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(54) Title: TWIN-FREE, SMALL LATTICE PARAMETER PEROVSKITE PSEUDO-SUBSTRATES ON SILICON CARRIER WAFERS AND FABRICATION METHODS THEREFOR

(57) Abstract: A new material that may be embodied in a wafer. The wafer may include a silicon (Si) substrate. The wafer may also include a strain control layer formed on the Si substrate. The strain control layer may include strontium titanate (STO) or calcium titanate (CTO). The wafer may further include a twin-free perovskite oxide layer formed on the strain control layer and having a residual in-plane biaxial tensile strain imposed at least in part by the strain control layer. The twin-free perovskite layer may include a single crystal rare earth aluminate.

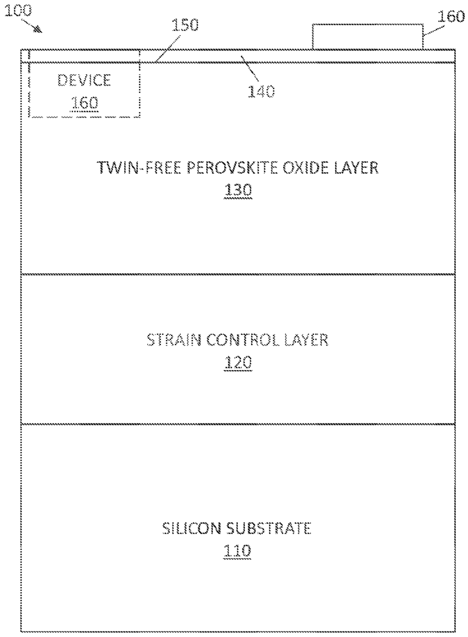

FIG. 1

WO 2025/155387 A1

TWIN-FREE, SMALL LATTICE PARAMETER PEROVSKITE PSEUDO-SUBSTRATES ON SILICON CARRIER WAFERS AND FABRICATION METHODS THEREFOR

TECHNICAL FIELD

[0001] Various embodiments of the present technology generally relate to fabrication of single crystal oxide layers on silicon (Si) substrates. More specifically, some embodiments of the present technology relate to epitaxial lanthanum aluminate on Si wafers and methods of fabricating the same.

BACKGROUND

[0002] A commonly used substrate material for growing perovskite oxide is lanthanum aluminate ($LaAlO_3$ or LAO). Its main distinction is its small lattice parameter of 3.792 Å compared to another other common perovskite substrate, strontium titanate ($SrTiO_3$, or STO), with a lattice parameter of 3.905 Å. The small lattice parameter of LAO can be particularly important for growing epitaxial films of the high temperature superconductor yttrium barium copper oxide ($YBa_2Cu_3O_7$, YBCO) and its relatives in the so-called a-axis orientation for making devices such as Josephson junctions. While LAO is available in wafers up to 3” in diameter, its main drawback is the occurrence of twinning. Twinning causes grain boundaries to form in the LAO crystal when cooled from above about 550 °C to below it due to the cubic to rhombohedral structural phase transition intrinsic in LAO. This twinning is detrimental to any film grown on top of LAO and eliminating twinning in LAO is needed for applications requiring epitaxial films.

[0003] The size limitations of LAO wafers is one challenge that needs to be addressed. Being able to grow LAO on silicon (Si)—which is readily available as large wafers (up to 12” diameter)—can overcome the wafer size limitations, which may be needed in certain industrial applications. There are other oxide substrates with a lattice parameter in between LAO and STO that have been developed but these are not as commonly used, and their wafer sizes are even smaller than those currently available for LAO.

[0004] The surface termination of LAO also appears to be important. LAO by itself has a temperature dependent surface termination. It switches from LaO-terminated at temperatures above 250 °C to AlO_2-terminated at temperatures below that. This may affect the growth process of certain materials when using LAO as a substrate. In a known process, twin-free LAO was formed on Si using an STO buffer, but neither control of the lattice parameter of the LAO layer, nor the surface termination LAO, was achieved.

[0005] Accordingly, a need exists for technology that overcomes the problems demonstrated above, as well as one that provides additional benefits. The examples provided herein of some prior or related devices, systems and methods, and their associated limitations, are intended to be illustrative and not exclusive. Other limitations of existing or prior systems will become apparent to those of skill in the art upon reading the following detailed description.

SUMMARY

[0006] Embodiments of the present technology may provide a wafer off LAO with residual in-plane biaxial tensile strain grown on a silicon carrier wafer, as well as the process for making such a wafer. The residual strain is used to completely eliminate the twinning problem in single crystal LAO or relaxed LAO films. The residual strain is imposed by a strain control buffer layer that is in between the Si and the LAO layer. By controlling the elastic energy stored in the strain control layer, one can additionally control the lattice parameter of the top LAO layer, varying it over a certain limited range. The LAO layer composition is also adjusted during growth to naturally produce a specific excess amount of either La or Al such that the surface termination of LAO can be guaranteed at any temperature.

[0007] Additionally, embodiments of the present technology may provide a fabrication process for making a wafer of single crystal oxide on a silicon carrier substrate. The top oxide layer has a small lattice parameter (<3.9 Å) that is adjustable. Such wafers are needed for growing certain materials like high temperature superconductors over a large area. Several other functional oxide materials such as magnetic oxides with out of plane magnetization can also be readily grown on silicon using wafers according to the present technology.

[0008] A first aspect of the disclosure provides a new material. The material may be embodied in a wafer. The wafer may include a silicon (Si) substrate. The wafer may also include a strain control layer formed on the Si substrate. The strain control layer may include strontium titanate (STO) or calcium titanate (CTO). The wafer may further include a twin-free perovskite oxide layer formed on the strain control layer and having a residual in-plane biaxial tensile strain imposed at least in part by the strain control layer. The twin-free perovskite layer may include a single crystal rare earth aluminate.

[0009] A second aspect of the disclosure provides a method or process for making the new material of the first aspect of the disclosure. The method or process may be a method for fabricating the wafer according to the first aspect. The method may include the step of

depositing, on a silicon (Si) substrate, a strain control layer including STO or CTO. The method may also include the step of depositing, on the strain control layer, a twin-free perovskite oxide layer including a single crystal rare earth aluminate and having a residual in-plane biaxial tensile strain imposed at least in part by the strain control layer.

[0010] Embodiments of the present technology shown and described herein may enable, among other things, commercial and practical improvements to oxide (e.g., LAO) on silicon wafers and associated fabrication methods to thereby realize more efficient and effective fabrication of useful devices and materials on larger surface area substrates above those achievable using presently known techniques, while simultaneously decreasing per area costs of known processes for growing oxides like LAO directly on Si.

[0011] While multiple embodiments are disclosed, still other embodiments of the present invention will become apparent to those skilled in the art from the following detailed description, which shows and describes illustrative embodiments of the invention. As will be realized, the invention is capable of modifications in various aspects, all without departing from the scope of the present invention. Accordingly, the drawings and detailed description are to be regarded as illustrative in nature and not restrictive.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] Embodiments of the present technology will be described and explained through the use of the accompanying drawings.

[0013] FIG. 1 depicts a cross-sectional view of a wafer according to some embodiments of the present technology.

[0014] FIG. 2 depicts a flowchart of a method for manufacturing a wafer, according to some embodiments of the present technology.

[0015] FIG. 3 depicts a plot of x-ray diffraction (XRD) results for a wafer having the stack layers of FIG. 1 as fabricated using the method of FIG. 2, according to some embodiments of the present technology.

[0016] FIG. 4 depicts an image of a reflection high energy electron diffraction (RHEED) pattern for the top surface of the twin-free perovskite oxide layer of the wafer corresponding to the XRD results of FIG. 3.

[0017] The drawings have not necessarily been drawn to scale. Similarly, some components and/or operations may be separated into different blocks or combined into a single block for the purposes of discussion of some of the embodiments of the present technology. Moreover, while the technology is amenable to various modifications and alternative forms, specific embodiments have been shown by way of example in the drawings and are described in detail below. The intention, however, is not to limit the technology to the particular embodiments described. On the contrary, the technology is intended to cover all modifications, equivalents, and alternatives falling within the scope of the technology as defined by the appended claims.

DETAILED DESCRIPTION

[0018] Various embodiments of the present technology generally relate to fabrication of single crystal oxide layers on silicon (Si) substrates. More specifically, some embodiments of the present technology relate to at least semi-Insulating epitaxial strontium titanate on Si wafers and methods of fabricating the same.

[0019] The present technology includes a wafer of LAO with residual in-plane biaxial tensile strain grown on an Si carrier wafer. The residual strain may be used to completely eliminate the twinning problem in single crystal LAO or relaxed LAO films. The residual strain may be imposed by a strain control buffer layer (e.g., STO) that is in between the Si and the LAO layer. By controlling the elastic energy stored in the strain control layer, one can additionally control the lattice parameter of the top LAO layer, varying it over a certain limited range. The LAO layer composition may also be adjusted during growth to naturally produce a specific excess amount of either La or Al such that the surface termination can be guaranteed at any temperature.

[0020] The present technology also includes a way of making a wafer of LAO with residual in-plane biaxial tensile strain grown on an Si carrier wafer. The process according to the present technology can allow for LAO film growers to have access to a large area stain control/buffer layer substrate as Si wafers are available in large sizes (e.g., 8”, 12”), which can allow for either more time and cost-efficient mass production, or to test multiple devices at the same time, among other practical and technical benefits.

[0021] In the following description, for the purposes of explanation, numerous specific details are set forth in order to provide a thorough understanding of embodiments of the present technology. It will be apparent, however, to one skilled in the art that embodiments of the present technology may be practiced without some of these specific details.

[0022] The phrases "in some embodiments," "according to some embodiments," "in the embodiments shown," "in other embodiments," and the like generally mean the particular feature, structure, or characteristic following the phrase is included in at least one implementation of the present technology and may be included in more than one implementation. In addition, such phrases do not necessarily refer to the same embodiments or different embodiments.

[0023] By growing LAO over a strain control layer, which is grown on Si, one can avoid the twinning problem in LAO. Any residual biaxial tensile strain in the LAO will cause it to stay cubic through its structural phase transition, which prevents the formation of twins. An additional effect of eliminating twinning is that by tuning the strain control layer to affect the amount of residual strain in LAO, one can produce LAO epitaxial layers with specified in-plane lattice parameters. For example, if STO is the strain control layer, it is possible to form LAO layers with lattice parameters ranging from 3.80 to 3.90 Å. This is most easily achieved by simply adjusting the relative thickness of the STO and LAO layers. The STO and LAO layers will find an equilibrium such that the elastic energy from strain is distributed proportionally. Other options are to adjust the composition of STO, for example, partially substituting Sr with either calcium (Ca) or barium (Ba) can easily control the strain imposed by the STO on the overlying LAO. A third way is to dope the LAO layer with another rare earth element (e.g., Y, Nd, Pr) besides La to further increase the residual strain.

[0024] The present technology enables twin-free LAO to be formed on Si using an STO buffer (strain control) layer with effective control of both the LAO layer’s lattice parameter and the surface termination of LAO.

[0025] Additional variations that may be incorporated into the present technology could make use of step-graded or continuously graded strain control buffer layers to further control strain without causing defects such as dislocations to form. Controlling the specific residual strain in the LAO layer without producing defects is critical for controlling its lattice parameter while preventing twinning.

[0026] Surface termination control can be achieved by biasing the LAO growth such that by the time the final thickness is achieved, an extra two monolayers of either LaO or AlO_2 have been grown gradually, which will prevent the temperature dependent surface termination property of stoichiometric LAO from occurring. In order to achieve variable composition during LAO deposition, the growth may be done using molecular-beam epitaxy (MBE) or another growth method where individual control of the metal flux is easily achievable on the fly. Sputtering (e.g., radio frequency, RF, type) or pulsed laser deposition (PLD) may be possible, but each thickness of LAO layer and each surface termination will require its own target.

Twin-Free, Small Lattice Parameter Perovskite Pseudo-Substrates on Si Carrier Wafers

[0027] FIG. 1 depicts a cross-sectional view of a wafer 100 according to some embodiments of the present technology. Wafer 100 may include a silicon (Si) substrate 110. Wafer 100 may also include a strain control layer 120 including strontium titanate (STO) or calcium titanate (CTO) formed on the Si substrate. Wafer 100 may further include a twin-free perovskite oxide layer 130 including a single crystal rare earth aluminate formed on the strain control layer and having a residual in-plane biaxial tensile strain imposed at least in part by the strain control layer. As used herein, the phrase “rare earth aluminate” means LAO, YAO, NAO and/or PAO. As used herein, the phrase “rare earth element” means La, Y, Nd and/or Pr. In some embodiments, use of CTO in the strain control layer would make a lattice constant of that layer closer to that of the twin-free perovskite oxide layer including LAO (e.g., because CTO has a psuedo cubic lattice constant 3.82 Å).

