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(74) Agent: **SANTANDREA, Robert P**; Corning Incorporated, Intellectual Property Department, SP-TI-3-1, Corning, New York 14831 (US).

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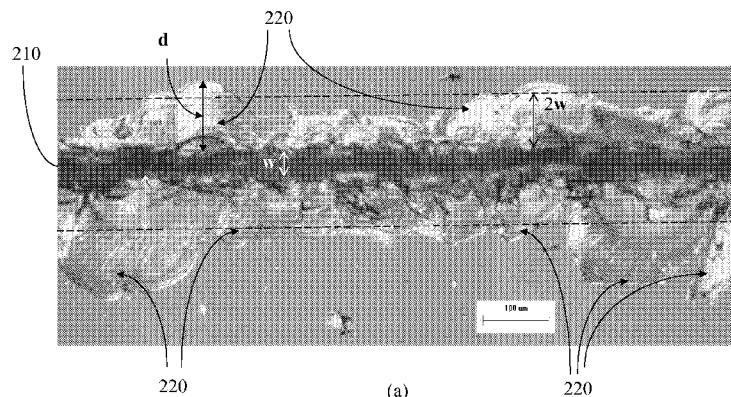
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FIG. 2



(57) **Abstract:** A glass and an enclosure, including windows, cover plates, and substrates for mobile electronic devices comprising the glass. The glass has a crack initiation threshold that is sufficient to withstand direct impact, has a retained strength following abrasion that is greater than soda lime and alkali aluminosilicate glasses, and is resistant to damage when scratched. The enclosure includes cover plates, windows, screens, and casings for mobile electronic devices and information terminal devices.

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CRACK AND SCRATCH RESISTANT GLASS AND ENCLOSURES MADE
THEREFROM

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Application No. 61/235,767, filed August 21, 2009.

BACKGROUND

[0002] The disclosure is related to glass enclosures, including windows, cover plates, and substrates for electronic devices. More particularly, the disclosure relates to crack- and scratch-resistant enclosures.

[0003] Glass is being designed into electronic devices, such as telephones, and entertainment devices, such as games, music players and the like, and information terminal (IT) devices, such as laptop computers. A predominant cause of breakage of cover glass in mobile devices is point contact or sharp impact. The solution for this problem has been to provide a bezel or similar protective structure to hold and protect the glass from such impacts. In particular, the bezel provides protection from impact on the edge of the glass. The edge of the cover glass is most vulnerable to fragmentation by direct impact. Incorporation of the bezel limits the use of glass to flat pieces in the device and prevents utilization of designs that exploit the crystal-like appearance of glass.

SUMMARY

[0004] A glass and a glass enclosure, including windows, cover plates, and substrates for mobile electronic devices comprising the glass are provided. The glass has a crack initiation threshold that is sufficient to withstand direct impact, a retained strength following abrasion that is greater than soda lime and alkali aluminosilicate glasses, and is more resistant to damage when scratched. The enclosure includes cover plates, windows, screens, touch panels, casings, and the like for electronic devices and information terminal devices. The glass can also be used in other

applications, such as a vehicle windshield, where light weight, high strength, and durable glass is be desired.

[0005] Accordingly, one aspect of the disclosure is to provide an aluminoborosilicate glass comprising at least 50 mol% SiO₂ in some embodiments, at least 58 mol% SiO₂, in other embodiments, and at least 60 mol% SiO₂ in still other embodiments, and at least one modifier selected from the group consisting of alkali metal oxides and alkaline earth metal oxides. The aluminoborosilicate glass is ion exchangeable, and exhibits the ratio $\frac{\text{Al}_2\text{O}_3(\text{mol}\%)+\text{B}_2\text{O}_3(\text{mol}\%)}{\sum \text{modifiers (mol \%)} } > 1$.

[0006] A second aspect of the disclosure is to provide an aluminoborosilicate glass. The aluminoborosilicate glass comprises: 50-72 mol% SiO₂; 9-17 mol% Al₂O₃; 2-12 mol% B₂O₃; 8-16 mol% Na₂O; and 0-4 mol % K₂O, wherein the ratio $\frac{\text{Al}_2\text{O}_3(\text{mol}\%)+\text{B}_2\text{O}_3(\text{mol}\%)}{\sum \text{modifiers (mol \%)} } > 1$, where the modifiers are selected from the group consisting of alkali metal oxides and alkaline earth metal oxides. The aluminoborosilicate glass is ion exchangeable.

[0007] A third aspect of the disclosure is to provide a glass enclosure for use in an electronic device. The glass enclosure comprises a strengthened glass that, when scratched with a Knoop diamond at a load of at least 5 N to form a scratch of width *w*, is free of chips having a size greater than three times the width *w*.

[0008] These and other aspects, advantages, and salient features will become apparent from the following detailed description, the accompanying drawings, and the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] FIGURE 1a is an schematic representation of a prior art glass cover plate held in place by a bezel;

[0010] FIGURE 1b is a schematic representation of glass cover plate that is proud of the bezel;

[0011] FIGURE 2a is a microscopic image of an ion exchanged alkali aluminosilicate glass of the prior art having a scratch formed with a Knoop diamond at a load of 10 N;

[0012] FIGURE 2b is a microscopic image of a strengthened aluminoborosilicate glass having a scratch formed with a Knoop diamond at a load of 10 N;

[0013] FIGURE 3a is a top view of a 1 kilogram force (kgf) Vickers indentation 305 in a soda lime silicate glass of the prior art that had not been ion exchanged;

[0014] FIGS. 3b is a side or cross-sectional view of a 1 kgf Vickers indentation in a soda lime silicate glass of the prior art that had not been ion exchanged;

[0015] FIGURE 4 is a side or cross-sectional view of a 1 kgf Vickers indentation of an ion-exchanged soda lime silicate glass of the prior art;

[0016] FIGURE 5a is a top view of a 1 kgf Vickers indentation in an aluminoborosilicate glass that had not been ion exchanged;

[0017] FIGURE 5b is a side or cross-sectional view of a 1 kgf Vickers indentation in an aluminoborosilicate glass that had not been ion exchanged;

[0018] FIGURE 6 is top view of a 30 kgf Vickers indentation of a ion exchanged aluminoborosilicate glass; and

[0019] FIGURE 7 is a plot of crack initiation thresholds measured of aluminoborosilicate glasses as a function of $\text{Al}_2\text{O}_3 + \text{B}_2\text{O}_3 - \text{Na}_2\text{O}$.

DETAILED DESCRIPTION

[0020] In the following description, like reference characters designate like or corresponding parts throughout the several views shown in the figures. It is also understood that, unless otherwise specified, terms such as "top," "bottom,"

“outward,” “inward,” and the like are words of convenience and are not to be construed as limiting terms. In addition, whenever a group is described as comprising at least one of a group of elements and combinations thereof, it is understood that the group may comprise, consist essentially of, or consist of any number of those elements recited, either individually or in combination with each other. Similarly, whenever a group is described as consisting of at least one of a group of elements or combinations thereof, it is understood that the group may consist of any number of those elements recited, either individually or in combination with each other. Unless otherwise specified, a range of values, when recited, includes both the upper and lower limits of the range as well as any sub-ranges therebetween. Unless otherwise specified, all compositions and relationships that include constituents of compositions described herein are expressed in mole percent (mol%).

[0021] Referring to the drawings in general, it will be understood that the illustrations are for the purpose of describing particular embodiments and are not intended to limit the disclosure or appended claims thereto. The drawings are not necessarily to scale, and certain features and views of the drawings may be shown exaggerated in scale or in schematic in the interest of clarity and conciseness.

[0022] As used herein, the terms “enclosure,” “cover plate,” and “window” are used interchangeably and refer to glass articles, including windows, cover plates, screens, panels, and substrates, that form the outer portion of a display screen, window, or structure for mobile electronic devices.

[0023] Glass is being designed into mobile electronic devices, such as telephones, and entertainment devices, including games, music players and the like; information terminal (IT) devices, such as laptop computers; and analogous stationary versions of such devices.

[0024] In some instances, such designs are limited to a flat piece of glass that is protected by a bezel; i.e., a rim that is used to hold and protect a glass window or cover plate in a given device. An example of a glass cover plate or window that is held in place by a bezel is schematically shown in FIG. 1a. Cover plate 110 rests in

rim 122 of bezel 120, which holds cover plate 110 in place on body 105 of device 100 and protects the edge 112 of cover plate 110 from sharp impacts.

[0025] In order to exploit the crystal-like appearance of glass windows, cover plates, and the like in such devices, designs are being extended to make the glass “proud” of the bezel. The term “proud of the bezel” means that the glass extends to the edge of the device and protrudes above and beyond any bezel or rim of the device. FIG. 1b schematically shows an example of a glass cover plate 110 that is proud of the bezel 120 and is affixed to body 105 of device 100. Glass cover plate 110 is mounted on the surface of bezel 120 such that edges 112 of glass cover plate 110 are exposed and otherwise not covered by bezel 120. Edges 112 of cover plate 110 extend to the edges of 107 of body 105.

[0026] The primary limitation to implementing a cover plate or window that is proud of the bezel in such designs is the inability of glass cover plate 110 – particularly edges 112 – to withstand direct impact, thus necessitating protection of edge 112 of glass cover plate 110 by bezel 120 (FIG. 1a). Furthermore, a glass cover plate 110 that is proud of the bezel 120 (FIG. 1b) will have a greater chance of being scratched during handling and use due to exposure of edge 112 of glass cover plate 110. In order to implement the aforementioned new designs, a glass cover plate must therefore be better able to withstand direct impacts than those glasses that are presently used in such applications. Moreover, a glass must also be resistant to scratching and should have a high retained strength after being scratched or abraded.

[0027] The predominant cause of glass breakage in applications such as windshields or cover glass in electronic devices is point contact or sharp impact. To serve as a cover glass or other enclosure in such applications, the crack initiation load of the glass has to be sufficiently high so that it can withstand direct impact. The depth of the surface layers of the glass that are under compressive stress has to be sufficient to provide a high retained strength and increased resistance to damage incurred upon being scratched or abraded.

[0028] Accordingly, a glass or glass article that is more resistant to sharp impact and is be able to withstand direct or point impacts is provided. Such glass articles include a windshield or glass enclosure such as, but not limited to, a cover plate, window, casing, screen, touch panel, or the like, for electronic devices. The glass enclosure comprises a strengthened glass which does not exhibit lateral damage such as, but not limited to, chipping when scratched at a rate of 0.4 mm/s with a Knoop diamond that is oriented so that the angle between the leading and trailing edges of the tip of the Knoop diamond is 172°30' at a load of 5 N and, in some embodiments, at a load of 10 N. As used herein, "chipping" refers to the removal or ejection of glass fragments from a surface of a glass when the surface is scratched with an object such as a stylus. As used herein, "chip" can refer to either a glass fragment removed during scratching of the glass surface or the region on the surface from which the chip is removed. In the latter sense, a chip is typically characterized as a depression in the vicinity of the scratch. When scratched, the glass article described herein does not exhibit chipping (i.e., chips are not generated, or the glass is free of chips) beyond a region extending laterally on either side of the scratch track (i.e., the scratch formed by the Knoop diamond) formed for a distance **d** that is greater than twice the width **w** of the scratch and, in another embodiment, three times the width **w** of the scratch. In other words, chipping generated by scratching is limited to a region bordering either side of the scratch track, wherein the width of the region is no greater than twice (in some embodiment, no greater than three times) the width **w** of the scratch. In one embodiment, the glass enclosure is proud of a bezel, extending above and protruding beyond the bezel, in those instances where a bezel is present. In one embodiment, the glass enclosure has a thickness in a range from about 0.1 mm up to about 2.0 mm. In another embodiment, the glass enclosure has a thickness in a range from about 0.1 mm up to about 2.3 mm and, in other embodiments, the glass enclosure has a thickness of up to about 5.0 mm.

[0029] The scratch resistance or response of a glass enclosure to scratching is illustrated in FIG. 2a. The glass shown in FIG. 2a is an alkali aluminosilicate glass having the composition 66 mol% SiO₂, 10.3 mol% Al₂O₃, 0.6 mol% B₂O₃, 14 mol% Na₂O, 2.45 mol% K₂O, and 0.21 mol% SnO₂, wherein the ratio (Al₂O₃ + B₂O₃)/Σ(

modifiers), expressed in mol%, is 0.66. The glass was strengthened by ion exchange by immersion in a molten KNO_3 salt bath at 410°C for 8 hrs. FIG. 2a is a microscopic image of the glass having a scratch 210 of width w formed at a rate of 0.4mm/s with a Knoop diamond at a load of 10 N. Numerous chips 220 are formed along scratch 210, with some chips extending from scratch 210 for a distance d exceeding twice the width w (2 w) of scratch 210. In contrast to the behavior of the glass shown in FIG. 2a, the response of the glass enclosure and glasses described herein to scratching is illustrated in FIG. 2b. FIG. 2b is a microscopic image of an aluminoborosilicate glass (64 mol% SiO_2 , 14.5 mol% Al_2O_3 , 8 mol% B_2O_3 , 11.5 mol% Na_2O , 0.1 mol% SnO_2 ; wherein the ratio $(\text{Al}_2\text{O}_3 + \text{B}_2\text{O}_3)/\sum(\text{modifiers})$, wherein Al_2O_3 , B_2O_3 , and Na_2O modifier concentrations are expressed in mol%, is 1.96) that is representative of those aluminoborosilicate glasses described herein. The glass shown in FIG. 2b was ion exchanged by immersion in a molten KNO_3 salt bath at 410°C for 8 hrs. The glass shown in FIG. 2b has a scratch 210 of width w formed with a Knoop diamond at a load of 10 N. The chips 220 formed in the aluminoborosilicate glass shown in FIG. 2b are significantly smaller than those seen in FIG. 2a. In FIG. 2b, chip formation is limited to a zone extending from an edge 212 of scratch 210 to a distance d . The width d of the zone or region in which such chipping occurs is significantly less than 2 w . In other words, most of the chips 220 seen in FIG. 2b extend for a distance d , which is less than about width w from crack 210. The glass retains at least 30% of its original load at failure and, in some embodiments, at least 50% of its original load at failure as a determined by ring on ring measurements after scratching with a 3 N Vickers load at a rate of 0.4 mm/s.

