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(54) **THIN-FILM ELECTRO-OPTICAL WAVEGUIDE MODULATOR DEVICE**

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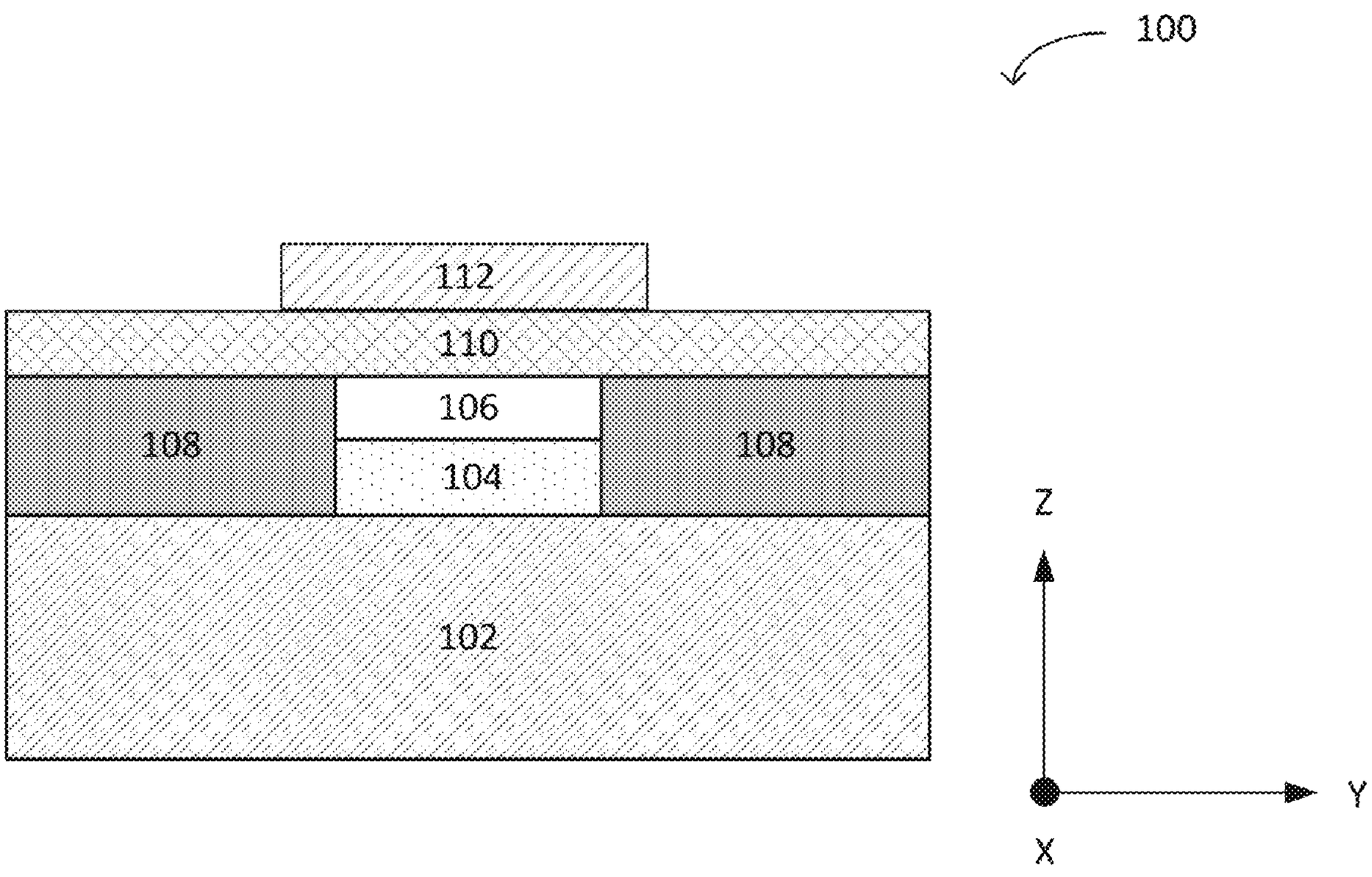
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(57) **ABSTRACT**

An electro-optical waveguide modulator device includes a seed layer on a substrate, the seed layer having a first crystallographic plane aligned with a surface of the seed layer, an electro-optical channel extending in a first direction on the seed layer and having a second crystallographic plane aligned with the surface of the seed layer, an insulator layer on both sides of the electro-optical channel on the substrate in a second direction perpendicular to the first direction, an electrode barrier layer on the electro-optical channel and the insulator layer, and one or more of electrodes extending in the second direction. The seed layer and the insulator layer each comprise material having a refractive index that is lower than the electro-optical channel.



