

GLASSES THAT REDUCE NON-VISCOUS RELAXION FOR IMPROVED TOTAL PITCH VARIATION

CROSS REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of priority under 35 U.S.C. §119 of U.S. Provisional Application Serial No. 63/583694 filed on September 19, 2023, the content of which is relied upon and incorporated herein by reference in its entirety.

FIELD

[0002] The present disclosure relates to glass compositions, and in particular glass compositions exhibiting reduced total pitch variation.

BACKGROUND

[0003] Display panel makers rely on predictable glass properties to manage glass component manufacture and assembly, such as backplane and color filter manufacture. The glass should have minimal dimensional change during thermal cycling, such as the temperature excursions, for example those experienced by the glass during thin film forming processes. More importantly, glass substrates used for such manufacture should have minimal, consistent total pitch variation from one glass substrate to the next glass substrate.

[0004] In view of these considerations, there is a need for glass compositions exhibiting reduced non-viscous relaxation, in combination with improved total pitch variation.

SUMMARY

[0005] In a first aspect, a glass is disclosed, comprising:

greater than or equal to 69.25 mol.% and less than or equal to 70.75 mol.% SiO₂,
greater than or equal to 12.00 mol.% and less than or equal to 13.50 mol.% Al₂O₃,
greater than or equal to 1.00 mol.% and less than or equal to 2.00 mol.% B₂O₃,
greater than or equal to 4.00 mol.% and less than or equal to 6.00 mol.% MgO,
greater than or equal to 5.00 mol.% and less than or equal to 6.50 mol.% CaO,
greater than or equal to 0.00 mol.% and less than or equal to 1.50 mol.% SrO,
greater than or equal to 2.50 mol.% and less than or equal to 4.00 mol.% BaO,
greater than or equal to 0.00 mol.% and less than or equal to 1.50 mol.% TiO₂,
greater than or equal to 0.00 mol.% and less than or equal to 0.75 mol.% ZnO,
greater than or equal to 0.00 mol.% and less than or equal to 1.00 mol.% Y₂O₃,

greater than or equal to 0.00 mol.% and less than or equal to 1.00 mol.% La_2O_3 ,

greater than or equal to 0.00 mol.% and less than or equal to 0.50 mol.% P_2O_5 ; and

wherein the glass satisfies the condition: $\text{Intercept} + \sum_{i=\text{SiO}_2}^{\text{P}_2\text{O}_5} X_i * Y_i \leq 16$, where the symbol

“*” means multiplication, and

Intercept = -11.20751259,

the coefficients X_i for the component oxides are:

$\text{SiO}_2 = -0.002926308$,

$\text{Al}_2\text{O}_3 = -0.004673511$,

$\text{B}_2\text{O}_3 = -0.001118634$,

$\text{MgO} = 1.126496816$,

$\text{CaO} = 1.615716878$,

$\text{SrO} = 3.063872526$,

$\text{BaO} = 1.551023535$,

$\text{TiO}_2 = -0.004673511$,

$\text{ZnO} = 0$,

$\text{Y}_2\text{O}_3 = -0.001118634$,

$\text{La}_2\text{O}_3 = -0.001118634$,

$\text{P}_2\text{O}_5 = -2.235863244$; and

wherein,

$\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{B}_2\text{O}_3$ is in a range from 82.25 mol% to 86.25 mol%,

$\text{MgO} + \text{CaO} + \text{BaO} + \text{SnO}_2$ is in a range from 13.00 mol% to 17.50 mol%,

$\text{TiO}_2 + \text{ZnO} + \text{La}_2\text{O}_3 + \text{La}_2\text{O}_3 + \text{P}_2\text{O}_5$ is in a range from 0.00 mol% to 4.75 mol%.

[0006] In a second aspect, a glass is disclosed, comprising:

greater than or equal to 69.25 mol.% and less than or equal to 70.75 mol.% SiO_2 ,

greater than or equal to 12.00 mol.% and less than or equal to 13.50 mol.% Al_2O_3 ,

greater than or equal to 1.00 mol.% and less than or equal to 2.00 mol.% B_2O_3 ,

greater than or equal to 4.00 mol.% and less than or equal to 6.00 mol.% MgO ,

greater than or equal to 5.00 mol.% and less than or equal to 6.50 mol.% CaO ,

greater than or equal to 0.00 mol.% and less than or equal to 1.50 mol.% SrO ,

greater than or equal to 2.50 mol.% and less than or equal to 4.00 mol.% BaO ,

greater than or equal to 0.00 mol.% and less than or equal to 1.50 mol.% TiO_2 ,

greater than or equal to 0.00 mol.% and less than or equal to 0.75 mol.% ZnO ,

greater than or equal to 0.00 mol.% and less than or equal to 1.00 mol.% Y_2O_3 ,

greater than or equal to 0.00 mol.% and less than or equal to 1.00 mol.% La_2O_3 ,
 greater than or equal to 0.00 mol.% and less than or equal to 0.50 mol.% P_2O_5 ; and
 wherein the glass satisfies the condition: $\text{Intercept} + \sum_{i=\text{SiO}_2}^{\text{P}_2\text{O}_5} X_i * Y_i \leq 13$, where the symbol
 “*” means multiplication, Intercept = -234.7571088, the values Y_i are the oxide component
 amounts in mol%, the coefficients X_i are:

$$\text{SiO}_2 = 2.232090497,$$

$$\text{Al}_2\text{O}_3 = 2.230475478,$$

$$\text{B}_2\text{O}_3 = 2.233717001,$$

$$\text{MgO} = 3.368563490,$$

$$\text{CaO} = 3.851331728,$$

$$\text{SrO} = 5.301366502,$$

$$\text{BaO} = 3.788612774,$$

$$\text{TiO}_2 = 2.230475478,$$

$$\text{ZnO} = 2.23468972,$$

$$\text{Y}_2\text{O}_3 = 2.233717001,$$

$$\text{La}_2\text{O}_3 = 2.233717001,$$

$$\text{P}_2\text{O}_5 = 0; \text{ and}$$

wherein,

$\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{B}_2\text{O}_3$ is in a range from 82.25 mol% to 86.25 mol%,

$\text{MgO} + \text{CaO} + \text{BaO} + \text{SnO}_2$ is in a range from 13.00 mol% to 17.50 mol%, and

$\text{TiO}_2 + \text{ZnO} + \text{La}_2\text{O}_3 + \text{P}_2\text{O}_5$ is in a range from 0.00 mol% to 4.75 mol%.

[0007] In a third aspect, a glass is disclosed, comprising:

greater than or equal to 69.25 mol.% and less than or equal to 70.75 mol.% SiO_2 ,

greater than or equal to 12.00 mol.% and less than or equal to 13.50 mol.% Al_2O_3 ,

greater than or equal to 1.00 mol.% and less than or equal to 2.00 mol.% B_2O_3 ,

greater than or equal to 4.00 mol.% and less than or equal to 6.00 mol.% MgO ,

greater than or equal to 5.00 mol.% and less than or equal to 6.50 mol.% CaO ,

greater than or equal to 0.00 mol.% and less than or equal to 1.50 mol.% SrO ,

greater than or equal to 2.50 mol.% and less than or equal to 4.00 mol.% BaO ,

greater than or equal to 0.00 mol.% and less than or equal to 1.50 mol.% TiO_2 ,

greater than or equal to 0.00 mol.% and less than or equal to 0.75 mol.% ZnO ,

greater than or equal to 0.00 mol.% and less than or equal to 1.00 mol.% Y_2O_3 ,

greater than or equal to 0.00 mol.% and less than or equal to 1.00 mol.% La_2O_3 ,

greater than or equal to 0.00 mol.% and less than or equal to 0.50 mol.% P₂O₅; and wherein the glass satisfies the condition:

Intercept + $\sum_{i=SiO_2}^{P_2O_5} X_i * Y_i \leq 10$, where the symbol “*” means multiplication, Intercept = -237.7578217, the values Y_i are the oxide component amounts in mol%, the coefficients X_i are:

$$SiO_2 = 2.25149345,$$

$$Al_2O_3 = 2.250724382,$$

$$B_2O_3 = 2.252392713,$$

$$MgO = 3.524128464,$$

$$CaO = 3.890462587,$$

$$SrO = 5.366534992,$$

$$BaO = 3.897785139,$$

$$TiO_2 = 2.250724382,$$

$$ZnO = 2.253175066,$$

$$Y_2O_3 = 2.252392713,$$

$$La_2O_3 = 2.252392713,$$

$$P_2O_5 = 0; \text{ and}$$

wherein,

SiO₂+Al₂O₃+B₂O₃ is in a range from 82.25 mol% to 86.25 mol%,

MgO+CaO+BaO+SnO₂ is in a range from 13.00 mol% to 17.50 mol%, and

TiO₂+ZnO+La₂O₃+La₂O₃+P₂O₅ is in a range from 0.00 mol% to 4.75 mol%.

[0008] In a fourth aspect, a glass is disclosed, comprising:

greater than or equal to 69.25 mol.% and less than or equal to 70.75 mol.% SiO₂,

greater than or equal to 12.00 mol.% and less than or equal to 13.50 mol.% Al₂O₃,

greater than or equal to 1.00 mol.% and less than or equal to 2.00 mol.% B₂O₃,

greater than or equal to 4.00 mol.% and less than or equal to 6.00 mol.% MgO,

greater than or equal to 5.00 mol.% and less than or equal to 6.50 mol.% CaO,

greater than or equal to 0.00 mol.% and less than or equal to 1.50 mol.% SrO,

greater than or equal to 2.50 mol.% and less than or equal to 4.00 mol.% BaO,

greater than or equal to 0.00 mol.% and less than or equal to 1.50 mol.% TiO₂,

greater than or equal to 0.00 mol.% and less than or equal to 0.75 mol.% ZnO,

greater than or equal to 0.00 mol.% and less than or equal to 1.00 mol.% Y₂O₃,

greater than or equal to 0.00 mol.% and less than or equal to 1.00 mol.% La₂O₃,

greater than or equal to 0.00 mol.% and less than or equal to 0.50 mol.% P₂O₅; and

wherein the glass satisfies the condition: $\text{Intercept} + \sum_{i=\text{SiO}_2}^{\text{P}_2\text{O}_5} X_i * Y_i \leq 8$, where the symbol “*” means multiplication, Intercept = -242.7132028, the values Y_i are the oxide component amounts in mol%, the coefficients X_i are:

$$\text{SiO}_2 = 2.260131924,$$

$$\text{Al}_2\text{O}_3 = 2.260271613,$$

$$\text{B}_2\text{O}_3 = 2.26056072,$$

$$\text{MgO} = 3.878171611,$$

$$\text{CaO} = 4.168656199,$$

$$\text{SrO} = 5.552077225,$$

$$\text{BaO} = 4.212721511,$$

$$\text{TiO}_2 = 2.260271613,$$

$$\text{ZnO} = 2.259907435,$$

$$\text{Y}_2\text{O}_3 = 2.26056072,$$

$$\text{La}_2\text{O}_3 = 2.26056072,$$

$$\text{P}_2\text{O}_5 = 0; \text{ and}$$

wherein,

$\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{B}_2\text{O}_3$ is in a range from 82.25 mol% to 86.25 mol%,

$\text{MgO} + \text{CaO} + \text{BaO} + \text{SnO}_2$ is in a range from 13.00 mol% to 17.50 mol%, and

$\text{TiO}_2 + \text{ZnO} + \text{La}_2\text{O}_3 + \text{La}_2\text{O}_3 + \text{P}_2\text{O}_5$ is in a range from 0.00 mol% to 4.75 mol%.

