

SEMICONDUCTOR STRUCTURE HAVING A CRYSTALLINE ALKALINE
EARTH METAL OXIDE INTERFACE WITH SILICON

Field of the Invention

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The present invention relates in general to a semiconductor structure including a crystalline alkaline earth metal oxide interface between a silicon substrate and other oxides, and more particularly to an interface including an atomic layer of an alkaline earth metal, silicon, and oxygen.

Background of the Invention

15 An ordered and stable silicon (Si) surface is most desirable for subsequent epitaxial growth of single crystal thin films on silicon for numerous device applications, e.g., ferroelectrics or high dielectric constant oxides for non-volatile high density memory and logic devices. It is pivotal to establish an ordered transition layer on the Si surface, especially for subsequent growth of single crystal oxides, e.g., perovskites.

Some reported growth of these oxides, such as BaO and BaTiO₃ on Si(100) was based on a BaSi₂ (cubic) template by depositing one fourth monolayer of Ba on Si(100) using reactive epitaxy at temperatures greater than 850°C. See for example: R. McKee et al., *Appl. Phys. Lett.* 59(7), pp 782-784 (12 August 1991); R. McKee et al., *Appl. Phys. Lett.* 63(20), pp. 2818-2820 (15 November 1993); R. McKee et al., *Mat. Res. Soc. Symp. Proc.*, Vol. 21, pp. 131-135 (1991); U.S. Patent No. 5,225,031, issued July 6, 1993, entitled "Process for Depositing an Oxide

Epitaxially onto a Silicon Substrate and Structures Prepared with the Process"; and U.S. Patent No. 5,482,003, issued January 9, 1996, entitled "Process for Depositing Epitaxial Alkaline Earth Oxide onto a Substrate and Structures Prepared with the Process". However, atomic level simulation of this proposed structure indicates that it likely is not stable at elevated temperatures.

Growth of SrTiO_3 on silicon (100) using an SrO buffer layer has been accomplished. T. Tambo et al., *Jpn. J. Appl. Phys.*, Vol. 37 (1998), pp. 4454-4459. However, the SrO buffer layer was thick (100Å), thereby limiting application for transistor films, and crystallinity was not maintained throughout the growth.

Furthermore, SrTiO_3 has been grown on silicon using thick metal oxide buffer layers (60-120Å) of Sr or Ti. B. K. Moon et al., *Jpn. J. Appl. Phys.*, Vol. 33 (1994), pp. 1472-1477. These thick buffer layers would limit the application for transistors.

Therefore, a thin, stable crystalline interface with silicon is needed.

Brief Description of the Drawings

FIGs. 1-2 illustrate a cross-sectional view of a clean semiconductor substrate having an interface formed thereon in accordance with the present invention;

FIGs. 3-6 illustrate a cross-sectional view of a semiconductor substrate having an interface formed from a silicon dioxide layer in accordance with the present invention; and

FIGs. 7-8 illustrate a cross-sectional view of an alkaline-earth-metal oxide layer formed on the structures

illustrated in FIGs. 1-6 in accordance with the present invention.

FIGs. 9-12 illustrate a cross-sectional view of a perovskite formed on the structures of FIGs. 1-8 in accordance with the present invention.

FIG. 13 illustrates a side view of the atomic structure of one embodiment of the layers of FIG. 12 in accordance with the present invention.

FIG. 14 illustrates a top view along view line AA of FIG. 13 of the interface.

FIG. 15 illustrates a top view along view line AA of FIG. 13 including the interface and the adjacent atomic layer of the substrate.

Detailed Description of the Preferred Embodiment

To form the novel interface between a silicon (Si) substrate and one or more layers of a single crystal oxide, various approaches may be used. Several examples will be provided for both starting with a Si substrate having a clean surface, and a Si substrate having silicon dioxide (SiO_2) on the surface. SiO_2 is amorphous rather than single crystalline and it is desirable for purposes of growing additional single crystal material on the substrate that a single crystal oxide be provided as the interface.

