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(54) GLASS COMPOSITION FOR CHEMICALLY STRENGTHENED ALKALI-ALUMINOSILICATE GLASS AND METHOD FOR THE MANUFACTURE THEREOF

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(57) ABSTRACT

A glass composition for producing chemically strengthened alkali-aluminosilicate glass and a method for manufacturing the chemically strengthened alkali-aluminosilicate glass. The chemically strengthened alkali-aluminosilicate glass is suitable for use as high-strength cover glass for touch displays, solar cell cover glass and laminated safety glass.

GLASS COMPOSITION FOR CHEMICALLY STRENGTHENED ALKALI-ALUMINOSILICATE GLASS AND METHOD FOR THE MANUFACTURE THEREOF

FIELD OF THE INVENTION

[0001] The present invention relates to a glass composition for chemically strengthened alkali-aluminosilicate glass, a method for manufacturing the chemically strengthened alkali-aluminosilicate glass and applications and uses for the chemically strengthened alkali-aluminosilicate glass. Such uses for the chemically strengthened alkali-aluminosilicate glass include touch displays using high strength cover glass, solar cell cover glass and laminate safety glass; and, more specifically, include touch displays using curved cover glass and 3D cover glass as well as vehicle glass.

BACKGROUND

[0002] Chemically strengthened glass is typically significantly stronger than annealed glass due to the glass composition and the chemical strengthening process used to manufacture the glass. Such chemical strengthening processes can be used to strengthen glass of all sizes and shapes without creating optical distortion which enables the production of thin, small, and complex-shaped glass samples that are not capable of being tempered thermally. These properties have made chemically strengthened glass, and more specifically, chemically strengthened alkali-aluminosilicate glass, a popular and widely used choice for consumer mobile electronic devices such as smart phones, tablets and notepads.

[0003] Touch glass and its applications have achieved wide market coverage, and there is also an increasing demand for curved formed glass. The formation of curved formed glass is largely controlled by the glass transition temperature (T_g) and the softening temperature (T_s) of the glass in question and generally when T_g is lower than 545° C. and T_s is lower than 765° C., the forming temperature of the curved glass is relatively decreased which lowers its cost and production rate.

[0004] Molding is the most commonly used curved glass forming technology. According to such molding techniques, a glass blank is first loaded into the molding tool. After reaching the glass transition temperature (T_g), the glass is formed and shaped to the contour of the mold cavity. After the molding has been completed, the glass is cooled and demolded, and is then removed from the molding tool. There is a greater choice of mold materials available when the glass transition temperature (T_g) and the glass softening temperature (T_s) are in the ranges noted above. When the glass transition temperature (T_g) is relatively low, the production rate and maintenance efficiency are increased, as the thermal cycling temperature range and molding tack time are relatively low too. Moreover, when the glass transition temperature (T_g) is relatively low, the thermal differential effect between the equipment and the molding cavity is small. Processing will be easier when the forming temperature is closer to the demolding temperature, even cavities cooling to complete demolding in a short time can be achieved with the help of additional cooling equipment. Table 1 below shows a comparison of T_s and T_g for several commercially available examples of strengthened cover glass. The glass transition temperature (T_g) and the glass softening temperature (T_s) for such commercially available examples of strengthened cover glass are not in the ranges noted above.

TABLE 1

Sample	AGC Dragontrail ™	NEG T2X-1	Schott Xensation ®	Corning Gorilla ® Glass 1	Corning Gorilla ® Glass 2	Corning Gorilla ® Glass 3
T_s	831° C.	868° C.	881° C.	847° C.	891° C.	900° C.
T_g	604° C.	605° C.	615° C.	606° C.	642° C.	n/a

[0005] The chemical strengthening processes typically include an ion exchange process. In such ion exchange processes, the glass is placed in a molten salt containing ions having a larger ionic radius than the ions present in the glass, such that the smaller ions present in the glass are replaced by larger ions from the heated solution. Typically, potassium ions in the molten salt replace smaller sodium ions present in the glass. The replacement of the smaller sodium ions present in the glass by larger potassium ions from the heated solution results in the formation of a compressive stress layer on both surfaces of the glass and a central tension zone sandwiched between the compressive stress layers. The tensile stress ("CT") of the central tension zone (typically expressed in megapascals (MPa)) is related to the compressive stress ("CS") of the compressive stress layer (also typically expressed in megapascals), and the depth of the compressive stress layer ("DOL") by the following equation:

$$CT=CS\times DOL/(t-2DOL)$$

where t is the thickness of the glass.