[0009] Both the foregoing general description and the following detailed description present embodiments intended to provide an overview or framework for understanding the nature and character of the embodiments disclosed herein. The accompanying drawings are included to provide further understanding and are incorporated into and constitute a part of this specification. The drawings illustrate various embodiments of the disclosure, and together with the description explain the principles and operations thereof.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] FIG. 1 is a plot of temperature (vertical axis) versus time (horizontal axis) for a test procedure that can be used to observe fast relaxation in a display glass. The times, temperatures, and slopes shown in this figure are not to scale. The test procedure includes a conditioning stage 10, 12, 14 and a measurement stage 16, 18, 20;

[0011] FIG. 2 is a schematic diagram, not to scale, illustrating another embodiment of a test like the test procedure of FIG. 1, wherein the vertical axis is temperature for heating periods 26, 28, 30, 32 and fictive temperature for curves 22 and 24, and the horizontal axis is time;

[0012] FIG. 3 is a schematic diagram, not to scale, illustrating dimensional changes as a result of the measurement stage of the testing procedure of FIG. 2, wherein the vertical axis is dimensional change in, for example, parts-per-million (ppm) and the horizontal scale is time;

[0013] FIG. 4 is a plot giving a representation of agreement between the genetic algorithm-based prediction from the best model and the measured data;

[0014] FIG. 5 is a plot showing the accuracy of the predicted results using a genetic algorithm-based model compared to measured data;

[0015] FIG. 6 is another plot showing the accuracy of the predicted results using a genetic algorithm-based model compared to measured data;

[0016] FIG. 7 is a plot of a convex hull in accordance with glass compositions disclosed herein where the Intercept is equal to or less than 16;

[0017] FIG. 8 is a plot of a convex hull in accordance with glass compositions disclosed herein where the Intercept is equal to or less than 13;

[0018] FIG. 9 is a plot of a convex hull in accordance with glass compositions disclosed herein where the Intercept is equal to or less than 10;

[0019] FIG. 10 is a plot of a convex hull in accordance with glass compositions disclosed herein where the Intercept is equal to or less than 8; and

[0020] FIG. 11 is a nested plot of the convex hulls of FIGS. 7-10.

DETAILED DESCRIPTION

[0021] Reference will now be made in detail to embodiments of the present disclosure, examples of which are illustrated in the accompanying drawings. Whenever possible, the same reference numerals will be used throughout the drawings to refer to the same or like parts. However, this disclosure can be embodied in many different forms and should not be construed as limited to the embodiments set forth herein.

[0022] As used herein, the term “about” means that amounts, sizes, formulations, parameters, and other quantities and characteristics are not and need not be exact, but may be approximate and/or larger or smaller, as desired, reflecting tolerances, conversion factors, rounding off, measurement error and the like, and other factors known to those of skill in the art.

[0023] As used herein, the term “about” means that amounts, sizes, formulations, parameters, and other quantities and characteristics are not and need not be exact, but may be approximate

and/or larger or smaller, as desired, reflecting tolerances, conversion factors, rounding off, measurement error and the like, and other factors known to those skilled in the art. When the term "about" is used in describing a value or an end point of a range, the disclosure should be understood to include the specific value or end point referred to. Whether or not a numerical value or end point of a range in the specification recites "about," the numerical value or end point of a range is intended to include two embodiments: one modified by "about," and one not modified by "about." It will be further understood that the end points of each of the ranges are significant both in relation to the other end point, and independently of the other end point.

[0024] Directional terms as may be used herein—for example, up, down, right, left, front, back, top, bottom—are made only with reference to the figures as drawn and are not intended to imply absolute orientation.

[0025] Unless otherwise expressly stated, it is in no way intended that any method set forth herein be construed as requiring that its steps be performed in a specific order, nor that with any apparatus, specific orientations be required. Accordingly, where a method claim does not actually recite an order to be followed by its steps, or that any apparatus claim does not actually recite an order or orientation to individual components, or it is not otherwise specifically stated in the claims or description that the steps are to be limited to a specific order, or that a specific order or orientation to components of an apparatus is not recited, it is in no way intended that an order or orientation be inferred in any respect. This holds for any possible non-express basis for interpretation, including matters of logic with respect to arrangement of steps, operational flow, order of components, or orientation of components; plain meaning derived from grammatical organization or punctuation, and; the number or type of embodiments described in the specification.

[0026] As used herein, the singular forms "a," "an," and "the" include plural references unless the context clearly dictates otherwise. Thus, for example, reference to "a" component includes aspects having two or more such components, unless the context clearly indicates otherwise.

[0027] The word "exemplary," "example," or various forms thereof are used herein to mean serving as an example, instance, or illustration. Any aspect or design described herein as "exemplary" or as an "example" should not be construed as preferred or advantageous over other aspects or designs. Furthermore, examples are provided solely for purposes of clarity and understanding and are not meant to limit or restrict the disclosed subject matter or relevant portions of this disclosure in any manner. It can be appreciated that a myriad of additional or alternate examples of varying scope could have been presented but have been omitted for purposes of brevity.

[0028] As used herein, the terms “comprising” and “including,” and variations thereof, shall be construed as synonymous and open-ended, unless otherwise indicated. A list of elements following the transitional phrases comprising or including is a non-exclusive list, such that elements in addition to those specifically recited in the list may also be present.

[0029] 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. For example, a “substantially planar” surface is intended to denote a surface that is planar or approximately planar. Moreover, “substantially” is intended to denote that two values are equal or approximately equal. In some embodiments, “substantially” may denote values within about 10% of each other, such as within about 5% of each other, within about 2% of each other, within about 1% of each other, or within 0.5% of each other.

[0030] For brevity, ranges of values disclosed herein, including compositional ranges or attribute (performance) ranges, or series of ranges, may be appended by the phrase “including all ranges and subranges therebetween,” which is to be interpreted as including whole number or decimal subranges as though explicitly presented. Thus, by way of example, a range between 6 and 8 (units omitted) implicitly includes a subrange between 6.4 and 8, or a subrange between 6 and 7.2, or a subrange between 6 and 7, and so forth. Additionally, a series of ranges, such as “in a range from 6 to 11 or in a range from 6 to 8” implicitly includes a range from 7 to 10, or subranges therebetween, such as 7.2 to 10.4, as though explicitly presented, provided the range does not exceed the minimum or maximum endpoints of the explicitly presented range or series of ranges.

[0031] The symbol “*” means multiplication when used in any formula herein.

[0032] Thermodynamically, glass is a non-equilibrium system that would like to relax to the metastable supercooled liquid state. This relaxation typically involves a continuous change in the volume, enthalpy, and other properties of the glass as it approaches the liquid state. While the presence of a thermodynamic driving force is a necessary condition for glass relaxation, by itself it is insufficient since the glass must also have enough thermal energy and/or time to enable the kinetics of relaxation. Assuming isobaric conditions, the kinetics of the glass depend on three factors: composition, temperature, and thermal history. The importance of thermal history cannot be overstated, since the dynamics of two glasses of the same composition and at the same temperature can vary by many orders of magnitude depending on the details of thermal history.

[0033] When a glass melt is cooled rapidly from high temperature, the movement of atoms within the cooling liquid slows down with decreasing temperature and eventually diminishes

to oscillations about fixed positions due to the normal thermal population of vibrational states. These positions are typically not those that would be adopted were the glass to be held for an extended period of time (ranging from seconds to days) at intermediate temperatures (e.g., the glass transition temperature or the strain or annealing points). Consequently, when a rapidly quenched glass is reheated to intermediate temperatures, the thermally populated vibrational states allow for relaxation of atoms into positions that better satisfy their individual and collective bonding requirements. Since this is typically accompanied by a decrease in the physical dimensions of a bulk piece of glass, thermal relaxation upon reheating is said to produce compaction of the glass.

[0034] The amount of compaction exhibited by any sample of glass upon reheating will depend on the fictive temperature of the glass at the beginning of reheating, i.e., $T_f(t_0)$, and on the change in fictive temperature over the course of the reheating, i.e., $T_f(t)$. Changes in fictive temperature with time resulting from reheating to a temperature T can be described by the following equation:

$$(T_f(t) - T) = (T_f(t_0) - T) * \exp [(-t/\tau(T))^b] \quad (1)$$

where b is a "stretching constant" and $\tau(T)$ is the relaxation time of the glass at the heat treatment temperature.

[0035] The relaxation time of the glass at a given temperature T can be approximated by the equation:

$$\tau(T) \approx \eta(T) / G \quad (2)$$

where $\eta(T)$ is the glass's shear viscosity at the given temperature and G is the glass's shear modulus which scales the viscosity into time space and to a first approximation is independent of temperature.

[0036] As can be seen from Equations (1) and (2), as the relaxation time is increased, e.g., by increasing $\eta(T)$, the change in fictive temperature of the glass in a set amount of time is significantly reduced, thereby reducing the measured compaction in a set thermal cycle.

[0037] While fictive temperature is commonly referred to as a single temperature for a given quench rate, this is merely a convenience of language since experimental evidence has clearly demonstrated the presence of a distribution of relaxation times in glasses of the type used as display substrates.

[0038] Glass sheets destined for incorporation into display substrates, and in particular as glass substrates for thin film deposition, begin as a molten material formed into a ribbon of glass, cooled to form an elastic solid, and cut into individual glass sheets. These glass sheets

are sold to display manufacturers that further process the glass sheets by depositing thin films in processes that can include exposure of the glass sheet to high temperature, e.g., in excess of 400°C. This exposure can result in dimensional changes in the glass compared to the as-manufactured state of the original glass sheet. Moreover, the presence of the one or more thin films, and stresses resulting therefrom, may affect the behavior of the glass.

[0039] Total pitch variation (TPV) is a glass sheet attribute that customers for high precision display (HPD) glass are concerned about in their panel making processes. TPV refers to the variation in dimension change from one glass sheet to another glass sheet. For example, by way of a simple experiment, consider a glass sheet sample placed on a flat surface, the flat surface comprising a fiducial mark. A corresponding mark is made on the glass sample. The flat surface includes stops arranged to allow the glass sheet to be placed in the same position after the glass sheet is removed, then placed back on the flat surface. The glass sample is removed from the flat surface and subjected to a thermal excursion sufficient to incur a dimensional change in the glass sheet sample. The glass sheet sample is then placed back on the flat surface using the stops to position the glass sheet in the same position it was previously in. A second mark is made on the glass sheet corresponding to the fiducial mark. The distance between the first mark on the glass sheet sample before the thermal excursion and the second mark on the glass sheet sample after the thermal excursion represents the pitch.

[0040] Thin film deposition processes rely on exacting registration between deposited layers. Display panel makers desire that each glass sheet is identical. Even very slight changes in registration, on the order of several micrometers, can have significant impact on TFT formation, including film deposition, photolithography, etching, and heat treatment processes. However, from the foregoing discussion, it is clear glass sheets will undergo dimensional change as a result of the thermal history of the glass sheet. Accordingly, it is at least desirable that a dimensional change (pitch) exhibited by the next glass sheet is identical to the dimensional change (pitch) experienced by the previous glass sheet. Panel makers can account for dimensional change if the dimensional change is consistent. However, if the pitch experienced by one glass sheet is different from the pitch experienced by a second glass sheet, accommodating this pitch variation becomes more problematic. TPV, then, is a variation in pitch exhibited over a population (or sample thereof) of glass articles, e.g., glass sheets.

[0041] There are four principal components that contribute to TPV that a display panel maker may measure when using glass in their processes: elastic distortion, stress relaxation, viscous relaxation (compaction), and non-viscous relaxation (which also contributes to compaction).