[0028] In one embodiment, an amount of the residual in-plane biaxial tensile strain, and thus also an in-plane lattice parameter, of the twin-free perovskite oxide layer 130 of wafer 100 may depend at least in part on an amount of elastic energy stored in the strain control layer. In some embodiments, the rare earth aluminate (e.g., LAO) of the twin-free perovskite oxide layer 130 of wafer 100 may have a cubic perovskite crystal structure. In one embodiment, the twin-free perovskite oxide layer 130 of wafer 100 may include epitaxial layers of the rare earth aluminate. In some embodiments, a psuedo cubic lattice parameter of the twin-free perovskite oxide layer 130 of wafer 100 may be from 3.80 Å to 3.90 Å. In other embodiments, the psuedo cubic lattice parameter of the twin-free perovskite oxide layer 130 of wafer 100 may be from about 3.80 Å to about 3.90 Å.

[0029] As used herein, the term “about” means approximately equal to the stated value, such as within a tolerance (±) range of the stated value that allows for variation in precision and/or accuracy as between two or more instruments of the same, or different, type, operators, or techniques, taking the measurement resulting in the value of the particular parameter (e.g., for comparison to the stated value). Depending on such factors as, for example and without limitation, the size or magnitude of the value, conditions under which the measurement is taken, conversions from standard units to metric or SI units, the nature of the measured physical or chemical property corresponding to the stated value, the availability of art-recognized standard measurements (e.g., as maintained by NIST or another formal or informal standards setting body), among other factors, about may take on a more narrow definition. As applied to a value or range of values for lattice constants as described and/or claimed herein, “about” means that the value or range of values may vary by ± 0.02 angstroms (Å)) from the stated value(s). As applied to a value or range of values for wafer diameter as described and/or claimed herein, “about” means that the value or range of values may vary by ± 0.3 inches from the stated value(s). As applied to a value or range of values for layer thickness as described and/or claimed herein, “about” means that the value or range of values in nanometers (nm) may vary by ± 10% from the stated value(s). As applied to a value or range of values for a fraction of a monolayer (e.g., a quarter, or a half, a monoloayer) as described and/or claimed herein, “about” means that the value or range of values may vary by ± 20% from the stated value(s). As applied to a value or range of values for annealing temperature as described and/or claimed herein, “about” means that the value or range of values in nanometers (nm) may vary by ± 50 °C from the stated value(s).

[0030] In some embodiments, a thickness of the strain control layer 120 may be less than a thickness of the twin-free perovskite oxide layer 130. In other embodiments, the thickness of the strain control layer 120 may be greater than the thickness of the twin-free perovskite oxide layer 130. In still other embodiments, the thickness of the strain control layer 120 may be equal (or about equal) to the thickness of the twin-free perovskite oxide layer 130. In an example of wafer 100 according to the present technology, an amount of the residual in-plane biaxial tensile strain, and thus also a value (or range of values) of an in-plane lattice parameter, of the twin-free perovskite oxide layer 130 may depend at least in part on the relative thicknesses of the strain control layer 120 and the twin-free perovskite oxide layer 130.

[0031] In one embodiment, the strain control layer 120 of wafer 100 may include STO. In another embodiment, the strain control layer 120 of wafer 100 may consist essentially of STO. In still other embodiments, the strain control layer 120 of wafer 100 may consist of STO. In some examples of wafer 100 according to the present technology, the strain control layer 120 may further include CTO, in addition to STO. In some embodiments, an amount of the residual in-plane biaxial tensile strain, and thus also a value (or range of values) of an in-plane lattice parameter, of the twin-free perovskite oxide layer 130 may depend at least in part on an amount of CTO substituted for STO (e.g., STO:CTO) in the strain control layer 120.

[0032] In some embodiments, the strain control layer 120 of wafer 100 may include CTO. In another embodiment, the strain control layer 120 of wafer 100 may consist essentially of CTO. In still other embodiments, the strain control layer 120 of wafer 100 may consist of CTO. In some examples of wafer 100 according to the present technology, the strain control layer 120 may further include STO, in addition to CTO. In some embodiments, an amount of the residual in-plane biaxial tensile strain, and thus also a value (or range of values) of an in-plane lattice parameter, of the twin-free perovskite oxide layer 130 may depend at least in part on an amount of STO substituted for CTO (e.g., CTO:STO) in the strain control layer 120.

[0033] In one embodiment, the rare earth aluminate of the twin-free perovskite layer 130 of wafer 100 may be selected from the group consisting of: lanthanum aluminate (LAO), yttrium aluminate (YAO), neodymium aluminate (NAO), and praseodymium aluminate (PAO). In some embodiments of wafer 100, the rare earth aluminate may include LAO, YAO, NAO, or PAO. In other embodiments of wafer 100, the rare earth aluminate may consist of LAO, YAO, NAO, or PAO. In still other embodiments of wafer 100, the rare earth aluminate may consist essentially of LAO, YAO, NAO, or PAO.

[0034] In some embodiments, the rare earth aluminate of the twin-free perovskite layer 130 may be, or may include, LAO. In some examples of wafer 100 according to the present technology, the twin-free perovskite oxide layer 130 may further include—e.g., in addition to the lanthanum (La) or LAO—at least one of yttrium (Y), neodymium (Nd), and praseodymium (Pr) (or just one of Y, Nd and Pr). In one embodiment, the LAO of the twin-free perovskite oxide layer 130 may be doped with Y, Nd, or Pr. In some examples of wafer 100 according to the present technology, the amount of the residual in-plane biaxial tensile strain, and thus also a value (or range of values) of the in-plane lattice parameter, of the twin-free perovskite oxide layer 130 may depend at least in part on an amount of Y, Nd, or Pr in the twin-free perovskite oxide layer 130.

[0035] In one embodiment, wafer 100 may also include one or more monolayers 140 of lanthanum oxide or aluminum oxide formed on a top surface 150 of the twin-free perovskite oxide layer 130 opposite the strain control layer 120 to prevent a temperature dependent surface termination property of stoichiometric LAO from occurring. In one example, the one or more monolayers 140 of lanthanum oxide or aluminum oxide may include up to four monolayers 140 of lanthanum oxide or aluminum oxide. In another example, the one or more monolayers 140 of lanthanum oxide or aluminum oxide may include two monolayers 140 of lanthanum oxide or aluminum oxide. In cases having two or more monoloayers 140, there could be alternating monolayers of lanthanum oxide and aluminum oxide in some embodiments. Two or more monolayers 140 of lanthanum oxide or aluminum oxide may be more practically feasible for wafer 100 according to the present technology, although one monolayer 140 of lanthanum oxide or aluminum oxide may can work if LAO is, or very near, perfectly stoichiometric. In some embodiments, the twin-free perovskite oxide layer 130 of wafer 100 may include a specific excess amount of either lanthanum (La) or aluminum (Al) to thereby provide a defined LAO surface termination at any given temperature.

[0036] In some embodiments, the rare earth aluminate of the twin-free perovskite layer 130 may be, or may include, YAO. In some examples of wafer 100 according to the present technology, the twin-free perovskite oxide layer 130 may further include—e.g., in addition to the yttrium (Y) or YAO—at least one of La, neodymium (Nd), and praseodymium (Pr) (or just one of La, Nd and Pr). In one embodiment, the YAO of the twin-free perovskite oxide layer 130 may be doped with La, Nd, or Pr. In some examples of wafer 100 according to the present technology, the amount of the residual in-plane biaxial tensile strain, and thus also a value (or range of values) of the in-plane lattice parameter, of the twin-free perovskite oxide layer 130 may depend at least in part on an amount of La, Nd, or Pr in the twin-free perovskite oxide layer 130.

[0037] In one embodiment, wafer 100 may also include one or more monolayers 140 of yttrium oxide or aluminum oxide formed on a top surface 150 of the twin-free perovskite oxide layer opposite the strain control layer 120 to prevent a temperature dependent surface termination property of stoichiometric YAO from occurring. In one example, the one or more monolayers 140 of yttrium oxide or aluminum oxide may include up to four monolayers 140 of yttrium oxide or aluminum oxide. In another example, the one or more monolayers 140 of yttrium oxide or aluminum oxide may include two monolayers 140 of yttrium oxide or aluminum oxide. In cases having two or more monolayers 140, there could be alternating monolayers of yttrium oxide and aluminum oxide in some embodiments. Two or more monolayers 140 of yttrium oxide or aluminum oxide may be more practically feasible for wafer 100 according to the present technology, although one monolayer 140 of yttrium oxide or aluminum oxide may can work if YAO is, or very near, perfectly stoichiometric. In some embodiments, the twin-free perovskite oxide layer 130 of wafer 100 may include a specific excess amount of either Y or Al to thereby provide a defined YAO surface termination at any given temperature.

[0038] In some embodiments, the rare earth aluminate of the twin-free perovskite layer 130 may be, or may include, NAO. In some examples of wafer 100 according to the present technology, the twin-free perovskite oxide layer 130 may further include—e.g., in addition to the neodymium (Nd) or NAO—at least one of La, Y, and Pr (or just one of La, Y and Pr). In one embodiment, the NAO of the twin-free perovskite oxide layer 130 may be doped with La, Y, or Pr. In some examples of wafer 100 according to the present technology, the amount of the residual in-plane biaxial tensile strain, and thus also a value (or range of values) of the in-plane lattice parameter, of the twin-free perovskite oxide layer 130 may depend at least in part on an amount of La, Y, or Pr in the twin-free perovskite oxide layer 130.

[0039] In one embodiment, wafer 100 may also include one or more monolayers 140 of neodymium oxide or aluminum oxide formed on a top surface 150 of the twin-free perovskite oxide layer opposite the strain control layer 120 to prevent a temperature dependent surface termination property of stoichiometric NAO from occurring. In one example, the one or more monolayers 140 of neodymium oxide or aluminum oxide may include up to four monolayers 140 of neodymium oxide or aluminum oxide. In another example, the one or more monolayers 140 of neodymium oxide or aluminum oxide may include two monolayers 140 of neodymium oxide or aluminum oxide. In cases having two or more monoloayers 140, there could be alternating monolayers of neodymium oxide and aluminum oxide in some embodiments. Two or more monolayers 140 of neodymium oxide or aluminum oxide may be more practically feasible for wafer 100 according to the present technology, although one monolayer 140 of neodymium oxide or aluminum oxide may can work if NAO is, or very near, perfectly stoichiometric. In some embodiments, the twin-free perovskite oxide layer 130 of wafer 100 may include a specific excess amount of either Nd or Al to thereby provide a defined NAO surface termination at any given temperature.

[0040] In some embodiments, the rare earth aluminate of the twin-free perovskite layer 130 may be, or may include, PAO. In some examples of wafer 100 according to the present technology, the twin-free perovskite oxide layer 130 may further include—e.g., in addition to the Pr or PAO—at least one of La, Y, and Nd (or just one of La, Y and Nd). In one embodiment, the PAO of the twin-free perovskite oxide layer 130 may be doped with La, Y, or Nd. In some examples of wafer 100 according to the present technology, the amount of the residual in-plane biaxial tensile strain, and thus also a value (or range of values) of the in-plane lattice parameter, of the twin-free perovskite oxide layer 130 may depend at least in part on an amount of La, Y, or Nd in the twin-free perovskite oxide layer 130.

[0041] In one embodiment, wafer 100 may also include one or more monolayers 140 of praseodymium oxide or aluminum oxide formed on a top surface 150 of the twin-free perovskite oxide layer opposite the strain control layer 120 to prevent a temperature dependent surface termination property of stoichiometric PAO from occurring. In one example, the one or more monolayers 140 of praseodymium oxide or aluminum oxide may include up to four monolayers 140 of praseodymium oxide or aluminum oxide. In another example, the one or more monolayers 140 of praseodymium oxide or aluminum oxide may include two monolayers 140 of praseodymium oxide or aluminum oxide. In cases having two or more monolayers 140, there could be alternating monolayers of praseodymium oxide and aluminum oxide in some embodiments. Two or more monolayers 140 of praseodymium oxide or aluminum oxide may be more practically feasible for wafer 100 according to the present technology, although one monolayer 140 of praseodymium oxide or aluminum oxide may can work if PAO is, or very near, perfectly stoichiometric. In some embodiments, the twin-free perovskite oxide layer 130 of wafer 100 may include a specific excess amount of either Pr or Al to thereby provide a defined PAO surface termination at any given temperature.

