

ALUMINOBOROSILICATE GLASS COMPOSITION AND PRODUCTS COMPRISING
THE SAME FOR DISPLAY APPLICATIONS

PRIORITY CLAIM AND CROSS-REFERENCE

[0001] This application claims the benefit of priority under 35 U.S.C. § 119 of U.S. Provisional Application Serial No. 63/562,453 filed on March 7, 2024, and further claims the benefit of priority under 35 U.S.C. § 120 of U.S. Application No. 18/224,780 filed July 21, 2023, which in turn, claims the benefit of priority under 35 U.S.C. § 119 of U.S. Provisional Application Serial No. 63/527,367 filed on July 18, 2023, the contents of each of which are relied upon and incorporated herein by reference in their entireties.

FIELD

[0002] The disclosure relates to glass compositions generally. More particularly, the disclosed subject matter relates to glass compositions having good properties and suitable for use in display applications; articles comprising the glass compositions; and methods for making the same.

BACKGROUND

[0003] Flat or curved substrates made of an optically transparent material such as glass are used for flat panel display, photovoltaic devices, and other suitable applications. In addition to the requirement for optical clarity, glass compositions need to meet different challenges depending on fabrication process and the applications.

[0004] For example, the production of liquid crystal displays such as active matrix liquid crystal display devices (AMLCDs) is complex, and the properties of the substrate glass are important. The glass substrates used in the production of AMLCD devices need to have their physical dimensions tightly controlled. The drawdown sheet drawing processes and, in particular, the fusion process, are capable of producing glass sheets that can be used as substrates without requiring costly post-forming finishing operations such as lapping and polishing. However, the fusion process places rather severe restrictions on the glass properties, which require relatively high liquidus viscosities.

[0005] In the liquid crystal display field, thin film transistors (TFTs) based on polycrystalline silicon are preferably used because of their ability to transport electrons more effectively. Polycrystalline based silicon transistors (p-Si) are characterized as having a

higher mobility than those based on amorphous-silicon based transistors (a-Si). This allows the manufacture of smaller and faster transistors, which ultimately produces brighter and faster displays. One problem with p-Si based transistors is that their manufacture requires higher process temperatures than those employed in the manufacture of a-Si transistors. These temperatures range from 450°C to 600°C compared to the 350°C peak temperatures employed in the manufacture of a-Si transistors.

[0006] The glass compositions used for display applications need to have good thermal and mechanical properties, and dimensional stability satisfying the processing and performance requirements. In addition, diffusion of meal ions into the thin film transistors may cause damages to the transistors. Such diffusion needs to be avoided.

[0007] Display technology, such as TV displays, is moving towards 8K technology. 8K refers to the horizontal resolution in the order of 8,000 pixels. For example, when an 8K TV has a screen with 7,680 horizontal and 4,320 vertical pixels, such a TV may have a total of approximately 33 million pixels. 8K technology offers an ultra-high resolution. With four times more pixels than a 4K TV, which has an ultra-high definition (UHD) resolution, 8K TVs show a sharper and more detailed picture quality.

SUMMARY

[0008] The present disclosure provides a glass composition, a product comprising such a glass composition, methods of making the glass composition and the product, and methods of using the glass composition and the product. Such a glass composition is an aluminoborosilicate glass, and includes oxides of alkaline earth metals and a low concentration of boron oxide and strontium oxide.

[0009] Such glass compositions may be substantially alkali-free. The glass compositions exhibit desirable physical and chemical properties, for example, high annealing point, high elastic modulus, low stress optical coefficient (SOC), low T(35kP) and T(200P), and desirable liquidus viscosity. The glass compositions are suitable for use as substrates for display applications such as in flat panel display devices with ultra-high resolution.

[0010] In one aspect, the present disclosure provides a glass or a glass composition.

[0011] In accordance with some embodiments, a glass or a glass composition provided herein comprises in mole percent on an oxide basis:

SiO₂: 66.17-74.31;

Al₂O₃: 11.72-13.86;

B₂O₃: 0.71-1.75;
MgO: 4.61-6.36;
CaO: 4.81-7.27;
SrO: 0.10-1.42; and
BaO: 2.38-4.00.

[0012] In accordance with some embodiments, a glass or a glass composition provided herein comprises in mole percent on an oxide basis:

SiO₂: 69.65-70.77;
Al₂O₃: 12.34-13.20;
B₂O₃: 0.75-1.67;
MgO: 4.85-6.06;
CaO: 5.06-6.92;
SrO: 0.11-1.35; and
BaO: 2.51-3.81.

[0013] The glass composition may include a tramp amount of oxides of alkali metals. In some embodiments, the glass composition or the glass is substantially alkali-free defined by a combined concentration of Li₂O, Na₂O, and K₂O less than 0.1 mol.%, for example, less than 0.09 mol.%, less than 0.08 mol.%, less than 0.07 mol.%, less than 0.06 mol.%, less than 0.05 mol.%, less than 0.04 mol.%, less than 0.03 mol.%, less than 0.02 %, less than 0.01 %, or 0%. In some embodiments, the glass composition has a combined concentration of Li₂O, Na₂O, and K₂O less than 0.06 mol.%.

[0014] In some embodiments, B₂O₃ is in a suitable range. For example, B₂O₃ is in a range of from 0.75 to 1.75 by mole percent, in a range of from 0.75 to 1.67 by mole percent, in a range of from 0.75 to 1.60 by mole percent, in a range of from 0.75 to 1.50 by mole percent, in a range of from 0.75 to 1.40 by mole percent, in a range of from 0.75 to 1.30 by mole percent, in a range of from 0.75 to 1.20 by mole percent, or in a range of from 0.75 to 1.00 by mole percent. In some embodiments, B₂O₃ is in a range of from 0.75 to 1.00 by mole percent.

[0015] In some embodiments, SrO is in a suitable range. For example, SrO is in a range of from 0.11 to 1.42 by mole percent, in a range of from 0.11 to 1.40 by mole percent, in a range of from 0.11 to 1.35 by mole percent, in a range of from 0.11 to 1.30 by mole percent, in a range of from 0.11 to 1.20 by mole percent, in a range of from 0.11 to 1.10 by mole percent, in a range of from 0.11 to 1.00 by mole percent, in a range of from 0.11 to 0.90 by mole percent, in a range of from 0.11 to 0.80 by mole percent, in a range of from 0.11 to

0.70 by mole percent, in a range of from 0.11 to 0.60 by mole percent, in a range of from 0.11 to 0.50 by mole percent, in a range of from 0.11 to 0.40 by mole percent, in a range of from 0.11 to 0.30 by mole percent, or in a range of from 0.11 to 0.20 by mole percent. In some embodiments, SrO is in a range of from 0.11 to 1.00 or 0.50 by mole percent.

[0016] In some embodiments, a ratio of RO/Al₂O₃ is in a range of from 1.13 to 1.31 and RO is the sum of the mole percents of MgO, CaO, SrO, and BaO. For example, the ratio of RO/Al₂O₃ is in a range of from 1.20 to 1.31 in some embodiments.

[0017] The glass may further comprise 0.01 mol.% to 0.4 mol.% of a chemical fining agent, which is selected from SnO₂, As₂O₃, Sb₂O₃, Fe₂O₃, CeO₂, MnO₂, F, Cl, Br, or any combination thereof. For example, the chemical fining agent comprises 0.08 mol.% to 0.14 mol.% of SnO₂ in some embodiments.

[0018] In some embodiments, the glass composition may include a tramp amount of Fe₂O₃, ZrO₂, or TiO₂. Each of Fe₂O₃, ZrO₂, and TiO₂ may be in a range of from 0 to 0.03 by mole percent. In some embodiments, each of Fe₂O₃, ZrO₂, and TiO₂ may be zero or less than 0.01 by mole percent.

[0019] The glass has high annealing point, for example, higher than 775°C. In some embodiments, the glass has an annealing point in a range from 790 °C to 810 °C, for example, in a range from 790 °C to 806 °C.

[0020] The glass also has high elastic modulus (Young's modulus). For example, in some embodiments, the glass has an elastic modulus in a range of from 83.30 GPa to 84.49 GPa.

[0021] The glass has a desirable low stress optical coefficient (SOC). For example, the glass provided in the present disclosure has a SOC in a range of from 26.70 to 30.59, for example, in a range of from 28.10 to 29.13 in some embodiments.

[0022] The glass also has desirable low T(35 kP) and T(200 P) temperatures. For example, in some embodiments, the glass has a T(35 kP) in a range of from 1,280 °C to 1,292 °C, and a T(200 P) in a range of from 1,654 °C to 1,666 °C. T(35 kP) and T(200 P) represent a temperature when the glass has a viscosity of 35 kilopoise (kP) and 200 poise (P), respectively.

[0023] In accordance with some embodiments, a glass provided in the present disclosure is an aluminoborosilicate glass, and comprises in mole percent on an oxide basis:

SiO₂: 66.17-74.31;

Al₂O₃: 11.72-13.86;

B₂O₃: 0.75-1.20;

MgO: 4.61-6.36;

CaO: 4.81-7.27;

SrO: 0.11-0.5; and

BaO: 2.38-4.00,

[0024] The glass has an elastic modulus in a range of from 83.30 GPa to 84.49 GPa, and the glass has a stress optical coefficient (SOC) in a range of from 26.70 to 30.59.

[0025] In accordance with some embodiments, a glass provided in the present disclosure comprises in mole percent on an oxide basis:

SiO₂: 69.65-70.77;

Al₂O₃: 12.34-13.20;

B₂O₃: 0.75-1.20;

MgO: 4.85-6.06;

CaO: 5.06-6.92;

SrO: 0.11-0.5; and

BaO: 2.51-3.81.

[0026] The glass is substantially alkali-free. In some embodiments, the glass composition has a combined concentration of Li₂O, Na₂O, and K₂O less than 0.06 mol.%.

[0027] In some embodiments, B₂O₃ is in a range of from 0.75 to 1.20, for example, from 0.75 to 1.00, by mole percent. SrO is in a range of from 0.11 to 1.00, for example, from 0.11 to 0.50, by mole percent.

[0028] The glass has a ratio of RO/Al₂O₃ in a range of from 1.14 to 1.31, for example, from 1.20 to 1.31, and RO is the sum of the mole percents of MgO, CaO, SrO, and BaO.

[0029] The glass further comprises 0.08 mol.% to 0.14 mol.% of SnO₂ as a chemical fining agent. In some embodiments, the glass composition may include a tramp amount of Fe₂O₃, ZrO₂, or TiO₂. Each of Fe₂O₃, ZrO₂, and TiO₂ may be in a range of from 0 to 0.03 by mole percent. In some embodiments, each of Fe₂O₃, ZrO₂, and TiO₂ may be zero or less than 0.01 by mole percent.

[0030] The glass has an annealing point in a range from 790 °C to 810 °C, for example, in a range from 799 °C to 806 °C. The glass has an elastic modulus in a range of from 83.30 GPa to 84.49 GPa, and a stress optical coefficient (SOC) in a range of from 28.10 to 29.13.

[0031] In some embodiments, the glass has a T(35 kP) in a range of from 1,280 °C to 1,292 °C, and a T(200 P) in a range of from 1,654 °C to 1,666 °C.

[0032] In another aspect, the present disclosure provides an article comprising the glass or the glass composition described herein. For example, a substrate for liquid crystal display comprises the glass or the glass composition described here.

[0033] In another aspect, the present disclosure provides a device for flat panel display, which comprises at least one sheet comprising the glass as described herein. Such a device may further comprise polycrystalline silicon thin film transistors.

[0034] In another aspect, a method for producing the glass or the glass composition as described herein is provided. Such a method comprises at least one step of mixing and melting raw materials in mole percent on an oxide basis so as to provide the oxides as described. Such a method may further comprise making a sheet comprising the glass composition through a downdraw sheet fabrication process or a fusion process.