Turning now to the drawings in which like elements are designated with like numbers throughout, FIGs. 1 and 2 illustrate a semiconductor structure including a Si substrate 10 having a clean surface 12. A clean (2x1) surface 12 may be obtained with any conventional cleaning procedure, for example, with thermal desorption of SiO_2 at a temperature greater than or equal to 850°C , or by

removal of the hydrogen from a hydrogen terminated Si(1x1) surface at a temperature greater than or equal to 300°C in an ultra high vacuum. Hydrogen termination is a well known process in which hydrogen is loosely bonded to dangling bonds of the silicon atoms at surface 12 to complete the crystalline structure. The interface 14 of a crystalline material may be formed by supplying (as shown by the arrows in FIG. 1) controlled amounts of a metal, Si, and O₂, either simultaneously or sequentially to the surface 12 at a temperature less than or equal to 900°C in a growth chamber with O₂ partial pressure less than or equal to 1×10^{-9} mBar. The metal applied to the surface 12 to form the interface 14 may be any metal, but in the preferred embodiment comprises an alkaline-earth-metal, such as barium (Ba) or strontium (Sr).

As the application of the Ba, Si, and O₂ form BaSiO₂ as the interface 14, the growth is monitored using Reflection High Energy Electron Diffraction (RHEED) techniques which are well documented in the art and which can be used in situ, i.e., while performing the exposing step within the growth chamber. The RHEED techniques are used to detect or sense surface crystalline structures and in the present process change rapidly to strong and sharp streaks by the forming of an atomic layer of the BaSiO₂. It will of course be understood that once a specific manufacturing process is provided and followed, it may not be necessary to perform the RHEED techniques on every substrate.

The novel atomic structure of the interface 14 will be described in subsequent paragraphs.

It should be understood by those skilled in the art that the temperatures and pressures given for these processes are recommended for the particular embodiment

described, but the invention is not limited to a particular temperature or pressure range.

Referring to FIGs. 3-6, another approach comprises forming a Si substrate 10 having a surface 12, and a
5 layer 16 of SiO₂ thereupon. The layer 16 of SiO₂ naturally exists (native oxide) once the Si substrate 10 is exposed to air (oxygen) or it may be formed purposely in a controlled fashion well known in the art, e.g., thermally by applying (arrows) oxygen onto the surface
10 12. The novel interface 14 may be formed at least in one of the two suggested embodiments as follows: By applying an alkaline-earth-metal to the surface 18 of SiO₂ layer 16 at 700-900°C, under an ultra high vacuum. More specifically, the Si substrate 10 and the amorphous SiO₂
15 layer 16 are heated to a temperature below the sublimation temperature of the SiO₂ layer 16 (generally below 900°C). This can be accomplished in a molecular beam epitaxy chamber or Si substrate 10 can be at least partially heated in a preparation chamber after which it
20 can be transferred to the growth chamber and the heating completed. Once the Si substrate 10 is properly heated and the pressure in the growth chamber has been reduced appropriately, the surface 12 of the Si substrate 10 having SiO₂ layer 16 thereon is exposed to a beam of
25 metal, preferably an alkaline-earth-metal, as illustrated in FIG. 5. In a preferred embodiment, the beam is Ba or Sr which is generated by resistively heating effusion cells or from e-beam evaporation sources. In a specific example, Si substrate 10 and SiO₂
30 layer 16 are exposed to a beam of Ba. The Ba joins the SiO₂ and converts the SiO₂ layer 16 into the interface 14 comprising BaSiO₂ in a crystalline form. Alternatively, an alkaline-earth-metal may be provided to the surface 18

at lower temperatures, annealing the result at 700-900°C, in an ultra high vacuum.

Once the interface 14 is formed, one or more layers of a single crystal oxide may be formed on the surface of the interface 14. However, an optional layer of an alkaline-earth-metal oxide, such as BaO or SrO, may be placed between the interface 14 and the single crystal oxide. This alkaline-earth-metal oxide provides a low dielectric constant (advantageous for certain uses such as memory cells) and also prevents oxygen from migrating from the single crystal oxide to the Si substrate 10.

Referring to FIGs. 7 and 8, the formation of alkaline-earth-metal oxide layer 22 may be accomplished by either the simultaneous or alternating supply to the surface 20 of the interface 14 of an alkaline-earth-metal and oxygen at less than or equal to 700°C and under O₂ partial pressure less than or equal to 1×10^{-5} mBar. This alkaline-earth-metal oxide layer 22 may, for example, comprise a thickness of 50-500 Å.