While both viscous and non-viscous relaxation contribute to the overall compaction portion of TPV, the distinction between the two is made in the temperature regime in which the compaction occurs. Non-viscous relaxation is believed to be driven by glass chemistry and occurs in temperature ranges very far below the anneal point in HPD-like glasses, e.g., $< 450^{\circ}\text{C}$. On the other hand, viscous relaxation occurs in a temperature range just below the anneal point down to about 450°C . Note that these temperature ranges are dependent on anneal point, and so the ranges expressed above are applicable only to HPD-like glasses with anneal points approximately 800°C and higher. Moreover, viscous relaxation is driven by the viscosity change that occurs as glasses are heated and undergo relaxation to their thermodynamically desired volume. In the higher temperature ranges it is thought that every glass experiences both viscous and non-viscous relaxation simultaneously. However, in the lower temperature range, glass viscosity is too high to undergo any relaxation (compaction) associated with viscosity changes in the one to two hours during which a panel maker processes the glass. Non-viscous relaxation, however, occurs very quickly, so much so that panel makers routinely see compaction at very low temperatures over short (30 minutes – 1 hour) processing times.

[0042] The dimensional behavior of a glass when subjected to a thermal cycle of the type used in the manufacturing of displays can be reasonably approximated and controlled by considering the glass as composed of two populations of relaxing species, i.e., "fast relaxers" and "slow relaxers." In particular, the fast relaxer-slow relaxer approach to controlling dimensional changes is applicable to thermal cycles in which a glass sheet is subjected to at least a first and a second heating stage, the first heating stage characterized by a maximum temperature T_1 and a post-stage cooling rate r_1 and the second heating stage characterized by a maximum temperature T_2 and a post-stage cooling rate r_2 , wherein:

$$T_1 < T_2 \text{ and } r_1 = r_2; \text{ or} \quad (3)$$

$$T_1 = T_2 \text{ and } r_1 < r_2; \text{ or} \quad (4)$$

$$T_1 < T_2 \text{ and } r_1 < r_2. \quad (5)$$

[0043] The principal thermal cycle in a display manufacturing process is normally the second heating stage of such a two-stage heating process and thus the ability to control the dimensional changes of a glass sheet during such a second heating stage through adjustment of relative amounts of fast and slow relaxers in the glass making up the sheet constitutes an important contribution to display manufacturing processes.

[0044] Generally, slow relaxers are involved in the dimensional changes described by the glass's viscosity versus temperature behavior, e.g., the glass's anneal temperature (i.e., the temperature at which the glass has a viscosity of $10^{13.18}$ poise). In particular, slow relaxers are

relaxers whose behavior can, to a first approximation, be described by Eq. (4), while fast relaxers are those that have relaxation times faster than that predicted by Eq. (4).

[0045] In practice, the presence of slow and fast relaxers can cause a glass to exhibit dimension changes when subjected to temperature steps that are biphasic. Specifically, the glass can undergo an expansion followed by a contraction. This is especially so in short thermal cycles, such as the "rapid thermal anneal" or "RTA" commonly used in display manufacture, where fast relaxers can play a significant role in the net dimensional change of the glass by causing expansion within short times instead of the traditional compaction.

[0046] The overall behavior can be controlled by selecting or adjusting the number and/or amount of fast relaxers in the glass. To do so, however, requires the ability to distinguish the effects of fast relaxers from those of slow relaxers. FIG. 1 shows a test procedure for obtaining such a separation between the effects of the slow and fast relaxers.

[0047] As can be seen in FIG. 1, the test procedure includes a conditioning stage (10, 12, 14 in FIG. 3; 26 in FIG. 2) and a measurement stage (16, 18, 20 in FIG. 1; 28, 30, 32 in FIG. 2). The conditioning stage includes three phases where:

- (i) in phase 1 of the conditioning stage, the glass is heated from room temperature (e.g., 20°C) to 656°C in four minutes (see 10 in FIG. 1);
- (ii) in phase 2 of the conditioning stage, the glass is held at 656°C for 8 hours (see 12 in FIG. 1);
- (iii) in phase 3 of the conditioning stage, the glass is cooled from 656°C to room temperature in 8 hours (see 14 in FIG. 1); and
- (iv) in phase 4 of the conditioning stage, dimensional changes are measured at the end of phase 3, for example by a fiducial method.

[0048] The test procedure may further include a first measuring stage comprising:

- (i) in phase 1 of the first measuring stage, the glass is heated from room temperature (e.g., 20°C) to 656°C in four minutes (see 10 in FIG. 1);
- (ii) in phase 2 of the first measuring stage, the glass is held at 656°C for 6 minutes (see 12 in FIG. 1);
- (iii) in phase 3 of the first measuring stage, the glass is rapidly cooled from 656°C to room temperature (see 14 in FIG. 1); and
- (iv) in phase 4 of the first measuring stage, dimensional changes are measured at the end of phase 3.

[0049] The test procedure may include a second measuring stage wherein phases 1-4 of the first measuring stage are repeated, or even a third measuring stage.

[0050] Dimensional changes can be determined in various ways using commercially available or customized equipment. For example, dimensional changes can be determined by scribing fiducial lines around a sample's edges and then measuring changes in the perimeter using, for example, a Mitutoyo Apex Vision System.

[0051] While the foregoing test procedure doesn't capture the true non-viscous relaxation, since the magnitude is very small, even in large size glass sheets, it can act as an accurate proxy that does in fact capture the relative non-viscous behavior of glasses. The test procedure can provide a single value, denoted here as N_v that represents this behavior, thus providing a convenient metric that allows a comparison of glass performance. The lower the N_v value, the lower the contribution of non-viscous relaxation to TPV and thus the lower the expected overall TPV value will be for that glass composition in a post-manufacture, downstream processes.

[0052] As persons skilled in the art will recognize from the present disclosure, test procedures employing other times, temperatures, and numbers of measurement stage repetitions can be used to distinguish the effects of fast relaxers from slow relaxers, provided the procedure employs a conditioning stage which has a long hold at a preselected elevated temperature and a slow quench rate followed by a measurement stage which uses the same preselected temperature and a faster quench rate.

[0053] In general terms, the conditioning stage of the test procedure serves to drastically reduce the contribution of slow relaxing species to the measured dimensional changes in the measurement stage. Typically, the glass sample will exhibit a dimensional change (compaction) on the order of 3300-1500 ppm during the conditioning stage. In addition to shutting down the slow relaxers, the conditioning stage sets the fast relaxers in a low fictive temperature state so they will expand in the measurement stage(s). The relative amount of observed expansion in the measurement stage can then serve as a measure of the fast relaxers present in the glass of interest. That is, the amount of expansion the glass experiences in the measuring stages compared to the conditioning stage represents the glass N_v expansion peak.

[0054] The ability of the procedure of FIG. 1 to separate the behavior of slow and fast relaxers can be understood through reference to FIGS. 2 and 3. Curves 22 and 24 of FIG. 2 respectively plot the fictive temperatures of the slow and fast relaxers as a function of time during the test procedure. As shown in this figure, the first part of the test procedure (the conditioning stage) shuts down the slow relaxers, i.e., curve 22 of FIG. 2 is essentially flat by the end of conditioning stage 26 and remains essentially flat during the measurement stage, i.e., during the heating-fast quenching steps 28, 30, and 32 in FIG. 2.

[0055] FIG. 3 illustrates the dimensional changes that take place during the measurement stage. In particular, curve 34 shows the dimensional changes attributable to the fast relaxers, curve 36 shows dimensional changes attributable to slow relaxers, and curve 38 shows the combined dimensional changes that result in measured data points 40, 42, and 44, which can be averaged to provide a measure of the glass's expansion peak. As these curves illustrate, because the slow relaxers have been substantially shut down by the conditioning stage, the fast relaxers are able to produce substantial observable expansion behavior during the measurement stage.

[0056] Using the test procedure of FIGS. 1-3, the effects of compositional changes on fast relaxation can be determined. The compositional change approach to enhancing the effect of fast relaxers can be applied to investigating compositions that minimize Nv. As known in the art, in general terms, display glasses include SiO₂ and Al₂O₃ as glass formers and CaO, SrO, and MgO as components for modifying the properties of the glass, e.g., the glass's CTE, strain point, anneal point, melting point, viscosity, etc. In addition to these components, the glasses can include a variety of other constituents, e.g., B₂O₃, BaO, fining agents, and the like.

[0057] Accordingly, the Nv thermal cycle was used to evaluate a number of high performance display-like compositions. Table 1 contains the compositions by sample Number (S#) expressed in mole % on an oxide basis, measured Nv values (in ppm), and anneal point (temperature) in degrees centigrade.

Table 1

S#	SiO ₂	Al ₂ O ₃	B ₂ O ₃	MgO	CaO	SrO	BaO	TiO ₂	ZnO	Y ₂ O ₃	La ₂ O ₃	P ₂ O ₅	Nv (ppm)	Anneal Point
S1	67.51	12.98	4.90	4.72	6.30	3.39	0.07	0.00	0.00	0.00	0.00	0.00	15.22	766
S2	67.29	13.08	5.01	4.61	6.41	3.42	0.05	0.00	0.00	0.00	0.00	0.00	14.14	766
S3	67.27	13.00	5.21	4.58	6.40	3.34	0.07	0.00	0.00	0.00	0.00	0.00	13.53	764
S4	71.23	12.47	0.26	10.15	1.15	4.51	0.10	0.00	0.00	0.00	0.00	0.00	8.29	811
S5	71.04	12.81	2.06	4.43	5.13	0.85	3.49	0.00	0.00	0.00	0.00	0.00	9.32	800
S6	68.77	12.90	1.67	5.19	6.84	0.08	4.35	0.00	0.00	0.00	0.00	0.00	9.53	786
S7	71.24	12.44	0.28	6.12	6.38	0.05	3.31	0.00	0.00	0.00	0.00	0.00	10.00	808
S8	70.05	13.37	1.72	4.61	6.13	0.10	3.85	0.00	0.00	0.00	0.00	0.00	10.19	801
S9	71.14	12.39	0.35	5.95	6.09	0.75	3.18	0.00	0.00	0.00	0.00	0.00	10.40	807
S10	71.02	12.50	0.28	10.50	4.09	0.78	0.67	0.00	0.00	0.00	0.00	0.00	10.49	806
S11	71.04	14.53	0.28	4.43	5.19	0.82	3.51	0.00	0.00	0.00	0.00	0.00	10.53	824
S12	70.95	12.66	0.66	5.40	5.95	0.88	3.32	0.00	0.00	0.00	0.00	0.00	11.74	
S13	70.12	12.89	0.29	5.16	6.93	0.08	4.36	0.00	0.00	0.00	0.00	0.00	11.87	807
S14	71.16	12.51	0.28	7.44	5.09	0.87	2.49	0.00	0.00	0.00	0.00	0.00	12.01	806
S15	71.06	12.48	0.44	5.80	6.06	0.78	3.22	0.00	0.00	0.00	0.00	0.00	12.04	
S16	70.97	12.54	0.61	5.62	6.01	0.81	3.27	0.00	0.00	0.00	0.00	0.00	12.19	