[0006] The current specifications for glass with a thickness of 0.7 mm is a depth of layer of about 40 μm, a compressive stress of not less than 650 MPa, and a tensile stress of the central tension zone of less than 60 MPa. Indeed, the tensile stress of the central tension zone should be kept within about 60-70 MPa to ensure a good cutting yield.

[0007] For use as cover glass for a touch display, it is desirable to increase the resistance of the glass to scratches and impaction damage. This can be accomplished by increasing the compressive stress and the depth of the compressive stress layer. However, to keep the tensile stress of the central tension zone within an acceptable range, an increase in both the compressive stress and the depth of the compressive stress layer undesirably results in an increase in the thickness of the glass.

[0008] Also, it is desirable for cover glass to be as thin as possible. However, since the tensile stress of the central tension zone increases as the thickness of the glass decreases, it is difficult to maintain an acceptable tensile stress of the central tension zone while also maintaining a high compressive stress and a high depth of the compressive stress layer.

[0009] The duration of the chemical strengthening process is a key factor in the manufacturing cost of chemically strengthened glass. Generally, the duration of the ion exchange process must be extended to increase the depth of the compressive stress layer. Shorter ion exchange times, however, are usually desired. The shorter the ion exchange time, the more competitive the production line and process. The ion exchange time is controlled by reaction temperature and ion diffusion rate. Decreasing the temperature can avoid warping, but increase the ion exchange time. Keeping the glass sheet at higher temperatures may increase the ion diffusion rate, but leads to warping and structural relaxation, which in turn can lead to a decrease in compressive stress. Thus, conducting the ion exchange process at a higher temperature may shorten the ion exchange time but has other undesirable results.

[0010] The chemical strengthening process can be performed in two ways: (1) the piece process and (2) the one glass solution (OGS) process. The piece process involves cutting a piece of glass into the final size to be used, and then drilling, grinding, beveling, and polishing the individual pieces. The processed pieces are then placed in molten potassium salt for chemical strengthening. The smaller sized pieces provide greater control over temperature and molten salt concentration. Moreover, the edges on both sides of the pieces can be chemically strengthened. Thus, high strength and a low rate of warping can be achieved, leading to a high yield.

[0011] In contrast, the OGS process involves strengthening the full sheet of glass first, adding touch sensors and printed circuits on the glass surface, then scribing the glass and finally cutting the glass. Compared to the piece process, a larger furnace is typically required in the OGS process. The way the glass is handled and placed may lead to warping of the glass or breakage. In the OGS process, the CS on the chemically strengthened glass surface facilitates resistance to outer damage, but may increase the cutting difficulty. Also, if the CT is too high, the scribing wheel may cause the glass to crack, chip or break when it enters the CT zone during cutting. The scribing edges and sides cannot be fully chemically strengthened in the OGS process, so the strength of glass made by the OGS process is generally lower than glass made by the piece process. Despite the difficulties in the OGS process, the cost-effectiveness and production efficiency of the OGS process are superior to the piece process.

[0012] As chemically strengthened glass becomes thinner and stronger, it becomes a challenge to keep a high DOL and a high CS without increasing the CT. A chemically strengthened glass that is thin, with a high CS and controlled CT, and that is produced with shortened ion exchange times is desired.

DETAILED DESCRIPTION

[0013] In several exemplary embodiments, the present invention provides an ion-exchangeable glass composition for producing chemically strengthened alkali-aluminosilicate glass having a surface compressive stress layer with high compressive stress (CS) and a low depth of layer (DOL). The high compressive stress (CS) together with the low depth of layer (DOL) is obtained through a chemical strengthening process in which sodium ions on the glass surface are replaced by larger potassium ions. A low DOL is beneficial for glass finishing since the yield of the scribing process is increased. Also, a glass surface with high compressive stress yields a stronger glass that can withstand increased external impaction forces and resist scratching.

[0014] In several exemplary embodiments, the ion-exchangeable glass composition for producing chemically strengthened alkali-aluminosilicate glass includes:

[0015] from about 59.0 to about 65.0 weight percent (wt %) of silicon dioxide (SiO_2),

[0016] from about 11.9 to about 13.0 wt % of aluminum oxide (Al_2O_3),

[0017] from about 16.0 to about 18.5 wt % of sodium oxide (Na_2O),

[0018] from about 0 to about 1.0 wt % of boron trioxide (B_2O_3),

[0019] from about 2.8 to about 3.3 wt % of potassium oxide (K_2O), and

[0020] from about 2.0 to about 6.0 wt % of magnesium oxide (MgO),

[0021] wherein the weight ratio of the combined total of B_2O_3, Na_2O and K_2O to Al_2O_3 is greater than 1.5; and

[0022] wherein the weight ratio of the combined total of Na_2O and K_2O to Al_2O_3 and MgO is greater than 1.0.

