glass substrates (> 150 μm) can be fabricated with better puncture resistance, but these substrates lack suitable fatigue resistance and mechanical reliability upon bending.

Thus, there is a need for glass materials, components and assemblies for reliable use in flexible substrate and/or display applications and functions, particularly for flexible electronic device applications.

SUMMARY

[0006] ~~According to one aspect, a~~A stack assembly is provided that comprises: a glass element having a thickness from about 25 μm to about 125 μm, a first primary surface, and a second primary surface, the glass element further comprising: (a) a first glass layer having a first primary surface; and (b) a compressive stress region extending from the first primary surface of the glass layer to a first depth in the glass layer, the region defined by a compressive stress of at least about 100 MPa at the first primary surface of the layer. The glass element is characterized by: (a) an absence of failure when the element is held at a bend radius from about 3 mm to about 20 mm for at least 60 minutes at about 25°C and about 50% relative humidity; (b) a puncture resistance of greater than about 1.5 kgf when the second primary surface of the element is supported by (i) an approximately 25 μm thick pressure-sensitive adhesive having an elastic modulus of less than about 1 GPa and (ii) an approximately 50 μm thick polyethylene terephthalate layer having an elastic modulus of less than about 10 GPa, and the first primary surface of the element is loaded with a stainless steel pin having a flat bottom with a 200 μm diameter; and (c) a pencil hardness of greater than or equal to 8H.

[0006a] In an aspect, there is provided a glass article, comprising: a glass element having a thickness from about 25 μm to about 125 μm, the glass element further comprising: (a) a first primary surface; (b) a second primary surface; and (c) a compressive stress region extending from the first primary surface of the glass element to a first depth in the glass element, the region defined by a compressive stress σI of at least about 100 MPa at the first primary surface of the glass element, wherein the glass element is characterized by: (a) a stress profile such that when the glass element is bent to a target bend radius of from 1 mm to 20 mm, with the center of curvature on the side of the second primary surface so as to induce a bending stress σB at the first primary surface, $\sigma I + \sigma B < 0$; and (b) a puncture resistance of greater than about 1.5 kgf when the first primary surface of the glass element is loaded with a tungsten carbide ball having a diameter of 1.5 mm.

[0007] According to one implementation, a foldable electronic device is provided that includes an electronic device having a foldable feature. The foldable feature includes a stack assembly according to the first aspect. In certain aspects, the foldable feature can include a display, printed circuit board, housing and other features of the electronic device.

[0007a] In another aspect, there is provided a foldable electronic device, comprising: an electronic device having a foldable feature, wherein the foldable feature comprises the glass element as defined above.

[0008] In some embodiments, the glass element can further comprise one or more additional glass layers and one or more respective compressive stress regions disposed beneath the first glass layer. For example, the glass element can comprise two, three, four or more additional glass layers with corresponding additional compressive stress regions beneath the first glass layer.

[0009] According to an additional ~~aspect~~embodiment, a glass article is provided that comprises: a glass layer having a thickness from about 25 μm to about 125 μm, the layer further comprising: (a) a first primary surface; (b) a second primary surface; and (c) a compressive stress region extending

from the first primary surface of the glass layer to a first depth in the glass layer, the region defined by a compressive stress of at least about 100 MPa at the first primary surface of the layer. The glass layer is characterized by: (a) an absence of failure when the layer is held at a bend radius from about 3 mm to about 20 mm for at least 60 minutes at about 25°C and about 50% relative humidity; (b) a puncture resistance of greater than about 1.5 kgf when the second primary surface of the layer is supported by (i) an approximately 25 μm thick pressure-sensitive adhesive having an elastic modulus of less than about 1 GPa and (ii) an approximately 50 μm thick polyethylene terephthalate layer having an elastic modulus of less than about 10 GPa, and the first primary surface of the layer is loaded with a stainless steel pin having a flat bottom with a 200 μm diameter; and (c) a pencil hardness of greater than or equal to 8H.

[0010] In certain embodiments~~aspects~~, the glass article may further include a glass structure having a thickness greater than the thickness of the glass layer and two substantially parallel edge surfaces, the structure comprising the glass layer, wherein the layer is arranged in a central region of the structure between the substantially parallel edge surfaces.

