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(54) **FUSION FORMABLE AND STEAM STRENGTHENABLE GLASS COMPOSITIONS WITH PLATINUM COMPATIBILITY**

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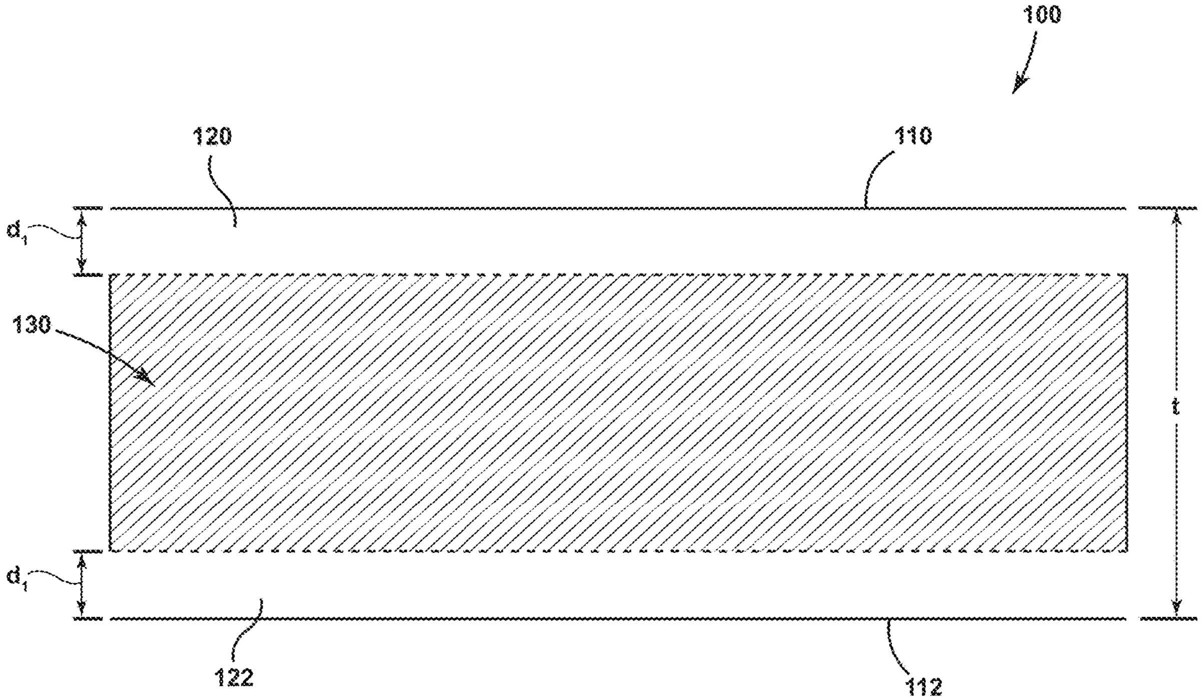
(57) **ABSTRACT**

Glass-based articles that include a compressive stress layer extending from a surface of the glass-based article to a depth of compression are formed by exposing glass-based substrates to water vapor containing environments. The glass-based substrates have compositions selected to be fusion formable, to be steam strengthen able, and to avoid the formation of platinum defects during the forming process. The methods of forming the glass-based articles may include elevated pressures and/or multiple exposures to water vapor containing environments.



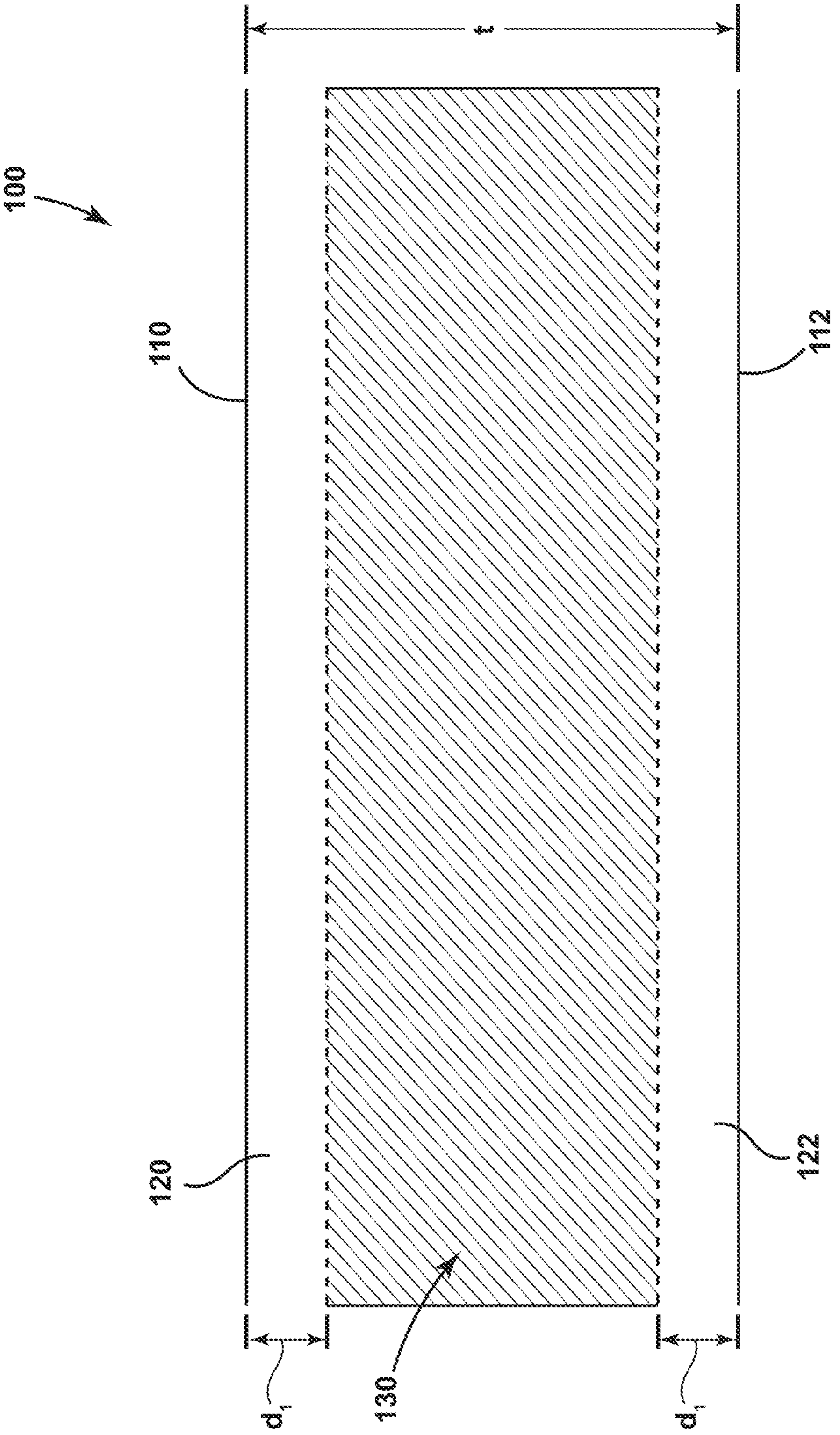


FIG. 1

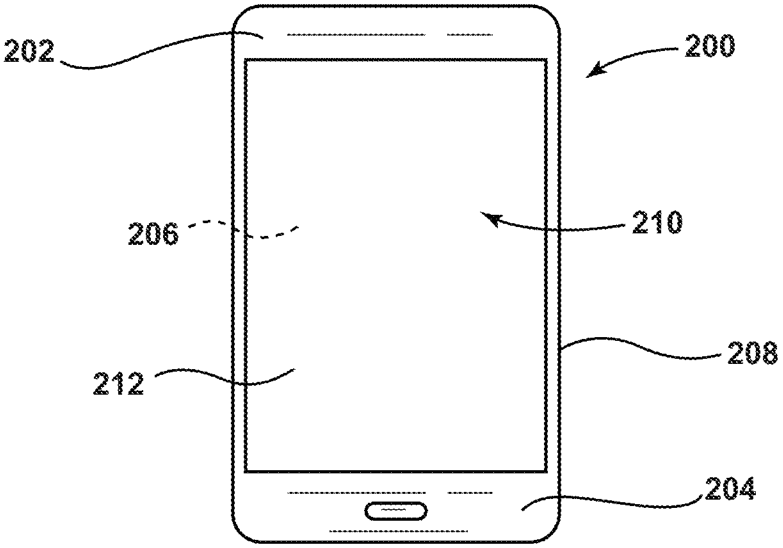


FIG. 2A

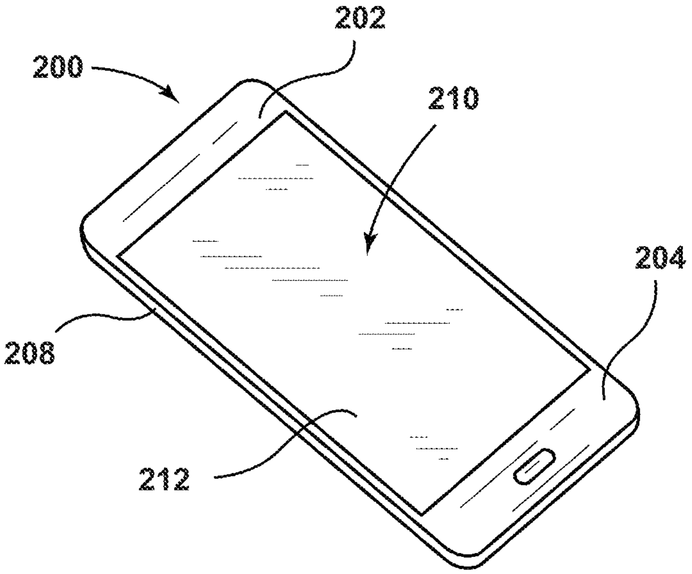


FIG. 2B

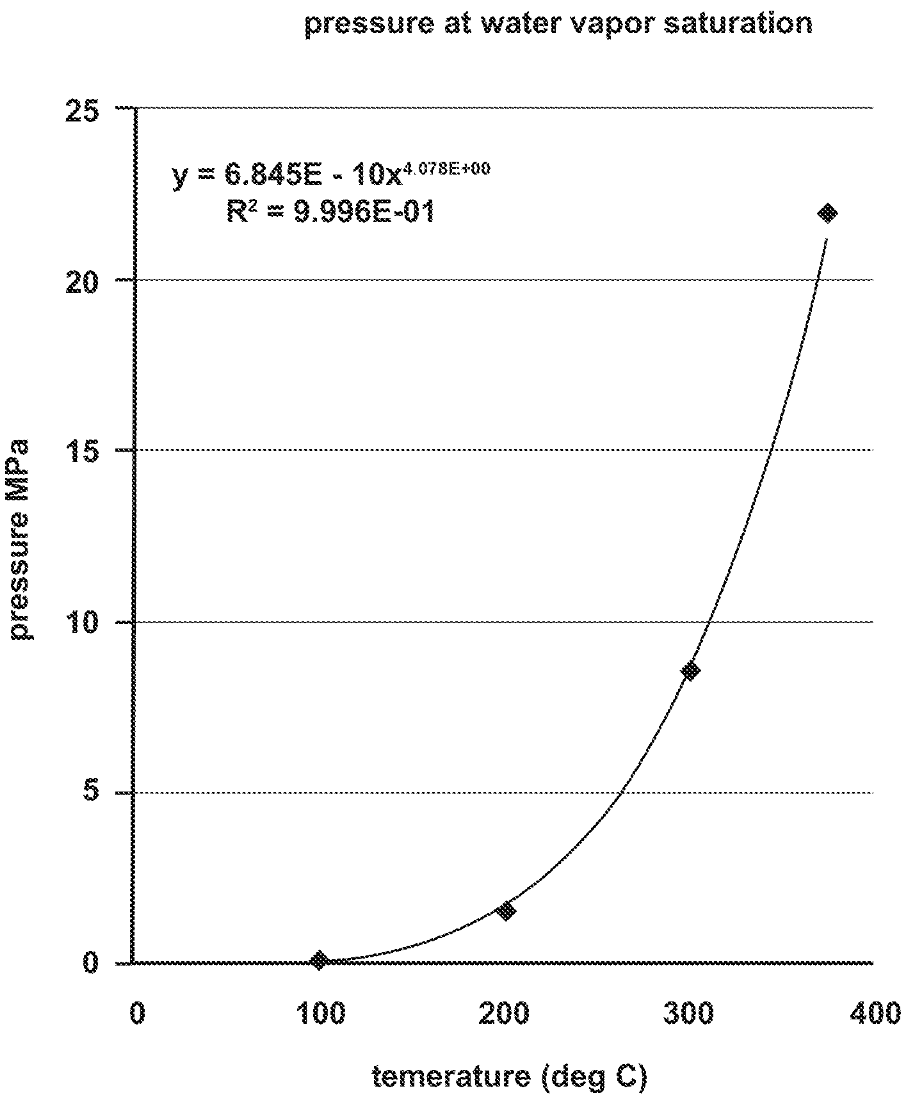

pressure at water vapor saturation
y = 6.845E - 10x^4.078E+00
R² = 9.996E-01
25
20
15
10
5
0
pressure MPa
0
100
200
300
400
temerature (deg C)

FIG. 3

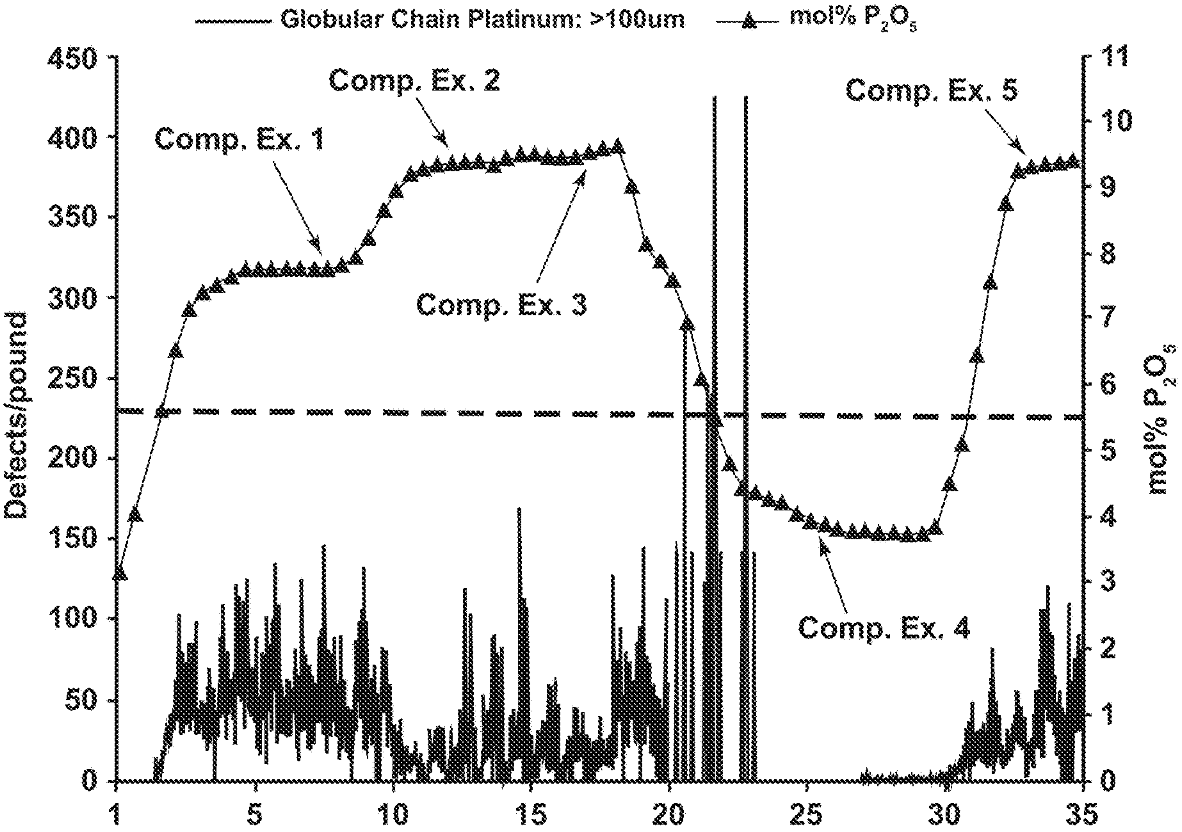

Globular Chain Platinum: >100um
mol% P_2O_5
Comp. Ex. 1
Comp. Ex. 2
Comp. Ex. 3
Comp. Ex. 4
Comp. Ex. 5
Defects/pound
mol% P_2O_5
0
50
100
150
200
250
300
350
400
450
0
1
2
3
4
5
6
7
8
9
10
11
1
5
10
15
20
25
30
35

