STRAINED LAYERS WITHIN SEMICONDUCTOR BUFFER STRUCTURES

BACKGROUND

Field

[0001] The present invention relates generally to the field of semiconductor manufacturing and more specifically to the formation of relaxed semiconductor buffer structures.

Description of the Related Art

[0002] Strained semiconductor materials advantageously provide improved electrical carrier mobility properties as compared to relaxed semiconductor materials, thus increasing the speed at which semiconductor circuits can operate. A semiconductor layer is said to be "strained" when it is constrained to have a lattice structure in at least one dimension that is the same as that of the underlying material's lattice structure, but different from the inherent lattice constant of the layer's material. Lattice strain occurs because the atoms in the deposited film depart from the positions normally occupied when the material is deposited over an underlying structure having a matching lattice structure. The degree of strain is related to several factors, including the thickness of the deposited layer and the degree of lattice mismatch between the deposited material and the underlying structure.

[0003] Strained semiconductor layers can be formed by epitaxially depositing silicon (Si) over a silicon-germanium (SiGe) buffer layer. Silicon-germanium films are used in a wide variety of semiconductor applications, such as in microelectronics fabrication. Because SiGe has a larger lattice constant than silicon, when epitaxial SiGe deposition occurs over silicon (such as during deposition on a silicon wafer), the epitaxially deposited SiGe is "strained" to the smaller underlying silicon lattice. If a strained silicon layer is to be deposited over the SiGe layer, the SiGe buffer layer should first be "relaxed" so that the silicon layer deposited thereover will be strained. In particular, because a strained SiGe layer has the dimensions of the underlying silicon lattice, a silicon layer deposited over a strained SiGe layer will not be strained. In contrast, a silicon layer deposited over a "relaxed" SiGe layer will be strained to conform to the larger underlying SiGe lattice. Thus, a strained silicon layer can be produced by

epitaxially depositing silicon over a relaxed SiGe layer. There are a number of approaches to forming a relaxed SiGe layer over silicon.

[0004] In one approach, a SiGe layer is deposited beyond the "critical thickness." As the thickness of a strained SiGe layer increases beyond a certain critical thickness, defects in the crystal structure of the strained SiGe layer appear, thereby inducing relaxation. After relaxation occurs, the degree of strain present in the SiGe layer is related to the amount of misfit dislocation generated in the layer during relaxation, which is a function of the elastic energy of the layer and the activation energy for dislocation nucleation and gliding. The critical thickness depends on a variety of factors, including growth rates, growth temperature, germanium concentration, and the number of defects within the layer underlying the SiGe layer. The SiGe can also be relaxed, for example due to macroscopic expansion, by annealing the workpiece after deposition.

[0005] Typically, a SiGe relaxed buffer layer is deposited with an increasing (or "graded") concentration of germanium from the underlying silicon substrate to the top surface of the relaxed buffer layer. For example, the concentration of germanium can increase from about 0% to between about 20% and 40%. Grading the germanium concentration of the SiGe layer to gradually increase lattice constant with distance from the substrate facilitates relaxation and can minimize the generation of threading dislocations and pile-ups of threading dislocations ("pile-ups").

SUMMARY

[0006] In certain embodiments, a semiconductor workpiece comprises a substrate, a relaxed buffer layer including a graded portion formed on the substrate, and at least one strained transitional layer within the graded portion of the relaxed buffer layer.

[0007] In certain embodiments, a semiconductor workpiece comprises a substrate, a relaxed buffer layer formed on the substrate, and at least one strained transitional layer within the relaxed buffer layer, the at least one strained transitional layer configured to reduce a threading dislocation density proximate to a top surface of the relaxed buffer layer to less than about $10^4/cm^2$.

[0008] In certain embodiments, an integrated circuit comprises a substrate, a relaxed buffer layer including a graded portion formed on the substrate, and at least one strained transitional layer within the graded portion of the relaxed buffer layer.

[0009] In certain embodiments, a method of manufacturing a semiconductor workpiece comprises providing a substrate, depositing a relaxed buffer layer on the

substrate, and during depositing the relaxed buffer layer, depositing at least one strained transitional layer configured to reduce a threading dislocation density proximate to a top surface of the relaxed buffer layer to less than about $10^4/cm^2$.

[0010] In certain embodiments, a method of manufacturing a semiconductor workpiece comprises providing a substrate, depositing a first portion of a relaxed buffer layer on the substrate by flowing silicon precursors and germanium precursors while increasing a germanium concentration in the growing first portion of the relaxed buffer layer, after depositing the first portion of the relaxed buffer layer, pausing flowing the germanium precursors while continuing to flow the silicon precursors, and, after pausing flowing the germanium precursors, depositing a second portion of the relaxed buffer layer by resuming flowing the germanium precursors and increasing a germanium concentration in the growing second portion of the relaxed buffer layer.

[0011] For purposes of summarizing the invention and the advantages achieved over the prior art, certain objects and advantages of the invention have been described herein above. Of course, it is to be understood that not necessarily all such objects or advantages may be achieved in accordance with any particular embodiment of the invention. Thus, for example, those skilled in the art will recognize that the invention may be embodied or carried out in a manner that achieves or optimizes one advantage or group of advantages as taught or suggested herein without necessarily achieving other objects or advantages as may be taught or suggested herein.