[0023] According to several exemplary embodiments, the ion-exchangeable glass composition for producing chemically strengthened alkali-aluminosilicate glass consists essentially of:

[0024] from about 59.0 to about 65.0 weight percent (wt %) of silicon dioxide (SiO_2),

[0025] from about 11.9 to about 13.0 wt % of aluminum oxide (Al_2O_3),

[0026] from about 16.0 to about 18.5 wt % of sodium oxide (Na_2O),

[0027] from about 0 to about 1.0 wt % of boron trioxide (B_2O_3),

[0028] from about 2.8 to about 3.3 wt % of potassium oxide (K_2O), and

[0029] from about 2.0 to about 6.0 wt % of magnesium oxide (MgO),

[0030] wherein the weight ratio of the combined total of B_2O_3, Na_2O and K_2O to Al_2O_3 is greater than 1.5; and

[0031] wherein the weight ratio of the combined total of Na_2O and K_2O to Al_2O_3 and MgO is greater than 1.0.

[0032] According to several exemplary embodiments, the ion-exchangeable glass composition for producing chemically strengthened alkali-aluminosilicate glass includes from about 59.0 to about 65.0 wt % of silicon dioxide (SiO_2). Silicon dioxide is the largest single component of the alkali-aluminosilicate glass composition and forms the matrix of the glass together with boron trioxide (B_2O_3). Silicon dioxide also serves as a structural coordinator of the glass and contributes formability, rigidity and chemical durability to the glass. According to several exemplary embodiments, the glass viscosity is enhanced when the SiO_2 is present in the ion-exchangeable glass composition for producing chemically strengthened alkali-aluminosilicate glass in a range of from about 59.0 wt % up to about 65.0 wt %. At concentrations above 65.0 wt %, silicon dioxide raises the melting temperature of the glass composition and may cause the liquidus temperature to increase substantially in glass compositions having relatively high concentrations of K_2O or MgO due to glass stability.

[0033] According to several exemplary embodiments, the ion-exchangeable glass composition for producing chemically strengthened alkali-aluminosilicate glass includes from about 11.9 to about 13.0 wt % of aluminum oxide (Al_2O_3). At concentrations of about 11.9 to about 13.0 wt %, the aluminum oxide enhances the strength of the chemically strengthened alkali-aluminosilicate glass and facilitates the ion-exchange between sodium ions in the surface of the glass and potassium ions in the ion exchange solution. According to several exemplary embodiments, the glass viscosity is enhanced when the Al_2O_3 is present in the ion-exchangeable glass composition for producing chemically strengthened alkali-aluminosilicate glass in a range of from about 11.9 wt % up to about 13.0 wt %. At concentrations of aluminum oxide above 13.0 wt %, the viscosity of the glass may become prohibitively high so that it tends to devitrify the glass and the liquidus temperature may become too high to perform a continuous sheet forming process. Therefore, the ratio of the total content of flux oxides (B_2O_3, Na_2O and K_2O) in the ion-exchangeable glass composition for producing chemically strengthened alkali-aluminosilicate glass to the total content of Al_2O_3 is greater than 1.5.

[0034] According to several exemplary embodiments, the ion-exchangeable glass composition for producing chemically strengthened alkali-aluminosilicate glass includes from about 16.0 to about 18.5 wt % of sodium oxide (Na_2O). Alkali metal oxides serve as aids in achieving low liquidus temperatures and low melting temperatures. In the case of sodium, Na_2O is also used to enable successful ion exchange. In order to permit sufficient ion exchange to produce substantially enhanced glass strength, sodium oxide is included in the composition in the concentrations set forth above. Also, to increase the possibility of ion exchange between sodium ions and potassium ions, according to several exemplary embodiments, the ion-exchangeable glass composition for producing chemically strengthened alkali-aluminosilicate glass includes from about 2.8 to about 3.3 wt % of potassium oxide (K_2O).

[0035] According to several exemplary embodiments, the ion-exchangeable glass composition for producing chemically strengthened alkali-aluminosilicate glass includes from about 0 to about 1.0 wt % of boron trioxide (B_2O_3). Together with silicon, trivalent boron is a network-forming element and also plays a role in increasing the glass formability. In addition, as noted above, boron trioxide serves as a flux. The B—O bond usually occurs in oxide glasses with coordination numbers of 3 and 4, which is of high field strength and indicate that the B—O bond is also very strong. However, the bonds between the groups of $[BO_n]$ structure units are very weak at high temperatures which are different from the behavior of the vitreous groups of $[SiO_n]$. The viscosity of boron oxide at high temperatures is much lower than that of silica, so that according to several exemplary embodiments of the ion-exchangeable glass composition for producing chemically strengthened alkali-aluminosilicate glass boron oxide acts as a very efficient flux.