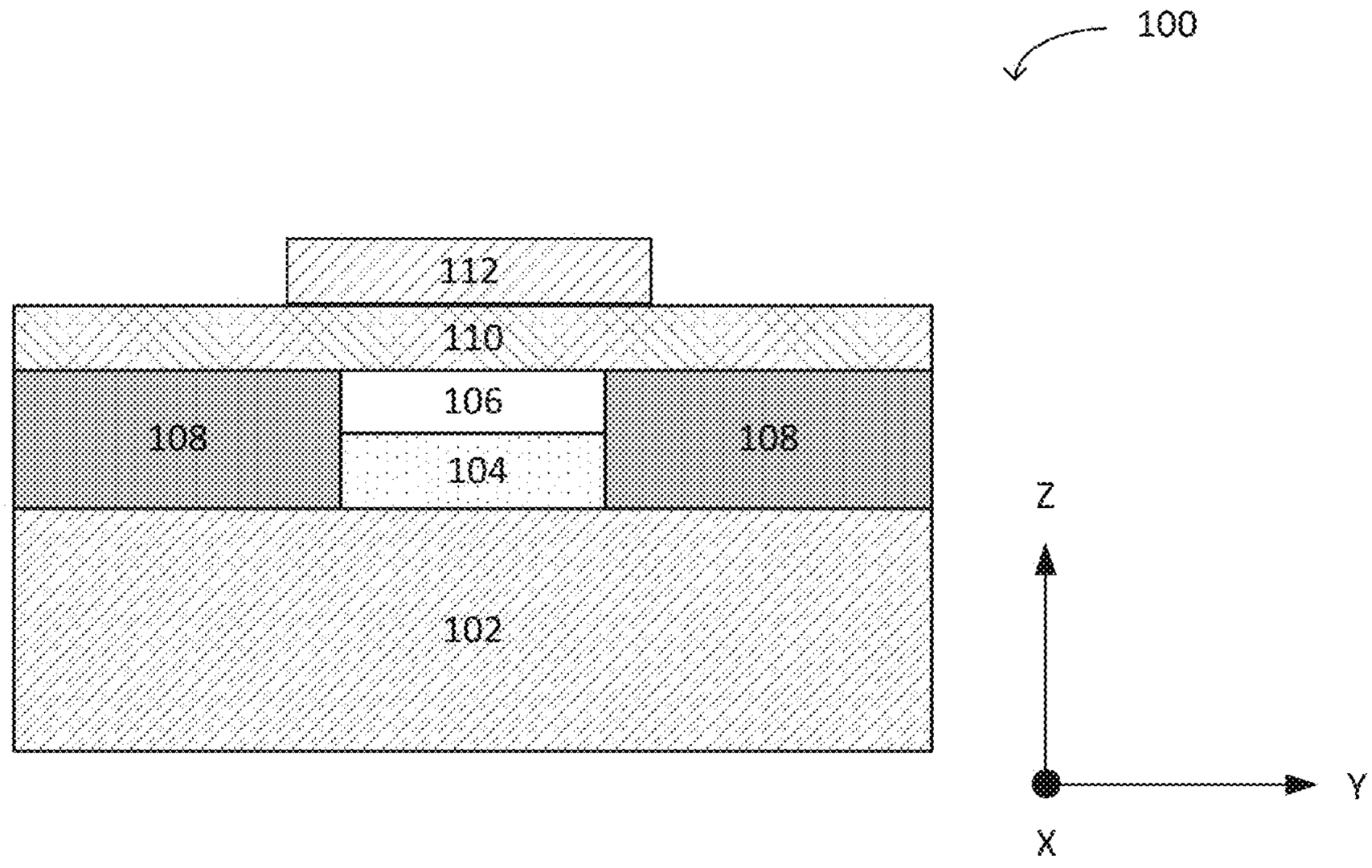


FIG. 1

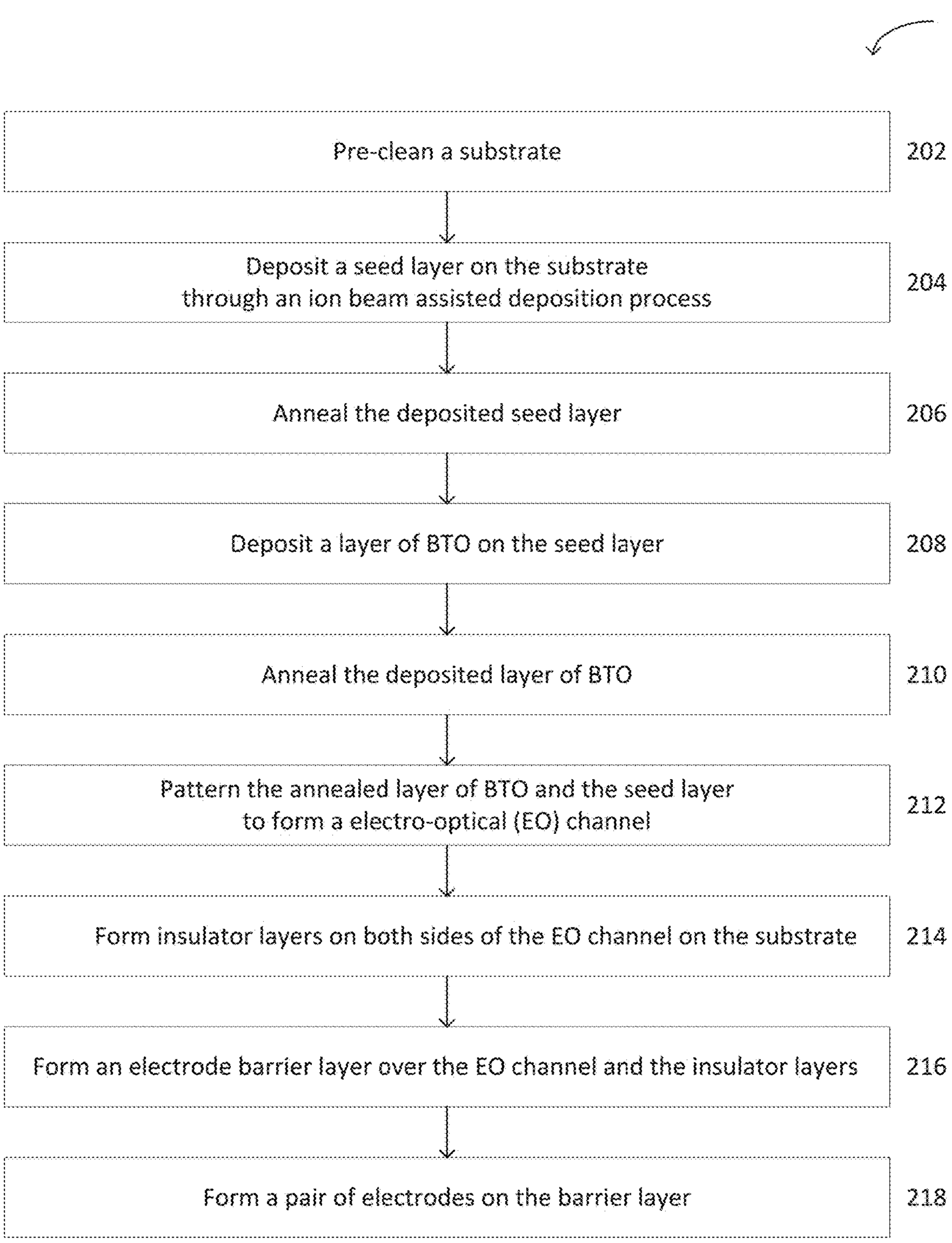

200
Pre-clean a substrate
202
Deposit a seed layer on the substrate through an ion beam assisted deposition process
204
Anneal the deposited seed layer
206
Deposit a layer of BTO on the seed layer
208
Anneal the deposited layer of BTO
210
Pattern the annealed layer of BTO and the seed layer to form a electro-optical (EO) channel
212
Form insulator layers on both sides of the EO channel on the substrate