[0030] The glass enclosures described herein comprise a strengthened glass that deforms upon indentation under an indentation load of at least 500 gf primarily by densification rather than by shear faulting. The glass is free of subsurface faulting and radial and median cracks upon deformation and is consequently more resistant to damage than typical ion-exchangeable glasses. In addition, the glass is more resistant to crack initiation by shear faulting when strengthened by ion exchange. In one embodiment, the glass enclosure comprises an ion exchanged glass and has a Vickers median/radial crack initiation threshold of at least 10 kilogram force (kgf). In a

second embodiment, the glass enclosure has a Vickers median/radial crack initiation threshold of at least about 20 kgf and, in a third embodiment, the glass enclosure has a Vickers median/radial crack initiation threshold of at least about 30 kgf. Unless otherwise specified, the Vickers median/radial crack threshold is determined by measuring the onset of median or radial cracks in 50% relative humidity at room temperature.

[0031] In another embodiment, the glass enclosures described herein are non-frangible. As used herein, the term “non-frangible” means that the glass enclosures and the glass comprising the glass enclosures do not exhibit forceful fragmentation upon fracture. Such forceful fragmentation is typically characterized by multiple crack branching with ejection or “tossing” of small glass pieces and/or particles from the glass enclosure in the absence of any external restraints, such as coatings, adhesive layers, or the like. More specifically frangible behavior is characterized by at least one of: breaking of the strengthened glass article (e.g., a plate or sheet) into multiple small pieces (e.g., ≤ 1 mm); the number of fragments formed per unit area of the glass article; multiple crack branching from an initial crack in the glass article; and violent ejection of at least one fragment a specified distance (e.g., about 5 cm, or about 2 inches) from its original location; and combinations of any of the foregoing breaking (size and density), cracking, and ejecting behaviors. The glass enclosure and the glass comprising the enclosure are deemed to be substantially non-frangible if they do not exhibit any of the foregoing criteria.

[0032] The strengthened glass comprising the glass enclosure can be strengthened by either thermal or chemical processes known in the art. The glass, in one embodiment, can be thermally tempered by heating the glass at a temperature that is between the strain point and the softening point of the glass, followed by cooling to room temperature. In another embodiment, the glass is chemically strengthened by ion exchange in which smaller metal ions in the glass are replaced or “exchanged” by larger metal ions of the same valence within a layer of the glass that extends from the outer surface of the glass to a depth below the surface (commonly referred to as the “depth of layer” or “DOL”). The replacement of smaller ions with larger ions creates a compressive stress within the layer. In one embodiment, the metal ions are

monovalent alkali metal ions (e.g., Na^+ , K^+ , Rb^+ , and the like), and ion exchange is accomplished by immersing the glass in a bath comprising at least one molten salt (e.g., KNO_3 , K_2SO_4 , KCl , or the like) of the larger metal ion that is to replace the smaller metal ion or ions (e.g., Na^+ ions) in the glass. Alternatively, other monovalent cations such as Ag^+ , Tl^+ , Cu^+ , and the like can be exchanged for the alkali metal cations in the glass. The ion exchange process or processes that are used to strengthen the glass can include, but are not limited to, immersion in a single bath or multiple baths of like or different compositions with washing and/or annealing steps between immersions.

[0033] The depth of the compressive stress layer (depth of layer) present in ion-exchanged glasses prevents the propagation of flaws at or near the surface of the glass. Glasses such as soda lime silicate and alkali aluminosilicate glasses deform with a high shear band density. Such behavior is known to lead to crack nucleation and propagation in the non-ion exchanged versions of such glasses. An example of shear fault formation and crack initiation is shown in FIGS. 3a and 3b. FIGS. 3a and 3b are top and side (i.e., cross-sectional) views, respectively, of a 1 kilogram force (kgf) Vickers indentation 305 in a soda lime silicate glass that has not been ion exchanged. Radial cracks 310 extend from the Vickers indentation 305 (FIG. 3a) and shear deformation zone A. Lateral cracks 317, median cracks 319, and subsurface shear faults 315 are seen in the side view of the glass (FIG. 3b). Shear faults 315 serve as initiation sites for lateral and median cracks 317, 319.

[0034] The compressive stress created in the surface layers of ion exchanged glasses prevents or mitigates the propagation of nucleated cracks, but does not totally eliminate shear deformation. FIG. 4 is a cross-sectional view of a 1 kgf Vickers indentation of an ion-exchanged soda lime silicate glass having a compressive stress of 400 MPa and a depth of layer of 13 μm . Although mitigated, deformation still occurs by the shearing mechanism and leads to crack initiation, as seen in the shear deformation zone A. The compressive layer prevents radial cracks 310 from extending far away from their nucleation sites in the shear deformation zone A. Under flexural loading, subsurface cracks 415 overcome the compressive stress

created by ion exchange and propagate into the central tensile region of the glass, thereby causing failure.

[0035] To improve the mechanical properties of glass enclosures beyond those of currently available ion-exchanged glasses, a glass having higher damage resistance is needed. Accordingly, the glass enclosure described herein comprises an ion-exchanged glass that does not exhibit deformation by subsurface shear faulting, but instead exhibits indentation deformation by densification when submitted to an indentation load of at least 500 gf, which makes flaw/crack initiation more difficult. An example of deformation by densification is shown in FIGS. 5a and 5b, which are top and side views, respectively, of a 1 kilogram force (kgf) Vickers indentation in an alkaline earth aluminoborosilicate (EAGLE XG™, manufactured by Corning, Inc.) glass that has not been strengthened by ion exchange. The top view (FIG. 5a) shows no radial cracks extending from the Vickers indentation 505. As seen in the cross-sectional view (FIG. 5b), the glass deforms primarily by densification (region “B” in FIG. 5b) with no shear faulting. A top view of a 30 kgf Vickers indentation of an aluminoborosilicate glass having the composition: 64 mol% SiO₂, 14.5 mol% Al₂O₃, 8 mol% B₂O₃, 11.5 mol% Na₂O, and 0.1 mol% SnO₂; wherein the ratio (Al₂O₃ + B₂O₃)/Σ(modifiers), with Al₂O₃, B₂O₃, and Na₂O modifier concentrations expressed in mol%, is 1.96, and strengthened by ion exchange by immersion in a molten KNO₃ salt bath at 410°C for 8 hours is shown in FIG. 6. At maximum load, the indenter tip has a depth of about 48 µm. No radial cracks extend from Vickers indentation 605.

[0036] The densification mechanism described hereinabove can be attributed to the absence or lack of non-bridging oxygens (NBOs) in the glass structure, high molar volume (at least 27 cm³/mol), and low Young’s modulus (less than about 69 GPa) of the glass. In the aluminoborosilicate glasses described herein, a structure having substantially no non-bridging oxygens (NBO-free) is achieved through compositions in which the relationship

$$\frac{\text{Al}_2\text{O}_3(\text{mol}\%)+\text{B}_2\text{O}_3(\text{mol}\%)}{\sum \text{modifiers (mol}\%)} > 1 \quad , \quad (1)$$

where Al_2O_3 and B_2O_3 are intermediate glass formers and alkali metal (e.g., Li_2O , Na_2O , K_2O , Rb_2O , Cs_2O) and alkaline earth metal oxides (e.g., MgO , CaO , SrO , BaO) are modifiers, is satisfied. Such modifiers are intentionally or actively included in the glass composition, and do not represent impurities that are inadvertently present in the batched material used to form the glass. To obtain sufficient depth of layer and compressive stress by ion exchange, it is preferable that $0.9 < \text{R}_2\text{O}/\text{Al}_2\text{O}_3 < 1.3$, wherein Al_2O_3 and R_2O modifier concentrations are expressed in mol%. Given a particular compressive stress and compressive depth of layer, any ion-exchangeable silicate glass composition that obeys equation (1) and contains alkali metals (e.g., Li^+ , Na^+ , K^+) should have a high resistance to both crack initiation and crack propagation following ion exchange. Prior to ion exchange, such aluminoborosilicate glasses have a Vickers median/radial crack initiation threshold of at least 500 gf and, in one embodiment, the glasses have Vickers median/radial crack initiation threshold of at least 1000 gf.

[0037] In some embodiments, the glass enclosure comprises, consists essentially of, or consists of a strengthened glass that, when ion exchanged, is resistant to damage, such as crack initiation and propagation. The glass comprises at least 50 mol% SiO_2 in some embodiments, at least 58 mol% SiO_2 in some embodiments, at least 60 mol% SiO_2 in other embodiments, and includes at least one alkali metal modifier, wherein the ratio $(\text{Al}_2\text{O}_3 + \text{B}_2\text{O}_3)/\sum(\text{modifiers}) > 1$, wherein Al_2O_3 , B_2O_3 , and modifier concentrations are expressed in mol%, and wherein the modifiers are selected from the group consisting of alkali metal oxides and alkaline earth metal oxides. In some embodiments, $(\text{Al}_2\text{O}_3 + \text{B}_2\text{O}_3)/\sum(\text{modifiers}) \geq 1.45$. As the value of this ratio increases, the damage resistance of the glass increases. In addition, an increase in the ratio or a substitution of B_2O_3 for Al_2O_3 results in a decrease in Young's modulus. In one embodiment, the Young's modulus of the aluminoborosilicate glass is less than about 69 GPa. In one embodiment, the Young's modulus of the aluminoborosilicate glass is less than about 65 GPa. In another embodiment, the Young's modulus of the aluminoborosilicate glass is in a range from about 57 GPa up to about 69 GPa. In another embodiment, the strengthened glass of the glass enclosure has a compressive stress of at least about 400 MPa and a depth of

layer of at least about 15 μm , in another embodiment, at least about 25 μm , and, in yet another embodiment, at least about 30 μm .

[0038] In one embodiment, the glass enclosure comprises, consists essentially of, or consists of an ion exchangeable aluminoborosilicate glass that has been strengthened, for example, by ion exchange. As used herein, “ion exchangeable” means that a glass is capable of exchanging cations located at or near the surface of the glass with cations of the same valence that are either larger or smaller in size. In a particular embodiment, the aluminoborosilicate glass comprises, consists essentially of, or consists of: 50-72 mol% SiO_2 ; 9-17 mol% Al_2O_3 ; 2-12 mol% B_2O_3 ; 8-16 mol% Na_2O ; and 0-4 mol % K_2O , wherein $(\text{Al}_2\text{O}_3 + \text{B}_2\text{O}_3)/\sum(\text{modifiers}) > 1$, and has a molar volume of at least 27 cm^3/mol . In another embodiment, the aluminoborosilicate glass comprises, consists essentially of, or consists of: 60-72 mol% SiO_2 ; 9-16 mol% Al_2O_3 ; 5-12 mol% B_2O_3 ; 8-16 mol% Na_2O ; and 0-4 mol % K_2O , wherein the ratio of concentrations of Al_2O_3 and B_2O_3 to the total concentrations of modifiers, $(\text{Al}_2\text{O}_3 + \text{B}_2\text{O}_3)/\sum(\text{modifiers})$, is greater than 1, and has a molar volume of at least 27 cm^3/mol . In the above embodiments, the modifiers are selected from alkali metal oxides (e.g., Li_2O , Na_2O , K_2O , Rb_2O , Cs_2O) and alkaline earth metal oxides (e.g., MgO , CaO , SrO , BaO). In some embodiments, the glass further includes 0-5 mol% of at least one of P_2O_5 , MgO , CaO , SrO , BaO , ZnO , and ZrO_2 . In other embodiments, the glass is batched with 0-2 mol% of at least one fining agent selected from a group that includes Na_2SO_4 , NaCl , NaF , NaBr , K_2SO_4 , KCl , KF , KBr , and SnO_2 . The aluminoborosilicate glass is, in some embodiments, substantially free of lithium, whereas in other embodiments, the aluminoborosilicate glass is substantially free of at least one of arsenic, antimony, and barium. In other embodiments, the aluminoborosilicate glass is down-drawable by processes known in the art, such as slot-drawing, fusion drawing, re-drawing, and the like, and has a liquidus viscosity of at least 130 kilopoise.

[0039] Various non-limiting compositions of the aluminoborosilicate glasses described herein are listed in Table 1. Table 1 also includes properties measured for these glass compositions. Crack initiation thresholds were measured by making multiple indentations (indents) in the glass using a Vickers diamond indenter loaded

onto the surface. The load was increased until formation of median or radial cracks extending out from the corners of the indent impression was observed at the surface of the glass in greater than 50% of indents. Crack initiation thresholds for the samples listed in Table 1 are plotted in FIG. 7 as a function of $\text{Al}_2\text{O}_3 + \text{B}_2\text{O}_3 - \text{Na}_2\text{O}$ in the glass samples.

