MANUFACTURING METHOD OF SMOOTHING A SEMICONDUCTOR SURFACE

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims priority to U.S. Provisional Patent Application No. 62/257,764 filed on 20 November 2015, the entire disclosure of which is hereby incorporated by reference in its entirety.

FIELD OF THE INVENTION

[0002] The present invention generally relates to the field of semiconductor wafer manufacture. More specifically, the present invention relates to a method for producing a semiconductor-on-insulator (e.g., silicon-on-insulator) structure, and more particularly to a method for producing a semiconductor-on-insulator (e.g., silicon-on-insulator) structure having a smooth exposed device layer surface.

BACKGROUND OF THE INVENTION

[0003] Semiconductor wafers are generally prepared from a single crystal ingot (e.g., a silicon ingot) which is trimmed and ground to have one or more flats or notches for proper orientation of the wafer in subsequent procedures. The ingot is then sliced into individual wafers. While reference will be made herein to semiconductor wafers constructed from silicon, other materials may be used to prepare semiconductor wafers, such as germanium, silicon carbide, silicon germanium, gallium arsenide, and other alloys of Group III and Group V elements, such as gallium nitride or indium phosphide, or alloys of Group II and Group IV elements, such as cadmium sulfide or zinc oxide.

[0004] Semiconductor wafers (e.g., silicon wafers) may be utilized in the preparation of composite layer structures. A composite layer structure (e.g., a semiconductor-on-insulator, and more specifically, a silicon-on-insulator (SOI) structure) generally comprises a handle wafer or layer, a device layer, and an insulating (i.e., dielectric) film (typically an oxide layer) between the handle layer and the device layer. Generally, the device layer is between 0.01 and 20 micrometers thick, such as between 0.05 and 20 micrometers thick. Thick film device layers may have a device layer

thickness between about 1.5 micrometers and about 20 micrometers. Thin film device layers may have a thickness between about 0.01 micrometer and about 0.20 micrometer. In general, composite layer structures, such as silicon-on-insulator (SOI), silicon-on-sapphire (SOS), and silicon-on-quartz, are produced by placing two wafers in intimate contact, thereby initiating bonding by van der Waal's forces, followed by a thermal treatment to strengthen the bond. The anneal may convert the terminal silanol groups to siloxane bonds between the two interfaces, thereby strengthening the bond.

[0005] After thermal anneal, the bonded structure undergoes further processing to remove a substantial portion of the donor wafer to achieve layer transfer. For example, wafer thinning techniques, e.g., etching or grinding, may be used, often referred to as back etch SOI (i.e., BESOI), wherein a silicon wafer is bound to the handle wafer and then slowly etched away until only a thin layer of silicon on the handle wafer remains. See, e.g., U.S. Pat. No. 5,189,500, the disclosure of which is incorporated herein by reference as if set forth in its entirety. This method is time-consuming and costly, wastes one of the substrates and generally does not have suitable thickness uniformity for layers thinner than a few microns.

[0006] Another common method of achieving layer transfer utilizes a hydrogen implant followed by thermally induced layer splitting. Particles (atoms or ionized atoms, e.g., hydrogen atoms or a combination of hydrogen and helium atoms) are implanted at a specified depth beneath the front surface of the donor wafer. The implanted particles form a cleave plane in the donor wafer at the specified depth at which they were implanted. The surface of the donor wafer is cleaned to remove organic compounds or other contaminants, such as boron compounds, deposited on the wafer during the implantation process.

[0007] The front surface of the donor wafer is then bonded to a handle wafer to form a bonded wafer through a hydrophilic bonding process. Prior to bonding, the donor wafer and/or handle wafer are activated by exposing the surfaces of the wafers to plasma containing, for example, oxygen or nitrogen. Exposure to the plasma modifies the structure of the surfaces in a process often referred to as surface activation, which activation process renders the surfaces of one or both of the donor water and handle

wafer hydrophilic. The surfaces of the wafers can be additionally chemically activated by a wet treatment, such as an SC1 clean or hydrofluoric acid. The wet treatment and the plasma activation may occur in either order, or the wafers may be subjected to only one treatment. The wafers are then pressed together, and a bond is formed there between. This bond is relatively weak, due to van der Waal's forces, and must be strengthened before further processing can occur.

[0008] In some processes, the hydrophilic bond between the donor wafer and handle wafer (i.e., a bonded wafer) is strengthened by heating or annealing the bonded wafer pair. In some processes, wafer bonding may occur at low temperatures, such as between approximately 300°C and 500°C. The elevated temperatures cause the formation of covalent bonds between the adjoining surfaces of the donor wafer and the handle wafer, thus solidifying the bond between the donor wafer and the handle wafer. Concurrently with the heating or annealing of the bonded wafer, the particles earlier implanted in the donor wafer weaken the cleave plane.

[0009] A portion of the donor wafer is then separated (i.e., cleaved) along the cleave plane from the bonded wafer to form the SOI wafer. Cleaving may be carried out by placing the bonded wafer in a fixture in which mechanical force is applied perpendicular to the opposing sides of the bonded wafer in order to pull a portion of the donor wafer apart from the bonded wafer. According to some methods, suction cups are utilized to apply the mechanical force. The separation of the portion of the donor wafer is initiated by applying a mechanical wedge at the edge of the bonded wafer at the cleave plane in order to initiate propagation of a crack along the cleave plane. The mechanical force applied by the suction cups then pulls the portion of the donor wafer from the bonded wafer, thus forming an SOI wafer.

[0010] According to other methods, the bonded pair may instead be subjected to an elevated temperature over a period of time to separate the portion of the donor wafer from the bonded wafer. Exposure to the elevated temperature causes initiation and propagation of cracks along the cleave plane, thus separating a portion of the donor wafer. The crack forms due to the formation of voids from the implanted ions, which grow by Ostwald ripening. The voids are filled with hydrogen and helium. The voids

become platelets. The pressurized gases in the platelets propagate micro-cavities and micro-cracks, which weaken the silicon on the implant plane. If the anneal is stopped at the proper time, the weakened bonded wafer may be cleaved by a mechanical process. However, if the thermal treatment is continued for a longer duration and/or at a higher temperature, the micro-crack propagation reaches the level where all cracks merge along the cleave plane, thus separating a portion of the donor wafer. This method allows for better uniformity of the transferred layer and allows recycle of the donor wafer, but typically requires heating the implanted and bonded pair to temperatures approaching 500°C.

[0011] The bonded structure may thereafter undergo a finishing process step, typically an epitaxial smoothing step to achieve a targeted device layer thickness and a targeted device layer surface roughness target. The cleaving process to prepare a semiconductor-on-insulator structure (e.g., a silicon-on-insulator structure) may cause high surface roughness on the exposed surface of the device layer prior to epitaxial smoothing. Due to the limited thermal budget of the epitaxial smoothing process, the surface roughness may be reduced to as low as about >1.7 angstrom (calculated using the root mean square over a 30 um X 30 um surface area). Achieving further reduced surface roughness has proven to be challenging. The fundamental barrier for the surface roughness reduction is the compressive stress in the device layer as a result of the thermal mismatch between the buried dielectric layer (e.g., buried oxide, such as SiO_2) and the device layer (e.g., single crystal silicon device layer). Another factor that contributes to the compressive stress in the device layer is the ion implant (typically, Hydrogen and or He) induced stress. The compressive stress leads to corrugation of the exposed surface of the device layer, resulting in long wavelength (um scale) surface roughness.

SUMMARY OF THE INVENTION

[0012] Among the provisions of the present invention may be noted a method of preparing a multilayer structure, the method comprising: depositing a layer of silicon dioxide on a back surface of a single crystal semiconductor handle wafer, wherein the single crystal semiconductor handle wafer comprises two major, parallel surfaces, one of which is the back surface of the single crystal semiconductor handle wafer and the other

of which is a front surface of the single crystal semiconductor handle wafer, a circumferential edge joining the front surface and the back surface of the single crystal semiconductor handle wafer, a central axis perpendicular to the front surface and the back surface of the single crystal semiconductor handle wafer, and a bulk region between the front and back surfaces of the semiconductor handle substrate; bonding the front surface of the single crystal semiconductor handle wafer to a front surface of a single crystal semiconductor donor wafer to thereby form a bonded structure, wherein the single crystal semiconductor donor wafer comprises two major, generally parallel surfaces, one of which is the front surface of the single crystal semiconductor donor wafer and the other of which is a back surface of the single crystal semiconductor donor wafer, a circumferential edge joining the front and back surfaces of the single crystal semiconductor donor wafer, and a bulk region between the front and back surfaces of the single crystal semiconductor donor wafer, and further wherein the front surface of the single crystal semiconductor donor wafer comprises a dielectric layer and the bulk region comprises a cleave plane; mechanically cleaving the bonded structure at the cleave plane of the single crystal semiconductor donor wafer to thereby prepare a cleaved structure comprising the layer of silicon dioxide in contact with the back surface of the single crystal semiconductor handle wafer, the single crystal semiconductor handle wafer, the dielectric layer in contact with the front surface of the single crystal semiconductor handle wafer, and a single crystal semiconductor device layer, wherein the single crystal semiconductor device layer comprises an exposed surface; and smoothing the exposed surface of the single crystal semiconductor device layer to a root mean square surface roughness over a 30 micrometer by 30 micrometer surface region of less than about 2 angstroms to thereby prepare the multilayer structure.

