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OPTICAL DEVICE CONFIGURED FOR STRESS MITIGATION

Abstract

An electro-optic device is described. The electro-optic device includes at least one optical material having an electro-optic effect. Further, the optical material(s) include lithium. The optical material(s) have a slab and a ridge waveguide. The slab has a top surface. The slab includes free surfaces. Each of the free surfaces is at a nonzero angle from the top surface of the slab and mitigates stress in the slab.

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Background/Summary

CROSS REFERENCE TO OTHER APPLICATIONS [0001] This application is a continuation of U.S. patent application Ser. No. 18/209,415 entitled OPTICAL DEVICE CONFIGURED FOR STRESS MITIGATION filed Jun. 13, 2023, which claims priority to U.S. Provisional Patent Application No. 63/352,135 entitled OPTICAL DEVICE CONFIGURED FOR STRESS MITIGATION filed Jun. 14, 2022, both of which are incorporated herein by reference for all purposes.

BACKGROUND OF THE INVENTION
[0002] Electro-optic devices (also termed optical devices herein) frequently include waveguides and electrodes in proximity to portions of the waveguides. The waveguide carries an optical signal and includes an electro-optic material. An electro-optic material exhibits the electro-optic effect and has its index of refraction modulated by an electric field. The electrodes are used to generate an electric field at or near the waveguide. This electric field causes a change in the index of refraction of the waveguide, which results in the optical signal being modulated. The desired modulation of the optical signal may be achieved by driving the appropriate electrode signal through electrodes.
[0003] Although electro-optic devices function, their performance may be limited by various factors. Bulk lithium niobate (LN), for example, may be desired to be used in electro-optic devices because of its large variation in refractive index for a given applied external electric field. However, bulk LN, as well as other technologies, suffer from significant drawbacks. Fabrication of LN optical devices having desired performance characteristics is challenging. For example, LN waveguides may have higher optical losses than desired. In some cases, scattering losses (e.g. from sidewalls) and absorption losses (e.g. from characteristics of the material itself) may be larger than desired. Consequently, techniques for improving the performance of electro-optic devices are desired.

Description

BRIEF DESCRIPTION OF THE DRAWINGS
[0004] Various embodiments of the invention are disclosed in the following detailed description and the accompanying drawings.
[0005] FIGS. **1**A-**1**D depict embodiments of electro-optic devices utilizing thin film electro-optic materials including lithium.
[0006] FIGS. **2**A-**2**D depict embodiments of electro-optic devices utilizing thin film electro-optic materials including lithium.
[0007] FIGS. **3**A-**3**B depict embodiments of electro-optic devices utilizing thin film electro-optic materials including lithium.
[0008] FIGS. **4**A-**4**B depict an embodiment of electro-optic devices utilizing thin film electro-optic materials including lithium.
[0009] FIG. **5** depicts an embodiment of electro-optic devices utilizing thin film electro-optic materials including lithium.
[0010] FIG. **6** is a flow chart depicting an embodiment of a method for providing an electro-optic devices utilizing thin film electro-optic materials including lithium.
[0011] FIG. **7** is a flow chart depicting an embodiment of a method for providing an electro-optic devices utilizing thin film electro-optic materials including lithium.
DETAILED DESCRIPTION
[0012] The invention can be implemented in numerous ways, including as a process; an apparatus; a system; a composition of matter; a computer program product embodied on a computer readable

storage medium; and/or a processor, such as a processor configured to execute instructions stored on and/or provided by a memory coupled to the processor. In this specification, these implementations, or any other form that the invention may take, may be referred to as techniques. In general, the order of the steps of disclosed processes may be altered within the scope of the invention. Unless stated otherwise, a component such as a processor or a memory described as being configured to perform a task may be implemented as a general component that is temporarily configured to perform the task at a given time or a specific component that is manufactured to perform the task. As used herein, the term ‘processor’ refers to one or more devices, circuits, and/or processing cores configured to process data, such as computer program instructions.

[0013] A detailed description of one or more embodiments of the invention is provided below along with accompanying figures that illustrate the principles of the invention. The invention is described in connection with such embodiments, but the invention is not limited to any embodiment. The scope of the invention is limited only by the claims and the invention encompasses numerous alternatives, modifications and equivalents. Numerous specific details are set forth in the following description in order to provide a thorough understanding of the invention. These details are provided for the purpose of example and the invention may be practiced according to the claims without some or all of these specific details. For the purpose of clarity, technical material that is known in the technical fields related to the invention has not been described in detail so that the invention is not unnecessarily obscured.

[0014] The basic elements of electro-optic devices (also termed optical devices), such as electro-optic modulators, include waveguides and electrodes around the waveguides. The waveguide carries an optical signal and includes an electro-optic material. An electro-optic material exhibits the electro-optic effect and has its index of refraction modulated by an electric field. The electrodes are used to generate an electric field, or voltage difference, at or near the waveguide. This electric field causes a change in the index of refraction of the waveguide, which results in the optical signal being modulated. For example, an electrode signal (e.g. a microwave signal) may be applied to the electrodes. Thus, the electrodes act as transmission lines. The electrode signal travels in the same direction as the optical signal propagating through the waveguide. The electrode signal generates a corresponding electric field at the waveguide, modulating the index of refraction of the waveguide. Therefore, the optical signal is modulated as the optical signal travels through the waveguide. Thus, the desired modulation of the optical signal may be achieved by driving the appropriate electrode signal through electrodes.

[0015] Although electro-optic devices function, their performance may be limited by a number of factors. Many technologies have been proposed to improve the optical devices. These technologies include waveguides utilizing semiconductors (e.g. silicon and/or indium phosphide), bulk lithium niobate (LN), barium titanate (BTO), and/or plasmonics. However, these and other technologies suffer significant drawbacks in one or more of the characteristics mentioned above. For example, LN is desired to be used in electro-optical devices. The desirability of LN is due at least in part to variation in the refractive index of LN with an applied external electric field. However, fabrication of LN optical devices having desired performance characteristics is challenging. For example, LN waveguides may have higher optical losses than desired. In some cases, scattering losses (e.g. from sidewalls) and absorption losses (e.g. from characteristics of the material itself) may be larger than desired.

[0016] An electro-optic device is described. The electro-optic device includes at least one optical material having an electro-optic effect. Further, the optical material(s) include lithium. The optical material(s) have a slab and a ridge waveguide. The slab has a top surface. The slab includes free surfaces. Each of the free surfaces is at a nonzero angle from the top surface of the slab and mitigates stress in the slab. The optical material(s) may include or consist of lithium niobate and/or lithium tantalate. Further, the optical material(s) may be thin films. Thus, the optical material(s) may have a thickness of not more than ten micrometers, not more than five micrometers, not more than three micrometers, not more than one micrometer, not more than seven hundred nanometers, not more than four hundred nanometers, and/or at least one hundred nanometers.