[0040] Samples a, b, c, and d in Table 1 have compositions that are nominally free of non-bridging oxygens; i.e., $\text{Al}_2\text{O}_3 + \text{B}_2\text{O}_3 = \text{Na}_2\text{O}$, or $\text{Al}_2\text{O}_3 + \text{B}_2\text{O}_3 - \text{Na}_2\text{O} = 0$ (i.e. $(\text{Al}_2\text{O}_3 + \text{B}_2\text{O}_3)/\sum(\text{modifiers}) = 1$). Regardless of whether B_2O_3 or Al_2O_3 is used to consume the NBOs created by the presence of the Na_2O modifier in these sample compositions, all of the above samples exhibited low (i.e., 100-300 gf) crack initiation thresholds.

[0041] In samples e and f, however, an excess of B_2O_3 is created by increasing the Al_2O_3 content while decreasing the concentration of alkali metal oxide modifiers. For samples e and f, $(\text{Al}_2\text{O}_3 + \text{B}_2\text{O}_3)/\sum(\text{modifiers}) > 1$. In these samples, the crack initiation threshold increases dramatically, as shown in FIG. 7. Specifically, sample e exhibited a crack initiation threshold of 700 gf prior to strengthening by ion exchange, whereas sample f exhibited a crack initiated threshold of 1000 gf prior to strengthening.

[0042] Non-limiting examples of the aluminoborosilicate glasses described herein are listed Table 2, which lists various compositions and properties of glasses. Several compositions (34, 35, 36, 37, 38, and 39), when ion exchanged, have crack initiation thresholds that are less than 10 kgf. These compositions are therefore outside the scope of the disclosure and appended claims and thus serve as comparative examples. Among the properties listed in Table 2 is the coefficient of thermal expansion (CTE), given in units of $1 \times 10^{-7} /^\circ\text{C}$. CTE is one consideration that is taken into account when designing devices that develop minimal thermal stresses upon temperature changes. Glasses having lower CTEs are desirable for down-draw processes (e.g., fusion-draw and slot-draw) to minimize sheet distortion during the drawing process. The liquidus temperature and corresponding liquidus viscosity (expressed in kP (kilopoise) or MP (megapoise)) indicate the suitability of glass

compositions for hot forming the glass into sheets or other shapes. For down-draw processes, it is desirable that the aluminoborosilicate glasses glass described herein have a liquidus viscosity of at least 130 kP. The 200P temperature is the temperature at which the glass has a viscosity of 200 Poise, and is the process temperature typically used in manufacturing to remove gaseous inclusions (fining) and melt any remaining batch materials. The columns labeled 8 and 15 hr DOL and CS in Table 2 are the depth of the compressive layer and the surface compressive stress resulting from ion exchange in 100% KNO₃ at 410°C in 8 and 15 hours, respectively.

[0043] To maintain desirable ion exchange properties for the glasses described herein, the total alkali metal oxide modifier concentration should equal that of Al₂O₃ and any excess (Al₂O₃ + B₂O₃) that is needed should be made up with B₂O₃ alone to increase the crack initiation load. For optimum ion exchange, the aluminoborosilicate glass should the total concentration of alkali metal oxide modifiers should equal that of alumina – i.e., (Li₂O + Na₂O + K₂O + Rb₂O + Cs₂O) = Al₂O₃ – to achieve the greatest compressive stress and depth of layer, with excess B₂O₃ to improve damage resistance of the glass. However, excess B₂O₃ content should be balanced against the rate of ion exchange. For deep (e.g., $\geq 20 \mu\text{m}$) ion exchange, the B₂O₃ concentration should, in some embodiments, be less than that of Al₂O₃. To achieve the lowest level of melting defects such as undissolved batch or gaseous inclusions, it is best to that R₂O/Al₂O₃ > 1.0 and, preferably, between $1.05 \geq \text{R}_2\text{O/Al}_2\text{O}_3 \geq 1.2$. Since this condition would create NBOs, given by R₂O – Al₂O₃, enough B₂O₃ should, in some embodiments, be added to consume the excess modifiers (i.e., B₂O₃ $> \text{R}_2\text{O} - \text{Al}_2\text{O}_3$) to maintain damage resistance. More preferably, B₂O₃ $> 2(\text{R}_2\text{O} - \text{Al}_2\text{O}_3)$.

[0044] Divalent cations can be added to lower the 200 P temperature (i.e., the typical melting viscosity) of the aluminoborosilicate glass and eliminate defects such as undissolved and/or unmelted batch materials. Smaller divalent cations, such as Mg²⁺, Zn²⁺, or the like are preferable, as they have beneficial impact on the compressive stress developed during ion exchange of the glass. Larger divalent cations such as Ca²⁺, Sr²⁺, and Ba²⁺ decrease the ion exchange rate and the compressive stress achieved by ion exchange. Likewise, the presence of smaller

monovalent cations such as Li^+ in the glass can have a positive effect on the crack initiation threshold, whereas larger ions such as K^+ are not as desirable. In addition, whereas small amounts of K_2O can increase the depth of layer of the compressive stress region, high concentrations of larger monovalent ions such as K^+ decrease compressive stress and should therefore be limited to less than 4%.

[0045] The aluminoborosilicate glass described herein comprises at least 50 mol%, 58 mol% SiO_2 in some embodiments, and in other embodiments, at least 60 mol% SiO_2 . The SiO_2 concentration plays a role in controlling the stability and viscosity of the glass. High SiO_2 concentrations raise the viscosity of the glass, making melting of the glass difficult. The high viscosity of high SiO_2 -containing glasses frustrates mixing, dissolution of batch materials, and bubble rise during fining. High SiO_2 concentrations also require very high temperatures to maintain adequate flow and glass quality. Accordingly, the SiO_2 concentration in the glass should not exceed 72 mol%.

[0046] As the SiO_2 concentration in the glass decreases below 60 mol%, the liquidus temperature increases. The liquidus temperature of $\text{SiO}_2\text{-Al}_2\text{O}_3\text{-Na}_2\text{O}$ compositions rapidly increases to temperatures exceeding 1500°C at SiO_2 contents of less than 50 mol%. As the liquidus temperature increases, the liquidus viscosity (the viscosity of the molten glass at the liquidus temperature) of the glass decreases. While the presence of B_2O_3 suppresses the liquidus temperature, the SiO_2 content should be maintained at greater than 50 mol% to prevent the glass from having excessively high liquidus temperature and low liquidus viscosity. In order to keep the liquidus viscosity from becoming too low or too high, the SiO_2 concentration of the glasses described herein should therefore be within the range between 50 mol% and 72 mol%, between 58 mol% in some embodiments, and between 60 mol% and 72 mol% in other embodiments.

[0047] The SiO_2 concentration also provides the glass with chemical durability with respect to mineral acids, with the exception of hydrofluoric acid (HF). Accordingly, the SiO_2 concentration in the glasses described herein should be greater than 50 mol% in order to provide sufficient durability.

Table 1. Compositions and properties of alkali aluminoborosilicate glasses.

| Mol % | a | b | c | d | e | f |
|--|----------|----------|----------|----------|----------|----------|
| SiO ₂ | 64 | 64 | 64 | 64 | 64 | 64 |
| Al ₂ O ₃ | 0 | 6 | 9 | 15 | 12 | 13.5 |
| B ₂ O ₃ | 18 | 12 | 9 | 3 | 9 | 9 |
| Na ₂ O | 18 | 18 | 18 | 18 | 15 | 13.5 |
| SnO ₂ | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Al ₂ O ₃ + B ₂ O ₃ - Na ₂ O | 0 | 0 | 0 | 0 | 6 | 9 |
| Strain Point (°C) | 537 | 527 | 524 | 570 | 532 | 548 |
| Anneal Point (°C) | 575 | 565 | 564 | 619 | 577 | 605 |
| Softening Point (°C) | 711 | 713 | 730 | 856 | 770 | 878 |
| Coefficient of Thermal Expansion (x10 ⁻⁷ /°C) | 81.7 | 81.8 | 84.8 | 88.2 | 78 | 74.1 |
| Density (g/cm ³) | 2.493 | 2.461 | 2.454 | 2.437 | 2.394 | 2.353 |
| Crack Initiation Load (gf) | 100 | 200 | 200 | 300 | 700 | 1100 |
| Vickers Hardness at 200 gf | | 511 | 519 | 513 | 489 | 475 |
| Indentation Toughness (MPa m ^{0.5}) | | 0.64 | 0.66 | 0.69 | 0.73 | 0.77 |
| Brittleness (μm ^{0.5}) | | 7.8 | 7.6 | 7.3 | 6.6 | 6 |
| IX at 410°C for 8 hrs in 100% KNO ₃ | | | | | | |
| DOL (μm) | 10.7 | 15.7 | 20.4 | 34.3 | 25.6 | 35.1 |
| CS (MPa) | 874 | 795 | 773 | 985 | 847 | 871 |

Table 2. Compositions, expressed in mol%, and properties of alkali aluminoborosilicate glasses.

Table 2

Composition (mol%)

| Sample | SiO ₂ | Al ₂ O ₃ | B ₂ O ₃ | Li ₂ O | Na ₂ O | K ₂ O | MgO | CaO | P ₂ O ₅ | SnO ₂ | ZnC |
|--------|------------------|--------------------------------|-------------------------------|-------------------|-------------------|------------------|------|------|-------------------------------|------------------|-----|
| 1 | 64.0 | 13.5 | 8.9 | | 13.4 | 0.0 | 0.0 | 0.0 | | 0.10 | |
| 2 | 65.7 | 12.3 | 9.0 | | 11.5 | 1.3 | 0.0 | 0.0 | | 0.10 | |
| 3 | 65.7 | 12.3 | 9.0 | | 9.5 | 3.3 | 0.0 | 0.0 | | 0.10 | |
| 4 | 65.7 | 12.3 | 9.0 | | 12.8 | 0.0 | 0.0 | 0.0 | | 0.10 | |
| 5 | 64.0 | 13.0 | 8.9 | | 13.9 | 0.00 | 0.02 | 0.05 | | 0.10 | |
| 6 | 64.0 | 13.5 | 8.9 | | 13.4 | 0.00 | 0.02 | 0.04 | | 0.10 | |
| 7 | 64.0 | 14.0 | 8.9 | | 12.9 | 0.00 | 0.02 | 0.04 | | 0.10 | |
| 8 | 64.0 | 14.5 | 7.9 | | 13.4 | 0.00 | 0.02 | 0.04 | | 0.10 | |
| 9 | 64.0 | 12.5 | 9.9 | | 13.4 | 0.00 | 0.02 | 0.04 | | 0.10 | |
| 10 | 64.0 | 13.5 | 8.9 | | 11.4 | 2.01 | 0.02 | 0.04 | | 0.10 | |
| 11 | 64.0 | 14.5 | 7.0 | | 14.4 | 0.00 | 0.00 | 0.05 | | 0.10 | |
| 12 | 64.0 | 13.5 | 7.9 | | 13.4 | 0.00 | 1.00 | 0.05 | | 0.10 | |
| 13 | 63.3 | 12.3 | 9.8 | | 12.3 | 0.99 | 0.00 | 0.02 | | 0.15 | |
| 14 | 64.0 | 13.5 | 8.5 | | 14.0 | 0.00 | | | | 0.10 | |
| 15 | 64.0 | 12.5 | 10.0 | | 13.0 | 0.50 | | | | 0.10 | |
| 16 | 64.0 | 13.5 | 9.0 | | 12.5 | 1.00 | | | | 0.10 | |
| 17 | 64.0 | 13.5 | 9.0 | | 13.5 | 0.00 | | | | 0.10 | |