FIG. 4

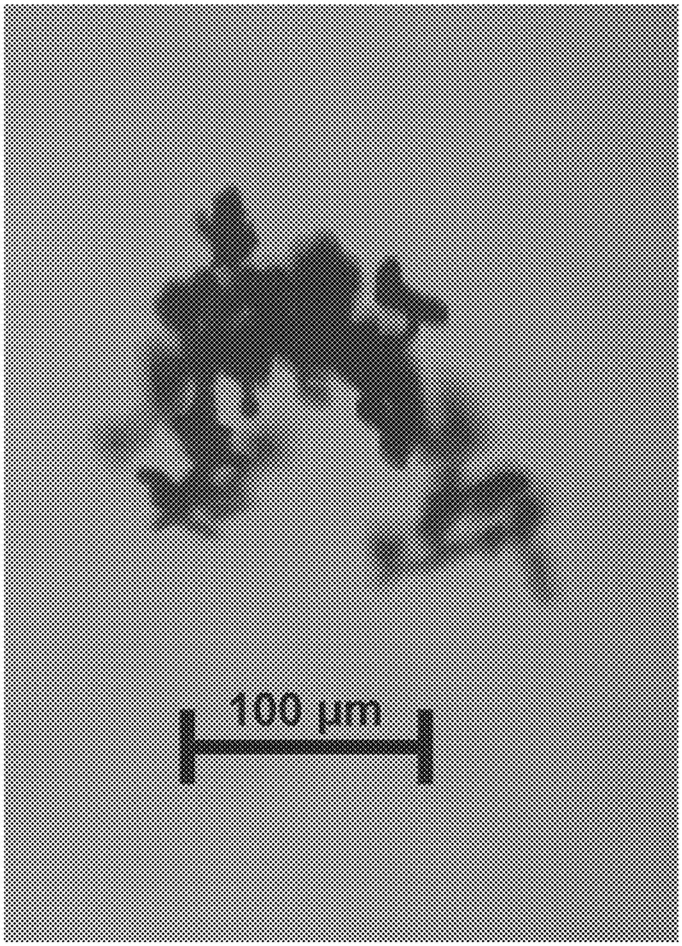


FIG. 5

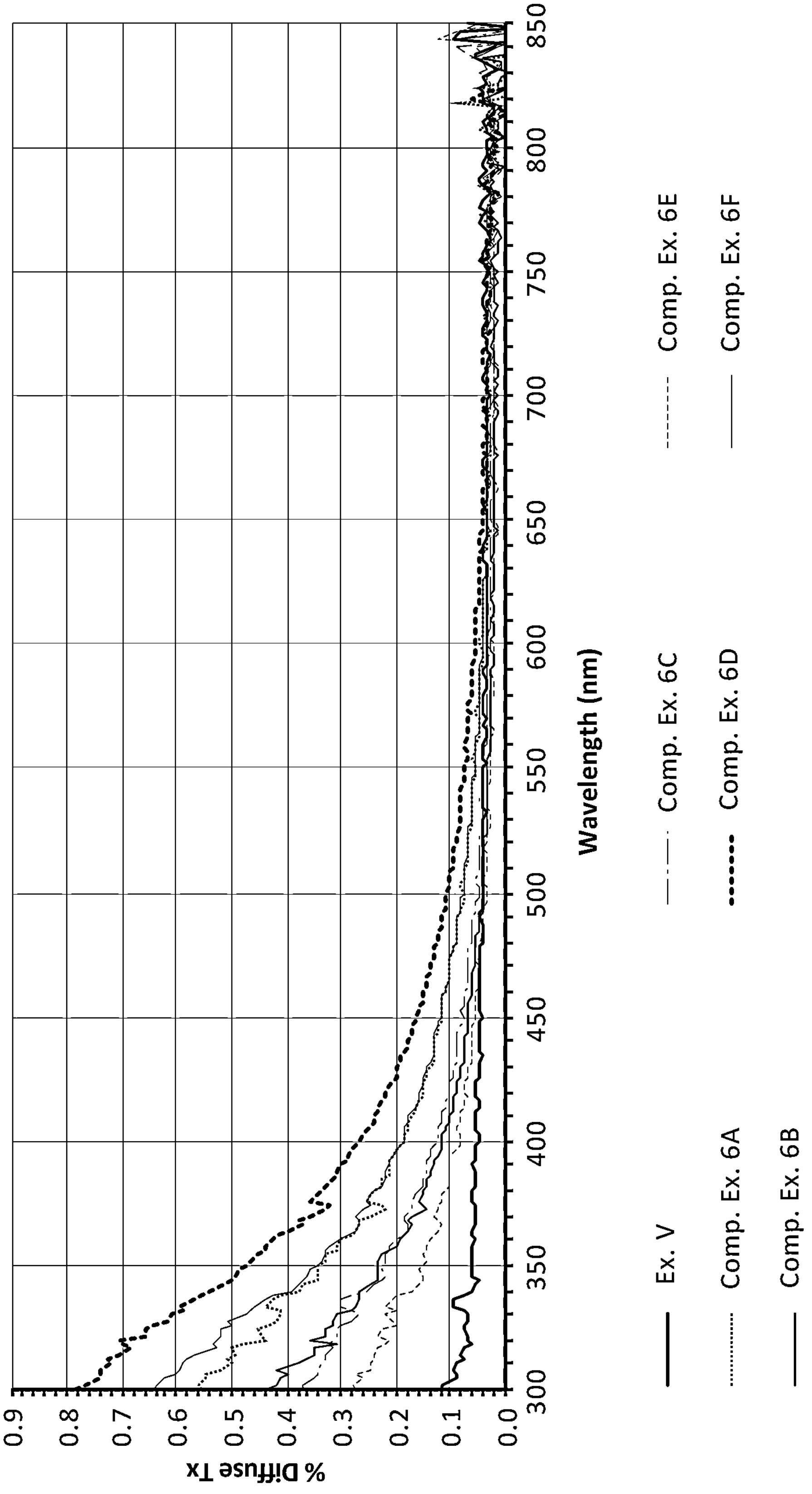

% Diffuse Tx
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
300
350
400
450
500
550
600
650
700
750
800
850
Wavelength (nm)
Ex. V
Comp. Ex. 6A
Comp. Ex. 6B
Comp. Ex. 6C
Comp. Ex. 6D
Comp. Ex. 6E
Comp. Ex. 6F

FIG. 6A

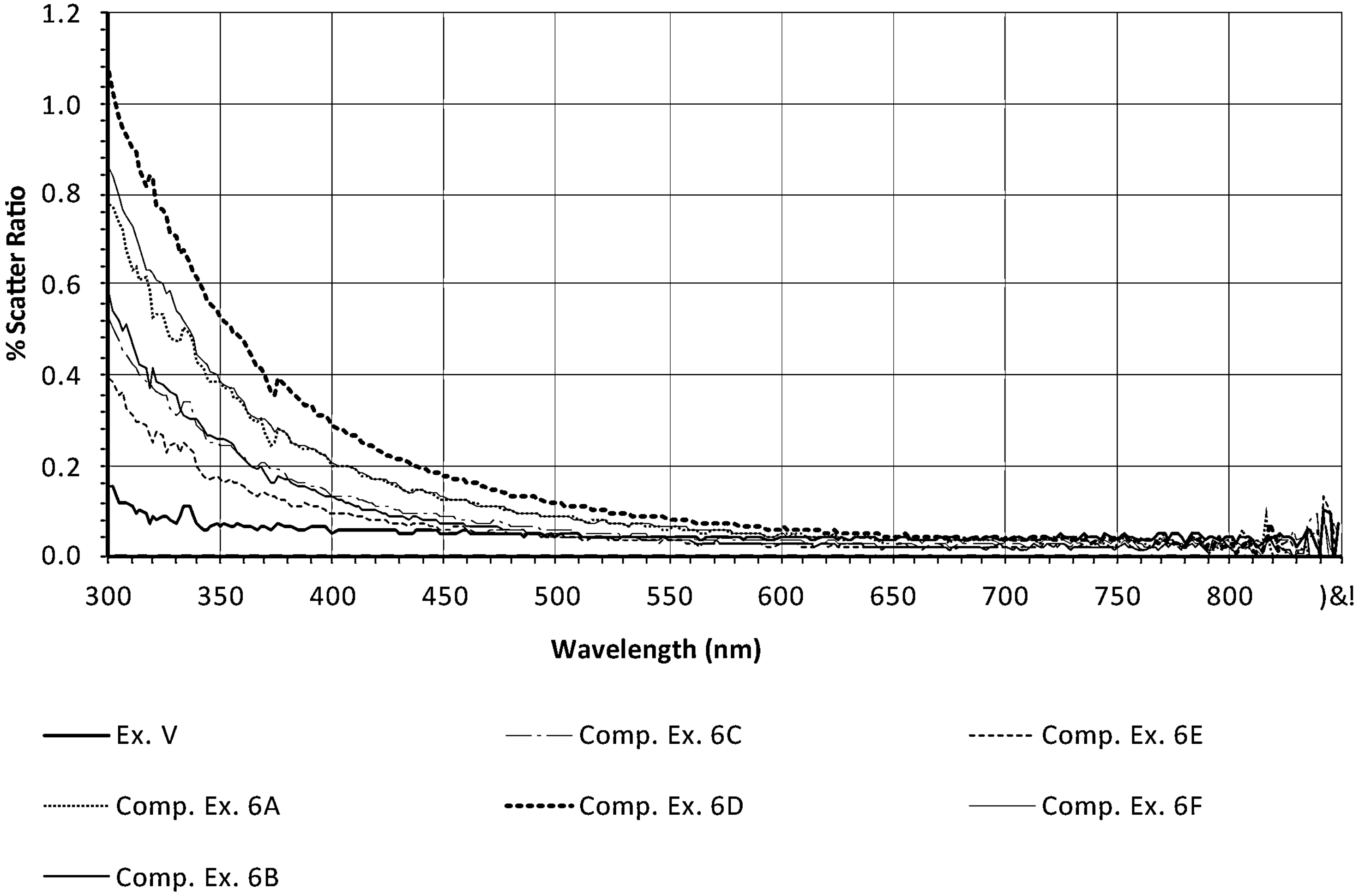

% Scatter Ratio
1.2
1.0
0.8
0.6
0.4
0.2
0.0
300
350
400
450
500
550
600
650
700
750
800
)&!
Wavelength (nm)
Ex. V
Comp. Ex. 6A
Comp. Ex. 6B
Comp. Ex. 6C
Comp. Ex. 6D
Comp. Ex. 6E
Comp. Ex. 6F

FIG. 6B

Comp. Ex. 6B – SEM of Fractured Cross-Section

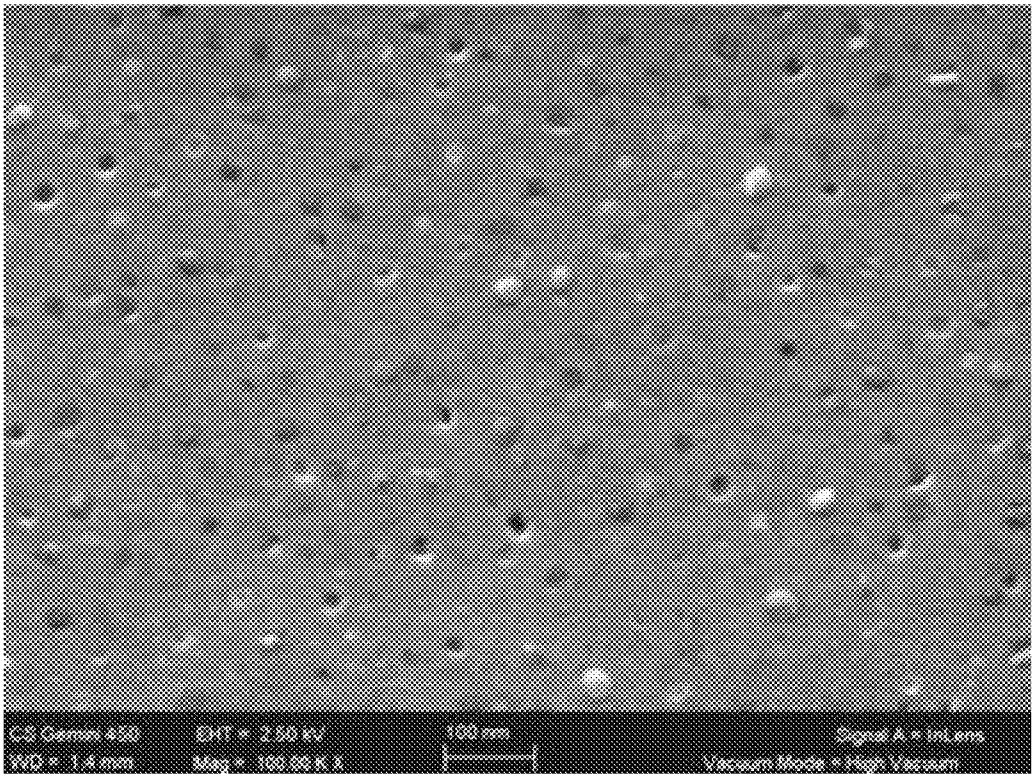


FIG. 7A

Comp. Ex. 6C – SEM of Fractured Cross-Section

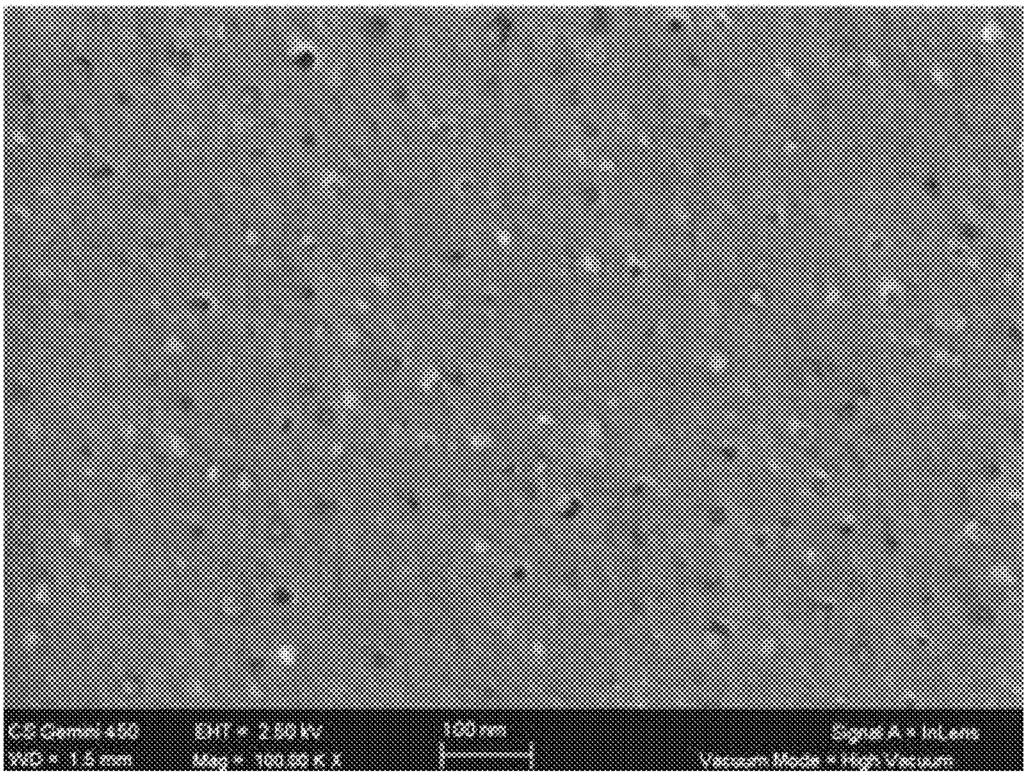


FIG. 7B

FUSION FORMABLE AND STEAM STRENGTHENABLE GLASS COMPOSITIONS WITH PLATINUM COMPATIBILITY

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application is a continuation of U.S. application Ser. No. 17/327870 filed on May 24, 2021, which is a continuation of International Patent Application Serial No. PCT/US2021/031524 filed on May 10, 2021, which claims the benefit of priority to under 35 U.S.C. § 119 of U.S. Provisional Application Ser. No. 63/023,518, filed May 12, 2020, the contents of which are relied upon and incorporated herein by reference in their entirety.

BACKGROUND

Field

[0002] This disclosure relates to glass-based articles strengthened by steam treatment, glass compositions utilized to form the glass-based articles, and methods of steam treatment to strengthen the glass-based articles.

Technical Background

[0003] Portable electronic devices, such as smartphones, tablets, and wearable devices (such as, for example, watches and fitness trackers), continue to get smaller and more complex. As such, materials that are conventionally used on at least one external surface of such portable electronic devices also continue to get more complex. For instance, as portable electronic devices get smaller and thinner to meet consumer demand, the display covers and housings used in these portable electronic devices also get smaller and thinner, resulting in higher performance requirements for the materials used to form these components.

[0004] Accordingly, a need exists for materials that exhibit higher performance, such as resistance to damage, along with lower cost and ease of manufacture for use in portable electronic devices.

SUMMARY

[0005] In aspect (1), a glass-based article is provided. The glass-based article comprises: a compressive stress layer extending from a surface of the glass-based article to a depth of compression, a hydrogen-containing layer extending from the surface of the glass-based article to a depth of layer, and a composition at the center of the glass-based article, comprising: SiO_2, Al_2O_3, K_2O, R_2O/Al_2O_3 in an amount that is less than or equal to 1.4, wherein R_2O is the total amount of monovalent metal oxides, greater than or equal to 3.5 mol % to less than or equal to 6.0 mol % P_2O_5, and greater than or equal to 2.0 mol % to less than or equal to 5.0 mol % Li_2O. The compressive stress layer comprises a compressive stress greater than or equal to 25 MPa, a hydrogen concentration of the hydrogen-containing layer decreases from a maximum hydrogen concentration to the depth of layer, and the depth of layer is greater than 5 μm.

[0006] In aspect (2), the glass-based article of aspect (1) is provided, further comprising a fusion line.

[0007] In aspect (3), the glass-based article of aspect (1) or (2) is provided, wherein the glass-based article comprises less than 1 globular chain platinum defect per pound.

[0008] In aspect (4), the glass-based article of aspect (1) or (2) is provided, wherein the glass-based article exhibits no substantial phase separation.

[0009] In aspect (5), the glass-based article of any one of aspects (1) to (4) is provided, wherein the composition at the center of the glass-based article further comprises B_2O_3.

[0010] In aspect (6), the glass-based article of any one of aspects (1) to (5) is provided, wherein the composition at the center of the glass-based article further comprises Na_2O.