[0012] All of these embodiments are intended to be within the scope of the invention herein disclosed. These and other embodiments will become readily apparent to those skilled in the art from the following detailed description of the preferred embodiments having reference to the attached figures, the invention not being limited to any particular preferred embodiment(s) disclosed.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] These and other features, aspects, and advantages of the invention disclosed herein are described below with reference to the drawings of preferred embodiments, which are intended to illustrate and not to limit the invention.

[0014] Figures 1A and 1B schematically depict workpiece bow due to a relaxed buffer layer.

[0015] Figures 2A through 2G schematically depict example embodiments of germanium concentration profiles across a relaxed buffer layer.

[0016] Figure 3 is a schematic cross-section of a relaxed buffer layer.

[0017] Figure 4 is a schematic cross-section of a relaxed buffer layer with one strained transitional layer.

[0018] Figure 5 is a schematic cross-section of a relaxed buffer layer with four strained transitional layers.

[0019] Figures 6A through 6D schematically depict an example schematic embodiment of a strained layer transfer process.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0020] Although certain preferred embodiments and examples are disclosed below, it will be understood by those in the art that the invention extends beyond the specifically disclosed embodiments and/or uses of the invention and obvious modifications and equivalents thereof. Thus, it is intended that the scope of the invention herein disclosed should not be limited by the particular embodiments described below.

[0021] Relaxed buffer layers grown at high temperatures on a substrate can put a workpiece into a state of tensile or compressive strain that can create workpiece bow and warp upon cooling, due at least in part to differences in the coefficients of thermal expansion between the relaxed buffer layer and the bulk substrate. A relaxed buffer layer can cause bow when the workpiece is cooled (e.g., to room temperature) from a deposition temperature (e.g., 900 °C) because the relaxed buffer layer will contract according to its coefficient of thermal expansion a different amount than the bulk substrate will contract according to its coefficient of thermal expansion. The workpiece remains bowed and warped when the workpiece is below the stability temperature (i.e., the temperature below which the stress due to differences in the coefficients of thermal expansion does not cause substantially more bow). Warp is a measure of the maximum and minimum deviations of the surface of the workpiece relative to a reference plane. Bow is a measure of how concave (e.g., as depicted by Figure 1A) or convex (e.g., as depicted by Figure 1B) the deformation of the surface of the workpiece is at its center point versus its edges independent of any thickness variations. In Figure 1A, the workpiece comprising a substrate 10 and a relaxed buffer layer 12 is compressively strained after cooling, causing upward bow (e.g., due to a relaxed SiGe buffer layer that has a larger coefficient of thermal expansion than silicon). In Figure 1B, the workpiece comprising a substrate 10 and a relaxed buffer layer 12 is tensile strained after cooling, causing downward bow. Although workpiece bow is described in detail herein, the

disclosed embodiments can similarly be applied to workpiece warp. Equation 1 mathematically describes the bow of a workpiece due to differences in coefficients of thermal expansion between a substrate and a layer grown on a substrate for temperature regimes in which the coefficients of thermal expansion are approximately independent of temperature, for example as a first order approximation at a relatively fixed temperature.

$$b \propto b_0 - H_f \cdot \left(\frac{d}{H_s}\right)^2 \cdot (\Delta\alpha \cdot \Delta T) \qquad \text{(Eqn. 1)}$$

[0022] As described by Equation 1, workpiece bow (b) is proportional to the thickness of the grown layer (H_f), the square of the ratio of the substrate diameter (d) to the substrate thickness (H_s), the difference in coefficient of thermal expansion between the substrate and the grown layer ($\Delta\alpha = \alpha_s - \alpha_f$), and the difference ($\Delta T$) between the deposition temperature and the stability temperature, plus the initial amount of bow (b_0).

[0023] In general, the bulk substrate physical parameters are constant. For example, a bare substrate typically has an initial bow close to zero (e.g., about -5 μm to about +5 μm for 300 mm silicon substrates) because there is nothing present on the substrate to cause it to bow, such as a relaxed layer with a different coefficient of thermal expansion (i.e., $b_0 \approx 0$). The deposition temperature or temperatures are known from the process parameters. The stability temperature is the temperature below which the differences in the coefficients of thermal expansion of the substrate and the grown layer do not cause significant differential expansion or contraction. The stability temperature is typically room temperature (e.g., 25 °C), but may be between about 400 °C and 500 °C.

[0024] The diameter of the substrate (d) is typically between about 50 and 450 millimeters, and the coefficient of thermal expansion of the substrate (α_s) does not substantially depend on temperature in the temperature ranges of interest. The bulk thickness of the substrate (H_s) is typically thicker for larger diameter workpieces. For example, a 200 mm substrate is generally about 725 microns (μm) thick and a 300 mm substrate is generally about 750 μm thick. Increasing the diameter of the substrate or decreasing the thickness of the substrate will have a measurable affect on workpiece bow due to the squared proportionality. For example, changing the workpiece from 200 mm diameter and 725 μm thick to 300 mm and 750 μm thick, while keeping all other variables (H_f, $\Delta\alpha$, ΔT) constant, can increase bow by 210%.