Table 2 Continued

| Sample | SiO ₂ | Al ₂ O ₃ | B ₂ O ₃ | Li ₂ O | Na ₂ O | K ₂ O | MgO | CaO | P ₂ O ₅ | SnO ₂ | ZnC |
|--------|------------------|--------------------------------|-------------------------------|-------------------|-------------------|------------------|------|------|-------------------------------|------------------|-----|
| 18 | 65.7 | 11.8 | 9.5 | | 11.5 | 1.3 | 0.0 | 0.0 | | 0.05 | |
| 19 | 64.0 | 12.5 | 10.9 | | 12.4 | 0.00 | 0.00 | 0.04 | | 0.10 | |
| 20 | 64.0 | 13.5 | 8.0 | | 14.5 | 0.00 | | | | 0.10 | |
| 21 | 64.0 | 13.5 | 8.9 | | 13.4 | 0.0 | 0.0 | 0.0 | | 0.10 | |
| 22 | 63.9 | 13.0 | 5.0 | | 11.0 | 3.0 | 4.0 | 0.0 | | 0.10 | |
| 23 | 65.7 | 11.8 | 10.0 | | 11.0 | 1.30 | 0.02 | 0.04 | | 0.05 | |
| 24 | 65.7 | 11.3 | 10.0 | | 11.5 | 1.3 | 0.0 | 0.0 | | 0.05 | |
| 25 | 65.7 | 10.7 | 10.6 | | 11.5 | 1.30 | 0.02 | 0.05 | | 0.05 | |
| 26 | 64.0 | 13.5 | 6.0 | | 13.4 | 0.00 | 3.02 | 0.06 | | 0.10 | |
| 27 | 64.0 | 13.5 | 7.0 | | 15.5 | 0.00 | | | | 0.10 | |
| 28 | 65.7 | 12.3 | 10.0 | | 10.5 | 1.30 | 0.02 | 0.04 | | 0.05 | |
| 29 | 64.0 | 12.0 | 11.9 | | 11.9 | 0.00 | 0.00 | 0.04 | | 0.10 | |
| 30 | 64.0 | 14.0 | 6.0 | | 11.4 | 2.50 | 2.02 | 0.05 | | 0.10 | |
| 31 | 64.0 | 13.5 | 7.0 | | 13.4 | 0.00 | 2.01 | 0.06 | | 0.10 | |
| 32 | 64.0 | 12.0 | 8.9 | | 14.9 | 0.0 | 0.0 | 0.0 | | 0.10 | |
| 33 | 62.0 | 14.0 | 6.0 | | 12.9 | 3.01 | 2.01 | 0.05 | | 0.10 | |
| 34 | 64.1 | 13.2 | 5.6 | | 12.2 | 2.83 | 1.89 | 0.05 | | 0.09 | |
| 35 | 64.0 | 12.5 | 6.0 | | 12.9 | 2.50 | 2.02 | 0.05 | | 0.10 | |
| 36 | 63.1 | 13.6 | 5.8 | | 12.6 | 2.92 | 1.95 | 0.05 | | 0.10 | |
| 37 | 64.0 | 12.5 | 5.5 | | 14.9 | 3.0 | 0.0 | 0.0 | | 0.10 | |
| 38 | 64.0 | 13.0 | 6.0 | | 12.4 | 2.50 | 2.01 | 0.05 | | 0.10 | |

Table 2 Continued

| Sample | SiO ₂ | Al ₂ O ₃ | B ₂ O ₃ | Li ₂ O | Na ₂ O | MgO | CaO | P ₂ O ₅ | SnO ₂ | ZnC |
|--------|------------------|--------------------------------|-------------------------------|-------------------|-------------------|------|------|-------------------------------|------------------|------|
| 39 | 65.7 | 10.3 | 11.0 | | 11.5 | 1.30 | 0.02 | 0.05 | 0.05 | 0.00 |
| 40 | 61.8 | 12.9 | 10.3 | 0.0 | 13.9 | 1.03 | 0.00 | 0.0 | 0.12 | 0.00 |
| 41 | 62.6 | 12.6 | 10.1 | 0.0 | 13.6 | 1.01 | 0.00 | 0.0 | 0.12 | 0.00 |
| 42 | 63.3 | 12.4 | 9.9 | 0.0 | 13.4 | 0.99 | 0.00 | 0.0 | 0.12 | 0.00 |
| 43 | 64.0 | 12.1 | 9.7 | 0.0 | 13.1 | 0.97 | 0.00 | 0.0 | 0.12 | 0.00 |
| 44 | 63.3 | 11.4 | 9.9 | 0.0 | 13.4 | 0.99 | 0.00 | 0.0 | 1.0 | 0.12 |
| 45 | 63.3 | 10.4 | 9.9 | 0.0 | 13.4 | 0.99 | 0.00 | 0.0 | 2.0 | 0.12 |
| 46 | 62.7 | 12.2 | 9.8 | 0 | 12.2 | 0.98 | 1.96 | 0.00 | 0 | 0.12 |
| 47 | 61.5 | 12.0 | 9.6 | 0 | 12.0 | 0.96 | 3.84 | 0.00 | 0 | 0.12 |
| 48 | 62.7 | 12.2 | 9.8 | 0 | 12.2 | 0.98 | 0.00 | 0.00 | 0 | 0.12 |
| 49 | 61.5 | 12.0 | 9.6 | 0 | 12.0 | 0.96 | 0.00 | 0.00 | 0 | 0.12 |
| 50 | 62.7 | 12.2 | 9.8 | 0 | 12.2 | 0.98 | 0.98 | 0.00 | 0 | 2.0 |
| 51 | 63.9 | 12.5 | 10.0 | 0 | 12.5 | 1.00 | 0.00 | 0.00 | 0 | 3.8 |
| 52 | 64.1 | 16.9 | 2.1 | | 15.6 | 1.01 | 0.02 | 0.12 | 0.98 | 0.00 |
| 53 | 64.0 | 16.4 | 2.1 | | 16.3 | 1.01 | 0.02 | 0.13 | 0.10 | 0.10 |
| 54 | 59.9 | 16.5 | 6.6 | | 16.2 | 0.5 | 0.0 | 0.1 | 0.1 | 0.1 |
| 55 | 50.5 | 20.2 | 9.8 | | | | | | | 0.1 |
| 56 | 52.3 | 19.4 | 9.3 | | | | | | | 0.1 |
| 57 | 55.2 | 20.3 | 9.7 | | | | | | | 0.1 |

Table 2 Continued

| Sample | Total | $(R_2O+RO)/(Al_2O_3+B_2O_3)$ | R_2O/Al_2O_3 | $(Al_2O_3+B_2O_3)/(R_2O+RO)$ | Density g/cm ³ | Molar Volume cm ³ /mol |
|--------|-------|------------------------------|----------------|------------------------------|------------------------------|---|
| 1 | 100.0 | 0.602 | 0.997 | 1.661 | 2.353 | 28.44 |
| 2 | 100.0 | 0.606 | 1.046 | 1.651 | 2.347 | 28.47 |
| 3 | 100.0 | 0.606 | 1.046 | 1.651 | 2.345 | 28.77 |
| 4 | 100.0 | 0.605 | 1.045 | 1.652 | 2.346 | 28.31 |
| 5 | 100.0 | 0.639 | 1.074 | 1.564 | 2.363 | 28.23 |
| 6 | 100.0 | 0.602 | 0.997 | 1.661 | 2.355 | 28.41 |
| 7 | 100.0 | 0.567 | 0.926 | 1.764 | 2.335 | 28.74 |
| 8 | 100.0 | 0.602 | 0.929 | 1.661 | 2.363 | 28.45 |
| 9 | 100.0 | 0.602 | 1.076 | 1.662 | 2.354 | 28.29 |
| 10 | 100.0 | 0.602 | 0.998 | 1.660 | 2.356 | 28.67 |
| 11 | 100.0 | 0.676 | 0.997 | 1.480 | 2.376 | 28.27 |
| 12 | 100.0 | 0.676 | 0.997 | 1.479 | 2.369 | 28.12 |
| 13 | 99.00 | 0.601 | 1.077 | 1.665 | 2.346 | 28.41 |
| 14 | 100.1 | 0.636 | 1.037 | 1.571 | | |
| 15 | 100.1 | 0.600 | 1.080 | 1.667 | | |
| 16 | 100.1 | 0.600 | 1.000 | 1.667 | | |
| 17 | 100.1 | 0.600 | 1.000 | 1.667 | | |
| 18 | 100.0 | 0.606 | 1.090 | 1.652 | | |
| 19 | 100.0 | 0.533 | 0.996 | 1.877 | | |

Table 2 Continued

| Sample | Total | $(R_2O+RO)/(Al_2O_3+B_2O_3)$ | R_2O/Al_2O_3 | $(Al_2O_3+B_2O_3)/(R_2O+RO)$ | Molar Volume cm ³ /mol |
|--------|-------|------------------------------|----------------|------------------------------|--------------------------------------|
| 20 | 100.1 | 0.674 | 1.074 | 1.483 | 2.354 |
| 21 | 100.0 | 0.602 | 0.997 | 1.661 | 2.407 |
| 22 | 100.0 | 1.002 | 1.076 | 0.998 | 27.62 |
| 23 | 100.0 | 0.569 | 1.048 | 1.759 | 2.336 |
| 24 | 100.0 | 0.606 | 1.138 | 1.651 | 2.347 |
| 25 | 100.0 | 0.606 | 1.203 | 1.651 | 2.349 |
| 26 | 100.0 | 0.850 | 0.997 | 1.176 | 2.395 |
| 27 | 100.1 | 0.756 | 1.148 | 1.323 | 28.21 |
| 28 | 100.0 | 0.533 | 0.964 | 1.875 | 27.56 |
| 29 | 100.0 | 0.502 | 0.997 | 1.994 | 2.326 |
| 30 | 100.0 | 0.804 | 0.998 | 1.244 | 2.392 |
| 31 | 100.0 | 0.758 | 0.996 | 1.319 | 2.385 |
| 32 | 100.0 | 0.717 | 1.246 | 1.395 | 27.81 |
| 33 | 100.0 | 0.903 | 1.141 | 1.108 | 2.394 |
| 34 | 100.0 | 0.903 | 1.141 | 1.108 | 27.7 |
| 35 | 100.0 | 0.949 | 1.237 | 1.053 | 2.418 |
| 36 | 100.0 | 0.903 | 1.141 | 1.108 | 2.409 |
| 37 | 100.0 | 1.002 | 1.438 | 0.998 | 2.444 |
| 38 | 100.0 | 0.897 | 1.151 | 1.115 | 2.406 |

Table 2 Continued

| Sample | Total | $(R_2O+RO)/(Al_2O_3+B_2O_3)$ | R_2O/Al_2O_3 | $(Al_2O_3+B_2O_3)/(R_2O+RO)$ | Molar Density g/cm ³ | Volume cm ³ /mol |
|--------|-------|------------------------------|----------------|------------------------------|---------------------------------|-----------------------------|
| 39 | 100.0 | 0.606 | 1.249 | 1.651 | 2.431 | 27.21 |
| 40 | 100.0 | 0.644 | 1.160 | 1.552 | 2.358 | |
| 41 | 100.0 | 0.644 | 1.160 | 1.552 | 2.355 | 28.48 |
| 42 | 100.0 | 0.644 | 1.160 | 1.552 | 2.352 | 28.46 |
| 43 | 100.0 | 0.644 | 1.160 | 1.552 | 2.350 | 28.42 |
| 44 | 100.0 | 0.644 | 1.261 | 1.552 | 2.356 | |
| 45 | 100.0 | 0.644 | 1.381 | 1.552 | 2.358 | |
| 46 | 100.0 | 0.689 | 1.080 | 1.452 | 2.369 | 28.03 |
| 47 | 100.0 | 0.778 | 1.080 | 1.286 | 2.386 | 27.62 |
| 48 | 100.0 | 0.600 | 1.080 | 1.667 | 2.395 | 28.06 |
| 49 | 100.0 | 0.600 | 1.080 | 1.667 | 2.432 | 27.75 |
| 50 | 100.0 | 0.644 | 1.080 | 1.552 | 2.383 | 28.04 |
| 51 | 100.0 | 0.600 | 1.080 | 1.667 | 2.354 | 28.04 |
| 52 | 100.0 | 0.877 | 0.979 | 1.141 | 2.425 | 28.07 |
| 53 | 100.0 | 0.940 | 1.052 | 1.064 | 2.433 | 27.89 |
| 54 | 100.0 | 0.727 | 1.013 | 1.375 | 2.399 | 28.32 |
| 55 | 100.0 | 0.647 | 0.960 | 1.546 | 2.412 | 28.97 |
| 56 | 100.0 | 0.659 | 0.974 | 1.519 | 2.413 | 28.73 |
| 57 | 99.9 | 0.487 | 0.719 | 2.055 | 2.399 | 29.09 |

Table 2 Continued

| Sample | Strain pt. (°C) | Anneal pt. (°C) | Softening pt. (°C) | CTE \times 10^7 K^{-1} | Liquidus T (°C) | Liquidus Viscosity (Mpoise) | 200 poise T (°C) | Elastic modul (GPa) |
|--------|--------------------|--------------------|-----------------------|---------------------------------------|--------------------|--------------------------------|---------------------|------------------------|
| 1 | 548 | 605 | 878 | 74.1 | >9706 | >1786 | 1690 | 63.4 |
| 2 | 543 | 603 | | | <750 | <750 | 1680 | 62.2 |
| 3 | 524 | 580 | | | <750 | <750 | 1684 | 62.7 |
| 4 | 538 | 593 | | | <750 | <750 | 1684 | 62.7 |
| 5 | 539 | 590 | 824 | 76.0 | >9706 | >1786 | 1690 | 63.4 |
| 6 | 548 | 605 | 864 | 72.8 | <750 | <750 | 1680 | 62.2 |
| 7 | 559 | 618 | 885 | 69.9 | <750 | <750 | 1684 | 62.7 |
| 8 | 566 | 625 | 893 | 72.1 | <750 | <750 | 1684 | 62.7 |
| 9 | 528 | 577 | 804 | 74.0 | <730 | >474 | 1650 | 63.3 |
| 10 | 534 | 590 | 864 | 78.4 | <745 | <745 | 1650 | 62.9 |
| 11 | 563 | 620 | 900 | 80.0 | <715 | >132346 | 1732 | 64.0 |
| 12 | 546 | 599 | 864 | 74.8 | <715 | >11212 | 1655 | 64.4 |
| 13 | 542 | 597 | | 75.4 | 75.7 | >11212 | 1669 | 61.6 |
| 14 | 547 | 600 | | | <720 | <720 | 1669 | 61.6 |
| 15 | 523 | 574 | | | <745 | <745 | 1669 | 61.6 |
| 16 | 539 | 595 | | | <720 | <720 | 1669 | 61.6 |
| 17 | 569 | 628 | | | <720 | <720 | 1669 | 61.6 |
| 18 | 518 | 570 | 820 | 72.8 | <720 | <720 | 1669 | 61.6 |
| | | | | | | | 1692 | 63.2 |