[0035] The glass compositions exhibit desirable physical properties and chemical properties. For example, the glass provided in the present disclosure has high annealing point (e.g., higher than 790°C), low stress optical coefficient (SOC), and desirable liquidus viscosity. Compared to a commercial product Corning LOTUS™ NXT Glass, the glass described herein has improved elastic modulus, and lower T(350 kP), T(35 kP), and/or T(200 P) temperatures. The glass can be made at lower cost. The glass compositions are suitable for use as substrates in flat panel display devices such as active matrix liquid crystal displays (AMLCDs) with ultra-high resolution, for example, in the 8K display technology.

BRIEF DESCRIPTION OF THE DRAWINGS

[0036] The present disclosure is best understood from the following detailed description when read in conjunction with the accompanying drawings. It is emphasized that, according to common practice, the various features of the drawings are not necessarily to scale. On the contrary, the dimensions of the various features are arbitrarily expanded or reduced for clarity. Like reference numerals denote like features throughout specification and drawings.

[0037] FIG. 1 shows the results of annealing point at different mole percentages of B₂O₃ in the glass compositions in accordance with some embodiments.

DETAILED DESCRIPTION

[0038] This description of the exemplary embodiments is intended to be read in connection with the accompanying drawings, which are to be considered part of the entire written description. In the description, relative terms such as “lower,” “upper,” “horizontal,”

“vertical,” “above,” “below,” “up,” “down,” “top” and “bottom” as well as derivative thereof (e.g., “horizontally,” “downwardly,” “upwardly,” etc.) should be construed to refer to the orientation as then described or as shown in the drawing under discussion. These relative terms are for convenience of description and do not require that the apparatus be constructed or operated in a particular orientation. Terms concerning attachments, coupling and the like, such as “connected” and “interconnected,” refer to a relationship wherein structures are secured or attached to one another either directly or indirectly through intervening structures, as well as both movable or rigid attachments or relationships, unless expressly described otherwise.

[0039] For purposes of the description hereinafter, it is to be understood that the embodiments described below may assume alternative variations and embodiments. It is also to be understood that the specific articles, compositions, and/or processes described herein are exemplary and should not be considered as limiting.

[0040] Open terms such as “include,” “including,” “contain,” “containing” and the like mean “comprising.” These open-ended transitional phrases are used to introduce an open ended list of elements, method steps or the like that does not exclude additional, unrecited elements or method steps. It is understood that wherever embodiments are described with the language “comprising,” otherwise analogous embodiments described in terms of “consisting of” and/or “consisting essentially of” are also provided.

[0041] The transitional phrase “consisting of” and variations thereof excludes any element, step, or ingredient not recited, except for impurities ordinarily associated therewith.

[0042] The transitional phrase “consists essentially of,” or variations such as “consist essentially of” or “consisting essentially of” excludes any element, step, or ingredient not recited except for those that do not materially change the basic or novel properties of the specified method, structure or composition.

[0043] In the present disclosure the singular forms “a,” “an,” and “the” include the plural reference, and reference to a particular numerical value includes at least that particular value, unless the context clearly indicates otherwise. When values are expressed as approximations, by use of the antecedent “about,” it will be understood that the particular value forms another embodiment. As used herein, “about X” (where X is a numerical value) preferably refers to $\pm 10\%$ of the recited value, inclusive. For example, the phrase “about 8” preferably refers to a value of 7.2 to 8.8, inclusive. Where present, all ranges are inclusive and combinable. For example, when a range of “1 to 5” is recited, the recited range should be construed as including ranges “1 to 4,” “1 to 3,” “1-2,” “1-2 & 4-5,” “1-3 & 5,” “2-5,” and

the like. In addition, when a list of alternatives is positively provided, such listing can be interpreted to mean that any of the alternatives may be excluded, e.g., by a negative limitation in the claims. For example, when a range of “1 to 5” is recited, the recited range may be construed as including situations whereby any of 1, 2, 3, 4, or 5 are negatively excluded; thus, a recitation of “1 to 5” may be construed as “1 and 3-5, but not 2”, or simply “wherein 2 is not included.” It is intended that any component, element, attribute, or step that is positively recited herein may be explicitly excluded in the claims, whether such components, elements, attributes, or steps are listed as alternatives or whether they are recited in isolation.

[0044] The terms “substantial,” “substantially,” and variations thereof as used herein are intended to note that a described feature is equal or approximately equal to a value or description. Moreover, “substantially similar” is intended to denote that two values are equal or approximately equal. In some embodiments, “substantially similar” may denote values within about 10% of each other, such as within about 5% of each other, or within about 2% of each other.

[0045] The present disclosure provides aluminoborosilicate glass compositions, products such as articles or devices comprising the same, and method for making the glass composition and the products. Such glass compositions include oxides of alkaline earth metals. The glass compositions include low or ultra-low concentrations of boron oxide and strontium oxide. For example, the boron oxide is in a range of from 0.71 to 1.75 by mole percent. The strontium oxide is in a range of from 0.10 to 1.40 by mole percent. Such glass compositions are substantially alkali-free in some embodiments.

[0046] The glass compositions exhibit desirable physical and chemical properties, for example, high annealing point, high elastic modulus, low stress optical coefficient (SOC), low T(35kP) and T(200P), and desirable liquidus viscosity. With low or ultra-low concentrations of boron oxide and strontium oxide, the glass compositions provide high annealing point and relatively low T(35kP) and T(200P) good for manufacturing. While the ratio of RO/Al₂O₃ is low, for example, in the range of from 1.14 to 1.31, the glass compositions with low contents of boron oxide and strontium oxide provide very high modulus and low SOC. In addition, the glasses also maintains or provide improvements in total pitch variation (TPV). The lower T(35kP) and T(200P) provide significant advantages in manufacturing. The higher elastic modulus provides significant benefits to some applications as it improves stiffness of the sheet during subsequent processing and aids in the improvement of TPV. The lower SOC helps with reduction or elimination of MURA effect, non-uniform brightness, or light leakage defects possibly observed in the final display. The

glass compositions are suitable for use as substrates for display applications such as in flat panel display devices with ultra-high resolution.

[0047] In some embodiments, the substrate is optically transparent. Examples of a substrate include, but are not limited to, a flat or curved glass panel.

[0048] Unless expressly indicated otherwise, the term “glass article” or “glass” used herein is understood to encompass any object made wholly or partly of glass. Glass articles include monolithic substrates, or laminates of glass and glass, glass and non-glass materials, glass and crystalline materials, and glass and glass-ceramics (which include an amorphous phase and a crystalline phase). Unless expressly indicated otherwise, the terms “glass” and “glass composition” used herein may be interchangeable.

[0049] The glass article such as a glass panel may be flat or curved, and is transparent or substantially transparent. As used herein, the term “transparent” is intended to denote that the article, at a thickness of approximately 1 mm, has a transmission of greater than about 85% in the visible region of the spectrum (400-700 nm). For instance, an exemplary transparent glass panel may have greater than about 85% transmittance in the visible light range, such as greater than about 90%, greater than about 95%, or greater than about 99% transmittance, including all ranges and subranges therebetween. According to various embodiments, the glass article may have a transmittance of less than about 50% in the visible region, such as less than about 45%, less than about 40%, less than about 35%, less than about 30%, less than about 25%, or less than about 20%, including all ranges and subranges therebetween. In certain embodiments, an exemplary glass panel may have a transmittance of greater than about 50% in the ultraviolet (UV) region (100-400 nm), such as greater than about 55%, greater than about 60%, greater than about 65%, greater than about 70%, greater than about 75%, greater than about 80%, greater than about 85%, greater than about 90%, greater than about 95%, or greater than about 99% transmittance, including all ranges and subranges therebetween.

[0050] Exemplary glasses include, but are not limited to, aluminoborosilicate having a composition as described herein. The glass article may be optionally strengthened. In some embodiments, the glass article may be strengthened mechanically by utilizing a mismatch of the coefficient of thermal expansion between portions of the article to create a compressive stress region and a central region exhibiting a tensile stress. In some embodiments, the glass article may be strengthened thermally by heating the glass to a temperature above the glass transition point and then rapidly quenching. In some other embodiments, the glass article may be chemically strengthening by ion exchange.

[0051] In the embodiments of the glass compositions described herein, the concentrations of constituent components (e.g., SiO_2 , Al_2O_3 , and the like) are specified in mole percent (mol. %) on an oxide basis, unless otherwise specified.

[0052] The terms “free” and “substantially free,” when used to describe the concentration and/or absence of a particular constituent component in a glass composition, means that the constituent component is not intentionally added to the glass composition. However, the glass composition may contain traces of the constituent component as a contaminant or tramp in amounts of less than 0.03 mol.% or less than 0.01 mol. %.

[0053] In some embodiments, the glass compositions provided herein are alkali-free or substantially alkali free. Unless expressly indicated otherwise, the term “alkali-free” or “substantially alkali-free” for a glass composition used herein is understood to encompass a glass composition having a combined concentration of Li_2O , Na_2O , and K_2O less than 0.1 mol.%, for example, less than 0.06 mol.%, less than 0.05 mol.%, less than 0.02 mol.%, less than 0.01 mol.%, or 0 mol%.

[0054] The term “a tramp amount” used herein can be understood as a trace amount of an oxide, which is not added in a formulation while sometimes such a trace amount may be introduced to the formulation from the processing equipment or other added ingredients comprising a trace amount of impurity. A tramp amount can be understood to encompass “substantially free of” or “free of.”

[0055] In the glass compositions described herein, the ratio of $\text{RO}/\text{Al}_2\text{O}_3$ is a ratio of a sum of the mole percents of RO to the mole percent of Al_2O_3 , where RO includes MgO , CaO , SrO , BaO , and ZnO . When a composition does not comprise ZnO , RO refers to the mole percents of the oxides of alkaline earth metals, and the ratio of $\text{RO}/\text{Al}_2\text{O}_3$ is the same as the ration of $(\text{MgO}+\text{CaO}+\text{SrO}+\text{BaO})/\text{Al}_2\text{O}_3$. In some embodiments, the glass contains no ZnO or only a tramp amount of ZnO .

[0056] The term “softening point,” as used herein, refers to the temperature at which the viscosity of the glass composition is $1 \times 10^{7.6}$ poise.

[0057] The term “annealing point,” as used herein, refers to the temperature at which the viscosity of the glass composition is 1×10^{13} poise.

[0058] The terms “strain point” and “ T_{strain} ” as used herein, refers to the temperature at which the viscosity of the glass composition is 3×10^{14} poise.

[0059] The liquidus temperature of a glass (T_{liq}) is the temperature ($^{\circ}\text{C}$) above which no crystalline phases can coexist in equilibrium with the glass. The liquidus viscosity is the viscosity of a glass at the liquidus temperature.

[0060] The term “CTE,” as used herein, refers to the coefficient of thermal expansion of the glass composition over a temperature range from about room temperature (RT) to about 300° C. The linear coefficient of thermal expansion (CTE) over the temperature range 25-300° C is expressed in terms of $\times 10^{-7}/^{\circ}\text{C}$, and determined following ASTM standard E228.

[0061] Young’s modulus values and shear modulus in terms of GPa, and Poisson’s ratio were determined using a resonant ultrasonic spectroscopy technique of the general type set forth in ASTM E1875-00e1. The terms “Young’s modulus” and “elastic modulus” may be interchangeable.

[0062] The fracture toughness may be measured using known methods in the art, for example, using a chevron notch, short bar, notched beam and the like, according to ASTM C1421-10, “Standard Test Methods for Determination of Fracture Toughness of Advanced Ceramics at Ambient Temperature.”

[0063] Stress optical coefficient (SOC) values can be measured as set forth in Procedure C (Glass Disc Method) of ASTM standard C770-16, entitled “Standard Test Method for Measurement of Glass Stress-Optical Coefficient.”

