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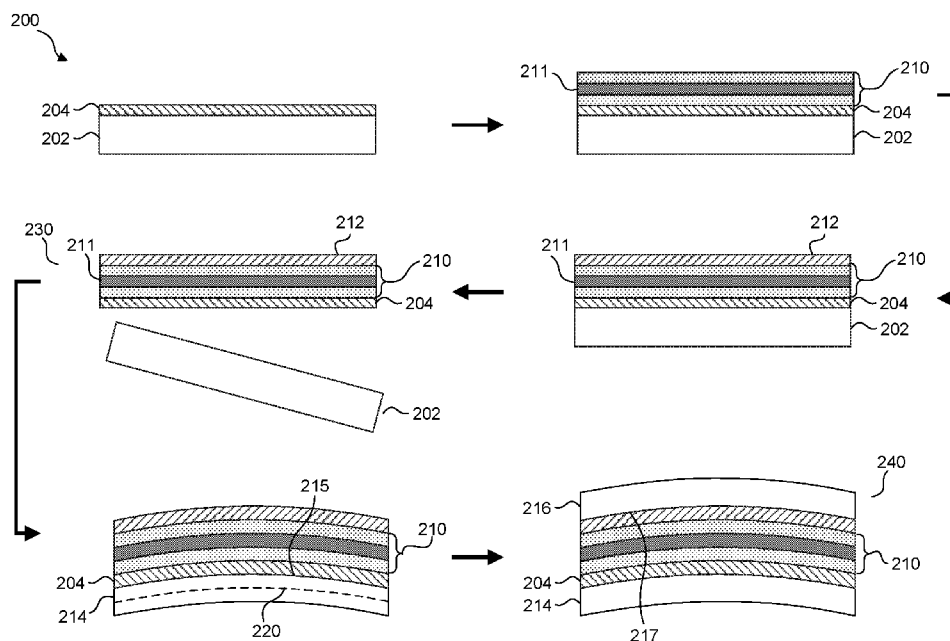


FIG. 2

(57) Abstract: Various embodiments of the present disclosure describe a method of forming electrically controlled variable-tint stacks and curved electrically controlled variable-tint glass articles. Methods may include disposing a flexible film on a flat carrier substrate, forming an electrically controlled variable-tint stack on the flexible film, and removing the flexible film with the electrically controlled variable-tint stack from the flat carrier substrate. After removal, the flexible film and the electrically controlled variable-tint stack may be disposed over a curved surface of a first curved glass substrate such that the electrically controlled variable-tint stack conforms to the curved surface. The electrically controlled variable-tint stack includes an electro-optic active layer that changes color and/or transparency upon application of an electric field across the layer.



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CURVED ELECTRICALLY CONTROLLED VARIABLE-TINT ARTICLES AND METHODS OF MAKING THE SAME

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of priority under 35 U.S.C. § 119 of U.S. Provisional Application Serial No. 62/719,618 filed on August 18, 2018 the content of which is relied upon and incorporated herein by reference in its entirety.

BACKGROUND

[0002] The present disclosure relates to forming a curved electrically controlled variable-tint article, for example, a curved electrochromic window.

[0003] Glass articles that can transmit a controllable fraction of incident light intensity are beneficial in a variety of applications. For example, windows of buildings or vehicles, windows between rooms, and personal items such as glasses or goggles are often used in situations in which it would be advantageous if their optical transparency could be adjusted, for example by electrical means.

[0004] Great efforts have been expended to improve processes for selectively controlling the transmission of light through window structures. A common approach to light control involves using an opaque window shade to reduce the transmission of light. Such shades may either be purely mechanical (the most common type) or may be controlled by a motor. Another approach to variable control of light transmission can be achieved by mechanically rotating a pair of polarizing films where the relative angle between polarizing axes of the polarizing films are changed. Another approach to light control involves the use of polymer films or doping glass with metal ions to absorb or reject certain wavelength ranges of light. Light transmission through windows using such technologies is fixed once the window is constructed.

[0005] Recently, there has been great interest in using variable light transmission glass or glazing to achieve light transmission control. Several different types of chromogenic switchable glazing structures have been discovered using suspended particle devices, electrochromic effects, and certain types of liquid crystals. In general, the structures absorb or diffuse incident light. A continuing need exists for innovations in forming an electrically controlled variable-tint film and glass with various shapes to accommodate various applications.

BRIEF SUMMARY

[0006] The present disclosure is directed to curved electrically controlled variable-tint articles, for example, a curved electrochromic window. In particular, the present disclosure is directed to methods of forming an electrically controlled variable-tint stack and a curved electrically controlled variable-tint article.

[0007] Some embodiments are directed to a method of forming an electrically controlled variable-tint stack, the method including disposing a flexible film on a flat carrier substrate; forming an electrically controlled variable-tint stack on the flexible film, the electrically controlled variable-tint stack including an electro-optic active layer; and removing the flexible film with the electrically controlled variable-tint stack from the flat carrier substrate.

[0008] In some embodiments, the method according to embodiments of the preceding paragraph may include a flexible film that includes a polymer material. In some embodiments, the polymer material may include polyimide. In some embodiments, the method according to embodiments of the preceding paragraph may include a flexible film that includes a flexible glass.

[0009] In some embodiments, the method according to embodiments of any of the preceding paragraphs may include a flat carrier substrate that includes a glass or a ceramic material.

[0010] In some embodiments, the method according to embodiments of any of the preceding paragraphs may include adhering the flexible film to the flat carrier substrate with an adhesive layer when disposing the flexible film on the flat carrier substrate. In some embodiments, the adhesive layer may include a UV-sensitive adhesive or a cationic polymer adhesive.

[0011] In some embodiments, the method according to embodiments of any of the preceding paragraphs may include forming the electrically controlled variable-tint stack on the flexible film with a process including physical vapor deposition, chemical vapor deposition, solution-based deposition, or a combination thereof.

[0012] In some embodiments, the method according to embodiments of any of the preceding paragraphs may include an electro-optic active layer that includes a suspended-particle layer, a polymer-dispersed liquid crystal layer, an electrokinetic layer, or an electrochromic layer.

[0013] In some embodiments, the method according to embodiments of any of the preceding paragraphs may include disposing an encapsulation layer over the electrically controlled variable-tint stack prior to removing the flexible film with the electrically controlled variable-tint stack from the flat carrier substrate. In some embodiments, the encapsulation layer may include a polymer layer or an inorganic hard coat layer.

[0014] In some embodiments, the method according to embodiments of any of the preceding paragraphs may include applying laser irradiation, applying a mechanical force, or a combination thereof when removing the flexible film with the electrically controlled variable-tint stack from the flat carrier substrate.

[0015] In some embodiments, the method according to embodiments of any of the preceding paragraphs may include disposing the electrically controlled variable-tint stack over a first curved surface of a first curved glass substrate such that the electrically controlled variable-tint stack conforms to the first curved surface. In some embodiments, the method may include disposing a second curved glass substrate including a second curved surface over the electrically controlled variable-tint stack opposite the first curved glass substrate. In some embodiments, the first curved surface of the first curved glass substrate may include at least one of a compound curve and a complex curve. In some embodiments, the method according to embodiments of any of the preceding paragraphs may include laminating the electrically controlled variable-tint stack between a first curved glass substrate and a second curved glass substrate such that the electrically controlled variable-tint stack conforms to a curvature profile defined by the first curved glass substrate and the second curved glass substrate.

[0016] In some embodiments, the method according to embodiments of any of the preceding paragraphs may include disposing the flexible film on the flat carrier substrate by depositing the flexible film with a process including physical vapor deposition or chemical vapor deposition.

[0017] Some embodiments are directed to a method of making a curved electrically controlled variable-tint glass article, the method including disposing a flexible film on a flat carrier substrate; forming an electrically controlled variable-tint stack on the flexible film, the electrically controlled variable-tint stack including an electro-optic active layer; disposing an encapsulation layer over the electrically controlled variable-tint stack, thereby forming an electrically controlled variable-tint assembly; removing the electrically controlled variable-tint assembly from the flat carrier substrate; and disposing the electrically controlled variable-tint assembly over a first curved surface of a first

curved glass substrate such that the electrically controlled variable-tint assembly conforms to the first curved surface.

[0018] In some embodiments, the method according to embodiments of the preceding paragraph may include disposing a second curved glass substrate including a second curved surface over the electrically controlled variable-tint assembly opposite the first curved glass substrate.

[0019] Some embodiments are directed to a curved electrically controlled variable-tint article including a flexible film; an electrically controlled variable-tint stack disposed on the flexible film; and two curved glass substrates, where the flexible film and the electrically controlled variable-tint stack are laminated between the two curved glass substrates and at least a portion of the two curved glass substrates includes a non-zero Gaussian curvature.