[0011] In aspect (7), the glass-based article of any one of aspects (1) to (6) is provided, wherein the composition at the center of the glass-based article further comprises SnO_2.

[0012] In aspect (8), the glass-based article of any one of aspects (1) to (7) is provided, wherein the composition at the center of the glass-based article has an average field strength of alkali modifiers that is less than or equal to 0.18.

[0013] In aspect (9), the glass-based article of any one of aspects (1) to (8) is provided, wherein the composition at the center of the glass-based article comprises: greater than or equal to 55.0 mol % to less than or equal to 65.0 mol % SiO_2, greater than or equal to 10.0 mol % to less than or equal to 15.0 mol % Al_2O_3, greater than or equal to 0 mol % to less than or equal to 10.0 mol % B_2O_3, and greater than or equal to 6.0 mol % to less than or equal to 15.0 mol % K_2).

[0014] In aspect (10), the glass-based article of any one of aspects (1) to (9) is provided, wherein the composition at the center of the glass-based article comprises greater than or equal to 4.5 mol % to less than or equal to 5.5 mol % P_2O_5.

[0015] In aspect (11), the glass-based article of any one of aspects (1) to (10) is provided, wherein the composition at the center of the glass-based article comprises greater than 0 mol % to less than or equal to 3.0 mol % B_2O_3.

[0016] In aspect (12), the glass-based article of any one of aspects (1) to (11) is provided, wherein a glass having the same composition as the composition at the center of the glass-based article has a zircon breakdown viscosity of less than or equal to 35 kP.

[0017] In aspect (13), the glass-based article of any one of aspects (1) to (12) is provided, wherein a glass having the same composition as the composition at the center of the glass-based article has a liquidus viscosity of greater than or equal to 100 kP.

[0018] In aspect (14), the glass-based article of any one of aspects (1) to (13) is provided, wherein the glass-based article has a substantially haze-free appearance.

[0019] In aspect (15), the glass-based article of any one of aspects (1) to (14) is provided, wherein the depth of compression is greater than 5μm.

[0020] In aspect (16), the glass-based article of any one of aspects (1) to (15) is provided, wherein the compressive stress layer comprises a compressive stress greater than or equal to 200 MPa.

[0021] In aspect (17), the glass-based article of any one of aspects (1) to (16) is provided, wherein the composition further comprises $1.4 < (R_2O+P_2O_5)/Al_2O_3 < 1.9$, wherein R_2O is the total amount of monovalent metal oxides.

[0022] In aspect (18), a consumer electronic product is provided. The consumer electronic product comprises: a housing comprising a front surface, a back surface and side surfaces; electrical components at least partially within the housing, the electrical components comprising at least a controller, a memory, and a display, the display at or adjacent the front surface of the housing; and a cover substrate disposed over the display. At least a portion of at least one of the housing or the cover substrate comprises the glass-based article of any one of aspects (1) to (17).

[0023] In aspect (19), a glass-based article is provided. The glass-based article comprises: a compressive stress layer extending from a surface of the glass-based article to a depth of compression, a hydrogen-containing layer extending from the surface of the glass-based article to a depth of layer, and a composition at the center of the glass-based article, comprising: SiO_2, Al_2O_3, K_2O, $1.4<(R_2O+P_2O_5)/Al_2O_3<1.9$, wherein R_2O is the total amount of monovalent metal oxides, greater than or equal to 3.5 mol % to less than or equal to 6.0 mol % P_2O_5, and greater than or equal to 2.0 mol % to less than or equal to 5.0 mol % Li_2O. The compressive stress layer comprises a compressive stress greater than or equal to 25 MPa, a hydrogen concentration of the hydrogen-containing layer decreases from a maximum hydrogen concentration to the depth of layer, and the depth of layer is greater than 5μm.

[0024] In aspect (20), the glass-based article of aspect (19) is provided, wherein the glass-based article comprises less than 1 globular chain platinum defect per pound.

[0025] In aspect (21), the glass-based article of aspect (19) or (20) is provided, wherein the glass-based article exhibits no substantial phase separation.

[0026] In aspect (22), a glass-based article is provided. The glass-based article comprises: a compressive stress layer extending from a surface of the glass-based article to a depth of compression, a hydrogen-containing layer extending from the surface of the glass-based article to a depth of layer, and a composition at the center of the glass-based article, comprising: SiO_2, Al_2O_3, K_2O, $1.4<(R_2O+P_2O_5)/Al_2O_3<1.9$, wherein R_2O is the total amount of monovalent metal oxides, and greater than or equal to 3.5 mol % to less than or equal to 6.0 mol % P_2O_5. The compressive stress layer comprises a compressive stress greater than or equal to 25 MPa, a hydrogen concentration of the hydrogen-containing layer decreases from a maximum hydrogen concentration to the depth of layer, and the depth of layer is greater than 5 μm.

[0027] In aspect (23), the glass-based article of aspect (22) is provided, wherein the glass-based article comprises less than 1 globular chain platinum defect per pound.

[0028] In aspect (24), the glass-based article of aspect (22) or (23) is provided, wherein the glass-based article exhibits no substantial phase separation.

[0029] In aspect (25), a method is provided. The method comprises exposing a glass-based substrate to a treatment environment with a pressure greater than or equal to 0.1 MPa, a water partial pressure of greater than or equal to 0.05 MPa, and a temperature greater than 85° C. to form a glass-based article. The glass-based substrate comprises: SiO_2, Al_2O_3, K_2O, R_{20}/Al_2O_3 in an amount that is less than or equal to 1.4, wherein R_2O is the total amount of monovalent metal oxides, greater than or equal to 3.5 mol % to less than or equal to 6.0 mol % P_2O_5, and greater than or equal to 2.0 mol % to less than or equal to 5.0 mol % Li_2O. The glass-based article comprises: a compressive stress layer extending from a surface of the glass-based article to a depth of compression, the compressive stress layer comprising a compressive stress greater than or equal to 25 MPa, a hydrogen-containing layer extending from the surface of the glass-based article to a depth of layer, a hydrogen concentration of the hydrogen-containing layer decreases from a maximum hydrogen concentration to the depth of layer, and the depth of layer is greater than 5 μm.

[0030] In aspect (26), the method of aspect (25) is provided, wherein the treatment environment is a saturated steam environment.

[0031] In aspect (27), the method of aspect (25) or (26) is provided, wherein the treatment environment has a pressure greater than or equal to 1 MPa.

[0032] In aspect (28), the method of any one of aspects (25) to (27) is provided, wherein the treatment environment has a temperature greater than or equal to 150° C.

[0033] In aspect (29), the method of any one of aspects (25) to (28) is provided, further comprising producing the glass-based substrate by a fusion forming process.

[0034] In aspect (30), the method of any one of aspects (25) to (29) is provided, wherein the glass-based substrate is not subjected to an ion-exchange treatment with an alkali ion source.

[0035] In aspect (31), the method of any one of aspects (25) to (30) is provided, wherein the glass-based substrate further comprises B_2O_3.

[0036] In aspect (32), the method of any one of aspects (25) to (31) is provided, wherein the glass-based substrate further comprises Na_2O.

[0037] In aspect (33), the method of any one of aspects (25) to (32) is provided, wherein the glass-based substrate further comprises SnO_2.

[0038] In aspect (34), the method of any one of aspects (25) to (33) is provided, wherein the glass-based substrate has an average field strength of alkali modifiers that is less than or equal to 0.18.

[0039] In aspect (35), the method of any one of aspects (25) to (34) is provided, wherein the glass-based substrate comprises: greater than or equal to 55.0 mol % to less than or equal to 65.0 mol % SiO_2, greater than or equal to 10.0 mol % to less than or equal to 15.0 mol % Al_2O_3, greater than or equal to 0 mol % to less than or equal to 10.0 mol % B_2O_3, and greater than or equal to 6.0 mol % to less than or equal to 15.0 mol % K_2O.

[0040] In aspect (36), the method of any one of aspects (25) to (35) is provided, wherein the glass-based substrate comprises greater than or equal to 4.5 mol % to less than or equal to 5.5 mol % P_2O_5.

[0041] In aspect (37), the method of any one of aspects (25) to (36) is provided, wherein the glass-based substrate comprises greater than 0 mol % to less than or equal to 3.0 mol % B_2O_3.

[0042] In aspect (38), the method of any one of aspects (25) to (37) is provided, wherein the glass-based substrate comprises a fusion line.

[0043] In aspect (39), the method of any one of aspects (25) to (38) is provided, wherein the glass-based substrate comprises less than 1 globular chain platinum defect per pound.

[0044] In aspect (40), the method of any one of aspects (25) to (39) is provided, wherein the glass-based substrate has a zircon breakdown viscosity of less than or equal to 35 kP.

[0045] In aspect (41), the method of any one of aspects (25) to (40) is provided, wherein the glass-based substrate has a liquidus viscosity of greater than or equal to 100 kP.

[0046] In aspect (42), the method of any one of aspects (25) to (41) is provided, wherein the glass-based article has a substantially haze-free appearance.

[0047] In aspect (43), the method of any one of aspects (25) to (42) is provided, wherein the depth of compression is greater than 5 μm.

[0048] In aspect (44), the method of any one of aspects (25) to (43) is provided, wherein the compressive stress layer comprises a compressive stress greater than or equal to 200 MPa.

[0049] In aspect (45), a glass is provided. The glass comprises: greater than or equal to 55.0 mol % to less than or equal to 65.0 mol % SiO_2, greater than or equal to 10.0 mol % to less than or equal to 15.0 mol % Al_2O_3, greater than or equal to 0 mol % to less than or equal to 10.0 mol % B_2O_3, greater than or equal to 6.0 mol % to less than or equal to 15.0 mol % K_2O, greater than or equal to 3.5 mol % to less than or equal to 6.0 mol % P_2O_5, greater than or equal to 2.0 mol % to less than or equal to 5.0 mol % Li_2O, and $1.4<(R_2O+P_2O_5)/Al_2O_3<1.9$, wherein R_2O is the total amount of monovalent metal oxides.

[0050] In aspect (46), the glass of aspect (45) is provided, comprising an average field strength of alkali modifiers that is less than or equal to 0.18.

[0051] In aspect (47), the glass of aspect (45) or (46) is provided, comprising greater than or equal to 4.5 mol % to less than or equal to 5.5 mol % P_2O_5.

[0052] In aspect (48), the glass of any one of aspects (45) to (47) is provided, further comprising B_2O_3.

[0053] In aspect (49), the glass of any one of aspects (45) to (48) is provided, further comprising greater than 0 mol % to less than or equal to 3 mol % B_2O_3.

[0054] In aspect (50), the glass of any one of aspects (45) to (49) is provided, further comprising Na_2O.

[0055] In aspect (51), the glass of any one of aspects (45) to (50) is provided, further comprising greater than or equal to 0 mol % to less than or equal to 11 mol % Na_2O.

[0056] In aspect (52), the glass of any one of aspects (45) to (51) is provided, further comprising SnO_2.

[0057] In aspect (53), the glass of any one of aspects (45) to (52) is provided, comprising a zircon breakdown viscosity of less than or equal to 35 kP.

[0058] In aspect (54), the glass of any one of aspects (45) to (53) is provided, comprising a liquidus viscosity of greater than or equal to 100 kP.

[0059] These and other aspects, advantages, and salient features will become apparent from the following detailed description, the accompanying drawings, and the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0060] FIG. **1** is a representation of a cross-section of a glass-based article according to an embodiment.

[0061] FIG. **2**A is a plan view of an exemplary electronic device incorporating any of the glass-based articles disclosed herein.

[0062] FIG. **2**B is a perspective view of the exemplary electronic device of FIG. **2**A.

[0063] FIG. **3** is a plot of the saturation condition for water as a function of pressure and temperature.

[0064] FIG. **4** is a plot of the number of globular chain platinum defects per pound of glass as a function of phosphorous content.

[0065] FIG. **5** is a microscopy image of a globular chain platinum defect in a glass.

[0066] FIG. **6**A is a plot of diffuse scattering in transmission vs. wavelength for a glass composition, according to an embodiment of the disclosure, and comparative glass compositions.

[0067] FIG. **6**B is a plot of the scatter ratio vs. wavelength for a glass composition, according to an embodiment of the disclosure, and comparative glass compositions.

[0068] FIGS. **7**A and **7**B are scanning electronic microscopy (SEM) images of two comparative glass compositions with evidence of phase separation.

DETAILED DESCRIPTION

[0069] In the following description, like reference characters designate like or corresponding parts throughout the several views shown in the figures. It is also understood that, unless otherwise specified, terms such as “top,” “bottom,” “outward,” “inward,” and the like are words of convenience and are not to be construed as limiting terms. Unless otherwise specified, a range of values, when recited, includes both the upper and lower limits of the range as well as any sub-ranges therebetween. As used herein, the indefinite articles “a,” “an,” and the corresponding definite article “the” mean “at least one” or “one or more,” unless otherwise specified. It also is understood that the various features disclosed in the specification and the drawings can be used in any and all combinations.

[0070] As used herein, the term “glass-based” is used in its broadest sense to include any objects made wholly or partly of glass, including glass ceramics (which include a crystalline phase and a residual amorphous glass phase). Unless otherwise specified, all compositions of the glasses described herein are expressed in terms of mole percent (mol %), and the constituents are provided on an oxide basis. Unless otherwise specified, all temperatures are expressed in terms of degrees Celsius (° C.).

[0071] It is noted that the terms “substantially” and “about” may be utilized herein to represent the inherent degree of uncertainty that may be attributed to any quantitative comparison, value, measurement, or other representation. These terms are also utilized herein to represent the degree by which a quantitative representation may vary from a stated reference without resulting in a change in the basic function of the subject matter at issue. For example, a glass that is “substantially free of K_2O” is one in which K_2O is not actively added or batched into the glass but may be present in very small amounts as a contaminant, such as in amounts of less than about 0.01 mol %. As utilized herein, when the term “about” is used to modify a value, the exact value is also disclosed. For example, the term “greater than about 10 mol %” also discloses “greater than or equal to 10 mol %.”

[0072] Reference will now be made in detail to various embodiments, examples of which are illustrated in the accompanying examples and drawings.

[0073] The glass-based articles disclosed herein are formed by steam treating a glass-based substrate to produce a compressive stress layer extending from a surface of the article to a depth of compression (DOC). The glass-based substrate compositions are selected to allow the glass-based substrates to be fusion formed and to avoid the formation of platinum defects during the forming process, such that the glass-based substrates are fusion formable and platinum compatible. The glass-based substrate compositions and the treatment methods are also selected to avoid the formation of haze on the surface of the glass-based articles. The compressive stress layer includes a stress that decreases from a maximum stress to the depth of compression. In some embodiments, the maximum compressive stress may be located at the surface of the glass-based article. As used herein, depth of compression (DOC) means the depth at which the stress in the glass-based article changes from compressive to tensile. Thus, the glass-based article also contains a tensile stress region having a maximum central tension (CT), such that the forces within the glass-based article are balanced.

[0074] The glass-based articles further include a hydrogen-containing layer extending from a surface of the article to a depth of layer. The hydrogen-containing layer includes a hydrogen concentration that decreases from a maximum hydrogen concentration of the glass-based article to the depth of layer. In some embodiments, the maximum hydrogen concentration may be located at the surface of the glass-based article.

[0075] The glass-based articles may be formed by exposing glass-based substrates to environments containing water vapor, thereby allowing hydrogen species to penetrate the glass-based substrates and form the glass-based articles having a hydrogen-containing layer and/or a compressive stress layer. As utilized herein, the term "hydrogen species" includes molecular water, hydroxyl, hydrogen ions, and hydronium. The composition of the glass-based substrates is selected to promote the interdiffusion of hydrogen species into the glass. As utilized herein, the term "glass-based substrate" refers to the precursor prior to exposure to a water vapor containing environment for the formation of a glass-based article that includes hydrogen-containing layers and/or compressive stress layers. Similarly, the term "glass-based article" refers to the post exposure article that includes a hydrogen-containing layer and/or a compressive stress layer.

[0076] The glass-based articles disclosed herein may exhibit a compressive stress layer without undergoing conventional ion exchange, thermal tempering, or lamination treatments. Ion exchange processes produce significant waste in the form of expended molten salt baths that require costly disposal, and also are applicable to only some glass compositions. Thermal tempering requires thick glass specimens as a practical matter, as thermal tempering of thin sheets utilizes small air gap quenching processes which commonly result in scratch damage, reducing performance and yield. Additionally, it is difficult to achieve uniform compressive stress across surface and edge regions when thermal tempering thin glass sheets. Laminate processes result in exposed tensile stress regions when large sheets are cut to usable sizes, which is undesirable.

[0077] The water vapor treatment utilized to form the glass-based articles allows for reduced waste and lower cost when compared to ion exchange treatments, as molten salts are not utilized. The water vapor treatment is also capable of strengthening thin (<2 mm) glass that would not be suitable for thermal tempering at such thicknesses. Additionally, the water vapor treatment may be performed at the part level, avoiding the undesirable exposed tensile stress regions associated with laminate processes. In sum, the glass-based articles disclosed herein may be produced with a low thickness and at a low cost while exhibiting a high compressive stress and deep depth of compression.

[0078] A representative cross-section of a glass-based article **100** according to some embodiments is depicted in FIG. **1**. The glass-based article **100** has a thickness t that extends between a first surface **110** and a second surface **112**. A first compressive stress layer **120** extends from the first surface **110** to a first depth of compression, where the first depth of compression has a depth d_1 measured from the first surface **110** into the glass-based article **100**. A second compressive stress layer **122** extends from the second surface **112** to a second depth of compression, where the second depth of compression has a depth d2 measured from the second surface **112** into the glass-based article **100**. A tensile stress region **130** is present between the first depth of compression and the second depth of compression. In embodiments, the first depth of compression d_1 may be substantially equivalent or equivalent to the second depth of compression d_2.