[0011] In some embodiments, the glass layer comprises an alkali-free or alkali-containing aluminosilicate, borosilicate, boroaluminosilicate, or silicate glass composition. The thickness of the glass layer can also range from about 50 μm to about 100 μm. The thickness can range from 60 μm to about 80 μm, according to some ~~aspects~~embodiments.

[0012] In some embodiments, the bend radius of the glass element or the glass layer can be from about 3 mm to about 20 mm. In other ~~aspects~~embodiments, the bend radius can be from about 3 mm to about 10 mm. The bend radius of the glass layer can be from about 1 mm to about 5 mm in some embodiments. Further, the bend radius can also be from about 5 mm to about 7 mm.

[0013] According to certain ~~aspects~~embodiments, the stack assembly can further comprise a second layer having a low coefficient of friction disposed on the first primary surface of the glass element or layer. According to certain ~~aspects~~embodiments, the second layer can be a coating comprising a fluorocarbon material selected from the group consisting of thermoplastics and amorphous fluorocarbons. The second layer can also be a coating comprising one or more of the group consisting of a silicone, a wax, a polyethylene, a hot-end, a parylene, and a diamond-like coating preparation. Further, the second layer can be a coating comprising a material selected from the group consisting of zinc oxide, molybdenum disulfide, tungsten disulfide, hexagonal boron nitride, and aluminum magnesium boride. According to some embodiments, the second layer can be a coating comprising an additive selected from the group consisting of zinc oxide, molybdenum disulfide, tungsten disulfide, hexagonal boron nitride, and aluminum magnesium boride.

[0014] In some ~~aspects~~embodiments, the compressive stress in the compressive stress region at the first primary surface is from about 600 MPa to 1000 MPa. The compressive stress region can also include a maximum flaw size of 5 μm or less at the first primary surface of the glass layer. In certain cases, the compressive stress region comprises a maximum flaw size of 2.5 μm or less, or even as low as 0.4 μm or less.

[0015] In other ~~aspects~~embodiments, the compressive stress region comprises a plurality of ion-exchangeable metal ions and a plurality of ion-exchanged metal ions, the ion-exchanged metal ions selected so as to produce compressive stress. In some ~~aspects~~embodiments, the ion-exchanged metal ions have an atomic radius larger than the atomic radius of the ion-exchangeable metal ions. According to another ~~aspect~~embodiment, the glass layer can further comprise a core region, and a first and a second clad region disposed on the core region, and further wherein the coefficient of thermal expansion for the core region is greater than the coefficient of thermal expansion for the clad regions.

[0016] According to an additional ~~aspect~~embodiment, a glass article is provided that comprises: a glass layer having a thickness, a first primary surface, and a second primary surface. The glass layer is characterized by: (a) an absence of failure when the layer is held at a bend radius from about 1 mm to about 5 mm for at least 60 minutes at about 25°C and about 50% relative humidity; (b) a puncture resistance of greater than about 1.5 kgf when the second primary surface of the layer is supported by (i) an approximately 25 μm thick pressure-sensitive adhesive having an elastic modulus of less than about 1 GPa and (ii) an approximately 50 μm thick polyethylene terephthalate layer having an elastic modulus of less than about 10 GPa, and the first primary surface of the layer is loaded with a stainless steel pin having a flat bottom with a 200 μm diameter; and (c) a pencil hardness of greater than or equal to 8H. The glass article also includes a glass structure having a thickness greater than the thickness of the glass layer and two substantially parallel edge surfaces. The structure includes the glass layer, and the layer is arranged in a central region of the structure between the substantially parallel edge surfaces. In some ~~aspects~~embodiments, the thickness of the glass structure may be equal to or greater than 125 μm. In an additional ~~aspect~~embodiment, the thickness of the glass layer may be set from about 20 μm to about 125 μm to achieve the bend radius. According to an exemplary embodiment, the thickness of the glass layer can be set from about 20 μm to about 30 μm to achieve the bend radius.

[0017] According to a further ~~aspect~~embodiment, a method of making a stack assembly is provided that comprises the steps: forming a first glass layer having a first primary surface, a compressive stress region extending from the first primary surface of the glass layer to a first depth in the

glass layer, and a final thickness, wherein the region is defined by a compressive stress of at least about 100 MPa at the first primary surface of the layer; and forming a glass element having a thickness from about 25 μm to about 125 μm, the element further comprising the glass layer, a first primary surface, and a second primary surface. The glass element is characterized by: (a) an absence of failure when the element is held at a bend radius from about 3 mm to about 20 mm for at least 60 minutes at about 25°C and about 50% relative humidity; (b) a puncture resistance of greater than about 1.5 kgf when the second primary surface of the element is supported by (i) an approximately 25 μm thick pressure-sensitive adhesive having an elastic modulus of less than about 1 GPa and (ii) an approximately 50 μm thick polyethylene terephthalate layer having an elastic modulus of less than about 10 GPa, and the first primary surface of the element is loaded with a stainless steel pin having a flat bottom with a 200 μm diameter; and (c) a pencil hardness of greater than or equal to 8H.