[0042] In an example of wafer 100 according to the present technology, the strain control layer 120 may be, or may include, a step-graded strain control layer. In another example of wafer 100 according to the present technology, the strain control layer 120 may be, or may include, a continuously graded strain control layer.

[0043] In some embodiments, the Si substrate 110 may be, or may include, an Si wafer. In one example, the Si wafer may have a diameter of from 1 inch to 18 inches (or from about 1 inch to about 18 inches). In another example, the Si wafer may have a diameter of from 2 inches to 12 inches (or from about 2 inches to about 12 inches). In yet another example, the Si wafer may have a diameter of from 4 inches to 8 inches (or from about 4 inches to about 8 inches).

[0044] In one embodiment, the Si substrate 110 may be, or may include, a silicon-on-insulator (SOI) wafer. In one example, the SOI wafer may have a diameter of from 1 inch to 18 inches (or from about 1 inch to about 18 inches). In another example, the SOI wafer may have a diameter of from 2 inches to 12 inches (or from about 2 inches to about 12 inches). In yet another example, the SOI wafer may have a diameter of from 4 inches to 8 inches (or from about 4 inches to about 8 inches).

[0045] In some embodiments, the twin-free perovskite oxide layer 130 of wafer 100 may include epitaxial LAO. In another example, the twin-free perovskite oxide layer 130 consists essentially of epitaxial LAO. In yet another example, the twin-free perovskite oxide layer 130 consists of epitaxial LAO. In other embodiments, the twin-free perovskite oxide layer 130 of wafer 100 may include epitaxial YAO. In another example, the twin-free perovskite oxide layer 130 consists essentially of epitaxial YAO. In yet another example, the twin-free perovskite oxide layer 130 consists of epitaxial YAO. In still other embodiments, the twin-free perovskite oxide layer 130 of wafer 100 may include epitaxial NAO. In another example, the twin-free perovskite oxide layer 130 consists essentially of epitaxial NAO. In yet another example, the twin-free perovskite oxide layer 130 consists of epitaxial NAO. In other embodiments, the twin-free perovskite oxide layer 130 of wafer 100 may include epitaxial PAO. In another example, the twin-free perovskite oxide layer 130 consists essentially of epitaxial PAO. In yet another example, the twin-free perovskite oxide layer 130 consists of epitaxial PAO. In any of these cases, the LAO, YAO, NAO, or PAO of the twin-free perovskite oxide layer 130 may be present therein in single crystal form. Furthermore, the twin-free perovskite oxide layer 130 of wafer 100 may be integrated epitaxially onto the Si substrate 110 via the strain control layer 120.

[0046] In one embodiment, wafer 100 may include at least one device 160 formed in or on the twin-free perovskite oxide layer 130. In an example of wafer 100 according to the present technology, the at least one device 160 may be, or may include, at least one of: a microelectronic device, an optoelectronic device, a micro-electromechanical system (MEMS), an integrated circuit, a transistor, a sensor, a semiconductor device, a photocathode device, a solar water splitter device, a superconductor device, a photonic device, a Josephson junction, and a capacitor. In some embodiments, at least a portion of the twin-free perovskite oxide layer 130 is at least one of: etched, polished, and annealed.

[0047] In some embodiments, the Si substrate 110 may be, or may include, Si (001). In one case, the strain control layer 120 may be, or may include, STO (001) formed on the Si (001) substrate. In another case, the strain control layer 120 may be, or may include, CTO (001) formed on the Si (001) substrate.

[0048] In one embodiment, the Si substrate 110 may be, or may include, Si (111). In one case, the strain control layer 120 may be, or may include, STO (111) formed on the Si (111) substrate. In another case, the strain control layer 120 may be, or may include, CTO (111) formed on the Si (111) substrate.

[0049] In some embodiments, the twin-free perovskite oxide layer 130 of wafer 100 may have a thickness of from 5 nanometers (nm) to 50 nm. In one example, the twin-free perovskite oxide layer 130 of wafer 100 may have a thickness of from about 5 nm to about 50 nm. In another example, the twin-free perovskite oxide layer 130 of wafer 100 may have a thickness of from 20 nm to 50 nm. In yet another example, the twin-free perovskite oxide layer 130 of wafer 100 may have a thickness of from about 20 nm to about 50 nm.

[0050] In one embodiment, wafer 100 may further include a film or layer of another material formed on the twin-free perovskite oxide layer 130. In one example, the film or layer of another material may be, or may include, yttrium barium copper oxide (e.g., a-axis oriented YBCO). In another example, the film or layer of another material may be, or may include, a magnetic oxide. In yet another example, the film or layer of another material may be, or may include, lanthanum strontium manganite (LMSO). In still another example, the film or layer of another material may be, or may include, supertetragonal barium titanate (BTO).

Methods for Manufacturing Twin-Free, Small Lattice Parameter Perovskite Pseudo-Substrates on Si Carrier Wafers

[0051] FIG. 2 depicts a flowchart of a method 200 for manufacturing a wafer (e.g., wafer 100 shown in FIG. 1), according to some embodiments of the present technology. With further reference being made to features described above and as shown in FIG. 1, method 200 may include the step of depositing 210, on silicon (Si) substrate 110, the strain control layer 120 including STO or CTO. The method 200 may also include the step of depositing 220, on the strain control layer 120, the twin-free perovskite oxide layer 130 including a single crystal rare earth aluminate and having a residual in-plane biaxial tensile strain imposed at least in part by the strain control layer.

[0052] In one embodiment, method 200 may also include the step of removing, prior to depositing 210 the strain control layer, native oxide from a surface of the Si substrate 110 upon which the strain control layer 120 is to be deposited. In one example of method 200 according to the present technology, the strain control layer may be, or may include, STO, and the removing step may include removing the native oxide using a strontium (Sr)-assisted oxide desorption process. In this case, method 200 may further include chemisorbing a quarter (¼) (or about a ¼) to a half (½) (or about a ½) monolayer of Sr onto the surface of the Si substrate after the removing and prior to depositing the strain control layer. In another example of method 200 according to the present technology, the strain control layer may be, or may include, CTO, and the removing step may include removing the native oxide using a calcium (Ca)-assisted oxide desorption process. In this case, method 200 may further include chemisorbing a ¼ (or about a ¼) to a ½ (or about a ½) monolayer of Ca onto the surface of the Si substrate after the removing and prior to depositing the strain control layer.

[0053] In some embodiments, the method 200 step of depositing 210 the strain control layer 120 may include depositing STO or CTO on the Si substrate 110 using molecular-beam epitaxy (MBE). In an example of method 200 according to the present technology, the step of depositing 210 the strain control layer 120 may also include: first depositing a portion of the strain control layer 120 on the Si substrate 110 using MBE, and second depositing, onto the MBE-deposited STO or CTO, a remainder of the strain control layer 120 using radio frequency (RF) sputtering or pulsed laser deposition (PLD). In an example, depositing 210 the strain control layer 120 in method 200 may include depositing a step-graded strain control layer on the Si substrate 110. In another example, depositing 210 the strain control layer 120 in method 200 may include depositing a continuously graded strain control layer on the Si substrate 110.

[0054] In one embodiment, method 200 may include the step of crystallizing the STO or CTO of the strain control layer 120 in vacuum. In some embodiments, method 200 may include the step of annealing the strain control layer 120. In an example, the annealing of the strain control layer 120 may be performed in method 200 at a temperature of 500 - 600 °C. In another example, the annealing of the strain control layer 120 may be performed in method 200 at a temperature of from about 500 °C to about 600 °C. In yet another example, the annealing of the strain control layer 120 may be performed in method 200 at a temperature of 550 °C. In still another example, the annealing of the strain control layer 120 may be performed in method 200 at a temperature of about 550 °C.

[0055] In some embodiments, depositing 210 the strain control layer 120 in method 200 may include depositing the strain control layer 120 on an Si wafer. In an example, depositing 210 the strain control layer 120 may include depositing the strain control layer 120 on an Si wafer having a diameter of from 1 inch to 18 inches. In another example, depositing 210 the strain control layer 120 may include depositing the strain control layer 120 on an Si wafer having a diameter of from about 1 inch to about 18 inches. In yet another example, depositing 210 the strain control layer 120 may include depositing the strain control layer 120 on an Si wafer having a diameter of from 2 inches to 12 inches. In still another example, depositing 210 the strain control layer 120 may include depositing the strain control layer 120 on an Si wafer having a diameter of from about 2 inches to about 12 inches. In another example, depositing 210 the strain control layer 120 may include depositing the strain control layer 120 on an Si wafer having a diameter of from 4 inches to 8 inches. In yet another example, depositing 210 the strain control layer 120 may include depositing the strain control layer 120 on an Si wafer having a diameter of from about 4 inches to about 8 inches.

[0056] In some embodiments, depositing 210 the strain control layer 120 in method 200 may include depositing the strain control layer 120 on an SOI wafer. In an example, depositing 210 the strain control layer 120 may include depositing the strain control layer 120 on an SOI wafer having a diameter of from 1 inch to 18 inches. In another example, depositing 210 the strain control layer 120 may include depositing the strain control layer 120 on an SOI wafer having a diameter of from about 1 inch to about 18 inches. In yet another example, depositing 210 the strain control layer 120 may include depositing the strain control layer 120 on an SOI wafer having a diameter of from 2 inches to 12 inches. In still another example, depositing 210 the strain control layer 120 may include depositing the strain control layer 120 on an SOI wafer having a diameter of from about 2 inches to about 12 inches. In another example, depositing 210 the strain control layer 120 may include depositing the strain control layer 120 on an SOI wafer having a diameter of from 4 inches to 8 inches. In yet another example, depositing 210 the strain control layer 120 may include depositing the strain control layer 120 on an SOI wafer having a diameter of from about 4 inches to about 8 inches.

[0057] In one embodiment, the method 200 step of depositing 210 the strain control layer 120 may include depositing the strain control layer on an Si (001) substrate 110. In an example, depositing 210 the strain control layer 120 may include forming the strain control layer 120 including STO (001) on the Si (001) substrate 110. In another example, depositing 210 the strain control layer 120 may include forming the strain control layer 120 including CTO (001) on the Si (001) substrate 110. In another example, depositing 210 the strain control layer 120 may include forming the strain control layer 120 including STO (001) and CTO (001) on the Si (001) substrate 110.

[0058] In some embodiments, the method 200 step of depositing 210 the strain control layer 120 may include depositing the strain control layer on an Si (111) substrate 110. In an example, depositing 210 the strain control layer 120 may include forming the strain control layer 120 including STO (111) on the Si (111) substrate 110. In another example, depositing 210 the strain control layer 120 may include forming the strain control layer 120 including CTO (111) on the Si (111) substrate 110. In another example, depositing 210 the strain control layer 120 may include forming the strain control layer 120 including STO (111) and CTO (111) on the Si (111) substrate 110.

[0059] Depositing 210 the strain control layer 120 on the Si substrate 110 in method 200 may further include forming the strain control layer 120 on the Si substrate 110 in the absence of defects of (e.g., on or within the material of) the strain control layer 120. The method 200 step of depositing 210 the strain control layer 120 on the Si substrate 110 may further include forming the strain control layer 120 on the Si substrate 110 in the absence of dislocations of (e.g., on or within the material of) the strain control layer 120.

[0060] In some embodiments, the method 200 step of depositing 220 the twin-free perovskite oxide layer 230 may include forming the twin-free perovskite oxide layer 230 having a cubic perovskite crystal structure. Practically, the aforementioned cubic perovskite crystal structure of the twin-free perovskite oxide layer 230 formed of, for example, LAO, may be “strained” cubic, which may appear as tetragonal using x-ray diffraction. This may be because in such cases, the LAO does not undergo transition to a rhombohedral crystal structure because of the twin-free perovskite oxide layer’s 130 experiencing residual in-plane biaxial tensile strain as a result of the strain control layer 120.