[0079] In some embodiments, the compressive stress layer of the glass-based article may include a compressive stress of greater than or equal to 25 MPa, such as greater than or equal to 30 MPa, greater than or equal to 40 MPa, greater than or equal to 50 MPa, greater than or equal to 60 MPa, greater than or equal to 70 MPa, greater than or equal to 80 MPa, greater than or equal to 90 MPa, greater than or equal to 100 MPa, greater than or equal to 110 MPa, greater than or equal to 120 MPa, greater than or equal to 130 MPa, greater than or equal to 140 MPa, greater than or equal to 145 MPa, greater than or equal to 150 MPa, greater than or equal to 160 MPa, greater than or equal to 170 MPa, greater than or equal to 180 MPa, greater than or equal to 190 MPa, greater than or equal to 200 MPa, greater than or equal to 210 MPa, greater than or equal to 220 MPa, greater than or equal to 230 MPa, greater than or equal to 240 MPa, greater than or equal to 250 MPa, greater than or equal to 260 MPa, greater than or equal to 270 MPa, greater than or equal to 280 MPa, greater than or equal to 290 MPa, greater than or equal to 300 MPa, greater than or equal to 310 MPa, greater than or equal to 320 MPa, greater than or equal to 330 MPa, greater than or equal to 340 MPa, greater than or equal to 350 MPa, greater than or equal to 360 MPa, greater than or equal to 370 MPa, greater than or equal to 380 MPa, greater than or equal to 390 MPa, greater than or equal to 400 MPa, greater than or equal to 410 MPa, greater than or equal to 420 MPa, or more. In some embodiments, the compressive stress layer may include a compressive stress of from greater than or equal to 25 MPa to less than or equal to 450 MPa, such as from greater than or equal to 30 MPa to less than or equal to 440 MPa, from greater than or equal to 40 MPa to less than or equal to 430 MPa, from greater than or equal to 50 MPa to less than or equal to 420 MPa, from greater than or equal to 60 MPa to less than or equal to 410 MPa, from greater than or equal to 70 MPa to less than or equal to 400 MPa, from greater than or equal to 80 MPa to less than or equal to 390 MPa, from greater than or equal to 90 MPa to less than or equal to 380 MPa, from greater than or equal to 100 MPa to less than or equal to 370 MPa, from greater than or equal to 110 MPa to less than or equal to 360 MPa, from greater than or equal to 120 MPa to less than or equal to 350 MPa, from greater than or equal to 130 MPa to less than or equal to 340 MPa, from greater than or equal to 140 MPa to less than or equal to 330 MPa, from greater than or equal to 150 MPa to less than or equal to 320 MPa, from greater than or equal to 160 MPa to less than or equal to 310 MPa, from greater than or equal to 170 MPa to less than or equal to 300 MPa, from greater than or equal to 180 MPa to less than or equal to 290 MPa, from greater than or equal to 190 MPa to less than or equal to 280 MPa, from greater than or equal to 200 MPa to less than or equal to 270 MPa, from greater than or equal to 210 MPa to less than or equal to 260 MPa, from greater than or equal to 220 MPa to less than or equal to 250 MPa, from greater than or equal to 220 MPa to less than or equal to 240 MPa, or any sub-ranges formed from any of these endpoints.

[0080] In some embodiments, the DOC of the compressive stress layer may be greater than or equal to 5 μm, such as greater than or equal to 7 μm, greater than or equal to 10 μm, greater than or equal to 15 μm, greater than or equal to 20 μm, greater than or equal to 25 μm, greater than or equal to 30 μm, or more. In some embodiments, the DOC of the compressive stress layer may be from greater than or equal to 5 μm to less than or equal to 100 μm, such as from greater than or equal to 7 μm to less than or equal to 90 μm, from greater than or equal to 10 μm to less than or equal to 80 μm, from greater than or equal to 15 μm to less than or equal to 70 μm, from greater than or equal to 20 μm to less than or equal to 60 μm, from greater than or equal to 25 μm to less than or equal to 50 μm, from greater than or equal to 30 μm to less than or equal to 40 μm, from greater than or equal to 30 μm to less than or equal to 35 μm, or any sub-ranges that may be formed from any of these endpoints.

[0081] In some embodiments, the glass-based articles may exhibit a deep depth of compression and a high compressive stress. For example, the glass-based articles may have any of the depths of compression and compressive stresses described herein in combination.

[0082] In some embodiments, the glass-based articles may have a DOC greater than or equal to 0.05t, wherein t is the thickness of the glass-based article, such as greater than or equal to 0.06t, greater than or equal to 0.07t, greater than or equal to 0.08t, greater than or equal to 0.09t, greater than or equal to 0.10t, greater than or equal to 0.11t, greater than or equal to 0.12t, greater than or equal to 0.13t, greater than or equal to 0.14t, greater than or equal to 0.15t, greater than or equal to 0.16t, greater than or equal to 0.17t, greater than or equal to 0.18t, greater than or equal to 0.19t, or more. In some embodiments, the glass-based articles may have a DOC from greater than or equal to 0.05t to less than or equal to 0.20t, such as from greater than or equal to 0.06t to less than or equal to 0.19t, from greater than or equal to 0.07t to less than or equal to 0.18t, from greater than or equal to 0.08t to less than or equal to 0.17t, from greater than or equal to 0.09t to less than or equal to 0.16t, from greater than or equal to 0.10t to less than or equal to 0.15t, from greater than or equal to 0.11t to less than or equal to 0.14t, from greater than or equal to 0.12t to less than or equal to 0.13t, or any sub-ranges formed from any of these endpoints.

[0083] Compressive stress (including surface CS) is measured by surface stress meter using commercially available instruments such as the FSM-6000 (FSM), manufactured by Orihara Industrial Co., Ltd. (Japan). Surface stress measurements rely upon the accurate measurement of the stress optical coefficient (SOC), which is related to the birefringence of the glass. SOC in turn is measured according to Procedure C (Glass Disc Method) described in ASTM standard C770-16, entitled "Standard Test Method for Measurement of Glass Stress-Optical Coefficient," the contents of which are incorporated herein by reference in their entirety. DOC is measured by FSM. Any maximum central tension (CT) values are measured using a scattered light polariscope (SCALP) technique known in the art.

[0084] The hydrogen-containing layer of the glass-based articles may have a depth of layer (DOL) greater than 5 μm. In some embodiments, the depth of layer may be greater than or equal to 10 μm, such as greater than or equal to 15 μm, greater than or equal to 20 μm, greater than or equal to 25 μm, greater than or equal to 30 μm, greater than or equal to 35 μm, greater than or equal to 40 μm, greater than or equal to 45 μm, greater than or equal to 50 μm, greater than or equal to 55 μm, greater than or equal to 60 μm, greater than or equal to 65 μm, greater than or equal to 70 μm, greater than or equal to 75 μm, greater than or equal to 80 μm, greater than or equal to 85 μm, greater than or equal to 90 μm, greater than or equal to 95 μm, or more. In some embodiments, the depth of layer may be from greater than 5 μm to less than or equal to 100 μm, such as from greater than or equal to 10 μm to less than or equal to 95 μm, from greater than or equal to 15 μm to less than or equal to 90 μm, from greater than or equal to 20 μm to less than or equal to 85 μm, from greater than or equal to 25 μm to less than or equal to 80 μm, from greater than or equal to 30 μm to less than or equal to 75 μm, from greater than or equal to 35 μm to less than or equal to 70 μm, from greater than or equal to 40 μm to less than or equal to 65 μm, from greater than or equal to 45 μm to less than or equal to 60 μm, from greater than or equal to 50 μm to less than or equal to 55 pm, or any sub-ranges formed by any of these endpoints. The hydrogen depth of layer is greater than or equal to the depth of compression, as measured by the FSM technique described above. In general, the depth of layer exhibited by the glass-based articles is greater than the depth of layer that may be produced by exposure to the ambient environment.

[0085] The hydrogen-containing layer of the glass-based articles may have a depth of layer (DOL) greater than 0.005t, wherein t is the thickness of the glass-based article. In some embodiments, the depth of layer may be greater than or equal to 0.010t, such as greater than or equal to 0.015t, greater than or equal to 0.020t, greater than or equal to 0.025t, greater than or equal to 0.030t, greater than or equal to 0.035t, greater than or equal to 0.040t, greater than or equal to 0.045t, greater than or equal to 0.050t, greater than or equal to 0.055t, greater than or equal to 0.060t, greater than or equal to 0.065t, greater than or equal to 0.070t, greater than or equal to 0.075t, greater than or equal to 0.080t, greater than or equal to 0.085t, greater than or equal to 0.090t, greater than or equal to 0.095t, greater than or equal to 0.10t, greater than or equal to 0.15t, greater than or equal to 0.20t, or more. In some embodiments, the DOL may be from greater than 0.005t to less than or equal to 0.205t, such as from greater than or equal to 0.010t to less than or equal to 0.200t, from greater than or equal to 0.015t to less than or equal to 0.195t, from greater than or equal to 0.020t to less than or equal to 0.190t, from greater than or equal to 0.025t to less than or equal to 0.185t, from greater than or equal to 0.030t to less than or equal to 0.180t, from greater than or equal to 0.035t to less than or equal to 0.175t, from greater than or equal to 0.040t to less than or equal to 0.170t, from greater than or equal to 0.045t to less than or equal to 0.165t, from greater than or equal to 0.050t to less than or equal to 0.160t, from greater than or equal to 0.055t to less than or equal to 0.155t, from greater than or equal to 0.060t to less than or equal to 0.150t, from greater than or equal to 0.065t to less than or equal to 0.145t, from greater than or equal to 0.070t to less than or equal to 0.140t, from greater than or equal to 0.075t to less than or equal to 0.135t, from greater than or equal to 0.080t to less than or equal to 0.130t, from greater than or equal to 0.085t to less than or equal to 0.125t, from greater than or equal to 0.090t to less than or equal to 0.120t, from greater than or equal to 0.095t to less than or equal to 0.115t, from greater than or equal to 0.100t to less than or equal to 0.110t, or any sub-ranges formed by any of these endpoints.

[0086] The depth of layer and hydrogen concentration are measured by a secondary ion mass spectrometry (SIMS) technique that is known in the art. The SIMS technique is capable of measuring the hydrogen concentration at a given depth but is not capable of distinguishing the hydrogen species present in the glass-based article. For this reason, all hydrogen species contribute to the SIMS measured hydrogen concentration. As utilized herein, the depth of layer (DOL) refers to the first depth below the surface of the glass-based article where the hydrogen concentration is equal to the hydrogen concentration at the center of the glass-based article. This definition accounts for the hydrogen concentration of the glass-based substrate prior to treatment, such that the depth of layer refers to the depth of the hydrogen added by the treatment process. As a practical matter, the hydrogen concentration at the center of the glass-based article may be approximated by the hydrogen concentration at the depth from the surface of the glass-based article where the hydrogen concentration becomes substantially constant, as the hydrogen concentration is not expected to change between such a depth and the center of the glass-based article. This approximation allows for the determination of the DOL without measuring the hydrogen concentration throughout the entire depth of the glass-based article. The presence of the hydrogen-containing layer may be indicated by the formation of a compressive stress layer in the glass-based article as a result of the water vapor treatment.

[0087] Without wishing to be bound by any particular theory, the hydrogen-containing layer of the glass-based articles may be the result of an interdiffusion of hydrogen species for ions contained in the compositions of the glass-based substrate. Hydrogen-containing species, such as H_3O^+, H_2O, and/or H^+, may diffuse into the glass-based substrate to form the glass-based article. Water could penetrate the glass-based substrates by forming silanol groups, breaking the network structure and causing a volume expansion of the glass. Such a volume expansion may generate a compressive stress layer in the glass-based articles. The compressive stress and depth of compression of the compressive stress layer may depend on the composition of the glass-based substrate utilized to form the glass-based article, and the water vapor treatment conditions, such as temperature, pressure, water content, and duration. The stress profile of the glass-based articles produced by the water vapor treatment may be similar to stress profiles produced by potassium for sodium ion exchange strengthening processes.

[0088] The glass-based articles that have compressive stress layers also exhibit weight gain when compared to the glass-based substrates prior to the water vapor treatment process. The weight gain of the glass-based articles indicates the formation of a hydrogen-containing layer as a result of the water vapor treatment. The amount of weight gain is directly related to the amount of hydrogen species that enter the glass-based article as a result of the water vapor treatment process.

[0089] The glass-based articles disclosed herein may be incorporated into another article such as an article with a display (or display articles) (e.g., consumer electronics, including mobile phones, tablets, computers, navigation systems, wearable devices (e.g., watches) and the like), architectural articles, transportation articles (e.g., automotive, trains, aircraft, sea craft, etc.), appliance articles, or any article that requires some transparency, scratch-resistance, abrasion resistance or a combination thereof An exemplary article incorporating any of the glass-based articles disclosed herein is shown in FIGS. **2**A and **2**B. Specifically, FIGS. **2**A and **2**B show a consumer electronic device **200** including a housing **202** having front **204**, back **206**, and side surfaces **208**; electrical components (not shown) that are at least partially inside or entirely within the housing and including at least a controller, a memory, and a display **210** at or adjacent to the front surface of the housing; and a cover plate **212** at or over the front surface of the housing such that it is over the display. In some embodiments, at least a portion of at least one of the cover plate **212** and the housing **202** may include any of the glass-based articles disclosed herein.

[0090] The glass-based articles may be formed from glass-based substrates having any appropriate composition. The composition of the glass-based substrate may be specifically selected to promote the diffusion of hydrogen-containing species, such that a glass-based article including a hydrogen-containing layer and a compressive stress layer may be formed efficiently, to allow the glass-based articles to be fusion formed, to avoid the formation of platinum defects during the production process, and to avoid the formation of haze as a result of the water vapor treatment process. In some embodiments, the glass-based substrates may have a composition that includes SiO_2, Al_2O_3, P_2O_5, K_2O, and optionally Li_2O. In some embodiments, the hydrogen species does not diffuse to the center of the glass-based article. Stated differently, the center of the glass-based article is the area least affected by the water vapor treatment. For this reason, the center of the glass-based article may have a composition that is substantially the same, or the same, as the composition of the glass-based substrate prior to treatment in the water containing environment. The composition at the center of the glass-based article refers to the composition as measured at any point that is located at a distance of at least 0.5t from every surface of the glass-based article, where t is the thickness of the glass-based article. The composition at the center of the glass-based article may be measured by any appropriate process, such as microprobe analysis, and may be approximated by the composition of the glass-based substrate utilized to form the glass-based article.

[0091] The glass-based substrate may include any appropriate amount of SiO_2. SiO_2 is the largest constituent and, as such, SiO_2 is the primary constituent of the glass network formed from the glass composition. If the concentration of SiO_2 in the glass composition is too high, the formability of the glass composition 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. In some embodiments, the glass-based substrate may include SiO_2 in an amount from greater than or equal to 55.0 mol % to less than or equal to 65.0 mol %, such as from greater than or equal to 55.5 mol % to less than or equal to 64.5 mol %, from greater than or equal to 56.0 mol % to less than or equal to 64.0 mol %, from greater than or equal to

56.5 mol % to less than or equal to 63.5 mol %, from greater than or equal to 57.0 mol % to less than or equal to 63.0 mol %, from greater than or equal to 57.5 mol % to less than or equal to 62.5 mol %, from greater than or equal to 58.0 mol % to less than or equal to 62.0 mol %, from greater than or equal to 58.5 mol % to less than or equal to 61.5 mol %, from greater than or equal to 59.0 mol % to less than or equal to 61.0 mol %, from greater than or equal to 59.5 mol % to less than or equal to 60.5 mol %, from greater than or equal to 60.0 mol % to less than or equal to 65.0 mol %, or any sub-ranges formed by any of these endpoints.

[0092] The glass-based substrate may include any appropriate amount of Al_2O_3. Al_2O_3 may serve as a glass network former, similar to SiO_2. Al_2O_3 may increase the viscosity of the glass composition due to its tetrahedral coordination in a glass melt formed from a glass composition, decreasing the formability of the glass composition when the amount of Al_2O_3 is too high. However, when the concentration of Al_2O_3 is balanced against the concentration of SiO_2 and the concentration of alkali oxides in the glass composition, Al_2O_3 can reduce the liquidus temperature of the glass melt, thereby enhancing the liquidus viscosity and improving the compatibility of the glass composition with certain forming processes, such as the fusion forming process. The inclusion of Al_2O_3 in the glass-based substrate prevents phase separation and reduces the number of non-bridging oxygens (NBOs) in the glass. Additionally, Al_2O_3 can improve the effectiveness of ion exchange. In some embodiments, the glass-based substrate may include Al_2O_3 in an amount of from greater than or equal to 10.0 mol % to less than or equal to 15.0 mol %, such as from greater than or equal to 10.5 mol % to less than or equal to 14.5 mol %, from greater than or equal to 11.0 mol % to less than or equal to 14.0 mol %, from greater than or equal to 11.5 mol % to less than or equal to 13.5 mol %, from greater than or equal to 12.0 mol % to less than or equal to 13.0 mol %, from greater than or equal to 12.5 mol % to less than or equal to 13.0 mol %, or any sub-ranges formed by any of these endpoints.