[0017] In some embodiments, the electro-optic device also includes an electrode. A portion of the slab is between the ridge waveguide and the electrode. In such embodiments, at least one of the free surfaces is further from the ridge waveguide than the electrode is. Thus, the electrode is on (e.g. directly on or above) the top surface of the slab. In some other embodiments, the electro-optic device also includes an electrode. At least a portion of the slab is between the ridge waveguide and the electrode. In such embodiments, at least one of the free surfaces is closer to the ridge waveguide than the electrode is. In some such embodiments, the electro-optic device also includes a cladding layer. At least a portion of the electrode is on the cladding layer. In some embodiments, the first edge and the second edge are substantially parallel to at least a portion of the ridge waveguide.

[0018] The slab may have an edge. At least one of the free surfaces is between the edge of the slab and the ridge waveguide. In some embodiments, the slab resides on a substrate. At least one of the free surfaces extends from the top surface of the slab to the substrate. The slab may reside on a substrate. The slab has a thickness. At least one of the free surfaces extends through the slab a distance less than the thickness. In some embodiments, the free surfaces define at least one aperture in the slab. The optical material(s) may include an additional ridge waveguide. Thus, multiple waveguides may be formed on or in by portions of the optical material. The slab may include a trench therein. The trench has a sidewall and is parallel to at least a portion of the ridge waveguide. A free surface of the plurality of free surfaces being the sidewall.

[0019] An electro-optic device including optical material(s), electrodes and a substrate is described. The optical material(s) exhibit an electro-optic effect and include lithium, The optical material(s) having a slab and a ridge waveguide. The slab has a top surface, a first edge, and a second edge. The first edge and the second edge are substantially parallel to a portion of the ridge waveguide. The ridge waveguide is between a first electrode and a second electrode of the plurality of electrodes. The substrate has substrate edges. The first edge of the slab is between the ridge waveguide and a first substrate edge. The second edge of the slab is between the ridge waveguide and a second substrate edge. The first edge and the second edge form free surfaces at a nonzero angle from the top surface of the slab. In some embodiments, the first edge of the slab is between the first electrode and the ridge waveguide/The second edge of the slab is between the second electrode and the ridge waveguide.

[0020] A method provides an electro-optic device. The method includes providing a ridge waveguide from optical material(s) having an electro-optic effect and including lithium. The optical material(s) have a slab and the ridge waveguide. The slab has a top surface. The method also includes providing, for the slab, a plurality of free surfaces. Each of the free surfaces is at a nonzero angle from the top surface of the slab and mitigating stress in the slab. In some embodiments, the optical material(s) include at least one of lithium niobate or lithium tantalate. In some embodiments, the method further includes annealing at least one anneal temperature greater than **300** degrees Celsius. In some such embodiments, the anneal temperature(s) are greater than one thousand degrees Celsius.

[0021] FIGS. **1**A-**1**D depict embodiments of electro-optic devices **100** and **100′**. FIGS. **1**A and **1**B depict perspective and cross-sectional views of an embodiment of electro-optic device **100** utilizing optical material **110** exhibiting the electro-optic effect. The optical material may also include lithium. For example, the optical material **110** may include or consist of one or more of lithium niobate (LN), lithium tantalate (LT), barium titanate (BTO), and/or plasmonics. Thus, although described in singular terms, optical material **110** may include multiple constituents. In some embodiments, the electro-optic effect includes a change in index of refraction in an applied electric field (e.g. due to the Pockels effect). Thus, in some embodiments, optical materials possessing the electro-optic effect in one or more the ranges described herein or consistent with the material(s) described are considered nonlinear optical materials regardless of whether the effect is linearly or nonlinearly dependent on the applied electric field. For example, a nonlinear optical material may exhibit the electro-optic effect of at least (e.g. greater than or equal to) 5 picometer/volt. In some embodiments, the nonlinear optical material has an effect that is at least 10 picometer/volt. In some such embodiments nonlinear optical material has an effect of at least 20 picometer/volt. The nonlinear optical material experiences a change in index of refraction in response to an applied electric field. In some embodiments, the nonlinear optical material is ferroelectric. The nonlinear optical material may be a non-centrosymmetric material. Therefore, the nonlinear optical material may be piezoelectric.

[0022] Electro-optic material **110** may also be a thin film. In some embodiments, electro-optic material **110** is not more than ten micrometers in thickness as-deposited. In some embodiments, electro-optic material **110** may be not more than three micrometers thick as-deposited. In some embodiments, electro-optic material **110** may be not more than one micrometer in thickness as-deposited. In some embodiments, the thickness of electro-optic material **110** as-deposited may be not more than seven hundred nanometers. In some such embodiments, this thickness may be not more than four hundred nanometers. In some embodiments, the thickness may be at least one hundred micrometers as-deposited. Other thicknesses are possible.

[0023] The optical material **110** is on a substrate **101**. In some embodiments, the substrate **101** includes an oxide layer **104** (e.g. SiO.sub.2) and an underlying wafer **102** (e.g. silicon). In some embodiments, oxide layer **104** is at least three micrometers thick. In some embodiments, oxide layer **104** is at least five micrometers thick. Other thicknesses are possible. In some embodiments, oxide layer **104** may be omitted. For example, for an underlying sapphire substrate **102**, no oxide layer may be present. Also shown is cladding **130**, which has an index of refraction that differs from that of ridge waveguide **112**. For example, cladding **130** may include or consist of silicon dioxide. For simplicity, cladding **130** is not shown in FIG. **1**A.

[0024] The optical material **110** has ridge waveguide **112** and slab **114** formed therefrom. In some embodiments, the thickness of ridge waveguide **112** is the thickness of optical material **110** as-deposited. For example, ridge waveguide **112** may have a height (or maximum height if there is a variation in height of ridge waveguide **112**) of four hundred nanometers, which may be the as-deposited thickness of optical material **110**. In such embodiments, slab **114** may have a height of two hundred nanometers. Ridge waveguide **112** may have a height of less than the thickness of optical material **110** in some embodiments. Slab **114** has a top surface and free surfaces **120**. For clarity, only some free surfaces **120** are labeled in FIGS. **1**A-**1**B. In the embodiment shown in FIGS. **1**A-**1**B, free surfaces **120** are formed by apertures **122** in optical material **110**. For clarity, not all apertures **122** are labeled. In some embodiments, apertures **122** extend through slab **114**. In some embodiments, one or more depressions in slab **114** are used in lieu of some or all of apertures **122**. Although indicated as terminating at oxide layer **104**, in some embodiments, apertures **122** may extend into or through oxide **104** (e.g. to or into the underlying substrate **102**). In some embodiments, apertures **122** may have another configuration. For example, apertures **122** may have other shape(s) (e.g. triangles, circles, hexagons, squares), be separated by other distance(s), and/or be distributed across slab **114** in another manner (e.g. a close-packed distribution and/or a non-rectangular array).