Referring to FIGs. 9-12, a single crystal oxide layer 26, such as an alkaline-earth-metal perovskite, may be formed on either the surface 20 of the interface 14 or the surface 24 of the alkaline-earth-metal oxide layer 22 by either the simultaneous or alternating supply of an alkaline-earth-metal oxide, oxygen, and a transition metal, such as titanium, at less than or equal to 700°C under an oxygen partial pressure less than or equal to 1×10^{-5} mBar. This single crystal oxide layer 26 may, for example, comprise a thickness of 50-1000 Å and will be substantially lattice matched with the underlying interface 14 or alkaline-earth-metal oxide layer 22. It should be understood that the single crystal oxide layer 26 may comprises one or more layers in other embodiments.

Referring to FIG. 13, a side view (looking in the $\langle 110 \rangle$ direction) of the atomic configuration of the Si substrate 10, interface 14, and alkaline-earth-metal metal oxygen layer 26 is shown. The configuration shown comprises, in relative sizes, for illustrative purposes, from larger to smaller, barium atoms 30, silicon atoms 32, oxygen atoms 34, and titanium atoms 36. The Si substrate 10 comprises only silicon atoms 32. The interface 14 comprises metal atoms (which in the preferred embodiment are illustrated as barium atoms 30), silicon atoms 32, and oxygen atoms 34. The alkaline-earth-metal metal oxygen layer 26 comprises barium atoms 30, oxygen atoms 34, and titanium atoms 36.

Referring to FIG. 14, a top view of the interface along view line AA of FIG. 13, shows the arrangement of the barium, silicon, and oxygen atoms 30, 32, 34.

Referring to FIG. 15, a top view along line AA of FIG. 13, shows the interface 14 and the top atomic layer 11 of the Si substrate 10.

For this discussion, a monolayer equals 6.8×10^{14} atoms/cm² and an atomic layer is one atom thick. It is seen that the interface 14 shown in the FIGs. comprises a single atomic layer, but could be more than one atomic layer, while the Si substrate 10 and the alkaline-earth-metal metal oxide layer may be many atomic layers. Note that in FIG. 13, only four atomic layers of the Si substrate 10 and only three atomic layers of the alkaline-earth-metal metal oxide layer 26 are shown. The interface 14 comprises a half monolayer of the alkaline-earth-metal, a half monolayer of silicon, and a monolayer of oxygen. Each barium atom 30 is substantially equally spaced from four of the silicon atoms 32 in the Si

substrate 10. The silicon atoms 32 in the interface 14 are substantially on a line and equally spaced between the alkaline-earth-metal atoms in the $\langle 110 \rangle$ direction. Each silicon atom 32 in the top layer of atoms in the Si
5 substrate 10 is bonded to an oxygen atom 34 in the interface 14 and each silicon atom 32 in the interface 14 is bonded to two oxygen atoms 34 in the interface 14. The interface 14 comprises rows of barium, silicon, and oxygen atoms 30, 32, 34 in a 2X1 configuration on a (001)
10 surface of the Si substrate 10, 1X in the $\langle \bar{1}10 \rangle$ direction and 2X in the $\langle 110 \rangle$ direction. The interface 14 has a 2X1 reconstruction.

A thin, crystalline interface 14 with silicon 10 has been described herein. The interface 14 may comprise a
15 single atomic layer. Better transistor applications are achieved by the interface 14 being thin, in that the electrical coupling of the overlying oxide layers to the Si substrate is not compromised, and in that the interface 14 is more stable since the atoms will more
20 likely maintain their crystallinity in processing.