Table 2 Continued

| Strain pt. (°C) | Anneal pt. (°C) | Softening pt. (°C) | CTE x 10^7 K^{-1} | Liquidus T (°C) | Liquidus T (°C) | Liquidus T (°C) | moduli (GPa) | Elastic moduli (GPa) |
|--------------------|--------------------|-----------------------|--------------------------------|--------------------|--------------------|--------------------|-----------------|----------------------------|
| 522 | 578 | 874 | 70.3 | <705 | <700 | <700 | 60.6 | 60.6 |
| 545 | 596 | 864 | 78.2 | <700 | <700 | >100 | 62.6 | 62.6 |
| 546 | 604 | 871 | 72.0 | 1115 | 1115 | 1665 | 62.4 | 62.4 |
| 556 | 608 | 864 | 81.8 | <700 | <700 | 1702 | 64.1 | 64.1 |
| 521 | 575 | 831 | 73.8 | 1663 | 1663 | 1663 | 64.6 | 64.6 |
| 517 | 568 | 798 | 75.2 | 1050 | 1050 | 1050 | 67.6 | 67.6 |
| 513 | 561 | 777 | 73.2 | <745 | <745 | <745 | 61.8 | 61.8 |
| 564 | 616 | 872 | 73.0 | <745 | <745 | >663 | 59.6 | 59.6 |
| 547 | 594 | 883 | 68.9 | <745 | <745 | 4.72 | 67.4 | 67.4 |
| 528 | 587 | 826 | 69.9 | 975 | 975 | 1689 | 66.2 | 66.2 |
| 509 | 563 | 882 | 79.5 | 945 | 945 | 1614 | 67.4 | 67.4 |
| 557 | 613 | 862 | 75.4 | 865 | 865 | 1671 | 68.8 | 68.8 |
| 550 | 603 | 577 | 770 | <710 | <710 | >885 | 69.0 | 69.0 |
| 532 | 587 | 830 | 87.7 | <730 | <730 | >518 | 69.0 | 69.0 |
| 538 | 591 | 839 | 82.1 | <710 | <710 | >1212 | 68.4 | 68.4 |
| 540 | 581 | 803 | 84.9 | <720 | <720 | >1212 | 72.1 | 72.1 |
| 533 | 588 | 830 | 85.7 | <710 | <710 | >1212 | | |
| 538 | 564 | 754 | 91.2 | <710 | <710 | >1212 | | |

Table 2 Continued

| Sample | Strain pt. (°C) | Anneal pt. (°C) | Softening pt. (°C) | CTE $\times 10^7 \text{ K}^{-1}$ | Liquidus T (°C) | Liquidus T (°C) | Viscosity (Mpoise) | poise T (°C) | 200 poise T (°C) | Elastic moduli (GPa) |
|--------|-----------------|-----------------|--------------------|----------------------------------|-----------------|-----------------|--------------------|--------------|------------------|----------------------|
| 38 | 537 | 586 | 827 | 82.1 | <720 | >1698 | >1653 | 1653 | 68.1 | 68.1 |
| 39 | 521 | 561 | 739 | 83.7 | 820 | 1.26 | 1480 | 1480 | 72.5 | 72.5 |
| 40 | 517 | 567 | 805 | 79.4 | <720 | <710 | <745 | 1662 | 1668 | 62.7 |
| 41 | 518 | 569 | 811 | 75.4 | <745 | <700 | <700 | 2053 | 1679 | 62.7 |
| 42 | 520 | 572 | 831 | 74.0 | <745 | <710 | <710 | <700 | 2053 | 62.6 |
| 43 | 519 | 571 | 824 | 76.4 | <745 | <745 | <745 | <700 | 1679 | 62.2 |
| 44 | 508 | 556 | 785 | 76.0 | <745 | <745 | <745 | <700 | 2053 | 63.6 |
| 45 | 500 | 547 | 785 | 75.7 | <745 | <745 | <745 | <700 | 1679 | 63.5 |
| 46 | 524 | 573 | 809 | 74.5 | <750 | <750 | <750 | <700 | 2053 | 63.5 |
| 47 | 526 | 573 | 791 | 74.8 | <750 | <750 | <750 | <700 | 2053 | 63.5 |
| 48 | 507 | 557 | 796 | 74.7 | <750 | <750 | <750 | <700 | 2053 | 63.5 |
| 49 | 507 | 554 | 781 | 74.0 | <750 | <750 | <750 | <700 | 2053 | 63.5 |
| 50 | 513 | 562 | 795 | 75.4 | <750 | <750 | <750 | <700 | 2053 | 63.5 |
| 51 | 489 | 539 | 791 | 74.8 | <750 | <750 | <750 | <700 | 2053 | 63.5 |
| 52 | 666 | 726 | 1016 | 88.8 | <750 | <750 | <750 | <700 | 2053 | 63.5 |
| 53 | 620 | 679 | 969 | 89.3 | <750 | <750 | <750 | <700 | 2053 | 63.5 |
| 54 | 588 | 643 | 905 | 87.4 | <750 | <750 | <750 | <700 | 2053 | 63.5 |
| 55 | 559.0 | 609.0 | 849.5 | 74.4 | <750 | <750 | <750 | <700 | 2053 | 63.5 |
| 56 | 559.0 | 610.0 | 841.0 | 92.4 | <750 | <750 | <750 | <700 | 2053 | 63.5 |

| Table 2 | Continued | Sample | Strain pt. (°C) | Anneal pt. (°C) | Softening pt. (°C) | CTE x 10^7 K^{-1} | Liquidus T (°C) | Liquidus T (°C) | Viscosity (Mpoise) | poise T (°C) | 200 Elastic moduli (GPa) |
|---------|-----------|--------|--------------------|--------------------|-----------------------|--------------------------------|--------------------|--------------------|-----------------------|-----------------|-----------------------------------|
| | | 57 | 577.0 | 631.0 | 877.7 | 68.9 | | | | | |

Table 2 Continued

| Sample | Poisson ratio | Pre-IX Crack initiation load (gf) | CS ¹ IX 8 hrs (MPa) | DOL ¹ IX 8 hrs (μm) | CS ² IX 15 hrs (MPa) | DOL ² , IX 15 hrs (μm) | Dam |
|--------|---------------|-----------------------------------|-----------------------------------|-----------------------------------|------------------------------------|--------------------------------------|-----|
| 1 | 0.219 | 1100 | 871 | 35.1 | | | |
| 2 | | 600 | | | | | |
| 3 | | 600 | | | | | |
| 4 | | 800 | | | | | |
| 5 | 0.213 | 500-1000 | 803 | 38.8 | 762 | 51.5 | |
| 6 | 0.215 | 500-1000 | 816 | 38.8 | 782 | 51.8 | |
| 7 | 0.219 | 500-1000 | 803 | 36.1 | 761 | 50.5 | |
| 8 | 0.213 | 500-1000 | 868 | 40.3 | 840 | 53.6 | |
| 9 | 0.223 | | 752 | 34.8 | 707 | 47.2 | |
| 10 | 0.209 | | 722 | 47.8 | 687 | 65.1 | |
| 11 | 0.216 | | 924 | 46 | 877 | 60.9 | |
| 12 | 0.219 | | 839 | 36.2 | 790 | 48.8 | |
| 13 | 0.214 | | 775 | 43.5 | 732 | 60.8 | |
| 14 | | | 850 | 38.5 | 792 | 50.7 | |
| 15 | | | 738 | 33.7 | 686 | 47.2 | |
| 16 | | | 763 | 40.7 | 716 | 55.5 | |
| 17 | | | 808 | 40.5 | 757 | 55.4 | |
| 18 | 0.212 | | | | | | |

Table 2 Continued

| Sample | Poisson ratio | Pre-IX Crack initiation load (gf) | IX 8 hrs (MPa) | DOL ¹ IX 8 hrs (µm) | CS ² IX 15 hrs (MPa) | DOL ² , IX 15 hrs (µm) | Dam |
|--------|---------------|-----------------------------------|----------------|--------------------------------|---------------------------------|-----------------------------------|-----|
| 19 | 0.224 | | 691 | 33.7 | 641 | 46.6 | |
| 20 | | | 868 | 37.1 | 810 | 52.1 | |
| 21 | 0.217 | | 824 | 35.8 | | | |
| 22 | | | 771 | 50.6 | 747 | 66 | |
| 23 | 0.222 | | | | | | |
| 24 | 0.218 | | | | | | |
| 25 | 0.216 | | | | | | |
| 26 | 0.217 | | 887 | 34.8 | 864 | 46.7 | |
| 27 | | | 887 | 34.7 | 835 | 48 | |
| 28 | 0.221 | | | | | | |
| 29 | 0.219 | | 623 | 31.3 | 557 | 4.3 | |
| 30 | 0.219 | 500-1000 | 791 | 54.1 | 772 | 67.5 | |
| 31 | 0.217 | | 870 | 35.2 | 833 | 46.9 | |
| 32 | 0.21 | 600 | 847 | 25.6 | | | |
| 33 | 0.216 | 500-1000 | 814 | 50.8 | 773 | 67 | |
| 34 | 0.217 | 300-500 | 825 | 46.3 | 792 | 63.6 | |
| 35 | 0.21 | 300-500 | 794 | 45.5 | 750 | 60.6 | |
| 36 | 0.217 | 300-500 | 801 | 51.2 | 779 | 66.2 | |
| 37 | 0.215 | 200-300 | 747 | 43.9 | 698 | 56.5 | |

Table 2 Continued

| Sample | Poisson ratio | Pre-IX Crack initiation load (gf) | IX 8 hrs (MPa) | DOL ¹ IX 8 hrs (µm) | CS ² IX 15 hrs (MPa) | DOL ² , IX 15 hrs (µm) | Dam |
|--------|---------------|-----------------------------------|----------------|--------------------------------|---------------------------------|-----------------------------------|-----|
| 38 | 0.208 | 200-300 | 803 | 46.4 | 761 | 63.3 | |
| 39 | 0.213 | | | | | | |
| 40 | | | 694 | 38.1 | 668 | 54.2 | |
| 41 | | | 707 | 40.1 | 654 | 50.6 | |
| 42 | | | 690 | 39.9 | 643 | 52.6 | |
| 43 | | | 689 | 38.6 | 627 | 55 | |
| 44 | | | 611 | 37.5 | 555 | 51.2 | |
| 45 | | | 533 | 37.4 | 502 | 50.4 | |
| 46 | | | 806 | 40.1 | 705 | 71.7 | |
| 47 | | | 753 | 27 | 716 | 36.3 | |
| 48 | | | 712 | 29.3 | 670 | 37.2 | |
| 49 | | | 720 | 25 | 688 | 34.8 | |
| 50 | | | 716 | 30.4 | 680 | 39.5 | |
| 51 | | | 574 | 32.5 | 540 | 43.1 | |
| 52 | | | | | | | |
| 53 | | | | | | | |
| 54 | | | 1029 | 51.2 | | | |
| 55 | | | 901 | 38.3 | 858 | 57.5 | |
| 56 | | | 967 | 37.8 | 964 | 50.7 | |

Table 2 Continued

| Sample | CS ¹ | CS ² | DOL ² , IX 15 hrs | Dam hrs (μm) |
|--------|--------------------------------------|-------------------|------------------------------------|-----------------|
| 57 | Pre-IX Crack initiation load (gf) | IX 8 hrs (MPa) | IX 8 hrs (μm) | 18.3 |

¹Compressive stress (CS) and depth of layer (DOL) after ion exchange (IX) in 100% KNO₃ at 410°C for 8 hrs.

²Compressive stress (CS) and depth of layer (DOL) after ion exchange (IX) in 100% KNO₃ at 410°C for 15 hrs.

³ After ion exchange (IX) in 100% KNO₃ at 410°C for 8 hrs.