[0025] Free surfaces **120** are at a nonzero angle from the top surface of slab **114**. In the embodiment shown, free surfaces **120** are substantially perpendicular (e.g. within ten degrees of perpendicular) to the top surface of slab **114** and/or the top surface of substrate **101**. In other embodiments, free surfaces **120** may be at another nonzero angle with respect to the top surface of slab **114** and/or substrate **101**. For example, free surfaces **120** may be at least fifty degrees and up to ninety degrees from horizontal surfaces (e.g. the top surface of substrate **101**). Free surfaces **120** may mitigate stress (e.g. in-plane stress) in slab **114**. For example, stress due to annealing and/or other processing may be reduced by free surfaces **120**.

[0026] Optical structures, such as ridge waveguide **112**, formed from optical material **110** may have improved performance. Such optical structures may be formed using UV and/or DUV lithography and other processing that allows for improved surface roughness. In some embodiments, the short-range root mean square (RMS) surface roughness is the RMS surface roughness for lengths (e.g. along direction the axis of ridge waveguide **112**) of not more than two hundred nanometers. The short-range RMS surface roughness of sidewalls of waveguide **112** in optical device **100** is less than ten nanometers. In some embodiments, the short-range RMS surface roughness is not more than five nanometers. The short-range RMS surface roughness of the sidewalls of ridge waveguide **112** do not exceed two nanometers in some embodiments. Further, the short-range RMS roughness of the top surfaces of ridge waveguide **112** is not more than one nanometer in some embodiments. In some embodiments, the long range (lengths greater than two hundred nanometers through two hundred micrometers) RMS surface roughness of the sidewalls of ridge waveguide **112** may differ from the short-range RMS surface roughness.

[0027] Further, optical material **110** may undergo higher temperature annealing. In some embodiments, optical material **110** is annealed at anneal temperatures greater than 300 degrees Celsius. Optical material **110** may be annealed at anneal temperatures greater than 400 degrees Celsius. In some embodiments, optical material **110** is annealed at anneal temperatures greater than 500 degrees Celsius. Optical material **110** may be annealed at anneal temperatures greater than 600 degrees Celsius. In some embodiments, optical material **110** is annealed at anneal temperatures greater than 700 degrees Celsius. Optical material **110** may be annealed at anneal temperatures greater than 800 degrees Celsius. In some embodiments, optical material **110** is annealed at anneal temperatures greater than 900 degrees Celsius. In some embodiments, optical material **110** is annealed at anneal temperatures greater than 1000 degrees Celsius. High temperature annealing may improve the crystal structure of the optical material (e.g. the structure of LN and/or LT). For example, losses due to absorption in optical material **110** may be reduced.

[0028] FIGS. **1**C and **1**D depict perspective and cross-sectional views of an embodiment of electro-optic device **100′** that is analogous to electro-optic device **100**. For example, the optical material **110** may include or consist of one or more of LN, LT, BTO, and/or plasmonics. Further, optical material **110** includes ridge waveguide **112** and slab **114** that are analogous to corresponding structures shown in FIGS. **1**A-**1**B. The optical material **110** is on substrate **101** including oxide layer **104**, and underlying wafer **102** that are analogous to that are analogous to corresponding structures shown in FIGS. **1**A-**1**B. In some embodiments, oxide layer **104** may be omitted. Also shown is cladding **130**, which is analogous to cladding **130** shown in FIG. **1**B. For clarity, cladding **130** is not shown in FIG. **1**C. Also depicted are apertures **122** and free surfaces **120** in slab **114**. In some embodiments, some or all of apertures **122** and free surfaces **120** may be omitted. Thus, slab **114** may not include free surfaces **120** in some embodiments.

[0029] Also shown in FIGS. **1**C and **1**D is depression **132** having free surface **130**. In contrast to apertures **122**, depression **132** does not extend through slab **114**. Free surface **130** may have a similar function as free surfaces **120**. In some embodiments, the ridge on which free surface **130** is present has a different height than ridge waveguide **112**. In other embodiments, the ridge on which free surface **130** is present has the same height as ridge waveguide **112**. In some embodiments, the portion of optical materials **110** below depression **132** has the same height as the remainder of slab **114**. In some embodiments, shown in FIGS. **1**C-**1**D, the portion of optical materials **110** under depression **132** has a different height than the remainder of slab **114**. In the embodiment shown, free surface **132** is on one side of ridge waveguide **112**. In other embodiments, depressions **132** and free surfaces **130** may be on both sides of ridge waveguide **112**.

[0030] Thus, electro-optic device(s) **100** and/or **100′** may have improved performance. Because optical material includes materials such as LN and/or LT, the modulation of the index of refraction of waveguide **112** and slab **114** by a given applied electric field may be increased. Because of the fabrication using UV or DUV lithography resulting in reduced surface roughness, optical losses (e.g. due to scattering) may be reduced. Further, annealing at optical material **110** at higher temperatures may further reduce optical losses. For example, optical losses due to absorption may be reduced. The presence of free surfaces **120** and/or **130** can mitigate stress in optical material **110** (e.g. slab **114** and ridge waveguide **112**) that might otherwise build up due to annealing. Consequently, optical material **110** may be less likely to undergo delamination or other stress-induced damage. Further, formation of free surface **130** may be accomplished with less etching of optical material **110** than for free surfaces **120**. Fabrication of electro-optic device **110′** may thus be facilitated. Thus, performance and reliability of electro-optic device(s) **100** and/or **100′** may be improved.

[0031] FIGS. **2**A-**2**D depict embodiments of electro-optic devices **200** and **200′**. FIGS. **2**A and **2**B depict perspective and cross-sectional views of an embodiment of electro-optic device **200** utilizing optical material **210** exhibiting the electro-optic effect. Electro-optic device **200** and optical material **210** are analogous to electro-optic device **100** and optical material **110**, respectively. For example, the optical material **210** may include or consist of one or more of LN, LT, BTO, and/or plasmonics. Further, optical material **210** includes ridge waveguide **212** and slab **214** that are analogous to ridge waveguide **112** and slab **114**. The optical material **210** is on substrate **201** including oxide layer **204**, and underlying wafer **202** that are analogous to substrate **101**, oxide layer **104**, and underlying wafer **102**. In some embodiments, oxide layer **204** may be omitted. Also shown is cladding **230**, which is analogous to cladding **130**.