[0036] According to several exemplary embodiments, the ion-exchangeable glass composition for producing chemically strengthened alkali-aluminosilicate glass includes from about 2.0 to about 8.0 wt % of magnesium oxide (MgO). Magnesium oxide is also believed to increase the strength of the glass and to decrease the specific weight of the glass as compared to other alkaline oxides such as calcium oxide (CaO), strontium oxide (SrO) and barium oxide (BaO).

[0037] According to several exemplary embodiments, the ion-exchangeable glass composition for producing chemically strengthened alkali-aluminosilicate glass includes a ratio of the combined total content of boron trioxide (B_2O_3), sodium oxide (Na_2O) and potassium oxide (K_2O) to the content of aluminum oxide (Al_2O_3) of greater than 1.5.

[0038] According to several exemplary embodiments, the ion-exchangeable glass composition for producing chemically strengthened alkali-aluminosilicate glass includes a ratio of the combined total content of sodium oxide (Na_2O) and potassium oxide (K_2O) to the combined total content of aluminum oxide (Al_2O_3) and magnesium oxide (MgO) of greater than 1.0.

[0039] According to several exemplary embodiments, the present invention provides a method for manufacturing a chemically strengthened alkali-aluminosilicate glass. According to several exemplary embodiments, the method includes:

[0040] mixing and melting the components to form a homogenous glass melt;

[0041] shaping the glass using the down-draw method, the floating method and combinations thereof;

[0042] annealing the glass; and

[0043] chemically strengthening the glass by ion exchange.

[0044] According to several exemplary embodiments, the manufacture of the chemically strengthened alkali-aluminosilicate glass may be carried out using conventional down-draw methods which are well known to those of ordinary skill in the art and which customarily include a directly or indirectly heated precious metal system consisting of a homogenization device, a device to lower the bubble content by means of fining (refiner), a device for cooling and thermal homogenization, a distribution device and other devices. The floating method includes floating molten glass on a bed of molten metal, typically tin, resulting in glass that is very flat and has a uniform thickness.

[0045] According to several exemplary embodiments of the method for manufacturing a chemically strengthened alkali-aluminosilicate glass described above, the ion-exchangeable glass composition is melted for up to about 12 hours at about 1650° C. According to several exemplary embodiments of the method for manufacturing a chemically strengthened alkali-aluminosilicate glass described above, the ion-exchangeable glass composition is melted for up to about 6 hours at about 1650° C. According to several exemplary embodiments of the method for manufacturing a chemically strengthened alkali-aluminosilicate glass described above, the ion-exchangeable glass composition is melted for up to about 4 hours at about 1650° C.

[0046] According to several exemplary embodiments of the method for manufacturing a chemically strengthened alkali-aluminosilicate glass described above, the ion-exchangeable glass composition is annealed at a rate of about 1.0° C./hour until the glass reaches 500° C., after which the glass composition is allowed to cool to room temperature (or about 21° C.).

[0047] According to several exemplary embodiments, the ion-exchangeable glass composition for producing chemically strengthened alkali-aluminosilicate glass described above is chemically strengthened according to conventional ion exchange conditions. According to several exemplary embodiments of the method for manufacturing a chemically strengthened alkali-aluminosilicate glass described above, the ion exchange process occurs in a molten salt bath. In several exemplary embodiments, the molten salt is potassium nitrate (KNO_3).

[0048] According to several exemplary embodiments of the method for manufacturing a chemically strengthened alkali-aluminosilicate glass described above, the ion exchange treatment takes place at a temperature range of from about 380° C. to about 450° C.

[0049] According to several exemplary embodiments of the method for manufacturing a chemically strengthened alkali-aluminosilicate glass described above, the ion exchange treatment is conducted for up to about 8 hours. According to several exemplary embodiments of the method for manufacturing a chemically strengthened alkali-aluminosilicate glass described above, the ion exchange treatment is conducted for up to about 4 hours. According to several exemplary embodiments of the method for manufacturing a chemically strengthened alkali-aluminosilicate glass described above, the ion exchange treatment is conducted for up to about 2 hours. According to several exemplary embodiments of the method for manufacturing a chemically strengthened alkali-aluminosilicate glass described above, the ion exchange treatment is conducted for about 2 hours to about 8 hours. According to several exemplary embodiments of the method for manufacturing a chemically strengthened alkali-aluminosilicate glass described above, the ion exchange treatment is conducted for about 4 hours at a temperature of about 420° C.