[0025] Wafer bow and warp can present numerous problems at subsequent process steps (e.g., steps after cooling the workpiece to room temperature) that can decrease the yield of the workpiece. Processing tools that perform an alignment may incorrectly orient the wafer, causing poor process uniformity between wafers and within each wafer. For example, photolithography tools may produce images that are misaligned. Bow and warp may also cause photolithography tools to produce images that are out of focus, which can produce incorrect patterns on the workpiece. Some process tools using vacuum handling may be unable to contact the wafer at all vacuum points, resulting in handling failure. Bow can also cause stress during the die grinding process that reduces dicing uniformity. In processes associating the top surfaces of two workpieces, for example the strained silicon-on-insulator (SSOI) process described below, bow may result in poor bonding between donor and receiving workpieces. Thus, the methods described herein below preferably reduce bow to less than about 50 μm, more preferably less than about 25 μm, and even more preferably less than about 5 μm in order for the workpieces to be bondable for 300 mm diameter substrates.

[0026] Bow and warp may disadvantageously increase due to the deposition of multiple layers. For example, the deposition of a strained active layer over a relaxed buffer layer over a substrate may cause strain, and thus bow and warp, due to the differences in the coefficients of thermal expansion between the relaxed buffer layer and the substrate and between the strained active layer and the relaxed buffer layer. The bow caused by such multiple layers can be mathematically described by Equation 2.

$$b_{fn} = b_0 - \frac{3}{4} \cdot \left(\frac{d}{H_s} \right)^2 \cdot \Delta T \cdot \left(\alpha_s \cdot \sum_n H_{fn} - \sum_n H_{fn} \cdot \alpha_n \right) \qquad \text{(Eqn. 2)}$$

[0027] Bow (b_{fn}) equals the square of the ratio of the substrate diameter (d) to the substrate thickness (H_s), the difference (ΔT) between the grown layer growth temperature and the stability temperature, and the product of the coefficient of thermal expansion for the bulk substrate (α_s) and the sum of the thicknesses (H_{fn}) of each of n grown layers minus the sum of the products of the thicknesses (H_{fn}) of n grown layers and the coefficients of thermal expansion (α_{fn}) for n grown layers, plus the initial amount of bow (b_0). Compared to Equation 1, the differences in coefficient of thermal expansion are expressed in combination with the thicknesses of the layers to represent the additive effects of the layers. It will be appreciated that Equation 2 reduces to Equation 1 for a

single grown layer. In some embodiments, a plurality of grown layers may make the problems due to bow and warp described above worse.

[0028] The coefficient of thermal expansion (α_x) for a SiGe relaxed buffer layer changes with the germanium concentration x, as described by Equations 3 and 4 for temperatures near room temperature. Equation 3 is generally accurate for germanium concentrations between 0% and 85% (i.e., $0 < x < 0.85$). Equation 4 is generally accurate for germanium concentrations between 85% and 100% (i.e., $0.85 < x < 1$). It will be appreciated that the equations may be different in other temperature ranges.

$$\alpha_x = (2.55 \cdot x + 2.6) \cdot 10^{-6} / K \quad \text{(Eqn. 3)}$$

$$\alpha_x = (7.53 \cdot x - 0.89) \cdot 10^{-6} / K \quad \text{(Eqn. 4)}$$

[0029] Insertion of Equations 3 and 4 into Equation 1 or 2 shows that higher germanium concentrations can lead to greater workpiece bow due to differences in coefficient of thermal expansion. Assuming that all other variables remain constant, the difference between the coefficient of thermal expansion of the substrate (α_s) and the coefficient of thermal expansion for the deposited layer (α_f) will be larger for silicon substrates as germanium concentration increases. For example, when the germanium concentration is 10%, application of Equation 1 yields a coefficient of thermal expansion ($\alpha_{0.10}$) of 2.86×10^{-6}/K, and when the germanium concentration is 40%, application of Equation 1 yields a coefficient of thermal expansion ($\alpha_{0.40}$) of 3.62×10^{-6}/K. Thus, for single grown layers of relaxed SiGe, the difference in thermal expansion ($\Delta\alpha$) from a silicon substrate with a coefficient of thermal expansion (α_s) of 2.6×10^{-6}/K, will be 0.26×10^{-6}/K for 10% germanium but will be 1.02×10^{-6}/K for 40% germanium, thereby causing the magnitude of the workpiece bow (b) to increase by about 400% for an increase in germanium concentration from 10% to 40%.