Table 2 Continued

| Sample | Damage Threshold (gf) ⁴ | Damage Threshold (gf) ⁵ | Damage Threshold (gf) ⁶ |
|--------|---------------------------------------|---------------------------------------|--|
| 1 | | | 30 |
| 2 | | | 30 |
| 3 | | | 29 |
| 4 | | | 30 |
| 5 | >30000 | 30 | 30 |
| 6 | >30000 | 30 | 30 |
| 7 | >30000 | 30 | 30 |
| 8 | >30000 | 30 | 30 |
| 9 | >30000 | 30 | 30 |
| 10 | >30000 | 30 | 30 |
| 11 | >30000 | 30 | 30 |
| 12 | >30000 | 30 | 30 |
| 13 | >30000 | 30 | 30 |
| 14 | >30000 | 30 | 30 |
| 15 | >30000 | 30 | 30 |
| 16 | >30000 | 30 | 30 |
| 17 | >30000 | 30 | 25 |
| 18 | | | |

Table 2

Continued

| Sample | Damage Threshold (gf) ⁴ | Damage Threshold (gf) ⁵ | Damage Threshold (gf) |
|--------|---------------------------------------|---------------------------------------|--------------------------|
| 19 | 25000 | | 25 |
| 20 | 25000 | | 25 |
| 21 | | 23000 | 23 |
| 22 | 200000-250000 | | 22 |
| 23 | | | 21 |
| 24 | | | 20 |
| 25 | | | 20 |
| 26 | 20000 | | 20 |
| 27 | <25000 | | 20 |
| 28 | | | 18 |
| 29 | 18000 | | 18 |
| 30 | 15000 | | 15 |
| 31 | 13000 | | 13 |
| 32 | | 11000 | 11 |
| 33 | 10000 | | 10 |
| 34 | 9000 | | 9 |
| 35 | 8000 | | 8 |
| 36 | 8000 | | 8 |
| 37 | 6000 | | 6 |

| Table 2 | Continued | Sample | Damage Threshold (gf) ⁴ | Damage Threshold (gf) ⁵ | Damage Threshold (gf) |
|---------|-------------|--------|---------------------------------------|---------------------------------------|--------------------------|
| 38 | 6000 | 38 | 6000 | 6 | 6 |
| 39 | | 39 | | 5 | 5 |
| 40 | 19000 | 40 | 19000 | 19 | 19 |
| 41 | 22000 | 41 | 22000 | 22 | 22 |
| 42 | >30000 | 42 | >30000 | 30 | 30 |
| 43 | | 43 | | | |
| 44 | 20000-25000 | 44 | 20000-25000 | 22.5 | 22.5 |
| 45 | | 45 | | | |
| 46 | 15000-20000 | 46 | 15000-20000 | 17.5 | 17.5 |
| 47 | >30000 | 47 | >30000 | >30 | >30 |
| 48 | >30000 | 48 | >30000 | >30 | >30 |
| 49 | >30000 | 49 | >30000 | >30 | >30 |
| 50 | >30000 | 50 | >30000 | >30 | >30 |
| 51 | 20000-25000 | 51 | 20000-25000 | 22.5 | 22.5 |
| 52 | | 52 | | | |
| 53 | | 53 | | | |
| 54 | 10000-15000 | 54 | 10000-15000 | 11.5 | 12.5 |
| 55 | 10000-15000 | 55 | 10000-15000 | 12.5 | 12.5 |
| 56 | <10000 | 56 | <10000 | 12.5 | 12.5 |

Table 2 Continued

| Sample | Damage Threshold (gf) ⁴ | Damage Threshold (gf) ⁵ | Damage Threshold (gf) |
|--------|---------------------------------------|---------------------------------------|-----------------------------|
| 57 | 10000-15000 | | 12.5 |

⁴ After ion exchange (IX) in 100% KNO₃ at 410°C for 15 hrs.

⁵ After ion exchange (IX) in 100% KNO₃ at 370°C for 64 hrs.

Example

[0048] The following example illustrates features and advantages of the glasses described herein, and is in no way intended to limit the disclosure or appended claims thereto.

[0049] The purpose of this example was to verify that pre-ion exchange crack resistance improves post-ion exchange crack resistance in a glass. Samples of crack resistant aluminoborosilicate glass having composition e in Table 1 (64 mol% SiO₂, 13.5 mol% Al₂O₃, 9 mol% B₂O₃, 13.5 mol% Na₂O, 0.1 mol% SnO₂) and a pre-ion exchange crack initiation threshold of 1100 gram force (gf), were ion exchanged by immersion in a molten KNO₃ salt bath at 410°C for 8 hrs to achieve depths of layer DOL and compressive stresses CS. One sample had a DOL of 55.8 μm and a CS of 838 MPa, and another sample had a DOL of 35.1 μm and a CS of 871 MPa.

[0050] For purposes of comparison, samples of Corning GORILLA™ Glass (an alkali aluminosilicate glass having the composition: 66.4 mol% SiO₂; 10.3 mol% Al₂O₃; 0.60 mol% B₂O₃; 4.0 mol% Na₂O; 2.10 mol% K₂O; 5.76 mol% MgO; 0.58 mol% CaO; 0.01 mol% ZrO₂; 0.21 mol% SnO₂; and 0.007 mol% Fe₂O₃) with a pre-ion exchange crack initiation threshold of 300 gf were then ion exchanged to closely match the compressive stress and depths of layer of the samples having composition f, listed in Table 1. One sample had a DOL of 54 μm and a CS of 751 MPa, and another sample had a DOL of 35 μm and a CS of 790 MPa. Compressive stresses and depths of layer of the ion exchanged samples of composition f and GORILLA Glass are listed in Table 3.

[0051] Following ion exchange, Vickers crack initiation loads were measured for each of composition f in Table 1 and the GORILLA Glass samples. Post-ion exchange crack initiation loads were measured using a Vickers diamond indenter as previously described herein and are listed in Table 3. The results of the crack initiation testing listed in Table 3 demonstrate that greater pre-ion exchange crack resistance improves post-ion exchange crack resistance. The GORILLA Glass samples required loads of 5,000-7,000 gf to initiate median/radial crack systems,

whereas the composition f samples required loads of greater than 30,000 gf, or 4-6 times the load needed to initiate such cracks in GORILLA Glass samples, to initiate median/radial crack systems. The GORILLA Glass samples fractured into several pieces when the indentation load exceeded the measured crack initiation loads, and in all cases fracture was observed by the point at which the load exceeded 10,000 gf. In contrast, the composition f samples did not fracture at any of the indentation loads (3,000 up to 30,000 gf) studied.

Table 3. Crack initiation loads of ion-exchanged glasses having composition f (listed in Table 1) and Gorilla® Glasses.

| Glass | Pre-Ion-Exchange Crack Initiation Load (gf) | DOL (microns) | Compressive Stress (MPa) | Post-Ion-Exchange Crack Initiation Load (gf) |
|------------------|---|------------------|-----------------------------|--|
| Comp. f | 1100 | 55.8 | 838 | 30000+ |
| Gorilla Glass | 300 | 54 | 751 | 7000 |
| Comp. f | 1100 | 35.1 | 871 | 30000+ |
| Gorilla Glass | 300 | 35 | 790 | 5000 |

[0052] While typical embodiments have been set forth for the purpose of illustration, the foregoing description should not be deemed to be a limitation on the scope of the disclosure or appended claims. Accordingly, various modifications, adaptations, and alternatives may occur to one skilled in the art without departing from the spirit and scope of the present disclosure or appended claims.

CLAIMS

1. An aluminoborosilicate glass, the aluminoborosilicate glass comprising at least 50 mol% SiO₂ and at least one modifier selected from the group consisting of alkali metal oxides and alkaline earth metal oxides, wherein the aluminoborosilicate glass is ion exchangeable, and wherein the ratio $\frac{\text{Al}_2\text{O}_3(\text{mol}\%)+\text{B}_2\text{O}_3(\text{mol}\%)}{\sum \text{modifiers (mol \%)} } > 1$.

2. The aluminoborosilicate glass of Claim 1, wherein the aluminoborosilicate glass is a strengthened aluminoborosilicate glass.

3. The aluminoborosilicate glass of Claim 2, wherein the strengthened aluminoborosilicate glass is an ion exchanged aluminoborosilicate glass.

4. The aluminoborosilicate glass of Claim 2 or Claim 3, wherein the ion exchanged aluminoborosilicate glass has a Vickers median/radial crack initiation threshold of at least 10 kgf.

5. The aluminoborosilicate glass of Claim 2 or Claim 3, wherein the ion exchanged aluminoborosilicate glass has a Vickers median/radial crack initiation threshold of at least 20 kgf.

6. The aluminoborosilicate glass of Claim 2 or Claim 3, wherein the ion exchanged aluminoborosilicate glass has a Vickers median/radial crack initiation threshold of at least 30 kgf.

7. The aluminoborosilicate glass of any one of Claims 2-6, wherein the ion exchanged aluminoborosilicate glass exhibits indentation deformation by densification deformation when submitted to an indentation load of at least 500 gf and is free of subsurface shear faulting.

8. The aluminoborosilicate glass of any one of Claims 2-7, wherein the ion exchanged aluminoborosilicate glass has a compressive stress of at least about 400 MPa and a depth of layer of at least about 15 μm .

9. The aluminoborosilicate glass of any one of Claims 2-8, wherein the ion exchanged aluminoborosilicate glass is substantially non-frangible.

10. The aluminoborosilicate glass of any one of Claims 2-9, wherein the ion exchanged aluminoborosilicate glass is free of lateral damage extending more than twice a width w of a scratch formed by a Knoop diamond at a load of at least 5 N.

11. The aluminoborosilicate glass of any of the preceding claims, wherein the aluminoborosilicate glass has a Vickers median/radial crack initiation threshold of at least 500 gf.

12. The aluminoborosilicate glass of any of the preceding claims, wherein the aluminoborosilicate glass exhibits indentation deformation by densification deformation when submitted to an indentation load of at least 500 gf and is free of subsurface shear faulting.

13. The aluminoborosilicate glass of any of the preceding claims, wherein the aluminoborosilicate glass has a molar volume of at least 27 cm³/mol.

14. The aluminoborosilicate glass of any of the preceding claims, wherein the aluminoborosilicate glass has a Young's modulus of less than about 69 MPa.

15. The aluminoborosilicate glass of any of the preceding claims, wherein

$$\frac{\text{Al}_2\text{O}_3(\text{mol}\%)+\text{B}_2\text{O}_3(\text{mol}\%)}{\sum \text{modifiers (mol \%)} } > 1.45.$$

16. The aluminoborosilicate glass of any of the preceding claims, wherein the aluminoborosilicate glass comprises: 50-72 mol% SiO₂; 9-17 mol% Al₂O₃; 2-12 mol% B₂O₃; 8-16 mol% Na₂O; and 0-4 mol % K₂O, wherein 8 ≤ Na₂O + K₂O ≤ 18.

17. The aluminoborosilicate glass of Claim 16, wherein the aluminoborosilicate glass is free of lithium.

18. The aluminoborosilicate glass of Claim 16 or 17, wherein the aluminoborosilicate glass is free of at least one of arsenic, antimony, and barium.

19. The aluminoborosilicate glass of any one of Claims 16-18, wherein the aluminoborosilicate glass is down-drawable.

20. The aluminoborosilicate glass of any one of Claims 16-19, wherein the aluminoborosilicate glass has a liquidus viscosity of at least 130 kilopoise.

21. The aluminoborosilicate glass of any of the preceding claims, wherein the at least one modifier includes at least one alkali metal oxide.

22. The aluminoborosilicate glass of any of the preceding claims, wherein the aluminoborosilicate glass is free of non-bridging oxygens.

23. The aluminoborosilicate glass of any of the preceding claims, wherein the aluminoborosilicate glass has a thickness in a range from about 0.1 mm up to about 2.0 mm.

24. The aluminoborosilicate glass of any of the preceding claims, wherein the aluminoborosilicate glass is strengthened and forms at least a portion of an enclosure for an electronic device.

25. The aluminoborosilicate glass of any of the preceding claims, wherein $0.9 < R_2O(\text{mol\%})/Al_2O_3(\text{mol\%}) < 1.3$.

26. The aluminoborosilicate glass of Claim 25, wherein $B_2O_3(\text{mol\%}) > R_2O(\text{mol\%}) - Al_2O_3(\text{mol\%})$.

27. The aluminoborosilicate glass of Claim 25, wherein $B_2O_3(\text{mol\%}) > 2(R_2O(\text{mol\%}) - Al_2O_3(\text{mol\%}))$.

28. An aluminoborosilicate glass, the aluminoborosilicate glass comprising: 50-72 mol% SiO_2 ; 9-17 mol% Al_2O_3 ; 2-12 mol% B_2O_3 ; 8-16 mol% Na_2O ; and 0-4 mol % K_2O , wherein the ratio $\frac{Al_2O_3(\text{mol\%}) + B_2O_3(\text{mol\%})}{\sum \text{modifiers (mol\%)}} > 1$, wherein the modifiers are selected from the group consisting of alkali metal oxides

and alkaline earth metal oxides, and wherein the aluminoborosilicate glass is ion exchangeable.

29. The aluminoborosilicate glass of Claim 28, wherein the aluminoborosilicate glass, when ion exchanged, has a Vickers median/radial crack initiation threshold of at least 10 kgf.

30. The aluminoborosilicate glass of Claim 29, wherein the Vickers median/radial crack initiation threshold is at least 20 kgf.

31. The aluminoborosilicate glass of Claim 29, wherein the Vickers median/radial crack initiation threshold is at least 30 kgf.

32. The aluminoborosilicate glass of any one of Claims 28-31, wherein the aluminoborosilicate glass exhibits indentation deformation by densification deformation when submitted to an indentation load of at least 500 gf and is free of subsurface shear faulting.

33. The aluminoborosilicate glass of any one of Claims 28-32, wherein the aluminoborosilicate glass has a Vickers median/radial crack initiation threshold of at least 500 gf.

34. The aluminoborosilicate glass of any one of Claims 28-33, wherein the glass has a molar volume of at least 27 cm³/mol.

35. The aluminoborosilicate glass of any one of Claims 28-34, wherein the aluminoborosilicate glass, when ion exchanged, has a compressive stress of about 400 MPa and a depth of layer of at least 15 µm.

36. The aluminoborosilicate glass of any one of Claims 28-35, wherein the aluminoborosilicate glass, when ion exchanged, is substantially non-frangible.