[0093] The glass-based substrate may include any amount of P_2O_5 sufficient to produce the desired hydrogen diffusivity. The inclusion of phosphorous in the glass-based substrate promotes faster interdiffusion. Thus, the phosphorous containing glass-based substrates allow the efficient formation of glass-based articles including a hydrogen-containing layer. The inclusion of P_2O_5 also allows for the production of a glass-based article with a deep depth of layer (e.g., greater than about 10 μm) in a relatively short treatment time. In cases where the amount of P_2O_5 is greater than 6.0 mol % the glass becomes susceptible to the formation of platinum defects when contacting platinum containing formation apparatuses, such as melting and/or fining apparatuses, which are commonly employed in commercial glass production. Stated differently, when the glass includes greater than 6.0 mol % P_2O_5 the glass is not platinum compatible. In cases where the amount of P_2O_5 is less than 3.5 mol % the glass does not exhibit the desired diffusivity, liquidus temperature, or zircon compatibility. Zircon compatibility is important for use with common glass forming apparatuses, such as zircon isopipes in fusion forming equipment. In embodiments, the glass-based substrate may include P_2O_5 in an amount of from greater than or equal to 3.5 mol % to less than or equal to 6.0 mol %, such as from greater than or equal to 3.5 mol % to less than or equal to 5.5 mol %, from greater than or equal to 3.6 mol % to less than or equal to 5.9 mol %, from greater than or equal to 3.7 mol % to less than or equal to 5.8 mol %, from greater than or equal to 3.8 mol % to less than or equal to 5.7 mol %, from greater than or equal to 3.9 mol % to less than or equal to 5.6 mol %, from greater than or equal to 4.0 mol % to less than or equal to 5.5 mol %, from greater than or equal to 4.1 mol % to less than or equal to 5.4 mol %, from greater than or equal to 4.2 mol % to less than or equal to 5.3 mol %, or any sub-ranges formed by any of these endpoints.

[0094] The glass-based substrate may include Li_2O in any appropriate amount. Other embodiments of the glass-based substrate do not include any intentional additions of Li_2O. The inclusion of Li_2O in the glass-based substrate increases the resistance of the glass-based article to haze formation as a result of steam strengthening. The content of Li_2O in the glass-based substrate is directly correlated with a reduction in the 200 P temperature of the glass-based substrate, such that the inclusion of Li_2O improves the meltability of the glass. The content of Li_2O in the glass-based substrate is also directly correlated to the coefficient of thermal expansion of the glass-based substrate. In some embodiments, the glass-based substrate may include Li_2O in an amount of from greater than or equal to 2.0 mol % to less than or equal to 5.0 mol %, such as from greater than or equal to 2.1 mol % to less than or equal to 4.9 mol %, from greater than or equal to 2.2 mol % to less than or equal to 4.8 mol %, from greater than or equal to 2.3 mol % to less than or equal to 4.7 mol %, from greater than or equal to 2.4 mol % to less than or equal to 4.6 mol %, from greater than or equal to 2.5 mol % to less than or equal to 4.5 mol %, from greater than or equal to 2.6 mol % to less than or equal to 4.4 mol %, from greater than or equal to 2.7 mol % to less than or equal to 4.3 mol %, from greater than or equal to 2.8 mol % to less than or equal to 4.2 mol %, from greater than or equal to 2.9 mol % to less than or equal to 4.1 mol %, from greater than or equal to 3.0 mol % to less than or equal to 4.0 mol %, from greater than or equal to 3.1 mol % to less than or equal to 3.9 mol %, from greater than or equal to 3.2 mol % to less than or equal to 3.8 mol %, from greater than or equal to 3.3 mol % to less than or equal to 3.7 mol %, from greater than or equal to 3.4 mol % to less than or equal to 3.6 mol %, from greater than or equal to 3.0 mol % to less than or equal to 3.5 mol %, or any and all sub-ranges formed from these endpoints.

[0095] The glass-based substrate may include K_2O in any appropriate amount. The inclusion of K_2O in the glass-based substrate increases the steam strengthening susceptibility of the glass-based article to a greater degree than other alkali metal oxides. In some embodiments, the glass-based substrate may include K_2O in an amount of from greater than or equal to 6.0 mol % to less than or equal to 15.0 mol %, such as from greater than or equal to 6.5 mol % to less than or equal to 14.5 mol %, from greater than or equal to 7.0 mol % to less than or equal to 14.0 mol %, from greater than or equal to 7.5 mol % to less than or equal to 13.5 mol %, from greater than or equal to 8.0 mol % to less than or equal to 13.0 mol %, from greater than or equal to 8.5 mol % to less than or equal to 12.5 mol %, from greater than or equal to 9.0 mol % to less than or equal to 12.0 mol %, from greater than or equal to 9.5 mol % to less than or equal to 11.5 mol %, from greater than or equal to 10.0 mol % to less than or equal to 11.0 mol %, from greater than or equal to 10.5 mol % to less than or equal to 11.0 mol %, or any and all sub-ranges formed from these endpoints.

[0096] The glass-based substrate may include Na_2O in any appropriate amount. In some embodiments, the glass-based substrate may include Na_2O in an amount of from greater than or equal to 0 mol % to less than or equal to 11.0 mol %, such as from greater than or equal to 0.5 mol % to less than or equal to 10.5 mol %, from greater than or equal to 1.0 mol % to less than or equal to 9.0 mol %, from greater than or equal to 1.5 mol % to less than or equal to 8.5 mol %, from greater than or equal to 2.0 mol % to less than or equal to 8.0 mol %, from greater than or equal to 2.5 mol % to less than or equal to 7.5 mol %, from greater than or equal to 3.0 mol % to less than or equal to 7.0 mol %, from greater than or equal to 3.5 mol % to less than or equal to 6.5 mol %, from greater than or equal to 4.0 mol % to less than or equal to 6.0 mol %, from greater than or equal to 4.5 mol % to less than or equal to 5.5 mol %, from greater than or equal to 4.0 mol % to less than or equal to 5.0 mol %, or any and all sub-ranges formed from these endpoints. In embodiments, the glass-based substrate may be substantially free or free of Na_2O.

[0097] The glass-based substrates may additionally include B_2O_3. The inclusion of B_2O_3 in the glass-based substrates may increase the damage resistance of the glass-based substrates, and thereby increase the damage resistance of the glass-based articles formed therefrom. In some embodiments, the glass-based substrates may include B_2O_3 in an amount from greater than or equal to 0 mol % to less than or equal to 10.0 mol %, such as from greater than or equal to 0.5 mol % to less than or equal to 9.5 mol %, from greater than or equal to 1.0 mol % to less than or equal to 9.0 mol %, from greater than or equal to 1.5 mol % to less than or equal to 8.5 mol %, from greater than or equal to 2.0 mol % to less than or equal to 8.0 mol %, from greater than or equal to 2.5 mol % to less than or equal to 7.5 mol %, from greater than or equal to 3.0 mol % to less than or equal to 7.0 mol %, from greater than or equal to 3.5 mol % to less than or equal to 6.5 mol %, from greater than or equal to 4.0 mol % to less than or equal to 6.0 mol %, from greater than or equal to 4.5 mol % to less than or equal to 5.5 mol %, from greater than or equal to 4.0 mol % to less than or equal to 5.0 mol %, from greater than or equal to 0.0 mol % to less than or equal to 3.0 mol %, or any and all sub-ranges formed from these endpoints. In embodiments, the glass-based substrates may be substantially free or free of B_2O_3.

[0098] The glass-based substrates may additionally include a fining agent. In some embodiments, the fining agent may include tin. In embodiments, the glass-based substrate may include SnO_2 in an amount from greater than or equal to 0 mol % to less than or equal to 0.5 mol %, such as from greater than 0 mol % to less than or equal to 0.1 mol %, or any and all sub-ranges formed from these endpoints. In embodiments, the glass-based substrate may be substantially free or free of SnO_2.

[0099] The glass-based substrate may be characterized by a R_2O/Al_2O_3 molar ratio, wherein R_2O is the total amount of monovalent metal oxides, such as alkali metal oxides. In some embodiments, the glass-based substrate has a R_2O/Al_2O_3 molar ratio of less than or equal to 1.4, such as less than or equal to 1.3, less than or equal to 1.2, less than or equal to 1.1, or less. In some embodiments, the glass-based substrate has a R_2O/Al_2O_3 molar ratio of from greater than or equal to 1.0 to less than or equal to 1.4, such as from greater than or equal to 1.1 to less than or equal to 1.4, from greater than or equal to 1.2 to less than or equal to 1.3, or any and all sub-ranges formed from these endpoints. Maintaining a R_2O/Al_2O_3 molar ratio of the glass-based substrate of less than or equal to 1.4 avoids the undesired formation of a second glassy phase in the glass-based substrate, commonly referred to as phase separation.

[0100] The glass-based substrate may also be characterized by a $(R_2O+P_2O_5)/Al_2O_3$ molar ratio, wherein R_2O is the total amount of monovalent metal oxides, such as alkali metal oxides. In some embodiments, the glass-based substrate has a $(R_2O+P_2O_5)/Al_2O_3$ molar ratio of greater than 1.4 and less than 1.9, such as 1.41 to 1.89, 1.425 to 1.875, 1.45 to 1.85, and all values and sub-ranges between these values. In some embodiments, the glass-based substrate has a $(R_2O+P_2O_5)/Al_2O_3$ molar ratio of 1.41, 1.42, 1.43, 1.44, 1.45, 1.5, 1.55, 1.6, 1.65, 1.70, 1.75, 1.80, 1.85, 1.86, 1.87, 1.88, 1.89, and all values between 1.4 and 1.9. Maintaining a $(R_2O+P_2O_5)/Al_2O_3$ molar ratio of the glass-based substrate between 1.4 and 1.9 also avoids phase separation.

[0101] The glass-based substrate may be characterized by an average field strength of alkali modifiers. The field strength of the glass-based substrate is calculated according to the following formula:

$$\frac{Z}{(r_A + r_O)^2}$$

where Z is the alkali modifier charge (fixed at 1), r_A is the ionic radius of the alkali ion in angstroms, and r_o is the ionic radius of oxygen in angstroms. The calculated field strength was 0.23 for Li, 0.19 for Na, and 0.13 for K. The average field strength of the alkali modifiers for the glass-based substrates is calculated as a weighted average based on the total alkali content. In embodiments, the glass-based substrates have an average field strength of the alkali modifiers of less than or equal to 0.18, such as less than or equal to 0.17, less than or equal to 0.16, less than or equal to 0.15, or less. In cases where the average field strength of the alkali modifiers in the glass-based substrate is less than or equal to 0.18 the glass-based substrates are resistant to phase separation, particularly where the R_2O content is greater than the Al_2O_3 content. In embodiments, the glass-based substrates have an average field strength of the alkali modifiers from greater than or equal to 0.14 to less than or equal to 0.18, such as from greater than or equal to 0.15 to less than or equal to 0.17, from greater than or equal to 0.16 to less than or equal to 0.18, or any and all sub-ranges formed from these endpoints.

[0102] In some embodiments, the glass-based substrates include Li_2O and P_2O_5, or P_2O_5 and no Li_2O, without exhibiting phase separation. As used herein, "phase separation", "phase-separated glass" or the like refer to a glass-based substrate which experiences the formation of a second glassy phase. Further, a "phase-separated glass" can be identified by an optical measurement using a spectrophotometer and/or SEM analysis. As to the former, a "phase separated glass" is any glass or glass-based substrate that exhibits greater than 0.2% diffuse transmission and/or scatter ratio (i.e., % diffuse transmission/% transmittance*100) at a wavelength of 300 nm with a test sample of the glass or glass-based substrate having a thickness of 1 mm. As to the latter, SEM analysis at a magnification of about 100kx on a cross-sectioned glass-based substrate can be employed to ascertain phase separation. Phase separation is undesirable in the glass-based substrates, as phase separation may result in a milky and/or bluish appearance of the glass-based substrates. The composition of the glass-based substrates may be specifically selected to avoid phase separation. For example, the glass-based substrates may have a composition selected such that the R_2O/Al_2O_3 molar ratio and the average field strength of the alkali modifiers are within the ranges described herein to prevent phase separation.

[0103] In embodiments, the glass-based substrates are compatible with platinum. This compatibility allows the glass-based substrates to be melted, fined, and formed using platinum containing apparatuses without producing globular chain platinum defects in the glass-based substrates. As utilized herein, a "globular chain platinum defect" refers to globular chain platinum observed in the glass-based substrates with a size of greater than 100 μm, as measured through optical microscopy with reflected light and/or scanning electron microscopy energy-dispersive x-ray (SEM-EDX) analysis. Further, the observed globular chain platinum is typically in the form of inclusions with two or more connected segments that appear 'globular'. These segments may be well-spaced or connected on multiple surfaces and wrapped closely. Further, the "globular chain platinum defects" herein are measured by optical microscopy and/or SEM-EDX inspection of glass-based substrates and are normalized by the total weight of the glass inspected to produce a defects per pound value. The size of the globular chain platinum is defined by the largest dimension thereof. According to some embodiments, the globular chain defects can include platinum and one or more of rhodium, tin and iron. In embodiments, the glass-based substrates include less than 1 globular chain platinum defect per pound, such as being substantially free of globular chain platinum defects, or free of globular chain platinum defects.

[0104] In some embodiments, the glass-based substrates may have a Young's modulus that is greater than or equal to 50 GPa. In embodiments, the glass-based substrates have a Young's modulus that is greater than or equal to 51 GPa, such as greater than or equal to 52 GPa, greater than or equal to 53 GPa, greater than or equal to 54 GPa, greater than or equal to 55 GPa, greater than or equal to 56 GPa, greater than or equal to 57 GPa, greater than or equal to 58 GPa, greater than or equal to 59 GPa, greater than or equal to 60 GPa, greater than or equal to 61 GPa, greater than or equal to 62 GPa, greater than or equal to 63 GPa, greater than or equal to 64 GPa, greater than or equal to 65 GPa, or more. In some embodiments, the glass-based substrates may have a Young's modulus in the range from greater than or equal to 50 GPa to less than or equal to 70 GPa, such as from greater than or equal to 51 GPa to less than or equal to 69 GPa, from greater than or equal to 52 GPa to less than or equal to 68 GPa, from greater than or equal to 53 GPa to less than or equal to 67 GPa, from greater than or equal to 54 GPa to less than or equal to 66 GPa, from greater than or equal to 55 GPa to less than or equal to 65 GPa, from greater than or equal to 56 GPa to less than or equal to 64 GPa, from greater than or equal to 57 GPa to less than or equal to 63 GPa, from greater than or equal to 58 GPa to less than or equal to 62 GPa, from greater than or equal to 59 GPa to less than or equal to 61 GPa, from greater than or equal to 59 GPa to less than or equal to 60 GPa, or any and all sub-ranges formed from these endpoints.

[0105] In some embodiments, the glass-based substrates may have a 200 P temperature of less than or equal to 1725° C., such as less than or equal to 1720° C., less than or equal to 1715° C., less than or equal to 1710° C., less than or equal to 1705° C., less than or equal to 1700° C., less than or equal to 1695° C., less than or equal to 1690° C., less than or equal to 1685° C., less than or equal to 1680° C., less than or equal to 1675° C., less than or equal to 1670° C., less than or equal to 1665° C., less than or equal to 1660° C., less than or equal to 1655° C., less than or equal to 1650° C., less than or equal to 1645° C., less than or equal to 1640° C., less than or equal to 1635° C., less than or equal to 1630° C., less than or equal to 1625° C., less than or equal to 1620° C., less than or equal to 1615° C., less than or equal to 1610° C., less than or equal to 1605° C., less than or equal to 1600° C., or less. The low 200 P temperature improves the meltability and thereby manufacturability of the glass-based substrate compositions.

[0106] In some embodiments, the glass-based substrates may have a liquidus viscosity of greater than or equal to 10 kP, such as greater than or equal to 100 kP, greater than or equal to 1000 kP, or more. Increases in the Li_2O content of the glass-based substrate decrease the liquidus viscosity of the glass-based substrate composition. Maintaining the liquidus viscosity of the glass-based substrate at greater than about 10 kP allows the glass-based substrates to be produced on a variety of manufacturing platforms, such as fusion forming platforms. It is particularly preferred that the glass-based substrates have a liquidus viscosity of greater than or equal to 100 kP to ensure compatibility with fusion forming. If the liquidus viscosity decreases too much, the manufacturability of the glass-based substrates is decreased.

[0107] In some embodiments, the glass-based substrates may have zircon breakdown viscosity of less than or equal to 35 kP, such as less than or equal to 30 kP, less than or equal to 25 kP, less than or equal to 20 kP, less than or equal to 19 kP, less than or equal to 18 kP, less than or equal to 17 kP, less than or equal to 16 kP, less than or equal to 15 kP, less than or equal to 14 kP, less than or equal to 13 kP, less than or equal to 12 kP, less than or equal to 11 kP, less than or equal to 10 kP, less than or equal to 9 kP, less than or equal to 8 kP, less than or equal to 7 kP, less than or equal to 6 kP, less than or equal to 5 kP, less than or equal to 4 kP, less than or equal to 3 kP, less than or equal to 2 kP, less than or equal to 1 kP, or less. The zircon breakdown viscosity is the viscosity of the glass at the zircon breakdown temperature. Maintaining the zircon breakdown viscosity in the range of less than or equal to 35 kP ensures that the composition is compatible with fusion forming processes that utilize zircon containing elements, such as zircon isopipes.