[0050] According to several exemplary embodiments of the chemically strengthened alkali-aluminosilicate glass described above, the glass has a surface compressive stress layer having a compressive stress of at least about 650 MPa. According to several exemplary embodiments of the chemically strengthened alkali-aluminosilicate glass described above, the glass has a surface compressive stress layer having a compressive stress of at least about 700 MPa. According to several exemplary embodiments of the chemically strengthened alkali-aluminosilicate glass described above, the glass has a surface compressive stress layer having a compressive stress of from about 720 MPa to about 755 MPa. According to several exemplary embodiments of the chemically strengthened alkali-aluminosilicate glass described above, the glass has a surface compressive stress layer having a compressive stress of at least about 1100 MPa. According to several exemplary embodiments of the chemically strengthened alkali-aluminosilicate glass described above, the glass has a surface compressive stress layer having a compressive stress of up to about 1350 MPa. According to several exemplary embodiments of the chemically strengthened alkali-aluminosilicate glass described above, the glass has a surface compressive stress layer having a compressive stress of from about 650 MPa to about 1350 MPa.

[0051] According to several exemplary embodiments of the chemically strengthened alkali-aluminosilicate glass described above, the glass has a compressive stress layer having a depth of at least about 30.0 μm. According to several exemplary embodiments of the chemically strengthened alkali-aluminosilicate glass described above, the glass has a compressive stress layer having a depth of at least about 35.0 μm. According to several exemplary embodiments of the chemically strengthened alkali-aluminosilicate glass described above, the glass has a compressive stress layer having a depth of from about 30.0 μm to about 45.0 μm. According to several exemplary embodiments of the chemically strengthened alkali-aluminosilicate glass described above, the glass has a compressive stress layer having a depth of from about 35.0 μm to about 45.0 μm.

[0052] According to several exemplary embodiments of the chemically strengthened alkali-aluminosilicate glass described above, the glass has a tensile stress (CT) of less than about 70 MPa. According to several exemplary embodiments of the chemically strengthened alkali-aluminosilicate glass described above, the glass has a tensile stress (CT) of less than about 55 MPa. According to several exemplary embodiments of the chemically strengthened alkali-aluminosilicate glass described above, the glass has a tensile stress (CT) of from about 40 MPa to about 55 MPa.

[0053] According to several exemplary embodiments of the chemically strengthened alkali-aluminosilicate glass described above, the glass has a thickness of from about 0.4 to about 2.0 mm.

[0054] According to several exemplary embodiments of the chemically strengthened alkali-aluminosilicate glass described above, the glass has a density of up to about 2.6 g/cm^3 and a linear coefficient of expansion $\alpha_{25\text{-}300}$ 10^{-7}/° C. in a range of from about 97.0 to about 105.0.

[0055] According to several exemplary embodiments of the chemically strengthened alkali-aluminosilicate glass described above, the glass may be used as a protective glass in applications such as solar panels, refrigerator doors, and other household products. According to several exemplary embodiments of the chemically strengthened alkali-aluminosilicate glass described above, the glass may be used as a protective glass for televisions, as safety glass for automated teller machines, and additional electronic products. According to several exemplary embodiments of the chemically strengthened alkali-aluminosilicate glass described above, the glass may be used as cover glass for consumer mobile electronic devices such as smart phones, tablets and note pads. According to several exemplary embodiments of the chemically strengthened alkali-aluminosilicate glass described above, the glass may be used as a touch display using high strength cover glass, solar cell cover glass and laminated safety glass and more particularly may be used as a touch display using curved cover glass and 3D cover glass as well as vehicle glass.

[0056] The following examples are illustrative of the compositions and methods discussed above.

Examples

[0057] An ion-exchangeable glass composition that included the components shown below in Table 2 was prepared as follows:

TABLE 2

Oxide	Wt %
SiO_2	63.35
Al_2O_3	12.0
Na_2O	16.5
B_2O_3	0.3
K_2O	3.0
MgO	4.85

[0058] Batch materials, as shown in Table 3 were weighed and mixed before being added to a 2 liter plastic container. The batch materials used were of chemical reagent grade quality.

TABLE 3

Batch raw materials	Batch weight (gm)
Sand	316.75
Alumina hydroxide	91.8
Soda ash	142.70
Borax	2.17
Potassium carbonate	22.01
Magnesia	22.25

[0059] The particle size of the sand was between 0.045 and 0.25 mm. A tumbler was used for mixing the raw materials to make a homogenous batch as well as to break up soft agglomerates. The mixed batch was transferred from the plastic container to an 800 ml. platinum-rhodium alloy crucible for glass melting. The platinum-rhodium crucible was placed in an alumina backer and loaded in a high temperature furnace equipped with MoSi heating elements operating at a temperature of 900° C. The temperature of the furnace was gradually increased to 1650° C. and the platinum-rhodium crucible with its backer was held at this temperature for 4 hours. The glass sample was then formed by pouring the molten batch materials from the platinum-rhodium crucible onto a stainless steel plate to form a glass patty. While the glass patty was still hot, it was transferred to an annealer and held at a temperature of 550° C. for 2 hours and was then cooled at a rate of 1.0° C./min to a temperature of 500° C. After that, the sample was cooled naturally to room temperature (21° C.).