37. The aluminoborosilicate glass of any one of Claims 28-36, wherein the aluminoborosilicate glass when ion exchanged, is free of chips having a size greater than two times a width w of a scratch formed by a Knoop diamond at a load of at least 5 N.

38. The aluminoborosilicate glass of any one of Claims 28-37, wherein the aluminoborosilicate glass is ion exchanged.

39. The aluminoborosilicate glass of any one of Claims 28-38, wherein the ion exchanged aluminoborosilicate glass forms at least a portion of an enclosure for an electronic device.

40. The aluminoborosilicate glass of any one of Claims 28-39, wherein $0.9 < R_2O(\text{mol\%})/Al_2O_3(\text{mol\%}) < 1.3$.

41. The aluminoborosilicate glass of Claim 40, wherein $B_2O_3(\text{mol\%}) > R_2O(\text{mol\%}) - Al_2O_3(\text{mol\%})$.

42. The aluminoborosilicate glass of Claim 41, wherein $B_2O_3(\text{mol\%}) > 2(R_2O(\text{mol\%}) - Al_2O_3(\text{mol\%}))$.

43. A glass enclosure for an electronic device, the glass enclosure comprising a strengthened glass that, when scratched with a Knoop diamond at a load of at least 5 N to form a scratch of width w , is free of chips having a size greater than twice the width w .

44. The glass enclosure of Claim 43, wherein the glass enclosure has a Vickers median/radial crack initiation threshold of at least 20 kgf.

45. The glass enclosure of Claim 44, wherein the glass enclosure has a Vickers median/radial crack initiation threshold of at least 30 kgf.

46. The glass enclosure of any one of Claims 43-45, wherein the glass enclosure exhibits indentation deformation by densification deformation when submitted to an indentation load of at least 500 gf and is free of subsurface shear faulting.

47. The glass enclosure of one of Claims 43-46, wherein the glass enclosure is disposed adjacent to a bezel, and wherein the glass enclosure is proud of the bezel.

48. The glass enclosure of one of Claims 43-47, wherein the strengthened glass is a strengthened aluminoborosilicate glass.

49. The glass enclosure of Claim 48, wherein the strengthened aluminoborosilicate glass is strengthened by ion exchange.

50. The glass enclosure of Claim 48 or 49, wherein the strengthened aluminoborosilicate glass comprises: 50-72 mol% SiO₂; 9-17 mol% Al₂O₃; 2-12 mol% B₂O₃; 8-16 mol% Na₂O; and 0-4 mol % K₂O, and wherein the ratio $\frac{\text{Al}_2\text{O}_3(\text{mol}\%)+\text{B}_2\text{O}_3(\text{mol}\%)}{\sum \text{modifiers (mol \%)} } > 1$, and wherein the modifiers are selected from the group consisting of alkali metal oxides and alkaline earth metal oxides.

51. The glass enclosure of any one of Claims 48-50, wherein the strengthened aluminoborosilicate glass is free of lithium.

52. The glass enclosure of any one of Claims 48-51, wherein the strengthened aluminoborosilicate glass is free of at least one of arsenic, antimony, and barium.

53. The glass enclosure of any one of Claims 48-52, wherein the strengthened aluminoborosilicate glass is down-drawable.

54. The glass enclosure of any one of Claims 48-53, wherein the strengthened aluminoborosilicate glass has a liquidus viscosity of at least 130 kilopoise.

55. The glass enclosure of any one of Claims 48-54, wherein the strengthened aluminoborosilicate glass has a molar volume of at least 27 cm³/mol.

56. The glass enclosure of any one of Claims 48-55, wherein the glass enclosure is unshielded and is capable of surviving a 1 m drop onto a surface having a roughness greater than or equal to concrete.

57. The glass enclosure of any one of Claims 48-56, wherein the glass enclosure is free of subsurface faulting and radial cracks and median cracks upon direct impact with a sharp object.

58. The glass enclosure of any one of Claims 48-57, wherein $0.9 < R_2O(\text{mol\%})/Al_2O_3(\text{mol\%}) < 1.3$.

59. The glass enclosure of Claim 58, wherein $B_2O_3(\text{mol\%}) > R_2O(\text{mol\%}) - Al_2O_3(\text{mol\%})$.

60. The glass enclosure of Claim 58, wherein $B_2O_3(\text{mol\%}) > 2(R_2O(\text{mol\%}) - Al_2O_3(\text{mol\%}))$.

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FIG. 1

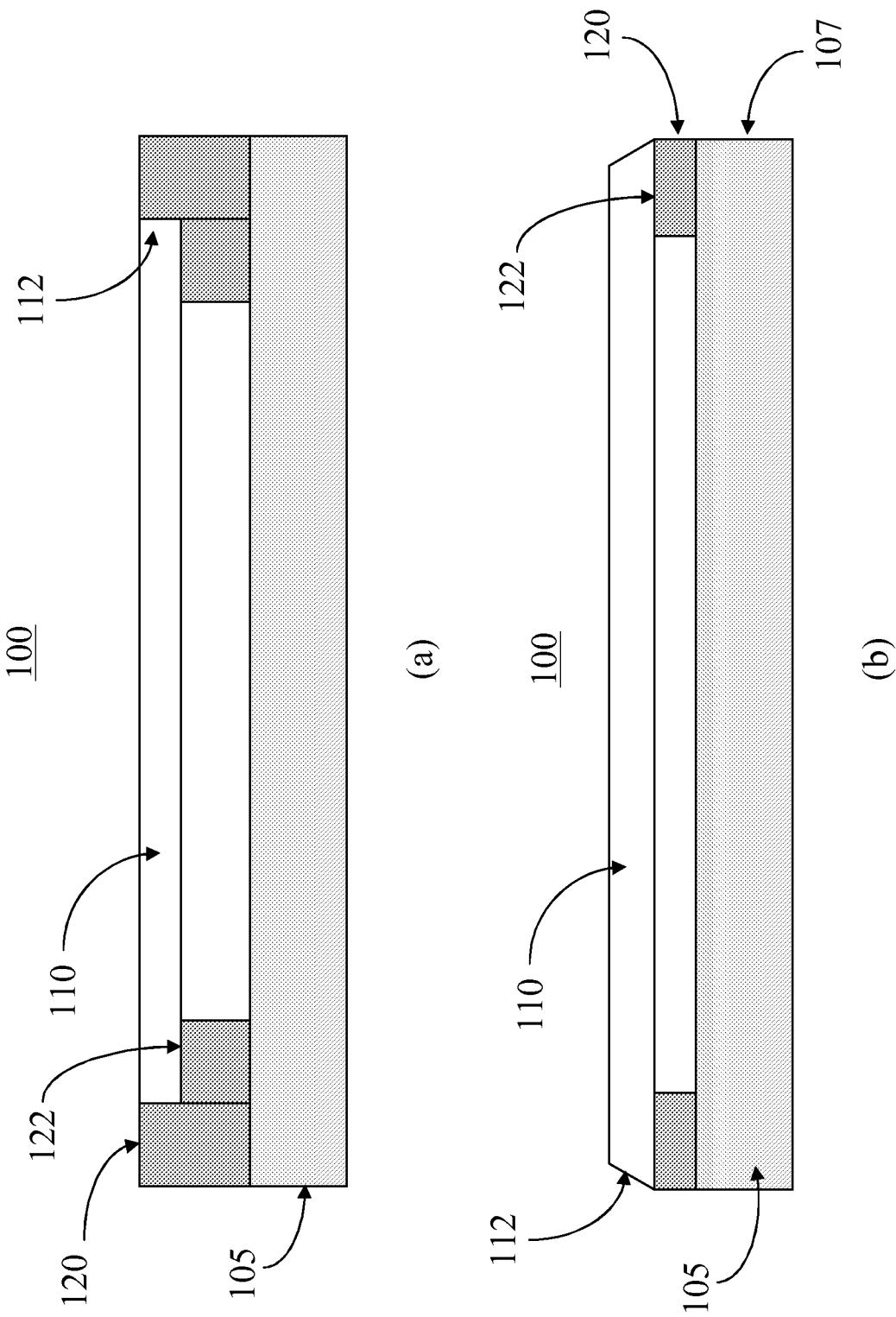
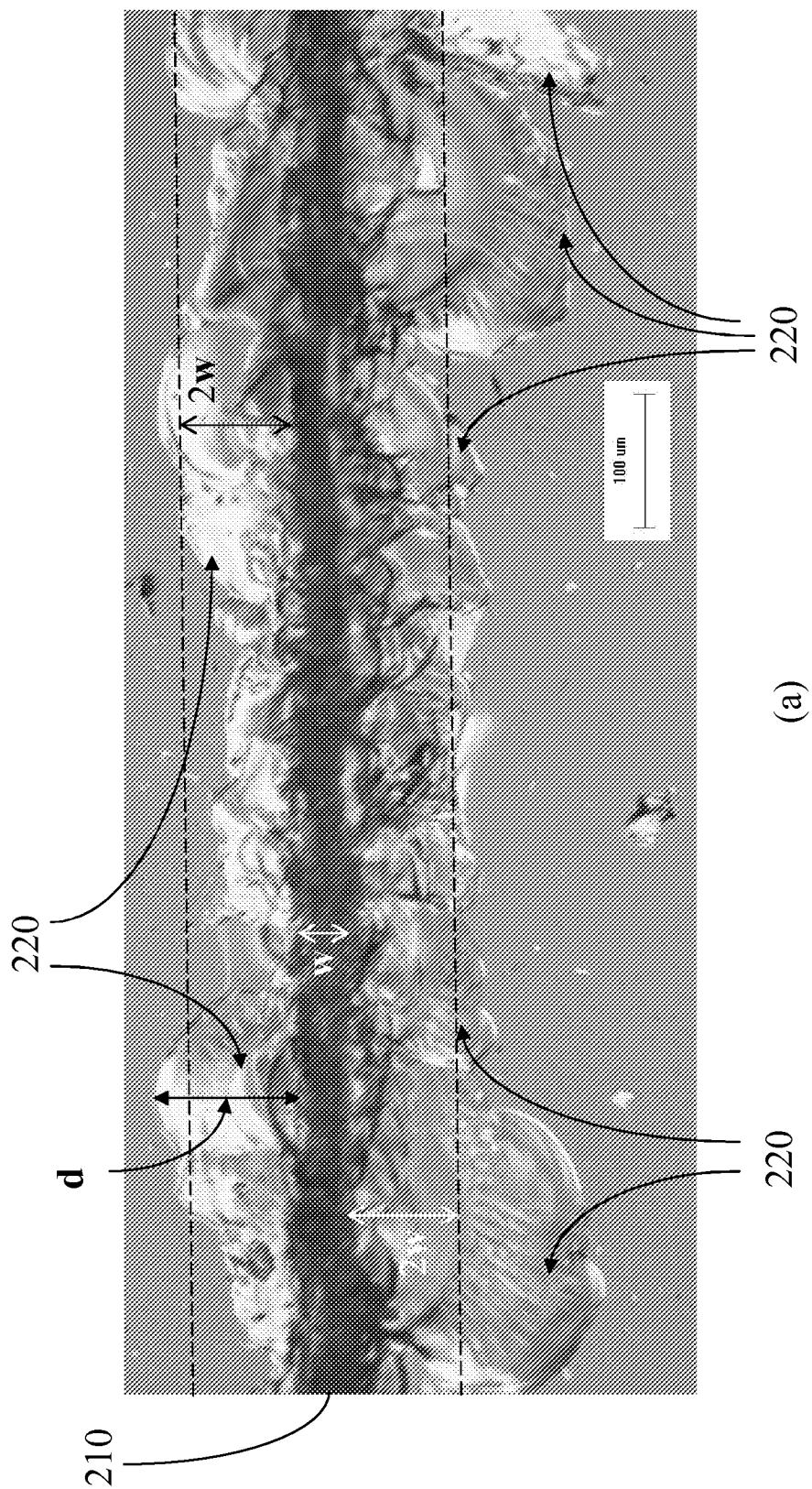