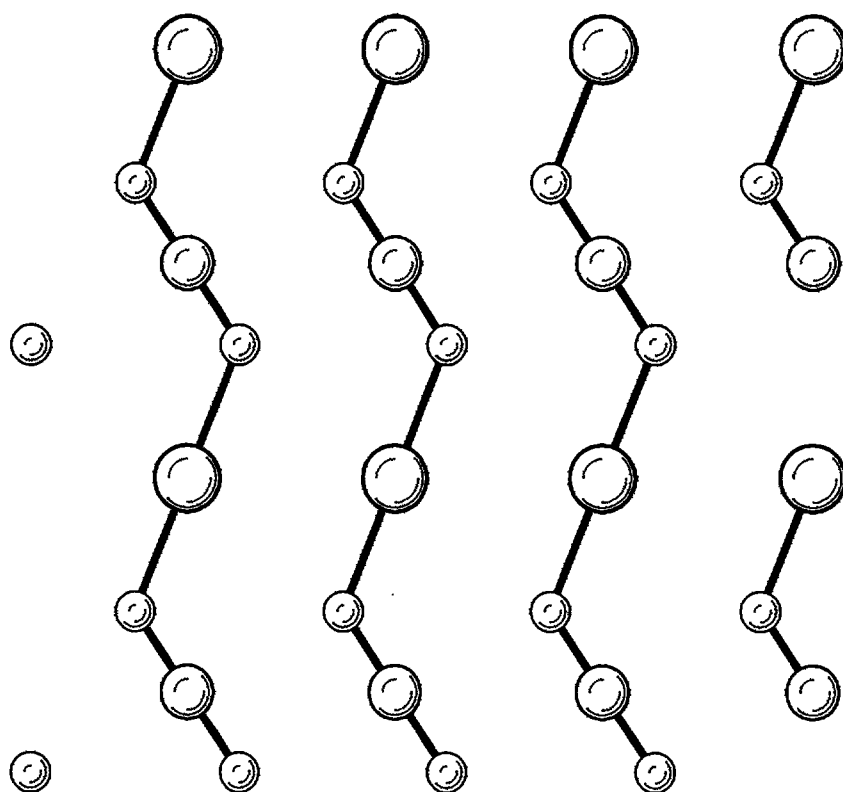
CLAIMS

What is claimed is:

- 5 1. A semiconductor structure comprising:
a silicon substrate;
one or more layers of single crystal oxides; and
an interface between the silicon substrate and the
one or more layers of single crystal oxides, the
10 interface comprising an atomic layer of a crystalline
material which matches the lattice constant of silicon,
the crystalline material comprising silicon, oxygen, and
a metal.
- 15 2. The semiconductor structure of claim 1 wherein the
one or more layers of single crystal oxides comprises an
oxide layer formed adjacent the interface, the oxide
layer having a first oxygen atom adjacent and aligned in
the <001> direction with a metal atom in the interface,
20 and having a second oxygen atom adjacent and aligned in
the <001> direction with a silicon atom in the interface.
3. The semiconductor structure of claim 1 wherein the
atomic layer of the interface comprises the structure
25 including metal atoms, silicon atoms, and oxygen atoms in
relative size from larger to smaller:

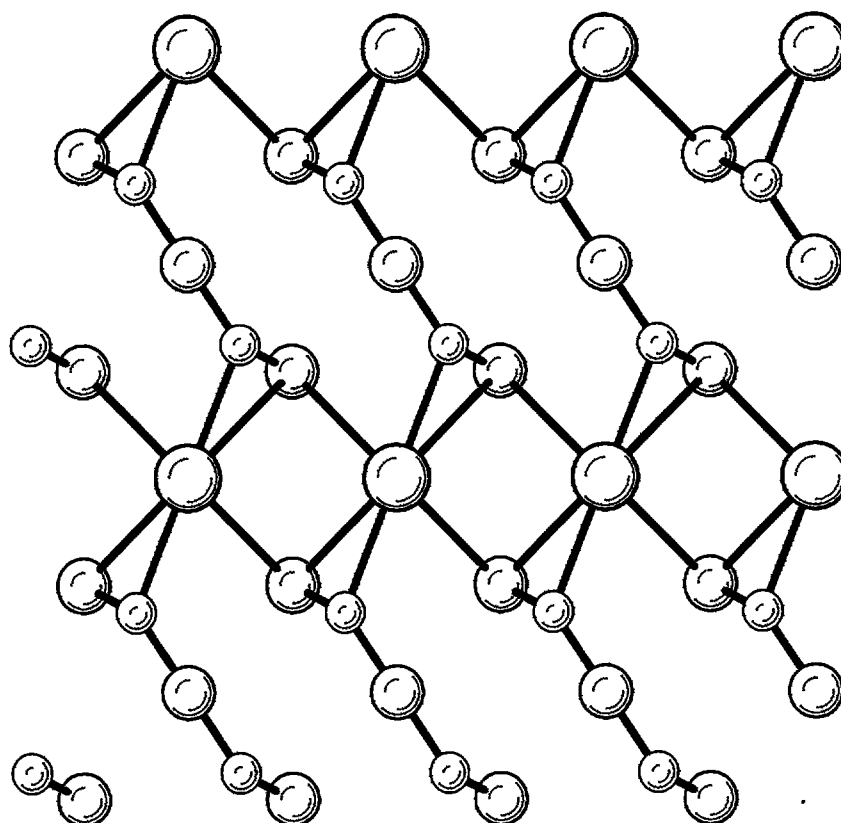


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4. The semiconductor structure of claim 1 wherein the interface and the atomic layer of the silicon substrate adjacent the interface comprises the structure including metal atoms, silicon atoms, and oxygen atoms in relative
5 size from larger to smaller:





5. The semiconductor structure of claim 1 wherein the metal is an alkaline-earth-metal.

6. The semiconductor structure of claim 5 wherein the alkaline-earth-metal is selected from the group of barium and strontium.

7. The semiconductor structure of claim 1 wherein the atomic layer of the interface comprises:

10 a half of a monolayer of an alkaline-earth-metal;
 a half of a monolayer of silicon; and
 a monolayer of oxygen.

8. The semiconductor structure of claim 7 wherein the silicon substrate includes a layer of silicon atoms adjacent to the interface, each atom of the alkaline-earth-metal in the atomic layer of the interface being substantially equally spaced from four silicon atoms in the silicon substrate.

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9. The semiconductor structure of claim 8 wherein the interface comprises rows of atoms in a 2X1 configuration on a (001) surface of the silicon substrate, 1X in the $\langle \bar{1}10 \rangle$ direction and 2X in the $\langle 110 \rangle$ direction.

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10. The semiconductor structure of claim 9 wherein the silicon atoms in the interface are substantially on a line and equally spaced between the alkaline-earth-metal atoms in the $\langle 110 \rangle$ direction.

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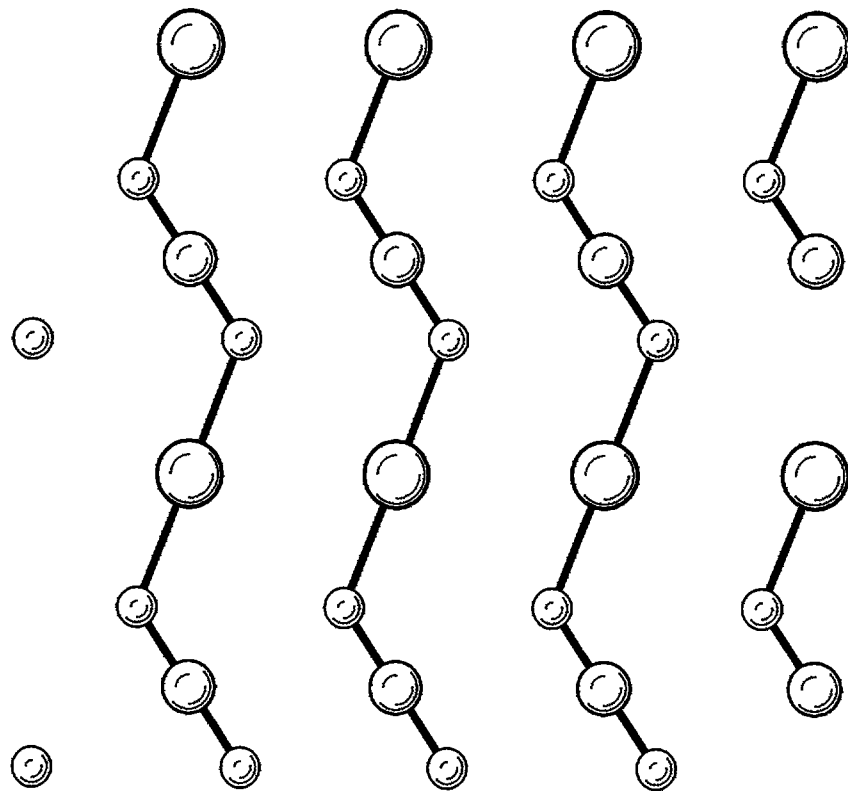


11. The semiconductor structure of claim 1 wherein each silicon atom in the layer of atoms in the silicon substrate adjacent to the interface is bonded to an oxygen atom in the interface and each silicon atom in the
5 interface is bonded to two oxygen atoms in the interface.