[0020] In some embodiments, the article according to embodiments of the preceding paragraph may include an encapsulation layer disposed over the electrically controlled variable-tint stack.

[0021] In some embodiments, the article according to embodiments of either of the two preceding paragraphs may include a flexible film that includes a polymer material or a flexible glass. In some embodiments, the flexible film may include the polymer material and the polymer material includes polyimide.

[0022] In some embodiments, the article according to embodiments of any of the three preceding paragraphs may include an electro-optic active layer that includes a suspended particle layer, a polymer-dispersed liquid crystal layer, an electrokinetic layer, or an electrochromic layer.

[0023] In some embodiments, the non-zero Gaussian curvature of the two layers of curved glass according to embodiments of any of the four preceding paragraphs may include a radius of curvature of 0.5 meters or more.

BRIEF DESCRIPTION OF THE DRAWINGS

[0024] The accompanying figures, which are incorporated herein, form part of the specification and illustrate embodiments of the present disclosure. Together with the description, the figures further serve to explain the principles of and to enable a person skilled in the relevant art(s) to make and use the disclosed embodiments. These figures are intended to be illustrative, not limiting. Although the disclosure is generally described in

the context of these embodiments, it should be understood that it is not intended to limit the scope of the disclosure to these particular embodiments. In the drawings, like reference numbers indicate identical or functionally similar elements.

[0025] FIG. 1 illustrates an exemplary method of making a curved electrically controlled variable-tint glass article according to some embodiments.

[0026] FIG. 2 illustrates a schematic of an exemplary process for making a curved electrically controlled variable-tint glass article according to some embodiments.

[0027] FIG. 3 illustrates a finite element model for electrically controlled variable-tint stacks sandwiched between two curved glass substrates with a sunroof geometry.

[0028] FIG. 4 illustrates the basic structure of an exemplary electrochromic stack according to some embodiments.

DETAILED DESCRIPTION

[0029] The following examples are illustrative, but not limiting, of the present disclosure. Other suitable modifications and adaptations of the variety of conditions and parameters normally encountered in the field, and which would be apparent to those skilled in the art, are within the spirit and scope of the disclosure.

[0030] Electrically controlled variable-tint glass has received strong interest in the automotive and architectural industries. However, the current technology suffers from high cost and production efficiency problems. The leading electrically controlled variable-tint technology is electrochromic (EC) technology. Currently electrochromic stacks are deposited on flat glass (e.g., soda-lime glass (SLG) or an aluminoborosilicate glass such as an EAGLE XG[®] glass substrate) using a physical vapor deposition (PVD) process. To use currently developed vapor deposition technology to create curved electrically controlled variable-tint glass articles it is necessary to either deposit on pre-formed curved glass, or to deposit on a flat substrate that can be curved without damaging the EC film. Currently developed PVD processes are not designed to deposit EC films on curved surfaces, and it would take a significant development effort to modify the process to deposit EC films on curved surfaces with sufficient quality. Moreover, once an EC film is deposited, it is practically impossible to shape the flat glass into a complex or compound curved shape using hot forming because the high temperatures required for such shaping damage the EC film. Due to these deficiencies, current processes are unable

to create electrically controlled variable-tint glass articles with complex or compound curved shapes and suitable quality.

[0031] Methods according to embodiments discussed herein use existing flat vapor deposition processes to create variable-tint films/stacks that can be formed to various curved shapes, including complexly curved shapes, such as compound 3D shapes. These methods will enable the use of vapor deposition technology designed to deposit flat variable-tint films/stacks to make curved articles.

[0032] The electrically controlled variable-tint films/stacks and glass articles including such electrically controlled variable-tint films/stacks laminates disclosed herein may be incorporated into another article such as an article with a display (or display articles) (e.g., consumer electronic products, including mobile phones, tablets, computers, navigation systems, wearable devices (e.g., watches and the like)), architectural articles (e.g., a window or window assembly), transportation articles (e.g., windows, sunroofs, displays, and decorative vehicular interior surfaces for automotive, trains, aircraft, sea craft, etc.), appliance articles, eyewear articles (e.g., glasses or goggles) or any article that may benefit from variable control of light transmission.

[0033] In some embodiments, an electrically controlled variable-tint stack formed on a flexible film as discussed herein may be used to retro-fit existing glass articles to include variable-tint technology. The existing glass article may be a flat article or a curved article as discussed herein. For example, an electrically controlled variable-tint stack formed on a flexible film according to embodiments discussed herein may be adhered to an existing glass substrate or article (e.g., a glass window) and a glass substrate may be adhered over the electrically controlled variable-tint stack opposite existing glass substrate or article to form an electrically controlled variable-tint glass article.

[0034] Various embodiments of the present disclosure describe a method of forming an electrically controlled variable-tint stack and a curved electrically controlled variable-tint glass article without the previously discussed technical limitations. Methods of forming an electrically controlled variable-tint stack may include disposing a flexible film on a flat carrier substrate; forming an electrically controlled variable-tint stack on the flexible film, the electrically controlled variable-tint stack including an electro-optic active layer; and removing the flexible film with the electrically controlled variable-tint stack from the flat carrier substrate. Methods of making a curved electrically controlled variable-tint glass article may include disposing a flexible film on a flat carrier substrate;

forming an electrically controlled variable-tint stack on the flexible film, the electrically controlled variable-tint stack including an electro-optic active layer; disposing an encapsulation layer over the electrically controlled variable-tint stack, thereby forming an electrically controlled variable-tint assembly; removing the electrically controlled variable-tint assembly from the flat carrier substrate; and disposing the electrically controlled variable-tint assembly over a first curved surface of a first curved glass substrate such that the electrically controlled variable-tint assembly conforms to the first curved surface.

[0035] Methods according to embodiments discussed herein offer the following advantages: 1) compatibility with existing electrically controlled variable-tint layer manufacture processes, which enables rapid integration with such processes; 2) the adoption of current flat surface electrically controlled variable-tint layer deposition techniques (e.g., PVD) to ensure good yield of film deposition; 3) deposition onto flat surfaces can achieve more consistent film thickness, resulting in uniform coloration during variable tinting; 4) high throughput because articles with different curvatures will require little or no retooling of the electrically controlled variable-tint film/stack deposition machine(s) and/or process(es); and 5) high production efficiency, as the electrically controlled variable-tint film/stack and curved glass substrate manufacturing are decoupled.

[0036] As used herein, the term “electrically controlled variable-tint stack” means a layered stack including a layer that is capable of reversibly changing color and/or transparency upon application and removal of an electric field across the layer.

[0037] As used herein, the term “electro-optic active layer” means a layer having a material that undergoes a reversible change when an electric field is applied across the layer. The reversible change may be, for example, an ionic reaction (redox reaction), a molecular alignment change, or a particle alignment change. The reversible change may produce a color and/or transparency change in the material. In some embodiments, the reversible change may be a change from an optically transparent state to an opaque state. In some embodiments, the reversible change may be a change from an optically transparent state to a state having a degree of transparency between optically transparent and opaque. The degree of transparency may be any transparency between optically transparent and opaque. Exemplary electro-optic active layers include, but are not limited to, suspended-particle layers, polymer-dispersed liquid crystal layers, electrokinetic layers, and electrochromic layers.

[0038] As used herein, “disposed on” means that a first layer/component is in direct contact with a second layer/component. A first layer/component “disposed on” a second layer/component may be deposited, formed, directly adhered, placed, or otherwise applied directly onto the second layer/component. In other words, if a first layer/component is disposed on a second layer/component, there are no layers (other than a possible adhesive layer) disposed between the first layer/component and the second layer/component. If a first layer/component is described as “disposed over” a second layer/component, other layers may or may not be present between the first layer/component and the second layer/component.

[0039] FIG. 1 illustrates an exemplary method 100 for making a curved electrically controlled variable-tint glass article according to some embodiments. Method 100 includes a method of forming an electrically controlled variable-tint stack and/or assembly according to some embodiments. Steps shown in method 100 are not exhaustive; other steps can be performed before, after, or between any of the illustrated steps. In some embodiments, steps of method 100 can be performed in a different order. Variations of method 100 are within the scope of the present disclosure. FIG. 2 illustrates a schematic of a process 200 for making a curved electrically controlled variable-tint glass article 240 according to some embodiments. Process 200 includes a process of forming an electrically controlled variable-tint stack 210 and/or assembly 230 according to some embodiments.