[0060] The glass sample was then chemically strengthened by placing it in a molten salt bath tank, in which the constituent sodium ions in the glass were exchanged with externally supplied potassium ions at a temperature of 420° C. which was less than the strain point of the glass for 4 hours. By this method, the glass sample was strengthened by ion exchange to produce a compressive stress layer at the treated surface.

[0061] The measurement of the compressive stress at the surface of the glass and the depth of the compressive stress layer (based on double refraction) were determined by using a polarization microscope (Berek compensator) on sections of the glass. The compressive stress of the surface of the glass was calculated from the measured dual refraction assuming a stress-optical constant of 0.26 (nm*cm/N) (Scholze, H., Nature, Structure and Properties, Springer-Verlag, 1988, p. 260).

[0062] The results for the composition shown in Table 2 above are shown below in Table 4 in the column designated as "Ex. 1". Additional compositions shown in Table 4 and designated as "Ex. 2" to "Ex. 10" were prepared in a similar manner as described above for the composition designated as Ex. 1.

TABLE 4

Oxide (wt %)	Ex. 1	Ex. 2	Ex. 3	Ex. 4	Ex. 5	Ex. 6	Ex. 7	Ex. 8	Ex. 9	Ex. 10
SiO_2	63.35	64.0	63.5	64.0	63.9	63.4	63.4	64.2	64.9	63.35
Al_2O_3	12.0	13.0	12.5	11.9	12.8	12.2	13.0	11.9	11.9	12.0
Na_2O	16.5	16.4	17.0	16.0	16.4	18.0	16.5	16.0	16.0	18.0
B_2O_3	0.3	0.3	0.3	0.8	0.5	0.2	0.4	0.8	0.9	0.2
K_2O	3.0	3.2	2.8	3.3	3.0	2.9	3.0	2.8	2.8	3.1
MgO	4.85	3.1	3.9	4.0	3.4	3.3	3.7	4.3	3.5	3.35
$(B_2O_3 + Na_2O + K_2O)/Al_2O_3$	1.65	1.53	1.61	1.69	1.55	1.73	1.53	1.65	1.66	1.78
$(Na_2O + K_2O)/(Al_2O_3 + MgO)$	1.16	1.22	1.21	1.21	1.20	1.35	1.17	1.16	1.22	1.37
d (g/cm^3)	2.46	2.44	2.45	2.44	2.44	2.44	2.45	2.44	2.43	2.44
n_D (20° C.)	1.503	1.499	1.501	1.501	1.501	1.500	1.501	1.502	1.500	1.501
α (25-300° C., ×10^{-7}/° C.)	99.5	98.7	100.1	98.8	98.5	103.5	98.6	97.5	97.5	104.3
$T_m(10^{2.5}P/° C.)$	1420	1458	1434	1438	1453	1419	1448	1439	1452	1414
$T_w(10^{4.0}P/° C.)$	1108	1125	1097	1111	1116	1097	1121	1119	1124	1092
$T_{liquidus}$(° C.)	900	860	880	900	880	860	890	910	890	880
$T_s(10^{7.6}P/° C.)$	752	761	753	757	761	742	759	759	761	738
$T_a(10^{13.0}P/° C.)$	542	550	544	545	549	537	549	547	549	535
$T_{st}(10^{14.5}P/° C.)$	501	510	503	505	509	498	508	506	508	495
$T_g(10^{13.4}P/° C.)$	536	542	535	538	541	528	540	538	541	526
VH (kgf/mm^2)	542	563	549	556	563	535	554	565	580	530
VH w/CS (kgf/mm^2)	625	640	627	635	643	612	634	647	652	600
CS (MPa)(420° C., 4 hrs)	731	743	733	723	734	752	746	726	730	721
DOL (μm)(420° C., 4 hrs)	42.0	43.0	40.0	40.0	43.0	41.0	44.0	38.0	37.0	41.0
CT (MPa)(420° C., 4 hrs)	50.0	52.0	47.0	47.0	51.0	50.0	54.0	44.0	43.0	48.0

[0063] The definitions of the symbols set forth in Table 4 are as follows:

[0064] d: density (g/cm^3), which is measured with the Archimedes method;