[0064] As the industry moves towards 8K display panels, thicker copper lines are needed to be used. Copper has a high CTE, and the thicker lines of copper will result in higher tensile film stress that will warp both the sheet and the panels. This could interfere with processing yield. Referring to Stoney’s equation, shown below in Equation 1,

$$(R = \frac{Et^3}{6(1-\nu)\sigma_f t_f}) \text{ (Equation 1),}$$

R is the radius of curvature, E is the Young’s modulus, t is the thickness of a cantilever, ν is Poisson’s ratio, and σ is the surface stress generated.

[0065] It can be seen that the amount of strain is proportional to E (elastic modulus). Therefore, higher modulus (E) will result in lower strain/warp for a given stress.

[0066] In addition, panel makers are moving towards a borderless panel design, which results in excessive stress-induced light leakage (mura). Mura intensity is related to the glass stress optical coefficient (SOC) by Equation 2:

$$\text{mura intensity} \propto (\text{SOC} \times t)^2 \text{ (Equation 2),}$$

where t is thickness of glass sheet.

[0067] It is expected that reduction of the glass SOC will result in improvement in mura or less light leakage.

[0068] In the present disclosure, glasses were designed to increase physical properties such as Young's modulus, and decrease stress optical coefficient (SOC). In addition, glasses were designed to increase annealing point and obtain desirable liquidus temperature. An existing product, Corning LOTUS™ NXT Glass, was chosen to be a benchmark for the developments described in the present disclosure.

[0069] Corning LOTUS™ NXT Glass (abbreviated as "Lotus" or "Lotus NXT") as an existing product, is a premium glass solution designed to withstand high-temperature processing requirements while providing industry-leading levels of low total pitch variation (TPV). This results in brighter, more energy-efficient displays with higher resolutions for consumers, and better yields for panel-makers. Thermally and dimensionally stable, LOTUS™ NXT Glass is formulated to perform exceptionally well in OLED and high-resolution LCD manufacturing processes, ideal for highest-resolution LTPS displays and other applications requiring precision glass. It is well suited for processing temperatures up to 600°C.

[0070] The glasses provided in the present disclosure have elastic modulus greater than that of Lotus NXT (incumbent glass) by up to 1% and SOC values lower than that of Lotus NXT by as much as 2%. These glasses also have an anneal point that is comparable to Lotus NXT, which will benefit overall TPV (total pitch variation). Overall, compared to Lotus NXT, these glasses have similar compaction behavior, higher Young's Modulus, and lower SOC, and are more favorable in terms of manufacturing from the perspective of having a lower 35 kP temperature for improved isopipe lifetime, a lower 200P temperature for lower Pt temperatures, lower batch costs, and in many cases improved liquidus viscosity. They have been developed as potential replacements for Lotus NXT with reduced manufacturing costs and improved asset lifetimes. The 200P temperature being lower allows to potentially put less power into the tank to melt the glass, which could result in longer electrode lifetimes. Also the lower temperatures will help with prolonging refractory lifetime.

[0071] In the present disclosure, the glasses were developed to improve the melting, forming and liquidus properties of Lotus NXT while maintaining or improving the customer facing attributes such as Young's modulus, SOC, and TPV (stress relaxation, compaction).

[0072] Lotus NXT has a strain point (fiber) of 752 °C, an annealing point (fiber) of 806 °C, a softening point (fiber) of 1,042.9 °C, a coefficient of thermal expansion (CTE) at 0-300 °C of 34.8, a density of 2.592 g/cm³, a Poisson ratio of 0.229, a shear modulus of 33.64 GPa, an elastic modulus of 82.70 GPa, a stress optical coefficient (SOC) of 28.64, a T(35kP) temperature of 1,296 °C, and a T(200P) temperature of 1,683 °C.

[0073] Table 1 shows exemplary ranges of ingredient contents and properties of the glasses designed, including the minimum and maximum of ingredient contents in exemplary glass compositions and their properties, including key properties such as annealing point, SOC, and elastic modulus. These glasses have similar to or better properties than Lotus NXT. These glasses also show a reduction in the T(200P) by 17-29 °C and T(35kP) temperature by 4-16 °C. This reduction in temperature can help enable longer tank (Pt system) and isopipe lifetimes, thereby reducing the manufacturing cost. Many of these glasses exhibit liquidus viscosities that are greater than that of NXT. This will enable less crystal growth on the isopipe edge directors during manufacturing, thereby less down time needed for cleaning and flushing to remove the crystals. The crystals lead to defects in the glass sheet and this is why cleaning and flushing needs to take place to restore the sheet to defect free.

[0074] Table 1.

mol %	MIN	MAX
SiO ₂	69.17	74.31
Al ₂ O ₃	11.34	13.86
B ₂ O ₃	0.71	1.75
MgO	4.61	6.36
CaO	4.81	6.27
SrO	0.10	1.42
BaO	2.38	4.00
SnO ₂	0.08	0.14
Fe ₂ O ₃ (tramp)	0	0.01
ZrO ₂ (tramp)	0	0.01
Na ₂ O (tramp)	0	0.05
K ₂ O (tramp)	0	0.01
TiO ₂ (tramp)	0	0.03
RO/Al ₂ O ₃	1.14	1.31
Physical Properties	MIN	MAX
Strain Point (fiber) °C	746	754
Annealing Point (fiber) °C	799	806
Softening Point (fiber) °C	1034.7	1041.3
CTE 0-300 °C (10 ⁻⁷)	34.1	37.3
Density (g/cc)	2.559	2.612
Young's Modulus (GPa)	83.3	84.49
Shear Modulus (GPa)	33.97	34.43
Poisson's ratio	0.221	0.230
SOC (nm/cm/MPa)	26.70	30.59
T(35kP)	1,280	1,292

T(200P)	1,654	1,666
Liquidus Viscosity (kP)	100	250

[0075] In Table 1, SnO₂ may be replaced by another suitable chemical fining agent as described herein.

[0076] In accordance with some embodiments, a glass or a glass composition provided herein comprises in mole percent on an oxide basis:

SiO₂: 66.17-74.31;
 Al₂O₃: 11.72-13.86;
 B₂O₃: 0.71-1.75;
 MgO: 4.61-6.36;
 CaO: 4.81-7.27;
 SrO: 0.10-1.42; and
 BaO: 2.38-4.00.

[0077] In accordance with some embodiments, a glass or a glass composition provided herein comprises in mole percent on an oxide basis:

SiO₂: 69.65-70.77;
 Al₂O₃: 12.34-13.20;
 B₂O₃: 0.75-1.67;
 MgO: 4.85-6.06;
 CaO: 5.06-6.92;
 SrO: 0.11-1.35; and
 BaO: 2.51-3.81.

[0078] Such a glass is an aluminoborosilicate glass. The alumina content is high, for example, in a range of from 12.34 to 13.20 by mole percent. In some embodiments, SiO₂ is in a range of from 69.9 to 70.7 by mole percent.

[0079] The glass composition may include a tramp amount of oxides of alkali metals. In some embodiments, the glass composition or the glass is substantially alkali-free defined by a combined concentration of Li₂O, Na₂O, and K₂O less than 0.1 mol.%, for example, less than 0.09 mol.%, less than 0.08 mol.%, less than 0.07 mol.%, less than 0.06 mol.%, less than 0.05 mol.%, less than 0.04 mol.%, less than 0.03 mol.%, less than 0.02 %, less than 0.01 %, or 0%. In some embodiments, the glass composition has a combined concentration of Li₂O, Na₂O, and K₂O less than 0.06 mol.%.

[0080] In some embodiments, B_2O_3 is in a suitable range. For example, B_2O_3 is in a range of from 0.75 to 1.75 by mole percent, in a range of from 0.75 to 1.67 by mole percent, in a range of from 0.75 to 1.60 by mole percent, in a range of from 0.75 to 1.50 by mole percent, in a range of from 0.75 to 1.40 by mole percent, in a range of from 0.75 to 1.30 by mole percent, in a range of from 0.75 to 1.20 by mole percent, or in a range of from 0.75 to 1.00 by mole percent. In some embodiments, B_2O_3 is in a range of from 0.75 to 1.00 by mole percent.

[0081] In some embodiments, SrO is in a suitable range. For example, SrO is in a range of from 0.11 to 1.42 by mole percent, in a range of from 0.11 to 1.40 by mole percent, in a range of from 0.11 to 1.35 by mole percent, in a range of from 0.11 to 1.30 by mole percent, in a range of from 0.11 to 1.20 by mole percent, in a range of from 0.11 to 1.10 by mole percent, in a range of from 0.11 to 1.00 by mole percent, in a range of from 0.11 to 0.90 by mole percent, in a range of from 0.11 to 0.80 by mole percent, in a range of from 0.11 to 0.70 by mole percent, in a range of from 0.11 to 0.60 by mole percent, in a range of from 0.11 to 0.50 by mole percent, in a range of from 0.11 to 0.40 by mole percent, in a range of from 0.11 to 0.30 by mole percent, or in a range of from 0.11 to 0.20 by mole percent. In some embodiments, SrO is in a range of from 0.11 to 1.00 or 0.50 by mole percent.

[0082] In some embodiments, a ratio of RO/Al_2O_3 is in a range of from 1.13 to 1.31 and RO is the sum of the mole percents of MgO, CaO, SrO, and BaO. No ZnO is added into the glass. For example, the ratio of RO/Al_2O_3 is in a range of from 1.13 to 1.31 in some embodiments.

[0083] The glass may further comprise 0.01 mol.% to 0.4 mol.% of a chemical fining agent, which is selected from SnO_2 , As_2O_3 , Sb_2O_3 , Fe_2O_3 , CeO_2 , MnO_2 , F, Cl, Br, or any combination thereof. For example, the chemical fining agent comprises 0.08 mol.% to 0.14 mol.% of SnO_2 in some embodiments.

[0084] In some embodiments, the glass composition may include a tramp amount of Fe_2O_3 , ZrO_2 , or TiO_2 . Each of Fe_2O_3 , ZrO_2 , and TiO_2 may be in a range of from 0 to 0.03 by mole percent. In some embodiments, each of Fe_2O_3 , ZrO_2 , and TiO_2 may be zero or less than 0.01 by mole percent.

[0085] The glass has high annealing point, for example, higher than 775°C. In some embodiments, the glass has an annealing point in a range from 790 °C to 810 °C, for example, in a range from 790 °C to 806 °C.

[0086] The glass also has high elastic modulus (Young's modulus). For example, in some embodiments, the glass has an elastic modulus in a range of from 83.30 GPa to 84.49 GPa.

[0087] The glass has a desirable stress optical coefficient (SOC), which is relatively lower compared to existing products. For example, the glass has a SOC in a range of from 26.70 to 30.59, for example, in a range of from 28.10 to 29.13.

[0088] The glass also has desirable low T(35 kP) and T(200 P) temperatures. For example, in some embodiments, the glass has a T(35 kP) in a range of from 1,280 °C to 1,292 °C, and a T(200 P) in a range of from 1,654 °C to 1,666 °C. T(35 kP) and T(200 P) represent a temperature when the glass has a viscosity of 35 kilopoise (kP) and 200 poise (P), respectively.

[0089] The glass has liquidus viscosity in a range of from 100,000 poise to 250,000 poise, for example, from 120,000 poise to 250,000 poise, from 150,000 poise to 250,000 poise, or from 200,000 poise to 250,000 poise.

[0090] The glass also has other properties of suitable ranges, for example, those as shown in Table 1.

[0091] In accordance with some embodiments, a glass provided in the present disclosure is an aluminoborosilicate glass, and comprises in mole percent on an oxide basis:

SiO₂: 66.17-74.31;
Al₂O₃: 11.72-13.86;
B₂O₃: 0.75-1.20;
MgO: 4.61-6.36;
CaO: 4.81-7.27;
SrO: 0.11-0.5; and
BaO: 2.38-4.00,

[0092] The glass has an elastic modulus in a range of from 83.30 GPa to 84.49 GPa, and the glass has a stress optical coefficient (SOC) in a range of from 26.70 to 30.59.