[0032] Slab **214** has a top surface and includes free surfaces **220**. For clarity, only some free surfaces **220** are labeled in FIGS. **2**A-**2**B. In the embodiment shown in FIGS. **2**A-**2**B, free surfaces **220** are formed by trenches **222** in optical material **210**. In some embodiments, trenches **222** extend through slab **214**. In some embodiments, one or more depressions in slab **214** (i.e. trenches that do not extend through slab **114**) are used in lieu of some or all of trenches **222**. Although indicating as terminating at oxide layer **204**, in some embodiments, trenches **222** may extend into or through oxide **204** (e.g. to or into the underlying substrate **202**). In some embodiments, trenches **222** may have another configuration. For example, trenches **222** may have other shape(s) (e.g. the width, length, and/or depth of the trench may vary along the trench), be separated by other distance(s), and/or be distributed across slab **214** in another manner (e.g. may not run parallel to ridge waveguide **212**). In some embodiments, trenches **222** may extend further than (i.e. are wider than) shown. For example, trenches **222** may extend to the edge of the slab **214**. Stated differently, optical material **210**, and thus slab **214**, may terminate at the edge of trenches **222** closes to ridge **212**.

[0033] Free surfaces **220** are at a nonzero angle from the top surface of slab **214**. In the embodiment shown, free surfaces **220** are substantially perpendicular (e.g. within ten degrees of perpendicular) to the top surface of slab **214** and/or the top surface of substrate **201**. In other embodiments, free surfaces **220** may be at another nonzero angle with respect to the top surface of slab **214** and/or substrate **201**. For example, free surfaces **220** may be at least fifty degrees and up to ninety degrees from horizontal surfaces (e.g. the top surface of substrate **201**). In some embodiments, slab **214** and ridge waveguide **212** may thus be considered to form a double trapezoid (e.g. ridge waveguide **212** is a trapezoid on a portion of slab **214** that is also trapezoidal in cross section). Free surfaces **220** may mitigate stress (e.g. in-plane stress) in slab **214**. For example, stress due to annealing and/or other processing may be reduced by free surfaces **220**.

[0034] Optical structures **212** and **214** (i.e. ridge waveguide **212** and slab **214**) are analogous to optical structures **112** and **114** and may be formed using analogous processes. As a result, optical structures **212** and **214** and electro-optic device **200** may have improved performance. Optical structures **212** and **214** may be formed using UV and/or DUV lithography and other processing that allows for improved surface roughness. In some embodiments, the short-range RMS surface roughness of sidewalls of waveguide **212** is in the ranges described for waveguide **112**. Further, the short-range RMS roughness of the top surfaces of ridge waveguide **212** may be in the same range as described for ridge waveguide **112**. In some embodiments, the long range (lengths greater than two hundred nanometers through two hundred micrometers) RMS surface roughness of the sidewalls of ridge waveguide **212** may differ from the short-range RMS surface roughness. The presence of trenches **222** may also improve optical confinement by ridge waveguide **212**. In some cases, the sidewalls of ridge waveguide **212** may be desired to be shallow (further from perpendicular to the top surface of slab **214**) to provide more efficient modulation. However, for sidewalls that are shallow, confinement of optical mode **213** may be reduced. Stated differently, optical mode **213** may extend laterally further than desired. The presence of trenches **222** and free surface **220** closest to ridge waveguide **212** enhances lateral confinement of optical mode **213**. Thus, modulation may be made more efficient through the use of shallower sidewalls of ridge waveguide **212**, while optical mode **213** confinement may be enhanced by the presence of trenches **222**. Thus, performance of optical device **200** may be improved.

[0035] Further, optical material **210** may undergo higher temperature annealing. In some embodiments, optical material **210** is annealed at anneal temperatures described for optical material **110**. High temperature annealing may improve the crystal structure of the optical material (e.g. the structure of LN and/or LT). For example, losses due to absorption in optical material **210** may be reduced.

[0036] FIGS. **2**C and **2**D depict perspective and cross-sectional views of an embodiment of electro-optic device **200′** that is analogous to electro-optic device **200**. For example, the optical material **210** may include or consist of one or more of LN, LT, BTO, and/or plasmonics. Further, optical material **210** includes ridge waveguide **212** and slab **214** that are analogous to corresponding structures shown in FIGS. **2**A-**2**B. The optical material **210** is on substrate **201** including oxide layer **204**, and underlying wafer **202** that are analogous to that are analogous to corresponding structures shown in FIGS. **2**A-**2**B. In some embodiments, oxide layer **204** may be omitted. Also shown is cladding **230**, which is analogous to cladding shown in FIG. **2**B. Also depicted are trench **222** and free surface **220** in slab **214**. In some embodiments, some or all of trench **222** and free surface **220** may be omitted. Thus, slab **214** may not have free surfaces **220** therein.

[0037] Also shown in FIGS. **2**C and **2**D is depression **232** having free surface **230**. In the embodiment shown, the portion of optical materials **210** below depression **232** has the same height as the remainder of slab **214**. In some embodiments, the portion of optical materials **110** under depression **132** has a different height than the remainder of slab **114**. Although one depression **232** is shown, multiple depressions may be present in ridge waveguide **212**. Free surface **230** may have a similar function as free surfaces **220**. In some embodiments, the ridge on which free surface **230** is present has a different height than ridge waveguide **212**. In other embodiments, the ridge on which free surface **230** is present has the same height as ridge waveguide **212**. In the embodiment shown, free surface **232** is on one side of ridge waveguide **212**. In other embodiments, depressions **232** and free surfaces **230** may be on both sides of ridge waveguide **212**.

[0038] Thus, electro-optic device(s) **200** and/or **200′** may share the benefits of electro-optic device **100**. Electro-optic material(s) such as LN and/or LT may be used, allowing for a larger modulation of the index of refraction for a given applied electric field. Because of the fabrication using UV or DUV lithography resulting in reduced surface roughness, optical losses (e.g. due to scattering) may be reduced. Further, annealing at optical material **210** at higher temperatures may further reduce optical losses (e.g. due to absorption). The presence of free surfaces **220** can mitigate stress in optical material **210** (e.g. slab **214**) that might otherwise build up due to annealing. Consequently, optical material **210** may be less likely to undergo stress-induced damage. Trenches **220** may also enhance confinement of optical mode **213** and improve efficiency of devices **200** and/or **200′** as optical modulators. Further, formation of free surface **230** may be accomplished with less etching of optical material **210** than for free surfaces **220**. Fabrication of electro-optic device **210′** may thus be facilitated. Thus, performance and reliability of electro-optic device(s) **200** and/or **200′** may be improved.