[0061] In one embodiment, the method 200 step of depositing 220 the twin-free perovskite oxide layer 230 may include forming the twin-free perovskite oxide layer 230 including epitaxial layers of the rare earth aluminate (e.g., LAO, YAO, NAO and/or PAO). These epitaxial layers of the rare earth aluminate may be epitaxially integrated into the Si substrate 110 via the strain control layer 120. In some embodiments, the method 200 step of depositing 220 the twin-free perovskite oxide layer 230 may include forming the twin-free perovskite oxide layer 230 having a psuedo cubic lattice parameter of from 3.80 angstrom (Å) to 3.90 Å (or from about 3.80 Å to about 3.90 Å).

[0062] In some embodiments, the method 200 step of depositing 220 the twin-free perovskite oxide layer 130 may include depositing the twin-free perovskite oxide layer 130 to have a defined thickness relative to a thickness of the strain control layer 120. In an example, depositing 220 the twin-free perovskite oxide layer 130 may include depositing the twin-free perovskite oxide layer 130 having a thickness less than a thickness of the strain control layer 120. In another example, depositing 220 the twin-free perovskite oxide layer 130 may include depositing the twin-free perovskite oxide layer 130 having a thickness greater than a thickness of the strain control layer 120. In yet another example, depositing 220 the twin-free perovskite oxide layer 130 may include depositing the twin-free perovskite oxide layer 130 having a thickness equal to a thickness of the strain control layer 120. In still another example, depositing 220 the twin-free perovskite oxide layer 130 may include depositing the twin-free perovskite oxide layer 130 having a thickness about equal to a thickness of the strain control layer 120.

[0063] In one embodiment, the method 200 step of depositing 220 the twin-free perovskite oxide layer 130 on the strain control layer 120 may include forming the twin-free perovskite oxide layer 130 in the absence of twinning of the rare earth aluminate. In some embodiments, method 200 may include the step of controlling, during depositing 210 the strain control layer 120 on the Si substrate 110, an amount of elastic energy stored in the strain control layer 120 to thereby also control a resultant amount of the residual in-plane biaxial tensile strain of the twin-free perovskite oxide layer 130.

[0064] In some embodiments, method 200 may include the step of controlling, during depositing 210 the strain control layer 120 and during depositing 220 the twin-free perovskite oxide layer 130, relative thicknesses of the strain control layer 120 and the twin-free perovskite oxide layer 130 to thereby also control a resultant amount of the residual in-plane biaxial tensile strain of the twin-free perovskite oxide layer 130. In an example, depositing 220 the twin-free perovskite oxide layer 130 in method 200 may include forming the twin-free perovskite oxide layer having a thickness greater than a thickness of the strain control layer 120. In another example, depositing 220 the twin-free perovskite oxide layer 130 in method 200 may include forming the twin-free perovskite oxide layer 130 having a thickness less than a thickness of the strain control layer 120. In yet another example, depositing 220 the twin-free perovskite oxide layer 130 in method 200 may include forming the twin-free perovskite oxide layer 130 having a thickness equal to a thickness of the strain control layer 120. In still another example, depositing 220 the twin-free perovskite oxide layer 130 in method 200 may include forming the twin-free perovskite oxide layer 130 having a thickness about equal to the thickness of the strain control layer 120.

[0065] Embodiments of method 200 according to the present technology may be practiced to manufacture the new material as, e.g., wafers 100, including strain control layers 120 formed of STO. In an example, the method 200 step of depositing 210 the strain control layer 120 may include depositing the strain control layer 120 including STO. In another example, the method 200 step of depositing 210 the strain control layer 120 may include depositing the strain control layer 120 consisting essentially of STO. In yet another example, the method 200 step of depositing 210 the strain control layer 120 may include depositing the strain control layer 120 consisting of STO.

[0066] In cases of wafers 100 manufactured according to the present technology using method 200 that have strain control layers 120 predominantly formed of STO, an amount of CTO may be included to a lesser extent as compared to STO (e.g., < 50% CTO). In such cases, the method 200 step of depositing 210 the strain control layer 120 may also include depositing the strain control layer 120 further including CTO. In some embodiments, method 200 may include controlling, during depositing 210 the strain control layer 120, an amount of CTO in the strain control layer 120 to thereby also control a resultant amount of the residual in-plane biaxial tensile strain of the twin-free perovskite oxide layer 130.

[0067] Embodiments of method 200 according to the present technology may be practiced to manufacture the new material as, e.g., wafers 100, including strain control layers 120 formed of CTO. In an example, the method 200 step of depositing 210 the strain control layer 120 may include depositing the strain control layer 120 including CTO. In another example, the method 200 step of depositing 210 the strain control layer 120 may include depositing the strain control layer 120 consisting essentially of CTO. In yet another example, the method 200 step of depositing 210 the strain control layer 120 may include depositing the strain control layer 120 consisting of CTO.

[0068] In cases of wafers 100 manufactured according to the present technology using method 200 that have strain control layers 120 predominantly formed of CTO, an amount of STO may be included to a lesser extent as compared to CTO (e.g., < 50% STO). In such cases, the method 200 step of depositing 210 the strain control layer 120 may also include depositing the strain control layer 120 further including STO. In some embodiments, method 200 may include controlling, during depositing 210 the strain control layer 120, an amount of STO in the strain control layer 120 to thereby also control a resultant amount of the residual in-plane biaxial tensile strain of the twin-free perovskite oxide layer 130.

[0069] In one embodiment, the method 200 step of depositing 220 the twin-free perovskite oxide layer 130 may include depositing the twin-free perovskite oxide layer 130 including the rare earth aluminate selected from the group consisting of: lanthanum aluminate (LAO), yttrium aluminate (YAO), neodymium aluminate (NAO), and praseodymium aluminate (PAO). In some embodiments, depositing 220 the twin-free perovskite oxide layer 130 may include depositing the twin-free perovskite oxide layer including LAO, YAO, NAO, or PAO. In other embodiments, depositing 220 the twin-free perovskite oxide layer 130 may include depositing the twin-free perovskite oxide layer including two or more of LAO, YAO, NAO, and PAO. In another embodiment, depositing 220 the twin-free perovskite oxide layer 130 may include depositing the twin-free perovskite oxide layer consisting essentially of LAO, YAO, NAO, or PAO. In other embodiments, depositing 220 the twin-free perovskite oxide layer 130 may include depositing the twin-free perovskite oxide layer consisting essentially of two or more of LAO, YAO, NAO, and PAO. In yet another embodiment, depositing 220 the twin-free perovskite oxide layer 130 may include depositing the twin-free perovskite oxide layer consisting of LAO, YAO, NAO, or PAO. In other embodiments, depositing 220 the twin-free perovskite oxide layer 130 may include depositing the twin-free perovskite oxide layer consisting of two or more of LAO, YAO, NAO, and PAO.

[0070] Embodiments of method 200 according to the present technology may be practiced to manufacture the new material as, e.g., wafers 100, including twin-free perovskite oxide layer 130 formed of LAO. In an example, the method 200 step of depositing 220 the twin-free perovskite oxide layer 130 may include depositing the twin-free perovskite oxide layer 130 including LAO. In cases of wafers 100 manufactured according to the present technology using method 200 that have twin-free perovskite oxide layers 130 predominantly formed of LAO, an amount of another rare earth element besides La may be included to a lesser extent as compared to the La in LAO (e.g., < 50% of the another rare earth element). In an example, the method 200 step of depositing 220 the twin-free perovskite oxide layer 130 may also include depositing the twin-free perovskite oxide layer 130 further including yttrium (Y), neodymium (Nd), or praseodymium (Pr). In another example, the method 200 step of depositing 220 the twin-free perovskite oxide layer 130 may include depositing the twin-free perovskite oxide layer 130 further including two or more of Y, Nd and Pr. In some embodiments, depositing 220 the twin-free perovskite oxide layer 130 in method 200 may include doping the LAO with Y, Nd, or Pr. In other embodiments, depositing 220 the twin-free perovskite oxide layer 130 in method 200 may include doping the LAO with two or more of Y, Nd, and Pr. In one embodiment, method 200 may include the step of controlling, during depositing 220 the twin-free perovskite oxide layer 130, an amount of Y, Nd, or Pr to thereby also control a resultant amount of the residual in-plane biaxial tensile strain of the twin-free perovskite oxide layer 130.

[0071] Referring again to FIG. 1, in some embodiments, method 200 may include depositing one or more monolayers 140 of lanthanum oxide or aluminum oxide on a top surface 150 of the twin-free perovskite oxide layer 130 opposite the strain control layer 120 to prevent a temperature dependent surface termination property of stoichiometric LAO from occurring. In an example, depositing the one or more monolayers 140 of lanthanum oxide or aluminum oxide may include depositing up to four monolayers of lanthanum oxide or aluminum oxide on the top surface 150 of the twin-free perovskite oxide layer 130. In another example, depositing the one or more monolayers of lanthanum oxide or aluminum oxide may include depositing two monolayers of lanthanum oxide or aluminum oxide on the top surface 150 of the twin-free perovskite oxide layer 130.

[0072] In one embodiment, the method 200 step of depositing 220 the twin-free perovskite oxide layer 130 may include controlling the depositing 220 of the twin-free perovskite oxide layer 130 on the strain control layer 120 such that the one or more monolayers 140 of lanthanum oxide or aluminum oxide are formed on the top surface 150 of the twin-free perovskite oxide layer 130 opposite the strain control layer 120 to thereby prevent temperature dependent surface termination property of stoichiometric LAO from occurring in the wafer 100 product. To achieve this advantageous property in wafers 100 fabricated according to the present technology, the method 200 step of controlling the depositing 220 of the twin-free perovskite oxide layer 130 may include gradually forming the one or more monolayers 140 of lanthanum oxide or aluminum oxide under process conditions that are both different from the conditions used for forming the remainder of the twin-free perovskite oxide layer 130, and sufficient to form the one or more monolayers 140. As such, method 200 may further include the step of preventing the temperature dependent surface termination property of stoichiometric LAO from occurring.

[0073] In some embodiments, one or both of the aforementioned method 200 steps of depositing 220 the twin-free perovskite oxide layer 130 and depositing one or more monolayers 140 of lanthanum oxide or aluminum oxide may include using a growth technique or process capable of achieving individual control of the metal flux on the fly in the method 200. As used herein, the phrase “on the fly” means that the growth technique or process enables quickly shutting off one of the elements being deposited, as in stopping either La or Al from being deposited after both were previously being deposited. For instance, the LAO being deposited 220 for the twin-free perovskite oxide layer 130 in method 200 would have both elements La and Al being deposited to form LAO, and then one of those elements would be stopped from being deposited to thereby provided the deposition of the monolayer(s) 140 of lanthanum oxide or aluminum oxide, as described herein. In an example, the aforementioned growth technique or process is or includes one or more of: molecular beam epitaxy (MBE), sputtering, and pulsed laser deposition (PLD). In another example, that growth technique or process is MBE.

[0074] In some embodiments, from one to up to four monolayers 140 of lanthanum oxide or aluminum oxide may be deposited in method 200. Notably, depositing just one monolayer 140 of lanthanum oxide or aluminum oxide may require LAO to be perfectly, or very nearly perfectly, stoichiometric. As such, depositing two monolayers 140 of lanthanum oxide or aluminum oxide in method 200 may be more practically feasible in some applications of method 200. In one embodiment of method 200 where two or more monolayers 140 of lanthanum oxide or aluminum oxide are deposited, the monolayers 140 may alternate from lanthanum oxide to aluminum oxide. In some embodiments, depositing 220 the twin-free perovskite oxide layer 130 in method 200 may include depositing the twin-free perovskite oxide layer 130 including a specific excess amount of either lanthanum (La) or aluminum (Al) to thereby provide a defined LAO surface termination at any given temperature.

[0075] Embodiments of method 200 according to the present technology may be practiced to manufacture the new material as, e.g., wafers 100, including twin-free perovskite oxide layer 130 formed of YAO. In an example, the method 200 step of depositing 220 the twin-free perovskite oxide layer 130 may include depositing the twin-free perovskite oxide layer 130 including YAO. In cases of wafers 100 manufactured according to the present technology using method 200 that have twin-free perovskite oxide layers 130 predominantly formed of YAO, an amount of another rare earth element besides Y may be included to a lesser extent as compared to the Y in YAO (e.g., < 50% of the another rare earth element). In an example, the method 200 step of depositing 220 the twin-free perovskite oxide layer 130 may also include depositing the twin-free perovskite oxide layer 130 further including La, Nd, or Pr. In another example, the method 200 step of depositing 220 the twin-free perovskite oxide layer 130 may include depositing the twin-free perovskite oxide layer 130 further including two or more of La, Nd, or Pr. In some embodiments, depositing 220 the twin-free perovskite oxide layer 130 in method 200 may include doping the YAO with La, Nd, or Pr. In other embodiments, depositing 220 the twin-free perovskite oxide layer 130 in method 200 may include doping the LAO with two or more of La, Nd, and Pr. In one embodiment, method 200 may include the step of controlling, during depositing 220 the twin-free perovskite oxide layer 130, an amount of La, Nd, or Pr to thereby also control a resultant amount of the residual in-plane biaxial tensile strain of the twin-free perovskite oxide layer 130.