[0013] The present invention is further directed to a method of preparing a multilayer structure, the method comprising: depositing a layer of silicon nitride on a back surface of a single crystal semiconductor handle wafer, wherein the single crystal semiconductor handle wafer comprises two major, parallel surfaces, one of which is the back surface of the single crystal semiconductor handle wafer and the other of which is a front surface of the single crystal semiconductor handle wafer, a circumferential edge joining the front surface and the back surface of the single crystal semiconductor handle wafer, a central axis perpendicular to the front surface and the back surface of the single

crystal semiconductor handle wafer, and a bulk region between the front and back surfaces of the semiconductor handle substrate; bonding the front surface of the single crystal semiconductor handle wafer to a front surface of a single crystal semiconductor donor wafer to thereby form a bonded structure, wherein the single crystal semiconductor donor wafer comprises two major, generally parallel surfaces, one of which is the front surface of the single crystal semiconductor donor wafer and the other of which is a back surface of the single crystal semiconductor donor wafer, a circumferential edge joining the front and back surfaces of the single crystal semiconductor donor wafer, and a bulk region between the front and back surfaces of the single crystal semiconductor donor wafer, and further wherein the front surface of the single crystal semiconductor donor wafer comprises a dielectric layer and the bulk region comprises a cleave plane; mechanically cleaving the bonded structure at the cleave plane of the single crystal semiconductor donor wafer to thereby prepare a cleaved structure comprising the layer of silicon nitride in contact with the back surface of the single crystal semiconductor handle wafer, the single crystal semiconductor handle wafer, the dielectric layer in contact with the front surface of the single crystal semiconductor handle wafer , and a single crystal semiconductor device layer, wherein the single crystal semiconductor device layer comprises an exposed surface; and smoothing the exposed surface of the single crystal semiconductor device layer to a root mean square surface roughness over a 30 micrometer by 30 micrometer surface region of less than about 2 angstroms to thereby prepare the multilayer structure.

[0014] The present invention is still further directed to a method of preparing a multilayer structure, the method comprising: depositing a layer of polycrystalline silicon carbide on a back surface of a single crystal semiconductor handle wafer, wherein the single crystal semiconductor handle wafer comprises two major, parallel surfaces, one of which is the back surface of the single crystal semiconductor handle wafer and the other of which is a front surface of the single crystal semiconductor handle wafer, a circumferential edge joining the front surface and the back surface of the single crystal semiconductor handle wafer, a central axis perpendicular to the front surface and the back surface of the single crystal semiconductor handle wafer, and a bulk region between the front and back surfaces of the semiconductor handle substrate; bonding the front surface of the single crystal semiconductor handle wafer to a front surface of a single

crystal semiconductor donor wafer to thereby form a bonded structure, wherein the single crystal semiconductor donor wafer comprises two major, generally parallel surfaces, one of which is the front surface of the single crystal semiconductor donor wafer and the other of which is a back surface of the single crystal semiconductor donor wafer, a circumferential edge joining the front and back surfaces of the single crystal semiconductor donor wafer, and a bulk region between the front and back surfaces of the single crystal semiconductor donor wafer, and further wherein the front surface of the single crystal semiconductor donor wafer comprises a dielectric layer and the bulk region comprises a cleave plane; mechanically cleaving the bonded structure at the cleave plane of the single crystal semiconductor donor wafer to thereby prepare a cleaved structure comprising the layer of polycrystalline silicon carbide or the layer of carbon-doped silicon in contact with the back surface of the single crystal semiconductor handle wafer, the single crystal semiconductor handle wafer, the dielectric layer in contact with the front surface of the single crystal semiconductor handle wafer , and a single crystal semiconductor device layer, wherein the single crystal semiconductor device layer comprises an exposed surface; and smoothing the exposed surface of the single crystal semiconductor device layer to a root mean square surface roughness over a 30 micrometer by 30 micrometer surface region of less than about 2 angstroms to thereby prepare the multilayer structure.

[0015] The present invention is still further directed to a method of preparing a multilayer structure, the method comprising: depositing a layer of boron-doped silicon on a back surface of a single crystal semiconductor handle wafer, wherein the single crystal semiconductor handle wafer comprises two major, parallel surfaces, one of which is the back surface of the single crystal semiconductor handle wafer and the other of which is a front surface of the single crystal semiconductor handle wafer, a circumferential edge joining the front surface and the back surface of the single crystal semiconductor handle wafer, a central axis perpendicular to the front surface and the back surface of the single crystal semiconductor handle wafer, and a bulk region between the front and back surfaces of the semiconductor handle substrate; bonding the front surface of the single crystal semiconductor handle wafer to a front surface of a single crystal semiconductor donor wafer to thereby form a bonded structure, wherein the single crystal semiconductor donor wafer comprises two major, generally parallel

surfaces, one of which is the front surface of the single crystal semiconductor donor wafer and the other of which is a back surface of the single crystal semiconductor donor wafer, a circumferential edge joining the front and back surfaces of the single crystal semiconductor donor wafer, and a bulk region between the front and back surfaces of the single crystal semiconductor donor wafer, and further wherein the front surface of the single crystal semiconductor donor wafer comprises a dielectric layer and the bulk region comprises a cleave plane; mechanically cleaving the bonded structure at the cleave plane of the single crystal semiconductor donor wafer to thereby prepare a cleaved structure comprising the layer of boron-doped silicon in contact with the back surface of the single crystal semiconductor handle wafer, the single crystal semiconductor handle wafer the dielectric layer in contact with the front surface of the single crystal semiconductor handle wafer , and a single crystal semiconductor device layer, wherein the single crystal semiconductor device layer comprises an exposed surface; and smoothing the exposed surface of the single crystal semiconductor device layer to a root mean square surface roughness over a 30 micrometer by 30 micrometer surface region of less than about 2 angstroms to thereby prepare the multilayer structure.

[0016] Other objects and features will be in part apparent and in part pointed out hereinafter.

BRIEF DESCRIPTION OF THE DRAWINGS

[0017] FIGS. 1A through 1F depict the process flow according to an exemplary, non-limiting embodiment of the invention.

[0018] FIG. 2 is a graph depicting the smoothness achievable on the exposed surface of a device layer of several multilayer structures.

DETAILED DESCRIPTION OF THE EMBODIMENT(S) OF THE INVENTION

[0019] According to the present invention, a method is provided for preparing a semiconductor-on-insulator structure (e.g., a silicon-on-insulator structure) comprising a device layer of acceptable smoothness for a wide variety of applications, including CMOS device fabrication. According to the method of the present invention, a stress layer is deposited on the backside of the handle wafer so that at the temperature of a

smoothing process a tensile stress is developed in the stress layer. The tensile stress on the backside is translated to the device layer, typically a single crystal semiconductor layer, such as single crystal silicon. The backside stress layer under tensile stress establishes a chemical gradient from the peak to valley, which drives surface diffusion of atoms from the peak to valley. The chemical potential gradient increases with surface curvature, which makes the wavy surface thermodynamically unstable. As a result, an atomically long-range flat surface can be obtained.

I. Semiconductor Handle Substrate

[0020] The substrates for use in the present invention include a semiconductor handle substrate, e.g., a single crystal semiconductor handle wafer. FIGS. 1A through 1F depict the process flow according to some embodiments of the present invention. With reference to FIG. 1A, an exemplary, non-limiting single crystal semiconductor handle wafer **10** is depicted. In general, the single crystal semiconductor handle wafer **10** comprises two major, generally parallel surfaces **12**, **14**. One of the parallel surfaces is a front surface **12** of the single crystal semiconductor handle wafer **10**, and the other parallel surface is a back surface **14** of the single crystal semiconductor handle wafer **10**. The single crystal semiconductor handle wafer **10** comprises a circumferential edge **16** joining the front and back surfaces **12, 14**. The single crystal semiconductor handle wafer **10** comprise a central axis **18** perpendicular to the two major, generally parallel surfaces **12, 14** and also perpendicular to a central plane defined by the points midway between the front and back surfaces **12, 14**. Since semiconductor wafers, e.g., silicon wafers, typically have some total thickness variation (TTV), warp, and bow, the midpoint between every point on the front surface **12** and every point on the back surface **14** may not precisely fall within a plane. As a practical matter, however, the TTV, warp, and bow are typically so slight that to a close approximation the midpoints can be said to fall within an imaginary central plane which is approximately equidistant between the front and back surfaces.

[0021] Prior to any operation as described herein, the front surface **12** and the back surface **14** of the single crystal semiconductor handle wafer **10** may be substantially identical. A surface is referred to as a "front surface" or a "back surface" merely for convenience and generally to distinguish the surface upon which the operations of

method of the present invention are performed. In the context of the present invention, a "front surface" of a single crystal semiconductor handle wafer **10**, e.g., a single crystal silicon handle wafer, refers to the major surface of the substrate that becomes an interior surface of the bonded structure. Accordingly, a "back surface" of a single crystal semiconductor handle wafer **10**, e.g., a handle wafer, refers to the major surface that becomes an exterior surface of the bonded structure. Similarly, a "front surface" of a single crystal semiconductor donor substrate, e.g., a single crystal silicon donor wafer, refers to the major surface of the single crystal semiconductor donor substrate that becomes an interior surface of the bonded structure, and a "back surface" of a single crystal semiconductor donor substrate, e.g., a single crystal silicon donor wafer, refers to the major surface that becomes an exterior surface of the bonded structure. Upon completion of conventional bonding and wafer thinning steps, the single crystal semiconductor donor substrate forms the semiconductor device layer of the semiconductor-on-insulator (e.g., silicon-on-insulator) composite structure.