[0030] In certain embodiments, altering the properties of the relaxed buffer layer can change the amount of bow in a workpiece. For example, the amount of bow in a workpiece will increase if the thickness of the relaxed buffer layer (H_f) increases while holding the other variables constant. A SiGe relaxed buffer layer deposited over a silicon substrate may comprise a concentration of germanium at the interface between the substrate and the relaxed buffer layer that is low enough that the crystallographic structure of the relaxed buffer layer is substantially similar to the crystallographic structure of the substrate. The proportion of germanium may increase gradually (e.g., linearly as depicted

in Figures 2A and 2B, stepwise as depicted in Figure 2C, curved as depicted in Figure 2D, combinations thereof, or any other suitable increases) through the thickness of the graded portion of the relaxed buffer layer from the substrate to the top surface of the graded portion of the relaxed buffer layer, although the increases in germanium proportion are low enough that the crystallographic structure of the relaxed buffer layer is not strained throughout its thickness. Figures 2E through 2G illustrate that the germanium concentration change from relaxed buffer layer to the strained transitional layers do not have to be immediate, but may be tapered (e.g., as illustrated by the strained transitional layers 2 in Figures 2E and 2F), curved (e.g., as illustrated by the strained transitional layers 1 in Figures 2E through 2G and the strained transitional layer 2 in Figure 2G), etc. As described above, the relaxed buffer layer may comprise a non-graded portion (e.g., between about 1 and 3 μm), depicted in Figures 2A-2G as the substantially flat concentrations at each $[Ge]_F$.

[0031] Figure 3 illustrates a partial schematic cross-section of an example workpiece comprising a substrate 10 and a relaxed buffer layer 12 increasing in germanium concentration from 0% to 40%. The substrate 10 is a silicon wafer with a diameter of 200 mm, a thickness of 725 μm, and a coefficient of thermal expansion of 2.6×10^{-6}/K. The relaxed buffer layer 12 has a thickness of 6.14 μm, a growth temperature of 900 °C (1173 K), and a stability temperature of 500 °C (773 K). Application of Equation 1 for the embodiment illustrated in Figure 3 results in a bow of about 75 μm.

[0032] If the relaxed buffer layer 12 has a thickness of 7.5 μm, application of Equation 3 results in a bow of about 92 μm. That is, workpiece bow increases when the thickness of the relaxed buffer layer (H_{fn}) increases. In order to produce a relaxed buffer layer with a germanium concentration that gradually increases from the substrate interface to the top surface of the relaxed buffer layer, the relaxed buffer layer is usually thick enough to allow relaxation at the plurality of intermediate crystal structures resulting from the plurality of intermediate germanium concentrations. For example, a $Si_{0.6}Ge_{0.4}$ relaxed buffer layer is typically thicker than a $Si_{0.8}Ge_{0.2}$ relaxed buffer layer to allow gentle grading to the ultimate desired (e.g., upper surface) germanium concentration to minimize vertically propogating defect formation during relaxation. In some embodiments, a relaxed buffer layer comprising 20% germanium at the top surface is between about 3 and 5 μm thick. In some embodiments, a relaxed buffer layer comprising 30% germanium at

the top surface is between about 4 and 6 μm thick. In some embodiments, a relaxed buffer layer comprising 40% germanium at the top surface is between about 5 and 7 μm thick. In some embodiments, a relaxed buffer layer comprising 60% germanium at the top surface is between about 6 and 8 μm thick. In some embodiments, a relaxed buffer layer comprising 80% germanium at the top surface is between about 7 and 9 μm thick. In some embodiments, a relaxed buffer layer comprising 100% germanium at the top surface is between about 8 and 10 μm thick.

[0033] In some embodiments, the relaxed buffer layer comprises a relaxed non-graded buffer segment or section comprising silicon and germanium having a substantially constant germanium concentration deposited on top of the graded portion of the relaxed buffer layer. The non-graded relaxed buffer segment generally has a germanium concentration corresponding to the germanium concentration at the top surface of the graded portion of the relaxed buffer layer such that the non-graded segment layer is substantially relaxed. The thickness of the non-graded buffer layer may be on the order of microns. For example, the thicknesses provided above for the relaxed buffer layer may include between about 1 and 3 μm (e.g., about 2 μm) of non-graded buffer segment.

[0034] The use of higher germanium concentrations can desirably make a strained active layer deposited on top of the relaxed buffer layer more strained because the crystal structure is more unlike the native crystal structure of silicon, thereby increasing the speed of devices formed in the strained active layer. Thus, although increases in device speed may desirably employ higher concentrations of germanium in relaxed buffer layers, higher concentrations of germanium may also undesirably result in increased workpiece bow due to both greater differences in coefficients of thermal expansion and a greater thickness of the relaxed SiGe buffer layer. Relaxed buffer layers may also be thicker for processes that transfer a strained active layer to another workpiece because the relaxed buffer layer is preferably thick enough to split, as described in detail below. Preferably, the non-graded portion of the relaxed buffer layer is thick enough to split (for example, and without limitation, at least 2 μm).

[0035] If the substrate 10 has a diameter of 300 mm and a thickness of 750 μm, and if the relaxed buffer layer 12 has a thickness of 6.14 μm, application of Equation 1 results in a bow of about 158 μm. That is, the bow is about 210% higher than the bow

of a workpiece with a diameter of 200 mm. The problems associated with workpiece bow may become increasingly important because the historical trend in semiconductor manufacturing has been to utilize substrates with increasingly higher diameters. For example, increasing the substrate diameter to 450 mm and the substrate thickness to 800 μm would result in workpiece bow of about 312 μm for the structure of Figure 3 (i.e., 417% higher than the bow for a substrate with a diameter of 200 mm).