[0076] Referring again to FIG. 1, in some embodiments, method 200 may include depositing one or more monolayers 140 of yttrium oxide or aluminum oxide on a top surface 150 of the twin-free perovskite oxide layer 130 opposite the strain control layer 120 to prevent a temperature dependent surface termination property of stoichiometric YAO from occurring. In an example, depositing the one or more monolayers 140 of yttrium oxide or aluminum oxide may include depositing up to four monolayers of yttrium oxide or aluminum oxide on the top surface 150 of the twin-free perovskite oxide layer 130. In another example, depositing the one or more monolayers of yttrium oxide or aluminum oxide may include depositing two monolayers of yttrium oxide or aluminum oxide on the top surface 150 of the twin-free perovskite oxide layer 130.

[0077] In one embodiment, the method 200 step of depositing 220 the twin-free perovskite oxide layer 130 may include controlling the depositing 220 of the twin-free perovskite oxide layer 130 on the strain control layer 120 such that the one or more monolayers 140 of yttrium oxide or aluminum oxide are formed on the top surface 150 of the twin-free perovskite oxide layer 130 opposite the strain control layer 120 to thereby prevent temperature dependent surface termination property of stoichiometric YAO from occurring in the wafer 100 product. To achieve this advantageous property in wafers 100 fabricated according to the present technology, the method 200 step of controlling the depositing 220 of the twin-free perovskite oxide layer 130 may include gradually forming the one or more monolayers 140 of yttrium oxide or aluminum oxide under process conditions that are both different from the conditions used for forming the remainder of the twin-free perovskite oxide layer 130, and sufficient to form the one or more monolayers 140. As such, method 200 may further include the step of preventing the temperature dependent surface termination property of stoichiometric YAO from occurring.

[0078] In some embodiments, one or both of the aforementioned method 200 steps of depositing 220 the twin-free perovskite oxide layer 130 and depositing one or more monolayers 140 of yttrium oxide or aluminum oxide may include using a growth technique or process capable of achieving individual control of the metal flux on the fly in the method 200. For instance, such a growth technique or process enables quickly shutting off either Y or Al from being deposited after both were previously being deposited. For example, the YAO being deposited 220 for the twin-free perovskite oxide layer 130 in method 200 would have both elements Y and Al being deposited to form YAO, and then one of those elements would be stopped from being deposited to thereby provided the deposition of the monolayer(s) 140 of yttrium oxide or aluminum oxide, as described herein. In an example, the aforementioned growth technique or process is or includes one or more of: molecular beam epitaxy (MBE), sputtering, and pulsed laser deposition (PLD). In another example, that growth technique or process is MBE.

[0079] In some embodiments, from one to up to four monolayers 140 of yttrium oxide or aluminum oxide may be deposited in method 200. Notably, depositing just one monolayer 140 of yttrium oxide or aluminum oxide may require YAO to be perfectly, or very nearly perfectly, stoichiometric. As such, depositing two monolayers 140 of yttrium oxide or aluminum oxide in method 200 may be more practically feasible in some applications of method 200. In one embodiment of method 200 where two or more monolayers 140 of yttrium oxide or aluminum oxide are deposited, the monolayers 140 may alternate from yttrium oxide to aluminum oxide. In some embodiments, depositing 220 the twin-free perovskite oxide layer 130 in method 200 may include depositing the twin-free perovskite oxide layer 130 including a specific excess amount of either Y or Al to thereby provide a defined YAO surface termination at any given temperature.

[0080] Embodiments of method 200 according to the present technology may be practiced to manufacture the new material as, e.g., wafers 100, including twin-free perovskite oxide layer 130 formed of NAO. In an example, the method 200 step of depositing 220 the twin-free perovskite oxide layer 130 may include depositing the twin-free perovskite oxide layer 130 including NAO. In cases of wafers 100 manufactured according to the present technology using method 200 that have twin-free perovskite oxide layers 130 predominantly formed of NAO, an amount of another rare earth element besides Nd may be included to a lesser extent as compared to the Nd in NAO (e.g., < 50% of the another rare earth element). In an example, the method 200 step of depositing 220 the twin-free perovskite oxide layer 130 may also include depositing the twin-free perovskite oxide layer 130 further including La, Y, or Pr. In another example, the method 200 step of depositing 220 the twin-free perovskite oxide layer 130 may include depositing the twin-free perovskite oxide layer 130 further including two or more of La, Y, or Pr. In some embodiments, depositing 220 the twin-free perovskite oxide layer 130 in method 200 may include doping the NAO with La, Y, or Pr. In other embodiments, depositing 220 the twin-free perovskite oxide layer 130 in method 200 may include doping the NAO with two or more of La, Y, and Pr. In one embodiment, method 200 may include the step of controlling, during depositing 220 the twin-free perovskite oxide layer 130, an amount of La, Y, or Pr to thereby also control a resultant amount of the residual in-plane biaxial tensile strain of the twin-free perovskite oxide layer 130.

[0081] Referring again to FIG. 1, in some embodiments, method 200 may include depositing one or more monolayers 140 of neodymium oxide or aluminum oxide on a top surface 150 of the twin-free perovskite oxide layer 130 opposite the strain control layer 120 to prevent a temperature dependent surface termination property of stoichiometric NAO from occurring. In an example, depositing the one or more monolayers 140 of neodymium oxide or aluminum oxide may include depositing up to four monolayers of neodymium oxide or aluminum oxide on the top surface 150 of the twin-free perovskite oxide layer 130. In another example, depositing the one or more monolayers of neodymium oxide or aluminum oxide may include depositing two monolayers of neodymium oxide or aluminum oxide on the top surface 150 of the twin-free perovskite oxide layer 130.

[0082] In one embodiment, the method 200 step of depositing 220 the twin-free perovskite oxide layer 130 may include controlling the depositing 220 of the twin-free perovskite oxide layer 130 on the strain control layer 120 such that the one or more monolayers 140 of neodymium oxide or aluminum oxide are formed on the top surface 150 of the twin-free perovskite oxide layer 130 opposite the strain control layer 120 to thereby prevent temperature dependent surface termination property of stoichiometric NAO from occurring in the wafer 100 product. To achieve this advantageous property in wafers 100 fabricated according to the present technology, the method 200 step of controlling the depositing 220 of the twin-free perovskite oxide layer 130 may include gradually forming the one or more monolayers 140 of neodymium oxide or aluminum oxide under process conditions that are both different from the conditions used for forming the remainder of the twin-free perovskite oxide layer 130, and sufficient to form the one or more monolayers 140. As such, method 200 may further include the step of preventing the temperature dependent surface termination property of stoichiometric NAO from occurring.

[0083] In some embodiments, one or both of the aforementioned method 200 steps of depositing 220 the twin-free perovskite oxide layer 130 and depositing one or more monolayers 140 of neodymium oxide or aluminum oxide may include using a growth technique or process capable of achieving individual control of the metal flux on the fly in the method 200. For instance, such a growth technique or process enables quickly shutting off either Nd or Al from being deposited after both were previously being deposited. For example, the NAO being deposited 220 for the twin-free perovskite oxide layer 130 in method 200 would have both elements Nd and Al being deposited to form NAO, and then one of those elements would be stopped from being deposited to thereby provided the deposition of the monolayer(s) 140 of neodymium oxide or aluminum oxide, as described herein. In an example, the aforementioned growth technique or process is or includes one or more of: molecular beam epitaxy (MBE), sputtering, and pulsed laser deposition (PLD). In another example, that growth technique or process is MBE.

[0084] In some embodiments, from one to up to four monolayers 140 of neodymium oxide or aluminum oxide may be deposited in method 200. Notably, depositing just one monolayer 140 of neodymium oxide or aluminum oxide may require NAO to be perfectly, or very nearly perfectly, stoichiometric. As such, depositing two monolayers 140 of neodymium oxide or aluminum oxide in method 200 may be more practically feasible in some applications of method 200. In one embodiment of method 200 where two or more monolayers 140 of neodymium oxide or aluminum oxide are deposited, the monolayers 140 may alternate from neodymium oxide to aluminum oxide. In some embodiments, depositing 220 the twin-free perovskite oxide layer 130 in method 200 may include depositing the twin-free perovskite oxide layer 130 including a specific excess amount of either Nd or Al to thereby provide a defined NAO surface termination at any given temperature.

[0085] Embodiments of method 200 according to the present technology may be practiced to manufacture the new material as, e.g., wafers 100, including twin-free perovskite oxide layer 130 formed of PAO. In an example, the method 200 step of depositing 220 the twin-free perovskite oxide layer 130 may include depositing the twin-free perovskite oxide layer 130 including PAO. In cases of wafers 100 manufactured according to the present technology using method 200 that have twin-free perovskite oxide layers 130 predominantly formed of PAO, an amount of another rare earth element besides Pr may be included to a lesser extent as compared to the Pr in PAO (e.g., < 50% of the another rare earth element). In an example, the method 200 step of depositing 220 the twin-free perovskite oxide layer 130 may also include depositing the twin-free perovskite oxide layer 130 further including La, Y, or Nd. In another example, the method 200 step of depositing 220 the twin-free perovskite oxide layer 130 may include depositing the twin-free perovskite oxide layer 130 further including two or more of La, Y, or Nd. In some embodiments, depositing 220 the twin-free perovskite oxide layer 130 in method 200 may include doping the PAO with La, Y, or Nd. In other embodiments, depositing

220 the twin-free perovskite oxide layer 130 in method 200 may include doping the PAO with two or more of La, Y, and Nd. In one embodiment, method 200 may include the step of controlling, during depositing 220 the twin-free perovskite oxide layer 130, an amount of La, Y, or Nd to thereby also control a resultant amount of the residual in-plane biaxial tensile strain of the twin-free perovskite oxide layer 130.

[0086] Referring again to FIG. 1, in some embodiments, method 200 may include depositing one or more monolayers 140 of praseodymium oxide or aluminum oxide on a top surface 150 of the twin-free perovskite oxide layer 130 opposite the strain control layer 120 to prevent a temperature dependent surface termination property of stoichiometric PAO from occurring. In an example, depositing the one or more monolayers 140 of praseodymium oxide or aluminum oxide may include depositing up to four monolayers of praseodymium oxide or aluminum oxide on the top surface 150 of the twin-free perovskite oxide layer 130. In another example, depositing the one or more monolayers of praseodymium oxide or aluminum oxide may include depositing two monolayers of praseodymium oxide or aluminum oxide on the top surface 150 of the twin-free perovskite oxide layer 130.

[0087] In one embodiment, the method 200 step of depositing 220 the twin-free perovskite oxide layer 130 may include controlling the depositing 220 of the twin-free perovskite oxide layer 130 on the strain control layer 120 such that the one or more monolayers 140 of praseodymium oxide or aluminum oxide are formed on the top surface 150 of the twin-free perovskite oxide layer 130 opposite the strain control layer 120 to thereby prevent temperature dependent surface termination property of stoichiometric PAO from occurring in the wafer 100 product. To achieve this advantageous property in wafers 100 fabricated according to the present technology, the method 200 step of controlling the depositing 220 of the twin-free perovskite oxide layer 130 may include gradually forming the one or more monolayers 140 of praseodymium oxide or aluminum oxide under process conditions that are both different from the conditions used for forming the remainder of the twin-free perovskite oxide layer 130, and sufficient to form the one or more monolayers 140. As such, method 200 may further include the step of preventing the temperature dependent surface termination property of stoichiometric PAO from occurring.

[0088] In some embodiments, one or both of the aforementioned method 200 steps of depositing 220 the twin-free perovskite oxide layer 130 and depositing one or more monolayers

140 of praseodymium oxide or aluminum oxide may include using a growth technique or process capable of achieving individual control of the metal flux on the fly in the method 200. For instance, such a growth technique or process enables quickly shutting off either Pr or Al from being deposited after both were previously being deposited. For example, the PAO being deposited 220 for the twin-free perovskite oxide layer 130 in method 200 would have both elements Pr and Al being deposited to form NAO, and then one of those elements would be stopped from being deposited to thereby provided the deposition of the monolayer(s) 140 of praseodymium oxide or aluminum oxide, as described herein. In an example, the aforementioned growth technique or process is or includes one or more of: molecular beam epitaxy (MBE), sputtering, and pulsed laser deposition (PLD). In another example, that growth technique or process is MBE.