[0040] In step 102, a flexible film (e.g., flexible film 204 as shown in FIG. 2) is disposed on a flat carrier substrate (e.g., flat carrier substrate 202 as shown in FIG. 2). In some embodiments, the flexible film may withstand a temperature between about 100 °C (degrees Celsius) and about 500 °C, including subranges. For example, the flexible film may withstand a temperature of about 100 °C, 150 °C, 200 °C, 250 °C, 300 °C, 350 °C, 400 °C, 450 °C, or 500 °C, or within any range having any two of these values as endpoints. A flexible film “withstands” a temperature if the film does not deform, chemically degrade, or melt when heated to and held at that temperature for at least 5 minutes. In some embodiments, a flexible film may withstand a temperature of about 100 °C, 150 °C, 200 °C, 250 °C, 300 °C, 350 °C, 400 °C, 450 °C, or 500 °C, or within any range having any two of these values as endpoints, for up to 30 minutes. Being able to withstand a specific temperature for a certain amount of time will ensure the flexible film does not deform, degrade, or melt during a vapor deposition process performed at that temperature.

[0041] In some embodiments, the flexible film may be optically transparent. As used herein, “optically transparent” means an average transmittance of 70% or more in the wavelength range of 400 nm to 700 nm through a 1.0 mm thick piece of a material. In some embodiments, an optically transparent material may have an average transmittance of 75% or more, 80% or more, 85% or more, or 90% or more in the wavelength range of 400 nm to 700 nm through a 1.0 mm thick piece of the material. The average transmittance in the wavelength range of 400 nm to 700 nm is calculated by measuring the transmittance of all wavelengths between 400 nm and 700 nm and averaging the measurements. As used herein, the term “opaque” means an average transmittance of 50% or less in the wavelength range of 400 nm to 700 nm through a 1.0 mm thick piece of a material. In some embodiments, an opaque material may have an average transmittance of 40% or less, 30% or less, 20% or less, 10% or less, or 0% in the wavelength range of 400 nm to 700 nm through a 1.0 mm thick piece of the material. In some embodiments, “opaque” means having a shade number of SN = 14, which corresponds to an optical density of OD = 5.6 and a total visible transmittance of $T = 3 \times 10^{-6}$.

[0042] In some embodiments, the flexible film may have a thickness between about 50 μm (microns, micrometers) and about 500 μm , between about 50 μm and about 400 μm , between about 50 μm and about 300 μm , between about 50 μm and about 200 μm , between about 50 μm and about 100 μm , between about 100 μm and about 400 μm , between about 100 μm and about 300 μm , between about 100 μm and about 200 μm , between about 200 μm and about 400 μm , or between about 200 μm and about 300 μm . In some embodiments, the flexible film can have a thickness of about 200 μm .

[0043] In some embodiments, the flexible film includes a polymer material. In some embodiments, the polymer material includes polyimide, polyethylene terephthalate (PET), polyethylene-naphthalate (PEN), polyvinyl butyral (PVB), or thermoplastic polyurethane (TPU). In some embodiments, the polymer material may be adhered to a surface of the flat carrier substrate. In some embodiments, the polymer material may be provided as prepared rolls or sheets that are capable of being adhered to a surface of the flat carrier substrate. In some embodiments, the polymer material may be deposited *in situ* on a surface of the flat carrier substrate by vapor deposition polymerization or other film processes.

[0044] In some embodiments, the flexible film includes a flexible glass. As used herein, the term “flexible glass” means a glass layer capable of bending to a radius of 1 m

(meter) or less. A glass layer achieves a bend radius of “X” if it resists failure when the glass layer is held at “X” radius for at least 60 minutes at about 25 °C and about 50% relative humidity. In some embodiments, a flexible glass layer may have a bend radius of 0.9 m or less, 0.8 m or less, 0.7 m or less, 0.6 m or less, 0.5 m or less, 0.4 m or less, 0.3 m or less, 0.2 m or less, 0.1 m or less, or 0.01 m or less.

[0045] In some embodiments, the flat carrier substrate includes a glass or a ceramic material. In some embodiments, the glass may include an alkali-containing aluminosilicate glass material. Other suitable materials for the glass include amorphous glass materials, such as but not limited to, soda lime glass, alkali-containing borosilicate glass, and alkali aluminoborosilicate glass. In some embodiments, the glass material may be free of lithia. The flat carrier substrate may be glass, ceramic, or other material which is substantially flat and capable of withstanding a high temperature (e.g., a temperature in the between about 100 °C and 500 °C). In some embodiments, the flat carrier substrate may be a metal substrate. As used herein, the term “flat glass substrate” or “flat layer/substrate” is any glass substrate or other layer/substrate that is not curved as defined herein. A “flat glass substrate” or “flat layer/substrate” may be a flexible film that is mechanically supported such that it is flat or may be a glass substrate or other layer/substrate that holds a flat shape at room temperature (23 °C). In such embodiments, the supporting layer/substrate may be a flat plate or platform disposed within a deposition apparatus, such as a physical vapor deposition apparatus.

[0046] In some embodiments, the flexible film may be adhered to the flat carrier substrate with an adhesive layer. In some embodiments, the adhesive layer includes a UV-sensitive adhesive or a cationic polymer adhesive. In some embodiments, the adhesive layer may include an optically transparent adhesive. Suitable optically transparent adhesives include, but are not limited to acrylic adhesives, such as 3M™ 8212 adhesive, or any optically transparent liquid adhesive, such as a Loctite® optically transparent liquid adhesive. In some embodiments, the adhesive layer may have a thickness between about 5 µm and about 50 µm, including subranges. For example, the adhesive layer may have a thickness of about 5 µm, about 10 µm, about 15 µm, about 20 µm, about 25 µm, about 30 µm, about 35 µm, about 40 µm, about 45 µm, or about 50 µm, or within any range having any two of these values as endpoints. In some embodiments, the adhesive layer may be in the range of about 25 µm to about 50 µm. In some embodiments, adhering the flexible film onto the flat carrier substrate may include a curing process (e.g., an ultra-violet curing process).

[0047] In step 104, an electrically controlled variable-tint stack (e.g., electrically controlled variable-tint stack 210 as shown in FIG. 2) is formed on the flexible film. The electrically controlled variable-tint stack includes an electro-optic active layer 211. The electrically controlled variable-tint stack may be formed using physical vapor deposition, chemical vapor deposition, solution-based deposition, or a combination thereof. In some embodiments, the electro-optic active layer 211 may include a suspended-particle layer, a polymer-dispersed liquid crystal layer, an electrokinetic layer, or an electrochromic layer.

[0048] In some embodiments, a suspended-particle stack may include a thin layer of rod-like nano-scale particles suspended in a liquid and placed between two pieces of glass or plastic, or attached to one substrate. When no voltage is applied, the suspended particles are randomly organized, thus blocking and absorbing light. When voltage is applied, the suspended particles align and let light pass. Varying the voltage across the stack varies the orientation of the suspended particles, thereby regulating the tint of the stack and the amount of light transmitted. A suspended-particle stack can be manually or automatically tuned to precisely control the amount of light, glare, and/or heat passing through it. U.S. Pat. No. 5,463,491, issued on October 31, 1995, describes the structure and materials of suspended-particle stacks according to some embodiments. This patent is hereby incorporated by reference in its entirety by reference thereto.

[0049] In some embodiments, a polymer-dispersed liquid crystal stack may include a polymer-dispersed liquid crystal layer formed by dissolving or dispersing liquid crystals into a liquid polymer followed by solidification or curing of the polymer. During the change of the polymer from a liquid to solid, the liquid crystals become incompatible with the solid polymer and form droplets throughout the solid polymer. The curing conditions affect the size of the droplets that in turn affect the final operating properties of the stack. Typically, the liquid mix of polymer and liquid crystals is placed between two layers of glass or plastic that include a thin layer of a transparent, conductive material followed by curing of the polymer, thereby forming the basic sandwich structure of the electrically controlled variable-tint stack. Electrodes from a power supply may be attached to the transparent electrodes. With no applied voltage, the liquid crystals are randomly arranged in the droplets, resulting in scattering of light as it passes through the stack. This results in a translucent, “milky white” appearance. When a voltage is applied to the electrodes, the electric field formed between the two transparent electrodes causes the liquid crystals to align, allowing light to pass through the droplets with very little scattering and resulting in a transparent state. The degree of transparency can be

controlled by the applied voltage. U.S. Pat. No. 4,994,204, issued on February 19, 1991, describes the structure and materials of polymer-dispersed liquid crystal stacks according to some embodiments. This patent is hereby incorporated by reference in its entirety by reference thereto.

[0050] In some embodiments, an electrokinetic stack may include a layer with electrically charged nanoparticles, suspended in an engineered fluid, allowing for electronic control of the color, transparency, and/or contrast of the layer. The electrokinetic layer may utilize an electrokinetic pixel structure, which combines the spectral performance of in-plane electrophoretic devices with the improved switching speeds of vertical electrophoresis. The electrophoretic dispersions may be dual-particle dual-colored and are controlled using two electrokinetic electrodes disposed on opposing sides of the electrokinetic layer, along with a third electrode appropriately located at the perimeter of each unit cell of the electrokinetic layer. U.S. Pat. No. 8,018,642, issued on September 13, 2011, describes the structure and materials of electrokinetic stacks according to some embodiments. This patent is hereby incorporated by reference in its entirety by reference thereto.