[0022] In preferred embodiments, the single crystal semiconductor handle wafer **10** comprises a material selected from the group consisting of silicon, silicon carbide, silicon germanium, gallium arsenide, gallium nitride, indium phosphide, indium gallium arsenide, germanium, and combinations thereof. The single crystal semiconductor handle wafer **10** of the present invention typically has a nominal diameter of at least about 150 mm, at least about 200 mm, at least about 300 mm, at least about 450 mm, or more. Wafer thicknesses may vary from about 250 micrometers to about 1500 micrometers, such as between about 300 micrometers and about 1000 micrometers, suitably within the range of about 500 micrometers to about 1000 micrometers. In some specific embodiments, the wafer thickness may be about 725 micrometers. In some embodiments, the wafer thickness may be about 775 micrometers.

[0023] In particularly preferred embodiments, the single crystal semiconductor handle wafer **10** comprises a single crystal silicon wafer, which has been sliced from a single crystal ingot grown in accordance with conventional Czochralski crystal growing methods or float zone growing methods. Such methods, as well as standard silicon slicing, lapping, etching, and polishing techniques are disclosed, for example, in F. Shimura, Semiconductor Silicon Crystal Technology, Academic Press,

1989, and Silicon Chemical Etching, (J. Grabmaier ed.) Springer-Verlag, N.Y., 1982 (incorporated herein by reference). Preferably, the wafers are polished and cleaned by standard methods known to those skilled in the art. See, for example, W.C. O'Mara et al., *Handbook of Semiconductor Silicon Technology*, Noyes Publications. If desired, the wafers can be cleaned, for example, in a standard SC1/ SC2 solution. In some embodiments, the single crystal silicon wafers of the present invention are single crystal silicon wafers which have been sliced from a single crystal ingot grown in accordance with conventional Czochralski ("Cz") crystal growing methods, typically having a nominal diameter of at least about 150 mm, at least about 200 mm, at least about 300 mm, at least about 450 mm, or more. Preferably, both the single crystal silicon handle wafer and the single crystal silicon donor wafer have mirror-polished front surface finishes that are free from surface defects, such as scratches, large particles, etc. Wafer thickness may vary from about 250 micrometers to about 1500 micrometers, suitably within the range of about 500 micrometers to about 1000 micrometers. In some specific embodiments, the wafer thickness may be between about 725 micrometers and about 800 micrometers, such as between about 750 micrometers and about 800 micrometers. In some embodiments, the wafer thickness may be about 725 micrometers. In some embodiments, the wafer thickness may be about 775 micrometers.

[0024] In some embodiments, the single crystal semiconductor handle wafer **10** comprises interstitial oxygen in concentrations that are generally achieved by the Czochralski-growth method. In some embodiments, the single crystal semiconductor handle wafer **10** comprises oxygen in a concentration between about 4 PPMA and about 18 PPMA. In some embodiments, the semiconductor wafers comprise oxygen in a concentration between about 10 PPMA and about 35 PPMA. In some embodiments, the single crystal silicon wafer comprises oxygen in a concentration of no greater than about 10 ppma. Interstitial oxygen may be measured according to SEMI MF 1188-1105.

[0025] In general, there are no constraints on the resistivity of the handle wafers of the SOI substrate. The single crystal semiconductor handle wafer **10** may have any resistivity obtainable by the Czochralski or float zone methods. Accordingly, the resistivity of the single crystal semiconductor handle wafer **10** is based on the requirements of the end use/application of the structure of the present invention. The

resistivity may therefore vary from milliohm or less to megaohm or more. In some embodiments, the single crystal semiconductor handle wafer **10** comprises a p-type or an n-type dopant. Suitable dopants include boron (p type), gallium (p type), phosphorus (n type), antimony (n type), and arsenic (n type). The dopant concentration is selected based on the desired resistivity of the handle wafer. In some embodiments, the single crystal semiconductor handle substrate comprises a p-type dopant. In some embodiments, the single crystal semiconductor handle substrate is a single crystal silicon wafer comprising a p-type dopant, such as boron.

[0026] In some embodiments, the single crystal semiconductor handle wafer **10** has a relatively low minimum bulk resistivity, such as below about 100 ohm-cm, below about 50 ohm-cm, below about 1 ohm-cm, below about 0.1 ohm-cm, or even below about 0.01 ohm-cm. In some embodiments, the single crystal semiconductor handle wafer **10** has a relatively low minimum bulk resistivity, such as below about 100 ohm-cm, or between about 1 ohm-cm and about 100 ohm-cm. Low resistivity wafers may comprise electrically active dopants, such as boron (p type), gallium (p type), phosphorus (n type), antimony (n type), and arsenic (n type).

[0027] In some embodiments, the single crystal semiconductor handle wafer **10** has a relatively high minimum bulk resistivity. High resistivity wafers are generally sliced from single crystal ingots grown by the Czochralski method or float zone method. High resistivity wafers may comprise electrically active dopants, such as boron (p type), gallium (p type), aluminum (p type), indium (p type), phosphorus (n type), antimony (n type), and arsenic (n type), in generally very low concentrations. Cz-grown silicon wafers may be subjected to a thermal anneal at a temperature ranging from about 600°C to about 1000°C in order to annihilate thermal donors caused by oxygen that are incorporated during crystal growth. In some embodiments, the single crystal semiconductor handle wafer **10** has a minimum bulk resistivity of at least 100 Ohm-cm, at least about 500 Ohm-cm, at least about 1000 Ohm-cm, or even at least about 3000 Ohm-cm, such as between about 100 Ohm-cm and about 100,000 Ohm-cm, or between about 500 Ohm-cm and about 100,000 Ohm-cm, or between about 1000 Ohm-cm and about 100,000 Ohm-cm, or between about 500 Ohm-cm and about 10,000 Ohm-cm, or between about 750 Ohm-cm and about 10,000 Ohm-cm, between about 1000 Ohm-cm

and about 10,000 Ohm-cm, between about 2000 Ohm-cm and about 10,000 Ohm-cm, between about 3000 Ohm-cm and about 10,000 Ohm-cm, or between about 3000 Ohm cm and about 5,000 Ohm-cm. In some embodiments, the single crystal semiconductor handle wafer **10** may comprise a p type dopant, such as boron, gallium, aluminum, or indium. In some embodiments, the single crystal semiconductor handle wafer **10** may comprise a n type dopant, such as phosphorus, antimony, or arsenic. Methods for preparing high resistivity wafers are known in the art, and such high resistivity wafers may be obtained from commercial suppliers, such as SunEdison Semiconductor Ltd. (St. Peters, MO; formerly MEMC Electronic Materials, Inc.).

[0028] The single crystal semiconductor handle wafer **10** may comprise single crystal silicon. The single crystal semiconductor handle wafer **10** may have any of (100), (110), or (111) crystal orientation, and the choice of crystal orientation may be dictated by the end use of the structure.

II. Deposition of Stress Layer

[0029] In some embodiments of the method of the present invention, and with reference to FIGS. 1A and 1B, a stress layer **20** is deposited on the back surface **14** of the single crystal semiconductor handle wafer **10**. The stress layer **20** can be any material capable of introducing stable tensile stress in the handle wafer **10** and does not cause unwanted contamination (e.g. organics, metals). In some embodiments, the stress layer **20** comprises silicon dioxide, SiO_2. In some embodiments, the stress layer **20** comprises silicon nitride, Si_3N_4. In some embodiments, the stress layer **20** comprises silicon oxynitride, which may have the composition SiO_yN_x, wherein x has a value between 0 and 3, such as between 0.1 and 3, or between 0.1 and 2.9, and y has a value from 0 to 2, such as between 0.1 and 2, or between 0.1 and 1.9. In some embodiments, the stress layer **20** comprises polycrystalline silicon carbide, SiC. In some embodiments, the stress layer **20** comprises carbon-doped silicon, C-doped Si. In some embodiments, the stress layer **20** comprises boron doped silicon, B-doped Si.

[0030] The tensile stress in the deposited stress layer **20** is required to achieve between about 60 micrometer and about 180 micrometer 3-point wafer bow. Depending on the film stress, the required stress layer **20** thickness is given in Table 1. This

requirement applies to any stress layer **20**. The stress is a function of deposition method, process conditions (e.g., plasma power for PECVD, deposition temperature for PECVD and LPCVD), and the precursors used.

Table 1.