214
Form an electrode barrier layer over the EO channel and the insulator layers
216
Form a pair of electrodes on the barrier layer
218

FIG. 2

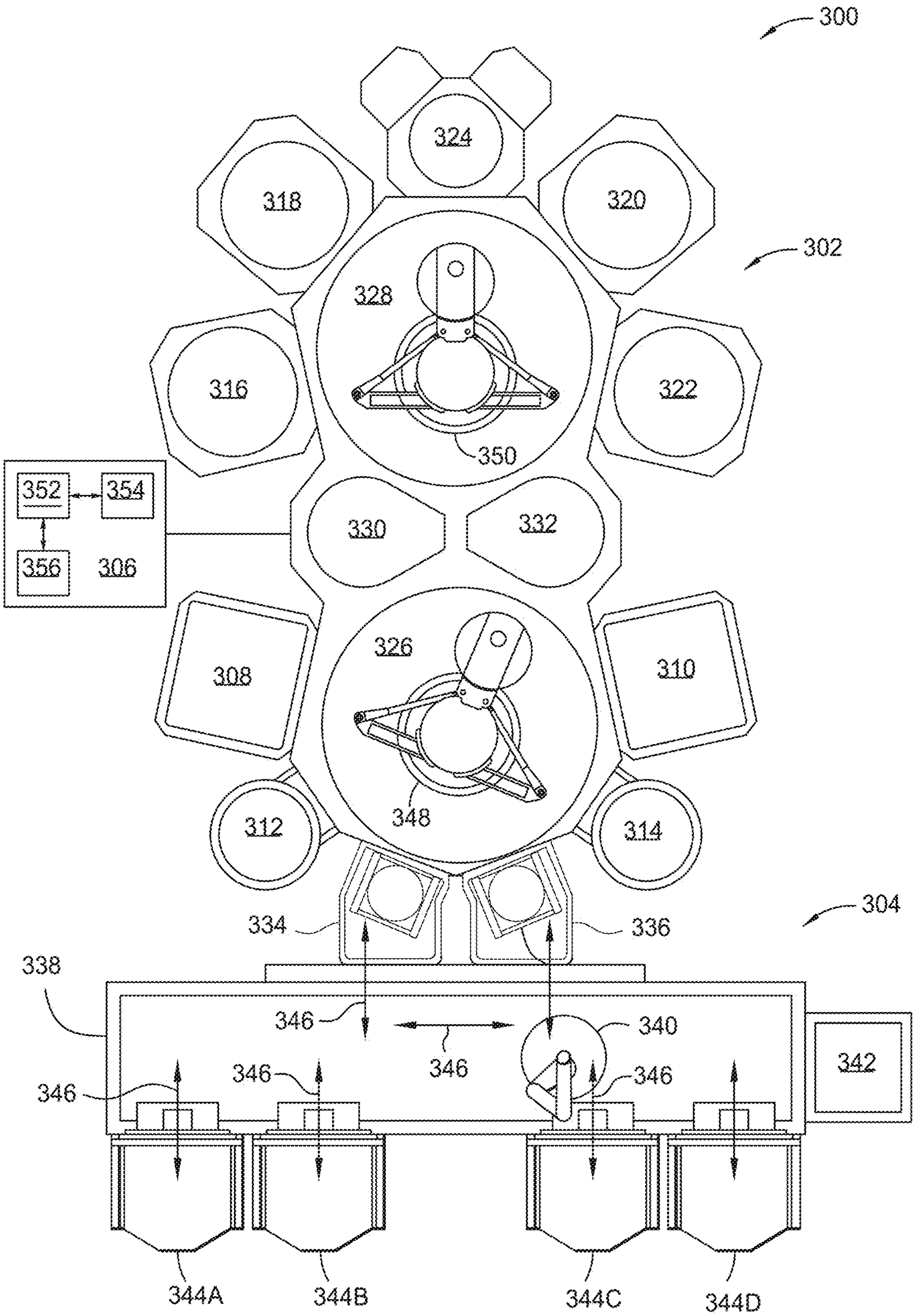

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FIG. 3

THIN-FILM ELECTRO-OPTICAL WAVEGUIDE MODULATOR DEVICE

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Provisional Patent Application Ser. No. 63/045,044, filed on Jun. 27, 2020, which is incorporated by reference herein.