[0089] In some embodiments, from one to up to four monolayers 140 of praseodymium oxide or aluminum oxide may be deposited in method 200. Notably, depositing just one monolayer 140 of praseodymium oxide or aluminum oxide may require NAO to be perfectly, or very nearly perfectly, stoichiometric. As such, depositing two monolayers 140 of praseodymium oxide or aluminum oxide in method 200 may be more practically feasible in some applications of method 200. In one embodiment of method 200 where two or more monolayers 140 of praseodymium oxide or aluminum oxide are deposited, the monolayers 140 may alternate from praseodymium oxide to aluminum oxide. In some embodiments, depositing 220 the twin-free perovskite oxide layer 130 in method 200 may include depositing the twin-free perovskite oxide layer 130 including a specific excess amount of either Pr or Al to thereby provide a defined PAO surface termination at any given temperature.

[0090] Utilizing different rare earth aluminates (e.g., LAO, YAO, NAO, PAO) having isostructural similarity, and optionally mixing in different rare earth elements (e.g., La, Y, Nd, Pr) in depositing 220 the twin-free perovskite oxide layer 220 in method 200 may enable tuning of the process, and thus also the properties of the resultant wafer 100 to suit a particular product application or post-processing requirement. One advantage of the present technology in this regard is that YAO, NAO and PAO may enable accessing even smaller lattice parameters (e.g., 3.75 Å or smaller) as a substrate on top of the twin-free perovskite oxide layer 130 as compared to LAO. Accordingly, method 200 may also include the step of controlling the resultant amount of residual in-plane biaxial tensile strain of the twin-free perovskite layer 130 to thereby also control the depositing 220 of the twin-free perovskite oxide layer 130 to have a specified resultant lattice parameter. In an example, method 200 may further include controlling the depositing 220 of the twin-free perovskite oxide layer 130 to have a resultant lattice parameter of from 3.60 Å to 3.90 Å. In another example, method 200 may further include controlling the depositing 220 of the twin-free perovskite oxide layer 130 to have a resultant lattice parameter of from 3.75 Å to 3.90 Å. In yet another example, method 200 may further include controlling the depositing 220 of the twin-free perovskite oxide layer 130 to have a resultant lattice parameter of from 3.80 Å to 3.90 Å.

[0091] In one embodiment, the method 200 step of depositing 220 the twin-free perovskite oxide layer 130 may include depositing the twin-free perovskite layer 130 to have a specified thickness. In an example, depositing 220 the twin-free perovskite oxide layer 130 in method 200 may include depositing the twin-free perovskite layer 130 having a thickness of from 5 nm to 50 nm. In another example, depositing 220 the twin-free perovskite oxide layer 130 in method 200 may include depositing the twin-free perovskite layer 130 having a thickness of from about 5 nm to about 50 nm. In yet another example, depositing 220 the twin-free perovskite oxide layer 130 in method 200 may include depositing the twin-free perovskite layer 130 having a thickness of from 20 nm to 50 nm. In yet another example, depositing 220 the twin-free perovskite oxide layer 130 in method 200 may include depositing the twin-free perovskite layer 130 having a thickness of from about 20 nm to about 50 nm.

[0092] In some embodiments, method 200 may include at least one of etching, polishing, and annealing at least a portion of the twin-free perovskite oxide layer 130. In one embodiment, method 200 may include forming at least one device 160 in or on the twin-free perovskite oxide layer 130. In an example, forming the at least one device 160 in method may include forming the at least one device 160 in or on the twin-free perovskite layer 130 as at least one of: a microelectronic device, an optoelectronic device, a micro-electromechanical system (MEMS), an integrated circuit, a transistor, a sensor, a semiconductor device, a photocathode device, a solar water splitter device, a superconductor device, a photonic device, a Josephson junction, and a capacitor.

[0093] In one embodiment, method 200 may include forming, causing to be formed, and/or depositing a film or layer on the twin-free perovskite oxide layer 130 (e.g., on the top surface 150 thereof). In some embodiments, at least a portion of the twin-free perovskite oxide layer

130 (e.g., at least a portion of the top surface 150 thereof) may undergo post-processing after performance of the depositing 220 step in method 200 in preparation for the aforementioned forming, causing to be formed, and/or depositing the film or layer on the twin-free perovskite oxide layer 130. In an example, forming, causing to be formed, and/or depositing the film or layer in method 200 may include forming, causing to be formed, and/or depositing the film or layer as, or including, YBCO on the twin-free perovskite oxide layer 130. In another example, forming, causing to be formed, and/or depositing the film or layer in method 200 may include forming, causing to be formed, and/or depositing the film or layer as, or including, LMSO on the twin-free perovskite oxide layer 130. In yet another example, forming, causing to be formed, and/or depositing the film or layer in method 200 may include forming, causing to be formed, and/or depositing the film or layer as, or including, a magnetic oxide on the twin-free perovskite oxide layer 130. In still another example, forming, causing to be formed, and/or depositing the film or layer in method 200 may include forming, causing to be formed, and/or depositing the film or layer as, or including, supertetragonal BTO on the twin-free perovskite oxide layer 130.

[0094] Embodiments of the present technology shown and described herein may enable commercial and practical improvements to oxide (e.g., LAO) on silicon wafers and associated fabrication methods to thereby allow for LAO film growers to have access to a large area stain control/buffer layer substrate as Si wafers are available in large sizes (e.g., 8”, 12”), which can allow for either more time and cost-efficient mass production, or to test multiple devices at the same time, while simultaneously decreased per area costs of known processes for growing oxides like LAO directly on Si.

[0095] Fields of technological endeavor that the present technology may positively impact include epitaxial oxide thin film deposition, especially of high-Tc superconductors (e.g., a-axis oriented $YBa_2Cu_3O_7$) and magnetic oxides with out of plane magnetization. The ability to have larger area substrates for oxide deposition makes scalable manufacturing feasible. The integration with Si can allow devices such as sensors to be easily inserted into a silicon-compatible process flow.

EXAMPLE

[0096] FIG. 3 depicts a plot of out-of-plane 2theta/theta x-ray diffraction (XRD) results for a wafer (e.g., wafer 100) having the stack layers of FIG. 1 as fabricated using the method 200 according to FIG. 2, according to some embodiments of the present technology. The plot of FIG.

3 provides counts per second (cps) data for a 2theta/theta XRD scan. The XRD scan providing the data in FIG. 3 was carried out on a wafer 100 having its twin-free perovskite oxide layer 130 in the form of 20 nm LAO. The XRD results depicted in the plot of FIG. 3 shows highly crystalline LAO with a single orientation.

[0097] FIG. 4 depicts an image of a reflection high energy electron diffraction (RHEED) pattern for the top surface 150 of the twin-free perovskite oxide layer 130 of the wafer 100 corresponding to the XRD results of FIG. 3. The RHEED pattern shown in FIG. 4 is representative of the top surface 150 of the twin-free perovskite layer 130 formed of LAO taken along the pseudo cubic 210 direction. The RHEED pattern shown in FIG. 4 demonstrates that the top surface 150 is very flat and highly crystalline. Additionally, FIG. 4 shows that the LAO of wafer 100 is oriented as a single crystal in the 210 pseudo cubic orientation. The RHEED pattern confirms the absence of any spot/streak splitting due to twinning and also shows that the film is epitaxial with a flat surface. The results of FIG. 4 further demonstrate the action of the strain control layer 120 in the present technology. The LAO layer is strained by layer 120 to take on and maintain the cubic phase, resulting in a twin-free layer 130 on wafer 100.

Conclusion

[0098] Unless the context clearly requires otherwise, throughout the description and the claims, the words "comprise," "comprising," and the like are to be construed in an inclusive sense, as opposed to an exclusive or exhaustive sense; that is to say, in the sense of "including, but not limited to." As used herein, the terms "connected," "coupled," or any variant thereof means any connection or coupling, either direct or indirect, between two or more elements; the coupling or connection between the elements can be physical, logical, or a combination thereof. Additionally, the words "herein," "above," "below," and words of similar import, when used in this application, refer to this application as a whole and not to any particular portions of this application. Where the context permits, words in the above Detailed Description using the singular or plural number may also include the plural or singular number respectively. The word "or," in reference to a list of two or more items, covers all of the following interpretations of the word: any of the items in the list, all of the items in the list, and any combination of the items in the list.

[0099] The above Detailed Description of examples of the technology is not intended to be exhaustive or to limit the technology to the precise form disclosed above. While specific examples of the technology are described above for illustrative purposes, various equivalent modifications are possible within the scope of the technology, as those skilled in the relevant art will recognize. The teachings of the technology provided herein can be applied to other devices, systems and methods, not necessarily the devices, systems and methods described above. The elements and acts of the various examples described above can be combined to provide further implementations of the technology. Some alternative implementations of the technology may include not only additional elements to those implementations noted above, but also may include fewer elements.

[0100] These and other changes can be made to the technology in light of the above Detailed Description. While the above description describes certain examples of the technology, and describes the best mode contemplated, no matter how detailed the above appears in text, the technology can be practiced in many ways. Details of the above described embodiments may vary considerably in their specific implementations, while still being encompassed by the technology disclosed herein. As noted above, particular terminology used when describing certain features or aspects of the technology should not be taken to imply that the terminology is being redefined herein to be restricted to any specific characteristics, features, or aspects of the technology with which that terminology is associated. In general, the terms used in the following claims should not be construed to limit the technology to the specific examples disclosed in the specification, unless the above Detailed Description section explicitly defines such terms. Accordingly, the actual scope of the technology encompasses not only the disclosed examples, but also all equivalent ways of practicing or implementing the technology under the claims.

[0101] To reduce the number of claims, certain aspects of the technology are presented below in certain claim forms, but the applicant contemplates the various aspects of the technology in any number of claim forms. For example, while only one aspect of the technology is recited as a device or a system, other aspects may likewise be embodied as a method or a process of manufacturing or operating such device or system. In some cases, aspects of the technology may be embodied in a means-plus-function claim. Any claims intended to be treated under 35 U.S.C. § 112(f) will begin with the words "means for", but use of the term "for" in any other context is not intended to invoke treatment under 35 U.S.C. § 112(f). Accordingly, the applicant reserves the right to pursue additional claims after filing this application to pursue such additional claim forms, in either this application or in a continuing application.

CLAIMS

What is claimed is:

1. A wafer comprising:

a silicon (Si) substrate;

a strain control layer comprising strontium titanate (STO) or calcium titanate (CTO) formed on the Si substrate; and

a twin-free perovskite oxide layer comprising a single crystal rare earth aluminate formed on the strain control layer and having a residual in-plane biaxial tensile strain imposed at least in part by the strain control layer.

2. The wafer of claim 1, wherein an amount of the residual in-plane biaxial tensile strain, and thus also an in-plane lattice parameter, of the twin-free perovskite oxide layer depends at least in part on an amount of elastic energy stored in the strain control layer.

3. The wafer of claim 1, wherein the rare earth aluminate of the twin-free perovskite oxide layer has a cubic perovskite crystal structure.

4. The wafer of claim 1, wherein the twin-free perovskite oxide layer comprises epitaxial layers of the rare earth aluminate.

5. The wafer of claim 1, wherein a psuedo cubic lattice parameter of the twin-free perovskite oxide layer is from about 3.80 angstrom (Å) to about 3.90 Å.

6. The wafer of claim 1, wherein an amount of the residual in-plane biaxial tensile strain, and thus also an in-plane lattice parameter, of the twin-free perovskite oxide layer depends at least in part on the relative thicknesses of the strain control layer and the twin-free perovskite oxide layer.

7. The wafer of claim 1, wherein the strain control layer comprises STO.

8. The wafer of claim 7, wherein the strain control layer further comprises CTO.

9. The wafer of claim 8, wherein an amount of the residual in-plane biaxial tensile strain, and thus also an in-plane lattice parameter, of the twin-free perovskite oxide layer depends at least in part on an amount of CTO substituted for STO in the strain control layer.

10. The wafer of claim 1, wherein the strain control layer comprises CTO.

11. The wafer of claim 10, wherein the strain control layer further comprises STO.

12. The wafer of claim 11, wherein an amount of the residual in-plane biaxial tensile strain, and thus also an in-plane lattice parameter, of the twin-free perovskite oxide layer depends at least in part on an amount of STO substituted for CTO in the strain control layer.