Film thickness (um)	Minimum Film stress (MPa)	Maximum Film stress (Mpa)
0.1	960	2880
0.2	480	1440
0.3	320	960
0.5	190	570

[0031] In general, the stress layer **20** may be deposited by metalorganic chemical vapor deposition (MOCVD), physical vapor deposition (PVD), chemical vapor deposition (CVD), plasma enhanced chemical vapor deposition (PECVD), low pressure chemical vapor deposition (LPCVD), or molecular beam epitaxy (MBE). In some embodiments, the stress layer **20** may be deposited by chemical vapor deposition (CVD), plasma enhanced chemical vapor deposition (PECVD), or low pressure chemical vapor deposition (LPCVD). A CVD reactor comprises a chamber comprising reactor walls, liner, a susceptor, gas injection units, and temperature control units. The parts of the reactor are made of materials resistant to and non-reactive with the precursor materials. To prevent overheating, cooling water may be flowing through the channels within the components of the reactor. A substrate sits on a susceptor which is at a controlled temperature. The susceptor is made from a material resistant to the precursors, such as ceramic, SiC, or graphite. For growing nitrides and related materials, a special coating on the graphite susceptor may be used to prevent corrosion by ammonia (NH_3) gas. Reactive gas is introduced by an inlet that controls the ratio of precursor reactants. The growth temperature may be between about 200°C and about 1200°C, between about 200°C and about 1150°C, between about 200°C and about 900°C, between about 200°C and about 500°C, or between about 900°C and about 1200°C, depending upon the composition of the stress layer. The stress layer may be formed under reduced pressure, such as between about 10^{-11} Torr (about $1x10^{-9}$ Pa) to about 760 Torr (about 101 kPa), or between about 1 Torr (about 0.13 kPa) and about 400 Torr (about 53.3 kPa), preferably between about 10 Torr (about 1.33 kPa) and about 80 Torr (about 10.67 kPa).

[0032] In some embodiments, the stress layer **20** comprises silicon dioxide (SiO_2). In some embodiments, the stress layer **20** comprising silicon dioxide (SiO_2) may be deposited on the back surface **14** of the single crystal semiconductor handle wafer **10** by physical vapor deposition (PVD), chemical vapor deposition (CVD), plasma enhanced chemical vapor deposition (PECVD), or low pressure chemical vapor deposition (LPCVD). Silicon precursors for LPCVD or PECVD include tetraorthosilicate (TEOS), methyl silane, silicon tetrahydride (silane), trisilane, disilane, pentasilane, neopentasilane, tetrasilane, dichlorosilane (SiH_2Cl_2), silicon tetrachloride ($SiCl_4$), among others. Oxygen gas or ozone gas are suitable sources of oxygen for the growth of a silicon dioxide stress layer. The growth temperature may be between about 20°C and about 1200°C, such as between about 200°C and about 1200°C, or between about 200°C and about 700°C, or between about 200°C and about 500°C. The stress layer may be formed under reduced pressure, such as between about 10^{-11} Torr (about $1x10^{-9}$ Pa) to about 760 Torr (about 101 kPa), or between about 1 Torr (about 0.13 kPa) and about 400 Torr (about 53.3 kPa), preferably between about 10 Torr (about 1.33 kPa) and about 80 Torr (about 10.67 kPa). In some embodiments, the stress layer **20** comprising silicon dioxide deposited on a back surface **14** of the single crystal semiconductor handle wafer **10** has a thickness between about 1000 angstroms and about 20,000 angstroms, as measured along the central axis **18** of the single crystal semiconductor handle wafer **10**, such as between about 1000 angstroms and about 5000 angstroms, as measured along the central axis **18** of the single crystal semiconductor handle wafer **10**.

[0033] In some embodiments, the stress layer **20** comprises silicon nitride (Si_3N_4). The stress layer **20** comprising silicon nitride may be deposited on the back surface **14** of the single crystal semiconductor handle wafer **10** by physical vapor deposition (PVD), chemical vapor deposition (CVD), plasma enhanced chemical vapor deposition (PECVD), or low pressure chemical vapor deposition (LPCVD). Silicon precursors for LPCVD or PECVD include methyl silane, silicon tetrahydride (silane), trisilane, disilane, pentasilane, neopentasilane, tetrasilane, dichlorosilane (SiH_2Cl_2), silicon tetrachloride ($SiCl_4$), among others. Nitrogen precursors include Ammonium, phenyl hydrazine, dimethyl hydrazine, tertiary butyl amine, and ammonia. The growth temperature may be between about 200°C and about 1200°C, such as between about

200°C and about 900°C. The stress layer may be formed under reduced pressure, such as between about 10^{-11} Torr (about $1x10^{-9}$ Pa) to about 760 Torr (about 101 kPa), or between about 1 Torr (about 0.13 kPa) and about 400 Torr (about 53.3 kPa), preferably between about 10 Torr (about 1.33 kPa) and about 80 Torr (about 10.67 kPa). In some embodiments, the stress layer **20** comprising silicon nitride deposited on the back surface **14** of the single crystal semiconductor handle wafer **10** has a thickness between about 500 angstroms and about 20,000 angstroms, as measured along the central axis **18** of the single crystal semiconductor handle wafer **10**, such as between about 1000 angstroms and about 5000 angstroms, as measured along the central axis **18** of the single crystal semiconductor handle wafer **10**.

[0034] In some embodiments, the stress layer **20** comprises silicon oxynitride, which may have the composition SiO_yN_x, wherein x has a value between 0 and 3, such as between 0.1 and 3, or between 0.1 and 2.9, and y has a value from 0 to 2, such as between 0.1 and 2, or between 0.1 and 1.9. Silicon oxynitride may be prepared by combining precursors for silicon, oxygen, and nitrogen, as described above with regard to the preparation of the silicon oxide and silicon nitride layers. In some embodiments, the stress layer **20** comprising silicon oxynitride deposited on the back surface **14** of the single crystal semiconductor handle wafer **10** has a thickness between about 500 angstroms and about 20,000 angstroms, as measured along the central axis **18** of the single crystal semiconductor handle wafer **10**, such as between about 1000 angstroms and about 5000 angstroms, as measured along the central axis **18** of the single crystal semiconductor handle wafer **10**.

[0035] In some embodiments, the stress layer **20** comprises polycrystalline silicon carbide or carbon-doped silicon. The stress layer **20** comprising polycrystalline silicon carbide or carbon-doped silicon may be deposited on the back surface **14** of the single crystal semiconductor handle wafer **10** by physical vapor deposition (PVD), chemical vapor deposition (CVD), plasma enhanced chemical vapor deposition (PECVD), or low pressure chemical vapor deposition (LPCVD). Silicon precursors for LPCVD or PECVD include methyl silane, silicon tetrahydride (silane), trisilane, disilane, pentasilane, neopentasilane, tetrasilane, dichlorosilane (SiH_2Cl_2), silicon tetrachloride ($SiCl_4$), among others. Suitable carbon precursors for CVD or PECVD include

methylsilane, methane, ethane, ethylene, among others. For LPCVD deposition, methylsilane is a particularly preferred precursor since it provides both carbon and silicon. For PECVD deposition, the preferred precursors include silane and methane. In some embodiments, the polycrystalline silicon carbide layer comprises a carbon concentration of between about 35% and about 65% on an atomic basis, such as between about 40% and about 60% on an atomic basis, or about 50% on an atomic basis. In some embodiments, the carbon-doped amorphous silicon layer comprises a carbon concentration of at least about 1% on an atomic basis, such as between about 1% and about 50%, or between about 5% and about 50%. The growth temperature may be between about 200°C and about 1200°C, such as between about 200°C and about 900°C. The stress layer may be formed under reduced pressure, such as between about 10^{-11} Torr (about $1x10^{-9}$ Pa) to about 760 Torr (about 101 kPa), or between about 1 Torr (about 0.13 kPa) and about 400 Torr (about 53.3 kPa), preferably between about 10 Torr (about 1.33 kPa) and about 80 Torr (about 10.67 kPa). In some embodiments, the stress layer **20** comprising polycrystalline silicon carbide deposited on the back surface **14** of the single crystal semiconductor handle wafer **10** has a thickness between about 500 angstroms and about 50,000 angstroms, as measured along the central axis **18** of the single crystal semiconductor handle wafer **10**, such as between about 500 angstroms and about 20,000 angstroms, as measured along the central axis **18** of the single crystal semiconductor handle wafer **10**, such as between about 500 angstroms and about 5,000 angstroms, as measured along the central axis **18** of the single crystal semiconductor handle wafer **10**.

[0036] In some embodiments, the stress layer **20** comprises boron-doped silicon. The stress layer **20** comprising boron-doped silicon may be deposited on the back surface **14** of the single crystal semiconductor handle wafer **10** by physical vapor deposition (PVD), chemical vapor deposition (CVD), plasma enhanced chemical vapor deposition (PECVD), or low pressure chemical vapor deposition (LPCVD). Silicon precursors for LPCVD or PECVD include methyl silane, silicon tetrahydride (silane), trisilane, disilane, pentasilane, neopentasilane, tetrasilane, dichlorosilane (SiH_2Cl_2), silicon tetrachloride ($SiCl_4$), among others. Boron precursors include diborane, boronchloride, 1,3,5-tri(N-methyl)borazine. The growth temperature may be between about 200°C and about 1200°C, such as between about 200°C and about 1150°C. In

some embodiments, the stress layer **20** comprising boron-doped silicon deposited on the back surface **14** of the single crystal semiconductor handle wafer **10** comprises a boron dopant concentration between about $1x10^{17}$ atoms/cm^3 and about $1x10^{22}$ atoms/cm^3, such as between about $1x10^{18}$ atoms/cm^3 and about $1x10^{21}$ atoms/cm^3. The stress layer may be formed under reduced pressure, such as between about 10^{-11} Torr (about $1x10^{-9}$ Pa) to about 760 Torr (about 101 kPa), or between about 1 Torr (about 0.13 kPa) and about 400 Torr (about 53.3 kPa), preferably between about 10 Torr (about 1.33 kPa) and about 80 Torr (about 10.67 kPa). In some embodiments, the stress layer **20** comprising boron-doped silicon deposited on the back surface **14** of the single crystal semiconductor handle wafer **10** has a thickness between about 5000 angstroms and about 50,000 angstroms, as measured along the central axis **18** of the single crystal semiconductor handle wafer **10**, such as between about 1000 angstroms and about 20,000 angstroms, as measured along the central axis **18** of the single crystal semiconductor handle wafer **10**.