[0051] In some embodiments, an electrochromic stack may include a thin film multilayer stack, including a cathode and an anode separated by an ion conductor (electrolyte) and one or more electrochromic layers. An electrochromic stack may include other layers, such as an ion storage layer. The anode and cathode may be transparent electron conductors. The electrochromic layer changes its optical transmittance from a first optical transmittance to one or more second optical transmittances and back upon charge transfer between the anode and the cathode. The first optical transmittance may be optically transparent and the second optical transmittance(s) may be non-optically transparent and may be colored. FIG. 4 illustrates an exemplary electrochromic stack 400.

[0052] In step 106, an encapsulation layer (e.g., encapsulation layer 212 as shown in FIG. 2) is disposed over the electrically controlled variable-tint stack. The encapsulation layer may serve to cover the electrically controlled variable-tint stack and prevent degradation of the electrically controlled variable-tint stack, and in particular the electro-optic active layer, due to environmental exposure (e.g., moisture and/or oxygen exposure). Together, flexible film 204 and electrically controlled variable-tint stack 210 (and, in some embodiments, encapsulation layer 212) may form an electrically controlled variable-tint assembly 230.

[0053] In some embodiments, the encapsulation layer may include a polymer layer, or an inorganic hard coat layer such as SiO₂ (silicon dioxide) or SiN_x (silicon nitride), or combinations thereof. Suitable polymeric materials for the encapsulation layer include, but are not limited to polyacrylate, alucone, and parylene. The encapsulation layer may be deposited using physical vapor deposition, chemical vapor deposition, solution-based deposition, or a combination thereof. In some embodiments, the encapsulation layer may be optically transparent. In some embodiments, the encapsulation layer can have a thickness between about 0.1 μm and about 10 μm, including subranges. For example, the encapsulation layer may have a thickness of 0.1 μm, 1 μm, 2 μm, 3 μm, 4 μm, 5 μm, 6 μm, 7 μm, 8 μm, 9 μm, or 10 μm, or within any range having any two of these values as endpoints.

[0054] In step 108, the flexible film is removed with the electrically controlled variable-tint stack from the flat carrier substrate (as shown in FIG. 2). In other words, the flexible film with the electrically controlled variable-tint stack formed thereon is removed from the flat carrier substrate. In some embodiments, removing the flexible film with the electrically controlled variable-tint stack from the flat carrier substrate may include the use of laser irradiation, mechanical force, or a combination thereof to separate the flexible film from the flat carrier substrate. In some embodiments, backside laser irradiation may be used to break down a UV-sensitive adhesive bonding the flexible film to the flat carrier substrate. In some embodiments, if the adhesion force is low enough, the flexible film with the electrically controlled variable-tint stack may be mechanically removed from the flat carrier substrate without damaging the electrically controlled variable-tint stack.

[0055] In step 110, the electrically controlled variable-tint stack formed on the flexible film is disposed over a curved surface of a first curved glass substrate (e.g., curved surface 215 of first curved glass substrate 214 as shown in FIG. 2) such that the electrically controlled variable-tint stack conforms to the curved surface of the curved glass substrate. In some embodiments, the electrically controlled variable-tint stack formed on the flexible film may be disposed on a curved surface of a first curved glass substrate such that the electrically controlled variable-tint stack conforms to the curved surface of the curved glass substrate. In some embodiments, a surface of the flexible film may be disposed on the curved surface of the first curved glass substrate such that the electrically controlled variable-tint stack conforms to the curved surface of the curved glass substrate.

[0056] As used herein, the term “curved glass substrate” or “curved layer/substrate” means a glass substrate or other layer/substrate having curved top and bottom surfaces and a curvature profile with a distortion of more than 3 mm (millimeters) per 1 m (meter). In other words, a “curved glass substrate” or “curved layer/substrate” has at least a portion that is curved at 3 mm per 1 m or more. A curvature profile is defined on the plane intersecting the mid-point of the thickness measured between the curved top and bottom surfaces of the glass layer or other layer/substrate along the length and width of the glass layer or other layer/substrate. If the curvature of the top and bottom surfaces of a glass layer or other layer/substrate is substantially different, the “curvature profile” of the glass layer or other layer/substrate is defined by the curvature of the surface facing an electrically controlled variable-tint stack. FIG. 2 illustrates an exemplary curvature profile 220 for first curved glass substrate 214.

[0057] In some embodiments, a “curved glass” or “curved layer/substrate” may be a glass substrate or other layer/substrate that holds a shape or curvature as described herein at room temperature (23 °C) and when not being subject to an external force (e.g., a bending force). In some embodiments, a “curved layer/substrate” may be a flexible film that deforms under its own weight at room temperature to form a curved layer/substrate.

[0058] In some embodiments, the curved surface of the first curved glass substrate may include at least one of a compound curve and a complex curve. As used herein, a “compound curve” has two or more curves with different radii that bend the same way and are on the same side of a common tangent. As used herein, a “complex curve” has at least two distinct radii of curvature in two independent directions. A complexly curved glass substrate or layer may thus be characterized as having “cross curvature,” where the glass substrate or layer is curved along an axis (i.e., a first axis) that is parallel to a given dimension and also curved along an axis (i.e., a second axis) that is perpendicular to the same dimension. The curvature of the glass substrate or layer can be even more complex when a significant minimum radius is combined with a significant cross curvature, and/or depth of bend. In some embodiments, the compound curve and/or complex curve may include a radius of curvature of about 0.5 meters or more. In some embodiments, the compound curve and/or the complex curve may include at least a portion with a radius of curvature of less than 0.5 meters.

[0059] In some embodiments, at least a portion of the first curved glass substrate may include a non-zero Gaussian curvature. In some embodiments, at least a portion of a curved surface of the first curved glass substrate may include a non-zero Gaussian

curvature. In some embodiments, the non-zero Gaussian curvature may include a radius of curvature of about 0.5 meters or more. In some embodiments, the non-zero Gaussian curvature may include a radius of curvature of less than 0.5 meters.

[0060] As used herein, the term “non-zero Gaussian curvature” means a curvature that cannot be formed with a sheet of paper by bending without also stretching, tearing, or wrinkling the paper. A “non-zero Gaussian curvature” may be referred to as a “non-developable curvature.” Exemplary non-zero Gaussian curvatures include, but are not limited to, spherical curvatures, spheroid curvatures, partially spheroid curvatures, and three-dimensional saddle curvatures. A “zero Gaussian curvature” means a curvature that can be formed with a sheet of paper by bending alone. A “zero Gaussian curvature” may be referred to as a “developable curvature.” Exemplary zero Gaussian curvatures include, but are not limited to, cylindrical and conical curvatures.

[0061] In step 112, a second curved glass substrate including a curved surface (e.g., second curved glass substrate 216 including curved surface 217 as shown in FIG. 2) is disposed over the electrically controlled variable-tint stack opposite the first curved glass substrate. In some embodiments, a second curved glass substrate including a curved surface may be disposed on the electrically controlled variable-tint stack opposite the first curved glass substrate. In some embodiments, a second curved glass substrate including a curved surface may be disposed on an encapsulation layer of an electrically controlled variable-tint assembly opposite the first curved glass substrate.

[0062] In some embodiments, the first and/or second curved glass substrates may be optically transparent. The first and second curved glass substrates may have a thickness suitable for a desired application (e.g., building or vehicle windows or eyewear, such as glasses or goggles). In some embodiments, the first and second curved glass substrates may be formed of an alkali-containing aluminosilicate glass material. Other suitable materials for the glass include amorphous glass materials, such as but not limited to, soda lime glass, alkali-containing borosilicate glass, and alkali aluminoborosilicate glass. In some embodiments, the glass material may be free of lithia. In some embodiments, a curved hard plastic substrate may be used in place of the first and/or second curved glass substrate. Suitable hard plastic materials include, but are not limited to, acrylics (e.g., plexiglass).

[0063] In some embodiments, the curved surface of the second curved glass substrate may include at least one of a compound curve and a complex curve. In some embodiments, the compound curve and/or the complex curve may include at least a

portion with a radius of curvature of about 0.5 meters or more. In some embodiments, the compound curve and/or the complex curve may include at least a portion with a radius of curvature of less than 0.5 meters. In some embodiments, at least a portion of the second curved glass substrate may include a non-zero Gaussian curvature. In some embodiments, at least a portion of a curved surface of the second curved glass substrate may include a non-zero Gaussian curvature. In some embodiments, the non-zero Gaussian curvature may include a radius of curvature of about 0.5 meters or more. In some embodiments, the non-zero Gaussian curvature may include a radius of curvature of less than 0.5 meters.