[0036] In certain embodiments, the formation of at least one strained transitional layer within the graded portion of the relaxed buffer layer can reduce or counter workpiece bow due to differential coefficients of thermal expansion between the substrate and the relaxed buffer layer upon cooling below a stability temperature. As used herein, the term "counter" is to be given its broadest ordinary meaning, including, but not limited to, to oppose and to act in an opposite direction. That is, the strained transitional layer need not reduce the amount of bow to zero, but preferably reduces the amount of bow to a value sufficient to result in a workpiece that is suitable for further processing. In some embodiments, the strained transitional layer preferably counters bow to a value low enough to perform a SSOI process as described above. In some embodiments, the strained transitional layer counters bow by about 25%, 50%, 75%, or whatever amount makes the workpiece suitable for subsequent processing. The strained transitional layer may comprise the same material as the substrate, the same material as a strained active layer deposited on top of the relaxed buffer layer, or another material. For example, embodiments in which a SiGe relaxed buffer layer is deposited on a silicon substrate, the strained transitional layer may comprise strained silicon or another material. The configuration of the number, thickness, and positioning of the strained transitional layer may be determined based on the overall thickness and concentration of the relaxed buffer layer and the diameter of the workpiece.

[0037] Referring again to Figure 2A, the germanium concentration gradually increases from $[Ge]_0$ to $[Ge]_F$ across the thickness of the graded portion of the relaxed buffer layer. Strained transitional layers 1, 2 (e.g., strained silicon) can be formed within the graded portion of the relaxed buffer layer in accordance with the present disclosure, for example as schematically depicted in Figures 2B through 2D. In Figure 2B, the germanium concentration increases linearly from $[Ge]_0$ to $[Ge]_F$, with decreases back to $[Ge]_0$ in strained transitional layers 1, 2. In Figure 2C, the germanium concentration increases stepwise from $[Ge]_0$ to $[Ge]_F$, with decreases back to $[Ge]_0$ in strained

transitional layers 1, 2. In Figure 2D, the germanium concentration increases in a curved fashion from $[Ge]_0$ to $[Ge]_F$, with decreases back to $[Ge]_0$ in strained transitional layers 1, 2. In certain preferred embodiments, $[Ge]_0$ is zero (i.e., there is no germanium at the interface between the relaxed buffer layer and the substrate or in the strained transitional layers 1, 2), although it will be appreciated that $[Ge]_0$ can be non-zero and the concentration in either or both of the strained transitional layers 1, 2 can be different from the initial relaxed buffer layer concentration $[Ge]_0$.

[0038] In some embodiments, the germanium concentration in a graded portion of the relaxed buffer layer at the bottom surface of the strained transitional layer is substantially the same as the germanium concentration in a graded portion of the relaxed buffer layer at the top surface of the strained transitional layer. For example, in Figures 2B and 2D, the concentration $[Ge]_1$ in the graded portion of the relaxed buffer layer is the same directly above and below the strained transitional layer 1, and the concentration $[Ge]_2$ in the graded portion of the relaxed buffer layer is the same directly above and below the strained transitional layer 2. In some embodiments, the germanium concentration in the graded portion of the relaxed buffer layer at the bottom surface of the strained transitional layer is different from the germanium concentration in the graded portion of the relaxed buffer layer at the top surface of the strained transitional layer. For example, in Figures 2B, the concentration $[Ge]_{1a}$ in the graded portion of the relaxed buffer layer below the strained transitional layer 1 is different from the concentration $[Ge]_{1b}$ in the graded portion of the relaxed buffer layer above the strained transitional layer 1, and the concentration $[Ge]_{2a}$ in the graded portion of the relaxed buffer layer below the strained transitional layer 2 is different from the concentration $[Ge]_{2b}$ in the graded portion of the relaxed buffer layer above the strained transitional layer 2. It will be appreciated that the germanium concentration differences directly above and below the strained transitional layers 1, 2 in Figure 2C are small enough that the graded portion of the relaxed buffer layer remains relaxed on either side of the transitional layers.

[0039] The germanium concentration in the relaxed buffer layer and the strained transitional layers may have any suitable profile such that the germanium concentration in the strained transitional layer is lower than the germanium concentration in the graded portion of the relaxed buffer layer at the top and bottom surfaces of that strained transitional layer (i.e., so the strained transitional layer is strained). For example,

the concentration of germanium in one or both of the strained transitional layers 1, 2 in Figures 2B-2D may be above or below $[Ge]_0$.