[0093] In accordance with some embodiments, a glass provided in the present disclosure is an aluminoborosilicate glass, and comprises in mole percent on an oxide basis:

SiO₂: 69.65-70.77;
Al₂O₃: 12.34-13.20;
B₂O₃: 0.75-1.20;
MgO: 4.85-6.06;
CaO: 5.06-6.92;

SrO: 0.11-0.5; and

BaO: 2.51-3.81.

[0094] The glass is substantially alkali-free defined by a combined concentration of Li_2O , Na_2O , and K_2O less than 0.1 mol.%. In some embodiments, the glass composition has a combined concentration of Li_2O , Na_2O , and K_2O less than 0.06 mol.%.

[0095] In some embodiments, B_2O_3 is in a range of from 0.75 to 1.20, for example, from 0.75 to 1.00, by mole percent. SrO is in a range of from 0.11 to 1.00, for example, from 0.11 to 0.50, by mole percent.

[0096] The glass has a ratio of $\text{RO}/\text{Al}_2\text{O}_3$ in a range of from 1.14 to 1.31, for example, from 1.20 to 1.31, and RO is the sum of the mole percents of MgO, CaO, SrO, and BaO.

[0097] The glass further comprises 0.08 mol.% to 0.14 mol.% of SnO_2 as a chemical fining agent. In some embodiments, the glass composition may include a tramp amount of Fe_2O_3 , ZrO_2 , or TiO_2 . Each of Fe_2O_3 , ZrO_2 , and TiO_2 may be in a range of from 0 to 0.03 by mole percent. In some embodiments, each of Fe_2O_3 , ZrO_2 , and TiO_2 may be zero or less than 0.01 by mole percent.

[0098] The glass has an annealing point in a range from 790 °C to 810 °C, for example, in a range from 799 °C to 806 °C. The glass has an elastic modulus in a range of from 83.30 GPa to 84.49 GPa, and a stress optical coefficient (SOC) in a range of from 28.10 to 29.13.

[0099] In some embodiments, the glass has a $T(35 \text{ kPa})$ in a range of from 1,280 °C to 1,292 °C, and a $T(200 \text{ Pa})$ in a range of from 1,654 °C to 1,666 °C.

[0100] The glass has other desirable properties as described herein.

[0101] The inventors have surprisingly found that the compositions with specified oxide contents such as a low content of B_2O_3 and SrO, particularly in combination with relatively high MgO content and a specified $\text{RO}/\text{Al}_2\text{O}_3$ ratio, provides glasses with suitably high values in high annealing point, high modulus, and low stress optical coefficient (SOC). The glass shows desirable improvements compared to the existing products such as Lotus NXT Glass. The compositions described herein provide a packed glass structure, which provides lower stress optical coefficient.

[0102] In the embodiments of the glass compositions described herein, SiO_2 is the largest constituent of the composition and, as such, is the primary constituent of the glass network. SiO_2 enhances the chemical durability of the glass and, in particular, the resistance of the glass composition to decomposition in acid, and provides a desirable liquidus temperature or liquidus viscosity. The resulting chemical durability make the glass suitable

for a flat panel display glass (e.g., an AMLCD glass). Accordingly, a high SiO_2 concentration is generally desired. However, if the content of SiO_2 is too high, the formability of the glass may be diminished as higher concentrations of SiO_2 increase the difficulty of melting the glass which, in turn, adversely impacts the formability of the glass.

[0103] In the embodiments described herein, the glass composition comprises SiO_2 in an amount greater than or equal to about 69.65 mol. % and less than or equal to about 70.77 mol. %. In some embodiments, SiO_2 is present in the glass composition in an amount greater than or equal to about 69.9 mol. % and less than or equal to about 70.7 mol. %.

[0104] The glass compositions described herein further include Al_2O_3 . Al_2O_3 at a concentration equal to or greater than a certain amount such as 12.34 mole percent provides the glass with a low liquidus temperature and high viscosity, resulting in a high liquidus viscosity. The use of at least 12.34 mole percent of Al_2O_3 also improves the glass's annealing point and modulus. Al_2O_3 improves the susceptibility of the glass to ion exchange strengthening. Moreover, additions of Al_2O_3 to the composition reduce the propensity of alkali constituents (such as Na and K), if there is any, from leaching out of the glass and, as such, additions of Al_2O_3 increase the resistance of the composition to hydrolytic degradation. Moreover, additions of Al_2O_3 may also increase the softening point of the glass thereby reducing the formability of the glass.

[0105] The glass compositions described herein include Al_2O_3 in an amount greater than or equal to about 12.34 mol. % and less than or equal to about 13.20 mol. %.

[0106] In some embodiments, in order to have the ratio of $\text{RO}/\text{Al}_2\text{O}_3$ in a range of from 1.14 to 1.31, and RO is the sum of the mole percents of MgO , CaO , SrO , and BaO , when there is no ZnO added, the content of Al_2O_3 is kept below 13.2 %. For example, the ratio of $\text{RO}/\text{Al}_2\text{O}_3$ is in a range of from 1.20 to 1.31.

[0107] B_2O_3 is both a glass former and a flux that aids melting and lowers the melting temperature. It has an impact on both liquidus temperature and viscosity. Increasing B_2O_3 can be used to increase the liquidus viscosity of a glass. To achieve these effects, the glass compositions of one or more embodiments may have B_2O_3 concentrations that are equal to or greater than 0.1 mole percent such as equal to or greater than 0.75%. As discussed above with regard to SiO_2 , glass durability is very important for LCD applications. Durability can be controlled somewhat by elevated concentrations of alkaline earth oxides, and significantly reduced by elevated B_2O_3 content. Annealing point decreases as B_2O_3 increases, so it may be helpful to keep B_2O_3 content low relative to its typical concentration in amorphous silicon substrates. Thus in some embodiments, the glass composition has B_2O_3 concentrations that

are in the range of about 0.75 and 1.67 mole percent. For example, B_2O_3 is in a range of from 0.75 to 1.2 by mole percent or from 0.75 to 1.0 by mole percent. It is surprisingly found that this low content of B_2O_3 together with low SrO content combined with other oxides increases elastic modulus of the resulting glass and provides other properties as described herein, for example, high annealing point, low stress optical coefficient, and reduced $T(35kP)$ and $T(200P)$. These properties make the glass more easily made and also suitable for the ultra-high resolution display applications such as in 8K display technology.

[0108] In addition to the glass formers (SiO_2 , Al_2O_3 , and B_2O_3), the glasses described herein also include alkaline earth oxides. In some embodiments, four alkaline earth oxides are present of the glass composition, e.g., MgO, CaO, BaO, and SrO. The alkaline earth oxides provide the glass with various properties important to melting, fining, forming, and ultimate use. Accordingly, to improve glass performance in these regards, in one embodiment, the $(MgO+CaO+SrO+BaO)/Al_2O_3$ ratio is greater than or equal to 1.14. As this ratio increases, viscosity tends to decrease more strongly than liquidus temperature, and thus it is increasingly difficult to obtain suitably high values for liquidus viscosity. Thus in another embodiment, the ratio $(MgO+CaO+SrO+BaO)/Al_2O_3$ is less than or equal to 1.31.

[0109] SrO content is low in the present disclosure. For example, SrO is in a range of from 0.11 to 1.35 by mole percent, in a range of from 0.11 to 1.30 by mole percent, in a range of from 0.11 to 1.20 by mole percent, in a range of from 0.11 to 1.00 by mole percent, or in a range of from 0.11 to 0.50 by mole percent, or any other ranges as described herein.

[0110] An decrease in the RO concentration and an increase in the Al_2O_3 content is also a factor helping to provide a packed glass structure, which decreases the stress optical coefficient of the resulting glass.

[0111] For certain embodiments, the alkaline earth oxides may be treated as what is in effect a single compositional component. This is because their impact upon viscoelastic properties, liquidus temperatures and liquidus phase relationships are qualitatively more similar to one another than they are to the glass forming oxides SiO_2 , Al_2O_3 and B_2O_3 . However, the alkaline earth oxides CaO, SrO and BaO can form feldspar minerals, notably anorthite ($CaAl_2Si_2O_8$) and celsian ($BaAl_2Si_2O_8$) and strontium-bearing solid solutions of same, but MgO does not participate in these crystals to a significant degree. Therefore, when a feldspar crystal is already in the liquidus phase, a superaddition of MgO may serves to stabilize the liquid relative to the crystal and thus lower the liquidus temperature. At the same time, the viscosity curve typically becomes steeper, reducing melting temperatures while having little or no impact on low-temperature viscosities. In this sense, the addition of

small amounts of MgO benefits melting by reducing melting temperatures, benefits forming by reducing liquidus temperatures and increasing liquidus viscosity, while preserving high annealing point and, thus, low compaction. Thus, in various embodiments, the glass composition comprises MgO in an amount in the range of about 4.85 mole percent to about 6.06 mole percent.

[0112] In addition to MgO, the glass composition comprises CaO in a range of about 5.06 mole percent to about 6.92. These alkaline earth metal oxides in combination with other oxides including SiO₂, Al₂O₃ and B₂O₃ at specified mole percentages provide the excellent properties described herein.

[0113] Calcium oxide present in the glass composition can produce low liquidus temperatures (high liquidus viscosities), high annealing points and moduli, and CTE's in the most desired ranges for flat panel applications, specifically, AMLCD applications. It also contributes favorably to chemical durability, and compared to other alkaline earth oxides, it is relatively inexpensive as a batch material. However, at high concentrations, CaO increases the density and CTE. Furthermore, at sufficiently low SiO₂ concentrations, CaO may stabilize anorthite, thus decreasing liquidus viscosity. Accordingly, in one embodiment, the CaO concentration can be between 5.06 mole percent and 6.92 mole percent.

[0114] SrO and BaO can both contribute to low liquidus temperatures (high liquidus viscosities) and, thus, the glasses described herein will contain at least both of these oxides. However, the selection and concentration of these oxides are selected in order to avoid an increase in CTE and density and a decrease in modulus and annealing point. The relative proportions of SrO and BaO can be balanced so as to obtain a suitable combination of physical properties and liquidus viscosity such that the glass can be formed by a drawdown process. In some embodiments, the glass comprises SrO in range of about 0.11 mole percent to about 1.35 mole percent, and BaO in the range of about 2.51 mole percent to about 3.81 mole percent. In some embodiments, SrO is less than 1 mole percent.

[0115] In addition to meltability and annealing point considerations, for AMLCD applications, the CTE of the glass should be compatible with that of silicon. To achieve such CTE values, exemplary glasses control the RO content of the glass. For a given Al₂O₃ content, controlling the RO content corresponds to controlling the RO/Al₂O₃ ratio.

[0116] In one or more embodiments, the glasses provided in the present disclosure for use in AMLCD applications have coefficients of thermal expansion (CTEs) (0-300°C) in the range of about $34.1 \times 10^{-7} / ^\circ\text{C}$ to about $37.3 \times 10^{-7} / ^\circ\text{C}$ (i.e., about 3.41 ppm/°C to about 3.73 ppm/°C).

[0117] The glasses can be formable by a downdraw process, e.g., a fusion process, which means that the liquidus viscosity of the glass needs to be relatively high. Individual alkaline earths play an important role in this regard and they can destabilize the crystalline phases that would otherwise form. BaO and SrO are particularly effective in controlling the liquidus viscosity and are included in exemplary glasses for at least this purpose. As illustrated in the examples presented below, the combinations of the four alkaline earth oxides will produce glasses having high liquidus viscosities, with the total of the alkaline earths satisfying the RO/ Al₂O₃ ratio constraints needed to achieve low melting temperatures, high annealing points, and suitable CTE's.