S17	71.06	12.48	0.28	5.11	5.95	0.94	4.00	0.00	0.00	0.00	0.00	0.00	12.63	809
S18	71.05	12.52	0.28	1.31	13.20	0.83	0.67	0.00	0.00	0.00	0.00	0.00	13.27	820
S19	71.18	12.48	0.28	5.90	6.12	0.70	3.17	0.00	0.00	0.00	0.00	0.00	13.62	808
S20	71.23	12.30	0.04	6.09	6.12	3.99	0.09	0.00	0.00	0.00	0.00	0.00	16.24	
S22	71.32	12.32	0.17	5.99	6.10	2.53	1.44	0.00	0.00	0.00	0.00	0.00	16.66	
S23	71.43	12.44	0.28	1.39	1.63	11.87	0.86	0.00	0.00	0.00	0.00	0.00	17.70	827
S24	70.75	13.35	0.81	4.33	5.76	1.18	3.67	0.00	0.00	0.00	0.00	0.00	11.08	801
S25	70.42	13.17	1.71	4.19	5.62	1.15	3.57	0.00	0.00	0.00	0.00	0.00	12.89	802
S26	69.49	12.04	3.27	4.84	5.80	1.25	3.16	0.00	0.00	0.00	0.00	0.00	11.20	775
S27	69.55	12.09	3.28	4.67	5.82	1.21	3.21	0.00	0.00	0.00	0.00	0.00	12.75	775
S28	69.26	12.52	4.25	4.30	5.58	3.91	0.05	0.00	0.00	0.00	0.00	0.00	12.49	775
S29	68.53	12.52	4.34	4.71	5.46	3.79	0.51	0.00	0.00	0.00	0.00	0.00	13.46	770
S30	68.41	12.63	4.40	4.61	5.57	3.48	0.75	0.00	0.00	0.00	0.00	0.00	13.90	769
S31	68.84	12.53	4.48	4.52	5.63	3.81	0.05	0.00	0.00	0.00	0.00	0.00	14.13	772
S32	68.61	12.55	4.41	4.64	5.32	4.29	0.05	0.00	0.00	0.00	0.00	0.00	14.13	771
S33	68.64	12.76	4.39	4.44	5.51	3.40	0.74	0.00	0.00	0.00	0.00	0.00	14.16	772
S34	68.64	12.76	4.37	5.18	5.73	3.18	0.04	0.00	0.00	0.00	0.00	0.00	14.44	
S35	68.51	12.55	4.91	4.22	5.58	4.06	0.05	0.00	0.00	0.00	0.00	0.00	14.76	769
S36	68.88	12.40	4.44	4.50	5.47	3.44	0.73	0.00	0.00	0.00	0.00	0.00	14.88	771
S37	68.47	12.54	4.91	4.21	5.57	4.11	0.05	0.00	0.00	0.00	0.00	0.00	15.15	766
S38	68.62	12.56	4.39	4.66	5.62	3.99	0.05	0.00	0.00	0.00	0.00	0.00	15.99	769
S39	72.00	11.56	0.04	16.10	0.14	0.01	0.00	0.00	0.00	0.00	0.00	0.00	7.10	831
S40	72.23	11.48	0.03	1.70	14.40	0.01	0.00	0.00	0.00	0.00	0.00	0.00	8.10	826
S41	72.31	11.45	0.04	0.69	15.34	0.01	0.00	0.00	0.00	0.00	0.00	0.00	8.50	831
S42	72.57	12.36	1.04	4.51	4.74	1.04	3.54	0.00	0.00	0.00	0.00	0.00	8.80	814
S43	72.10	11.53	0.04	5.19	11.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	11.40	818
S45	70.69	11.82	0.04	0.02	0.03	0.74	16.38	0.00	0.00	0.00	0.00	0.00	11.44	825
S46	72.27	11.73	0.16	5.08	5.36	1.18	4.03	0.00	0.00	0.00	0.00	0.00	12.40	815
S47	72.02	11.58	0.04	0.03	0.63	15.31	0.14	0.00	0.00	0.00	0.00	0.00	13.00	830
S48	71.44	11.74	0.03	0.00	0.06	1.71	14.75	0.00	0.00	0.00	0.00	0.00	13.69	822
S49	72.00	11.57	0.04	0.07	1.74	14.20	0.14	0.00	0.00	0.00	0.00	0.00	16.60	827
S50	71.30	11.74	0.04	0.02	0.18	5.45	11.00	0.00	0.00	0.00	0.00	0.00	21.56	820
S51	72.19	11.54	0.03	0.19	5.28	10.45	0.10	0.00	0.00	0.00	0.00	0.00	26.17	825
S52	72.00	11.56	0.04	16.10	0.14	0.01	0.00	0.00	0.00	0.00	0.00	0.00	4.89	831
S53	71.68	11.99	0.00	16.14	0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.82	850
S54	71.84	11.95	0.00	15.91	0.13	0.00	0.05	0.00	0.00	0.00	0.00	0.00	5.18	832
S55	70.42	13.34	1.68	4.59	5.28	0.88	3.62	0.00	0.00	0.00	0.00	0.00	7.85	803
S56	71.88	13.32	0.00	4.67	5.38	0.89	3.67	0.00	0.00	0.00	0.00	0.00	8.50	831
S57	71.88	12.87	0.00	4.80	5.56	0.92	3.78	0.00	0.00	0.00	0.00	0.00	8.85	825
S58	71.84	13.41	0.19	4.57	5.31	0.88	3.62	0.00	0.00	0.00	0.00	0.00	9.06	827
S59	71.90	12.34	0.00	4.96	5.73	0.95	3.90	0.00	0.00	0.00	0.00	0.00	9.19	819
S60	71.27	13.38	0.84	4.57	5.28	0.88	3.60	0.00	0.00	0.00	0.00	0.00	9.20	816
S61	71.60	13.43	0.41	4.59	5.30	0.88	3.61	0.00	0.00	0.00	0.00	0.00	9.45	823
S62	71.78	11.98	0.11	5.07	5.88	0.98	4.01	0.00	0.00	0.00	0.00	0.00	10.74	813
S63	71.86	11.97	0.00	3.62	0.08	12.06	0.20	0.00	0.00	0.00	0.00	0.00	10.87	824
S64	70.88	11.83	1.32	5.06	5.81	0.96	3.95	0.00	0.00	0.00	0.00	0.00	11.07	795

S65	71.58	11.95	0.37	5.07	5.87	0.97	3.99	0.00	0.00	0.00	0.00	0.00	11.49	808
S66	70.96	12.08	0.00	0.03	0.10	0.33	16.16	0.00	0.00	0.00	0.00	0.00	12.01	828
S67	71.84	12.03	0.02	5.06	5.88	0.97	4.01	0.00	0.00	0.00	0.00	0.00	12.07	814
S68	70.48	11.76	1.91	4.96	5.80	0.96	3.94	0.00	0.00	0.00	0.00	0.00	12.11	784
S69	71.36	11.91	0.71	5.05	5.83	0.97	3.97	0.00	0.00	0.00	0.00	0.00	12.24	803
S70	71.08	12.03	0.00	0.04	0.31	0.53	15.69	0.00	0.00	0.00	0.00	0.00	12.58	827
S71	71.53	12.31	0.42	4.17	4.26	3.20	3.91	0.00	0.00	0.00	0.00	0.00	14.53	813
S72	71.62	12.13	0.11	4.13	4.07	3.71	4.02	0.00	0.00	0.00	0.00	0.00	14.66	815
S73	71.69	12.05	0.02	4.10	3.98	3.92	4.04	0.00	0.00	0.00	0.00	0.00	16.94	816
S74	71.86	11.96	0.00	5.45	5.21	5.22	0.15	0.00	0.00	0.00	0.00	0.00	18.57	815
S75	71.82	11.97	0.00	5.10	4.88	4.85	1.21	0.00	0.00	0.00	0.00	0.00	19.09	814
S76	71.95	11.95	0.00	5.44	5.22	5.21	0.08	0.00	0.00	0.00	0.00	0.00	19.38	815
S77	71.68	12.01	0.00	0.18	5.28	5.31	5.30	0.00	0.00	0.00	0.00	0.00	26.89	818
S78	71.74	12.00	0.00	0.45	5.27	5.29	5.01	0.00	0.00	0.00	0.00	0.00	29.21	817
S79	70.09	12.42	2.19	14.61	0.11	0.38	0.00	0.00	0.00	0.00	0.00	0.00	4.28	
S80	70.01	12.30	2.50	14.94	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.70	
S81	69.43	12.37	2.94	14.97	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.96	
S82	70.07	12.36	2.43	0.30	14.70	0.01	0.00	0.00	0.00	0.00	0.00	0.00	6.29	
S83	70.47	12.19	2.18	0.29	14.71	0.01	0.00	0.00	0.00	0.00	0.00	0.00	6.46	
S84	70.25	12.32	2.22	1.67	0.05	13.31	0.00	0.00	0.00	0.00	0.00	0.00	6.51	
S85	71.25	12.40	0.27	5.96	6.09	0.75	3.18	0.00	0.00	0.00	0.00	0.00	10.40	
S86	70.52	13.15	1.71	4.19	5.62	1.15	3.56	0.00	0.00	0.00	0.00	0.00	10.88	
S87	71.06	12.64	0.66	5.39	5.94	0.88	3.32	0.00	0.00	0.00	0.00	0.00	11.74	
S88	70.52	13.15	1.71	4.19	5.62	1.15	3.56	0.00	0.00	0.00	0.00	0.00	11.90	
S89	71.07	12.57	0.51	5.63	6.02	0.81	3.27	0.00	0.00	0.00	0.00	0.00	13.01	
S90	69.75	12.36	2.25	0.08	2.19	0.25	12.76	0.00	0.00	0.00	0.00	0.00	13.81	
S91	69.37	12.36	2.48	0.04	0.71	0.29	14.39	0.00	0.00	0.00	0.00	0.00	14.13	
S92	71.66	11.97	0.00	0.79	0.07	15.03	0.24	0.00	0.00	0.00	0.00	0.00	14.36	
S93	70.95	12.35	0.24	6.12	6.14	4.01	0.09	0.00	0.00	0.00	0.00	0.00	16.24	
S94	71.25	12.34	0.24	5.99	6.11	2.53	1.44	0.00	0.00	0.00	0.00	0.00	16.66	
S95	70.44	13.23	1.59	4.26	5.58	1.21	3.57	0.00	0.00	0.00	0.00	0.00	9.44	
S96	70.17	13.25	1.05	5.45	6.07	0.09	3.75	0.00	0.00	0.00	0.00	0.00	8.64	
S97	70.14	12.02	1.06	5.65	6.12	0.08	3.77	0.97	0.00	0.00	0.00	0.00	8.26	
S98	69.22	13.23	1.08	5.42	6.08	0.08	3.71	0.98	0.00	0.00	0.00	0.00	7.78	
S99	69.61	13.30	1.07	4.33	6.09	0.08	3.79	1.53	0.00	0.00	0.00	0.00	6.53	
S100	70.60	13.31	1.69	4.36	5.60	0.70	2.62	0.00	0.00	0.97	0.00	0.00	6.69	
S101	70.30	13.24	1.71	4.29	5.56	1.22	2.60	0.01	0.00	0.00	0.93	0.00	8.11	
S102	70.34	13.23	1.69	4.30	5.61	1.20	2.56	0.00	0.00	0.95	0.00	0.00	7.11	
S103	70.12	13.32	1.68	4.34	5.58	1.20	3.16	0.45	0.00	0.00	0.00	0.00	7.12	
S104	70.07	13.29	1.67	4.34	5.59	1.14	3.20	0.03	0.00	0.00	0.00	0.52	8.49	
S105	70.12	13.23	1.65	4.37	5.60	0.71	3.63	0.03	0.00	0.00	0.00	0.51	6.82	
S106	70.60	13.21	1.34	4.35	5.59	1.19	3.05	0.01	0.54	0.00	0.00	0.00	9.31	
S107	70.22	13.20	1.08	4.45	6.10	0.08	3.71	0.97	0.00	0.00	0.00	0.00	6.76	
S108	69.77	12.40	1.01	5.48	6.16	0.09	3.93	0.00	0.00	0.97	0.00	0.00	7.38	

[0058] To better understand the distribution of the N_v values inside the space of interest, the experimentally obtained N_v data of from Table 1 was used to build a mathematical representation of the variation of N_v within that space.