[0040] In certain embodiments, the number of strained layers is between about one and eleven for a relaxed buffer layer that has a germanium concentration between about 1% and 100% at the top surface of the relaxed buffer layer. The ratio of silicon to germanium is thus between about 99:1 and 0:100. In certain embodiments, the number of strained layers is about one or two for a relaxed buffer layer that has a germanium concentration between about 15% and 25% at the top surface of the relaxed buffer layer. The ratio of silicon to germanium is thus between about 85:15 and 75:25. In certain embodiments, the number of strained transitional layers is about two or three for a relaxed buffer layer with a germanium concentration between about 25% and 35% at the top surface of the relaxed buffer layer. The ratio of silicon to germanium is thus between about 75:25 and 65:35. In certain embodiments, the number of strained transitional layers is between about three and five for a relaxed buffer layer with a germanium concentration between about 35% and 45% at the top surface of the relaxed buffer layer. The ratio of silicon to germanium is thus between about 65:35 and 55:45. In certain embodiments, the number of strained transitional layers is between about four and six for a relaxed buffer layer with a germanium concentration between about 45% and 55% at the top surface of the relaxed buffer layer. The ratio of silicon to germanium is thus between about 55:45 and 45:55. In certain embodiments, the number of strained transitional layers is between about five and seven for a relaxed buffer layer with a germanium concentration between about 55% and 65% at the top surface of the relaxed buffer layer. The ratio of silicon to germanium is thus between about 45:55 and 35:65. In certain embodiments, the number of strained transitional layers is between about six and eight for a relaxed buffer layer with a germanium concentration between about 65% and 75% at the top surface of the relaxed buffer layer. The ratio of silicon to germanium is thus between about 35:65 and 25:75. In certain embodiments, the number of strained transitional layers is between about seven and nine for a relaxed buffer layer with a germanium concentration between about 75% and 85% at the top surface of the relaxed buffer layer. The ratio of silicon to germanium is thus between about 25:75 and 15:85. In certain embodiments, the number of strained transitional layers is between about nine and eleven for a relaxed buffer layer with a germanium concentration between about 85% and 95% at the top surface of the relaxed buffer layer. The ratio of silicon to germanium is thus between about 15:85 and 5:95. It

will be appreciated that the ratios of silicon to germanium may be different if the relaxed buffer layer comprises other elements.

[0041] The quantity of strained transitional layers may be higher for substrates with larger diameters. For example, the quantities provided above may be appropriate for workpieces with a diameter of 200 mm, but an additional strained transitional layer may be formed for workpieces with diameters of 300 mm and two additional strained transitional layers may be formed for workpieces with diameters of 450 millimeters. The quantity of strained transitional layers can also be selected based on the thickness of the relaxed buffer layer and/or the deposition temperature.

[0042] The thickness of the strained transitional layer is generally thin compared to the thickness of the relaxed buffer layer. As deposited, the buffer layer is relaxed because the changes in internal lattice stress due to different germanium concentrations are gradual enough that the buffer layer may relax during deposition at each of the plurality of concentration changes. However, the transitional layer is strained because the internal lattice stress difference due to the abrupt change (e.g., back to $[Ge]_0$) in does not allow the transitional layer to relax. That is, the transitional layer adopts the crystal lattice of the layer on which it is formed. The buffer layer formed on top of the strained transitional layer also adopts the crystal lattice of the layer on which it is formed, so it is also relaxed because the crystal lattice of the strained transitional layer matches the relaxed buffer layer below it (e.g., $[Ge]_1$).

[0043] For a given germanium concentration in a SiGe relaxed buffer layer, the critical thickness of a strained silicon transitional layer decreases as the deposition temperature of the SiGe relaxed buffer layer increases. For a given deposition temperature of a SiGe relaxed buffer layer, the critical thickness of a strained silicon transitional layer decreases as the germanium concentration in the SiGe relaxed buffer layer increases. If the thickness of the strained transitional layer is greater than the critical thickness, defects may occur at the top and/or bottom interfaces between the strained transitional layer and the relaxed buffer layer, thereby inducing relaxation. Thus, the critical thickness for a strained transitional layer in a SiGe relaxed buffer layer with a high germanium concentration grown at a high temperature (e.g., 900 °C) is low. In some embodiments, the critical thickness of the strained silicon transitional layers is less than 100 Å (0.01 μm, 10 nm), less than 80 Å (0.008 μm, 8 nm), less than 50 Å (0.005 μm, 5 nm), or less than 20 Å (0.002 μm, 2 nm). In some embodiments, the preferred thickness

of the strained transitional layer is between about 10 Å (0.001 μm, 1 nm) and 100 Å (0.01 μm, 10 nm), between about 40 Å (0.004 μm, 4 nm) and 90 Å (0.009 μm, 9 nm), or between about 60 Å (0.006 μm, 6 nm) and 80 Å (0.008 μm, 8 nm).

[0044] Positioning of the strained transitional layer also depends on the thickness and concentration of the graded portion of the relaxed buffer layer. In certain embodiments, the strained transitional layers are positioned roughly evenly spaced throughout the thickness of the graded portion of the relaxed buffer layer. In some embodiments, the strained transitional layers change in proportion to germanium concentration in the graded portion of the relaxed buffer layer. In certain embodiments, the strained transitional layers are formed within the graded portion of the relaxed buffer layer at variable intervals. For example, a single strained transitional layer may be placed at approximately 3.07 μm from the substrate if the graded portion of the relaxed buffer layer is 6.14 μm thick. For another example, four strained transitional layers may be placed at approximately 1.0 μm, 2.1 μm, 3.1 μm, and 3.7 μm from the substrate if the graded portion of the relaxed buffer layer is 6.14 μm thick.