[0118] In addition to the above components, the glass compositions described herein can include various other oxides to adjust various physical, melting, fining, and forming attributes of the glasses. Examples of such other oxides include, but are not limited to, TiO₂, MnO, Fe₂O₃, ZnO, Nb₂O₅, MoO₃, ZrO₂, Ta₂O₅, WO₃, Y₂O₃, La₂O₃, and CeO₂. In some embodiments, these oxides are not added. In some embodiments, the amount of each of these oxides can be less than or equal to 0.5 mole percent such as less than 0.1 mole percent including zero percent, and their total combined concentration can be less than or equal to 2.0 mole percent such as less than 1.0 mole percent. In some embodiments, the total combination concentration of these oxides is in a tamped amount, for example, less than 0.1 mole percent.

[0119] The glass compositions described herein can also include various contaminants associated with batch materials and/or introduced into the glass by the melting, fining, and/or forming equipment used to produce the glass, particularly Fe₂O₃ and ZrO₂. The glasses can also contain SnO₂ either as a result of Joule melting using tin-oxide electrodes and/or through the batching of tin containing materials, e.g., SnO₂, SnO, SnCO₃, and SnC₂O₂. In some embodiments, the glass is substantially free or free of Fe₂O₃, TiO₂, and ZrO₂.

[0120] As₂O₃ and Sb₂O₃ are effective high temperature fining agents for AMLCD glasses. However, special handling during the glass manufacturing process is needed because of their toxicity.

[0121] EXAMPLES

[0122] The following examples are set forth below to illustrate the methods and results according to the disclosed subject matter. These examples are not intended to be inclusive of all embodiments of the subject matter disclosed herein, but rather to illustrate representative methods and results. These examples are not intended to exclude equivalents and variations of the present disclosure which are apparent to one skilled in the art.

[0123] Efforts have been made to ensure accuracy with respect to numbers (e.g., amounts, temperature, etc.) but some errors and deviations should be accounted for. Unless indicated otherwise, temperature is in °C or is at ambient temperature, and pressure is at or near atmospheric. The compositions themselves are given in mole percent on an oxide basis and have been normalized to 100%. There are numerous variations and combinations of reaction conditions, e.g., component concentrations, temperatures, pressures and other reaction ranges and conditions that can be used to optimize the product purity and yield obtained from the described process. Only reasonable and routine experimentation will be required to optimize such process conditions.

[0124] The glass properties set forth in tables were determined in accordance with techniques conventional in the glass art. Thus, the linear coefficient of thermal expansion (CTE) over the temperature range 25-300°C is expressed in terms of $\times 10^{-7}/^{\circ}\text{C}$ and the annealing point is expressed in terms of °C. These were determined from fiber elongation techniques (ASTM references E228-85 and C336, respectively). The density in terms of grams/cm³ was measured via the Archimedes method (ASTM C693). The melting temperature in terms of °C (defined as the temperature at which the glass melt demonstrates a viscosity of 200 poises) was calculated employing a Fulcher equation fit to high temperature viscosity data measured via rotating cylinders viscometry (ASTM C965-81).

[0125] The viscosity of the glass at high temperatures is measured in accordance with ASTM C965-96 (2012), titled “Standard Practice for Measuring Viscosity of Glass Above the Softening Point.” As used herein, the “Vogel-Fulcher-Tamman” (VFT) relation describes the temperature dependence of the viscosity and is represented by the following equation:

$$\log \eta = A + \frac{B}{T - T_0}$$

where η is viscosity. To determine VFT A, VFT B, and VFT T_0 , the viscosity of the glass composition is measured over a given temperature range. The raw data of viscosity versus temperature is then fit with the VFT equation by least-squares fitting to obtain A, B, and T_0 . With these values, a viscosity point (e.g., 200 Poise (P) Temperature, 35,000 P Temperature, and 200,000 P Temperature) at any temperature above softening point may be calculated.

[0126] The liquidus temperature of the glass in terms of °C was measured using the standard gradient boat liquidus method of ASTM C829-81. This involves placing crushed glass particles in a platinum boat, placing the boat in a furnace having a region of gradient temperatures, heating the boat in an appropriate temperature region for 24 hours, and determining by means of microscopic examination the highest temperature at which crystals appear in the interior of the glass. More particularly, the glass sample is removed from the Pt

boat in one piece, and examined using polarized light microscopy to identify the location and nature of crystals which have formed against the Pt and air interfaces, and in the interior of the sample. Because the gradient of the furnace is very well known, temperature vs. location can be well estimated, within 5-10°C. The temperature at which crystals are observed in the internal portion of the sample is taken to represent the liquidus of the glass (for the corresponding test period). Testing is sometimes carried out at longer times (e.g. 72 hours), to observe slower growing phases. The liquidus viscosity in poises was determined from the liquidus temperature and the coefficients of the Fulcher equation.

[0127] Young's modulus values and shear modulus in terms of GPa, and Poisson's ratio were determined using a resonant ultrasonic spectroscopy technique of the general type set forth in ASTM E1875-00e1.

[0128] Stress optical coefficient (SOC) values can be measured as set forth in Procedure C (Glass Disc Method) of ASTM standard C770-16, entitled "Standard Test Method for Measurement of Glass Stress-Optical Coefficient."

[0129] Exemplary glasses including Samples 1-42 are shown in Tables 2-8. As can be seen in Tables 2-8, the exemplary glasses have density, annealing point, Young's modulus, CTE, and stress optical coefficient (SOC) that make the glasses suitable for display applications, such as AMLCD substrate applications, and more particularly for low-temperature polysilicon and oxide thin film transistor applications. Although not shown in Tables 2-8, the glasses have durabilities in acid and base media that are similar to those obtained from commercial AMLCD substrates, and thus are appropriate for AMLCD applications. The exemplary glasses can be formed using downdraw techniques, and in particular are compatible with the fusion process, via the aforementioned criteria.

[0130] The exemplary glasses in the tables were prepared using a commercial sand as a silica source, milled such that 90% by weight passed through a standard U.S. 100 mesh sieve. Alumina was the alumina source, periclase was the source for MgO, limestone the source for CaO, strontium carbonate, strontium nitrate or a mix thereof was the source for SrO, barium carbonate was the source for BaO, and tin (IV) oxide was the source for SnO₂. The raw materials were thoroughly mixed, loaded into a platinum vessel suspended in a furnace heated by silicon carbide glowbars, melted and stirred for several hours at temperatures between 1600 and 1650 °C to ensure homogeneity, and delivered through an orifice at the base of the platinum vessel. The resulting patties of glass were annealed at or near the annealing point, and then subjected to various experimental methods to determine physical, viscous and liquidus attributes.

[0131] These methods are not unique, and the glasses of Tables 1-8 can be prepared using standard methods well-known to those skilled in the art. Such methods include a continuous melting process, such as would be performed in a continuous melting process, wherein the melter used in the continuous melting process is heated by gas, by electric power, or combinations thereof.

[0132] Raw materials appropriate for producing exemplary glasses include commercially available sands as sources for SiO_2 ; alumina, aluminum hydroxide, hydrated forms of alumina, and various aluminosilicates, nitrates and halides as sources for Al_2O_3 ; boric acid, anhydrous boric acid and boric oxide as sources for B_2O_3 ; periclase, dolomite (also a source of CaO), magnesia, magnesium carbonate, magnesium hydroxide, and various forms of magnesium silicates, aluminosilicates, nitrates and halides as sources for MgO ; limestone, aragonite, dolomite (also a source of MgO), wolastonite, and various forms of calcium silicates, aluminosilicates, nitrates and halides as sources for CaO ; and oxides, carbonates, nitrates and halides of strontium and barium. If a chemical fining agent is desired, tin can be added as SnO_2 , as a mixed oxide with another major glass component (e.g., CaSnO_3), or in oxidizing conditions as SnO , tin oxalate, tin halide, or other compounds of tin known to those skilled in the art.

[0133] The glasses in Tables 1-8 contain SnO_2 as a fining agent, but other chemical fining agents could also be employed to obtain glass of sufficient quality for TFT substrate applications. For example, exemplary glasses could employ any one or combinations of As_2O_3 , Sb_2O_3 , CeO_2 , Fe_2O_3 , and halides as deliberate additions to facilitate fining, and any of these could be used in conjunction with the SnO_2 chemical fining agent shown in the examples. Of these, As_2O_3 and Sb_2O_3 are generally recognized as hazardous materials, subject to control in waste streams such as might be generated in the course of glass manufacture or in the processing of TFT panels. It is therefore desirable to limit the concentration of As_2O_3 and Sb_2O_3 individually or in combination to no more than 0.005 mol%.

[0134] In addition to the elements deliberately incorporated into exemplary glasses, nearly all stable elements in the periodic table are present in glasses at some level, either through low levels of contamination in the raw materials, through high-temperature erosion of refractories and precious metals in the manufacturing process, or through deliberate introduction at low levels to fine tune the attributes of the final glass. For example, zirconium may be introduced as a contaminant via interaction with zirconium-rich refractories. As a further example, platinum and rhodium may be introduced via interactions

with precious metals. As a further example, iron may be introduced as a tramp in raw materials, or deliberately added to enhance control of gaseous inclusions. As a further example, manganese may be introduced to control color or to enhance control of gaseous inclusions.

[0135] As a further example, alkalis may be present as a tramp component at levels up to about 0.1 mol% for the combined concentration of Li_2O , Na_2O and K_2O .

[0136] Hydrogen is inevitably present in the form of the hydroxyl anion, OH^- , and its presence can be ascertained via standard infrared spectroscopy techniques. Dissolved hydroxyl ions significantly and nonlinearly impact the annealing point of exemplary glasses, and thus to obtain the desired annealing point it may be necessary to adjust the concentrations of major oxide components so as to compensate. Hydroxyl ion concentration can be controlled to some extent through choice of raw materials or choice of melting system. For example, boric acid is a major source of hydroxyls, and replacing boric acid with boric oxide can be a useful means to control hydroxyl concentration in the final glass. The same reasoning applies to other potential raw materials comprising hydroxyl ions, hydrates, or compounds comprising physisorbed or chemisorbed water molecules. If burners are used in the melting process, then hydroxyl ions can also be introduced through the combustion products from combustion of natural gas and related hydrocarbons, and thus it may be desirable to shift the energy used in melting from burners to electrodes to compensate. Alternatively, one might instead employ an iterative process of adjusting major oxide components so as to compensate for the deleterious impact of dissolved hydroxyl ions.

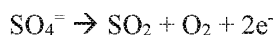
[0137] Sulfur is often present in natural gas, and likewise is a tramp component in many carbonate, nitrate, halide, and oxide raw materials. In the form of SO_2 , sulfur can be a troublesome source of gaseous inclusions. The tendency to form SO_2 -rich defects can be managed to a significant degree by controlling sulfur levels in the raw materials, and by incorporating low levels of comparatively reduced multivalent cations into the glass matrix. While not wishing to be bound by theory, it appears that SO_2 -rich gaseous inclusions arise primarily through reduction of sulfate (SO_4^{2-}) dissolved in the glass.

[0138] The elevated barium concentrations of exemplary glasses appear to increase sulfur retention in the glass in early stages of melting, but as noted above, barium is required to obtain low liquidus temperature, and hence high $T_{35k}-T_{liq}$ and high liquidus viscosity. Deliberately controlling sulfur levels in raw materials to a low level is a useful means of reducing dissolved sulfur (presumably as sulfate) in the glass. In particular, sulfur is

preferably less than 200 ppm by weight in the batch materials, and more preferably less than 100 ppm by weight in the batch materials.

[0139] Reduced multivalents can also be used to control the tendency of exemplary glasses to form SO₂ blisters. While not wishing to be bound to theory, these elements behave as potential electron donors that suppress the electromotive force for sulfate reduction.