13. The wafer of claim 1, wherein the rare earth aluminate is selected from the group consisting of: lanthanum aluminate (LAO), yttrium aluminate (YAO), neodymium aluminate (NAO), and praseodymium aluminate (PAO).

14. The wafer of claim 13, wherein the rare earth aluminate comprises LAO.

15. The wafer of claim 13 or claim 14, wherein the twin-free perovskite oxide layer further comprises yttrium (Y), neodymium (Nd), or praseodymium (Pr).

16. The wafer of claim 15, wherein an amount of the residual in-plane biaxial tensile strain, and thus also an in-plane lattice parameter, of the twin-free perovskite oxide layer depends at least in part on an amount of Y, Nd, or Pr in the twin-free perovskite oxide layer.

17. The wafer of claim 14, further comprising one or more monolayers of lanthanum oxide or aluminum oxide formed on a top surface of the twin-free perovskite oxide layer opposite the strain control layer to prevent a temperature dependent surface termination property of stoichiometric LAO from occurring.

18. The wafer of claim 14, wherein the twin-free perovskite oxide layer includes a specific excess amount of either lanthanum (La) or aluminum (Al) to thereby provide a defined LAO surface termination at any given temperature.

19. The wafer of claim 1, wherein the strain control layer comprises a step-graded strain control layer.

20. The wafer of claim 1, wherein the strain control layer comprises a continuously graded strain control layer.

21. The wafer of claim 1, wherein the Si substrate is an Si wafer.

22. The wafer of claim 21, wherein the Si wafer has a diameter of from about 1 inch to about 18 inches.

23. The wafer of claim 1, wherein the Si substrate is a silicon-on-insulator (SOI) wafer.

24. The wafer of claim 23, wherein the SOI wafer has a diameter of from about 1 inch to about 18 inches.

25. The wafer of claim 1, wherein the twin-free perovskite oxide layer comprises epitaxial LAO.

26. The wafer of claim 1, wherein the twin-free perovskite oxide layer is integrated epitaxially onto the Si substrate via the strain control layer.

27. The wafer of claim 1 further comprising at least one device formed in or on the twin-free perovskite oxide layer.

28. The wafer of claim 27, wherein the at least one device includes at least one of: a microelectronic device, an optoelectronic device, a micro-electromechanical system (MEMS), an integrated circuit, a transistor, a sensor, a semiconductor device, a photocathode device, a solar

water splitter device, a superconductor device, a photonic device, a Josephson junction, and a capacitor.

29. The wafer of claim 1, wherein the Si substrate comprises silicon (001).

30. The wafer of claim 29, wherein the strain control layer comprises at least one of STO (001) and CTO (001).

31. The wafer of claim 1, wherein the Si substrate comprises silicon (111).

32. The wafer of claim 31, wherein the twin-free perovskite oxide layer comprises STO (111).

33. The wafer of claim 1, wherein the twin-free perovskite oxide layer has a thickness of from about 5 nanometers (nm) to about 50 nm.

34. The wafer of claim 1 further comprising a film or layer formed on the twin-free perovskite oxide layer.

35. The wafer of claim 34, wherein the film or layer formed on the twin-free perovskite oxide layer comprises yttrium barium copper oxide (YBCO), lanthanum strontium manganite (LMSO), a magnetic oxide, or supertetragonal BTO.

36. A method comprising:

depositing, on a silicon (Si) substrate, a strain control layer comprising strontium titanate (STO) or calcium titanate (CTO); and

depositing, on the strain control layer, a twin-free perovskite oxide layer comprising a single crystal rare earth aluminate and having a residual in-plane biaxial tensile strain imposed at least in part by the strain control layer.

37. The method of claim 36 further comprising removing, prior to depositing the strain control layer, native oxide from a surface of the Si substrate upon which the strain control layer is to be deposited.

38. The method of claim 37, wherein the strain control layer comprises STO, and wherein the removing step comprises removing the native oxide using a strontium (Sr)-assisted oxide desorption process.

39. The method of claim 38, further comprising chemisorbing about a quarter (¼) to about a half (½) monolayer of Sr onto the surface of the Si substrate after the removing and prior to depositing the strain control layer.

40. The method of claim 37, wherein the strain control layer comprises CTO, and wherein the removing step comprises removing the native oxide using a calcium (Ca)-assisted oxide desorption process.

41. The method of claim 40, further comprising chemisorbing about a quarter (¼) to about a half (½) monolayer of Ca onto the surface of the Si substrate after the removing and prior to depositing the strain control layer.

42. The method of claim 36, wherein depositing the strain control layer comprises depositing STO or CTO on the Si substrate using molecular-beam epitaxy (MBE).

43. The method of claim 42, wherein depositing the strain control layer further comprises first depositing a portion of the strain control layer on the Si substrate using MBE and second depositing a remainder of the strain control layer using radio frequency (RF) sputtering or pulsed laser deposition (PLD).

44. The method of claim 36 further comprising crystallizing the STO or CTO of the strain control layer in vacuum.

45. The method of claim 36 further comprising annealing the strain control layer at a temperature of from about 500 to about 600 °C.

46. The method of claim 36, wherein depositing the twin-free perovskite oxide layer comprises forming the twin-free perovskite oxide layer comprising epitaxial layers of the rare earth aluminate.

47. The method of claim 36, wherein depositing the twin-free perovskite oxide layer comprises forming the twin-free perovskite oxide layer having a psuedo cubic lattice parameter of from about 3.80 angstrom (Å) to about 3.90 Å.

48. The method of claim 36 further comprising controlling, during depositing the strain control layer on the Si substrate, an amount of elastic energy stored in the strain control layer to thereby also control a resultant amount of the residual in-plane biaxial tensile strain of the twin-free perovskite oxide layer.

49. The method of claim 36 further comprising controlling, during depositing the strain control layer and during depositing the twin-free perovskite oxide layer, relative thicknesses of the strain control layer and the perovskite oxide layer to thereby also control a resultant amount of the residual in-plane biaxial tensile strain of the twin-free perovskite oxide layer.

50. The method of claim 36, wherein depositing the strain control layer comprises depositing the strain control layer comprising STO.

51. The method of claim 50, wherein depositing the strain control layer comprises depositing the strain control layer further comprising CTO.

52. The method of claim 51 further comprising controlling, during depositing the strain control layer, an amount of CTO in the strain control layer to thereby also control a resultant amount of the residual in-plane biaxial tensile strain of the twin-free perovskite oxide layer.

53. The method of claim 36, wherein depositing the strain control layer comprises depositing the strain control layer comprising CTO.

54. The method of claim 53, wherein depositing the strain control layer comprises depositing the strain control layer further comprising STO.

55. The method of claim 54 comprising controlling, during depositing the strain control layer, an amount of STO in the strain control layer to thereby also control a resultant amount of the residual in-plane biaxial tensile strain of the twin-free perovskite oxide layer.

56. The method of claim 36, wherein depositing the twin-free perovskite oxide layer comprises depositing the twin-free perovskite oxide layer comprising the rare earth aluminate selected from the group consisting of: lanthanum aluminate (LAO), yttrium aluminate (YAO), neodymium aluminate (NAO), and praseodymium aluminate (PAO).

57. The method of claim 56, wherein depositing the twin-free perovskite oxide layer comprises depositing the twin-free perovskite oxide layer comprising LAO.

58. The method of claim 57, wherein depositing the twin-free perovskite oxide layer comprises depositing the twin-free perovskite oxide layer further comprising yttrium (Y), neodymium (Nd), or praseodymium (Pr).

59. The method of claim 58, further comprising controlling, during depositing the twin-free perovskite oxide layer, an amount of Y, Nd, or Pr to thereby also control a resultant amount of the residual in-plane biaxial tensile strain of the twin-free perovskite oxide layer.

60. The method of claim 57 further comprising depositing one or more monolayers of lanthanum oxide or aluminum oxide on a top surface of the twin-free perovskite oxide layer opposite the strain control layer to prevent a temperature dependent surface termination property of stoichiometric LAO from occurring.

61. The method of claim 60, wherein depositing the twin-free perovskite oxide layer comprises controlling the depositing of the twin-free perovskite oxide layer on the strain control layer such that one or more monolayers of lanthanum oxide or aluminum oxide are formed on a top surface of the twin-free perovskite oxide layer opposite the strain control layer to prevent a temperature dependent surface termination property of stoichiometric LAO from occurring.

62. The method of claim 61, wherein controlling the depositing of the twin-free perovskite oxide layer comprises gradually forming the one or more monolayers of lanthanum oxide or aluminum oxide under process conditions that are: different from the conditions used for forming the remainder of the twin-free perovskite oxide layer, and sufficient to form the one or more monolayers.

63. The method of claim 62 further comprising preventing the temperature dependent surface termination property of stoichiometric LAO from occurring.

64. The method of any one of claims 60-63, wherein the steps of: depositing the twin-free perovskite oxide layer, or depositing one or more monolayers of lanthanum oxide or aluminum oxide, comprises using a growth technique or process capable of achieving individual control of the metal flux on the fly in the method.

65. The method of claim 64, wherein the growth technique or process is or includes one or more of: molecular beam epitaxy (MBE), sputtering, and pulsed laser deposition (PLD).

66. The method of claim 65, wherein the growth technique or process is MBE.

67. The method of claim 57, wherein depositing the twin-free perovskite oxide layer comprises depositing the twin-free perovskite oxide layer including a specific excess amount of either lanthanum (La) or aluminum (Al) to thereby provide a defined LAO surface termination at any given temperature.

68. The method of claim 59, further comprising controlling the resultant amount of residual in-plane biaxial tensile strain of the twin-free perovskite layer to thereby also control the depositing of the twin-free perovskite oxide layer to have a specified resultant lattice parameter.

69. The method of claim 68 further comprising controlling the depositing of the twin-free perovskite oxide layer to have a resultant lattice parameter of from about 3.60 Å to about 3.90 Å.

70. The method of claim 36, wherein depositing the strain control layer comprises depositing a step-graded strain control layer on the Si substrate.

71. The method of claim 36, wherein depositing the strain control layer comprises depositing a continuously graded strain control layer on the Si substrate.

72 The method of claim 36, wherein depositing the strain control layer comprises forming the strain control layer on an Si wafer.

73. The method of claim 36, wherein depositing the strain control layer on the Si wafer comprises forming the strain control layer on an Si wafer having a diameter of from about 1 inch to about 18 inches.

74. The method of claim 36, wherein depositing the strain control layer comprises forming the strain control layer on a silicon-on-insulator (SOI) wafer.

75. The method of claim 74, wherein depositing the strain control layer on the SOI wafer comprises forming the strain control layer on an SOI wafer having a diameter of from about 1 inch to about 18 inches.

76. The method of claim 36 further comprising forming at least one device in or on the twin-free perovskite oxide layer.

77. The method of claim 76, wherein forming the at least one device comprises forming the at least one device in or on the twin-free perovskite layer as at least one of: a microelectronic device, an optoelectronic device, a micro-electromechanical system (MEMS), an integrated circuit, a transistor, a sensor, a semiconductor device, a photocathode device, a solar water splitter device, a superconductor device, a photonic device, a Josephson junction, and a capacitor.

78. The method of claim 36 further comprising at least one of: etching, polishing, and annealing, at least a portion of the twin-free perovskite oxide layer.

79. The method of claim 36, wherein depositing the strain control layer comprises depositing the strain control layer on an Si (001) substrate.

80. The method of claim 79, wherein depositing the strain control layer comprises forming the strain control layer comprising at least one of STO (001) and CTO (001) on the Si (001) substrate.

81. The method of claim 36, wherein depositing the strain control layer comprises depositing the strain control layer on an Si (111) substrate.

82. The method of claim 81, wherein depositing the strain control layer comprises forming the strain control layer comprising at least one of STO (111) and CTO (111) on the Si (111) substrate.

83. The method of claim 36, wherein depositing the twin-free perovskite oxide layer comprises depositing the twin-free perovskite layer having a thickness of from about 5 nanometers (nm) to about 50 nm.

84. The method of claim 36 further comprising depositing a film or layer on the twin-free perovskite oxide layer.

85. The method of claim 84, wherein depositing the film or layer comprises depositing a film or layer of yttrium barium copper oxide (YBCO), lanthanum strontium manganite (LMSO), a magnetic oxide, or supertetragonal BTO, on the twin-free perovskite oxide layer.