[0045] As described above, the critical thickness of the strained transitional layers deposited within a SiGe relaxed buffer layer depends in part on the germanium concentration. Process parameters may limit the controllable thickness of the strained transitional layers, and thus formation of strained transitional layers at lower germanium concentrations may result in increased process control. In certain preferred embodiments, the strained transitional layers are not positioned proximate to the top of the graded portion of the relaxed buffer layer.

[0046] Figure 4 illustrates an embodiment of a workpiece in accordance with the present invention where the relaxed buffer layer and the strained transitional layer are deposited at about at 900 °C (1173 K). The workpiece comprises a substrate 10, a first portion of a SiGe relaxed buffer layer 14 linearly increasing in germanium concentration from 0% proximate to the substrate 10 to 20% at the top surface of the first portion of the relaxed buffer layer 14, a strained silicon transitional layer 16, and a second portion of the SiGe relaxed buffer layer 18 linearly increasing in germanium concentration from 20% proximate to the strained transitional layer 16 to 40% at the top surface of the second portion of the relaxed buffer layer 18. The first portion 14 of the SiGe relaxed buffer layer has a thickness of 3.07 μm from the substrate 10 to the strained transitional layer 16.

The strained transitional layer 16 has a thickness of 40 Å (0.004 μm, 4 nm). The second portion 18 of the SiGe relaxed buffer layer has a thickness of 3.07 μm from the strained transitional layer 16 to the top surface of the SiGe relaxed buffer layer. The inclusion of the strained silicon transitional layer within the SiGe relaxed buffer layer reduces the amount of workpiece bow to approximately 55 μm. Other configurations can reduce the amount of workpiece bow to approximately 20 μm or lower. As noted above, the manner of grading can be other than linear.

[0047] Figure 5 illustrates another embodiment of a workpiece in accordance with the present invention where the relaxed buffer layer and the strained transitional layers are deposited at about at 900 °C (1173 K). The workpiece comprises a substrate 10, a first portion of a SiGe relaxed buffer layer 20 linearly increasing in germanium concentration from 0% proximate to the substrate 10 to 6.5% at the top surface of the first portion of the relaxed buffer layer 20, a first strained transitional layer 22, a second portion of the SiGe relaxed buffer layer 24 linearly increasing in germanium concentration from 6.5% proximate to the first strained transitional layer 22 to 13.7% at the top surface the second portion of the relaxed buffer layer 24, a second strained transitional layer 26, a third portion of the SiGe relaxed buffer layer 28 linearly increasing in germanium concentration from 13.7% proximate to the second strained transitional layer 26 to 20.2% at the top surface of the third portion of the relaxed buffer layer 28, a third strained transitional layer 30, a fourth portion of the SiGe relaxed buffer layer 32 linearly increasing in germanium concentration from 20.2% proximate to the third strained transitional layer 30 to 24.1% at the top surface of the fourth portion of the relaxed buffer layer 32, a fourth strained transitional layer 34, and a fifth portion of the SiGe relaxed buffer layer 36 linearly increasing in germanium concentration from 24.1% proximate to the fourth strained transitional layer 34 to 40% at the top surface of the fifth portion of the relaxed buffer layer 36. The first portion 20 of the SiGe relaxed buffer layer has a thickness of 1.0 μm from the substrate 10 to the first strained transitional layer 22. The first strained transitional layer 22 has a thickness of 65 Å (0.0065 μm, 6.5 nm). The second portion 24 of the SiGe relaxed buffer layer has a thickness of 1.07 μm from the first strained transitional layer 22 to the second strained transitional layer 26. The second strained transitional layer 26 has a thickness of 78 Å (0.0078 μm, 7.8 nm). The third portion 28 of the SiGe relaxed buffer layer has a thickness of 1.02 μm from the

second strained transitional layer 26 to the third strained transitional layer 30. The third strained transitional layer 30 has a thickness of 73 Å (0.0073 μm, 7.3 nm). The fourth portion 32 of the SiGe relaxed buffer layer has a thickness of 0.63 μm from the third strained transitional layer 30 to the fourth strained transitional layer 34. The fourth strained transitional layer 34 has a thickness of 69 Å (0.0069 μm, 6.9 nm). The fifth portion 36 of the SiGe relaxed buffer layer has a thickness of 2.42 μm from the fourth strained transitional layer 34 to the top surface of the SiGe relaxed buffer layer. The deposition of the four strained silicon transitional layers within the SiGe relaxed buffer layer reduces the amount of workpiece bow to approximately 20 μm. Other configurations can reduce the amount of workpiece bow to approximately 10 μm.

[0048] In a preferred embodiment, the relaxed buffer layer is grown in a single-wafer epitaxial deposition reactor, for example the Epsilon® 3000 (for 300 mm workpieces) from ASM America, Inc. of Phoenix, Arizona. More preferably, the relaxed buffer layer including strained transitional layers is grown within the epitaxial deposition reactor. In certain embodiments in which the relaxed buffer layer comprises SiGe, the germanium concentration may be linearly increased within each portion (or "segment") of the relaxed buffer layer by adjusting deposition parameters. For example, the temperature of the deposition may be adjusted and/or, more preferably, the flow of reactants comprising silicon precursors may be reduced, the flow of reactants comprising germanium precursors may be increased. Examples of reactants comprising silicon precursors include, but are not limited to, silane, disilane, trisilane, chlorosilane, and dichlorosilane. Examples of reactants comprising germanium precursors include, but are not limited to, germane, digermane, chlorogermane, and dichlorogermane. In embodiments in which the deposition is performed at high temperatures, thereby inducing higher bow as described above, precursors comprising chlorine are preferred.