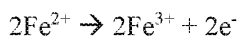
Sulfate reduction can be written in terms of a half reaction such as



where e⁻ denotes an electron. The “equilibrium constant” for the half reaction is

$$K_{\text{eq}} = [\text{SO}_2][\text{O}_2][\text{e}^-]^2/[\text{SO}_4^{2-}]$$

where the brackets denote chemical activities. Ideally one would like to force the reaction so as to create sulfate from SO₂, O₂ and 2e⁻. Adding nitrates, peroxides, or other oxygen-rich raw materials may help, but also may work against sulfate reduction in the early stages of melting, which may counteract the benefits of adding them in the first place. SO₂ has very low solubility in most glasses, and so is impractical to add to the glass melting process. Electrons may be “added” through reduced multivalents. For example, an appropriate electron-donating half reaction for ferrous iron (Fe²⁺) is expressed as



[0140] This “activity” of electrons can force the sulfate reduction reaction to the left, stabilizing SO₄²⁻ in the glass. Suitable reduced multivalents include, but are not limited to, Fe²⁺, Mn²⁺, Sn²⁺, Sb³⁺, As³⁺, V³⁺, Ti³⁺, and others familiar to those skilled in the art. In each case, it may be important to minimize the concentrations of such components so as to avoid deleterious impact on color of the glass, or in the case of As and Sb, to avoid adding such components at a high enough level so as to complication of waste management in an end-user’s process.

[0141] In addition to the major oxides components of exemplary glasses, and the minor or tramp constituents noted above, halides may be present at various levels, either as contaminants introduced through the choice of raw materials, or as deliberate components used to eliminate gaseous inclusions in the glass. As a fining agent, halides may be incorporated at a level of about 0.4 mol% or less, though it is generally desirable to use lower amounts if possible to avoid corrosion of off-gas handling equipment. In some embodiments, the concentrations of individual halide elements are below about 200 ppm by weight for each individual halide, or below about 800 ppm by weight for the sum of all halide elements.

[0142] In addition to these major oxide components, minor and tramp components, multivalents and halide fining agents, it may be useful to incorporate low concentrations of

other colorless oxide components to achieve desired physical, optical or viscoelastic properties. Such oxides include, but are not limited to, TiO_2 , ZrO_2 , HfO_2 , Nb_2O_5 , Ta_2O_5 , MoO_3 , WO_3 , ZnO , In_2O_3 , Ga_2O_3 , Bi_2O_3 , GeO_2 , PbO , SeO_3 , TeO_2 , Y_2O_3 , La_2O_3 , Gd_2O_3 , and others known to those skilled in the art. Through an iterative process of adjusting the relative proportions of the major oxide components of exemplary glasses, such colorless oxides can be added to a level of up to about 2 mol% without unacceptable impact to annealing point, $T_{35k}-T_{liq}$ or liquidus viscosity.

[0143] The samples and their data are summarized in Tables 2- 8.

[0144] In the Tables, the lowest isothermal pass (pass <2% internal crystal) is the lowest temperature, at which the percentage of crystallinity is less than 2% internally or on the Pt. interface. This lowest isothermal pass is the lowest temperature at which crystals are found in glass during isothermal hold for 72 hours. The symbol (- -) represents not tested yet.

[0145] Table 2 shows examples of glasses (samples 1-6)

[0146] Table 2.

mol %	1	2	3	4	5	6
SiO_2	70.05	70.06	70.09	70.09	70.13	70.02
Al_2O_3	12.52	12.54	12.54	12.58	12.6	12.67
B_2O_3	0.82	0.82	0.82	0.81	0.79	0.78
MgO	5.76	5.73	5.75	5.72	5.71	5.73
CaO	6.43	6.42	6.42	6.42	6.41	6.43
SrO	0.41	0.4	0.38	0.37	0.35	0.34
BaO	3.78	3.79	3.78	3.8	3.8	3.81
SnO_2	0.13	0.13	0.13	0.13	0.13	0.13
Fe_2O_3 (tramp)	0.01	0.01	0.01	0.01	0.01	0
ZrO_2 (tramp)	0.01	0.01	0.01	0.01	0.01	0.01
Na_2O (tramp)	0.04	0.05	0.05	0.04	0.04	0.04
K_2O (tramp)	0.01	0.01	0.01	0.01	0.01	0.01
TiO_2 (tramp)	0.02	0.02	0.02	0.02	0.02	0.02
$\text{RO}/\text{Al}_2\text{O}_3$	1.31	1.30	1.30	1.30	1.29	1.29
Physical properties	1	2	3	4	5	6
Strain point (fiber) °C	748	749	751	750	750	751

Annealing point (fiber) °C	801	802	803	803	803	803
Softening point (fiber) °C	1036	1037	1035	1039	1037	1038
CTE (10^{-7} , 0-300 °C)	36.60	36.50	36.70	36.80	36.10	37.30
Density (g/cm ³)	2.61	2.61	2.61	2.61	2.61	2.61
Poisson's ratio	0.23	0.23	0.23	0.23	0.23	0.23
Shear modulus (GPa)	34.17	34.19	34.16	34.11	34.17	34.17
Elastic modulus (GPa)	83.83	83.79	83.86	83.62	83.79	83.79
Stress Optic Coefficient (nm/cm/MPa)	28.13	28.13	28.18	28.1	28.14	28.19
High Temperature Viscosity	1	2	3	4	5	6
A	-3.17	-3.16	-3.16	-3.16	-3.16	-3.17
B	6970.77	6971.02	6970.43	6968.86	6968.20	6963.31
To	380.67	380.89	381.04	381.54	382.06	382.66
T(200P) (°C)	1656	1656	1656	1657	1658	1656
T(35kP) (°C)	1285	1285	1285	1286	1286	1285
Isothermal hold results	1	2	3	4	5	6
1200°C crystallinity	2%Pt / Yes Zr	2%Pt / Yes Zr	2%Pt / Yes Zr	3%Pt / Yes Zr	2%Pt / Yes Zr	3%Pt / Yes Zr
1200°C phase(s)	Anorthite	Anorthite	Anorthite	Anorthite	Anorthite	Anorthite
1200°C secondary phase(s)	Cordierit e	Cordierit e	Cordierit e	Cordierit e	Cordierit e	Cordierit e
1210°C crystallinity	1%Pt / Yes Zr	1%Pt / Yes Zr	1%Pt / Yes Zr	1%Pt / Yes Zr	2%Pt / Yes Zr	2%Pt / Yes Zr
1210°C phase(s)	Anorthite	Anorthite	Anorthite	Anorthite	Anorthite	Anorthite
1210°C secondary phase(s)	Cordierit e	Cordierit e	Cordierit e	Cordierit e	Cordierit e	Cordierit e
1220°C crystallinity	1%Pt / Yes Zr	1%Pt / Yes Zr	1%Pt / Yes Zr	1%Pt / Yes Zr	2%Pt / Yes Zr	2%Pt / Yes Zr
1220°C phase(s)	Anorthite	Anorthite	Anorthite	Anorthite	Anorthite	Anorthite
1220°C secondary phase(s)	Cordierit e	Cordierit e	Cordierit e	Cordierit e	Cordierit e	Cordierit e
Lowest isothermal pass (pass is <2% internal crystal), °C	1200	1200	1200	1205	1200	1205
Liquidus viscosity (kP)	220	222	222	199	228	199

[0147] Table 3 shows examples of glasses (samples 7-12)

[0148] Table 3.

mol %	7	8	9	10	11	12
SiO ₂	69.81	70.14	70.14	70.05	69.83	70.19
Al ₂ O ₃	13.2	12.83	12.87	12.7	12.5	12.34
B ₂ O ₃	1.56	1.3	1.67	1.35	1.44	1.13
MgO	5.36	5.45	4.85	5.52	5.65	5.66
CaO	6.08	6.26	6.5	6.22	6.28	6.35
SrO	0.11	0.11	0.11	0.26	0.44	0.38
BaO	3.64	3.68	3.63	3.68	3.64	3.73
SnO ₂	0.13	0.13	0.13	0.13	0.13	0.13
Fe ₂ O ₃ (tramp)	0.01	0.01	0	0	0.01	0.01
ZrO ₂ (tramp)	0.01	0.01	0.01	0.01	0.01	0.01
Na ₂ O (tramp)	0.04	0.04	0.04	0.04	0.04	0.04
K ₂ O (tramp)	0.01	0.01	0.01	0.01	0.01	0.01
TiO ₂ (tramp)	0.03	0.03	0.03	0.03	0.03	0.03
RO/Al ₂ O ₃	1.15	1.21	1.17	1.23	1.28	1.31
Physical properties	7	8	9	10	11	12
Strain point (fiber) °C	749	749	746	747	744	746
Annealing point (fiber) °C	802	802	800	800	796	799
Softening point (fiber) °C	--	--	--	--	--	--
CTE (10 ⁻⁷ , 0-300 °C)	35.07	35.51	35.41	35.81	36.31	36.47
Density (g/cm ³)	2.59	2.59	2.59	2.60	2.60	2.61
Poisson's ratio	--	--	--	--	--	--
Shear modulus (Gpa)	--	--	--	--	--	--
Elastic modulus (GPa)	83.95	84.00	83.35	83.89	83.78	83.93
Stress Optic Coefficient (nm/cm/MPa)	28.74	28.61	28.86	28.58	28.53	28.41
High Temperature Viscosity	7	8	9	10	11	12
A	-3.16	-3.15	-3.13	-3.15	-3.17	-3.15
B	6969.57	6978.50	6993.47	6983.56	6988.83	6991.06
To	381.71	380.64	377.70	378.32	374.63	376.34

T(200P) °C	1658	1662	1665	1659	1652	1659
T(35kP) °C	1286	1288	1289	1286	1281	1285
Isothermal hold results	7	8	9	10	11	12
1200°C crystallinity	5%Pt / Yes Zr	7%Pt / Yes Zr	3%Pt / Yes Zr	3%Pt / Yes Zr	2%Pt / Yes Zr	2%Pt / Yes Zr
1200°C phase(s)	Cordierite	Cordierite	Anorthite	Cordierite	Cordierite	Cordierite
1200°C secondary phase(s)	Anorthite	--	Cordierite	Anorthite	Anorthite	--
1210°C crystallinity	3%Pt / Yes Zr	2%Pt / Yes Zr	1%Pt / Yes Zr	2%Pt / Yes Zr	1%Pt / Yes Zr	1%Pt / Yes Zr
1210°C phase(s)	Cordierite	Cordierite	Anorthite	Cordierite	Cordierite	Cordierite
1210°C secondary phase(s)	Anorthite	--	Cordierite	Anorthite	Anorthite	
1220°C crystallinity	3%Pt / Yes Zr	2%Pt / Yes Zr	1%Pt / Yes Zr	2%Pt / Yes Zr	1%Pt / Yes Zr	1%Pt / Yes Zr
1220°C phase(s)	Cordierite	Cordierite	Anorthite	Cordierite	Cordierite	Cordierite
1220°C secondary phase(s)	Anorthite	--	Cordierite	Anorthite	Anorthite	--
Lowest isothermal pass (pass is <2% internal crystal), °C	1215	1210	1210	1210	1200	1200
Liquidus viscosity (kP)	160	185	187	176	199	218

[0149] Table 4 shows examples of glasses (samples 13- 18)

[0150] Table 4.

mol %	13	14	15	16	17	18
SiO ₂	70.77	70.46	70.21	70.22	70.3	70.54
Al ₂ O ₃	12.53	13.06	12.55	12.54	12.7	12.69
B ₂ O ₃	0.77	0.75	0.77	0.76	0.76	0.76
MgO	5.77	5.79	5.78	6.06	6.06	6.04
CaO	6.92	6.45	6.71	6.43	6.44	6.44
SrO	0.44	0.45	0.46	0.46	0.45	0.45
BaO	2.64	2.88	3.36	3.36	3.11	2.92
SnO ₂	0.13	0.12	0.12	0.12	0.12	0.12
Fe ₂ O ₃ (tramp)	0.01	0.01	0.01	0.01	0.01	0.01