[0064] In some embodiments, steps 110 and 112 may include laminating the electrically controlled variable-tint stack between the first curved glass substrate and the second curved glass substrate such that the electrically controlled variable-tint stack conforms to a curvature profile defined by the first curved glass substrate and the second curved glass substrate. In some embodiments, an adhesive layer may be disposed between the first curved glass substrate and the electrically controlled variable-tint stack to bond the first curved glass substrate to the electrically controlled variable-tint stack. The adhesive layer between the first curved glass substrate and the electrically controlled variable-tint stack may include an optically transparent adhesive as discussed herein. In some embodiments, an adhesive layer may be disposed between the second curved glass substrate and the electrically controlled variable-tint stack to bond the second curved glass substrate to the electrically controlled variable-tint stack. The adhesive layer between the second curved glass substrate and the electrically controlled variable-tint stack may include an optically transparent adhesive as discussed herein.

[0065] In some embodiments, methods according to embodiments discussed herein may be used to make flat electrically controlled variable-tint glass articles. In such embodiments, the electrically controlled variable-tint stack formed on the flexible film may be disposed over or on a flat surface of a flat glass substrate, disposed between two flat glass substrates, or laminated between two flat glass substrates in the same fashion as discussed in regard the curved substrates of method 100 and process 200.

[0066] Methods according to embodiments discussed herein allow the manufacture of curved variable-tint glass articles while avoiding certain issues that arise during traditional curved variable-tint glass article manufacturing. Stresses created by bending a flat electrically controlled variable-tint glass article can cause damage to an electrically controlled variable-tint stack. Experiments with cold bending of EC stacks deposited on flat 0.7 mm EAGLE XG[®] Glass substrates have shown that the EC stacks can withstand

moderate amounts of tensile stress (down to about 0.5 m radius of curvature) without changes in tinting performance. If EC stacks are deposited on flat glass, the curvature of an article made with the EC stacks will be restricted to the cold-bending limits of the glass and the EC stack. Bending methods that require the application of significant amounts of heat cannot be used to bend a flat electrically controlled variable-tint glass article because the heat required to bend the article can damage the electrically controlled variable-tint stack. Because of this, such articles will be limited to primarily cylindrical bends with relatively large radii of curvature achievable by cold bending.

[0067] By using methods according to embodiments discussed herein, electrically controlled variable-tint articles with compound curvatures, complex curvatures, non-zero Gaussian curvatures, and/or relatively smaller radii of curvature may be formed. In methods according to embodiments discussed herein, the degree and type of curvature for glass substrate(s) can be formed prior to disposing an electrically controlled variable-tint stack over the substrate, or between two glass substrates. Therefore, a wider range of bending methods, including those that require the application of heat, can be utilized to form curved glass substrates according to embodiments discussed herein. Further, a need to bend a glass substrate to achieve a desired curvature after deposition of an electrically controlled variable-tint stack may be avoided. Avoiding the need to bend a glass substrate having an electrically controlled variable-tint stack deposited thereon avoids any damage to the stack created during a bending process.

[0068] However, disposing an electrically controlled variable-tint stack on a curved surface of a curved substrate (or laminating the electrically controlled variable-tint stack between opposing curved surfaces of opposing curved substrates) can cause cracking or wrinkling of the stack, a flexible film, an encapsulation layer, or any other layer of an electrically controlled variable-tint assembly. This cracking or wrinkling may occur near the edges of a curved glass article. But, such cracking or wrinkling does not pose a problem for curved glass articles that include a boarder or other mask covering the edges.

[0069] Finite element modeling was performed to illustrate the effectiveness of forming curved electrically controlled variable-tint glass articles according to embodiments discussed herein. FIG. 3 illustrates finite element modeling of electrically controlled variable-tint stacks sandwiched between two hot-formed curved glass substrates with a sunroof geometry. In the modeling, different thicknesses of PET (polyethylene terephthalate) were used to model the behavior of electrically controlled variable-tint stacks with different thicknesses. From left to right, FIG. 3 illustrates the

modeling results of a PET film with a thickness of 100 μm , 300 μm , and 500 μm . The 100 μm PET film showed some edge wrinkling. The 300 μm PTE film showed increased edge wrinkling relative to the 100 μm film. And the 500 μm PET film showed smooth edge compression with some centrally located stretching.

[0070] This finite element modeling suggests that disposing an electrically controlled variable-tint stack or assembly over a curved surface (or laminating the electrically controlled variable-tint stack between opposing curved surfaces) mostly creates compressive strain at edges, rather than tensile strain in the center of an article. Any wrinkling that does occur is present at the edges of the article. Typically, the thickest layer of a stack or assembly (e.g., flexible film 204) will be the primary contributor for any wrinkling.

[0071] Edge wrinkling does not pose a significant problem for some glass articles, however, because the area around a peripheral outer edge (e.g., a peripheral band having a thickness of about 1 centimeter) of an electrically controlled variable-tint glass article is typically hidden. The outer periphery may be hidden for a variety of reasons. For example, it may be hidden so that the visual field is uniform and free from visible bus bars or laser patterning. As another example, it may be hidden due to the presence of a peripheral encapsulation material that protects the electrically controlled variable-tint stack from damage. The hidden nature of the outer periphery for such articles will also hide any edge wrinkles.

[0072] FIG. 4 illustrates a schematic of the basic structure of an electrochromic (EC) stack 400 according to some embodiments. EC stack 400 includes a first transparent electrode 402. Examples of transparent electrodes include, but are not limited to, indium tin oxide (ITO), fluorine doped tin oxide (FTO), antimony doped tin oxide (ATO), aluminum-doped zinc oxide (AZO), zinc oxide (ZnO), conjugated polymers, and a silver nano-wire grid. An exterior surface 403 of first transparent electrode 402 may be functionalized to have a positive or negative charge. For example, first transparent electrode 402 may be cleaned with polar solvents, may be activated with abrasives or silanes, or may be plasma-treated.

[0073] An EC layer 404 is disposed over exterior surface 403 of first transparent electrode 402 and includes at least one electro-optic active material. Optionally, one or more ion conductive layers (e.g., an ion conductive layer like optional layer 408) may be disposed over EC layer 404. The electro-optical active material of EC layer 404 causes a reversible color/transmission change when a charge is applied between first transparent

electrode 402 and second transparent electrode 410. Electro-optical active materials that can be utilized include, but are not limited to, electro-chromic metal oxides, such as, but not limited to, WO_x (tungsten oxide), NiO (nickel oxide), Ir_2O_3 (iridium oxide), V_2O_5 (vanadium oxide), MoO_3 (molybdenum oxide), Nb_2O_5 (niobium oxide), TiO_2 (titanium oxide), CuO (copper oxide), Cr_2O_3 (chromium oxide), Co_2O_3 (cobalt oxide), Mn_2O_3 (manganese oxide), or a combination thereof.

[0074] Disposed over EC layer 404 and optional ion conductive layer(s) is an electrolyte 406. In some embodiments, electrolyte 406 may be a solid-state electrolyte or gel electrolyte. Some embodiments may include a solid electrolyte 406 made of a polar polymer matrix, for example, but not limited to, polyvinylidene fluoride (PVDF), succinonitrile, or poly(ethylene oxide) (PEO) with salts (e.g., lithium salts, potassium salts, or sodium salts) and/or ionic liquids.

[0075] In some embodiments, electrolyte 406 may be a multi-layer ionic transport layer. In such embodiments, electrolyte 406 may include two or more ion transport layers separated by one or more buffer layers. Ion transport layer(s) may be composed of an insulator, such as, but not limited to, silicon oxide, aluminum oxide, aluminum nitride, niobium oxide, tantalum oxide, titanium oxide, zirconium oxide, yttrium oxide, hafnium oxide, and mixtures thereof. In some embodiments, the material of buffer layer(s) may be selected from the group of tungsten oxides, nickel oxides, cerium oxides, molybdenum oxides, vanadium oxides, and mixtures thereof. In some embodiments, the buffer layer may be composed of a lithium-based ceramic material including a lithium silicate, a lithium aluminum silicate, a lithium aluminum borate, a lithium borate, a lithium silicon oxynitride, a lithium zirconium silicate, a lithium niobate, a lithium borosilicate, a lithium phosphosilicate, a lithium nitride, a lithium aluminum fluoride, and mixtures thereof.

[0076] Electrolyte 406 may be applied by vapor deposition (e.g., PVD), spin-coating, or spraying from a solution. In the case of gel electrolytes, they can be applied as a liquid by dip-coating, spray coating, or spin-coating methods, and then “solidified” by UV exposure, thermal heating, or air exposure, for example.

[0077] On the side of electrolyte 406 opposite first transparent electrode 402 is an optional layer 408 and a second transparent electrode 410. Optional layer 408 includes at least one of an EC layer and one or more ion conductive layers. Second transparent electrode 410 is similar to or identical to first transparent electrode 402 and may also be functionalized.