[0065] n_D: refractive index, which is measured by refractometry;

[0066] α: coefficient of thermal expansion (CTE) which is the amount of linear dimensional change from 25 to 300° C., as measured by dilatometry;

[0067] T_m ($10^{2.5}$ P/° C.): the temperature at the viscosity of $10^{2.5}$ poise, as measured by high temperature cylindrical viscometry;

[0068] T_w ($10^{4.0}$ P/° C.): glass working temperature at the viscosity of $10^{4.0}$ poise by high temperature cylindrical viscometry;

[0069] $T_{liquidus}$ (° C.): liquidus temperature where the first crystal is observed in a boat within a gradient temperature furnace, generally test is 72 hours for crystallization;

[0070] T_s ($10^{7.6}$ P/° C.): glass softening temperature at the viscosity of $10^{7.6}$ poise as measured by the fiber elongation method;

[0071] T_a ($10^{13.0}$ P/° C.): glass annealing temperature at the viscosity of 10^{13} poise as measured by the fiber elongation method;

[0072] T_{st} ($10^{14.5}$ P/° C.): glass strain temperature at the viscosity of $10^{14.5}$ poise and measured by the fiber elongation method;

[0073] T_g ($10^{13.4}$ P/° C.): glass transition temperature at the viscosity of $10^{13.4}$ poise and measured by a push-rod dilatometer;

[0074] VH: Vicker's Hardness;

[0075] VH w/CS: Vicker's Hardness after chemical strengthening;

[0076] CS (MPa) (420° C., 4 hrs): compressive stress (in-plane stress which tends to compact the atoms in the surface);

[0077] DOL (μm) (420° C., 4 hrs): depth of layer which represents the depth of the compressive stress layer below the surface to the nearest zero stress plane;

[0078] CT (MPa) (420° C., 4 hrs): central tensile stress which is calculated by the formula: CT=CS×DOL/(t−2DOL) where t is the thickness of the glass.

[0079] While the present invention has been described in terms of certain embodiments, those of ordinary skill in the art will recognize that the invention can be practiced with modification within the spirit and scope of the appended claims.

[0080] Any spatial references such as, for example, "upper," "lower," "above," "below," "between," "bottom," "vertical," "horizontal," "angular," "upwards," "downwards," "side-to-side," "left-to-right," "left," "right," "right-to-left," "top-to-bottom," "bottom-to-top," "top," "bottom," "bottom-up," "top-down," etc., are for the purpose of illustration only and do not limit the specific orientation or location of the structure described above.

[0081] The present disclosure has been described relative to certain embodiments. Improvements or modifications that become apparent to persons of ordinary skill in the art only after reading this disclosure are deemed within the spirit and scope of the application. It is understood that several modifications, changes and substitutions are intended in the foregoing disclosure and in some instances some features of the invention will be employed without a corresponding use of other features. Accordingly, it is appropriate that the appended claims be construed broadly and in a manner consistent with the scope of the invention.

What is claimed is:

1. An ion-exchangeable glass composition for producing chemically strengthened alkali-aluminosilicate glass, comprising:

from about 59.0 to about 65.0 wt % of SiO_2,
from about 11.9 to about 13.0 wt % of Al_2O_3,
from about 16.0 to about 18.5 wt % of Na_2O,
from about 0 to about 1.0 wt % of B_2O_3,
from about 2.8 to about 3.3 wt % of K_2O, and
from about 2.0 to about 6.0 wt % of MgO,
wherein 1.5 is $>(B_2O_3+Na_2O+K_2O)/Al_2O_3$; and
wherein 1.0 is $>(Na_2O+K_2O)/(Al_2O_3+MgO)$.

2. A chemically strengthened alkali-alumino-silicate glass made from a glass composition comprising:

from about 59.0 to about 65.0 wt % of SiO_2,
from about 11.9 to about 13.0 wt % of Al_2O_3,
from about 16.0 to about 18.5 wt % of Na_2O,
from about 0 to about 1.0 wt % of B_2O_3,
from about 2.8 to about 3.3 wt % of K_2O, and
from about 2.0 to about 6.0 wt % of MgO,
wherein 1.5 is $>(B_2O_3+Na_2O+K_2O)/Al_2O_3$;
wherein 1.0 is $>(Na_2O+K_2O)/(Al_2O_3+MgO)$;
wherein the glass composition is ion-exchanged and has a surface compressive stress layer and a central tension zone.

3. The chemically strengthened alkali-alumino-silicate glass according to claim **2**, wherein the surface compressive stress layer has a compressive stress of at least about 650 MPa.