[0108] The glass-based substrate may have any appropriate geometry. In some embodiments, the glass-based substrate may have a thickness of less than or equal to 2.0 mm, such as less than or equal to 1.9 mm, less than or equal to 1.8 mm, less than or equal to 1.7 mm, less than or equal to 1.6 mm, less than or equal to 1.5 mm, less than or equal to 1.4 mm, less than or equal to 1.3 mm, less than or equal to 1.2 mm, less than or equal to 1.1 mm, less than or equal to 1 mm, less than or equal to 900 μm, less than or equal to 800 μm, less than or equal to 700 μm, less than or equal to 600 μm, less than or equal to 500 μm, less than or equal to 400 μm, less than or equal to 300 μm, or less. In embodiments, the glass-based substrate may have a thickness from greater than or equal to 300 μm to less than or equal to 2 mm, such as from greater than or equal to 400 μm to less than or equal to 1.9 mm, from greater than or equal to 500 μm to less than or equal to 1.8 mm, from greater than or equal to 600 μm to less than or equal to 1.7 mm, from greater than or equal to 700 μm to less than or equal to 1.6 mm, from greater than or equal to 800 μm to less than or equal to 1.5 mm, from greater than or equal to 900 μm to less than or equal to 1.4 mm, from greater than or equal to 1 mm to less than or equal to 1.3 mm, from greater than or equal to 1.1 mm to less than or equal to 1.2 mm, or any and all sub-ranges formed from these endpoints. In some embodiments, the glass-based substrate may have a plate or sheet shape. In some other embodiments, the glass-based substrates may have a 2.5D or 3D shape. As utilized herein, a "2.5D shape" refers to a sheet shaped article with at least one major surface being at least partially nonplanar, and a second major surface being substantially planar. As utilized herein, a "3D shape" refers to an article with first and second opposing major surfaces that are at least partially nonplanar. The glass-based articles may have dimensions and shapes substantially similar or the same as the glass-based substrates from which they are formed.

[0109] The glass-based substrates may be formed by any suitable method, such as slot forming, float forming, rolling processes, fusion forming processes, etc. The glass-based substrates, and glass-based articles produced therefrom, may be characterized by the manner in which they are formed. For instance, a glass-based substrate may be characterized as float-formable (i.e., formed by a float process), down-drawable and, in particular, fusion-formable or slot-drawable (i.e., formed by a down draw process such as a fusion draw process or a slot draw process).

[0110] Some embodiments of the glass-based substrates described herein may be formed by a down-draw process. Down-draw processes produce glass-based substrates having a uniform thickness that possess relatively pristine surfaces. Because the average flexural strength of the glass-based substrate is controlled by the amount and size of surface flaws, a pristine surface that has had minimal contact has a higher initial strength. In addition, down drawn glass-based substrates have a very flat, smooth surface that can be used in its final application without costly grinding and polishing.

[0111] Some embodiments of the glass-based substrates may be described as fusion-formable (i.e., formable using a fusion draw process). The fusion draw process uses a drawing tank that has a channel for accepting molten glass raw material. The channel has weirs that are open at the top along the length of the channel on both sides of the channel. When the channel fills with molten material, the molten glass overflows the weirs. Due to gravity, the molten glass flows down the outside surfaces of the drawing tank as two flowing glass films. These outside surfaces of the drawing tank extend down and inwardly so that they join at an edge below the drawing tank. The two flowing glass films join at this edge to fuse and form a single flowing glass article. The fusion of the glass films produces a fusion line within the glass-based substrate, and this fusion line allows glass-based substrates that were fusion formed to be identified without additional knowledge of the manufacturing history. The fusion draw method offers the advantage that, because the two glass films flowing over the channel fuse together, neither of the outside surfaces of the resulting glass article comes in contact with any part of the apparatus. Thus, the surface properties of the fusion drawn glass article are not affected by such contact.

[0112] The compositions of the glass-based substrates described herein are specifically selected to be compatible with the fusion forming process. This compatibility is dependent on the liquidus viscosity and zircon breakdown viscosity of the composition of the glass-based substrates. In embodiments, the glass-based substrates have a liquidus viscosity of greater than or equal to 100 kP and a zircon breakdown viscosity of less than or equal to 35 kP.

[0113] Some embodiments of the glass-based substrates described herein may be formed by a slot draw process. The slot draw process is distinct from the fusion draw method. In slot draw processes, the molten raw material glass is provided to a drawing tank. The bottom of the drawing tank has an open slot with a nozzle that extends the length of the slot. The molten glass flows through the slot/nozzle and is drawn downward as a continuous glass-based substrate and into an annealing region.

[0114] The glass-based articles may be produced from the glass-based substrate by exposure to water vapor under any appropriate conditions. The exposure may be carried out in any appropriate device, such as a furnace with relative humidity control. The exposure may also be carried out at an elevated pressure, such as in a furnace or autoclave with relative humidity and pressure control.

[0115] In some embodiments, the glass-based articles may be produced by exposing a glass-based substrate to an environment with a pressure greater than ambient pressure and containing water vapor. The environment may have a pressure greater than 0.1 MPa and a water partial pressure of greater than or equal to 0.05 MPa, such as greater than or equal to 0.075 MPa. The elevated pressure in the exposure environment allows for a higher concentration of water vapor in the environment, especially as temperatures are increased. As the temperature increases the amount of water available for diffusion into the glass-based substrates to form glass-based articles decreases for a fixed volume, such as the interior of a furnace or autoclave. Thus, while increasing the temperature of the water vapor treatment environment may increase the rate of diffusion of hydrogen species into the glass-based substrate, reduced total water vapor concentration and stress relaxation at higher temperatures produce decreased compressive stress when pressure remains constant. As temperatures increase, such as those above the atmospheric pressure saturation condition, applying increased pressure to reach the saturation condition increases the concentration of water vapor in the environment significantly.

[0116] At atmospheric pressure (0.1 MPa), the water vapor saturation condition is 99.61° C. As the temperature increases the amount of water available for diffusion into the glass-based substrates to form glass-based articles decreases for a fixed volume, such as the interior of a furnace or autoclave. Thus, while increasing the temperature of the water vapor treatment environment may increase the rate of diffusion of hydrogen species into the glass-based substrate, reduced total water vapor concentration may reduce the effectiveness of the treatment.

[0117] As temperatures increase, such as those above the atmospheric pressure saturation condition, applying increased pressure to reach the saturation condition increases the concentration of water vapor in the environment significantly. The saturation condition for water vapor as a function of pressure and temperature is shown in FIG. **3**. As shown in FIG. **3**, the regions above the curve will result in condensation of water vapor into liquid which is undesirable. Thus, the water vapor treatment conditions utilized herein may preferably fall on or under the curve in FIG. **3**, with further preferred conditions being on or just under the curve to maximize water vapor content. For these reasons, the water vapor treatment of the glass-based substrates may be carried out at elevated pressure.

[0118] High temperature and pressure conditions have been shown to produce glass-based articles with a hazy appearance. The hazy appearance is correlated to the concentration of added hydrogen species in the glass-based article, with higher temperature and pressure conditions producing higher concentrations of hydrogen species in the glass-based article. The formation of haze during the water treatment process may be addressed by utilizing the lithium containing compositions described herein or by selecting the treatment conditions to manage the amount of hydrogen species added to the glass-based article. For example, at high temperatures treatment pressures below the saturation pressure may be utilized to reduce the concentration of hydrogen species in the glass-based article. The concentration of the hydrogen species may be reduced by decreasing the total amount of hydrogen species diffused into the glass-based article, as evidenced by reduced weight gain during water vapor treatment, or by increasing the depth of layer for the same amount of weight gain. The approaches for mitigating haze, composition and treatment conditions may be utilized in conjunction.

[0119] In some embodiments, the lithium containing glass-based substrates described herein may be exposed to a water vapor treatment in a saturated steam environment at a temperature of greater than or equal to 85° C. The glass-based substrates containing lithium allow the use of a wider process window with higher temperatures and pressures while avoiding haze, thereby decreasing treatment times and increasing the efficiency of the strengthening process. The glass-based articles produced utilizing these haze mitigation strategies are substantially haze-free or haze-free in appearance.

[0120] In some embodiments, the glass-based substrates may be exposed to an environment at a pressure greater than or equal to 0.1 MPa, such as greater than or equal to 0.2 MPa, greater than or equal to 0.3 MPa, greater than or equal to 0.4 MPa, greater than or equal to 0.5 MPa, greater than or equal to 0.6 MPa, greater than or equal to 0.7 MPa, greater than or equal to 0.8 MPa, greater than or equal to 0.9 MPa, greater than or equal to 1.0 MPa, greater than or equal to 1.1 MPa, greater than or equal to 1.2 MPa, greater than or equal to 1.3 MPa, greater than or equal to 1.4 MPa, greater than or equal to 1.5 MPa, greater than or equal to 1.6 MPa, greater than or equal to 1.7 MPa, greater than or equal to 1.8 MPa, greater than or equal to 1.9 MPa, greater than or equal to 2.0 MPa, greater than or equal to 2.1 MPa, greater than or equal to 2.2 MPa, greater than or equal to 2.3 MPa, greater than or equal to 2.4 MPa, greater than or equal to 2.5 MPa, greater than or equal to 2.6 MPa, greater than or equal to 2.7 MPa, greater than or equal to 2.8 MPa, greater than or equal to 2.9 MPa, greater than or equal to 3.0 MPa, greater than or equal to 3.1 MPa, greater than or equal to 3.2 MPa, greater than or equal to 3.3 MPa, greater than or equal to 3.4 MPa, greater than or equal to 3.5 MPa, greater than or equal to 3.6 MPa, greater than or equal to 3.7 MPa, greater than or equal to 3.8 MPa, greater than or equal to 3.9 MPa, greater than or equal to 4.0 MPa, greater than or equal to 4.1 MPa, greater than or equal to 4.2 MPa, greater than or equal to 4.3 MPa, greater than or equal to 4.4 MPa, greater than or equal to 4.5 MPa, greater than or equal to 4.6 MPa, greater than or equal to 4.7 MPa, greater than or equal to 4.8 MPa, greater than or equal to 4.9 MPa, greater than or equal to 5.0 MPa, greater than or equal to 5.1 MPa, greater than or equal to 5.2 MPa, greater than or equal to 5.3 MPa, greater than or equal to 5.4 MPa, greater than or equal to 5.5 MPa, greater than or equal to 5.6 MPa, greater than or equal to 5.7 MPa, greater than or equal to 5.8 MPa, greater than or equal to 5.9 MPa, greater than or equal to 6.0 MPa, or more. In embodiments, the glass-based substrates may be exposed to an environment at a pressure of from greater than or equal to 0.1 MPa to less than or equal to 25 MPa, such as from greater than or equal to 0.2 MPa to less than or equal to 24 MPa, from greater than or equal to 0.3 MPa to less than or equal to 23 MPa, from greater than or equal to 0.4 MPa to less than or equal to 22 MPa, from greater than or equal to 0.5 MPa to less than or equal to 21 MPa, from greater than or equal to 0.6 MPa to less than or equal to 20 MPa, from greater than or equal to 0.7 MPa to less than or equal to 19 MPa, from greater than or equal to 0.8 MPa to less than or equal to 18 MPa, from greater than or equal to 0.9 MPa to less than or equal to 17 MPa, from greater than or equal to 1.0 MPa to less than or equal to 16 MPa, from greater than or equal to 1.1 MPa to less than or equal to 15 MPa, from greater than or equal to 1.2 MPa to less than or equal to 14 MPa, from greater than or equal to 1.3 MPa to less than or equal to 13 MPa, from greater than or equal to 1.4 MPa to less than or equal to 12 MPa, from greater than or equal to 1.5 MPa to less than or equal to 11 MPa, from greater than or equal to 1.6 MPa to less than or equal to 10 MPa, from greater than or equal to 1.7 MPa to less than or equal to 9 MPa, from greater than or equal to 1.8 MPa to less than or equal to 8 MPa, from greater than or equal to 1.9 MPa to less than or equal to 7 MPa, from greater than or equal to 1.9 MPa to less than or equal to 6.9 MPa, from greater than or equal to 2.0 MPa to less than or equal to 6.8 MPa, from greater than or equal to 2.1 MPa to less than or equal to 6.7 MPa, from greater than or equal to 2.2 MPa to less than or equal to 6.6 MPa, from greater than or equal to 2.3 MPa to less than or equal to 6.5 MPa, from greater than or equal to 2.4 MPa to less than or equal to 6.4 MPa, from greater than or equal to 2.5 MPa to less than or equal to 6.3 MPa, from greater than or equal to 2.6 MPa to less than or equal to 6.2 MPa, from greater than or equal to 2.7 MPa to less than or equal to 6.1 MPa, from greater than or equal to 2.8 MPa to less than or equal to 6.0 MPa, from greater than or equal to 2.9 MPa to less than or equal to 5.9 MPa, from greater than or equal to 3.0 MPa to less than or equal to 5.8 MPa, from greater than or equal to 3.1 MPa to less than or equal to 5.7 MPa, from greater than or equal to 3.2 MPa to less than or equal to 5.6 MPa, from greater than or equal to 3.3 MPa to less than or equal to 5.5 MPa, from greater than or equal to 3.4 MPa to less than or equal to 5.4 MPa, from greater than or equal to 3.5 MPa to less than or equal to 5.3 MPa, from greater than or equal to 3.6 MPa to less than or equal to 5.2 MPa, from greater than or equal to 3.7 MPa to less than or equal to 5.1 MPa, from greater than or equal to 3.8 MPa to less than or equal to 5.0 MPa, from greater than or equal to 3.9 MPa to less than or equal to 4.9 MPa, from greater than or equal to 4.0 MPa to less than or equal to 4.8 MPa, from greater than or equal to 4.1 MPa to less than or equal to 4.7 MPa, from greater than or equal to 4.2 MPa to less than or equal to 4.6 MPa, from greater than or equal to 4.3 MPa to less than or equal to 4.5 MPa, 4.4 MPa, or any and all sub-ranges formed from any of these endpoints. In some embodiments, the glass-based substrates may be exposed to an environment at ambient pressure, such as 0.1 MPa.

[0121] In some embodiments, the glass-based substrates may be exposed to an environment with a water partial pressure greater than or equal to 0.05 MPa, such as greater than or equal to 0.075 MPa, greater than or equal to 0.1 MPa, greater than or equal to 0.2 MPa, greater than or equal to 0.3 MPa, greater than or equal to 0.4 MPa, greater than or equal to 0.5 MPa, greater than or equal to 0.6 MPa, greater than or equal to 0.7 MPa, greater than or equal to 0.8 MPa, greater than or equal to 0.9 MPa, greater than or equal to 1.0 MPa, greater than or equal to 1.1 MPa, greater than or equal to 1.2 MPa, greater than or equal to 1.3 MPa, greater than or equal to 1.4 MPa, greater than or equal to 1.5 MPa, greater than or equal to 1.6 MPa, greater than or equal to 1.7 MPa, greater than or equal to 1.8 MPa, greater than or equal to 1.9 MPa, greater than or equal to 2.0 MPa, greater than or equal to 2.1 MPa, greater than or equal to 2.2 MPa, greater than or equal to 2.3 MPa, greater than or equal to 2.4 MPa, greater than or equal to 2.5 MPa, greater than or equal to 2.6 MPa, greater than or equal to 2.7 MPa, greater than or equal to 2.8 MPa, greater than or equal to 2.9 MPa, greater than or equal to 3.0 MPa, greater than or equal to 3.1 MPa, greater than or equal to 3.2 MPa, greater than or equal to 3.3 MPa, greater than or equal to 3.4 MPa, greater than or equal to 3.5 MPa, greater than or equal to 3.6 MPa, greater than or equal to 3.7 MPa, greater than or equal to 3.8 MPa, greater than or equal to 3.9 MPa, greater than or equal to 4.0 MPa, greater than or equal to 4.1 MPa, greater than or equal to 4.2 MPa, greater than or equal to 4.3 MPa, greater than or equal to 4.4 MPa, greater than or equal to 4.5 MPa, greater than or equal to 4.6 MPa, greater than or equal to 4.7 MPa, greater than or equal to 4.8 MPa, greater than or equal to 4.9 MPa, greater than or equal to 5.0 MPa, greater than or equal to 5.1 MPa, greater than or equal to 5.2 MPa, greater than or equal to 5.3 MPa, greater than or equal to 5.4 MPa, greater than or equal to 5.5 MPa, greater than or equal to 5.6 MPa, greater than or equal to 5.7 MPa, greater than or equal to 5.8 MPa, greater than or equal to 5.9 MPa, greater than or equal to 6.0 MPa, greater than or equal to 7.0 MPa, greater than or equal to 8.0 MPa, greater than or equal to 9.0 MPa, greater than or equal to 10.0 MPa, greater than or equal to 11.0 MPa, greater than or equal to 12.0 MPa, greater than or equal to 13.0 MPa, greater than or equal to 14.0 MPa, greater than or equal to 15.0 MPa, greater than or equal to 16.0 MPa, greater than or equal to 17.0 MPa, greater than or equal to 18.0 MPa, greater than or equal to 19.0 MPa, greater than or equal to 20.0 MPa, greater than or equal to 21.0 MPa, greater than or equal to 22.0 MPa, or more. In embodiments, the glass-based substrates may be exposed to an environment with a water partial pressure from greater than or equal to 0.05 MPa to less than or equal to 22 MPa, such as from greater than or equal to 0.075 MPa to less than or equal to 22 MPa, from greater than or equal to 0.1 MPa to less than or equal to 21 MPa, from greater than or equal to 0.2 MPa to less than or equal to 20 MPa, from greater than or equal to 0.3 MPa to less than or equal to 19 MPa, from greater than or equal to 0.4 MPa to less than or equal to 18 MPa, from greater than or equal to 0.5 MPa to less than or equal to 17 MPa, from greater than or equal to 0.6 MPa to less than or equal to 16 MPa, from greater than or equal to 0.7 MPa to less than or equal to 15 MPa, from greater than or equal to 0.8 MPa to less than or equal to 14 MPa, from greater than or equal to 0.9 MPa to less than or equal to 13 MPa, from greater than or equal to 1.0 MPa to less than or equal to 12 MPa, from greater than or equal to 1.1 MPa to less than or equal to 11 MPa, from greater than or equal to 1.2 MPa to less than or equal to 10 MPa, from greater than or equal to 1.3 MPa to less than or equal to 9 MPa, from greater than or equal to 1.4 MPa to less than or equal to 8 MPa, from greater than or equal to 1.5 MPa to less than or equal to 7 MPa, from greater than or equal to 1.6 MPa to less than or equal to 6.9 MPa, from greater than or equal to 1.7 MPa to less than or equal to 6.8 MPa, from greater than or equal to 1.8 MPa to less than or equal to 6.7 MPa, from greater than or equal to 1.9 MPa to less than or equal to 6.6 MPa, from greater than or equal to 2.0 MPa to less than or equal to 6.5 MPa, from greater than or equal to 2.1 MPa to less than or equal to 6.4 MPa, from greater than or equal to 2.2 MPa to less than or equal to 6.3 MPa, from greater than or equal to 2.3 MPa to less than or equal to 6.2 MPa, from greater than or equal to 2.4 MPa to less than or equal to 6.1 MPa, from greater than or equal to 2.5 MPa to less than or equal to 6.0 MPa, from greater than or equal to 2.6 MPa to less than or equal to 5.9 MPa, from greater than or equal to 2.7 MPa to less than or equal to 5.8 MPa, from greater than or equal to 2.8 MPa to less than or equal to 5.7 MPa, from greater than or equal to 2.9 MPa to less than or equal to 5.6 MPa, from greater than or equal to 3.0 MPa to less than or equal to 5.5 MPa, from greater than or equal to 3.1 MPa to less than or equal to 5.4 MPa, from greater than or equal to 3.2 MPa to less than or equal to 5.3 MPa, from greater than or equal to 3.3 MPa to less than or equal to 5.2 MPa, from greater than or equal to 3.4 MPa to less than or equal to 5.1 MPa, from greater than or equal to 3.5 MPa to less than or equal to 5.0 MPa, from greater than or equal to 3.6 MPa to less than or equal to 4.9 MPa, from greater than or equal to 3.7 MPa to less than or equal to 4.8 MPa, from greater than or equal to 3.8 MPa to less than or equal to 4.7 MPa, from greater than or equal to 3.9 MPa to less than or equal to 4.6 MPa, from greater than or equal to 4.0 MPa to less than or equal to 4.5 MPa, from greater than or equal to 4.1 MPa to less than or equal to 4.4 MPa, from greater than or equal to 4.2 MPa to less than or equal to 4.3 MPa, or any and all sub-ranges formed from any of these endpoints.