[0078] In some embodiments, EC stack 400 may have a construction the same as or similar to the EC stacks disclosed in U.S. Pat. No. 8,730,552, which is hereby incorporated by reference in its entirety by reference thereto. Other types of electrically controlled variable-tint stacks discussed herein (e.g., suspended-particle stacks, polymer-dispersed liquid crystal stacks, or electrokinetic stacks) may include opposing transparent electrodes like EC stack 400, but with the appropriate electro-optic active layer (and any other associated layers) disposed between the opposing transparent electrodes.

[0079] According to an aspect (1) of the present disclosure, a method of forming an electrically controlled variable-tint stack is provided. The method comprises: disposing a flexible film on a flat carrier substrate; forming an electrically controlled variable-tint stack on the flexible film, the electrically controlled variable-tint stack comprising an electro-optic active layer; and removing the flexible film with the electrically controlled variable-tint stack from the flat carrier substrate.

[0080] According to an aspect (2) of the present disclosure, the method of aspect (1) is provided, wherein the flexible film comprises a polymer material.

[0081] According to an aspect (3) of the present disclosure, the method of aspect (2) is provided, wherein the polymer material comprises polyimide.

[0082] According to an aspect (4) of the present disclosure, the method of aspect (1) is provided, wherein the flexible film comprises a flexible glass.

[0083] According to an aspect (5) of the present disclosure, the method of aspect (1) is provided, wherein the flat carrier substrate comprises a glass or a ceramic material.

[0084] According to an aspect (6) of the present disclosure, the method of aspect (1) is provided, wherein disposing the flexible film on the flat carrier substrate comprises adhering the flexible film to the flat carrier substrate with an adhesive layer.

[0085] According to an aspect (7) of the present disclosure, the method of aspect (6) is provided, wherein the adhesive layer comprises a UV-sensitive adhesive or a cationic polymer adhesive.

[0086] According to an aspect (8) of the present disclosure, the method of aspect (1) is provided, wherein forming the electrically controlled variable-tint stack on the flexible film comprises physical vapor deposition, chemical vapor deposition, solution-based deposition, or a combination thereof.

[0087] According to an aspect (9) of the present disclosure, the method of aspect (1) is provided, wherein the electro-optic active layer comprises a suspended-particle layer, a polymer-dispersed liquid crystal layer, an electrokinetic layer, or an electrochromic layer.

[0088] According to an aspect (10) of the present disclosure, the method of aspect (1) is provided, further comprising disposing an encapsulation layer over the electrically controlled variable-tint stack prior to removing the flexible film with the electrically controlled variable-tint stack from the flat carrier substrate.

[0089] According to an aspect (11) of the present disclosure, the method of aspect (10) is provided, wherein the encapsulation layer comprises a polymer layer or an inorganic hard coat layer.

[0090] According to an aspect (12) of the present disclosure, the method of aspect (1) is provided, wherein removing the flexible film with the electrically controlled variable-tint stack from the flat carrier substrate comprises applying laser irradiation, applying a mechanical force, or a combination thereof.

[0091] According to an aspect (13) of the present disclosure, the method of aspect (1) is provided, further comprising disposing the electrically controlled variable-tint stack over a first curved surface of a first curved glass substrate such that the electrically controlled variable-tint stack conforms to the first curved surface.

[0092] According to an aspect (14) of the present disclosure, the method of aspect (13) is provided, further comprising disposing a second curved glass substrate comprising a second curved surface over the electrically controlled variable-tint stack opposite the first curved glass substrate.

[0093] According to an aspect (15) of the present disclosure, the method of aspect (13) is provided, wherein the first curved surface of the first curved glass substrate comprises at least one of a compound curve and a complex curve.

[0094] According to an aspect (16) of the present disclosure, the method of aspect (1) is provided, further comprising laminating the electrically controlled variable-tint stack between a first curved glass substrate and a second curved glass substrate such that the electrically controlled variable-tint stack conforms to a curvature profile defined by the first curved glass substrate and the second curved glass substrate.

[0095] According to an aspect (17) of the present disclosure, the method of aspect (1) is provided, wherein disposing the flexible film on the flat carrier substrate comprises depositing the flexible film by physical vapor deposition or chemical vapor deposition.

[0096] According to an aspect (18) of the present disclosure, a method of making a curved electrically controlled variable-tint glass article is provided. The method comprises: disposing a flexible film on a flat carrier substrate; forming an electrically controlled variable-tint stack on the flexible film, the electrically controlled variable-tint

stack comprising an electro-optic active layer; disposing an encapsulation layer over the electrically controlled variable-tint stack, thereby forming an electrically controlled variable-tint assembly; removing the electrically controlled variable-tint assembly from the flat carrier substrate; and disposing the electrically controlled variable-tint assembly over a first curved surface of a first curved glass substrate such that the electrically controlled variable-tint assembly conforms to the first curved surface.

[0097] According to an aspect (19) of the present disclosure, the method of aspect (18) is provided, further comprising disposing a second curved glass substrate comprising a second curved surface over the electrically controlled variable-tint assembly opposite the first curved glass substrate.

[0098] According to an aspect (20) of the present disclosure, a curved electrically controlled variable-tint article is provided. The curved electrically controlled variable-tint article comprises: a flexible film; an electrically controlled variable-tint stack disposed on the flexible film; and two curved glass substrates, wherein the flexible film and the electrically controlled variable-tint stack are laminated between the two curved glass substrates, and wherein at least a portion of the two curved glass substrates comprises a non-zero Gaussian curvature.

[0099] According to an aspect (21) of the present disclosure, the curved electrically controlled variable-tint article of aspect (20) is provided, further comprising an encapsulation layer disposed over the electrically controlled variable-tint stack.

[0100] According to an aspect (22) of the present disclosure, the curved electrically controlled variable-tint article of aspect (20) is provided, wherein the flexible film comprises a polymer material or a flexible glass.

[0101] According to an aspect (23) of the present disclosure, the curved electrically controlled variable-tint article of aspect (22) is provided, wherein the flexible film comprises the polymer material and wherein the polymer material comprises polyimide.

[0102] According to an aspect (24) of the present disclosure, the curved electrically controlled variable-tint article of aspect (20) is provided, wherein the electro-optic active layer comprises a suspended particle layer, a polymer-dispersed liquid crystal layer, an electrokinetic layer, or an electrochromic layer.

[0103] According to an aspect (25) of the present disclosure, the curved electrically controlled variable-tint article of aspect (20) is provided, wherein the non-zero Gaussian curvature of the two layers of curved glass comprises a radius of curvature of 0.5 meters or more.

[0104] While various embodiments have been described herein, they have been presented by way of example only, and not limitation. It should be apparent that adaptations and modifications are intended to be within the meaning and range of equivalents of the disclosed embodiments, based on the teaching and guidance presented herein. It therefore will be apparent to one skilled in the art that various changes in form and detail can be made to the embodiments disclosed herein without departing from the spirit and scope of the present disclosure. The elements of the embodiments presented herein are not necessarily mutually exclusive, but may be interchanged to meet various situations as would be appreciated by one of skill in the art.

[0105] Embodiments of the present disclosure are described in detail herein with reference to embodiments thereof as illustrated in the accompanying drawings, in which like reference numerals are used to indicate identical or functionally similar elements. References to “one embodiment,” “an embodiment,” “some embodiments,” “in certain embodiments,” etc., indicate that the embodiment described may include a particular feature, structure, or characteristic, but every embodiment may not necessarily include the particular feature, structure, or characteristic. Moreover, such phrases are not necessarily referring to the same embodiment. Further, when a particular feature, structure, or characteristic is described in connection with an embodiment, it is submitted that it is within the knowledge of one skilled in the art to affect such feature, structure, or characteristic in connection with other embodiments whether or not explicitly described.

[0106] The term “or,” as used herein, is inclusive; more specifically, the phrase “A or B” means “A, B, or both A and B.” Exclusive “or” is designated herein by terms such as “either A or B” and “one of A or B,” for example. The indefinite articles “a” and “an” and the definite article “the” to describe an element or component means that one or at least one of these elements or components is present, unless otherwise stated in specific instances.

[0107] Where a range of numerical values is recited herein, comprising upper and lower values, unless otherwise stated in specific circumstances, the range is intended to include the endpoints thereof, and all integers and fractions within the range. It is not intended that the scope of the claims be limited to the specific values recited when defining a range. Further, when an amount, concentration, or other value or parameter is given as a range, one or more preferred ranges or a list of upper preferable values and lower preferable values, this is to be understood as specifically disclosing all ranges

formed from any pair of any upper range limit or preferred value and any lower range limit or preferred value, regardless of whether such pairs are separately disclosed.