ZrO ₂ (tramp)	0.01	0.01	0.01	0.01	0.01	0.01
Na ₂ O (tramp)	0.02	0.02	0.02	0.03	0.02	0.02
K ₂ O (tramp)	0.01	0.01	0.01	0.01	0.01	0.01
TiO ₂ (tramp)	0.00	0.00	0.00	0.00	0.00	0.00
RO/Al ₂ O ₃	1.26	1.19	1.30	1.30	1.26	1.25
Physical properties	13	14	15	16	17	18
Strain point (fiber) °C	753	753	748	749	750	746
Annealing point (fiber) °C	805	805	801	801	802	799
Softening point (fiber) °C	1039.8	1037.1	1034.7	1034.9	1035.7	1037.8
CTE (10 ⁻⁷ , 0-300 °C)	35.3	34.3	35.6	35.6	35.5	34.6
Density (g/cm ³)	2.568	2.575	2.594	2.597	2.587	2.579
Poisson's ratio	0.227	0.228	0.227	0.226	0.226	0.228
Shear modulus (Gpa)	34.38	34.41	34.29	34.39	34.43	34.40
Elastic modulus (GPa)	84.34	84.49	84.12	84.35	84.40	84.46
Stress Optic Coefficient	28.61	28.53	28.4	28.33	28.48	28.53
High Temperature Viscosity	13	14	15	16	17	18
A	-3.159	-3.170	-3.177	-3.177	-3.178	-3.167
B	6956.0	6937.1	6959.2	6958.8	6950.0	6951.0
T ₀	386.25	390.89	383.05	383.12	385.81	386.82
T(200P) °C	1660	1659	1653	1653	1654	1658
T(35kP) °C	1289	1290	1284	1284	1286	1288
Isothermal hold results	13	14	15	16	17	18
1200°C crystallinity	--	--	--	--	--	--
1200°C phase(s)	--	--	--	--	--	--
1200°C secondary phase(s)	--	--	--	--	--	--
1210°C crystallinity	--	--	--	--	--	--
1210°C phase(s)	--	--	--	--	--	--
1210°C secondary phase(s)	--	--	--	--	--	--
1220°C crystallinity	--	--	--	--	--	--
1220°C phase(s)	--	--	--	--	--	--

1220°C secondary phase(s)	--	--	--	--	--	--
Lowest isothermal pass	--	--	--	--	--	--
Liquidus viscosity (kP)	--	--	--	--	--	--

[0151] Table 5 shows examples of glasses (samples 19 - 24)

[0152] Table 5.

mol %	19	20	21	22	23	24
SiO ₂	70.09	70.04	69.89	69.89	70.01	70.06
Al ₂ O ₃	12.83	12.86	13.09	13.08	13.05	13.13
B ₂ O ₃	0.84	0.84	1.21	1.21	1.12	1.4
MgO	5.92	6.03	5.84	5.86	5.86	5.38
CaO	6.26	6.18	5.06	5.27	5.27	6
SrO	0.57	0.57	1.35	1.14	1.14	0.31
BaO	3.3	3.3	3.38	3.38	3.39	3.52
SnO ₂	0.1	0.1	0.1	0.1	0.09	0.13
Fe ₂ O ₃ (tramp)	0.01	0.01	0	0	0	0.01
ZrO ₂ (tramp)	0.01	0.01	0.01	0.01	0.01	0.01
Na ₂ O (tramp)	0.03	0.03	0.02	0.03	0.02	0.03
K ₂ O (tramp)	0.01	0.01	0.01	0.01	0.01	0.01
TiO ₂ (tramp)	0.02	0.02	0.02	0.02	0.02	0.02
RO/Al ₂ O ₃	1.25	1.25	1.19	1.20	1.20	1.16
Physical properties	19	20	21	22	23	24
Strain point (fiber) °C	753	752	751	750	752	750
Annealing point (fiber) °C	805	804	804	804	805	804
Softening point (fiber) °C	1038.2	1038.1	1038.2	1038.8	1041.1	1039.0
CTE (10 ⁻⁷ , 0-300 °C)	35.1	36.0	35.1	35.2	34.9	35.2
Density (g/cm ³)	2.597	2.591	2.603	2.600	2.600	2.590

Poisson's ratio	0.229	0.226	0.226	0.226	0.222	0.224
Shear modulus (Gpa)	34.20	34.30	34.10	34.20	34.30	34.10
elastic modulus (GPa)	84.10	84.10	83.60	83.80	83.70	83.60
Stress Optic Coefficient	28.53	28.4	28.6	28.73	28.61	28.72
High Temperature Viscosity	19	20	21	22	23	24
A	-3.180	-3.185	-3.162	-3.168	-3.162	-3.151
B	6951.2	6948.3	6965.7	6962.8	6962.9	6969.2
To	385.25	385.50	382.76	383.01	383.75	383.03
T(200P) °C	1654	1652	1658	1656	1658	1661
T(35kP) °C	1285	1284	1287	1286	1287	1289
Isothermal hold results	19	20	21	22	23	24
1200°C crystallinity	20%Pt/Yes Zr	10%Pt/Yes Zr	7%Pt/Yes Zr	5%Pt/Yes Zr	10%Pt/Yes Zr	7%Pt/Yes Zr
1200°C phase(s)	Anorthite	Anorthite	Anorthite	Indialite	Indialite	Indialite
1200°C secondary phase(s)	Indialite	Indialite	Indialite	Anorthite	Anorthite	Anorthite
1210°C crystallinity	--	--	--	--	--	--
1210°C phase(s)	--	--	--	--	--	--
1210°C secondary phase(s)	--	--	--	--	--	--
1220°C crystallinity	--	--	--	--	--	--
1220°C phase(s)	--	--	--	--	--	--
1220°C secondary phase(s)	--	--	--	--	--	--
Lowest isothermal pass	--	--	1210 (est)	1210 (est)	--	1210 (est)
Liquidus viscosity (kP)	--	--	181	179	--	189

[0153] Table 6 shows examples of glasses (samples 25-30).

[0154] Table 6.

mol %	25	26	27	28	29	30
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SiO ₂	70.04	70.12	70.13	70.07	70.02	70.15
Al ₂ O ₃	12.69	12.54	12.54	12.69	12.7	12.68
B ₂ O ₃	0.98	0.92	0.79	0.91	0.75	0.88
MgO	6.06	5.78	5.89	5.76	5.78	5.73
CaO	5.81	6.19	6.12	6.07	6.19	6.02
SrO	0.75	0.75	0.77	0.75	0.75	0.75
BaO	3.49	3.52	3.59	3.56	3.61	3.61
SnO ₂	0.14	0.14	0.13	0.14	0.13	0.14
Fe ₂ O ₃ (tramp)	0	0	0	0	0.01	0
ZrO ₂ (tramp)	0	0	0.01	0.01	0.01	0
Na ₂ O (tramp)	0.03	0.02	0.03	0.03	0.03	0.03
K ₂ O (tramp)	0.01	0.01	0.01	0.01	0.01	0.01
TiO ₂ (tramp)	0.00	0.00	0.00	0.00	0.00	0.00
RO/Al ₂ O ₃	1.27	1.30	1.31	1.27	1.29	1.27
Physical properties	25	26	27	28	29	30
Strain point (fiber) °C	750	750	752	749	752	750
Annealing point (fiber) °C	803	803	804	803	805	803
Softening point (fiber) °C	1037.4	1037.8	1038.4	1036.8	1037.5	1039.0
CTE (10 ⁻⁷ , 0-300 °C)	35.8	36.1	36.5	36.2	36.2	36.1
Density (g/cm ³)	2.601	2.603	2.608	2.604	2.609	2.605
Poisson's ratio	0.227	0.226	0.227	0.226	0.227	0.224
Shear modulus (Gpa)	34.21	34.12	34.15	34.13	34.15	34.12
Elastic modulus (GPa)	83.92	83.66	83.84	83.72	83.80	83.56
Stress Optic Coefficient	28.34	28.12	28.32	28.29	28.29	28.24
High Temperature Viscosity	25	26	27	28	29	30
A	-3.171	-3.165	-3.168	-3.166	-3.172	-3.159

B	6966.3	6972.0	6968.0	6967.2	6960.5	6969.2
To	381.49	380.40	381.41	381.91	383.21	382.11
T(200P) °C	1654	1656	1656	1656	1655	1659
T(35kP) °C	1284	1285	1285	1286	1285	1287
Isothermal hold results	25	26	27	28	29	30
1200°C crystallinity	7%Pt/Ye s Zr	trace%Pt/Y es Zr	7%Pt/Ye s Zr	5%Pt/Ye s Zr	15%Pt/Y es Zr	7%Pt/Ye s Zr
1200°C phase(s)	Anorthite	Anorthite	Anorthite	Anorthite	Anorthite	Anorthite
1200°C secondary phase(s)	Indialite Cordierit e	Indialite Cordierite	Indialite Cordierit e	Indialite Cordierit e	Indialite Cordierite	Indialite Cordierit e
1210°C crystallinity	5%Pt/Ye s Zr	2%Pt/No Zr	2%Pt/N o Zr	1%Pt/N o Zr	1%Pt/No Zr	1%Pt/N o Zr
1210°C phase(s)	Cordierit e	Anorthite	Cordierit e	Cordierit e	Anorthite	Cordierit e
1210°C secondary phase(s)	--	Cordierite	--	--	Indialite Cordierite	--
1220°C crystallinity	1%Pt/N o Zr	0%Pt/No Zr	0%Pt/N o Zr	trace%Pt /No Zr	0%Pt/No Zr	0%Pt/N o Zr
1220°C phase(s)	Cordierit e	--	--	--	--	--
1220°C secondary phase(s)	--	--	--	--	--	--
Lowest isothermal pass	1215	1200	1210	1210	1210	1210
Liquidus viscosity (kP)	154	219	175	177	176	182

[0155] Table 7 shows examples of glasses (samples 31-36)

[0156] Table 7.

mol %	31	32	33	34	35	36
SiO ₂	69.95	69.89	69.79	69.8	69.84	69.94
Al ₂ O ₃	12.67	12.71	12.82	12.78	12.77	12.72
B ₂ O ₃	0.89	0.78	0.8	0.98	1	0.91
MgO	5.97	5.91	6.06	5.8	5.57	5.72
CaO	5.93	6.11	5.86	5.99	6.16	6.09
SrO	0.75	0.75	0.76	0.76	0.76	0.75
BaO	3.65	3.66	3.72	3.71	3.72	3.69

SnO ₂	0.14	0.14	0.14	0.13	0.13	0.13
Fe ₂ O ₃ (tramp)	0	0	0	0	0	0
ZrO ₂ (tramp)	0	0	0	0	0.01	0
Na ₂ O (tramp)	0.03	0.03	0.03	0.03	0.03	0.03
K ₂ O (tramp)	0.01	0.01	0.01	0.01	0.01	0.01
TiO ₂ (tramp)	0.00	0.00	0.01	0.00	0.00	0.00
RO/Al ₂ O ₃	1.29	1.29	1.28	1.27	1.27	1.28
Physical properties	31	32	33	34	35	36
Strain point (fiber) °C	752	751	752	752	751	751
Annealing point (fiber) °C	804	804	804	805	803	803
Softening point (fiber) °C	1038.4	1038.8	1038.6	1038.2	1037.2	1036.4
CTE (10 ⁻⁷ , 0-300 °C)	36.4	36.3	36.6	36.2	36.5	36.7
Density (g/cm ³)	2.608	2.610	2.612	2.607	2.608	2.609
Poisson's ratio	0.223	0.226	0.222	0.224	0.221	0.227
Shear modulus (Gpa)	34.23	34.21	34.33	34.10	34.10	34.10
Elastic modulus (GPa)	83.75	83.87	83.89	83.46	83.30	83.67
Stress Optic Coefficient	28.38	28.26	28.23	28.43	28.39	28.26
High Temperature Viscosity	31	32	33	34	35	36
A	-3.174	-3.182	-3.187	-3.180	-3.174	-3.172
B	6965.5	6958.6	6954.6	6963.9	6967.1	6966.0
To	381.38	382.65	383.31	381.22	380.93	381.56
T(200P)	1654	1652	1651	1652	1653	1654
T(35kP)	1284	1283	1283	1283	1284	1284
Isothermal hold results	31	32	33	34	35	36
1200°C crystallinity	10%Pt/ye s Zr	7%Pt/ye s Zr	7%Pt/ye s Zr	7%Pt/ye s Zr	5%Pt/ye s Zr	7%Pt/ye s Zr