12. The semiconductor structure of claim 1 wherein the interface has a 2X1 reconstruction.

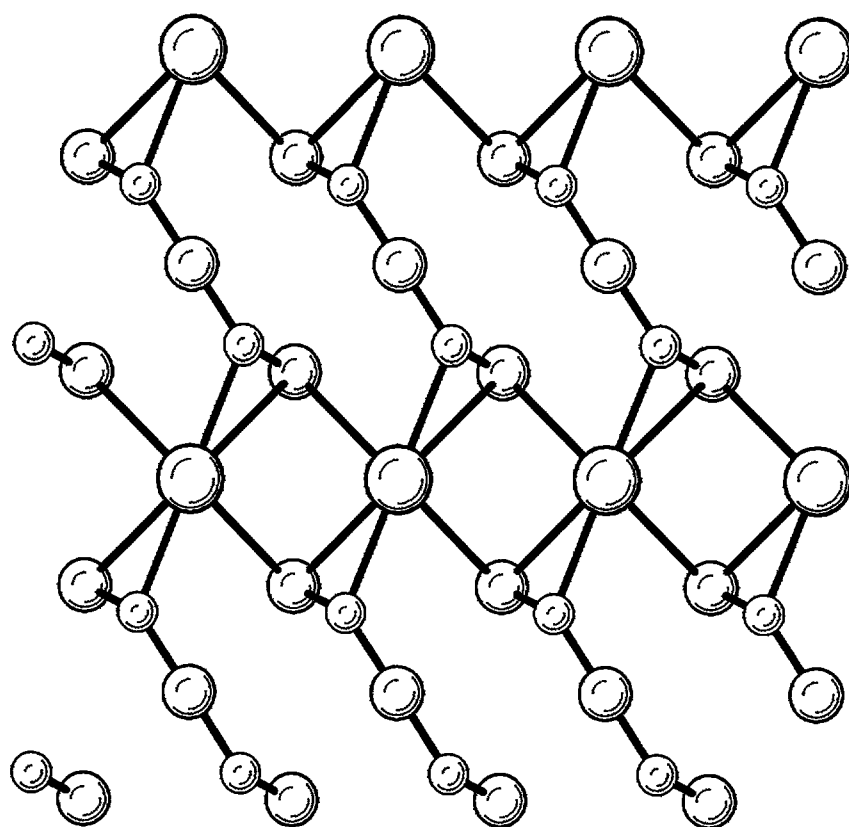


13. A semiconductor structure comprising:
a silicon substrate having a surface;
a material; and
a layer comprising XSiO_2 forming an interface between
5 the surface of the silicon substrate and the material,
where X is a metal.
14. The semiconductor structure of claim 13 wherein the
layer is a single atomic layer.
- 10 15. The semiconductor structure of claim 13 wherein the
metal comprises an alkaline-earth-metal.
16. The semiconductor structure of claim 15 wherein the
15 alkaline-earth-metal is selected from the group of barium
and strontium.
17. The semiconductor structure of claim 13 wherein the
material comprises an oxide layer formed adjacent the
20 interface, the oxide layer having an oxygen atom adjacent
and aligned in the $\langle 001 \rangle$ direction with a metal atom in
the interface, and having an oxygen atom adjacent and
aligned in the $\langle 001 \rangle$ direction with a silicon atom in the
interface.
- 25 18. The semiconductor structure of claim 13 wherein the
atomic layer of the interface comprises the structure
including metal atoms, silicon atoms, and oxygen atoms in
relative size from larger to smaller:





19. The semiconductor structure of claim 13 wherein the atomic layer of the interface and the atomic layer of the silicon substrate adjacent the interface comprises the structure including metal atoms, silicon atoms, and
5 oxygen atoms in relative size from larger to smaller:



20. The semiconductor structure of claim 13 wherein the atomic layer of the interface comprises:

- a half of a monolayer of an alkaline-earth-metal;
- a half of a monolayer of silicon; and
- 5 a monolayer of oxygen.