BACKGROUND

Field

[0002] Embodiments of the present disclosure generally relate to electro-optical devices, and more specifically, to thin-film electro-optical waveguide modulator devices integrated in a silicon platform.

Description of the Related Art

[0003] Silicon photonics has become a platform for dense and low-cost integrated photonic circuits for a wide range of applications. Adding an electro-optical (EO) material, such as barium titanate ($BaTiO_3$, BTO) to silicon photonics enables a number of novel active photonic devices, such as modulators and switches, that could reduce power consumption and increase operation speed. Electro-optical devices integrated in a silicon platform, including electro-optical (EO) waveguide phase modulators, can also be key elements in emerging quantum technologies such as all-optical quantum computing using a single photon source and a single photon detector.

[0004] However, the development of architectures for integrated electro-optical devices that are scalable and replicable remains a missing element for progress of near-future quantum technologies.

SUMMARY

[0005] Embodiments of the present disclosure generally relate to an electro-optical waveguide modulator device. The electro-optical device includes a seed layer on a substrate, the seed layer having a first crystallographic plane aligned with a surface of the seed layer, an electro-optical channel extending in a first direction on the seed layer and having a second crystallographic plane aligned with the surface of the seed layer, an insulator layer on both sides of the electro-optical channel on the substrate in a second direction perpendicular to the first direction, an electrode barrier layer on the electro-optical channel and the insulator layer, and one or more of electrodes extending in the second direction. The seed layer and the insulator layer each comprise material having a refractive index that is lower than the electro-optical channel.

[0006] Embodiments of the present disclosure also relate to a method of forming a substrate having a crystallographically aligned surface. The method includes depositing a seed layer on a substrate through a process selected from an ion beam assisted deposition process and a pulsed laser deposition process, and annealing the deposited seed layer to align a first crystallographic plane of the seed layer with a surface of the seed layer.

[0007] Embodiments of the present disclosure further relate to a method of forming an electro-optical waveguide modulator device. The method includes depositing a seed layer on a substrate through a process selected from an ion beam assisted deposition process and a pulsed laser deposition process, annealing the deposited seed layer to align a first crystallographic plane of the seed layer with a surface of the seed layer, depositing a layer of an electro-optical material on the seed layer, annealing the deposited layer of the electro-optical material to align a second crystallographic plane of the layer of the electro-optical material with the surface of the seed layer, and patterning the layer of the electro-optical material to form an electro-optical channel extending in a first direction on the seed layer. The seed layer comprises material having a refractive index that is lower than the electro-optical channel.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] So that the manner in which the above recited features of the present disclosure can be understood in detail, a more particular description of the disclosure, briefly summarized above, may be had by reference to embodiments, some of which are illustrated in the appended drawings. It is to be noted, however, that the appended drawings illustrate only exemplary embodiments and are therefore not to be considered limiting of its scope, and may admit to other equally effective embodiments.

[0009] FIG. **1** is a schematic diagram of an electro-optical (EO) waveguide modulator according to one embodiment.

[0010] FIG. **2** illustrates a flow diagram of a processing sequence used to fabricate an EO waveguide according to one embodiment.

[0011] FIG. **3** is a schematic diagram of a substrate processing system according to one embodiment.

[0012] To facilitate understanding, identical reference numerals have been used, where possible, to designate identical elements that are common to the figures. It is contemplated that elements and features of one embodiment may be beneficially incorporated in other embodiments without further recitation.

DETAILED DESCRIPTION

[0013] Embodiments of the present disclosure generally relate to electro-optical (EO) devices, and more specifically, to thin-film electro-optical (EO) waveguide modulator devices integrated in a silicon platform.

[0014] In the embodiments described herein, thin film electro-optical (EO) waveguide phase modulators integrated in a silicon platform are of high quality having an EO material with crystallographic orientations aligned such that the EO material has a high electro-optic coefficient (e.g., Pockel Coefficient>700 pm/V), leading to high sensitivity to an applied electric field. The alignment of crystallographic orientations of the EO material and an underlying seed layer formed on a substrate is performed by annealing processes, such as a laser anneal process, at high temperatures as crystallographic orientations of the EO material and the seed layer as deposited are not aligned. The anneal processes are performed without breaking vacuum while the substrate is transferred between a pre-clean chamber for pre-cleaning the substrate and a process chamber for depositing the EO material and/or the seed layer.

[0015] Such thin film electrode waveguide phase modulators can have different refractive indices depending on the strength of an applied electric field to modulate phases of incident light, and thus, when combined with optical fibers, or single photon sources and single photon detectors, can be

used as enabling elements in the next generation optical communications and quantum technologies.

[0016] Conventionally, electro-optical (EO) devices are fabricated on bulk lithium niobate ($LiNbO_3$) single crystals and are combined with other optical and electronic components due to their ability to be grown as large and high quality single crystals. Recent developments towards integrated and compact optical systems on silicon call for fabrication and characterization of thin film optical and electro-optical (EO) components (e.g., waveguides, sources, modulators, and detectors) with ferroelectric oxide materials having much higher electro-optic coefficients, such as barium titanate ($BaTiO_3$, BTO), than $LiNbO_3$. In the embodiments described herein, examples of thin film electro-optical (EO) waveguide phase modulators formed on a silicon based platform are described. However, the present disclosure is not limited to use in this particular application and can be applied to other thin film electro-optical (EO) components.

[0017] FIG. **1** is a schematic diagram of an electro-optical (EO) waveguide modulator **100** according to one or more embodiments. FIG. **2** illustrates a flow diagram of a processing sequence **200** used to fabricate an EO waveguide modulator **100** according to one or more embodiments. The processing sequence **200** to fabricate the EO waveguide modulator **100** on a substrate **102** are performed in a substrate processing system, such as a cluster tool **300** described below in conjunction with FIG. **3**.