4. The chemically strengthened alkali-alumino-silicate glass according to claim **2**, wherein the surface compressive stress layer has a compressive stress of at least about 700 MPa.

5. The chemically strengthened alkali-alumino-silicate glass according to claim **4**, wherein the surface compressive stress layer has a compressive stress of from about 720 MPa to about 755 MPa.

6. The chemically strengthened alkali-alumino-silicate glass according to claim **2**, wherein the depth of the surface compressive stress layer is at least about 30.0 μm.

7. The chemically strengthened alkali-alumino-silicate glass according to claim **2**, wherein the depth of the surface compressive stress layer is at least about 35.0 μm.

8. The chemically strengthened alkali-alumino-silicate glass according to claim **2**, wherein the depth of the surface compressive stress layer is from about 30.0 μm to about 45.0 μm.

9. The chemically strengthened alkali-alumino-silicate glass according to claim **8**, wherein the depth of the surface compressive stress layer is from about 35.0 μm to about 45.0 μm.

10. The chemically strengthened alkali-alumino-silicate glass according to claim **2**, wherein the central tension zone has a central tension of up to about 70 MPa.

11. The chemically strengthened alkali-alumino-silicate glass according to claim **2**, wherein the central tension zone has a central tension of up to about 55 MPa.

12. The chemically strengthened alkali-alumino-silicate glass according to claim **2**, wherein the central tension zone has a central tension of from about 40 MPa to about 55 MPa.

13. The chemically strengthened alkali-aluminosilicate glass according to claim **2**, wherein the glass has a density of up to about 2.6 g/cm^3.

14. The chemically strengthened alkali-aluminosilicate glass according to claim **2**, wherein the glass has a linear coefficient of expansion ($\alpha_{25\text{-}300}$ 10^{-7}/° C.) of from about 97.0 to about 105.0.

15. The chemically strengthened alkali-aluminosilicate glass according to claim **2**, wherein the glass has a transition temperature of less than 545° C.

16. The chemically strengthened alkali-aluminosilicate glass according to claim **2**, wherein the glass has a softening temperature of less than 765° C.

17. An ion-exchangeable glass composition for producing chemically strengthened alkali-aluminosilicate glass, consisting essentially of:

from about 59.0 to about 65.0 wt % of SiO_2,
from about 11.9 to about 13.0 wt % of Al_2O_3,
from about 16.0 to about 18.5 wt % of Na_2O,
from about 0 to about 1.0 wt % of B_2O_3,

from about 2.8 to about 3.3 wt % of K_2O, and
from about 2.0 to about 6.0 wt % of MgO,
wherein 1.5 is $>(B_2O_3+Na_2O+K_2O)/Al_2O_3$; and
wherein 1.0 is $>(Na_2O+K_2O)/(Al_2O_3+MgO)$.

18. A method for producing a chemically strengthened alkali-aluminosilicate glass, comprising:

mixing and melting glass raw material components to form a homogenous glass melt comprising:
from about 59.0 to about 65.0 wt % of SiO_2,
from about 11.9 to about 13.0 wt % of Al_2O_3,
from about 16.0 to about 18.5 wt % of Na_2O,
from about 0 to about 1.0 wt % of B_2O_3,
from about 2.8 to about 3.3 wt % of K_2O, and
from about 2.0 to about 6.0 wt % of MgO,
wherein 1.5 is $>(B_2O_3+Na_2O+K_2O)/Al_2O_3$; and
wherein 1.0 is $>(Na_2O+K_2O)/(Al_2O_3+MgO)$;
shaping the glass using a method selected from the down-draw method, the floating method and combinations thereof;
annealing the glass; and
chemically strengthening the glass by ion exchange.

19. The method of claim **18**, wherein the glass raw material components are melted for up to about 12 hours at a temperature of about 1650° C.

20. The method of claim **19**, wherein the glass raw material components are melted for up to about 4 hours at a temperature of about 1650° C.

21. The method of claim **18**, wherein the glass is annealed at a rate of about 1.0° C./hour.

22. The method of claim **18**, wherein the glass is chemically strengthened by ion exchange in a molten salt bath.

23. The method of claim **22**, wherein the molten salt is KNO_3.

24. The method of claim **18**, wherein the glass is chemically strengthened by ion exchange at a temperature of from about 380° C. to about 450° C.

25. The method of claim **24**, wherein the glass is chemically strengthened by ion exchange at a temperature of about 420° C.

26. The method of claim **18**, wherein the glass is chemically strengthened by ion exchange for up to about 8 hours.

27. The method of claim **26**, wherein the glass is chemically strengthened by ion exchange for up to about 4 hours.

28. The method of claim **27**, wherein the glass is chemically strengthened by ion exchange for up to about 2 hours.

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