III. Wafer Bonding and Cleaving

[0037] According to the method of the present invention and with reference to FIGS. 1B and 1C, the single crystal semiconductor handle wafer **10** comprising the stress layer **20** is next bonded to a single crystal semiconductor donor wafer **30**. In general, the single crystal semiconductor donor wafer **30** comprises two major, generally parallel surfaces **32, 34**. One of the parallel surfaces is a front surface **32** of the single crystal semiconductor donor wafer **30**, and the other parallel surface is a back surface **34** of the single crystal semiconductor donor wafer **30**. The single crystal semiconductor donor wafer **30** comprises a circumferential edge **36** joining the front and back surfaces **32, 34**. The single crystal semiconductor donor wafer **30** comprises a central axis **38** perpendicular to the two major, generally parallel surfaces **32, 34** and also perpendicular to a central plane defined by the points midway between the front and back surfaces **32, 34**. Since semiconductor wafers, e.g., silicon wafers, typically have some total thickness variation (TTV), warp, and bow, the midpoint between every point on the front surface **32** and every point on the back surface **34** may not precisely fall within a plane. As a practical matter, however, the TTV, warp, and bow are typically so slight that to a close approximation the midpoints can be said to fall within an imaginary central plane which is approximately equidistant between the front and back surfaces.

[0038] In preferred embodiments, the single crystal semiconductor donor wafer **30** comprises a material selected from the group consisting of silicon, silicon carbide, silicon germanium, gallium arsenide, gallium nitride, indium phosphide, indium gallium arsenide, germanium, and combinations thereof. The single crystal semiconductor donor wafer **30** of the present invention typically has a nominal diameter of at least about 150 mm, at least about 200 mm, at least about 300 mm, at least about 450 mm, or more. Wafer thicknesses may vary from about 250 micrometers to about 1500 micrometers, suitably within the range of about 500 micrometers to about 1000 micrometers. In particularly preferred embodiments, the single crystal semiconductor donor wafer **30** comprises a single crystal silicon wafer, which has been sliced from a single crystal ingot grown in accordance with conventional Czochralski crystal growing methods or float zone growing methods.

[0039] The single crystal semiconductor donor wafer **30** was subjected to standard process steps including oxidation, implant, and post implant cleaning. Accordingly, the single crystal semiconductor donor wafer **30** additionally comprises a cleave plane **40** and a dieletric layer **42** in contact with the front surface **32** of the single crystal semiconductor donor wafer **30**. Suitable dielectric layers may comprise a material selected from among silicon dioxide, silicon nitride, silicon oxynitride, hafnium oxide, titanium oxide, zirconium oxide, lanthanum oxide, barium oxide, and a combination thereof. In some embodiments, the dielectric layer has a thickness of at least about 5 nanometer thick, at least about 10 nanometer thick, such as between about 10 nanometers and about 10,000 nanometers, between about 10 nanometers and about 5,000 nanometers, between 50 nanometers and about 400 nanometers, or between about 100 nanometers and about 400 nanometers, such as about 50 nanometers, 100 nanometers, or 200 nanometers, or between about 100 nanometers and about 800 nanometers, such as about 600 nanometers.

[0040] In some embodiments, the dielectric layer comprises one or more insulating material selected from the group consisting of silicon dioxide, silicon nitride, silicon oxynitride, and any combination thereof. In some embodiments, the dielectric layer has a thickness of at least about 5 nanometer thick, at least about 10 nanometer thick, such as between about 10 nanometers and about 10,000 nanometers, between

about 10 nanometers and about 5,000 nanometers, between 50 nanometers and about 400 nanometers, or between about 100 nanometers and about 400 nanometers, such as about 50 nanometers, 100 nanometers, or 200 nanometers, or between about 100 nanometers and about 800 nanometers, such as about 600 nanometers.

[0041] In some embodiments, the dielectric layer comprises multiple layers of insulating material. The dielectric layer may comprise two insulating layers, three insulating layers, or more. Each insulating layer may comprise a material selected from among silicon dioxide, silicon oxynitride, silicon nitride, hafnium oxide, titanium oxide, zirconium oxide, lanthanum oxide, barium oxide, and any combination thereof. In some embodiments, each insulating layer may comprise a material selected from the group consisting of silicon dioxide, silicon nitride, siliconoxynitride, and any combination thereof. Each insulating layer may have a thickness of at least about 5 nanometer thick, at least about 10 nanometer thick, such as between about 10 nanometers and about 10,000 nanometers, between about 10 nanometers and about 5,000 nanometers, between 50 nanometers and about 400 nanometers, or between about 100 nanometers and about 400 nanometers, such as about 50 nanometers, 100 nanometers, or 200 nanometers, or between about 100 nanometers and about 800 nanometers, such as about 600 nanometers.

[0042] The cleave plane **40** of the single crystal semiconductor donor wafer **30** may be prepared by a conventional ion implantation method, followed by annealing of the bonded structure (see FIG. 1D). Ion implantation may be carried out in a commercially available instrument, such as an Applied Materials Quantum II, a Quantum LEAP, or a Quantum X. Implanted ions include He, H, H_2, or combinations thereof. Ion implantation is carried out as a density and duration sufficient to form a damage layer in the semiconductor donor substrate. Implant density may range from about 10^{12} ions/cm^2 to about 10^{17} ions/cm^2, such as from about 10^{14} ions/cm^2 to about 10^{17} ions/cm^2, such as from about 10^{15} ions/cm^2 to about 10^{16} ions/cm^2. Implant energies may range from about 1 keV to about 3,000 keV, such as from about 5 keV to about 1,000 keV, or from about 5 keV to about 200 keV, or from 5 keV to about 100 keV, or from 5 keV to about 80 keV. The depth of implantation determines amount of material transferred onto a handle substrate. In some embodiments it may be desirable to subject the single crystal

semiconductor donor wafer **30** to a clean after the implant. In some preferred embodiments, the clean could include a Piranha clean followed by a DI water rinse and SC1/SC2 cleans.

[0043] In some embodiments, the ion-implanted and optionally cleaned single crystal semiconductor donor wafer **30** is subjected to oxygen plasma and/or nitrogen plasma surface activation. In some embodiments, the oxygen plasma surface activation tool is a commercially available tool, such as those available from EV Group, such as EVG®810LT Low Temp Plasma Activation System. The ion-implanted and optionally cleaned single crystal semiconductor donor wafer is loaded into the chamber. The chamber is evacuated and backfilled with O_2 to a pressure less than atmospheric to thereby create the plasma. The single crystal semiconductor donor wafer **30** is exposed to this plasma for the desired time, which may range from about 1 second to about 120 seconds. Oxygen plasma surface oxidation is performed in order to render the front surface of the single crystal semiconductor donor wafer **30** hydrophilic and amenable to bonding to a single crystal semiconductor handle wafer **10** prepared according to the method described above.

[0044] According to the method of the present invention and with reference to FIG. 1D, the hydrophilic front surface layer **32** of the single crystal semiconductor donor wafer **30** comprising the dielectric layer **42** and the front surface **12** of the single crystal semiconductor handle wafer **10** are next brought into intimate contact to thereby form a bonded structure **50**. Since the mechanical bond is relatively weak, the bonded structure **50** is further annealed to solidify the bond between the single crystal semiconductor donor wafer **30** and the single crystal semiconductor handle wafer **10**. In some embodiments of the present invention, the bonded structure **50** is annealed at a temperature sufficient to form a thermally activated cleave plane **40** in the single crystal semiconductor donor wafer **30**. An example of a suitable tool might be a simple Box furnace, such as a Blue M model. In some preferred embodiments, the bonded structure **50** is annealed at a temperature of from about 200°C to about 1200°C, such as from about 225°C to about 500°C, preferably about 300°C, or from about 500°C to about 1200°C, such as from about 800°C to about 1200°C. Thermal annealing may occur for a duration of from about 0.5 hours to about 10 hour, preferably a duration of about 2 hours.

Thermal annealing within these temperatures ranges is sufficient to form a thermally activated cleave plane **40**. After the thermal anneal to activate the cleave plane, the bonded structure **50** may be cleaved.