[0059] Once the full data set was obtained, the data set was split into a training set and a test set. Given the small size of the data set, two models based on symbolic regression and gaussian processes were built. For the symbolic regression model, a genetic algorithm was used to build and iteratively improve the prediction accuracy over a large population of models, represented by mathematical formulas, that were capable of predicting N_v correctly. The best formula selection from the trained population was based on the best performance on a test set. FIG. 4 gives a representation of agreement between the genetic algorithm-based prediction from the best model and the measured data. To have high confidence in the predictions, gaussian processes were considered, which represented a probability-based approach that can compute a standard deviation during inference and based on the data distribution. The more a data point is surrounded by experimental neighbors, the higher the confidence in the prediction. Accuracy of such an implementation is shown in FIGS. 5-6. For each model, about 20% of the data was used for the test set. In the symbolic regression the size of the population and the maximum depth of the tree representing the formulas was varied. This helped resolve the nonlinearity of N_v . For the gaussian processes, a Monte Carlo tree search was implemented to iteratively increase the complexity of the function that described the covariance within the data up to a depth of four by a smart combination of the basic co-variance functions. Once an accurate model was generated from each method, the models were used to predict N_v values for the subset of the compositions that was held out for validation. Because of the consistency between the predictions from the two models in the whole data range, predictions from the gaussian process were used, as it also provides guidance with the predicted variance. The explored compositional ranges expressed in mole % on an oxide basis are shown in Table 2.

Table 2

SiO ₂	Al ₂ O ₃	B ₂ O ₃	MgO	CaO	SrO	BaO	TiO ₂	ZnO	Y ₂ O ₃	La ₂ O ₃	P ₂ O ₅
69.25	12.00	1.00	4.00	5.00	0.00	2.50	0.00	0.00	0.00	0.00	0.00
70.75	13.50	2.00	6.00	6.50	1.50	4.00	1.50	0.75	1.00	1.00	0.50

[0060] Within this composition range, the models were used to predict N_v values in a grid of 0.25 mole% steps for each of the oxides. The set of glass compositions with N_v values less than 16 ppm were then chosen. From there, the glass compositional space of interest was

described by a Convex Hull, which is the smallest convex boundary that contains a set of points in a given dimensional space.

[0061] The Nv value resulting from the Nv thermal cycle will be relative to the method of manufacture of the glass used. This is at least due to the fact that hydroxyl content (“water”) of the glass may vary from process to process, and high water content is believed to be a driver for non-viscous relaxation. For example, melts produced on one set of equipment may be drier than glass produced on another set of equipment. Therefore, the Nv value may vary even within the same composition. Nevertheless, it has been found that the models described herein still accurately capture Nv cycle values even with the water discrepancy, indicating that overall water concentration change between melting systems is not large enough to affect the ability to model relative changes among glass compositions accurately.

[0062] The glass composition may include silica (SiO_2). Silica plays a role of a main glass former. Silica may help increase the liquidus viscosity and, therefore, protect a glass composition from crystallization. However, adding SiO_2 to a glass composition may cause liquid-liquid phase separation, which may cause devitrification and/or reduce the transmittance of the resulting glass. Also, SiO_2 is a low refractive index component and makes it difficult to achieve high index glasses. In embodiments, the glass may contain SiO_2 in an amount from greater than or equal to 69 mol.% to less than or equal to 72 mol.%, for example in a range from about 69 mol.% to about 71.8 mol%, in a range from about 69 mol% to about 71.6 mol%, in a range from about 69 mol% to about 71.4 mol%, in a range from about 69 mol% to about 71.2 mol%, in a range from about 69 mol% to about 71 mol%, in a range from about 69 mol% to about 69.8 mol%, in a range from about 69 mol% to about 69.6 mol%, or in a range from about 69 mol% to about 69.4 mol%, including all ranges and sub-ranges therebetween. In further embodiments, the glass composition may contain SiO_2 in an amount in a range from about 69.2 mol% to about 72 mol%, in a range from about 69.4 mol% to about 72 mol%, in a range from about 69.6 mol% to about 72 mol%, in a range from about 69.8 mol% to about 72 mol%, in a range from about 70.0 to about 72 mol%, in a range from about 70.2 mol% to about 72 mol%, in a range from about 70.4 mol% to about 72 mol%, in a range from about 70.6 mol% to about 72 mol%, in a range from about 70.8 mol% to about 72 mol%, in a range from about 71 mol% to about 72 mol%, in a range from about 71.2 mol% to about 72 mol%, in a range from about 71.4 mol% to about 72 mol%, in a range from about 71.6 mol% to about 72 mol%, or in a range from about 71.8 mol% to about 72 mol%, including all ranges and subranges therebetween.

[0063] Glass compositions described herein comprise phosphorus oxide (P_2O_5) as a glass former. Greater amounts of P_2O_5 increase the melt viscosity at a given temperature, which inhibits crystallization from the melt when cooling and, therefore, improves the glass-forming ability of the melt (i.e., lowers the critical cooling rate of the melt). However, P_2O_5 , when added to a glass composition, significantly decreases the refractive index, which makes it more difficult to reach a high refractive index. Accordingly, the content of P_2O_5 in high-index glasses may be limited. In embodiments, the glass may contain P_2O_5 in an amount from equal to or less than about 1 mol.%, for example equal to or less than about 0.75 mol.%, or equal to or less than about 0.5 mol.%, including all ranges and sub-ranges therebetween.

[0064] The glass composition may include divalent metal oxides (RO). Divalent metal oxides, such as alkaline earth metal oxides (e.g., MgO, CaO, SrO and BaO), zinc oxide (ZnO), cadmium oxide (CdO), lead oxide (PbO) and others, when added to a glass, provide comparably high refractive indexes, greater than those for most of monovalent oxides. Some divalent metal oxides, such as, for example, CaO, SrO, and ZnO, also provide comparably low density, therefore, increasing the ratio of the refractive index to density and, accordingly, improving the performance of optical glasses in certain applications. In addition, divalent metal oxides may help to increase the solubility of high index components, such as TiO_2 , which indirectly leads to a further increase in the refractive index at a comparable density. Also, some divalent metal oxides, such as, for example, ZnO and MgO, provide comparably low thermal expansion coefficient, which may reduce the thermal stresses formed in the glass articles when cooling and, therefore, improve the quality of the glass articles. However, when adding at high amounts, divalent metal oxides may cause crystallization of refractory minerals from the melts or liquid-liquid phase separation, which may reduce the glass-forming ability of glasses. Accordingly, the amount of some divalent metal oxides in glass compositions of the present disclosure may be limited.

[0065] The glass composition may include calcium oxide (CaO). Calcium oxide provides the highest ratio of the refractive index to density of glasses among the known monovalent and divalent metal oxides. Also, in some embodiments, CaO may help to increase the solubility of Nb_2O_5 and TiO_2 , which additionally contributes to an increase in refractive index at comparably low density. In embodiments, the glass may contain CaO in an amount from greater than or equal to 0 mol.% to less than or equal to 16 mol.%, for example in a range from about 0 mol% to about 15 mol%, in a range from about 0 mol% to about 14 mol%, in a range from about 0 mol% to about 13 mol%, in a range from about 0 mol% to about 12 mol%, in a range from about 0 mol% to about 11 mol%, in a range from about 0 mol% to about 10 mol%,

in a range from about 0 mol% to about 9 mol%, in a range from about 0 mol% to about 8 mol%, in a range from about 0 mol% to about 7 mol%, in a range from about 0 mol% to about 6 mol%, in a range from about 0 mol% to about 5 mol%, in a range from about 0 mol% to about 4 mol%, in a range from about 0 mol% to about 3 mol%, in a range from about 0 mol% to about 2 mol%, or in a range from about 0 mol% to about 1 mol%, including all ranges and subranges therebetween. In embodiments, the glass composition may contain CaO in an amount in a range from about 1 mol% to about 16 mol%, for example in a range from about 2 mol% to about 16 mol%, in a range from about 3 mol% to about 16 mol%, in a range from about 4 mol% to about 16 mol%, in a range from about 5 mol% to about 16 mol%, in a range from about 6 mol% to about 16 mol%, in a range from about 7 mol% to about 16 mol%, in a range from about 8 mol% to about 16 mol%, in a range from about 9 mol% to about 16 mol%, in a range from about 10 mol% to about 16 mol%, in a range from about 11 mol% to about 16 mol%, in a range from about 12 mol% to about 16 mol%, in a range from about 13 mol% to about 16 mol%, in a range from about 14 mol% to about 16 mol%, or in a range from about 15 mol% to about 16 mol%, including all ranges and subranges therebetween.

[0066] The glass composition may include barium oxide (BaO). Barium oxide may increase the solubility of high index components, such as TiO₂, more than other divalent metal oxides, which may indirectly lead to a further increase in the refractive index at comparably low density. However, barium is a heavy element and, being added in a high amount, may increase the density of the glass. Also, at high concentration, it may cause crystallization of such minerals as barium titanate (BaTiO₃), barium niobate (BaNb₂O₆), barium orthophosphate (Ba₃P₂O₈) and others, which may cause crystallization of a melt when cooling. Accordingly, the amount of BaO in glasses of the present disclosure may contain barium oxide (BaO) in an amount from about 0 mol% to about 17.0 mol%, for example in a range from about 1 mol% to about 17 mol%, in a range from about 2 mol% to about 17 mol%, in a range from about 3 mol% to about 17 mol%, in a range from about 4 mol% to about 17 mol%, in a range from about 5 mol% to about 17 mol%, in a range from about 6 mol% to about 17 mol%, in a range from about 7 mol% to about 17 mol%, in a range from about 8 mol% to about 17 mol%, in a range from about 9 mol% to about 17 mol%, in a range from about 10 mol% to about 17 mol%, in a range from about 11 mol% to about 17 mol%, in a range from about 12 mol% to about 17 mol%, in a range from about 13 mol% to about 17 mol%, in a range from about 14 mol% to about 17 mol%, in a range from about 15 mol% to about 17 mol%, or in a range from about 16 mol% to about 17 mol%, including all ranges and subranges therebetween and all ranges and sub-ranges between the foregoing values.

[0067] The glass composition may contain BaO in an amount in a range from about 0 mol% to about 16 mol%, for example in a range from about 0 mol% to about 15 mol%, in a range from about 0 mol% to about 14 mol%, in a range from about 0 mol% to about 13 mol%, in a range from about 0 mol% to about 12 mol%, in a range from about 0 mol% to about 11 mol%, in a range from about 0 mol% to about 10 mol%, in range from about 0 mol% to about 9 mol%, in a range from about 0 mol% to about 8 mol%, in a range from about 0 mol% to about 7 mol%, in a range from about 0 mol% to about 6 mol%, in a range from about 0 mol% to about 5 mol%, in a range from about 0 mol% to about 4 mol%, in a range from about 0 mol% to about 3 mol%, in a range from about 0 mol% to about 2 mol%, or in a range from about 0 mol% to about 1 mol%, including all ranges and subranges therebetween.

[0068] The glass composition may include magnesia (MgO). Magnesia reduces the thermal expansion coefficient, which may be useful for reduction of thermal stresses formed in the glass articles when cooling them. However, magnesia provides a lower refractive index and a lower increase in the solubility of high index components than other divalent metal oxides, such as, for example, BaO, SrO, CaO and ZnO. Accordingly, the amount of MgO in glass compositions of the present disclosure may be limited, or the glasses may be substantially free of MgO. In embodiments, the glasses may contain magnesia (MgO) in an amount from about 0 mol.% to about 17 mol% including all ranges and sub-ranges between the foregoing values.