[0108] As used herein, the term “about” means that amounts, sizes, formulations, parameters, and other quantities and characteristics are not and need not be exact, but may be approximate and/or larger or smaller, as desired, reflecting tolerances, conversion factors, rounding off, measurement error and the like, and other factors known to those of skill in the art. When the term “about” is used in describing a value or an end-point of a range, the disclosure should be understood to include the specific value or end-point referred to. Whether or not a numerical value or end-point of a range in the specification recites “about,” the numerical value or end-point of a range is intended to include two embodiments: one modified by “about,” and one not modified by “about.”

[0109] 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.

[0110] As used herein the term “glass” is meant to include any material made at least partially of glass, including glass and glass-ceramics. “Glass-ceramics” include materials produced through controlled crystallization of glass. In embodiments, glass-ceramics have about 30% to about 90% crystallinity. Non-limiting examples of glass ceramic systems that may be used include $\text{Li}_2\text{O} \times \text{Al}_2\text{O}_3 \times \text{nSiO}_2$ (i.e., LAS system), $\text{MgO} \times \text{Al}_2\text{O}_3 \times \text{nSiO}_2$ (i.e., MAS system), and $\text{ZnO} \times \text{Al}_2\text{O}_3 \times \text{nSiO}_2$ (i.e., ZAS system).

[0111] The present embodiment(s) have been described above with the aid of functional building blocks illustrating the implementation of specified functions and relationships thereof. The boundaries of these functional building blocks have been arbitrarily defined herein for the convenience of the description. Alternate boundaries can be defined so long as the specified functions and relationships thereof are appropriately performed.

WHAT IS CLAIMED IS:

1. A method of forming an electrically controlled variable-tint stack, the method comprising:
 - disposing a flexible film on a flat carrier substrate;
 - forming an electrically controlled variable-tint stack on the flexible film, the electrically controlled variable-tint stack comprising an electro-optic active layer; and
 - removing the flexible film with the electrically controlled variable-tint stack from the flat carrier substrate.
2. The method of claim 1, wherein the flexible film comprises a polymer material.
3. The method of claim 2, wherein the polymer material comprises polyimide.
4. The method of claim 1, wherein the flexible film comprises a flexible glass.
5. The method of claim 1, wherein the flat carrier substrate comprises a glass or a ceramic material.
6. The method of claim 1, wherein disposing the flexible film on the flat carrier substrate comprises adhering the flexible film to the flat carrier substrate with an adhesive layer.
7. The method of claim 6, wherein the adhesive layer comprises a UV-sensitive adhesive or a cationic polymer adhesive.
8. The method of claim 1, wherein forming the electrically controlled variable-tint stack on the flexible film comprises physical vapor deposition, chemical vapor deposition, solution-based deposition, or a combination thereof.

9. The method of claim 1, wherein the electro-optic active layer comprises a suspended-particle layer, a polymer-dispersed liquid crystal layer, an electrokinetic layer, or an electrochromic layer.
10. The method of claim 1, further comprising disposing an encapsulation layer over the electrically controlled variable-tint stack prior to removing the flexible film with the electrically controlled variable-tint stack from the flat carrier substrate.
11. The method of claim 10, wherein the encapsulation layer comprises a polymer layer or an inorganic hard coat layer.
12. The method of claim 1, wherein removing the flexible film with the electrically controlled variable-tint stack from the flat carrier substrate comprises applying laser irradiation, applying a mechanical force, or a combination thereof.
13. The method of claim 1, further comprising disposing the electrically controlled variable-tint stack over a first curved surface of a first curved glass substrate such that the electrically controlled variable-tint stack conforms to the first curved surface.
14. The method of claim 13, further comprising disposing a second curved glass substrate comprising a second curved surface over the electrically controlled variable-tint stack opposite the first curved glass substrate.
15. The method of claim 13, wherein the first curved surface of the first curved glass substrate comprises at least one of a compound curve and a complex curve.
16. The method of claim 1, further comprising laminating the electrically controlled variable-tint stack between a first curved glass substrate and a second curved glass substrate such that the electrically controlled variable-tint stack conforms to a curvature profile defined by the first curved glass substrate and the second curved glass substrate.

17. The method of claim 1, wherein disposing the flexible film on the flat carrier substrate comprises depositing the flexible film by physical vapor deposition or chemical vapor deposition.

18. A method of making a curved electrically controlled variable-tint glass article, the method comprising:

disposing a flexible film on a flat carrier substrate;

forming an electrically controlled variable-tint stack on the flexible film, the electrically controlled variable-tint stack comprising an electro-optic active layer;

disposing an encapsulation layer over the electrically controlled variable-tint stack, thereby forming an electrically controlled variable-tint assembly;

removing the electrically controlled variable-tint assembly from the flat carrier substrate; and

disposing the electrically controlled variable-tint assembly over a first curved surface of a first curved glass substrate such that the electrically controlled variable-tint assembly conforms to the first curved surface.

19. The method of claim 18, further comprising disposing a second curved glass substrate comprising a second curved surface over the electrically controlled variable-tint assembly opposite the first curved glass substrate.

20. A curved electrically controlled variable-tint article, comprising:

a flexible film;

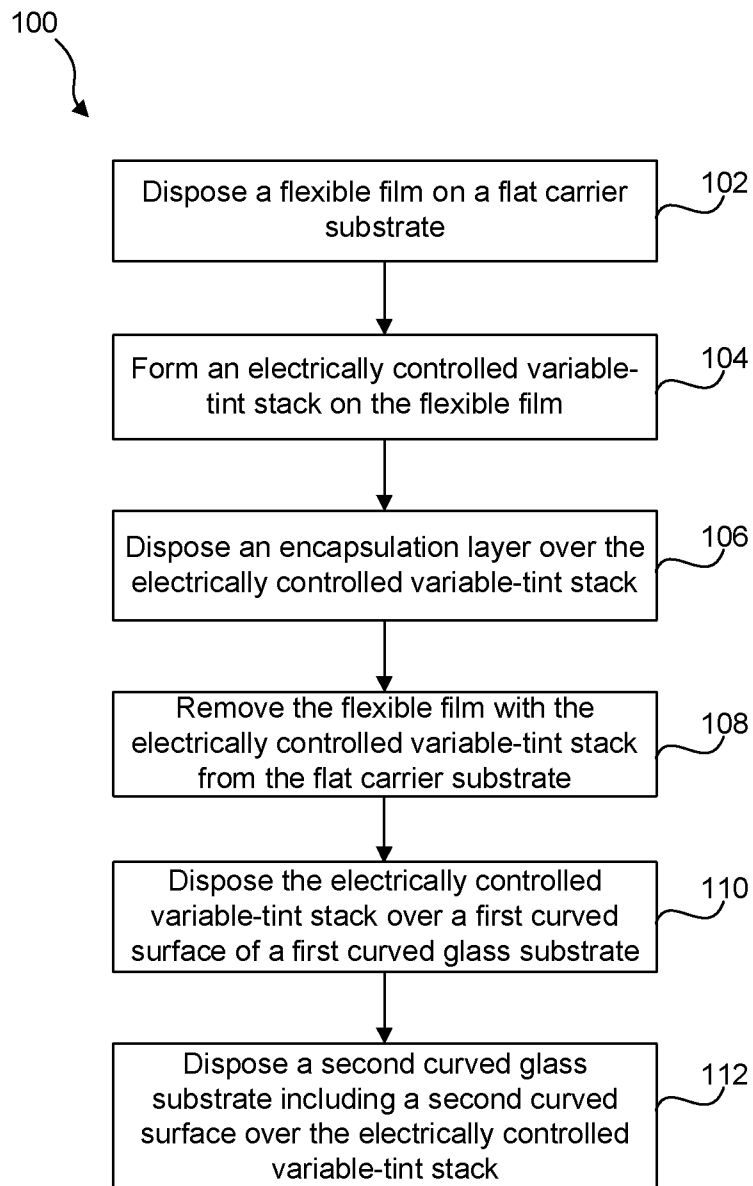
an electrically controlled variable-tint stack disposed on the flexible film; and

two curved glass substrates,

wherein the flexible film and the electrically controlled variable-tint stack are laminated between the two curved glass substrates, and

wherein at least a portion of the two curved glass substrates comprises a non-zero Gaussian curvature.

21. The curved electrically controlled variable-tint article of claim 20, further comprising an encapsulation layer disposed over the electrically controlled variable-tint stack.
22. The curved electrically controlled variable-tint article of claim 20, wherein the flexible film comprises a polymer material or a flexible glass.
23. The curved electrically controlled variable-tint article of claim 22, wherein the flexible film comprises the polymer material and wherein the polymer material comprises polyimide.
24. The curved electrically controlled variable-tint article of claim 20, wherein the electro-optic active layer comprises a suspended particle layer, a polymer-dispersed liquid crystal layer, an electrokinetic layer, or an electrochromic layer.
25. The curved electrically controlled variable-tint article of claim 20, wherein the non-zero Gaussian curvature of the two layers of curved glass comprises a radius of curvature of 0.5 meters or more.