[0018] In some embodiments, the step of forming the first glass layer can comprise a forming process selected from the group consisting of fusion, slot drawing, rolling, redrawing and float processes, the forming process further configured to form the glass layer to the final thickness. Other forming processes can be employed depending on the final shape factor for the glass layer and/or intermediate dimensions of a glass precursor used for the final glass layer. The forming process can also include a material removal process configured to remove material from the glass layer to reach the final thickness.

[0019] According to some ~~aspects~~ embodiments of the method, the step of forming a compressive stress region extending from the first primary surface of the glass layer to a first depth in the glass layer comprises: providing a strengthening bath comprising a plurality of ion-exchanging metal ions having an atomic radius larger in size than the atomic radius of a plurality ion-exchangeable metal ions contained in the glass layer; and submersing the glass layer in the strengthening bath to exchange a portion of the plurality of ion-exchangeable metal ions in the glass layer with a portion of the plurality of the ion-exchanging metal ions in the strengthening bath to form a compressive stress region extending from the first primary surface to the first depth in the glass layer. In certain cases, the submersing step comprises submersing the glass layer in the strengthening bath at about 400°C to about 450°C for about 15 minutes to about 180 minutes.

[0020] In certain embodiments, the method can also include a step of removing about 1 μm to about 5 μm from the final thickness of the glass layer at the first primary surface after the compressive stress region is created. The removing step can be conducted such that the compressive stress region comprises a maximum flaw size of 5 μm or less at the first primary

surface of the glass layer. The removing step can also be conducted such that the compressive stress region comprises a maximum flaw size of 2.5 μm or less, or even as low as 0.4 μm or less, at the first primary surface of the glass layer.

[0020a] In another aspect, there is provided a method of making a glass article, comprising the steps: forming a glass element having a thickness from about 25 μm to about 125 μm, the glass element further comprising: (a) a first primary surface; (b) a second primary surface; and (c) a compressive stress region extending from the first primary surface of the glass element to a first depth in the glass element, the region defined by a compressive stress σI of at least about 100 MPa at the first primary surface of the glass element, wherein the glass element is characterized by: (a) a stress profile such that when the glass element is bent to a target bend radius of from 1 mm to 20 mm, with the center of curvature on the side of the second primary surface so as to induce a bending stress σB at the first primary surface, $\sigma I + \sigma B < 0$; and (b) a puncture resistance of greater than about 1.5 kgf when the first primary surface of the glass element is loaded with a tungsten carbide ball having a diameter of 1.5 mm.

[0021] Additional features and advantages will be set forth in the detailed description which follows, and in part will be readily apparent to those skilled in the art from that description or recognized by practicing the embodiments as described herein, including the detailed description which follows, the claims, as well as the appended drawings.

[0022] It is to be understood that both the foregoing general description and the following detailed description are merely exemplary, and are intended to provide an overview or framework to understanding the nature and character of the claims. The accompanying drawings are included to provide a further understanding, and are incorporated in and constitute a part of this specification. The drawings illustrate one or more embodiments, and together with the description serve to explain principles and operation of the various embodiments. Directional terms as used herein—for example, up, down, right, left, front, back, top, bottom—are made only with reference to the figures as drawn and are not intended to imply absolute orientation.

BRIEF DESCRIPTION OF THE DRAWINGS

[0023] FIG. 1 is a perspective view of a stack assembly comprising a glass element with a glass layer according to an aspect of this disclosure.

[0024] FIG. 1A is perspective view of the stack assembly depicted in FIG. 1 subjected to bending forces.

[0025] FIG. 1B is a cross-sectional view of the stack assembly depicted in FIG. 1.

[0026] FIG. 1C is a cross-sectional view of a stack assembly comprising a glass element with compressive stress regions formed by an ion exchange process according to a further aspect of this disclosure.