[0039] Use of optical structures having reduced surface roughness and higher anneal temperatures may improve performance of a variety of electro-optic devices. For example, FIGS. **3**A and **3**B depict top and perspective views of an embodiment of electro-optic device **300** utilizing optical material **310** exhibiting the electro-optic effect. Electro-optic device **300** is an optical modulator. Electro-optic device **300** and optical material **310** are analogous to electro-optic device **100** and optical material **110**, respectively. For example, the optical material **310** may include one or more of LN, LT, BTO, and/or plasmonics. Optical material **310** includes slab **314** and ridge waveguides **312** and **316**. Waveguides **312** and **316** are analogous to ridge waveguide **112**. Slab **314** is analogous to slab **114**. Also shown are electrodes **340**, **350**, **360**, and **370**. Although four electrodes **340**, **350**, **360**, and **370** are shown, in some embodiments, another number and/or configuration of electrodes may be used. Cladding **330** and substrate **301** including oxide **304** and underlying wafer **302** are analogous to cladding **130**, substrate **101**, oxide **104**, and wafer **102**. In some embodiments, oxide **304** is sufficiently thick to reduce or prevent the intersection of a microwave mode due to an electrode signal carried by one or more of electrodes **340**, **350**, **360**, and/or **370** with silicon wafer **302**. In some embodiments, oxide layer **304** may be omitted. Although shown has having a particular size, distance from slab **314** and separation, in some embodiments, electrodes **340**, **350**, **360**, and/or **370** may be configured differently. For example, electrodes **340**, **350**, **360**, and **370** may be further from slab **314** and/or closer to waveguide **312** or **316**. In other embodiments, electrodes **340**, **350**, **360**, and/or **370** may be set into slab **314**.

[0040] Slab **314** has a top surface and includes free surfaces **320** that are analogous to free surfaces **120**. Thus, slab **314** has a distribution of apertures **322**. For clarity, only some free surfaces **320** and apertures **322** are labeled in FIGS. **3**A-**3**B. Some embodiments (e.g. the embodiment shown in FIGS. **3**A-**3**B), apertures **322** extend through slab **314**. In some embodiments, one or more depressions in slab **314** are used in lieu of some or all of apertures **322**. Although indicating as terminating at oxide layer **304**, in some embodiments, apertures **322** may extend into or through oxide **304** (e.g. to or into the underlying substrate **302**). In the embodiment shown, the portion of slab **314** between electrodes **340** and **350** and waveguide **316** and the portion of slab **314** between electrodes **360** and **370** and waveguide **312** are free from apertures **322**. In some embodiments, one or more apertures may exist in one or both of these regions. Thus, one or more free surfaces **320** may be between the electrodes **360** and **370** and waveguide **312**. In some embodiments, no apertures **322** are between electrodes **340**, **350**, **360**, and **370** and the underlying substrate **301** (e.g. none are aligned with and directly under electrodes **340**, **350**, **360**, and/or **370**). In some embodiments, apertures may exist in these regions. Thus, one or more free surfaces **320** may be between the electrodes **360** and **370** and underlying substrate **301**. Although shown with a particular size, shape, and distribution, these and other characteristics of apertures **322** may be varied. In some embodiments, trenches analogous to trenches **222** may be used in lieu of or in addition to apertures **322**. Although not shown in FIGS. **3**A-**3**B, in some embodiments, depression(s) analogous to depression **132** and/or **232** may be present in addition to or in lieu of apertures **322**.

[0041] Optical modulator **300** may have improved performance. As discussed with respect to optical device **100**, optical properties of optical material **310** may be improved. For example, the sidewall roughnesses of waveguides **312** and **316** may be in the ranges described for waveguide **112**. Further, optical material **310** may be annealed. Thus, optical losses may be reduced. Further, waveguides **312** and **316** cross in the embodiment shown. Because of the improved surface roughness and anneal, waveguides **312** and **316** may cross (as shown in FIG. **3**A) while maintaining lower optical losses. Electrodes **340**, **350**, **360**, and **370** may also be formed without crossings. Because materials such as LN and/or LT may be used for optical material **310**, electrodes **340**, **350**, **360**, and **370** may induce a larger change in the indices of refraction for waveguides **312** and **316**. As indicated in FIG. **3**A, both waveguides **312** and **316** and electrodes **340**, **350**, **360**, and **370** have turns. As a result, the velocities of the optical signals in waveguides **312** and **316** may be matched with the velocities of the microwave signals in electrodes **340**, **350**, **360**, and/or **370**. Further, the optical losses for such turns may be reduced due to the improved surface roughnesses of waveguides **312** and **316**. Thus, performance of optical modulator **300** may be improved.

[0042] In another example, FIGS. **4**A and **4**B depict top and perspective views of an embodiment of electro-optic device **400** utilizing optical material **410** exhibiting the electro-optic effect. Electro-optic device **400** is an optical modulator. Electro-optic device **400** and optical material **410** are analogous to electro-optic device **200** and optical material **210**, respectively. For example, the optical material **410** may include one or more of LN, LT, BTO, and/or plasmonics. Optical material **410** includes slab **414** and ridge waveguides **412** and **416**. Waveguides **412** and **416** are analogous to ridge waveguide **212**. Slab **414** is analogous to slab **214**. Also shown are electrodes **440**, **450**, **460**, and **470**. Although four electrodes **440**, **450**, **460**, and **470** are shown, in some embodiments, another number and/or configuration of electrodes may be used. Cladding **430** and substrate **401** including oxide **404** and underlying wafer **402** are analogous to cladding **230**, substrate **201**, oxide **204**, and wafer **202**. In some embodiments, oxide **204** is sufficiently thick to reduce or prevent the intersection of a microwave mode due to an electrode signal carried by one or more of electrodes **440**, **450**, **460**, and/or **470** with silicon wafer **402**. In some embodiments, oxide layer **404** may be omitted.