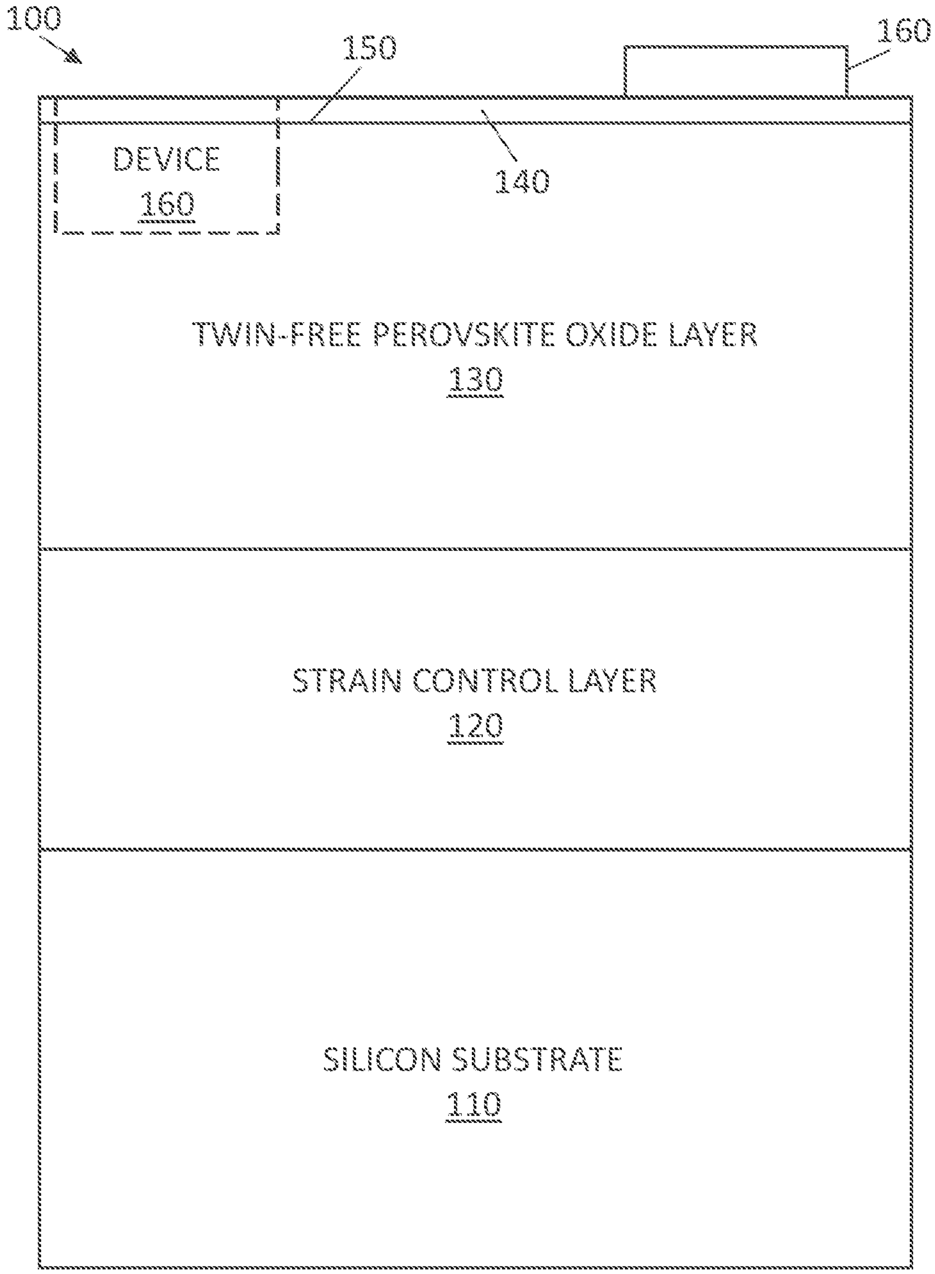
100
150
160
DEVICE
160
140
TWIN-FREE PEROVSKITE OXIDE LAYER
130
STRAIN CONTROL LAYER
120
SILICON SUBSTRATE
110

FIG. 1

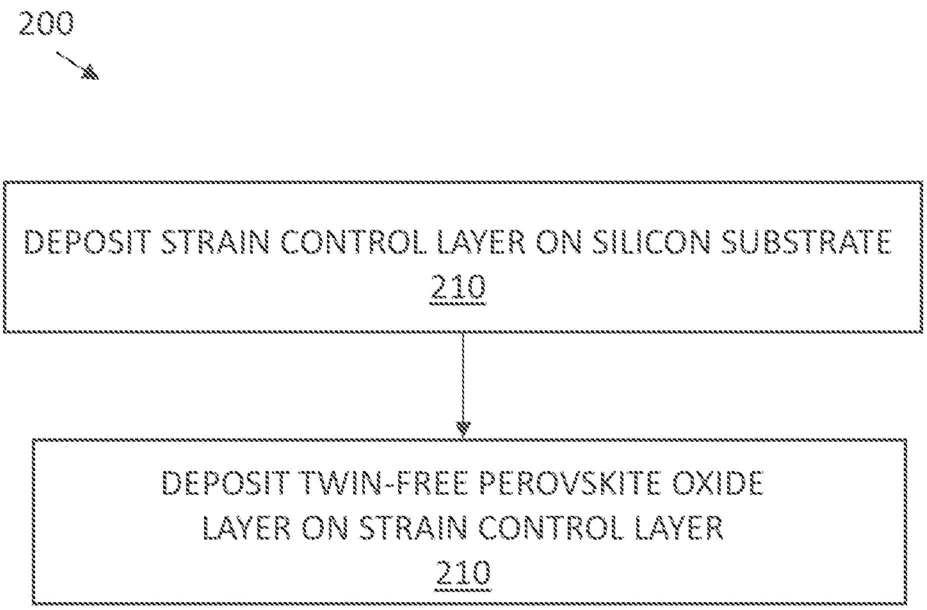
200
DEPOSIT STRAIN CONTROL LAYER ON SILICON SUBSTRATE
210
DEPOSIT TWIN-FREE PEROVSKITE OXIDE
LAYER ON STRAIN CONTROL LAYER
210

FIG. 2

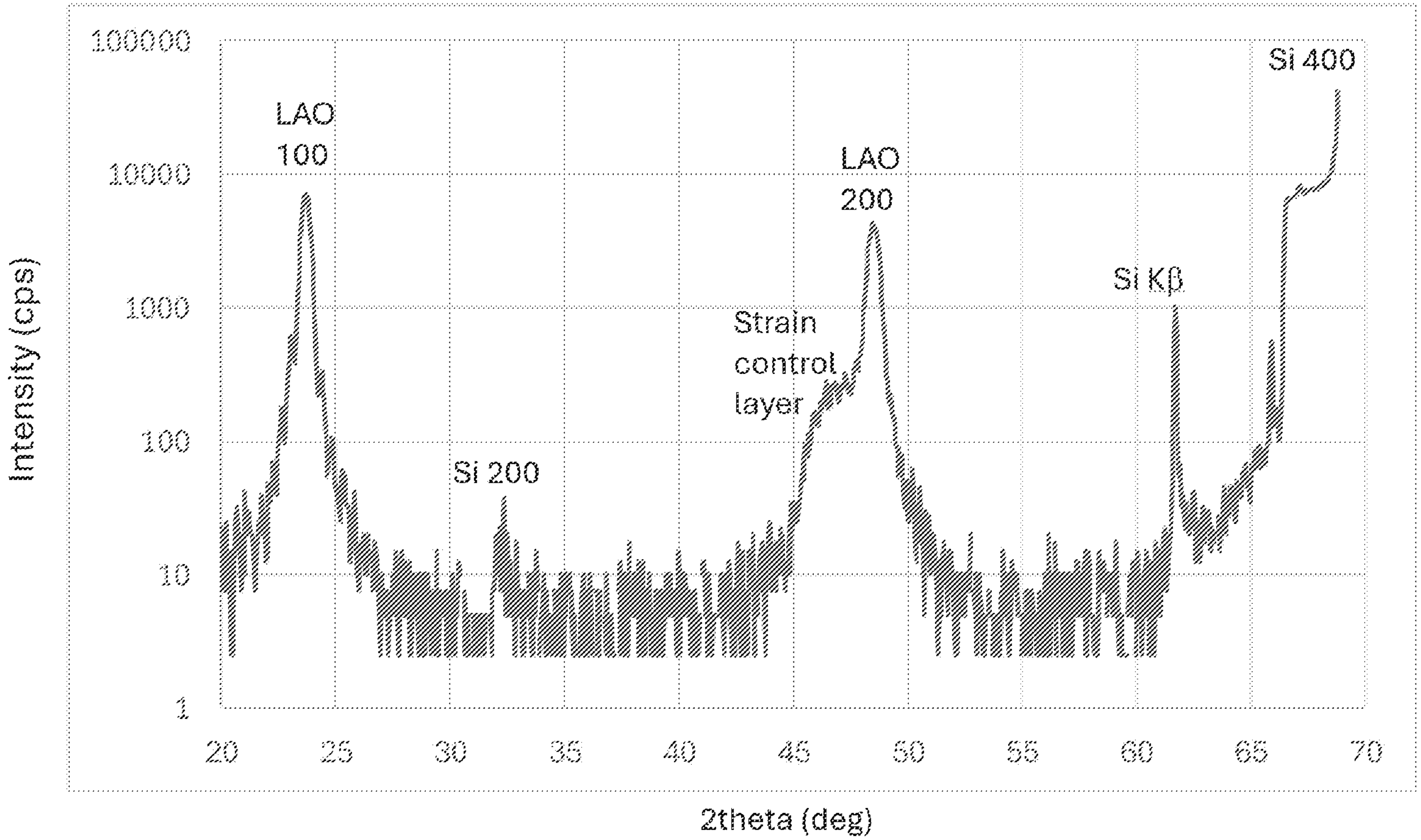
Intensity (cps)
100000
10000
1000
100
10
1
20
25
30
35
40
45
50
55
60
65
70
2theta (deg)
LAO 100
Si 200
Strain control layer
LAO 200
Si Kβ
Si 400

FIG. 3

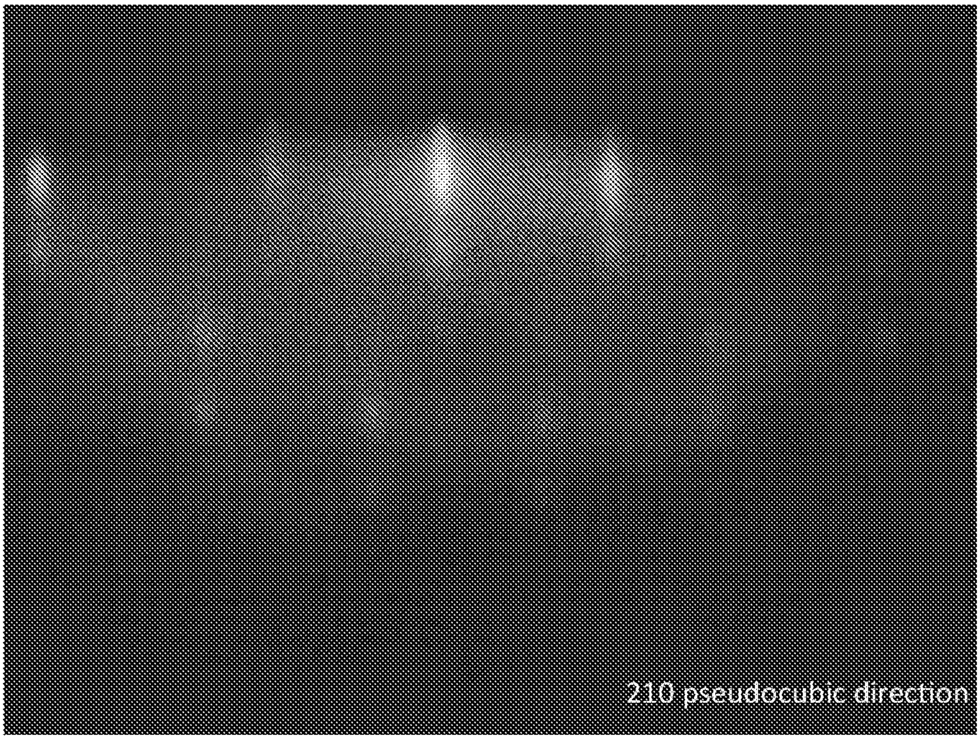

FIG. 4