[0018] As used herein, the term "substrate" refers to a layer of material that serves as a basis for subsequent processing operations and includes a surface to be disposed for forming the EO waveguide modulator **100** thereon. The substrate **102** may be a (001) silicon wafer, silicon oxide, strained silicon, silicon germanium, doped or undoped polysilicon, doped or undoped silicon wafers, patterned or non-patterned wafers silicon on insulator (SOI), carbon doped silicon oxides, silicon nitride, indium phosphide, germanium, gallium arsenide, gallium nitride, quartz, fused silica, glass, or sapphire. Moreover, the substrate **102** is not limited to any particular size or shape. The substrate **102** can be a round wafer having a 200 mm diameter, a 300 mm diameter or other diameters, such as 450 mm, among others. The substrate **102** can also be any polygonal, square, rectangular, curved or otherwise non-circular workpiece, such as a polygonal glass substrate.

[0019] In block **202** of the processing sequence **200**, a surface of the substrate **102** is pre-cleaned to remove native oxides or other sources of contaminants prior to fabricating the EO waveguide modulator **100** thereon. For example, the substrate **102** may be pre-cleaned by a wet etch process using a dilute hydrofluoric acid (dHF) etching solution at a temperature between about 24° C. and about 50° C. Alternatively, the substrate **102** may be pre-cleaned by a vapor etch process in a pre-clean chamber, such as a SICONI™ chamber, which is available from Applied Materials, Inc., Santa Clara, Calif. The pre-clean gas may be a mixture of nitrogen (N_2) and hydrogen (H_2) gases. A purge gas or carrier gas, such as argon (Ar), can also be added to the pre-clean gas mixture.

[0020] The EO waveguide modulator **100** includes a seed layer **104** formed on the substrate **102**. The seed layer **104** is formed of magnesium oxide (or magnesia, MgO) in the X-Y plane and has a thickness in the Z-direction of between about 0.25 nm and about 15 nm. The seed layer **104** is formed to have the (001) crystallographic plane parallel to the X-Y plane that is aligned with the crystallographic plane of the underlying substrate **102** (e.g., (001) silicon wafer). In some embodiments, the seed layer **104** is formed by depositing MgO on the pre-cleaned substrate **102** by a physical vapor deposition (PVD) process with a plasma based on a mixture gas including argon (Ar) and oxygen (**02**) gases at room temperature, in which a target housed in the PVD chamber is comprised of MgO. In block **204** of the processing sequence **200**, the seed layer **104** is formed by other chemical deposition processes, such as a chemical vapor deposition (CVD) process, metal organic chemical vapor deposition (MOCVD), an atomic layer deposition (ALD) process, or a molecular beam epitaxy (MBE) process. However, the seed layer **104** as deposited may include multiple domains of crystallites of varying sizes and crystallographic orientations, such as (**200**), (**220**), and (**222**) of the body-centered cubic (BCC) or the face-centered cubic (FCC) crystal lattice structure, and is thus further treated such that the seed layer **104** includes larger domains of MgO crystallites having a (001) crystallographic plane parallel to the X-Y plane. For example, MgO may be further deposited on the substrate **102** through an ion beam assisted deposition (IBAD) process. In an IBAD process, as MgO is deposited, MgO is simultaneously etched by a beam of high energy (about 300 eV and about 2000 eV) ions such as argon ions (Ar^+) or oxygen ions (0+) depending on the crystallographic orientations of the MgO crystallites. When an ion beam is incident at a 45° angle with respect to the surface of the seed layer **104** (i.e., the X-Y plane), crystallites having a (001) crystallographic plane (out-of-plane to the ion beam) and a (101) crystallographic plane (in-plane and parallel to the ion beam) are preferentially formed while crystallites having other planes are removed. In some embodiments, the seed layer **104** is formed via a pulsed laser deposition (PLD) process.

[0021] In block **206** of the processing sequence **200**, the seed layer **104** may be further annealed to recreate crystalline structures from domains that are not yet aligned with the crystallographic plane (001), by a laser anneal process, a rapid thermal anneal (RTA) process, a furnace anneal process, or an anneal process in a vacuum anneal chamber. In the laser anneal process, the surface of the seed layer **104** is irradiated in an atmosphere containing oxygen (O_2), hydrogen (H_2), and nitrogen (N_2) with a purge gas or carrier gas, such as argon (Ar), for a duration of between about 0.1 seconds and about 24 hours at a temperature of between about 700° C. and about 1100° C. at atmospheric pressure. In the RTA process, the anneal process lasts for a duration of between about 0.1 seconds and about 24 hours in an atmosphere containing oxygen (O_2), hydrogen (H_2), and nitrogen (N_2) with a purge gas or carrier gas, such as argon (Ar) at a temperature of between about 200° C. and about 1000° C. at a high vacuum pressure. The anneal process may be a furnace anneal in a rapid thermal processing (RTP) chamber, in which the seed layer **104** is heated to a temperature of between about 200° C. and about 1000° C. in an atmosphere containing oxygen (**02**), hydrogen (H_2), and nitrogen (N_2) with a purge gas or carrier gas, such as argon (Ar) for between about 0.1 seconds and about 24 hours at a high vacuum. The anneal process may be performed in a vacuum anneal or high pressure chamber at a temperature of about

1000° C. for a time duration of between about 5 minutes and about 90 minutes with a purge gas or carrier gas, such as argon (Ar).

[0022] In another embodiment, which can be combined with other embodiments described herein, the deposition process in block **204** and the anneal process in block **206** are repeated until a desired thickness of the seed layer **104** having a desired domain size of MgO crystallites having crystallographic plane (001) is achieved.

