	–
G018-249	10.1	365	–	–	–	7.13	500	10	68	0.307
G018-250	7.0	380	–	–	–	5.7	510	10	–	–
G018-255	9.4	396	–	–	–	6.71	520	15	76	0.237
G018-256	9.2	316	–	–	–	5.79	420	15	–	–
G018-266	6.9 (glassy)	585	–	673	780	4.55	770	15	111	0.304
G018-281	12	652	656	864	1196	2.72	960	30	–	–
G018-311	9.1 (glassy) 9.9 (p.c.)**	622	690	–	873	3.8	850	30	–	–
G018-339	9.2 (p.c.)**	627	–	–	–	–	990	15	–	–
G018-346	7.3 (glassy)	720	–	–	–	–	1270	15	–	–
G018-354	9.2	643	–	753	908	3.9	850	30	–	–
G018-358	8.5 (glassy) 8.8 (p.c.)**	658	–	–	–	3.24	940	15	–	–
G018-381	4.6 (glassy) 12 (a.c.)**	652	–	–	–	2.3	900	60	–	–
G018-385	8.4 (p.c.)**	992**	696	808	862	3.14	950	30	123**	–
GM31107	10.0 (a.c.)**	532	–	632	750	3.7	700	30	–	–

** partially crystalline

Table 20. Characteristic values of technical glasses

9 Heat conductivity λ at 90 °C	10 t_{k100}	11 Logarithm of the electric volume resistance in Ω cm at		12 Dielectric properties for 1 MHz at 25 °C		13 Refractive index nd (λ_d = 587.6 nm)	14 Stress-optical coefficient K	15 Classes of chemical stability			16 Glass no.
[W/(m·K)]	[°C]	250 °C	350 °C	ε_r	tanδ $[10^{-4}]$		$[10^{-6}\ mm^2/N]$	Water	Acid	Alkaline solution	
–	550	12.7	10.7	–	–	1.486	–	3	3	3	8660
1.2	314	9.1	7.5	5.0	20	1.498	3.9	3	3	3	8689
1.65	175	6.6	5.2	7.6	21.8	1.53694	–	1	3	1	8708
–	191	7.0	5.7	5.9	143	1.490	4.6	1	1	2	8800
–	–	–	–	6.8	37	–	–	–	–	–	G017-002
–	–	–	–	–	–	–	–	–	–	–	G017-004
–	–	–	–	–	–	–	–	–	–	–	G017-052
–	–	–	–	–	–	–	–	–	–	–	G017-096R
–	–	–	–	–	–	–	–	–	–	–	G017-230
–	–	–	–	–	–	–	–	–	–	–	G017-339
–	–	–	–	–	–	–	–	–	–	–	G017-340
–	–	–	–	–	–	–	–	–	–	–	G017-388
–	–	–	–	–	–	–	–	–	–	–	G017-393
–	–	–	–	–	–	–	–	–	–	–	G017-712
–	–	–	–	–	–	–	–	–	–	–	G017-725
–	–	–	–	–	–	–	–	–	–	–	G017-997
–	–	–	–	–	–	–	–	–	–	–	G018-133
–	–	–	–	–	–	–	–	–	–	–	G018-197
–	–	–	–	–	–	–	–	–	–	–	G018-200
–	–	–	–	–	–	–	–	–	–	–	G018-205
–	–	–	–	–	–	–	–	–	–	–	G018-228
–	–	–	–	–	–	–	–	–	–	–	G018-229
–	–	–	–	–	–	–	–	–	–	–	G018-249
–	–	–	–	–	–	–	–	–	–	–	G018-250
–	–	–	–	–	–	–	–	–	–	–	G018-255
–	–	–	–	–	–	–	–	–	–	–	G018-256
–	–	–	–	–	–	–	–	–	–	–	G018-266
–	–	–	–	–	–	–	–	–	–	–	G018-281
–	–	–	–	–	–	–	–	–	–	–	G018-311
–	–	–	–	–	–	–	–	–	–	–	G018-339
–	–	–	–	–	–	–	–	–	–	–	G018-346
–	–	–	–	–	–	–	–	–	–	–	G018-354
–	–	–	–	–	–	–	–	–	–	–	G018-358
–	–	–	–	–	–	–	–	–	–	–	G018-381
–	–	–	–	–	–	–	–	–	–	–	G018-385
–	–	–	–	–	–	–	–	–	–	–	GM31107

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