[0045] After the thermal anneal and with reference to FIGS. 1D and 1E, the bond between the single crystal semiconductor donor wafer **30** and the single crystal semiconductor handle wafer **10** is strong enough to initiate layer transfer via cleaving the bonded structure **50** at the cleave plane **40**. Cleaving may occur according to techniques known in the art. In some embodiments, the bonded structure **50** may be placed in a conventional cleave station affixed to stationary suction cups on one side and affixed by additional suction cups on a hinged arm on the other side. A crack is initiated near the suction cup attachment and the movable arm pivots about the hinge cleaving the bonded structure **50** apart to thereby form a cleaved structure **60**. Cleaving removes a portion of the single crystal semiconductor donor wafer **30**, thereby leaving a single crystal semiconductor device layer **62**, preferably a single crystal silicon device layer, on the semiconductor-on-insulator cleaved structure **60**. In some embodiments, the single crystal semiconductor device layer **62** is between about 40 angstroms and about 1000 angstroms, such as between about 100 angstroms and about 500 angstroms.

[0046] After cleaving, the cleaved structure **60** is subjected to a high temperature anneal in order to further strengthen the bond between the transferred single crystal semiconductor device layer **62** and the single crystal semiconductor handle wafer **10**. An example of a suitable tool might be a vertical furnace, such as an ASM A400. In some preferred embodiments, the cleaved structure **60** is annealed at a temperature of from about 1000°C to about 1200°C, preferably at about 1000°C. Thermal annealing may occur for a duration of from about 0.5 hours to about 8 hours, preferably a duration of about 4 hours. Thermal annealing within these temperatures ranges is sufficient to strengthen the bond between the transferred single crystal semiconductor device layer **62** and the single crystal semiconductor handle wafer **10**.

IV. Wafer Smoothing

[0047] After cleaving and annealing, with reference to FIG. 1F, the cleaved structure **60** may be subjected to a cleaning process designed to remove thin thermal

oxide and clean particulates from the exposed surface of the single crystal semiconductor device layer **62**. If desired, the wafers can be cleaned, for example, in a standard SC1/ SC2 solution.

[0048] In some embodiments, the exposed surface **64** of the single crystal semiconductor device layer **62** may be brought to a desired thickness and smoothness. In the fabrication of multilayer structures, e.g., semiconductor on insulator structures, regardless of the cleaving methods used, the surface roughness of the exposed surface **64** of the transferred single crystal semiconductor device layer **62** is relatively rough. Commonly, the surface roughness may be greater than 100 angstroms, as measured by a root mean square surface roughness over a 30 micrometer by 30 micrometer surface region. The surface roughness is generally measured by atomic force microscopy over the 30 micrometer by 30 micrometer surface region.

[0049] Approaches used to finish the rough surface include plasma etching, chemical mechanical polishing (CMP), high temperature anneal in inert or reducing ambient, and epitaxial smoothing.

[0050] Plasma etching takes place in low temperature regime (e.g., generally less than about 600°C). In this temperature regime, the surface diffusivity of silicon atoms is low. Accordingly, plasma etching of a conventionally prepared structure may only achieve a root mean square roughness on the order of 10 angstroms. This method is not often used in CMOS SOI fabrication due to the high surface roughness.

[0051] Chemical mechanical polishing (CMP) may be able to smooth the exposed surface of the silicon device layer on the order of 1.0 to 1.5 angstroms as calculated by the root mean square method over a 30 um x 30 um surface area. However, the drawback of CMP is that it is not able to achieve uniform etching, leading to thickness uniformity concern. The state of the art CMOS device technology requires tight single crystal semiconductor device layer **62** thickness uniformity (e.g., within the range of <10-20 angstroms), which is beyond the capability of typical CMP processes. CMP finishing can only be applied to semiconductor-on-insulator structure (e.g., a silicon-on-insulator structure) with relatively loose thickness uniformity requirements for the device layer.

[0052] High temperature anneal in inert (e.g., Ar, He) or reducing ambient (e.g., H_2) requires extensive thermal budget. Accordingly, the temperature may range from about 1000°C to about 1200°C, and the duration may range from about 1 minute to about 6 hours, such as between about 2 hours and 6 hours. According to conventional techniques, wafer slip and silicon dewetting are common issues. Surface diffusion is enabled by the high temperature and long processing time. However, the long-range surface roughness is still constrained by the compressive stress in the single crystal semiconductor device layer **62** due to the mismatch of coefficient of thermal expansion between the single crystal semiconductor device layer **62** and the underlying dielectric, e.g., SiO_2, layer. Typical roughness is on the order of 2 angstroms as calculated by the root mean square method over a 30 um x 30 um surface area. According to the present invention, at temperatures between about 1000°C and about 1200°C, the mobility of Si atoms on the Si surface is high enough for effective surface diffusion. The driving force for the surface diffusion is the chemical gradient that is a function of the local surface curvature and stress. Tensile stress promotes surface diffusion from the peak to valley so that the surface becomes smooth. High temperature and tensile stress are the criteria for effective surface smoothing.

[0053] Epitaxial smoothing is a thermal process that employs an etching gas (such as Cl_2 or HCl) in combination with a carrier gas (typically H_2) in a horizontal flow single wafer epitaxial reactor to smooth the single crystal semiconductor device layer **62** surface at relatively high temperatures, such as between about 900°C and about 1150°C, or between about 1000°C and about 1100°C. The process duration is in the order of a few minutes, such as between about 1 minute and about 60 minutes. Because of the limited thermal budget, the surface roughness of the finished single crystal semiconductor device layer **62** is generally on the order of 2 angstroms to 4 angstroms as calculated by the root mean square method over a 30 um x 30 um surface area. However, conventional epi smoothing is not able to reduce roughness from ~100A (root mean square method over a 30 um X 30um surface scan) down to between 1 and 1.5 angstroms as calculated by the root mean square method over a 30 um x 30 um surface area. Again the roughness is limited by the compressive stress in the single crystal semiconductor device layer **62**. According to the method of the present invention, the effect of tensile stress in the single crystal semiconductor device layer **62** on smoothing has to be realized

at high temperature (e. g. 1000°C and above). The fundamental mechanism is that tensile stress contributes to the chemical gradient on an undulated surface, which drives the diffusion of surface atoms moving from the peak to valley of a surface.

[0054] According to the method of the present invention, the exposed surface of the single crystal semiconductor device layer **62** may be subjected to a smoothing process, such as epitaxial smoothing and/or chemical mechanical polishing (CMP) to reduce the surface roughness, preferably to the level of RMS $_{2x2\ um2}$ is less than about 2 angstroms, even more preferably less than about 1.5 angstroms, or even less than about 1.0 angstrom, such as between about 0.8 angstroms and about 1.2 angstroms, or between about 0.8 angstroms and about 1.0 angstroms. The root mean squared is calculated according to the following equation:

$$R_q = \sqrt{\frac{1}{n}\sum_{i=1}^{n} y_i^2}$$

[0055] The roughness profile contains ordered, equally spaced points along the trace, and y_i is the vertical distance from the mean line to the data point. Roughness is measured over a 30 micrometer by 30 micrometer surface area.

[0056] Optionally, the backside layer may be removed or may be left on the handle wafer, depending upon the requirements of the end use of the multilayer structure. Preferably, the backside layer is removed after smoothing the single crystal semiconductor device layer **62**. Once the single crystal semiconductor device layer **62** is smoothed, removing the backside stress layer will not change the surface roughness. A silicon dioxide layer, for example, can be removed using plasma etching or wet etch (like HF solution with 5%-49% vol. concentration in a conventional wafer cleaning tool).

[0057] Having described the invention in detail, it will be apparent that modifications and variations are possible without departing from the scope of the invention defined in the appended claims.

EXAMPLES

[0058] The following non-limiting examples are provided to further illustrate the present invention.

Example 1.

[0059] Stress layers comprising boron-doped silicon were deposited upon the back surfaces of single crystal silicon handle wafers. For each wafer, the thickness of the stress layer was 4 micrometers. A first wafer was deposited with a boron-doped silicon stress layer at a boron concentration at a concentration of $1x10^{21}$ atoms/cm^3 ("High Stress Layer" or "High SL"). A second wafer was deposited with a boron-doped silicon stress layer at a boron concentration at a concentration of $1x10^{18}$ atoms/cm^3 ("Low Stress Layer" or "Low SL"). A third wafer was deposited with a boron-doped silicon stress layer at a boron concentration at a concentration of $1x10^{20}$ atoms/cm^3 ("Medium Stress Layer" or "Medium SL"). In this example, the handle wafers comprises 300 mm diameter P- single crystal silicon wafers. The thickness of the wafers was 775 micrometers, and each was boron doped to a concentration of $1.0x10^{15}$ atoms/cm^3. The Boron doped epitaxial layers were deposited on the backside of the wafers using trichlorosilane (TCS) and Diborane as the Si and Boron precursors, respectively. An ASM E3200 epi reactor was used for the deposition of the boron-doped silicon backside layer with H_2 carrier gas at atmospheric pressure and at a temperature of at 1100°C. The back side boron-doped silicon layer was deposited to a thickness of 4 micrometers.