[0023] The EO waveguide modulator **100** further includes an EO channel **106** formed in the X-direction on the (001) crystallographic plane of the seed layer **104**. The EO channel **106** defines a waveguide region of the EO waveguide modulator **100**. The EO channel **106** is formed of material exhibiting a Pockels effect (also referred to as linear EO effect) that changes the refractive index proportionally to an electric field applied to the material. In some embodiments, the EO channel **106** is formed of barium titanate ($BaTiO_3$, BTO) with the c-axis of BTO oriented in the Z-direction. Bulk BTO has the largest Pockels coefficient (>1000 pm/V) among well-known materials. The EO channel **106** has a width in the Y-direction of between about 4 nm and about 500 nm, and a thickness in the Z-direction of between about 100 nm and about 300 nm. The EO channel **106** is fabricated by forming a layer of BTO on the seed layer **104** and patterning the layer of BTO on the seed layer **104**. In block **208** of the processing sequence **200**, the layer of BTO may be formed by deposition processes, such as a PVD process, a CVD process, or an ALD process, or epitaxially grown. In block **210** of the processing sequence **200**, the layer of BTO as deposited may be annealed, substantially similarly to the annealing processes in block **206**, to form large domains of BTO crystallites having a (001) crystallographic plane in the X-Y plane (i.e., the c-axis along the Z-axis). In some embodiments, the EO channel **106** is formed of barium strontium titanate (BaO_4SrTi, BSTO). In another embodiment, which can be combined with other embodiments described herein, the deposition process in block **208** and the anneal process in block **210** are repeated until a desired thickness of the seed layer **104** having a desired domain size of BTO crystallites having crystallographic plane (001) is achieved.

[0024] In block **212** of the processing sequence **200**, the layer of BTO along with the underling seed layer **104** is etched to form the EO channel **106**.

[0025] The lattice mismatch between cubic MgO (a=4.2313 Å at 300 K) and tetragonal BTO (a=3.992 Å, c=4.036 Å, at 300 K) is quite large. However, MgO is often used as the seed layer **104** for its low refractive index (about 1.7 at 1.55 μm wavelength) and optical transparency. The seed layer **104** optically separates the EO channel **106** from an underlying silicon substrate **102**, as the low refractive index of the seed layer **104** (that is lower than the refractive index of the EO channel **106**, which is about 2.3 when no electric field applied at 1.55 μm wavelength) insures confinement of light in the Z-direction within the EO channel **106**.

[0026] In some embodiments, the seed layer **104** is formed of strontium titanate ($SrTiO_3$, STO), and the EO channel **106** is formed of lanthanum titanate ($La_2Ti_2O_7$, LTO).

[0027] The EO waveguide modulator **100** further includes insulator layers **108** on the substrate **102** on both sides of the EO channel **106** in the X-direction. The insulator layers **108** may be formed of dielectric material having low refractive index, such as silicon oxide (SiO_2, refractive index of about 1.4 at 1.55 μm wavelength), silicon nitride (Si_3N_4, refractive index of about 2.0 at 1.55 μm wavelength), low-k, ultra-low-k, or extreme-low-k dielectric materials, SiCH, SiCNH, SiCONH, black diamond, porous or airgap materials. In block **214** of the processing sequence **200**, the insulator layers **108** are formed by depositing a blanket layer of the dielectric material on the exposed surface of the seed layer **104** and the EO channel **106** by deposition processes, such as a PVD process, a CVD process, or an ALD process, and subsequently partially etching back or chemically polishing the blanket layer of the dielectric material, such that the EO channel **106** is exposed and planarized with the insulator layers **108**.

[0028] Over the EO channel **106** and the insulator layers **108**, the EO waveguide modulator **100** further includes an electrode barrier layer **110**. The electrode barrier layer **110** is formed of material selected from tantalum nitride (TaN), titanium nitride (TiN), titanium (Ti), and tantalum oxide (Ta_2O_5). The barrier layer **110** has a thickness in the Z-direction of between about 0.25 nm and about 15 nm. In block **216** of the processing sequence **200**, the electrode barrier layer **110** may be formed by deposition processes, such as a PVD process, a CVD process, or an ALD process.

[0029] The EO waveguide modulator **100** further includes one or more of coplanar electrodes **112** extending in the Y-direction formed on the sides of the EO channel **106**. The electrodes **112** are formed of nickel (Ni), tungsten (W), ruthenium (Ru), aluminum (Al), molybdenum (Mo), copper (Cu), or cobalt (Co). Each of the electrodes **112** has a width in the Y-direction of between about 0.4 nm and about 500 nm, and a thickness in the Z-direction between about 1 nm and about 1000 nm, for example, about 100 nm. When a DC or low-frequency voltage is applied to the electrodes **112**, the refractive index of the EO channel **106** changes, resulting in modulation of phase of light propagating through the waveguide region of the EO channel **106**. In block **218** of the processing sequence **200**, the electrodes **112** are formed by depositing a layer of metal such as nickel (Ni), tungsten (W), ruthenium (Ru), aluminum (Al), molybdenum (Mo), copper (Cu), or cobalt (Co) by deposition processes, such as a PVD process, a CVD process, or an ALD process, patterning the deposited layer of metal. The electrodes **112** may be annealed, substantially similarly to the annealing processes in block **206**.

[0030] FIG. **3** illustrates a substrate processing system **300** in which the EO waveguide modulator **100** may be fabricated according to one or more embodiments. Examples of the substrate processing system **300** are the ENDURA® system and the Centura® system, commercially available from Applied Materials, Inc. of Santa Clara, Calif. Alternatively, other substrate processing systems may be also be modified in accordance with the present disclosure.