[0122] In some embodiments, the glass-based substrates may be exposed to an environment with a relative humidity of greater than or equal to 10%, such as greater than or equal to 25%, greater than or equal to 50%, greater than or equal to 75%, greater than or equal to 80%, greater than or equal to 85%, greater than or equal to 90%, greater than or equal to 95%, greater than or equal to 99%, or more. In some embodiments, the glass-based substrate may be exposed to an environment with 100% relative humidity. In some embodiments, the environment may be a saturated steam environment.

[0123] In some embodiments, the glass-based substrates may be exposed to an environment with a temperature of greater than or equal to 85° C., such as greater than or equal to 90° C., greater than or equal to 100° C., greater than or equal to 110° C., greater than or equal to 120° C., greater than or equal to 130° C., greater than or equal to 140° C., greater than or equal to 150° C., greater than or equal to 160° C., greater than or equal to 170° C., greater than or equal to 180° C., greater than or equal to 190° C., greater than or equal to 200° C., greater than or equal to 210° C., greater than or equal to 220° C., greater than or equal to 230° C., greater than or equal to 240° C., greater than or equal to 250° C., greater than or equal to 260° C., greater than or equal to 270° C., greater than or equal to 280° C., greater than or equal to 290° C., greater than or equal to 300° C., greater than or equal to 310° C., greater than or equal to 320° C., greater than or equal to 330° C., greater than or equal to 340° C., greater than or equal to 350° C., greater than or equal to 360° C., greater than or equal to 370° C., greater than or equal to 380° C., greater than or equal to 390° C., greater than or equal to 400° C., or more. In some embodiments, the glass-based substrates may be exposed to an environment with a temperature from greater than or equal to 85° C. to less than or equal to 400° C., such as from greater than or equal to 100° C. to less than or equal to 390° C., from greater than or equal to 110° C. to less than or equal to 380° C., from greater than or equal to 115° C. to less than or equal to 370° C., from greater than or equal to 120° C. to less than or equal to 360° C., from greater than or equal to 125° C. to less than or equal to 350° C., from greater than or equal to 130° C. to less than or equal to 340° C., from greater than or equal to 135° C. to less than or equal to 330° C., from greater than or equal to 140° C. to less than or equal to 320° C., from greater than or equal to 145° C. to less than or equal to 310° C., from greater than or equal to 150° C. to less than or equal to 300° C., from greater than or equal to 155° C. to less than or equal to 295° C., from greater than or equal to 160° C. to less than or equal to 290° C., from greater than or equal to 165° C. to less than or equal to 285° C., from greater than or equal to 170° C. to less than or equal to 280° C., from greater than or equal to 175° C. to less than or equal to 275° C., from greater than or equal to 180° C. to less than or equal to 270° C., from greater than or equal to 185° C. to less than or equal to 265° C., from greater than or equal to 190° C. to less than or equal to 260° C., from greater than or equal to 195° C. to less than or equal to 255° C., from greater than or equal to 200° C. to less than or equal to 250° C., from greater than or equal to 205° C. to less than or equal to 245° C., from greater than or equal to 210° C. to less than or equal to 240° C., from greater than or equal to 215° C. to less than or equal to 235° C., from greater than or equal to 220° C. to less than or equal to 230° C., from greater than or equal to 220° C. to less than or equal to 225° C., or any and all sub-ranges formed from any of these endpoints.

[0124] In some embodiments, the glass-based substrate may be exposed to the water vapor containing environment for a time period sufficient to produce the desired degree of hydrogen-containing species diffusion and the desired compressive stress layer. In some embodiments, the glass-based substrate may be exposed to the water vapor containing environment for greater than or equal to 2 hours, such as greater than or equal to 4 hours, greater than or equal to 6 hours, greater than or equal to 8 hours, greater than or equal to 10 hours, greater than or equal to 12 hours, greater than or equal to 14 hours, greater than or equal to 16 hours, greater than or equal to 18 hours, greater than or equal to 20 hours, greater than or equal to 22 hours, greater than or equal to 24 hours, greater than or equal to 30 hours, greater than or equal to 36 hours, greater than or equal to 42 hours, greater than or equal to 48 hours, greater than or equal to 54 hours, greater than or equal to 60 hours, greater than or equal to 66 hours, greater than or equal to 72 hours, greater than or equal to 78 hours, greater than or equal to 84 hours, greater than or equal to 90 hours, greater than or equal to 96 hours, greater than or equal to 102 hours, greater than or equal to 108 hours, greater than or equal to 114 hours, greater than or equal to 120 hours, greater than or equal to 126 hours, greater than or equal to 132 hours, greater than or equal to 138 hours, greater than or equal to 144 hours, greater than or equal to 150 hours, greater than or equal to 156 hours, greater than or equal to 162 hours, greater than or equal to 168 hours, or more. In some embodiments, the glass-based substrate may be exposed to the water vapor containing environment for a time period from greater than or equal to 2 hours to less than or equal to 10 days, such as from greater than or equal to 4 hours to less than or equal to 9 days, from greater than or equal to 6 hours to less than or equal to 8 days, from greater than or equal to 8 hours to less than or equal to 168 hours, from greater than or equal to 10 hours to less than or equal to 162 hours, from greater than or equal to 12 hours to less than or equal to 156 hours, from greater than or equal to 14 hours to less than or equal to 150 hours, from greater than or equal to 16 hours to less than or equal to 144 hours, from greater than or equal to 18 hours to less than or equal to 138 hours, from greater than or equal to 20 hours to less than or equal to 132 hours, from greater than or equal to 22 hours to less than or equal to 126 hours, from greater than or equal to 24 hours to less than or equal to 120 hours, from greater than or equal to 30 hours to less than or equal to 114 hours, from greater than or equal to 36 hours to less than or equal to 108 hours, from greater than or equal to 42 hours to less than or equal to 102 hours, from greater than or equal to 48 hours to less than or equal to 96 hours, from greater than or equal to 54 hours to less than or equal to 90 hours, from greater than or equal to 60 hours to less than or equal to 84 hours, from greater than or equal to 66 hours to less than or equal to 78 hours, 72 hours, or any and all sub-ranges formed from any of these endpoints.

[0125] In some embodiments, the glass-based substrates may be exposed to multiple water vapor containing environments. In embodiments, the glass-based substrate may be exposed to a first environment to form a first glass-based article with a first compressive stress layer extending from a surface of the first glass-based article to a first depth of compression, and the first glass-based article may then be exposed to a second environment to form a second glass-based article with a second compressive stress layer extending from a surface of the second glass-based article to a second depth of compression. The first environment has a first water partial pressure and a first temperature, and the glass-based substrate is exposed to the first environment for a first time period. The second environment has a second water partial pressure and a second temperature, and the first glass-based article is exposed to the second environment for a second time period.

[0126] The first water partial pressure and the second water partial pressure may be any appropriate partial pressure, such as greater than or equal to 0.05 MPa or greater than or equal to 0.075 MPa. The first and second partial pressure may be any of the values disclosed herein with respect to the water partial pressures employed in the treatment method. In embodiments, the first and second environments may have, independently, a relative humidity of greater than or equal to 10%, such as greater than or equal to 25%, greater than or equal to 50%, greater than or equal to 75%, greater than or equal to 80%, greater than or equal to 90%, greater than or equal to 95%, or equal to 100%. In some embodiments, at least one of the first environment and the second environment has a relative humidity of 100%. In embodiments, the first and second environments may be, independently, a saturated steam environment.

[0127] The first compressive stress layer includes a first maximum compressive stress, and the second compressive stress layer includes a second maximum compressive stress. In embodiments, the first maximum compressive stress is less than the second maximum compressive stress. The second maximum compressive stress may be compared to a compressive stress "spike" of the type formed through multi-step or mixed bath ion exchange techniques. The first and second maximum compressive stress may have any of the values disclosed herein with respect to the compressive stress of the glass-based article. In embodiments, the second maximum compressive stress may be greater than or equal to 50 MPa.

[0128] The first depth of compression may be less than or equal to the second depth of compression. In some embodiments, the first depth of compression is less than the second depth of compression. The first depth of compression and the second depth of compression may have any of the values disclosed herein with respect to the depth of compression. In embodiments, the second depth of compression is greater than 5 μm.

[0129] The first temperature may be greater than or equal to the second temperature. In embodiments, the first temperature is greater than the second temperature. The first and second temperatures may be any of the temperatures disclosed in connection with the treatment method.

[0130] The first time period may be less than or equal to the second time period. In embodiments, the first time period is less than the second time period. The first and second time periods may be any of the time periods disclosed in connection with the elevated pressure method.

[0131] In embodiments, any or all of the multiple exposures to a water vapor containing environment may be performed at an elevated pressure. For example, at least one of the first environment and the second environment may have a pressure greater than 0.1 MPa. The first and second environments may have any pressure disclosed in connection with the treatment method.

[0132] In some embodiments, the multiple water vapor environment exposure technique may include more than two exposure environments. In embodiments, the second glass-based article may be exposed to a third environment to form a third glass-based article. The third environment has a third water partial pressure and a third temperature, and the second glass-based article is exposed to the third environment for a third time period. The third glass-based article includes a third compressive stress layer extending from a surface of the article to a third depth of compression and having a third maximum compressive stress. The third water partial pressure may be greater than or equal to 0.05 MPa or greater than or equal to 0.075 MPa. The values of any of the properties of the third environment and third glass-based article may be selected from those disclosed for the corresponding properties in connection with the elevated pressure method.

[0133] In some embodiments, the first glass-based article may be cooled to ambient temperature or otherwise removed from the first environment after the conclusion of the first time period and prior to being exposed to the second environment. In some embodiments, the first glass-based article may remain in the first environment after the conclusion of the first time period, and the first environment conditions may be changed to the second environment conditions without cooling to ambient temperature or removing the first glass-based article from the water vapor containing environment.

[0134] The methods of producing the glass-based articles disclosed herein may be free of an ion exchange treatment with an alkali ion source. In embodiments, the glass-based articles are produced by methods that do not include an ion exchange with an alkali ion source. Stated differently, in some embodiments the glass-based substrates and glass-based articles are not subjected to an ion exchange treatment with an alkali ion source.

[0135] The exposure conditions may be modified to reduce the time necessary to produce the desired amount of hydrogen-containing species diffusion into the glass-based substrate. For example, the temperature and/or relative humidity may be increased to reduce the time required to achieve the desired degree of hydrogen-containing species diffusion and depth of layer into the glass-based substrate.

[0136] The methods and glass-based substrate compositions disclosed herein may produce glass-based articles that have a substantially haze-free or haze-free appearance.

Exemplary Embodiments

[0137] Glass compositions that are particularly suited for formation of the glass-based articles described herein were formed into glass-based substrates, and the glass compositions are provided in Table I below (Exs. A-V). The density of the glass compositions was determined using the buoyancy method of ASTM C693-93(2013). The strain point and anneal point were determined using the beam bending viscosity method of ASTM C598-93(2013). The Young's modulus values refer to values as measured by a resonant ultrasonic spectroscopy technique of the general type set forth in ASTM E2001-13, titled "Standard Guide for Resonant Ultrasound Spectroscopy for Defect Detection in Both Metallic and Non-metallic Parts." The stress optical coefficient (SOC) was measured according to Procedure C (Glass Disc Method) described in ASTM standard C770-16, entitled "Standard Test Method for Measurement of Glass Stress-Optical Coefficient." The refractive index was measured at a wavelength of 589.3 nm. The liquidus temperature was measured in accordance with ASTM C829-81(2015), titled "Standard Practice for Measurement of Liquidus Temperature of Glass by the Gradient Furnace Method." The liquidus viscosity was calculated from the measured liquidus temperature (T) via the equation:

$$\log_{10}\eta = A + \frac{B}{T - T_0}$$

where η is viscosity, and A, B and T_0 were fitted from high-temperature viscosity (HTV) measurement, which is measured by rotation viscometers according to ASTM C965-96(2012), titled "Standard Practice for Measuring Viscosity of Glass Above the Softening Point." The zircon breakdown temperature was measured in the same manner as the liquidus temperature by positioning a zircon refractory strip in the Pt/Rh boat surrounded by glass cullet. After a testing time of 72 hours the test slab was examined by polarized light microscopy, reflective light microscopy, and scanning electron microscopy to detect secondary zirconia and determine the temperature at which zirconia was produced. The zircon breakdown viscosity is calculated based on the measured zircon breakdown temperature in the same manner as the liquidus viscosity described above.

TABLE I

Composition (mol %)	Ex. A	Ex. B	Ex. C	Ex. D	Ex. E	Ex. F	Ex. G	Ex. H
SiO_2	60.7	60.9	61.0	60.5	60.9	61.0	62.3	62.2
Al_2O_3	12.0	12.0	12.1	12.0	12.0	12.1	12.9	12.9
P_2O_5	5.5	5.4	5.5	5.4	5.4	5.4	5.3	5.3
B_2O_3	9.2	8.3	7.4	9.3	8.2	7.2	1.6	2.6
Li_2O	3.0	3.8	4.5	2.3	3.0	3.8	3.7	3.7
Na_2O	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1
K_2O	9.5	9.4	9.4	10.4	10.4	10.4	14.1	13.1
SnO_2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Average field strength	0.15	0.16	0.16	0.15	0.15	0.16	0.15	0.15
R_2O/Al_2O_3	1.04	1.10	1.16	1.06	1.11	1.17	1.38	1.30
$(R_2O + P_2O_5)/Al_2O_3$	1.50	1.55	1.61	1.52	1.56	1.62	1.79	1.72
Density (g/cm^3)	2.318	2.327	2.331	2.322	2.331	2.338	2.385	2.375
Strain Pt (° C.)	476	476	**	483	481	484	600	574
Anneal Pt (° C.)	525	524	**	534	530	531	663	634
200 P Temperature (° C.)	1651	1629	1600	1667	1647	1612	1716	1717
35 kP Temperature (° C.)	1147	1129	1094	1173	1137	1105	1218	1217
100 kP Temperature (° C.)	1074	1056	1026	1099	1066	1037	1149	1146
Zircon Breakdown Temperature (° C.)	>1375	1370	1370	1355	1355	**	1255	1295
Zircon Breakdown Viscosity (kP)	<2.32	2.0	1.3	3.8	2.6	**	20.9	12.3
Liquidus Temperature (° C.)	<760	<815	<800	<805	<880	**	1240	1135
Liquidus Viscosity (kP)	>43955	>8128	>10467	>21613	>2857	**	26	119
Young's Modulus (GPa)	57.0	58.4	**	55.9	57.5	58.5	60.9	60.3
Stress Optical Coefficient (nm/mm/MPa)	3.561	3.572	**	**	3.459	3.383	**	3.139
Refractive Index (@589.3 nm)	1.4875	1.4856	**	1.485	1.4883	1.4868	1.491	1.4903
Appearance	Non-phase separated	Non-phase separated	Non-phase separated	Non-phase separated	Non-phase separated	Non-phase separated	Non-phase separated	Non-phase separated