[0069] In embodiments, the glass composition may contain MgO in a range from about 1 mol% to about 17 mol%, in a range from about 2 mol% to about 17 mol%, in a range from about 3 mol% to about 17 mol%, in a range from about 4 mol% to about 17 mol%, in a range from about 5 mol% to about 17 mol%, in a range from about 6 mol% to about 17 mol%, in a range from about 7 mol% to about 17 mol%, in range from about 8 mol% to about 17 mol%, in a range from about 9 mol% to about 17 mol%, in a range from about 10 mol% to about 17 mol%, in a range from about 11 mol% to about 17 mol%, in a range from about 12 mol% to about 17 mol%, in a range from about 13 mol% to about 17 mol%, in a range from about 14 mol% to about 17 mol%, in a range from about 15 mol% to about 17 mol%, or in a range from about 16 mol% to about 17 mol%, including all ranges and subranges therebetween.

[0070] The glass composition may contain MgO in an amount in a range from about 1 mol% to about 16 mol%, for example in a range from about 1 mol% to about 15 mol%, in a range from about 1 mol% to about 14 mol%, in a range from about 1 mol% to about 13 mol%, in a range from about 1 mol% to about 12 mol%, in a range from about 1 mol% to about 11 mol%, in a range from about 1 mol% to about 10 mol%, in range from about 1 mol% to about 9 mol%, in a range from about 1 mol% to about 8 mol%, in a range from about 1 mol% to about 7 mol%,

in a range from about 1 mol% to about 6 mol%, in a range from about 1 mol% to about 5 mol%, in a range from about 1 mol% to about 4 mol%, in a range from about 1 mol% to about 3 mol%, or in a range from about 1 mol% to about 2 mol%, including all ranges and subranges therebetween.

[0071] The glass composition may include strontium oxide (SrO) in an amount from about 0 mol% to about 16 mol%, for example or in a range from about 1 mol% to about 16 mol%, in a range from about 2 mol% to about 16 mol%, in a range from about 3 mol% to about 16 mol%, in a range from about 4 mol% to about 16 mol%, in a range from about 5 mol% to about 16 mol%, in a range from about 6 mol% to about 16 mol%, in a range from about 7 mol% to about 16 mol%, in range from about 8 mol% to about 16 mol%, in a range from about 9 mol% to about 16 mol%, in a range from about 10 mol% to about 16 mol%, in a range from about 11 mol% to about 16 mol%, in a range from about 12 mol% to about 16 mol%, in a range from about 13 mol% to about 16 mol%, in a range from about 14 mol% to about 16 mol%, or in a range from about 15 mol% to about 16 mol%, including all ranges and subranges therebetween and all ranges and sub-ranges between the foregoing values.

[0072] The glass composition may contain SrO in an amount in a range from about 1 mol% to about 15 mol%, in a range from about 1 mol% to about 14 mol%, in a range from about 1 mol% to about 13 mol%, in a range from about 1 mol% to about 12 mol%, in a range from about 1 mol% to about 11 mol%, in a range from about 1 mol% to about 10 mol%, in range from about 1 mol% to about 9 mol%, in a range from about 1 mol% to about 8 mol%, in a range from about 1 mol% to about 7 mol%, in a range from about 1 mol% to about 6 mol%, in a range from about 1 mol% to about 5 mol%, in a range from about 1 mol% to about 4 mol%, in a range from about 1 mol% to about 3 mol%, or in a range from about 1 mol% to about 2 mol%, including all ranges and subranges therebetween.

[0073] In embodiments, the glass composition may comprise ZnO in an amount in a range from about 0 mol% to about 1 mol%, for example in a range from about 0.25 mol% to about 1 mol%, in a range from about 0.5 mol% to about 1 mol%, or in a range from about 0.75 mol% to about 1 mol%, including all ranges and subranges therebetween.

[0074] The glass composition may include alumina (Al_2O_3). Alumina may increase the viscosity of glass-forming melts at high temperature, which may reduce the critical cooling rate and improve the glass forming ability. However, in high-index phosphate glasses, addition of Al_2O_3 may cause crystallization of refractory minerals, such as aluminum phosphate (AlPO_4), aluminum titanate (Al_2TiO_5), aluminum niobate (AlNbO_4) and others, in the glass-forming melts when cooling. Accordingly, the amount of Al_2O_3 in glasses of the present disclosure is

limited, or glasses may be substantially free of Al_2O_3 . In embodiments, the glass may contain alumina (Al_2O_3) in an amount from about 11 mol% to about 15 mol%, for example in a range from about 12 mol% to about 15 mol%, in a range from about 13 mol% to about 15 mol%, in a range from about 14 mol% to about 15 mol%, including all ranges and subranges therebetween. The glass may contain alumina (Al_2O_3) in an amount from about 11 mol% to about 14 mol%, for example in a range from about 11 mol% to about 13 mol%, or in a range from about 11 mol% to about 12 mol%, including all ranges and subranges therebetween.

[0075] The glass composition may include titania (TiO_2). High refractive index glasses typically include species, such as TiO_2 , that absorb at least a portion of optical light, particularly light in the blue and near-UV regions of the electromagnetic spectrum. In embodiments, the glass may contain titania (TiO_2) in an amount from greater than or equal to 0 mol.% to about 2 mol%, for example in a range from about 0.5 mol% to about 2 mol%, in a range from about 1 mol% to about 2 mol%, or in a range from about 1.5 mol% to about 2 mol%, including all ranges and sub-ranges therebetween.

[0076] In embodiments, the glass may comprise Y_2O_3 in an amount in a range from about 0 mol% to about 1 mol%, for example in a range from about 0.25 mol% to about 1 mol%, in a range from about 0.5 mol% to about 1 mol%, or in a range from about 0.75 mol% to about 1 mol%, including all ranges and subranges therebetween.

[0077] In embodiments, the glass may comprise La_2O_3 in an amount in a range from about 0 mol% to about 1 mol%, for example in a range from about 0.25 mol% to about 1 mol%, in a range from about 0.5 mol% to about 1 mol%, or in a range from about 0.75 mol% to about 1 mol%, including all ranges and subranges therebetween.

[0078] In embodiments, an anneal point (temperature) of the glasses may be equal to or greater than about 760°C , for example in a range from about 760°C to about 900°C , for example in a range from about 760°C to about 890°C , in a range from about 760°C to about 880°C , in a range from about 760°C to about 870°C , in a range from about 760°C to about 860°C , in a range from about 760°C to about 840°C , in a range from about 760°C to about 830°C , in a range from about 760°C to about 820°C , in a range from about 760°C to about 810°C , in a range from about 760°C to about 800°C , in a range from about 760°C to about 800°C , in a range from about 760°C to about 790°C , in a range from about 760°C to about 780°C , or in a range from about 760°C to about 770°C , including all ranges and subranges therebetween.

[0079] In embodiments, the anneal point of the glasses may be in a range from about 770°C to about 900°C, for example in a range from about 780°C to about 900°C, in a range from about 790°C to about 900°C, in a range from about 800°C to about 900°C, in a range from about 810°C to about 900°C, in a range from about 820°C to about 900°C, in a range from about 830°C to about 900°C, in a range from about 840°C to about 900°C, in a range from about 850°C to about 900°C, in a range from about 860°C to about 900°C, in a range from about 870°C to about 900°C, in a range from about 880°C to about 900°C, or in a range from about 890°C to about 900°C, including all ranges and subranges therebetween

[0080] In embodiments, a convex hull containing exemplary glass compositions can be described, wherein the glass composition comprises:

greater than or equal to 69.25 mol.% and less than or equal to 70.75 mol.% SiO₂,
 greater than or equal to 12.00 mol.% and less than or equal to 13.50 mol.% Al₂O₃,
 greater than or equal to 1.00 mol.% and less than or equal to 2.00 mol.% B₂O₃,
 greater than or equal to 4.00 mol.% and less than or equal to 6.00 mol.% MgO,
 greater than or equal to 5.00 mol.% and less than or equal to 6.50 mol.% CaO,
 greater than or equal to 0.00 mol.% and less than or equal to 1.50 mol.% SrO,
 greater than or equal to 2.50 mol.% and less than or equal to 4.00 mol.% BaO,
 greater than or equal to 0.00 mol.% and less than or equal to 1.50 mol.% TiO₂,
 greater than or equal to 0.00 mol.% and less than or equal to 0.75 mol.% ZnO,
 greater than or equal to 0.00 mol.% and less than or equal to 1.00 mol.% Y₂O₃,
 greater than or equal to 0.00 mol.% and less than or equal to 1.00 mol.% La₂O₃,
 greater than or equal to 0.00 mol.% and less than or equal to 0.50 mol.% P₂O₅; and

wherein the glass satisfies the condition:

Intercept + $\sum_{i=SiO_2}^{P_{205}} X_i * Y_i \leq 16$, where the symbol "*" means multiplication, and

Intercept = -11.20751259, and the coefficients X_i for the component oxides are:

SiO₂ = -0.002926308,

Al₂O₃ = -0.004673511,

B₂O₃ = -0.001118634,

MgO = 1.126496816,

CaO = 1.615716878,

SrO = 3.063872526,

BaO = 1.551023535,

TiO₂ = -0.004673511,

$$\text{ZnO} = 0,$$

$$\text{Y}_2\text{O}_3 = -0.001118634,$$

$$\text{La}_2\text{O}_3 = -0.001118634, \text{ and}$$

$$\text{P}_2\text{O}_5 = -2.235863244.$$

[0081] The Intercept and the coefficients X_i for the various component oxides are listed above, while the Y_i values are the corresponding concentrations in mol%. The oxides can be divided into three groups, group V1, group V2, and group V3, where:

$$\text{V1} = \text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{B}_2\text{O}_3$$

$$\text{V2} = \text{MgO} + \text{CaO} + \text{BaO} + \text{SnO}_2$$

$$\text{V3} = \text{TiO}_2 + \text{ZnO} + \text{La}_2\text{O}_3 + \text{La}_2\text{O}_3 + \text{P}_2\text{O}_5, \text{ and where}$$

V1 is in a range from 82.25 to 86.25,

V2 is in a range from 13.00 to 17.50, and

V3 is in a range from 0.00 to 4.75.

[0082] A graphical representation of the convex hull is shown in FIG. 9. Boundary points of the convex hull are provided below in Table 3.