[0060] Five silicon-on-insulator structures were prepared according to the SMART CUT® technique. After the layer transfer process, the silicon-on-insulator structures comprises the handle wafer with the boron-doped silicon backside layer, a silicon dioxide dielectric layer having a thickness of 250 angstroms, and a single crystal silicon device layer having a thickness of 500 angstroms. The exposed surface of the single crystal silicon device layer was smoothed by epitaxial smoothing in the same ASM E3200 epi reactor at a temperature of 1000°C for 200s with H_2 carrier gas and HCl and at a partial pressure of 2.8 Torr. Three SOI structures were prepared comprising the handle wafers comprising the High Stress Layer, the Medium Stress Layer, and the Low Stress Layer. Two more SOI structures were prepared comprising handle wafers having

no stress layers. The control SOI sample did not receive epi smoothing process. The no stress later sample was subjected to the same epi smoothing process as the structures comprising backside stress layer.

[0061] The surface roughness, as measured by the root mean square method over a 30 um x 30 um surface area, are shown in FIG. 2. As shown in FIG. 2, the two SOI structures prepared without stress layer (labelled No SL and control) exhibited a smoothed exposed surface of the device layer of about 1.9 Angstroms or 2 angstroms. For the SOI structures prepared with a backside stress layer, the roughness of the exposed surface of the device layer decreased with increasing concentration of boron. The High SL structure had the best roughness at 1.2 angstroms, which is the smoothest surface achievable.

[0062] When introducing elements of the present invention or the preferred embodiments(s) thereof, the articles "a", "an", "the" and "said" are intended to mean that there are one or more of the elements. The terms "comprising", "including" and "having" are intended to be inclusive and mean that there may be additional elements other than the listed elements.

[0063] In view of the above, it will be seen that the several objects of the invention are achieved and other advantageous results attained.

[0064] As various changes could be made in the above products and methods without departing from the scope of the invention, it is intended that all matter contained in the above description and shown in the accompanying drawings shall be interpreted as illustrative and not in a limiting sense.

What is claimed is:

1. A method of preparing a multilayer structure, the method comprising:

depositing a layer of silicon dioxide on a back surface of a single crystal semiconductor handle wafer, wherein the single crystal semiconductor handle wafer comprises two major, parallel surfaces, one of which is the back surface of the single crystal semiconductor handle wafer and the other of which is a front surface of the single crystal semiconductor handle wafer, a circumferential edge joining the front surface and the back surface of the single crystal semiconductor handle wafer, a central axis perpendicular to the front surface and the back surface of the single crystal semiconductor handle wafer, and a bulk region between the front and back surfaces of the semiconductor handle substrate;

bonding the front surface of the single crystal semiconductor handle wafer to a front surface of a single crystal semiconductor donor wafer to thereby form a bonded structure, wherein the single crystal semiconductor donor wafer comprises two major, generally parallel surfaces, one of which is the front surface of the single crystal semiconductor donor wafer and the other of which is a back surface of the single crystal semiconductor donor wafer, a circumferential edge joining the front and back surfaces of the single crystal semiconductor donor wafer, and a bulk region between the front and back surfaces of the single crystal semiconductor donor wafer, and further wherein the front surface of the single crystal semiconductor donor wafer comprises a dielectric layer and the bulk region comprises a cleave plane;

mechanically cleaving the bonded structure at the cleave plane of the single crystal semiconductor donor wafer to thereby prepare a cleaved structure comprising the layer of silicon dioxide in contact with the back surface of the single crystal semiconductor handle wafer, the single crystal semiconductor handle wafer, the dielectric layer in contact with the front surface of the single crystal semiconductor handle wafer , and a single crystal semiconductor device layer, wherein the single crystal semiconductor device layer comprises an exposed surface; and

smoothing the exposed surface of the single crystal semiconductor device layer to a root mean square surface roughness over a 30 micrometer by 30 micrometer surface region of less than about 2 angstroms to thereby prepare the multilayer structure.

2. The method of claim 1 wherein the single crystal semiconductor handle wafer comprises a single crystal silicon wafer sliced from a single crystal silicon ingot grown by the Czochralski method or the float zone method.

3. The method of claim 1 wherein the layer of silicon dioxide deposited on the back surface of the single crystal semiconductor handle wafer has a thickness between about 1000 angstroms and about 20,000 angstroms, as measured along the central axis of the single crystal semiconductor handle wafer.

4. The method of claim 1 wherein the layer of silicon dioxide deposited on the back surface of the single crystal semiconductor handle wafer has a thickness between about 1000 angstroms and about 5000 angstroms, as measured along the central axis of the single crystal semiconductor handle wafer.

5. The method of claim 1 wherein a layer of silicon dioxide is deposited on the front surface of the single crystal semiconductor handle wafer simultaneously with deposition of the layer of silicon dioxide on the back surface of the single crystal semiconductor handle wafer, and the method further comprises removing the layer of silicon dioxide deposited on the front surface of the single crystal semiconductor handle wafer prior to the bonding step.

6. The method of claim 1 wherein the single crystal semiconductor device layer is between about 40 angstroms and about 1000 angstroms thick, as measured along the central axis of the single crystal semiconductor handle wafer.

7. The method of claim 1 wherein the single crystal semiconductor device layer comprises single crystal silicon.

8. The method of claim 1 wherein the exposed surface of the single crystal semiconductor device layer is smoothed to a root mean square surface roughness over a 30 micrometer by 30 micrometer surface region of less than about 1.5 angstroms.

9. The method of claim 1 wherein the exposed surface of the single crystal semiconductor device layer is smoothed to a root mean square surface roughness over a 30 micrometer by 30 micrometer surface region of less than about 1.0 angstroms.

10. The method of claim 1 wherein the exposed surface of the single crystal semiconductor device layer is smoothed to a root mean square surface roughness over a 30 micrometer by 30 micrometer surface region of between about 0.8 angstroms and about 1.2 angstroms.

11. The method of claim 1 wherein the exposed surface of the single crystal semiconductor device layer is smoothed to a root mean square surface roughness over a 30 micrometer by 30 micrometer surface region of between about 0.8 angstroms and about 1.0 angstroms.

12. The method of claim 1 wherein the exposed surface of the single crystal semiconductor device layer is smoothed by epitaxial smoothing.

13. A method of preparing a multilayer structure, the method comprising:

depositing a layer of silicon nitride on a back surface of a single crystal semiconductor handle wafer, wherein the single crystal semiconductor handle wafer comprises two major, parallel surfaces, one of which is the back surface of the single crystal semiconductor handle wafer and the other of which is a front surface of the single crystal semiconductor handle wafer, a circumferential edge joining the front surface and the back surface of the single crystal semiconductor handle wafer, a central axis perpendicular to the front surface and the back surface of the single crystal semiconductor handle wafer, and a bulk region between the front and back surfaces of the semiconductor handle substrate;

bonding the front surface of the single crystal semiconductor handle wafer to a front surface of a single crystal semiconductor donor wafer to thereby form a bonded structure, wherein the single crystal semiconductor donor wafer comprises two major, generally parallel surfaces, one of which is the front surface of the single crystal semiconductor donor wafer and the other of which is a back surface of the single crystal semiconductor donor wafer, a circumferential edge joining the front and back surfaces of the single crystal semiconductor donor wafer, and a bulk region between the front and back surfaces of the single crystal semiconductor donor wafer, and further wherein the front surface of the single crystal semiconductor donor wafer comprises a dielectric layer and the bulk region comprises a cleave plane;

mechanically cleaving the bonded structure at the cleave plane of the single crystal semiconductor donor wafer to thereby prepare a cleaved structure comprising the layer of silicon nitride in contact with the back surface of the single crystal semiconductor handle wafer, the single crystal semiconductor handle wafer, the dielectric layer in contact with the front surface of the single crystal semiconductor handle wafer , and a single crystal semiconductor device layer, wherein the single crystal semiconductor device layer comprises an exposed surface; and

smoothing the exposed surface of the single crystal semiconductor device layer to a root mean square surface roughness over a 30 micrometer by 30 micrometer surface region of less than about 2 angstroms to thereby prepare the multilayer structure.

14. The method of claim 13 wherein the single crystal semiconductor handle wafer comprises a single crystal silicon wafer sliced from a single crystal silicon ingot grown by the Czochralski method or the float zone method.

15. The method of claim 13 wherein the layer of silicon nitride deposited on the back surface of the single crystal semiconductor handle wafer has a thickness between about 500 angstroms and about 20,000 angstroms, as measured along the central axis of the single crystal semiconductor handle wafer.

16. The method of claim 13 wherein the layer of silicon nitride deposited on the back surface of the single crystal semiconductor handle wafer has a thickness between about 1000 angstroms and about 5000 angstroms, as measured along the central axis of the single crystal semiconductor handle wafer.

17. The method of claim 13 wherein the single crystal semiconductor device layer is between about 40 angstroms and about 1000 angstroms thick, as measured along the central axis of the single crystal semiconductor handle wafer.

18. The method of claim 13 wherein the single crystal semiconductor device layer comprises single crystal silicon.

19. The method of claim 13 wherein the exposed surface of the single crystal semiconductor device layer to a root mean square surface roughness over a 30 micrometer by 30 micrometer surface region of less than about 1.5 angstroms.

20. The method of claim 13 wherein the exposed surface of the single crystal semiconductor device layer to a root mean square surface roughness over a 30 micrometer by 30 micrometer surface region of less than about 1.0 angstroms.