[0043] Slab **414** has a top surface and includes free surfaces **420** that are analogous to free surfaces **420**. Thus, slab **414** has a distribution of trenches **422**. For clarity, only some free surfaces **420** and trenches **422** are labeled in FIGS. **4**A-**4**B. Some embodiments (e.g. the embodiment shown in FIGS. **4**A-**4**B), trenches **422** extend through slab **414**. In some embodiments, one or more depressions in slab **414** are used in lieu of some or all of trenches **422**. Although indicating as terminating at oxide layer **404**, in some embodiments, trenches **422** may extend into or through oxide **404** (e.g. to or into the underlying substrate **402**). In the embodiment shown, the portion of slab **414** between electrodes **440** and **450** and waveguide **416** and the portion of slab **414** between electrodes **460** and **470** and waveguide **412** are free from trenches **422**. In some embodiments, one or more trenches may exist in one or both of these regions. Thus, one or more free surfaces **420** may be between the electrodes **460** and **470** and waveguide **412**. In some embodiments, no trenches **422** are between electrodes **440**, **450**, **460**, and **470** and the underlying substrate **401** (e.g. none are aligned with and directly under electrodes **440**, **450**, **460**, and/or **470**). Thus, one or more free surfaces **420** may be between the electrodes **460** and **470** and underlying substrate **401**. In some embodiments, trenches may exist in these regions. Although shown as extending through slab **414** to the edge of device **400**, in some embodiments, trenches **422** may extend over a smaller region. For example, trenches **422** may only be in the region of electrodes **462** and **472**. Although shown with a particular size, shape, and distribution, these and other characteristics of trenches **422** may be varied. In some embodiments, trenches **422** may extend further than (i.e. are wider than) shown. For example, trenches **422** may extend to the edge of the slab **414**. Stated differently, optical material **410** may terminate at the edge of trenches **422** closes to ridge **412**. In some embodiments, apertures analogous to apertures **122** may be used in lieu of or in addition to trenches **422**. Although not shown in FIGS. **4**A-**4**B, in some embodiments, depression(s) analogous to depression **132** and/or **232** may be present in addition to or in lieu of trenches **422**.

[0044] Electrodes **440**, **450**, **460**, and **470** include channel regions and extensions. For clarity, channel regions **462** and **472** and extensions **464** and **474** are labeled only in FIG. **4**B. In the embodiment shown, extensions **464** and **474** include a connecting portion **464**A and **474**A, respectively, and a retrograde portion **464**B and **474**B, respectively. In some embodiments, extensions **464** and **474** may have a different shape. For example, extensions **464** and/or **474** may have an "L"-shape, may omit the retrograde portion, may be rectangular, trapezoidal, parallelogram-shaped, may partially or fully wrap around a portion of waveguide **412**, and/or have another shape. Similarly, channel regions **462** and/or **472**, which are shown as having a rectangular cross-section, may have another shape. Further, extensions **464** and/or **474** may have different sizes. Although all extensions **464** and **474** are shown as the same distance from ridge **412**, some of extensions **464** and/or some of extensions **474** may be different distances from ridge **412**. In some embodiments, extensions **464** and **474** are desired to have a length that corresponds to a frequency less than the Bragg frequency of the signal for electrodes **460** and **470**. Thus, the length of extensions **464** and/or **474** may be desired to be not more than the microwave wavelength of the electrode signal divided by x at the highest frequency of operation for electrodes **460** and **470**. In some embodiments, the length of extensions **464** and/or **474** is desired to be less than the microwave wavelength divided by twelve. For example, if the maximum operation frequency is 300 GHz, which corresponds to a microwave wavelength of 440 micrometers in the substrate, extensions **464** and **474** are desired to be smaller than approximately 37 micrometers. Individual extensions **464** and/or **474** may be irregularly spaced or may be periodic. Periodic extensions have a constant pitch. In some embodiments, the pitch is desired to be a distance corresponding to a frequency that is less than the Bragg frequency. Thus, the pitch for extensions **464** and **474** may be desired to be not more than the microwave wavelength of the electrode signal divided by x at the highest frequency of operation for electrodes **460** and **470**. In some embodiments, the pitch is desired to be less than the microwave wavelength divided by twelve. In some embodiments, the pitch is desired to be less than the microwave wavelength divided by seventy-two, allowing for a low ripple in group velocity. Although shown as having a particular size, distance from slab **414** and separation, in some embodiments, electrodes **440**, **450**, **460**, and/or **470** may be configured differently. For example, electrodes **440**, **450**, **460**, and **470** may be further from slab **414** such that portions of the extensions are over waveguide **412** or **416**. In other words, the separation between the extension may be less than the width of ridge waveguide **410**. In other embodiments, electrodes **440**, **450**, **460**, and/or **470** may be set into slab **414**.

[0045] Optical modulator **400** may have improved performance. As discussed with respect to optical device **200**, optical properties of optical material **410** may be improved. For example, the sidewall roughnesses of waveguides **412** and **416** may be in the ranges described for waveguide **212**. Further, optical material **410** may be annealed. Thus, optical losses may be reduced. In addition, confinement of the optical mode (not shown in FIGS. **4**A-**4**B) may be improved by trenches **422**. In some embodiments, sidewalls of ridge waveguide **412** may be shallower to enhance modulation while maintaining optical mode confinement using trenches **222**. Thus, flexibility of optical device **400** may be improved. Further, waveguides **412** and **416** cross in the embodiment shown. Because of the improved surface roughness and anneal, waveguides **412** and **416** may cross (as shown in FIG. **4**A) while maintaining lower optical losses. Electrodes **440**, **450**, **460**, and **470** may also be formed without crossings. Because materials such as LN and/or LT may be used for optical material **410**, electrodes **440**, **450**, **460**, and **470** may induce a larger change in the indices of refraction for waveguides **412** and **416**. As indicated in FIG. **4**A, both waveguides **412** and **416** and electrodes **440**, **450**, **460**, and **470** have turns. As a result, the velocities of the optical signals in waveguides **412** and **416** may be matched with the velocities of the microwave signals in electrodes **440**, **450**, **460**, and/or **470**. Further, the optical losses for such turns may be reduced due to the improved surface roughnesses of waveguides **412** and **416**. Moreover, use of electrodes **440**, **450**, **460**, and/or **470** having extensions may further improve modulation, reduce microwave losses, and allow for enhanced velocity matching. Extensions, such as extensions **464** and **474**, allow for the electric field to be enhanced at the waveguide **412** (because extensions are closer to waveguide **412**), while allowing the microwave signal to be carried by channels **462** and **472**. Thus, a higher optical modulation may be obtained while reducing the microwave losses. Moreover, extensions in combination with engineering of substrate **401** may improve velocity matching between the optical and microwave signals. Thus, performance of optical modulator **400** may be improved.