1200°C phase(s)	Indialite	Indialite	Indialite	Indialite	Indialite	Indialite
1200°C secondary phase(s)	Anorthite	Anorthite	Anorthite	Anorthite	--	--
1210°C crystallinity	7%Pt/yes Zr	3%Pt/yes Zr	5%Pt/yes Zr	5%Pt/yes Zr	3%Pt/yes Zr	3%Pt/yes Zr
1210°C phase(s)	Indialite	Indialite	Indialite	Indialite	Indialite	Indialite
1210°C secondary phase(s)	--	--	--	--	--	--
1220°C crystallinity	5%Pt/yes Zr	2%Pt/yes Zr	3%Pt/yes Zr	3%Pt/yes Zr	1%Pt/yes Zr	1%Pt/yes Zr
1220°C phase(s)	Indialite	Indialite	Indialite	Indialite	Indialite	Indialite
1220°C secondary phase(s)	--	--	--	--	--	--
Lowest isothermal pass	1230 (est)	1220	1225 (est)	1225 (est)	1215	1215
Liquidus viscosity (kP)	108	134	119	118	151	154

[0157] Table 8 shows examples of glasses (samples 37-42)

[0158] Table 8.

mol %	37	38	39	40	41	42
SiO ₂	70.51	70.03	70.21	70.07	69.65	69.94
Al ₂ O ₃	13.02	13.02	13.01	13	13.13	13.04
B ₂ O ₃	1.49	1.35	1.15	1.24	1.1	1.3
MgO	5.46	5.3	5.3	5.51	5.95	5.61
CaO	6.09	6.46	6.1	5.77	5.77	5.88
SrO	0.81	0.77	0.78	0.79	0.79	0.83
BaO	2.51	2.96	3.32	3.49	3.48	3.28
SnO ₂	0.08	0.08	0.08	0.08	0.08	0.08
Fe ₂ O ₃ (tramp)	0	0	0	0	0	0
ZrO ₂ (tramp)	0.01	0.01	0.01	0	0.01	0.01
Na ₂ O (tramp)	0	0.01	0.02	0.03	0.02	0.02
K ₂ O (tramp)	0.01	0.01	0.01	0.01	0.01	0.01

TiO ₂ (tramp)	0.00	0.00	0.00	0.00	0.00	0.00
RO/Al ₂ O ₃	1.14	1.19	1.19	1.20	1.22	1.20
Physical properties	37	38	39	40	41	42
Strain point (fiber) °C	752	752	754	752	751	750
Annealing point (fiber) °C	805	805	806	805	804	803
Softening point (fiber) °C	1041.3	1037.6	1041.2	1039.4	1037.2	1038.8
CTE (10 ⁻⁷ , 0-300 °C)	34.1	35.0	35.1	35.4	35.5	35.4
Density (g/cm ³)	2.559	2.579	2.591	2.594	2.599	2.589
Poisson's ratio	0.225	0.227	0.228	0.227	0.23	0.229
Shear modulus (Gpa)	34.14	34.13	34.06	34.04	34.15	33.97
Elastic modulus (GPa)	83.67	83.78	83.62	83.50	83.97	83.53
Stress Optic Coefficient	29.13	28.81	28.66	28.6	28.56	28.73
High Temperature Viscosity	37	38	39	40	41	42
A	-3.151	-3.178	-3.153	-3.156	-3.199	-3.174
B	6965.4	6958.4	6964.7	6968.9	6946.7	6961.5
To	384.26	383.15	384.18	382.47	384.37	382.66
T(200P)	1662	1653	1661	1659	1647	1654
T(35kP)	1289	1284	1289	1287	1282	1285
Isothermal hold results	37	38	39	40	41	42
1200°C crystallinity	--	--	--	--	--	--
1200°C phase(s)	--	--	--	--	--	--
1200°C secondary phase(s)	--	--	--	--	--	--
1210°C crystallinity	--	--	--	--	--	--
1210°C phase(s)	--	--	--	--	--	--
1210°C secondary phase(s)	--	--	--	--	--	--

1220°C crystallinity	5%Pt/Y es Zr	3%Pt/Y es Zr	5%Pt/Y es Zr	3%Pt/Y es Zr	5%Pt/Y es Zr	3%Pt/Y es Zr
1220°C phase(s)	Cordierite	Cordierite	Indialite	Indialite	Indialite	Indialite
1220°C secondary phase(s)	--	--	--	--	--	--
Lowest isothermal pass	1230 (est)	1225 (est)	1230 (est)	1225 (est)	1230 (est)	1225 (est)
Liquidus viscosity (kP)	122	122	121	130	104	123

[0159] FIG. 1 shows the results of annealing point at different mole percentages of B₂O₃ in the glass compositions. The higher annealing point from lower B₂O₃ results in improved or lower stress relaxation.

[0160] The glass and the compositions provided in the present disclosure have significant advantages. For example, the glass compositions exhibit desirable physical properties and chemical properties, for example, high annealing point (e.g., higher than 790°C), high elastic modulus, low stress optical coefficient (SOC), and desirable liquidus viscosity. The glass compositions are suitable for use as substrates in flat panel display devices such as active matrix liquid crystal displays (AMLCDs) with ultra-high resolution, for example, in the 8K display technology.

[0161] In another aspect, the present disclosure provides an article comprising the glass or the glass composition described herein. For example, a substrate for liquid crystal display comprises the glass or the glass composition described here.

[0162] In another aspect, the present disclosure provides a device for flat panel display, which comprises at least one sheet comprising the glass as described herein. Such a device may comprise polycrystalline silicon thin film transistors.

[0163] In another aspect, a method for producing the glass or the glass composition as described herein is provided. Such a method comprises at least one step of mixing and melting raw materials in mole percent on an oxide basis so as to provide the oxides as described. Such a method may further comprise making a sheet comprising the glass composition through a downdraw sheet fabrication process or a fusion process.

[0164] Although the subject matter has been described in terms of exemplary embodiments, it is not limited thereto. Rather, the appended claims should be construed broadly, to include other variants and embodiments, which may be made by those skilled in the art.

What is claimed is:

1. A glass comprising in mole percent on an oxide basis:
SiO₂: 66.17-74.31;
Al₂O₃: 11.72-13.86;
B₂O₃: 0.71-1.75;
MgO: 4.61-6.36;
CaO: 4.81-7.27;
SrO: 0.10-1.42; and
BaO: 2.38-4.00,
wherein the glass is substantially alkali-free defined by a combined concentration of Li₂O, Na₂O, and K₂O less than 0.1 mol.%.
2. The glass of claim 1, wherein the glass comprises in mole percent on an oxide basis:
SiO₂: 69.65-70.77;
Al₂O₃: 12.34-13.20;
B₂O₃: 0.75-1.67;
MgO: 4.85-6.06;
CaO: 5.06-6.92;
SrO: 0.11-1.35; and
BaO: 2.51-3.81.
3. The glass of claim 1, wherein B₂O₃ is in a range of from 0.75 to 1.50 by mole percent.
4. The glass of claim 1, wherein B₂O₃ is in a range of from 0.75 to 1.20 by mole percent.
5. The glass of claim 1, wherein SrO is in a range of from 0.11 to 1.00 by mole percent.
6. The glass of claim 1, wherein SrO is in a range of from 0.11 to 0.50 by mole percent.
7. The glass of claim 1, wherein a ratio of RO/Al₂O₃ is in a range of from 1.14-1.31, and RO is the sum of the mole percents of MgO, CaO, SrO, and BaO.
8. The glass of claim 1, wherein a ratio of RO/Al₂O₃ is in a range of from 1.20 to 1.31.

9. The glass of claim 1, further comprising 0.01 mol.% to 0.4 mol.% of a chemical fining agent selected from SnO_2 , As_2O_3 , Sb_2O_3 , Fe_2O_3 , CeO_2 , MnO_2 , F, Cl, Br, or any combination thereof.
10. The glass of claim 9, wherein the chemical fining agent comprises 0.08 mol.% to 0.14 mol.% of SnO_2 .
11. The glass of claim 1, wherein the glass has an annealing point in a range from 790 °C to 810 °C.
12. The glass of claim 1, wherein the glass has an annealing point in a range from 799 °C to 806 °C.
13. The glass of claim 1, wherein the glass has an elastic modulus in a range of from 83.30 GPa to 84.49 GPa.
14. The glass of claim 1, wherein the glass has a stress optical coefficient (SOC) in a range of from 26.70 to 30.59.
15. The glass of claim 1, wherein the glass has a stress optical coefficient (SOC) in a range of from 28.10 to 29.13.
16. The glass of claim 1, wherein the glass has a T(35 kP) in a range of from 1,280 °C to 1,292 °C, and a T(200 P) in a range of from 1,654 °C to 1,666 °C, and T(35 kP) and T(200 P) represent a temperature when the glass has a viscosity of 35 kilopoise (kP) and 200 poise (P), respectively.
17. A glass comprising in mole percent on an oxide basis:
 SiO_2 : 66.17-74.31;
 Al_2O_3 : 11.72-13.86;
 B_2O_3 : 0.75-1.20;
 MgO: 4.61-6.36;
 CaO: 4.81-7.27;
 SrO: 0.11-0.5; and
 BaO: 2.38-4.00,

wherein the glass is substantially alkali-free defined by a combined concentration of Li_2O , Na_2O , and K_2O less than 0.1 mol.%,

the glass has an elastic modulus in a range of from 83.30 GPa to 84.49 GPa, and

the glass has a stress optical coefficient (SOC) in a range of from 26.70 to 30.59.

18. The glass of claim 17, wherein the glass comprises in mole percent on an oxide basis:

SiO_2 : 69.65-70.77;

Al_2O_3 : 12.34-13.20;

B_2O_3 : 0.75-1.20;

MgO : 4.85-6.06;

CaO : 5.06-6.92;

SrO : 0.11-0.5; and

BaO : 2.51-3.81.

19. The glass of claim 17, wherein B_2O_3 is in a range of from 0.75 to 1.0 by mole percent.

20. The glass of claim 17, wherein a ratio of $\text{RO}/\text{Al}_2\text{O}_3$ is in a range of from 1.20 to 1.31, and RO is the sum of the mole percents of MgO , CaO , SrO , and BaO .

21. The glass of claim 17, further comprising 0.08 mol.% to 0.14 mol.% of SnO_2 as a chemical fining agent.

22. The glass of claim 17, wherein each of Fe_2O_3 , ZrO_2 , and TiO_2 is in a range of from 0 to 0.03 by mole percent.

23. The glass of claim 17, wherein the stress optical coefficient (SOC) is in a range of from 28.10 to 29.13.

24. The glass of claim 17, wherein the glass has a $T(35 \text{ kP})$ in a range of from 1,280 °C to 1,292 °C, and a $T(200 \text{ P})$ in a range of from 1,654 °C to 1,666 °C, and $T(35 \text{ kP})$ and $T(200 \text{ P})$ represent a temperature when the glass has a viscosity of 35 kilopoise (kP) and 200 poise (P), respectively.

25. An article comprising the glass of claim 1.

26. A substrate for liquid crystal display comprising the glass of claim 1.
27. A device for flat panel display comprising at least one sheet comprising the glass of claim 1, and polycrystalline silicon thin film transistors.
28. A method for producing the glass of claim 1, comprising mixing and melting raw materials in mole percent on an oxide basis.
29. The method of claim 28, further comprising making a sheet comprising the glass through a downdraw sheet fabrication process or a fusion process.