21. The method of claim 13 wherein the exposed surface of the single crystal semiconductor device layer is smoothed to a root mean square surface roughness over a 30 micrometer by 30 micrometer surface region of between about 0.8 angstroms and about 1.2 angstroms.

22. The method of claim 13 wherein the exposed surface of the single crystal semiconductor device layer is smoothed to a root mean square surface roughness over a 30 micrometer by 30 micrometer surface region of between about 0.8 angstroms and about 1.0 angstroms.

23. The method of claim 13 wherein the exposed surface of the single crystal semiconductor device layer is smoothed by epitaxial smoothing.

24. A method of preparing a multilayer structure, the method comprising:

depositing a layer of polycrystalline silicon carbide on a back surface of a single crystal semiconductor handle wafer, wherein the single crystal semiconductor handle wafer comprises two major, parallel surfaces, one of which is the back surface of the single crystal semiconductor handle wafer and the other of which is a front surface of the single crystal semiconductor handle wafer, a circumferential edge joining the front surface and the back surface of the single crystal semiconductor handle wafer, a central axis perpendicular to the front surface and the back surface of the single crystal semiconductor handle wafer, and a bulk region between the front and back surfaces of the semiconductor handle substrate;

bonding the front surface of the single crystal semiconductor handle wafer to a front surface of a single crystal semiconductor donor wafer to thereby form a bonded structure, wherein the single crystal semiconductor donor wafer comprises two major,

generally parallel surfaces, one of which is the front surface of the single crystal semiconductor donor wafer and the other of which is a back surface of the single crystal semiconductor donor wafer, a circumferential edge joining the front and back surfaces of the single crystal semiconductor donor wafer, and a bulk region between the front and back surfaces of the single crystal semiconductor donor wafer, and further wherein the front surface of the single crystal semiconductor donor wafer comprises a dielectric layer and the bulk region comprises a cleave plane;

mechanically cleaving the bonded structure at the cleave plane of the single crystal semiconductor donor wafer to thereby prepare a cleaved structure comprising the layer of polycrystalline silicon carbide or the layer of carbon-doped silicon in contact with the back surface of the single crystal semiconductor handle wafer, the single crystal semiconductor handle wafer, the dielectric layer in contact with the front surface of the single crystal semiconductor handle wafer , and a single crystal semiconductor device layer, wherein the single crystal semiconductor device layer comprises an exposed surface; and

smoothing the exposed surface of the single crystal semiconductor device layer to a root mean square surface roughness over a 30 micrometer by 30 micrometer surface region of less than about 2 angstroms to thereby prepare the multilayer structure.

25. The method of claim 24 wherein the layer of polycrystalline silicon carbide comprises between about 5 atomic % and about 50 atomic % carbon.

26. The method of claim 24 wherein the single crystal semiconductor handle wafer comprises a single crystal silicon wafer sliced from a single crystal silicon ingot grown by the Czochralski method or the float zone method.

27. The method of claim 24 wherein the layer of polycrystalline silicon carbide deposited on the back surface of the single crystal semiconductor handle wafer has a thickness between about 500 angstroms and about 50,000 angstroms, as measured along the central axis of the single crystal semiconductor handle wafer.

28. The method of claim 24 wherein the layer of polycrystalline silicon carbide deposited on the back surface of the single crystal semiconductor handle wafer

has a thickness between about 500 angstroms and about 20,000 angstroms, as measured along the central axis of the single crystal semiconductor handle wafer.

29. The method of claim 24 wherein the layer of polycrystalline silicon carbide deposited on the back surface of the single crystal semiconductor handle wafer has a thickness between about 500 angstroms and about 5,000 angstroms, as measured along the central axis of the single crystal semiconductor handle wafer.

30. The method of claim 24 wherein the layer of polycrystalline silicon carbide deposited on the back surface of the single crystal semiconductor handle wafer has a thickness between about 40 angstroms and about 1000 angstroms, as measured along the central axis of the single crystal semiconductor handle wafer.

31. The method of claim 24 wherein the single crystal semiconductor device layer comprises single crystal silicon.

32. The method of claim 24 wherein the exposed surface of the single crystal semiconductor device layer to a root mean square surface roughness over a 30 micrometer by 30 micrometer surface region of less than about 1.5 angstroms.

33. The method of claim 24 wherein the exposed surface of the single crystal semiconductor device layer to a root mean square surface roughness over a 30 micrometer by 30 micrometer surface region of less than about 1.0 angstroms.

34. The method of claim 24 wherein the exposed surface of the single crystal semiconductor device layer is smoothed to a root mean square surface roughness over a 30 micrometer by 30 micrometer surface region of between about 0.8 angstroms and about 1.2 angstroms.

35. The method of claim 24 wherein the exposed surface of the single crystal semiconductor device layer is smoothed to a root mean square surface roughness over a 30 micrometer by 30 micrometer surface region of between about 0.8 angstroms and about 1.0 angstroms.

36. The method of claim 24 wherein the exposed surface of the single crystal semiconductor device layer is smoothed by epitaxial smoothing.

37. A method of preparing a multilayer structure, the method comprising:

depositing a layer of boron-doped silicon on a back surface of a single crystal semiconductor handle wafer, wherein the single crystal semiconductor handle wafer comprises two major, parallel surfaces, one of which is the back surface of the single crystal semiconductor handle wafer and the other of which is a front surface of the single crystal semiconductor handle wafer, a circumferential edge joining the front surface and the back surface of the single crystal semiconductor handle wafer, a central axis perpendicular to the front surface and the back surface of the single crystal semiconductor handle wafer, and a bulk region between the front and back surfaces of the semiconductor handle substrate;

bonding the front surface of the single crystal semiconductor handle wafer to a front surface of a single crystal semiconductor donor wafer to thereby form a bonded structure, wherein the single crystal semiconductor donor wafer comprises two major, generally parallel surfaces, one of which is the front surface of the single crystal semiconductor donor wafer and the other of which is a back surface of the single crystal semiconductor donor wafer, a circumferential edge joining the front and back surfaces of the single crystal semiconductor donor wafer, and a bulk region between the front and back surfaces of the single crystal semiconductor donor wafer, and further wherein the front surface of the single crystal semiconductor donor wafer comprises a dielectric layer and the bulk region comprises a cleave plane;

mechanically cleaving the bonded structure at the cleave plane of the single crystal semiconductor donor wafer to thereby prepare a cleaved structure comprising the layer of boron-doped silicon in contact with the back surface of the single crystal semiconductor handle wafer, the single crystal semiconductor handle wafer the dielectric layer in contact with the front surface of the single crystal semiconductor handle wafer , and a single crystal semiconductor device layer, wherein the single crystal semiconductor device layer comprises an exposed surface; and

smoothing the exposed surface of the single crystal semiconductor device layer to a root mean square surface roughness over a 30 micrometer by 30 micrometer surface region of less than about 2 angstroms to thereby prepare the multilayer structure.

38. The method of claim 37 wherein the single crystal semiconductor handle wafer comprises a single crystal silicon wafer sliced from a single crystal silicon ingot grown by the Czochralski method or the float zone method.

39. The method of claim 37 wherein the layer of boron-doped silicon deposited on the back surface of the single crystal semiconductor handle wafer has a thickness between about 500 angstroms and about 50,000 angstroms, as measured along the central axis of the single crystal semiconductor handle wafer.

40. The method of claim 37 wherein the layer of boron-doped silicon deposited on the back surface of the single crystal semiconductor handle wafer has a thickness between about 1000 angstroms and about 20,000 angstroms, as measured along the central axis of the single crystal semiconductor handle wafer.

41. The method of claim 37 wherein the layer of boron-doped silicon deposited on the back surface of the single crystal semiconductor handle wafer comprises a boron dopant concentration between about $1x10^{17}$ atoms/cm^3 and about $1x10^{22}$ atoms/cm^3.

42. The method of claim 37 wherein the layer of boron-doped silicon deposited on the back surface of the single crystal semiconductor handle wafer comprises a boron dopant concentration between about $1x10^{18}$ atoms/cm^3 and about $1x10^{21}$ atoms/cm^3.

43. The method of claim 37 wherein the single crystal semiconductor device layer is between about 40 angstroms and about 1000 angstroms thick, as measured along the central axis of the single crystal semiconductor handle wafer.

44. The method of claim 37 wherein the single crystal semiconductor device layer comprises single crystal silicon.

45. The method of claim 37 wherein the exposed surface of the single crystal semiconductor device layer to a root mean square surface roughness over a 30 micrometer by 30 micrometer surface region of less than about 1.5 angstroms.

46. The method of claim 37 wherein the exposed surface of the single crystal semiconductor device layer to a root mean square surface roughness over a 30 micrometer by 30 micrometer surface region of less than about 1.0 angstroms.

47. The method of claim 37 wherein the exposed surface of the single crystal semiconductor device layer is smoothed to a root mean square surface roughness over a 30 micrometer by 30 micrometer surface region of between about 0.8 angstroms and about 1.2 angstroms.

48. The method of claim 37 wherein the exposed surface of the single crystal semiconductor device layer is smoothed to a root mean square surface roughness over a 30 micrometer by 30 micrometer surface region of between about 0.8 angstroms and about 1.0 angstroms.

49. The method of claim 37 wherein the exposed surface of the single crystal semiconductor device layer is smoothed by epitaxial smoothing.