Composition (mol %)	Ex. I	Ex. J	Ex. K	Ex. L	Ex. M	Ex. N	Ex. O	Ex. P
SiO_2	62.5	62.4	62.5	62.4	62.4	62.4	62.4	62.5
Al_2O_3	13.0	12.9	13.0	13.0	13.0	13.0	12.9	13.0
P_2O_5	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4
B_2O_3	3.0	3.5	4.0	4.5	5.0	5.5	1.6	1.6
Li_2O	3.5	3.5	3.5	3.6	3.6	3.5	3.6	3.6
Na_2O	0.0	0.0	0.0	0.0	0.0	0.0	1.8	3.8
K_2O	12.5	12.0	11.4	11.0	10.5	10.0	12.1	10.1
SnO_2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Average field strength	0.15	0.15	0.15	0.15	0.16	0.16	0.16	0.16
R_2O/Al_2O_3	1.23	1.20	1.16	1.12	1.09	1.05	1.35	1.34
$(R_2O + P_2O_5)/Al_2O_3$	1.65	1.62	1.57	1.54	1.51	1.47	1.77	1.76
Density (g/cm^3)	2.396	2.363	2.357	**	**	**	2.39	2.39
Strain Pt (° C.)	557	541	534	516	512	500	588	578
Anneal Pt (° C.)	616	600	592	572	567	554	651	641
200 P Temperature (° C.)	1716	1705	**	1718	1699	**	1698	1694
35 kP Temperature (° C.)	1218	1210	**	1213	1192	**	1200	1193
100 kP Temperature (° C.)	1147	1140	**	1140	1122	**	1132	1123
Zircon Breakdown Temperature (° C.)	1285	1310	1300	1320	>1310	>1325	1290	1295
Zircon Breakdown Viscosity (kP)	14.1	9.3	**	8.9	<7.5	**	10.3	9.0

TABLE I-continued

Liquidus Temperature (° C.)	1080	980	925	910	<820	<780	1160	1075
Liquidus Viscosity (kP)	306	1754	**	6543	>61004	**	64	223
Young's Modulus (GPa)	60.2	60.0	59.8	59.6	59.4	59.3	62.9	64.4
Stress Optical Coefficient (nm/mm/MPa)	3.156	3.209	3.226	3.263	3.304	3.37	3.042	3.004
Refractive Index (@589.3 nm)	1.4899	1.4892	1.4887	1.4882	1.4877	1.4873	1.4914	1.4917
Appearance	Non-phase separated	Non-phase separated	Non-phase separated	Non-phase separated	Non-phase separated	Non-phase separated	Non-phase separated	Non-phase separated

Composition (mol %)	Ex. Q	Ex. R	Ex. S	Ex. T	Ex. U	Ex. V
SiO_2	62.5	62.6	62.7	62.3	62.6	62.4
Al_2O_3	13.0	13.0	13.0	13.0	13.3	13.3
P_2O_5	5.4	5.3	5.3	5.4	5.5	5.3
B_2O_3	1.5	2.5	2.5	2.6	0.0	0.0
Li_2O	3.5	3.5	3.5	3.5	2.5	0.0
Na_2O	5.8	1.8	3.8	5.8	8.9	11.4
K_2O	8.2	11.1	9.1	7.2	7.2	7.3
SnO_2	0.1	0.1	0.1	0.1	0.1	0.1
Average field strength	0.17	0.16	0.17	0.17	0.17	0.17
R_2O/Al_2O_3	1.35	1.26	1.25	1.28	1.40	1.40
$(R_2O + P_2O_5)/Al_2O_3$	1.76	1.67	1.66	1.69	1.81	1.80
Density (g/cm^3)	2.393	2.377	2.378	2.381	2.406	2.413
Strain Pt (° C.)	566	559	554	538	609	605
Anneal Pt (° C.)	628	622	616	597	668	663
200 P Temperature (° C.)	1675	1703	1706	1674	1675	1701
35 kP Temperature (° C.)	1176	1209	1198	1176	1191	1222
100 kP Temperature (° C.)	1107	1138	1127	1107	1123	1114
Zircon Breakdown Temperature (° C.)	1295	1270	1295	1330	1250	>1225
Zircon Breakdown Viscosity (kP)	7.2	15.3	9.8	4.9	15.5	**
Liquidus Temperature (° C.)	955	1035	945	905	995	995
Liquidus Viscosity (kP)	1713	571	2912	4649	985	2052
Young's Modulus (GPa)	65.5	62.7	62.8	65.1	65.02	64.05
Stress Optical Coefficient (nm/mm/MPa)	**	3.072	**	**	2.998	2.995
Refractive Index (@589.3 nm)	1.4918	1.4906	1.4908	1.4911	1.4912	1.49
Appearance	Non-phase separated	Non-phase separated	Non-phase separated	Non-phase separated	Non-phase separated	Non-phase separated

[0138] Samples having the compositions shown in Table I (Ex. A-T) were exposed to water vapor containing environments to form glass articles having compressive stress layers. The samples were exposed to steam treatment at a pressure of 1.6 MPa, and a temperature of 200° C., for a duration of 16 hours. The exposure environments were saturated. The resulting maximum compressive stress and depth of compression as measured by surface stress meter (FSM) are reported in Table II. If the stress optical coefficient (SOC) and/or refractive index (RI) were not available, default values of 3.0 nm/mm/MPa and 1.5 were used, respectively. The depth of the hydrogen containing layer in the treated articles was greater than or equal to the measured depth of compression (DOC).

TABLE II

Composition	CS (MPa)	DOC (microns)
A	249	10
B	268	9
D	233	12
E	255	10
F	286	10
G	323	18
H	302	16

TABLE II-continued

Composition	CS (MPa)	DOC (microns)
I	297	15
J	293	14
K	277	14
L	300	12
M	287	11
N	288	12
O	299	15
P	319	12
Q	328	10
R	310	12
S	345	10
T	395	8

[0139] Samples having the compositions shown in Table I (Exs. G-T) were exposed to water vapor containing environments to form glass articles having compressive stress layers. The samples were exposed to steam treatment at a pressure of 2.6 MPa, and a temperature of 225° C., for a duration of 16 hours. The exposure environments were saturated. The resulting maximum compressive stress and depth of compression as measured by surface stress meter (FSM) are reported in Table III. If the stress optical coefficient (SOC) and/or refractive index (RI) were not available, default values of 3.0 nm/mm/MPa and 1.5 were used, respectively. The depth of the hydrogen containing layer in the treated articles was greater than or equal to the measured depth of compression (DOC).

TABLE III

Composition	CS (MPa)	DOC (microns)
G	312	26
H	290	22
I	288	21
L	260	17
N	248	16
O	299	21
P	318	18
Q	324	15
R	307	17
S	313	14
T	327	12

[0140] Samples having the compositions shown in Table I (Exs. D-T) were exposed to water vapor containing environments to form glass articles having compressive stress layers. The samples were exposed to steam treatment at a pressure of 0.76 MPa, and a temperature of 175° C., for a duration of 96 hours. The resulting maximum compressive stress and depth of compression as measured by surface stress meter (FSM) are reported in Table IV. If the stress optical coefficient (SOC) and/or refractive index (RI) were not available, default values of 3.0 nm/mm/MPa and 1.5 were used, respectively. The depth of the hydrogen containing layer in the treated articles was greater than or equal to the measured depth of compression (DOC).

TABLE IV

Composition	CS (MPa)	DOC (microns)
D	292	12
G	337	20
H	334	17
I	344	15
J	335	14
K	338	14
L	331	12
M	335	11
N	317	11
O	351	15
P	375	11
Q	418	9
R	350	12
S	381	9
T	423	7

[0141] Samples having the compositions shown in Table I (Exs. A-T) were exposed to water vapor containing environments to form glass articles having compressive stress layers. The samples were exposed to steam treatment at a pressure of 0.1 MPa, and a temperature of 300° C., for a duration of 16 hours. The resulting maximum compressive stress and depth of compression as measured by surface stress meter (FSM) are reported in Table V. If the stress optical coefficient (SOC) and/or refractive index (RI) were not available, default values of 3.0 nm/mm/MPa and 1.5 were used, respectively. The depth of the hydrogen containing layer in the treated articles was greater than or equal to the measured depth of compression (DOC).

TABLE V

Composition	CS (MPa)	DOC (microns)
A	55	17
B	42	16
D	45	21
E	43	18
F	39	18
G	46	33
H	43	26
I	39	32
J	38	26
L	38	25
M	36	24
O	40	30
P	39	24
Q	43	23
R	36	29
S	37	24
T	41	21

[0142] Comparative Examples were prepared with the compositions shown in Table VI (Comp. Exs. 1-5). The comparative examples were produced on a glass melting apparatus by gradually modifying the composition of the glass melt to arrive at the desired composition. All comparative example compositions included significant amounts of globular chain platinum defects, except for comparative example 4 which did not include sufficient phosphorous to produce the desired hydrogen species diffusivity and was determined to be incompatible with zircon apparatuses at fusion forming viscosities, also due to insufficient phosphorous content. Also, each of these comparative glass compositions exhibited a R_2O/Al_2O_3 ratio of greater than 1.4 and, with the exception of comparative example 4, a $(R_2O+P_2O_5)/Al_2O_3$ ratio of greater than 1.9.

TABLE VI

Composition (mol %)	Comp. Ex. 1	Comp. Ex. 2	Comp. Ex. 3	Comp. Ex. 4	Comp. Ex. 5
SiO_2	60.3	62.1	60.1	59.7	60.8
Al_2O_3	12.8	11.2	10.7	15.0	11.1
P_2O_5	7.8	9.4	9.5	3.8	9.4
B_2O_3	0.6	0.0	0.0	0.0	0.0
Li_2O	3.1	2.7	0.8	0.0	0.0
Na_2O	0.1	0.1	0.1	11.8	18.4
K_2O	15.2	14.3	18.5	9.5	0.1
SnO_2	0.1	0.1	0.1	0.1	0.1
ZrO_2	0.1	0.1	0.1	0.1	0.1
R_2O/Al_2O_3	1.44	1.53	1.81	1.42	1.67
$(R_2O + P_2O_5)/Al_2O_3$	2.05	2.37	2.70	1.67	2.51
Globular Chain Platinum Defects (per pound)	145	119	127	0	121

[0143] The measured globular chain platinum defects (per pound) as a function of phosphorous (P_2O_5) content is shown in FIG. **4**. As shown in FIG. **4**, glasses with P_2O_5 contents in excess of about 6 mol % contain problematic globular chain platinum defects. The globular chain platinum defect measurements were performed on glass strips, the strips had a width of 12 cm, a length of 50 cm, and a thickness of 0.4 cm and weighed about 1.25 pounds. The observed number of defects were then normalized by the weight of the glass inspected to produce the reported number of globular chain platinum defects per pound. A globular chain platinum defect as detected at 10× magnification is shown in FIG. **5**.

[0144] Additional Comparative Examples were prepared with the compositions shown in Table VII (Comp. Exs. 6A-6F) below. The comparative examples were produced on a glass melting apparatus by gradually modifying the composition of the glass melt to arrive at the desired composition. All of these comparative example compositions included substantial amounts of phase separation. Also, each of these comparative glass compositions exhibited a R_2O/Al_2O_3 ratio of greater than 1.4 and a $(R_2O+P_2O_5)/Al_2O_3$ ratio of greater than 1.9.

TABLE VII

Composition (mol %)	Comp. Ex. 6A	Comp. Ex. 6B	Comp. Ex. 6C	Comp. Ex. 6D	Comp. Ex. 6E	Comp. Ex. 6F
SiO_2	61.9	61.9	61.9	61.9	61.9	61.9
Al_2O_3	13	13	13	13	13	13
P_2O_5	5.5	5.5	5.5	5.5	5.5	5.5
Li_2O	3.5	3.5	3.5	3.5	3.5	3.5
Na_2O	2.5	3.5	4.5	5.5	6.5	7.5
K_2O	13.5	12.5	11.5	10.5	9.5	8.5
SnO_2	0.1	0.1	0.1	0.1	0.1	0.1
R_2O/Al_2O_3	1.50	1.50	1.50	1.50	1.50	1.50
$(R_2O + P_2O_5)/Al_2O_3$	1.92	1.92	1.92	1.92	1.92	1.92
Appearance	Phase-separated	Phase-separated	Phase-separated	Phase-separated	Phase-separated	Phase-separated

[0145] FIG. **6**A is a plot of diffuse scattering in transmission (%) vs. wavelength (i.e., 300 nm to 850 nm) for an inventive glass composition from Table I (Ex. V) and comparative glass compositions (Comp. Exs. 6A-6F). FIG. **6**B is a plot of the scatter ratio (%) vs. wavelength for these same glass compositions. A UV-Vis-NIR spectrophotometer was employed to make the measurements shown in FIGS. **6**A and **6**B, as configured with an integrating sphere or a standard axial detector for samples having a thickness of 1 mm. While data is reported in FIGS. **6**A and **6**B using light wavelengths from 300 nm to 850 nm, data was also analyzed at more typical visible wavelength ranges from 380 to 780 nm and 400 to 700 nm. Further, the diffuse scattering in transmission (%) data shown in FIG. **6**A is generated from the spectrophotometer. As to the scatter ratio (%) shown in FIG. **6**B, this value is given by the $(\% T_{diffuse}\% T_{total})*100$, where $T_{diffuse}$ is the diffuse transmittance shown in FIG. **6**A and T_{total} is the total transmittance of the sample. With regard to the data shown in FIGS. **6**A and **6**B, it is evident that the comparative glass compositions that exhibit phase separation (Comp. Exs. 6A-6F) have both scatter ratio and diffuse transmittance levels well above 0.2% at 300 nm and the inventive glass composition (Ex. V) has scatter ratio and diffuse transmittance levels <0.2% at 300 nm. Hence, measured scatter ratio and diffuse transmittance levels can be employed to quantify the degree of phase separation in the glass compositions of the disclosure. Without being bound by theory, it is expected that the phase-separation threshold of 0.2% will change for samples having a thickness that differs from the 1 mm samples employed.

[0146] Turning now to FIGS. **7**A and **7**B, these figures are scanning electronic microscopy (SEM) images of two comparative glass compositions with evidence of phase separation, Comp. Ex. 6B and Comp. Ex. 6C, respectively (see also Table VII above). These images were generated by cross-sectioning the noted comparative samples, evaporating a conductive carbon coating on their surfaces, and then using a Zeiss Gemini 450 SEM to image them at 2 kV at a magnification of up to 100kx. As is evident from these SEM images, the secondary phase is in the range of about 10 to 40 nm for these comparative glass compositions.

[0147] While typical embodiments have been set forth for the purpose of illustration, the foregoing description should not be deemed to be a limitation on the scope of the disclosure or appended claims. Accordingly, various modifications, adaptations, and alternatives may occur to one skilled in the art without departing from the spirit and scope of the present disclosure or appended claims.

What is claimed is:

1. A method, comprising:

exposing a glass-based substrate to a treatment environment with a pressure greater than or equal to 0.1 MPa, a water partial pressure of greater than or equal to 0.05 MPa, and a temperature greater than 85° C. to form a glass-based article, wherein the glass-based substrate comprises:

SiO_2,
Al_2O_3,
K_2O,
R_2O/Al_2O_3 in an amount that is less than or equal to 1.4, wherein R_2O is the total amount of monovalent metal oxides,
greater than or equal to 3.5 mol % to less than or equal to 6.0 mol % P_2O_5, and
greater than or equal to 2.0 mol % to less than or equal to 5.0 mol % Li_2O,
wherein the glass-based article comprises:
a compressive stress layer extending from a surface of the glass-based article to a depth of compression, the compressive stress layer comprising a compressive stress greater than or equal to 25 MPa,
a hydrogen-containing layer extending from the surface of the glass-based article to a depth of layer, a hydrogen concentration of the hydrogen-containing layer decreases from a maximum hydrogen concentration to the depth of layer, and
the depth of layer is greater than 5 μm.

2. The method of claim **1**, wherein the treatment environment is a saturated steam environment.

3. The method of claim **1**, wherein the treatment environment has a pressure greater than or equal to 1 MPa.

4. The method of claim **1**, wherein the treatment environment has a temperature greater than or equal to 150° C.

5. The method of claim **1**, further comprising producing the glass-based substrate by a fusion forming process.

6. The method of claim **1**, wherein the glass-based substrate is not subjected to an ion-exchange treatment with an alkali ion source.

7. The method of claim **1**, wherein the glass-based substrate further comprises B_2O_3.

8. The method of claim **1**, wherein the glass-based substrate further comprises Na_2O.

9. The method of claim **1**, wherein the glass-based substrate further comprises SnO_2.

10. The method of claim **1**, wherein the glass-based substrate has an average field strength of alkali modifiers that is less than or equal to 0.18.

11. The method of claim **1**, wherein the glass-based substrate comprises:
greater than or equal to 55.0 mol % to less than or equal to 65.0 mol % SiO_2,
greater than or equal to 10.0 mol % to less than or equal to 15.0 mol % Al_2O_3,
greater than or equal to 0 mol % to less than or equal to 10.0 mol % B_2O_3, and
greater than or equal to 6.0 mol % to less than or equal to 15.0 mol % K2O.

12. The method of claim **1**, wherein the glass-based substrate comprises greater than or equal to 4.5 mol % to less than or equal to 5.5 mol % P_2O_5.

13. The method of claim **1**, wherein the glass-based substrate comprises greater than 0 mol % to less than or equal to 3.0 mol % B_2O_3.

14. The method of claim **1**, wherein the glass-based substrate comprises a fusion line.

15. The method of claim **1**, wherein the glass-based substrate comprises less than 1 globular chain platinum defect per pound.

16. The method of claim **1**, wherein the glass-based substrate has a zircon breakdown viscosity of less than or equal to 35 kP.

17. The method of claim **1**, wherein the glass-based substrate has a liquidus viscosity of greater than or equal to 100 kP.

18. The method of claim **1**, wherein the glass-based article has a substantially haze-free appearance.

19. The method of claim **1**, wherein the depth of compression is greater than 5 μm.

20. The method of claim **1**, wherein the compressive stress layer comprises a compressive stress greater than or equal to 200 MPa.

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