[0046] In another example, FIG. **5** depicts a perspective view of a portion of an embodiment of electro-optic device **500** utilizing optical material **510** exhibiting the electro-optic effect and including lithium. Electro-optic device **500** is an optical modulator. Electro-optic device **500** and optical material **510** are analogous to electro-optic device **400** and optical material **410**, respectively. For example, the optical material **510** may include one or more of LN, LT, BTO, and/or plasmonics. Optical material **510** includes slab **514** and ridge waveguide **512**. Waveguide **512** is analogous to ridge waveguide **412**. Slab **514** is analogous to slab **414**. Thu, trenches **522** and free surfaces **520** are analogous to trenches **420** and free surfaces **422**. Also shown are electrodes **560** and **570** that are analogous to electrodes **460** and **470**. Thus, extensions **564** and **574** having connecting portions **564**A and **574**A and retrograde portions **564**B and **574**B are analogous to extensions **464** and **474**. For simplicity, only one waveguide **412** and two electrodes **460** and **470** are shown. However, typically multiple waveguides and more pairs of electrodes (e.g. as in FIGS. **4**A and **4**B) are utilized. Although two electrodes **560** and **570** are shown, in some embodiments, another number and/or configuration of electrodes may be used. Cladding **530** and substrate **501** including oxide **504** and underlying wafer **502** are analogous to cladding **430**, substrate **401**, oxide **404**, and wafer **402**. In some embodiments, oxide **504** is sufficiently thick to reduce or prevent the intersection of a microwave mode due to an electrode signal carried by one or more of electrodes **560** and/or **570** with silicon wafer **502**. In some embodiments, oxide layer **504** may be omitted.

[0047] In the embodiment shown, trenches **522** extend to the region between ridge waveguide **512** and extensions **564** and **574**. In some embodiments, trenches **522** extend to retrograde portions **564**B and **574**B. In such embodiments, slab **514** extends from ridge waveguide **512** to retrograde portions **564**B and **574**B. In some embodiments, trenches **522** extend to the region between retrograde portions **564** and **574** and channels **562** and **572**. Thus, slab **514** extends from ridge waveguide **512** to retrograde portions **564**B and **574**B. In some embodiments, trenches **522** extend to the channels **562** and **572**. Thus, slab **514** extends from ridge waveguide **512** to channels **560** and **570**. Thus, in some embodiments, slab **514** need not and does not extend past electrodes **560** and **570**. Electro-optic device **500** shares some or all of the benefits of electro-optical device **400**, though is configured somewhat differently.

[0048] Electro-optic devices **100**, **100′**, **200**, **200′**, **300**, **400**, and **500** have been described. Various feature(s) of devices **100**, **100′**, **200**, **200′**, **300**, **400**, and/or **500** may be combined in manners not explicitly described herein.

[0049] FIG. **6** depicts an embodiment of method **600** for providing an electro-optic device, such as one or more devices **100**, **200**, **300**, and/or **400**. Method **600** is described in the context of processes that may have sub-processes. Although described in a particular order, another order not inconsistent with the description herein may be utilized. Although fabrication of a single device is described, multiple devices are typically fabricated together. Method **600** starts after an electro-optic material, such as an LN and/or LT layer has been provided on a substrate. In some embodiments, the LN and/or LT layer may be thin, for example, not more than ten micrometers in thickness. In some embodiments, the LN and/or LT layer may be not more than three micrometers thick. In some embodiments, the LN layer may be not more than one micrometer in thickness. In some embodiments, the thickness of the LN layer may be not more than seven hundred nanometers. In some such embodiments, the thickness may be not more than four hundred nanometers. In some embodiments, the thickness may be at least one hundred micrometers. Other thicknesses are possible. Underlayers, such as silicon dioxide, may exist between the LN layer and a carrier wafer. In some embodiments, the carrier wafer may include silicon, quartz, silica, LN, sapphire and/or another material. For example, the LN layer may reside on a silicon dioxide underlayer having a thickness of nominally at least two and not more than five micrometers. Other thicknesses, additional layers and/or other layers may be present. Method **600** may also be used in connection with one or more of the techniques described in the above-identified co-pending applications.

[0050] Optical and stress relief components are provided for the electro-optic device at **602**. In some embodiments, these components are formed from the electro-optic material. For example,

602 may include utilizing the methods described in the above-identified patent applications to form ridge and/or channel waveguide(s) as well as stress relief components such as free surfaces. Other optical components, such as mode converter(s) and polarization beam rotator(s), may also be formed.

[0051] Electrical components are formed, at **604**. In some embodiments, **604** may include forming electrodes for an optical modulator. Other electrical components, such as CMOS or other components, may also be formed at **604**.

[0052] Using method **600**, electro-optic devices such as devices **100**, **200**, **300** and/or **400** may be formed. Thus, the benefits described herein, including but not limited to stress management, may be achieved.

[0053] FIG. **7** depicts an embodiment of method **700** for providing an electro-optic device, such as one or more devices **100**, **200**, **300**, and/or **400**. Method **700** is described in the context of processes that may have sub-processes. Although described in a particular order, another order not inconsistent with the description herein may be utilized. Although fabrication of a single device is described, multiple devices are typically fabricated together. Method **700** starts after an electro-optic material, such as an LN and/or LT layer has been provided on a substrate. In some embodiments, the LN and/or LT layer may be thin, for example, not more than ten micrometers in thickness. In some embodiments, the LN layer may be not more than one micrometer in thickness. In some embodiments, the thickness of the LN layer may be not more than seven hundred nanometers. In some such embodiments, the thickness may be not more than four hundred nanometers. Other thicknesses are possible. Underlayers, such as silicon dioxide, may exist between the LN layer and a carrier wafer. In some embodiments, the carrier wafer may include silicon, quartz, silica, LN, sapphire and/or another material. For example, the LN layer may reside on a silicon dioxide underlayer having a thickness of nominally at least two and not more than five micrometers. Other thicknesses, additional layers and/or other layers may be present. Method **700** may also be used in connection with one or more of the techniques described in the above-identified co-pending applications.

[0054] A ridge waveguide is provided from optical material(s) having an electro-optic effect, at **702**. In some embodiments, one or more depressions analogous to depressions **130** and/or **230** may be formed as part of **702**. Thus, **702** may include utilizing lithography and etch(es) to pattern one or more electro-optic materials. Such processing may be performed using techniques analogous to those described in the above-identified co-pending applications. Consequently, the electro-optic material has been formed into at least the ridge waveguide and slab. In some embodiments, multiple ridge waveguides and/or additional structures such as mode converters are also formed at **702**.