21. The semiconductor structure of claim 20 wherein the silicon substrate includes a layer of silicon atoms adjacent to the interface, each atom of the alkaline-
10 earth-metal in the atomic layer adjacent to the substrate being substantially equally spaced from four silicon atoms in the silicon substrate.

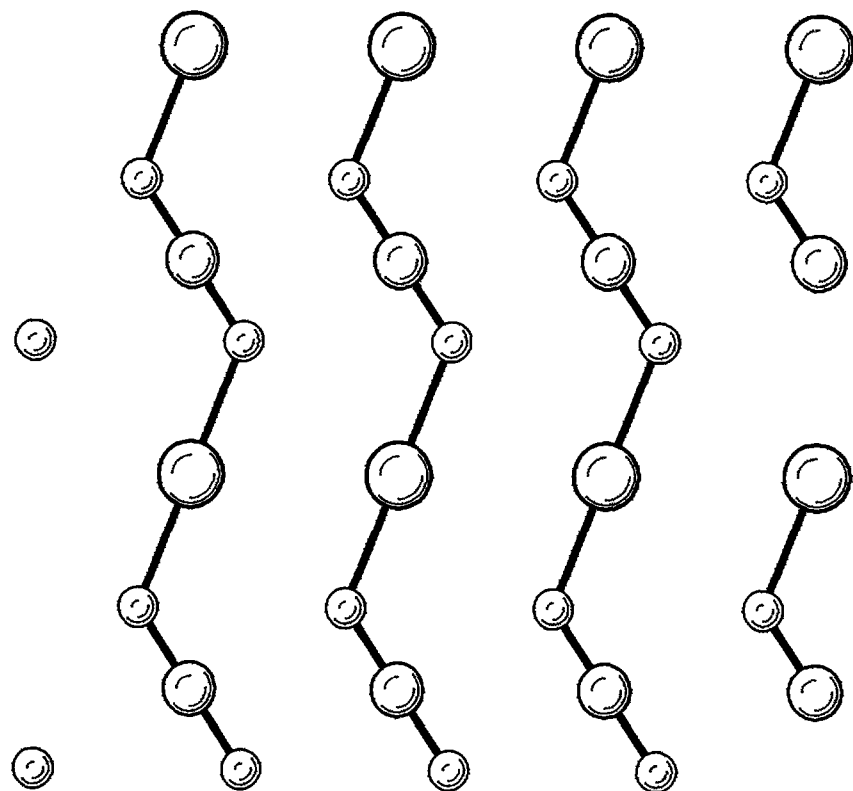
22. The semiconductor structure of claim 21 wherein the
15 interface comprises rows of atoms in a 2X1 configuration on a (001) surface of the silicon substrate, 1X in the $\langle\bar{1}10\rangle$ direction and 2X in the $\langle 110\rangle$ direction.

23. The semiconductor structure of claim 22 wherein the
20 silicon atoms in the interface are substantially on a line and equally spaced between the alkaline-earth-metal atoms in the $\langle 110\rangle$ direction.