[0027] FIG. 1D is a cross-sectional view of a stack assembly comprising a glass element having a glass layer with a core region and two clad regions according to an aspect of this disclosure.

[0028] FIG. 2 is a perspective view of a stack assembly comprising a glass element with three glass layers according a further aspect of this disclosure.

[0029] FIG. 2A is a perspective view of the stack assembly depicted in FIG. 2 subjected to bending forces.

[0030] FIG. 3 is a perspective view of a stack assembly comprising a glass structure and a glass element according to an aspect of this disclosure.

10. The article of any one of claims 1-9, wherein the compressive stress at the first primary surface of the glass element is from about 600 MPa to 1000 MPa.

11. The article of any one of claims 1-10, wherein the first depth is set at approximately one third of the thickness of the glass element or less from the first primary surface of the glass element.

12. The article of any one of claims 1-11, further comprising:

a second layer having a low coefficient of friction disposed on the first primary surface of the glass element.

13. The article of any one of claims 1-12, wherein the compressive stress region comprises a maximum flaw size of 5 μm or less at the first primary surface of the glass element.

14. The article of any one of claims 1-13, wherein the compressive stress region comprises a plurality of ion-exchangeable metal ions and a plurality of ion-exchanged metal ions, the ion-exchanged metal ions having an atomic radius larger than the atomic radius of the ion-exchangeable metal ions.

15. The article of any one of claims 1-14, wherein the glass element further comprises an edge, and an edge compressive stress region extending from the edge to an edge depth in the glass element, the edge compressive stress region defined by a compressive stress of at least about 100 MPa at the edge.

16. A foldable electronic device, comprising:

an electronic device having a foldable feature,

wherein the foldable feature comprises the ~~stack assembly~~glass article according to any one of claims 1-15.

17. A method of making a ~~stack assembly~~glass article, comprising the steps:

forming a glass element having a thickness from about 25 μm to about 125 μm, the glass element further comprising:

(a) a first primary surface;

(b) a second primary surface; and

(c) a compressive stress region extending from the first primary surface of the glass element to a first depth in the glass element, the region defined by a compressive stress σI of at least about 100 MPa at the first primary surface of the glass element,

wherein the glass element is characterized by:

(a) a stress profile such that when the glass element is bent to a target bend radius of from 1 mm to 20 mm, with the center of curvature on the side of the second primary surface so as to induce a bending stress σB at the first primary surface, σI + σB < 0; and

(b) a puncture resistance of greater than about 1.5 kgf when the first primary surface of the glass element is loaded with a tungsten carbide ball having a diameter of 1.5 mm.

18. The ~~glass article~~method of claim 17, wherein σI + σB < 0 to a depth of at least one micron below the first primary surface.

19. The method of claim 17 or claim 18, wherein the step of forming the ~~first glass layer~~glass element comprises a forming process selected from the group consisting of fusion, slot drawing, rolling, redrawing and float processes, the forming process further configured to form the glass element~~layer~~ to the final thickness.

20. The method of any one of claims 17-19, wherein the step of forming the ~~first glass layer~~glass element comprises a forming process selected from the group consisting of fusion, slot drawing, rolling, redrawing and float processes, and a material removal process that removes material from the glass element~~layer~~ to reach the final thickness.

21. The method of any one of claims 17-20, wherein the step of forming a compressive stress region extending from the first primary surface of the glass ~~layer~~ element to a first depth in the glass ~~layer~~ element comprises:

providing a strengthening bath comprising a plurality of ion-exchanging metal ions having an atomic radius larger in size than the atomic radius of a plurality ion-exchangeable metal ions contained in the glass ~~layer~~element; and

submersing the glass ~~layer~~ element in the strengthening bath to exchange a portion of the plurality of ion-exchangeable metal ions in the glass ~~layer~~ element with a portion of the plurality of the ion-exchanging metal ions in the strengthening bath to form a compressive stress region extending from the first primary surface to the first depth in the glass ~~layer~~element.

22. The method of claim 21, wherein the submersing step comprises submersing the glass ~~layer~~ element in the strengthening bath at about 400°C to about 450°C for about 15 minutes to about 180 minutes.

23. The method of claim 21, further comprising the step:

removing about 1 μm to about 5 μm from the final thickness of the glass ~~layer~~ element at the first primary surface after the step of forming the compressive stress region, wherein the removing step is conducted after the submersing the glass ~~layer~~ element step.