[0055] Free surfaces are formed in the slab, at **704**. In some embodiments, **704** includes forming depressions, trenches and/or apertures in the slab. The free surfaces may be formed using lithography and etch(es) of the electro-optic materials. Such processing may be performed using techniques analogous to those described in the above-identified co-pending applications. In some embodiments, **702** and **704** may be performed together. In some embodiments, **704** is performed prior to **702**. In other embodiments, **704** is performed after **702**. As indicated above, the free surfaces are at nonzero angle(s) from the top surface of the slab and mitigate stress in the slab.

[0056] The device being fabricated is annealed at anneal temperature(s) greater than 300 degrees Celsius, at **706**. In some embodiments, optical material **110** is annealed at anneal temperatures greater than 400 degrees Celsius. Optical material **110** may be annealed at anneal temperatures greater than 500 degrees Celsius. In some embodiments, the anneal temperature(s) are greater than 600 degrees Celsius. In some embodiments, the anneal temperature(s) are greater than 700 degrees Celsius. In some embodiments, the anneal temperature(s) are greater than 800 degrees Celsius. In some embodiments, the anneal temperature(s) are greater than 900 degrees Celsius. In some embodiments, the anneal temperature(s) are greater than 1000 degrees Celsius. In some

embodiments, **706** includes performing multiple anneals, at least one of which is at the anneal temperature(s) described herein. The anneal performed at **706** may be performed after **704** has been completed. In some embodiments, the anneal is performed after **702** and **704** are performed.
[0057] Fabrication of the electro-optic device is completed, at **708**. For example, other optical structures may be formed and electrical components fabricated. The individual electro-optic device may also be separated from the wafer (or array of devices being fabricated) at **708**.
[0058] Using method **700**, electro-optic devices such as devices **100**, **200**, **300** and/or **400** may be formed. Thus, the benefits described herein, including but not limited to stress management, may be achieved.
[0059] Although the foregoing embodiments have been described in some detail for purposes of clarity of understanding, the invention is not limited to the details provided. There are many alternative ways of implementing the invention. The disclosed embodiments are illustrative and not restrictive.

Claims

1. An electro-optic device, comprising: at least one optical material having an electro-optic effect and including lithium, the at least one optical material having a slab and a ridge waveguide, the slab having a top surface and a bottom surface, the ridge waveguide having a first height and sidewalls, the slab having a second height less than the first height; an electrode, a portion of the slab being between the ridge waveguide and the electrode; and wherein the slab includes a plurality of free surfaces, the plurality of free surfaces being at a nonzero angle from the top surface of the slab and mitigating stress caused in the at least one optical material during fabrication of the electro-optic device.
2. The electro-optic device of claim 1, wherein the slab and ridge waveguide are treated by an anneal performed after formation of the plurality of free surfaces; and wherein the plurality of free surfaces mitigate stress in the at least one optical material caused by the anneal.
3. The electro-optic device of claim 2, wherein the anneal has an annealing temperature greater than three hundred degrees Celsius.
4. The electro-optic device of claim 1, wherein the at least one optical material includes at least one of lithium niobate or lithium tantalate.
5. The electro-optic device of claim 1, wherein at least one free surface of the plurality of free surfaces is further from the ridge waveguide than the electrode is.
6. The electro-optic device of claim 1, wherein at least one free surface of the plurality of free surfaces is closer to the ridge waveguide than the electrode is.
7. The electro-optic device of claim 6, further comprising: a cladding layer, at least a portion of the electrode residing on the cladding layer.
8. The electro-optic device of claim 6, wherein the free surface is a first edge of the slab; and wherein the plurality of free surfaces includes an additional free surface, the ridge waveguide being between the free surface and the additional free surface, the additional free surface being a second edge of the slab.
9. The electro-optic device of claim 8, wherein the first edge and the second edge are substantially parallel to at least a portion of the ridge waveguide.
10. The electro-optic device of claim 1, wherein the slab has an edge and wherein at least one of the plurality of free surfaces is between the edge of the slab and the ridge waveguide.
11. The electro-optic device of claim 1, wherein the slab resides on a substrate and wherein at least one free surface of the plurality of free surfaces extends from the top surface of the slab to the substrate.
12. The electro-optic device of claim 1, wherein the slab resides on a substrate, the slab has a thickness, and at least one free surface of the plurality of free surfaces extends through the slab a

distance less than the thickness.
13. The electro-optic device of claim 1, wherein the plurality of free surfaces defines at least one aperture in the slab.
14. The electro-optic device of claim 1, wherein the at least one optical material includes an additional ridge waveguide.
15. The electro-optic device of claim 1, wherein the slab includes a trench therein, the trench having a sidewall and being parallel to at least a portion of the ridge waveguide, a free surface of the plurality of free surfaces being the sidewall.
16. An electro-optic device, comprising: at least one optical material having an electro-optic effect and including lithium, the at least one optical material having a slab and a ridge waveguide, the slab having a top surface, a first edge, and a second edge, the first edge and the second edge being substantially parallel to a portion of the ridge waveguide; a plurality of electrodes, the ridge waveguide being between a first electrode and a second electrode of the plurality of electrodes; and a substrate having a plurality of substrate edges, the first edge of the slab being between the ridge waveguide and a first substrate edge of the plurality of substrate edges, the second edge of the slab being between the ridge waveguide and a second substrate edge of the plurality of substrate edges; wherein the first edge and the second edge form a plurality of free surfaces at a nonzero angle from the top surface of the slab and mitigating stress caused in the at least one optical material during fabrication of the electro-optic device.
17. A method for providing an electro-optic device, comprising: providing a ridge waveguide from at least one optical material having an electro-optic effect and including lithium, the at least one optical material having a slab and the ridge waveguide, the slab having a top surface and a bottom surface,, the ridge waveguide having a first height and sidewalls, the slab having a second height less than the first height; and providing, for the slab, a plurality of free surfaces, each of the plurality of free surfaces at a nonzero angle from the top surface of the slab and mitigating stress in the slab; annealing after formation of the plurality of free surfaces, the annealing reducing optical propagation losses; providing an electrode, a portion of the slab being between the ridge waveguide and the electrode; wherein the plurality of free surfaces mitigate stress caused in the at least one optical material during fabrication of the electro-optic device.
18. The method of claim 17, wherein the plurality of free surfaces mitigate at least a portion of the stress in the at least one optical material caused by the annealing.
19. The method of claim 18, wherein the annealing has an annealing temperature greater than three hundred degrees Celsius.
20. The method of claim 17, wherein the at least one optical material includes at least one of lithium niobate or lithium tantalate.