Table 3

V1	V2	V3
82.25	13.00	4.75
82.50	13.00	4.50
82.75	13.00	4.25
83.00	13.00	4.00
83.25	13.00	3.75
83.50	13.00	3.50
83.75	13.00	3.25
84.00	13.00	3.00
84.25	13.00	2.75
84.50	13.00	2.50
84.75	13.00	2.25
85.00	13.00	2.00
85.25	13.00	1.75
85.50	13.00	1.50
85.75	13.00	1.25
86.00	13.00	1.00
86.25	13.00	0.75
86.25	13.50	0.25
86.00	14.00	0.00
85.50	14.50	0.00
85.00	15.00	0.00
84.50	15.50	0.00

84.00	16.00	0.00
83.50	16.50	0.00
83.00	17.00	0.00
82.50	17.50	0.00
82.25	17.50	0.25
82.25	17.00	0.75
82.25	16.50	1.25
82.25	16.00	1.75
82.25	15.50	2.25
82.25	15.00	2.75
82.25	14.50	3.25
82.25	14.00	3.75
82.25	13.50	4.25
82.25	13.00	4.75

[0083] In other embodiments, another convex hull containing exemplary glass compositions can be described, the glass composition comprising:

greater than or equal to 69.25 mol.% and less than or equal to 70.75 mol.% SiO₂,
greater than or equal to 12.00 mol.% and less than or equal to 13.50 mol.% Al₂O₃,
greater than or equal to 1.00 mol.% and less than or equal to 2.00 mol.% B₂O₃,
greater than or equal to 4.00 mol.% and less than or equal to 6.00 mol.% MgO,
greater than or equal to 5.00 mol.% and less than or equal to 6.50 mol.% CaO,
greater than or equal to 0.00 mol.% and less than or equal to 1.50 mol.% SrO,
greater than or equal to 2.50 mol.% and less than or equal to 4.00 mol.% BaO,
greater than or equal to 0.00 mol.% and less than or equal to 1.50 mol.% TiO₂,
greater than or equal to 0.00 mol.% and less than or equal to 0.75 mol.% ZnO,
greater than or equal to 0.00 mol.% and less than or equal to 1.00 mol.% Y₂O₃,
greater than or equal to 0.00 mol.% and less than or equal to 1.00 mol.% La₂O₃,
greater than or equal to 0.00 mol.% and less than or equal to 0.50 mol.% P₂O₅; and

wherein the glass satisfies the condition: $\text{Intercept} + \sum_{i=\text{SiO}_2}^{P2O5} X_i * Y_i \leq 13$, where the symbol “*” means multiplication, Intercept = -234.7571088, the values Y_i are the oxide component amounts in mol%, the coefficients X_i are:

SiO₂ = 2.232090497,
Al₂O₃ = 2.230475478,
B₂O₃ = 2.233717001,
MgO = 3.368563490,
CaO = 3.851331728,
SrO = 5.301366502,

$\text{BaO} = 3.788612774,$
 $\text{TiO}_2 = 2.230475478,$
 $\text{ZnO} = 2.23468972,$
 $\text{Y}_2\text{O}_3 = 2.233717001,$
 $\text{La}_2\text{O}_3 = 2.233717001,$ and
 $\text{P}_2\text{O}_5 = 0.$

[0084] The Intercept and the coefficients X_i for the various component oxides are listed above, while the Y_i values are the corresponding concentrations in mole%. The oxides can be divided into three groups, group V1, group V2, and group V3, where:

$\text{V1} = \text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{B}_2\text{O}_3$
 $\text{V2} = \text{MgO} + \text{CaO} + \text{BaO} + \text{SnO}_2$
 $\text{V3} = \text{TiO}_2 + \text{ZnO} + \text{La}_2\text{O}_3 + \text{P}_2\text{O}_5,$ and where
 V1 is in a range from 82.25 to 86.25,
 V2 is in a range from 13.00 to 17.50, and
 V3 is in a range from 0.00 to 4.75.

[0085] A graphical representation of the convex hull is shown in FIG. 10. Boundary points of the convex hull are provided below in Table 4.

Table 4

V1	V2	V3
82.25	13.00	4.75
82.50	13.00	4.50
82.75	13.00	4.25
83.00	13.00	4.00
83.25	13.00	3.75
83.50	13.00	3.50
83.75	13.00	3.25
84.00	13.00	3.00
84.25	13.00	2.75
84.50	13.00	2.50
84.75	13.00	2.25
85.00	13.00	2.00
85.25	13.00	1.75
85.50	13.00	1.50
85.75	13.00	1.25
86.00	13.00	1.00
86.25	13.00	0.75
86.25	13.50	0.25

86.00	14.00	0.00
85.50	14.50	0.00
85.00	15.00	0.00
84.50	15.50	0.00
84.00	16.00	0.00
83.50	16.50	0.00
83.00	17.00	0.00
82.75	17.00	0.25
82.50	17.00	0.50
82.25	17.00	0.75
82.25	16.50	1.25
82.25	16.00	1.75
82.25	15.50	2.25
82.25	15.00	2.75
82.25	14.50	3.25
82.25	14.00	3.75
82.25	13.50	4.25
82.25	13.00	4.75

[0086] In still other embodiments, another convex hull containing exemplary glass compositions can be described, the glass composition comprising:

greater than or equal to 69.25 mol.% and less than or equal to 70.75 mol.% SiO₂,
greater than or equal to 12.00 mol.% and less than or equal to 13.50 mol.% Al₂O₃,
greater than or equal to 1.00 mol.% and less than or equal to 2.00 mol.% B₂O₃,
greater than or equal to 4.00 mol.% and less than or equal to 6.00 mol.% MgO,
greater than or equal to 5.00 mol.% and less than or equal to 6.50 mol.% CaO,
greater than or equal to 0.00 mol.% and less than or equal to 1.50 mol.% SrO,
greater than or equal to 2.50 mol.% and less than or equal to 4.00 mol.% BaO,
greater than or equal to 0.00 mol.% and less than or equal to 1.50 mol.% TiO₂,
greater than or equal to 0.00 mol.% and less than or equal to 0.75 mol.% ZnO,
greater than or equal to 0.00 mol.% and less than or equal to 1.00 mol.% Y₂O₃,
greater than or equal to 0.00 mol.% and less than or equal to 1.00 mol.% La₂O₃,
greater than or equal to 0.00 mol.% and less than or equal to 0.50 mol.% P₂O₅; and

wherein the glass satisfies the condition: $\text{Intercept} + \sum_{i=\text{SiO}_2}^{P2O5} X_i * Y_i \leq 10$, where the symbol “*” means multiplication, Intercept = -237.7578217, the values Y_i are the oxide component amounts in mol%, the coefficients X_i are:

$$\text{SiO}_2 = 2.25149345,$$

$$\text{Al}_2\text{O}_3 = 2.250724382,$$

$$\text{B}_2\text{O}_3 = 2.252392713,$$

$\text{MgO} = 3.524128464,$
 $\text{CaO} = 3.890462587,$
 $\text{SrO} = 5.366534992,$
 $\text{BaO} = 3.897785139,$
 $\text{TiO}_2 = 2.250724382,$
 $\text{ZnO} = 2.253175066,$
 $\text{Y}_2\text{O}_3 = 2.252392713,$
 $\text{La}_2\text{O}_3 = 2.252392713,$ and
 $\text{P}_2\text{O}_5 = 0.$

[0087] The Intercept and the coefficients X_i for the various component oxides are listed above, while the Y_i values are the corresponding concentrations in mole%. The oxides can be divided into three groups, group V1, group V2, and group V3, where:

$$\text{V1} = \text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{B}_2\text{O}_3$$

$$\text{V2} = \text{MgO} + \text{CaO} + \text{BaO} + \text{SnO}_2$$

$$\text{V3} = \text{TiO}_2 + \text{ZnO} + \text{La}_2\text{O}_3 + \text{P}_2\text{O}_5, \text{ and where}$$

V1 is in a range from 82.25 to 86.25

V2 is in a range from 13.00 to 17.50

V3 is in a range from 0.00 to 4.75

[0088] A graphical representation of the convex hull is shown in FIG. 11. Boundary points of the convex hull are provided below in Table 5.

Table 5

V1	V2	V3
82.25	13.00	4.75
82.50	13.00	4.50
82.75	13.00	4.25
83.00	13.00	4.00
83.25	13.00	3.75
83.50	13.00	3.50
83.75	13.00	3.25
84.00	13.00	3.00
84.25	13.00	2.75
84.50	13.00	2.50
84.75	13.00	2.25
85.00	13.00	2.00
85.25	13.00	1.75
85.50	13.00	1.50

85.75	13.00	1.25
86.00	13.00	1.00
86.25	13.00	0.75
86.25	13.50	0.25
86.00	14.00	0.00
85.50	14.50	0.00
85.00	15.00	0.00
84.50	15.50	0.00
83.75	16.00	0.25
83.00	16.50	0.50
82.75	16.50	0.75
82.50	16.50	1.00
82.25	16.50	1.25
82.25	16.00	1.75
82.25	15.50	2.25
82.25	15.00	2.75
82.25	14.50	3.25
82.25	14.00	3.75
82.25	13.50	4.25
82.25	13.00	4.75

[0089] In yet other embodiments, another convex hull containing exemplary glass compositions can be described, the glass composition comprising:

greater than or equal to 69.25 mol.% and less than or equal to 70.75 mol.% SiO₂,
greater than or equal to 12.00 mol.% and less than or equal to 13.50 mol.% Al₂O₃,
greater than or equal to 1.00 mol.% and less than or equal to 2.00 mol.% B₂O₃,
greater than or equal to 4.00 mol.% and less than or equal to 6.00 mol.% MgO,
greater than or equal to 5.00 mol.% and less than or equal to 6.50 mol.% CaO,
greater than or equal to 0.00 mol.% and less than or equal to 1.50 mol.% SrO,
greater than or equal to 2.50 mol.% and less than or equal to 4.00 mol.% BaO,
greater than or equal to 0.00 mol.% and less than or equal to 1.50 mol.% TiO₂,
greater than or equal to 0.00 mol.% and less than or equal to 0.75 mol.% ZnO,
greater than or equal to 0.00 mol.% and less than or equal to 1.00 mol.% Y₂O₃,
greater than or equal to 0.00 mol.% and less than or equal to 1.00 mol.% La₂O₃,
greater than or equal to 0.00 mol.% and less than or equal to 0.50 mol.% P₂O₅; and

wherein the glass satisfies the condition: $\text{Intercept} + \sum_{i=\text{SiO}_2}^{P2O5} X_i * Y_i \leq 8$, where the symbol “*” means multiplication, Intercept = -242.7132028, the values Y_i are the oxide component amounts in mol%, the coefficients X_i are:

SiO₂ = 2.260131924,

$\text{Al}_2\text{O}_3 = 2.260271613,$
 $\text{B}_2\text{O}_3 = 2.26056072,$
 $\text{MgO} = 3.878171611,$
 $\text{CaO} = 4.168656199,$
 $\text{SrO} = 5.552077225,$
 $\text{BaO} = 4.212721511,$
 $\text{TiO}_2 = 2.260271613,$
 $\text{ZnO} = 2.259907435,$
 $\text{Y}_2\text{O}_3 = 2.26056072,$
 $\text{La}_2\text{O}_3 = 2.26056072,$ and
 $\text{P}_2\text{O}_5 = 0.$

[0090] The Intercept and the coefficients X_i for the various component oxides are listed above, while the Y_i values are the corresponding concentrations in mole%. The oxides can be divided into three groups, group V1, group V2, and group V3, where:

$V1 = \text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{B}_2\text{O}_3$
 $V2 = \text{MgO} + \text{CaO} + \text{BaO} + \text{SnO}_2$
 $V3 = \text{TiO}_2 + \text{ZnO} + \text{La}_2\text{O}_3 + \text{P}_2\text{O}_5,$ and where
 V1 is in a range from 82.25 to 86.25
 V2 is in a range from 13.00 to 17.50
 V3 is in a range from 0.00 to 4.75

[0091] A graphical representation of the convex hull is shown in FIG. 12. Boundary points of the convex hull are provided below in Table 6.

Table 6

V1	V2	V3
82.25	13.00	4.75
82.50	13.00	4.50
82.75	13.00	4.25
83.00	13.00	4.00
83.25	13.00	3.75
83.50	13.00	3.50
83.75	13.00	3.25
84.00	13.00	3.00
84.25	13.00	2.75
84.50	13.00	2.50
84.75	13.00	2.25
85.00	13.00	2.00

85.25	13.00	1.75
85.50	13.00	1.50
85.75	13.00	1.25
86.00	13.00	1.00
86.25	13.00	0.75
86.25	13.50	0.25
85.75	14.00	0.25
85.00	14.50	0.50
84.75	14.50	0.75
84.50	14.50	1.00
84.25	14.50	1.25
84.00	14.50	1.50
83.75	14.50	1.75
83.50	14.50	2.00
83.25	14.50	2.25
83.00	14.50	2.50
82.75	14.50	2.75
82.50	14.50	3.00
82.25	14.50	3.25
82.25	14.00	3.75
82.25	13.50	4.25
82.25	13.00	4.75

[0092] FIG. 11 is a plot showing the convex hulls illustrated in FIGS. 7-10, nested into the same plot.