FIG. 2



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FIG. 2

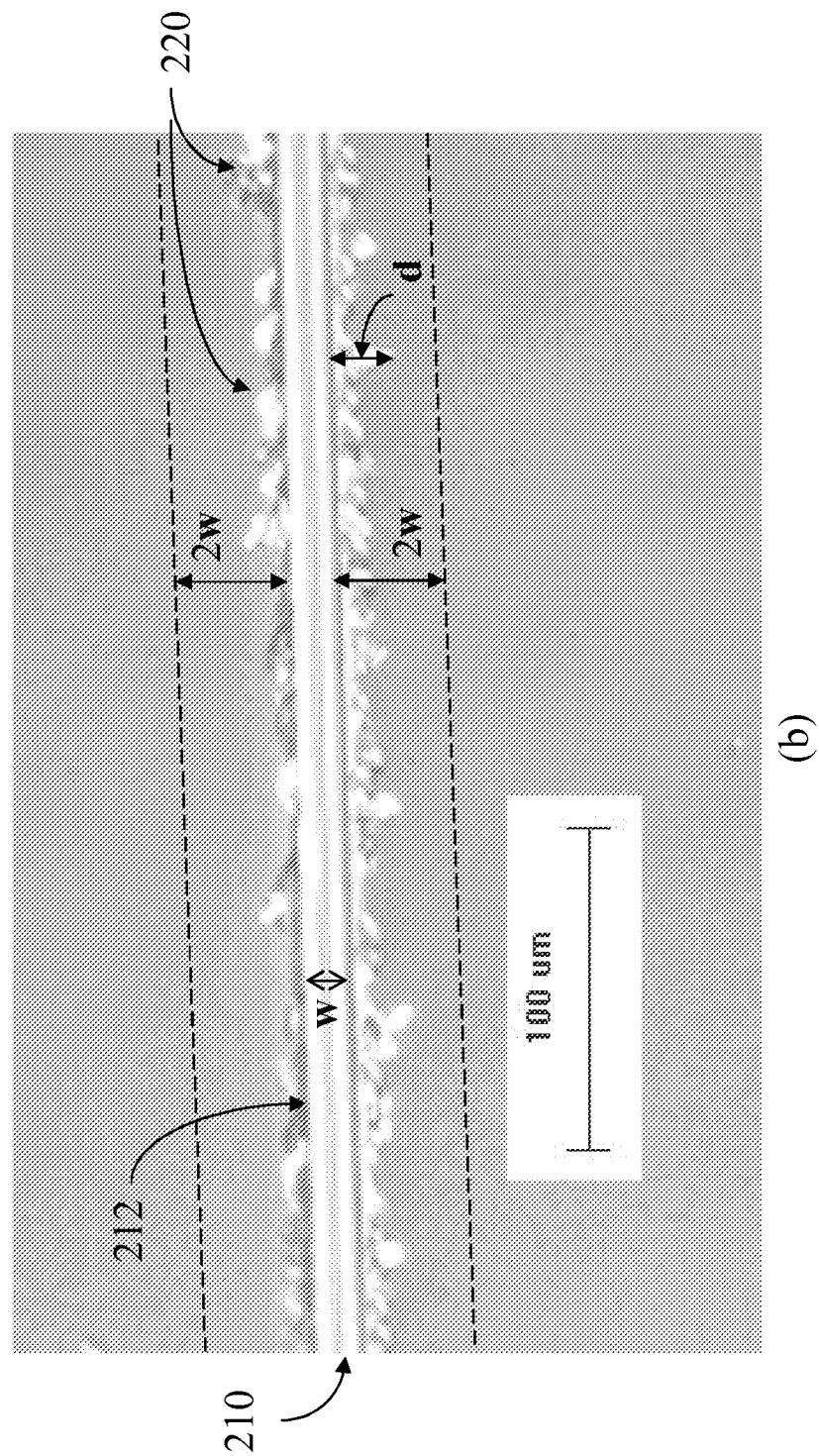


FIG. 3

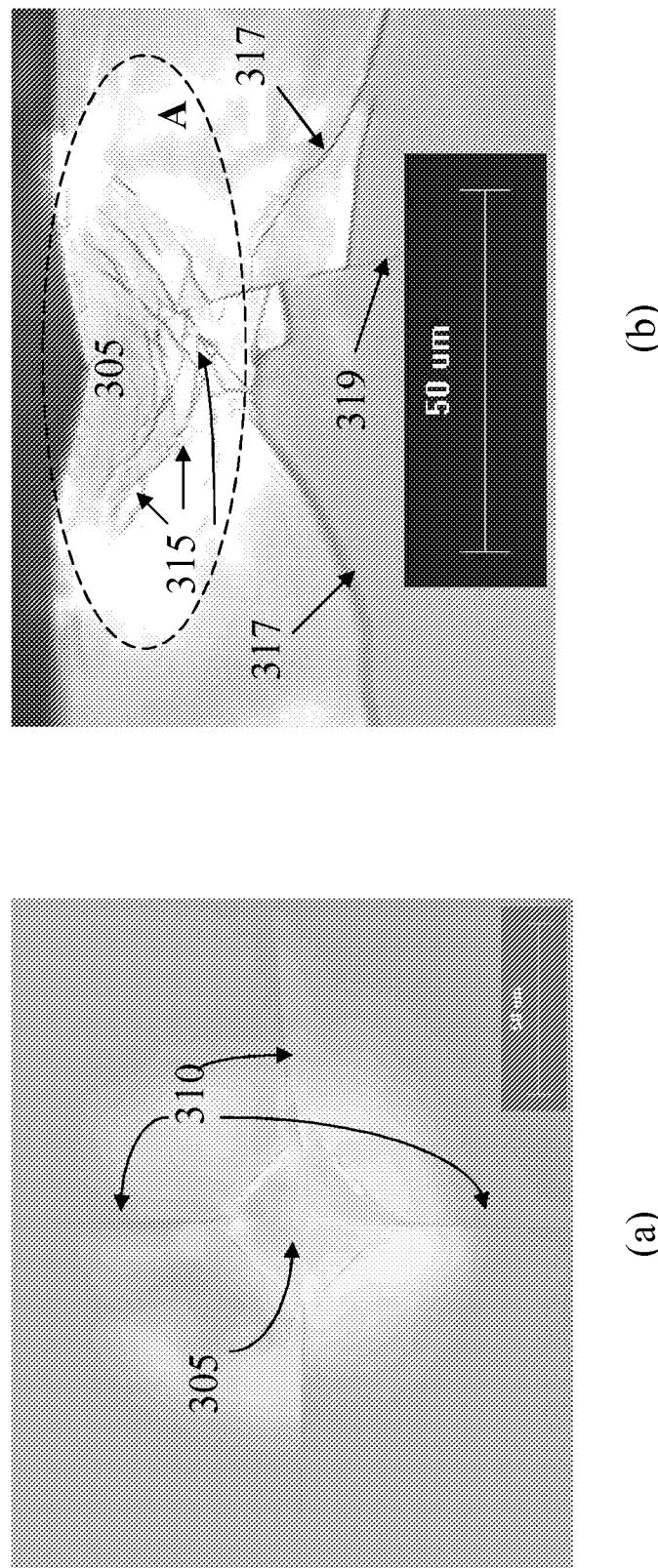
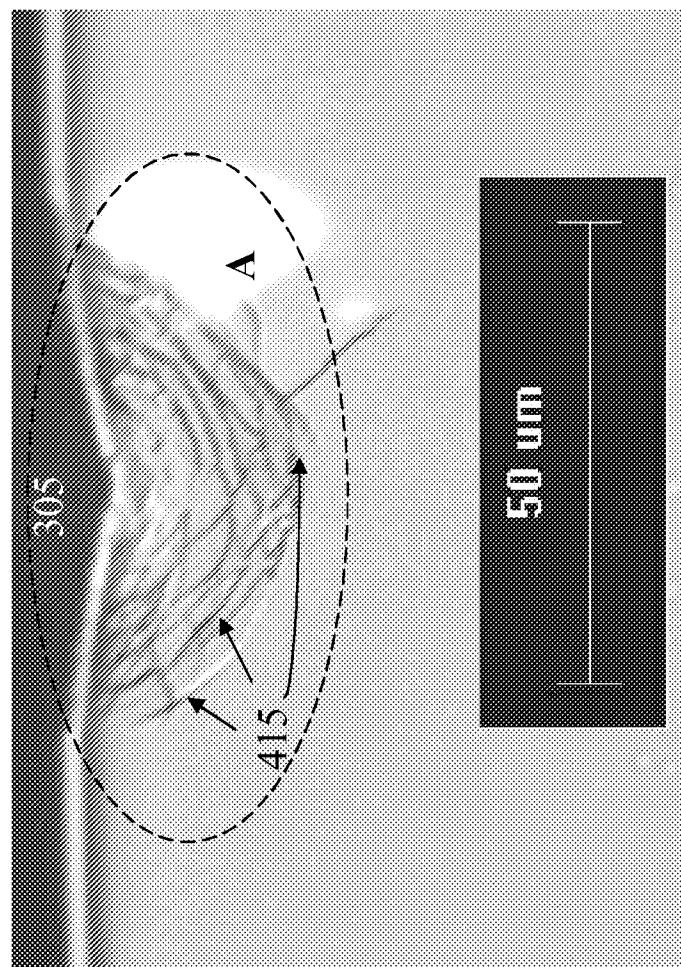


FIG. 4



Prior Art

FIG. 5

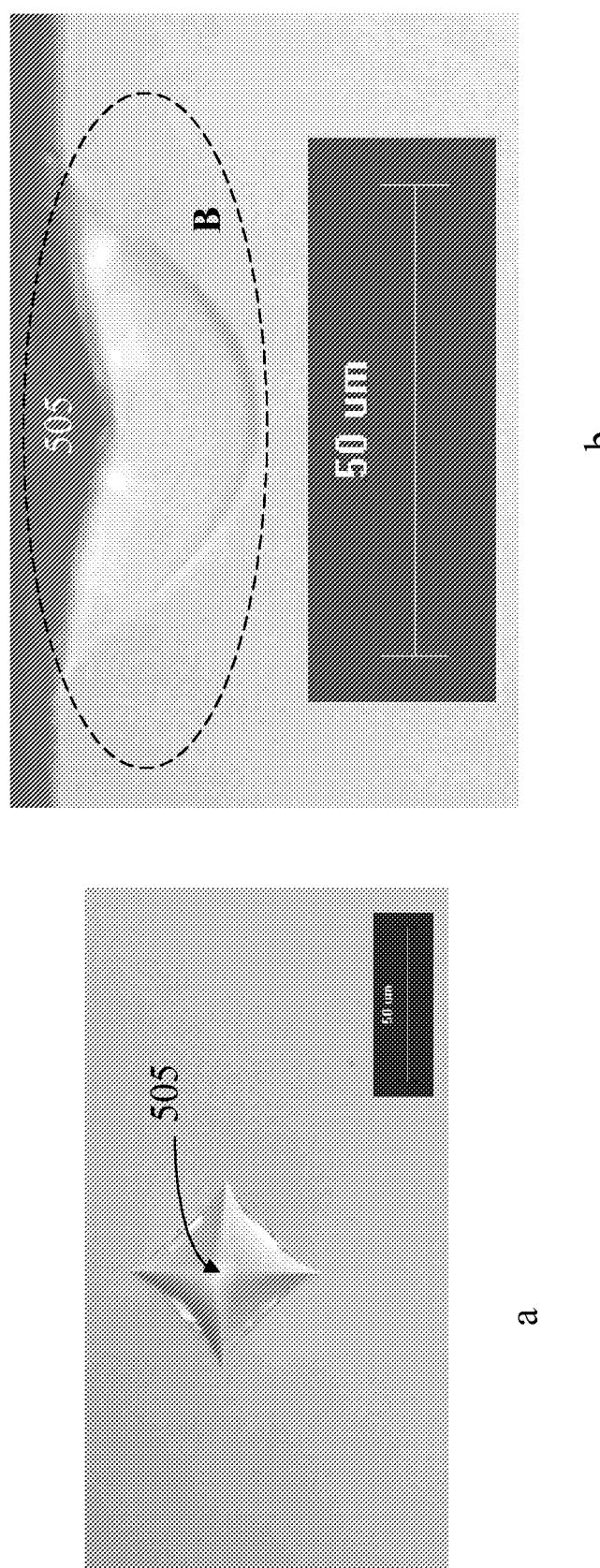
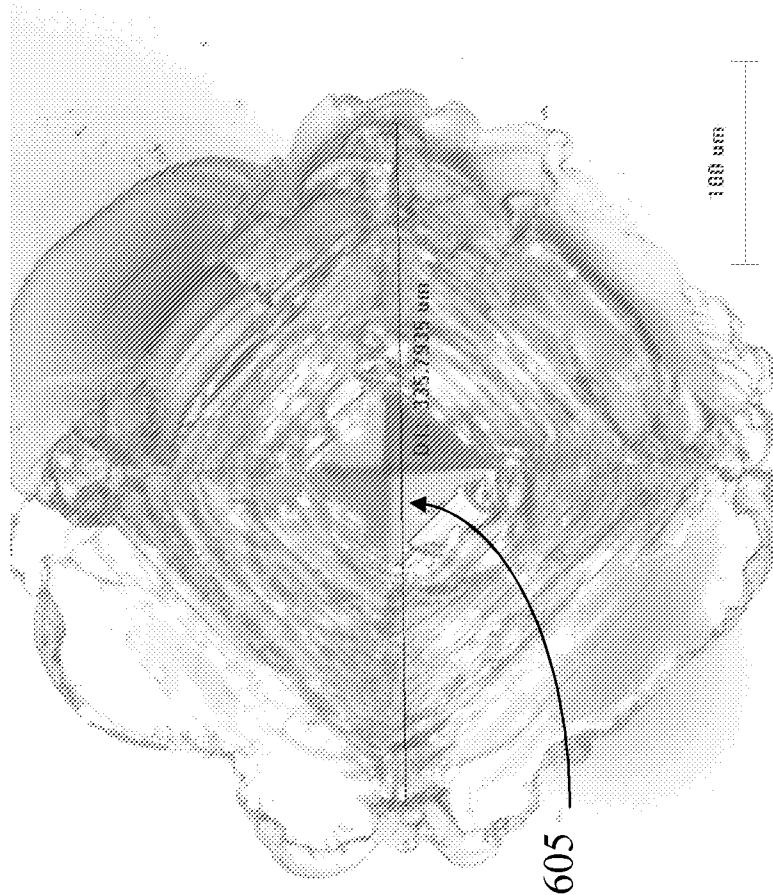


FIG. 6



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FIG. 7