[0031] The substrate processing system **300** includes a vacuum-tight processing platform **302**, a factory interface **304**, and a controller **306**. Further, the substrate processing system **300** may also be referred to as a cluster tool or multi-chamber processing system.

[0032] The processing platform **302** includes one or more processing chambers. For example, the processing platform **302** may include processing chambers **308**, **310**, **312**, **314**, **316**, **318**, **320**, **322**, **324**. Further, the processing platform **302** includes one or more transfer chambers. For example, as is illustrated in FIG. **3**, the processing platform **302** includes transfer chambers **326**, **328**. The processing platform **302**

may also include one or more pass-through chambers that allow a substrate to be transferred between transfer chambers. For example, pass-through chambers **330**, **332** may allow a substrate to be transferred between the transfer chambers **326** and **328**.

[0033] The processing platform **302** may also include one or more load lock chambers. For example, as is illustrated in FIG. **3**, the processing platform **302** includes load lock chambers **334**, **336**. The load lock chambers **334**, **336** may be pumped down to be operated under a vacuum before transferring substrates from the factory interface **304** to the transfer chamber **326**.

[0034] The factory interface **304** includes one or more docking stations **338**, one or more factory interface robots **340**, and a charging station **342**. The docking stations **338** include one or more front opening unified pods (FOUPs) **344**A, **344**B, **344**C, **344**D. The factory interface robot **340** may be capable of linear and rotational movement illustrated by arrows **346**. Further, the factory interface robot **340** may transfer substrates between the FOUPs **344**A-D, the load lock chambers **334**, **336**, and the charging station **342**. The substrate may be transferred by the factory interface robot **340** from the charging station **342** to one or more of the load lock chambers **334**, **336** for processing the substrate within the processing platform **302**. Subsequently, the processed substrate may be transferred from the load lock chambers **334**, **336** to one of the FOUPs **344**A-D by the factory interface robot **340**.

[0035] The transfer chamber **326** includes a transfer robot **348**. The transfer robot **348** transfers substrates to and from the load lock chambers **334**, **336** to and from the processing chambers **308**, **310**, **312**, **314**, and to and from pass-through chambers **330**, **332**. The pass-through chambers **330** and **332** may be utilized to maintain vacuum conditions while allowing substrates to be transferred within the processing platform **302** between the transfer chambers **326** and **328**. The transfer chamber **328** includes a transfer robot **350**. The transfer robot **350** transfers substrates between the pass-through chambers **330**, **332** and the processing chambers **316**, **318**, **320**, **322**, **324**, and among the processing chambers **316**, **318**, **320**, **320**, **322**, **324**.

[0036] The processing chambers **308**, **310**, **312**, **314**, **316**, **318**, **320**, **322**, **324** may be configured in any manner suitable to process a substrate. For example, the processing chambers **308**, **310**, **312**, **314**, **316**, **318**, **320**, **322**, **324** may be configured to deposit one or more material layers and apply one or more cleaning processes to a substrate.

[0037] The processing chambers, e.g., the processing chambers **308**, **310**, **312**, **314** may be configured to perform a pre-clean process to eliminate contaminants and/or degas volatile components from a substrate prior to transferring the substrate into another process chamber. The processing chamber **322** may be configured to deposit one or more layers on a substrate. Further, the processing chamber **324** may be configured to position a mask (e.g., a shadow mask) on a substrate before the substrate is transferred to one or more of the processing chambers **316**, **318**, **320**, **322** and unload a mask from a substrate after processing within one or more of the processing chambers **316**, **318**, **320**, **322**. The processing chambers **316**, **318**, **320**, **322** may be configured to deposit materials using a deposition process such as chemical vapor deposition (CVD), atomic layer deposition (ALD), metalorganic chemical vapor deposition (MOCVD), plasma-enhanced chemical vapor deposition (PECVD), and physical vapor deposition (PVD) (e.g., sputtering process or evaporation process), among others. The processing chambers **316**, **318**, **320** can be Rapid Thermal Annealing (RTA) chambers, or Rapid Thermal Process (RTP) chambers, that can anneal substrates at vacuum or near vacuum pressures. An example of an RTA chamber is a RADIANCE™ chamber, commercially available from Applied Materials, Inc., Santa Clara, Calif. Alternatively, the processing chambers **316**, **318**, **320** can be W×Z™ deposition chambers capable of performing high temperature CVD deposition, annealing processes, or in situ deposition and annealing processes.

[0038] The controller **306** is configured to control the components of the substrate processing system **300**. The controller **306** may be any suitable controller for controlling the operation of one or more of the processing chambers **308**, **310**, **312**, **314**, **316**, **318**, **320**, **322**, **324**, the transfer chambers **326** and **328**, pass-through chambers **330**, **332**, and the factory interface **304**. For example, the controller **306** may be configured to control the operation of the transfer robot **348**, the transfer robot **350**, and the factory interface robot **340**. The controller **306** includes a central processing unit (CPU) **352**, a memory **354**, and support circuits **356**. The CPU **352** may be any general purpose computer processor that may be utilized in an industrial environment. The support circuits **356** are coupled to the CPU **352** and may include cache, clock circuits, input/output subsystems, power supplies and the like. Software routines may be stored within the memory **354**. The software routines may be executed by the CPU **352** and thus be adapted to cause various components within the substrate processing system **300** to perform one or more of the methods described herein. Alternatively, or additionally, one or more of the software routines may be executed by a second CPU (not illustrated). The second CPU may be part of the controller **306** or remote from the controller **306**.