[0093] Given a composition defined by all oxides listed in Table 2, to test if the composition falls within an exemplary convex hull, one can proceed as follows:

[0094] Project the composition(s) in the reduced space with coordinates as:

- a. $V1 = \text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{B}_2\text{O}_3$
- b. $V2 = \text{MgO} + \text{CaO} + \text{SrO} + \text{BaO}$
- c. $V3 = \text{TiO}_2 + \text{ZnO} + \text{La}_2\text{O}_3 + \text{P}_2\text{O}_5 + \text{Y}_2\text{O}_3$

[0095] Run the code distributed by MatLab®,

inhul(P,K) where K is the set of boundary points depending on the convex hull being tested.

[0096] If the response is 0, the point(s) K is (are) not within the space delimited by K

[0097] If the response is 1, the point(s) K is (are) within the space delimited by K

[0098] It will be apparent to those skilled in the art that various modifications and variations can be made to embodiments of the present disclosure without departing from the spirit and scope of the disclosure. Thus, it is intended that the present disclosure cover such modifications

and variations provided they come within the scope of the appended claims and their equivalents.

What is claimed is:

1. A glass comprising a plurality of components, the glass having a composition of the components comprising, on an oxide basis:

greater than or equal to 69.25 mol.% and less than or equal to 70.75 mol.% SiO₂,
 greater than or equal to 12.00 mol.% and less than or equal to 13.50 mol.% Al₂O₃,
 greater than or equal to 1.00 mol.% and less than or equal to 2.00 mol.% B₂O₃,
 greater than or equal to 4.00 mol.% and less than or equal to 6.00 mol.% MgO,
 greater than or equal to 5.00 mol.% and less than or equal to 6.50 mol.% CaO,
 greater than or equal to 0.00 mol.% and less than or equal to 1.50 mol.% SrO,
 greater than or equal to 2.50 mol.% and less than or equal to 4.00 mol.% BaO,
 greater than or equal to 0.00 mol.% and less than or equal to 1.50 mol.% TiO₂,
 greater than or equal to 0.00 mol.% and less than or equal to 0.75 mol.% ZnO,
 greater than or equal to 0.00 mol.% and less than or equal to 1.00 mol.% Y₂O₃,
 greater than or equal to 0.00 mol.% and less than or equal to 1.00 mol.% La₂O₃,
 greater than or equal to 0.00 mol.% and less than or equal to 0.50 mol.% P₂O₅; and

wherein the glass satisfies the condition: $\text{Intercept} + \sum_{i=\text{SiO}_2}^{P_{2O5}} X_i * Y_i \leq 16$, where the symbol “*” means multiplication, Intercept = -11.20751259, the values Y_i are the oxide component amounts in mol%, the coefficients X_i are,

SiO₂ = -0.002926308,
 Al₂O₃ = -0.004673511,
 B₂O₃ = -0.001118634,
 MgO = 1.126496816,
 CaO = 1.615716878,
 SrO = 3.063872526,
 BaO = 1.551023535,
 TiO₂ = -0.004673511,
 ZnO = 0,
 Y₂O₃ = -0.001118634,
 La₂O₃ = -0.001118634,
 P₂O₅ = -2.235863244; and

wherein,

$\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{B}_2\text{O}_3$ is in a range from 82.25 mol% to 86.25 mol%,

$\text{MgO} + \text{CaO} + \text{BaO} + \text{SnO}_2$ is in a range from 13.00 mol% to 17.50 mol%, and

$\text{TiO}_2 + \text{ZnO} + \text{La}_2\text{O}_3 + \text{P}_2\text{O}_5$ is in a range from 0.00 mol% to 4.75 mol%.

2. A glass comprising a plurality of components, the glass having a composition of the components comprising, on an oxide basis:

greater than or equal to 69.25 mol.% and less than or equal to 70.75 mol.% SiO_2 ,

greater than or equal to 12.00 mol.% and less than or equal to 13.50 mol.% Al_2O_3 ,

greater than or equal to 1.00 mol.% and less than or equal to 2.00 mol.% B_2O_3 ,

greater than or equal to 4.00 mol.% and less than or equal to 6.00 mol.% MgO ,

greater than or equal to 5.00 mol.% and less than or equal to 6.50 mol.% CaO ,

greater than or equal to 0.00 mol.% and less than or equal to 1.50 mol.% SrO ,

greater than or equal to 2.50 mol.% and less than or equal to 4.00 mol.% BaO ,

greater than or equal to 0.00 mol.% and less than or equal to 1.50 mol.% TiO_2 ,

greater than or equal to 0.00 mol.% and less than or equal to 0.75 mol.% ZnO ,

greater than or equal to 0.00 mol.% and less than or equal to 1.00 mol.% Y_2O_3 ,

greater than or equal to 0.00 mol.% and less than or equal to 1.00 mol.% La_2O_3 ,

greater than or equal to 0.00 mol.% and less than or equal to 0.50 mol.% P_2O_5 ; and

wherein the glass satisfies the condition: $\text{Intercept} + \sum_{i=\text{SiO}_2}^{\text{P}_2\text{O}_5} X_i * Y_i \leq 13$, where the symbol “*” means multiplication, Intercept = -234.7571088, the values Y_i are the oxide component amounts in mol%, the coefficients X_i are,

$\text{SiO}_2 = 2.232090497$,

$\text{Al}_2\text{O}_3 = 2.230475478$,

$\text{B}_2\text{O}_3 = 2.233717001$,

$\text{MgO} = 3.368563490$,

$\text{CaO} = 3.851331728$,

$\text{SrO} = 5.301366502$,

$\text{BaO} = 3.788612774$,

$\text{TiO}_2 = 2.230475478$,

$\text{ZnO} = 2.23468972$,

$\text{Y}_2\text{O}_3 = 2.233717001$,

$\text{La}_2\text{O}_3 = 2.233717001$,

$P_2O_5 = 0$; and

wherein,

$SiO_2 + Al_2O_3 + B_2O_3$ is in a range from 82.25 mol% to 86.25 mol%

$MgO + CaO + BaO + SnO_2$ is in a range from 13.00 mol% to 17.50 mol%, and

$TiO_2 + ZnO + La_2O_3 + P_2O_5$ is in a range from 0.00 mol% to 4.75 mol%.

3. A glass comprising a plurality of components, the glass having a composition of the components comprising, on an oxide basis:

greater than or equal to 69.25 mol.% and less than or equal to 70.75 mol.% SiO_2 ,

greater than or equal to 12.00 mol.% and less than or equal to 13.50 mol.% Al_2O_3 ,

greater than or equal to 1.00 mol.% and less than or equal to 2.00 mol.% B_2O_3 ,

greater than or equal to 4.00 mol.% and less than or equal to 6.00 mol.% MgO ,

greater than or equal to 5.00 mol.% and less than or equal to 6.50 mol.% CaO ,

greater than or equal to 0.00 mol.% and less than or equal to 1.50 mol.% SrO ,

greater than or equal to 2.50 mol.% and less than or equal to 4.00 mol.% BaO ,

greater than or equal to 0.00 mol.% and less than or equal to 1.50 mol.% TiO_2 ,

greater than or equal to 0.00 mol.% and less than or equal to 0.75 mol.% ZnO ,

greater than or equal to 0.00 mol.% and less than or equal to 1.00 mol.% Y_2O_3 ,

greater than or equal to 0.00 mol.% and less than or equal to 1.00 mol.% La_2O_3 ,

greater than or equal to 0.00 mol.% and less than or equal to 0.50 mol.% P_2O_5 ; and

wherein the glass satisfies the condition: $\text{Intercept} + \sum_{i=SiO_2}^{P_2O_5} X_i * Y_i \leq 10$, where the symbol “*” means multiplication, Intercept = -237.7578217, the values Y_i are the oxide component amounts in mol%, the coefficients X_i are,

$SiO_2 = 2.25149345$,

$Al_2O_3 = 2.250724382$,

$B_2O_3 = 2.252392713$,

$MgO = 3.524128464$,

$CaO = 3.890462587$,

$SrO = 5.366534992$,

$BaO = 3.897785139$,

$TiO_2 = 2.250724382$,

$ZnO = 2.253175066$,

$Y_2O_3 = 2.252392713$,

$$\text{La}_2\text{O}_3 = 2.252392713,$$

$$\text{P}_2\text{O}_5 = 0; \text{ and}$$

wherein,

$$\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{B}_2\text{O}_3 \text{ is in a range from } 82.25 \text{ mol\% to } 86.25 \text{ mol\%,}$$

$$\text{MgO} + \text{CaO} + \text{BaO} + \text{SnO}_2 \text{ is in a range from } 13.00 \text{ mol\% to } 17.50 \text{ mol\%, and}$$

$$\text{TiO}_2 + \text{ZnO} + \text{La}_2\text{O}_3 + \text{La}_2\text{O}_3 + \text{P}_2\text{O}_5 \text{ is in a range from } 0.00 \text{ mol\% to } 4.75 \text{ mol\%}.$$

4. A glass comprising a plurality of components, the glass having a composition of the components comprising, on an oxide basis:

greater than or equal to 69.25 mol.% and less than or equal to 70.75 mol.% SiO_2 ,

greater than or equal to 12.00 mol.% and less than or equal to 13.50 mol.% Al_2O_3 ,

greater than or equal to 1.00 mol.% and less than or equal to 2.00 mol.% B_2O_3 ,

greater than or equal to 4.00 mol.% and less than or equal to 6.00 mol.% MgO ,

greater than or equal to 5.00 mol.% and less than or equal to 6.50 mol.% CaO ,

greater than or equal to 0.00 mol.% and less than or equal to 1.50 mol.% SrO ,

greater than or equal to 2.50 mol.% and less than or equal to 4.00 mol.% BaO ,

greater than or equal to 0.00 mol.% and less than or equal to 1.50 mol.% TiO_2 ,

greater than or equal to 0.00 mol.% and less than or equal to 0.75 mol.% ZnO ,

greater than or equal to 0.00 mol.% and less than or equal to 1.00 mol.% Y_2O_3 ,

greater than or equal to 0.00 mol.% and less than or equal to 1.00 mol.% La_2O_3 ,

greater than or equal to 0.00 mol.% and less than or equal to 0.50 mol.% P_2O_5 ; and

wherein the glass satisfies the condition: $\text{Intercept} + \sum_{i=\text{SiO}_2}^{\text{P}_2\text{O}_5} X_i * Y_i \leq 10$, where the symbol “*” means multiplication, Intercept = -242.7132028, the values Y_i are the oxide component amounts in mol%, the coefficients X_i are,

$$\text{SiO}_2 = 2.260131924,$$

$$\text{Al}_2\text{O}_3 = 2.260271613,$$

$$\text{B}_2\text{O}_3 = 2.26056072,$$

$$\text{MgO} = 3.878171611,$$

$$\text{CaO} = 4.168656199,$$

$$\text{SrO} = 5.552077225,$$

$$\text{BaO} = 4.212721511,$$

$$\text{TiO}_2 = 2.260271613,$$

$$\text{ZnO} = 2.259907435,$$

$$\text{Y}_2\text{O}_3 = 2.26056072,$$

$$\text{La}_2\text{O}_3 = 2.26056072,$$

$$\text{P}_2\text{O}_5 = 0; \text{ and}$$

wherein,

$\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{B}_2\text{O}_3$ is in a range from 82.25 mol% to 86.25 mol%,

$\text{MgO} + \text{CaO} + \text{BaO} + \text{SnO}_2$ is in a range from 13.00 mol% to 17.50 mol%, and

$\text{TiO}_2 + \text{ZnO} + \text{La}_2\text{O}_3 + \text{P}_2\text{O}_5$ is in a range from 0.00 mol% to 4.75 mol%.