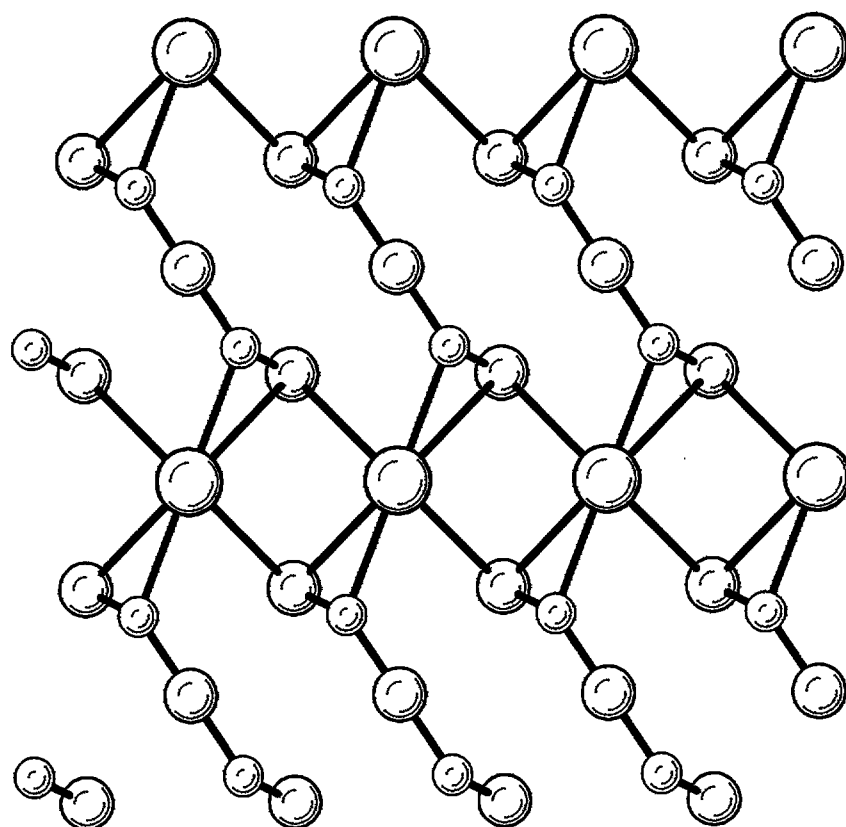
24. The semiconductor structure of claim 13 wherein each
25 silicon atom in the layer of atoms in the silicon substrate adjacent to the interface is bonded to an oxygen atom in the interface and each silicon atom in the interface is bonded to two oxygen atoms in the interface.

30 25. The semiconductor structure of claim 13 wherein the interface has a 2X1 reconstruction.

26. A semiconductor structure comprising:
a silicon substrate having a surface;
one or more successively adjacent layers of single
crystal oxides; and
5 an interface between the surface of the silicon
substrate and one of the one or more successively
adjacent layers of single crystal oxides, comprising a
single atomic layer of XSiO_2 , where X is a metal and is
lattice matched with the one of the one or more
10 successively adjacent layers of single crystal oxides.
27. The semiconductor structure of claim 26 wherein the
metal comprises an alkaline-earth-metal.
- 15 28. The semiconductor structure of claim 27 wherein the
alkaline-earth-metal is selected from the group of barium
and strontium.
29. The semiconductor structure of claim 26 wherein the
20 one or more successively adjacent layers of single
crystal oxides comprises an oxide layer formed adjacent
the interface, the oxide layer having an oxygen atom
adjacent and aligned in the $\langle 001 \rangle$ direction with a metal
atom in the interface, and having an oxygen atom adjacent
25 and aligned in the $\langle 001 \rangle$ direction with a silicon atom in
the interface.
30. The semiconductor structure of claim 26 wherein the
atomic layer of the interface comprises the structure
30 including metal atoms, silicon atoms, and oxygen atoms in
relative size from larger to smaller:



31. The semiconductor structure of claim 26 wherein the atomic layer of the interface and the atomic layer of the silicon substrate adjacent the interface comprises the structure including metal atoms, silicon atoms, and
5 oxygen atoms in relative size from larger to smaller:



32. The semiconductor structure of claim 26 wherein the atomic layer of the interface comprises:

- a half of a monolayer of an alkaline-earth-metal;
- a half of a monolayer of silicon; and
- 5 a monolayer of oxygen.

33. The semiconductor structure of claim 32 wherein the silicon substrate includes a layer of silicon atoms adjacent to the interface, each atom of the alkaline-
10 earth-metal in the atomic layer of the interface being substantially equally spaced from four silicon atoms in the silicon substrate.

34. The semiconductor structure of claim 33 wherein the
15 interface comprises rows of atoms in a 2X1 configuration on a (001) surface of the silicon substrate, 1X in the $\langle\bar{1}10\rangle$ direction and 2X in the $\langle 110\rangle$ direction.

35. The semiconductor structure of claim 34 wherein the
20 silicon atoms in the interface are substantially on a line and equally spaced between the alkaline-earth-metal atoms in the $\langle 110\rangle$ direction.

36. The semiconductor structure of claim 26 wherein each
25 silicon atom in the layer of atoms in the silicon substrate adjacent to the interface is bonded to an oxygen atom in the interface and each silicon atom in the interface is bonded to two oxygen atoms in the interface.

30 37. The semiconductor structure of claim 26 wherein the interface has a 2X1 reconstruction.