[0039] One or more processing chambers **308**, **310**, **312**, **314**, **316**, **318**, **320**, **322**, **324**, one or more transfer chambers **326** and **328**, one or more pass-through chambers **330**, **332**, and/or the factory interface **304** may have a dedicated controller or controllers (not shown) configured to control at least a portion of the methods disclosed herein. The dedicated controllers may be configured similar to the controller **306** and may be coupled with the controller **306** to synchronize processing of a substrate within the substrate processing system **300**.

[0040] In the embodiments described herein, thin film electro-optical (EO) waveguide phase modulators integrated in a silicon platform are of high quality having an electro-optical material with crystallographic orientations aligned. Such thin film electrode waveguide phase modulators, when combined with optical fibers, or single photon sources and single photon detectors, can be used as enabling elements in the next generation optical communications and quantum technologies.

[0041] While the foregoing is directed to embodiments of the present disclosure, other and further embodiments of the disclosure may be devised without departing from the basic scope thereof, and the scope thereof is determined by the claims that follow.

What is claimed is:

1. An electro-optical waveguide modulator device, comprising:

a seed layer on a substrate, the seed layer having a first crystallographic plane aligned with a surface of the seed layer;

an electro-optical channel extending in a first direction on the seed layer and having a second crystallographic plane aligned with the surface of the seed layer;

an insulator layer on both sides of the electro-optical channel on the substrate in a second direction perpendicular to the first direction;

an electrode barrier layer on the electro-optical channel and the insulator layer; and

one or more of electrodes extending in the second direction, wherein

the seed layer and the insulator layer each comprise material having a refractive index that is lower than the electro-optical channel.

2. The electro-optical waveguide modulator device according to claim **1**, wherein the seed layer comprises magnesium oxide (MgO) having (001) crystallographic plane aligned with the surface of the seed layer.

3. The electro-optical waveguide modulator device according to claim **2**, wherein the electro-optical channel comprises material selected from barium titanate ($BaTiO_3$) and and barium strontium titanate (BaO_4SrTi, BSTO) having (001) crystallographic plane aligned with the surface of the seed layer.

4. The electro-optical waveguide modulator device according to claim **1**, wherein the seed layer has a thickness of between about 0.25 nm and about 5 nm.

5. The electro-optical waveguide modulator device according to claim **1**, wherein the electro-optical channel has a width in the second direction of between about 4 nm and about 500 nm, and a thickness of between about 100 nm and about 300 nm.

6. The electro-optical waveguide modulator device according to claim **1**, wherein the seed layer comprises strontium titanate ($SrTiO_3$).

7. The electro-optical waveguide modulator device according to claim **1**, wherein the electro-optical channel comprises lanthanum titanate ($La_2Ti_2O_7$).

8. A method of forming a substrate having a crystallographically aligned surface, comprising:

depositing a seed layer on a substrate through a process selected from an ion beam assisted deposition process and a pulsed laser deposition process; and

annealing the deposited seed layer to align a first crystallographic plane of the seed layer with a surface of the seed layer.

9. The method according to claim **8**, wherein the annealing of the deposited seed layer comprises a laser anneal process.

10. The method according to claim **8**, wherein the seed layer comprises magnesium oxide (MgO) having (001) crystallographic plane aligned with the surface of the seed layer.

11. The method according to claim **8**, wherein the seed layer has a thickness of between about 0.25 nm and about 5 nm.

12. A method of forming an electro-optical waveguide modulator device, comprising:

depositing a seed layer on a substrate through a process selected from an ion beam assisted deposition process and a pulsed laser deposition process;

annealing the deposited seed layer to align a first crystallographic plane of the seed layer with a surface of the seed layer;

depositing a layer of an electro-optical material on the seed layer;

annealing the deposited layer of the electro-optical material to align a second crystallographic plane of the layer of the electro-optical material with the surface of the seed layer; and

patterning the layer of the electro-optical material and the seed layer to form an electro-optical channel extending in a first direction on the seed layer, wherein the seed layer comprises material having a refractive index that is lower than the electro-optical channel.

13. The method according to claim **12**, wherein

the annealing of the deposited seed layer comprises a laser anneal process, and

the annealing of the deposited layer of the electro-optical material comprises a laser anneal process.

14. The method according to claim **12**, wherein the depositing of the seed layer and the annealing of the deposited seed layer are repeated.

15. The method according to claim **12**, wherein the depositing of the layer of the electro-optical material and the annealing of the deposited layer of the electro-optical material are repeated.

16. The method according to claim **12**, further comprising:

pre-cleaning the substrate prior to the depositing of the seed layer on the substrate.

17. The method according to claim **12**, further comprising:

depositing an insulator layer on either sides of the electro-optical channel on the substrate in a second direction perpendicular to the first direction;

an electrode barrier layer on the electro-optical channel and the insulator layer; and

one or more of electrodes extending in the second direction, wherein

the seed layer and the insulator layer each comprise material having a refractive index that is lower than the electro-optical channel.

18. The method according to claim **12**, wherein

the seed layer comprises magnesium oxide (MgO) having (001) crystallographic plane aligned with the surface of the seed layer, and

the electro-optical channel comprises material selected from barium titanate ($BaTiO_3$) and barium strontium titanate (BaO_4SrTi, BSTO) having (001) crystallographic plane aligned with the surface of the seed layer.

19. The method according to claim **12**, wherein

the seed layer has a thickness of between about 0.25 nm and about 5 nm, and

the electro-optical channel has a width of between about 4 nm and about 500 nm, and a thickness of between about 100 nm and about 300 nm.

20. The method according to claim **12**, wherein

the seed layer comprises strontium titanate ($SrTiO_3$), and the electro-optical channel comprises lanthanum titanate ($La_2Ti_2O_7$).

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