**FIG. 1**

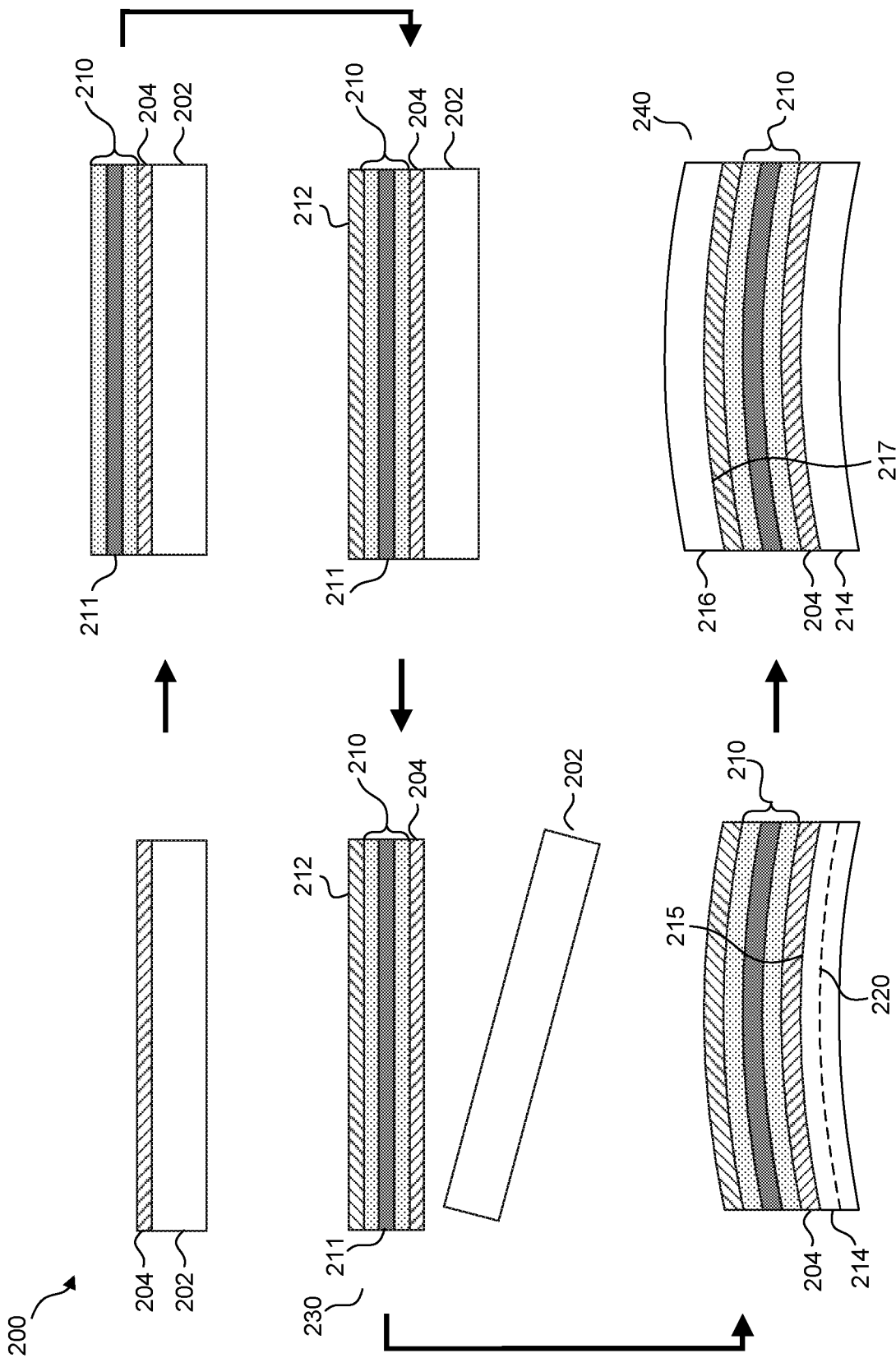


FIG. 2

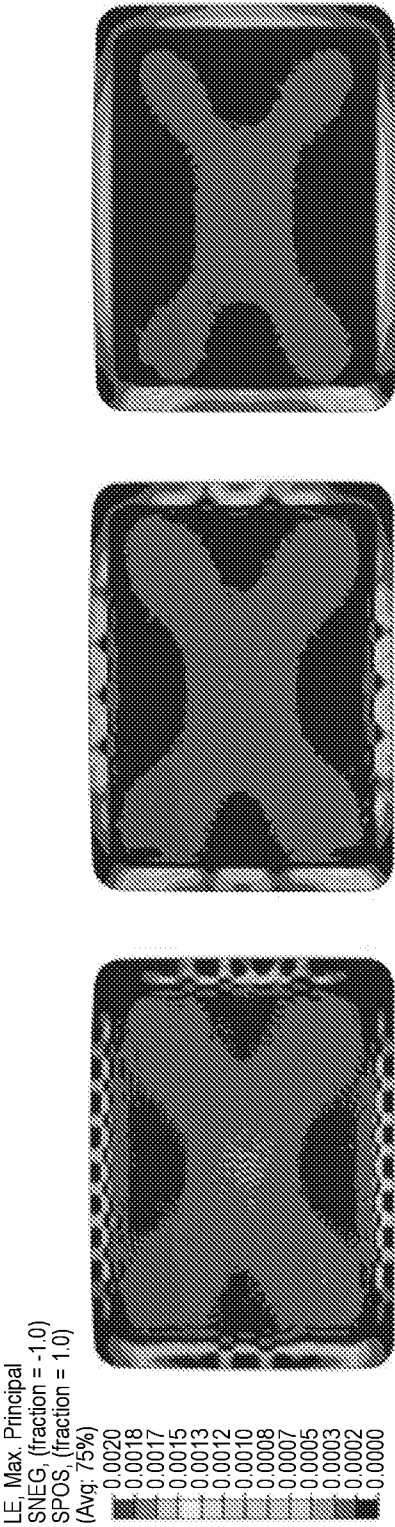


FIG. 3

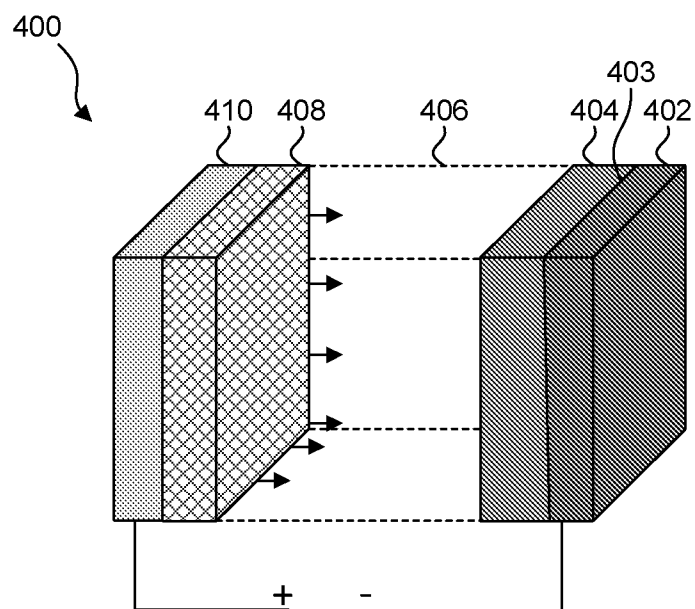


FIG. 4

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2019/045389

A. CLASSIFICATION OF SUBJECT MATTER INV. G02F1/1333 G02F1/153 G02F1/1675 E06B3/67 ADD. B29D11/00 G02C7/10 G02C7/08 B60J3/04 B32B17/06 E06B9/24 G02F1/17 G02F1/1334 G02F1/13		
According to International Patent Classification (IPC) or to both national classification and IPC		
B. FIELDS SEARCHED Minimum documentation searched (classification system followed by classification symbols) G02F E06B B29D G02C B32B B60J Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) EPO-Internal, WPI Data		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2015/163824 A1 (UNIV NANYANG TECH [SG]) 29 October 2015 (2015-10-29) abstract; figures 1-6 the whole document -----	1-19
X	US 2007/218217 A1 (FERNANDO PRIMAL [US] ET AL) 20 September 2007 (2007-09-20) abstract; figures 1-19 the whole document -----	20-25
X	US 5 598 293 A (GREEN MINO [GB]) 28 January 1997 (1997-01-28) abstract; figure 1 the whole document -----	20-25
☐ Further documents are listed in the continuation of Box C. ☒ See patent family annex.		
* Special categories of cited documents : "A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier application or patent but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art "&" document member of the same patent family		
Date of the actual completion of the international search 15 November 2019		Date of mailing of the international search report 27/11/2019
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016		Authorized officer Wolfrum, Georg

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/US2019/045389

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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