[0049] In certain embodiments in which the relaxed buffer layer comprises SiGe and the strained transitional layer comprises strained silicon, the strained silicon transitional layer can be formed *in situ* in an epitaxial deposition reactor by pausing flowing the reactants comprising germanium precursors, for example by shunting the reactants comprising germanium precursors to vent or stopping the flow of the reactants comprising germanium precursors. In certain embodiments, "pausing" flowing the reactants comprising germanium precursors still allows the deposition of silicon

germanium, for example due to a relatively low flow of reactants comprising germanium precursors or an amount of reactants comprising germanium precursors remaining in the reactant lines. In certain embodiments, the duration of depositing the strained transitional layer is preferably between about 0.1 and 10 seconds and is more preferably between about 0.5 and 5 seconds. In some embodiments, the duration of depositing the strained transitional layer is at least one rotation (e.g., an integer number of rotations) of a rotatable susceptor holding the workpiece in the deposition chamber. In certain embodiments, the germanium concentration in the graded portion of the relaxed buffer layer is substantially the same proximate to the bottom of the strained transitional layer as the germanium concentration in the graded portion of the relaxed buffer layer proximate to the top of the strained transitional layer, for example by using the same deposition parameters before and after the deposition of the strained transitional layer. Deposition of strained transitional layers using previously existing semiconductor processing equipment desirably represents low integration costs and the *in situ* deposition of the strained transitional layers does not substantially affect the throughput of the reactor or increase the cost of the workpiece.

[0050] A strained active layer may be deposited on the surface of the relaxed buffer layer. Figure 6A illustrates a partial schematic cross-section of an example workpiece comprising a substrate 10, relaxed SiGe buffer layer portions 14, 18 both increasing in germanium concentration with distance from the substrate 10, a strained silicon transitional layer 16, and a strained active layer 42. Together, the relaxed SiGe buffer layer portions 14, 18 and the strained transitional layer 16 form a buffer layer structure 39. In certain embodiments, the strained active layer 42 is transferred from a donor workpiece to a receiving substrate (or "handle wafer") 44. After the strained active layer 42 is deposited, a region of weakness can be created in the donor workpiece, for example by implanting hydrogen (e.g., H^+, H_2^+) to a specific depth. Figure 6A shows a region of weakness 40 in the relaxed buffer layer 18. However, the region of weakness may be anywhere within the donor workpiece, for example and without limitation in the relaxed buffer layer 14, the strained transitional layer 16, and the substrate 10. In some embodiments, a further layer (e.g., an insulating layer comprising, for example, SiO_2, tetraethylorthosilicate (TEOS), silicon nitride (e.g., Si_3N_4), silicon oxynitride (SiO_xN_y)) (not shown) is deposited on the strained active layer 42 prior to association. After the strained active layer 42 is deposited, the donor workpiece can be associated with (or

"bonded to") the receiving substrate 44 to form a composite structure (e.g., as depicted in Figure 6B). The region of weakness 40 is configured to facilitate splitting of the composite structure. The composite structure can be split in the region of weakness 40 in the relaxed buffer layer 18, resulting in a donor workpiece comprising a portion of the relaxed buffer layer 18 and a receiving substrate 44 with a strained active layer 42 (e.g., as depicted in Figure 6C). If the receiving substrate 44 has some of the relaxed buffer layer 18 on it, a polishing, etchback, or other suitable process may be used to leave only the strained active layer 42 (e.g., as depicted in Figure 6D). The region of weakness 40 is preferably in the relaxed buffer layer 18 because the donor workpiece can be reused in such embodiments by depositing a second strained active layer on the remaining relaxed buffer layer 18 (e.g., after creating a second area of weakness). In some embodiments including an insulating layer, the insulator remains so as to be the insulator portion of a SSOI device. In some other embodiments including an insulating layer, the insulator protects the surface of the workpiece during formation of the region of weakness 40, and is removed before bonding. SSOI processes for creating a region of weakness, associating the donor workpiece to the receiving substrate, and splitting the composite structure are described in detail in U.S. Patent No. 6,953,736, issued October 11, 2005, entitled "Process for Transferring a Layer of Strained Semiconductor Material," incorporated herein by reference in its entirety.

[0051] In certain embodiments, bow and warp present problems when attempting to associate a donor workpiece comprising a strained active layer and a receiving substrate. Assuming that the amount of bow in the receiving substrate is about 0 μm, the amount of bow in the donor workpiece is preferably below 50 μm, more preferably below 25 μm, and even more preferably below 5 μm for 300 mm diameter substrates. As an example, a donor workpiece comprising a 6.14 μm relaxed buffer layer comprising $Si_{0.6}Ge_{0.4}$ at the top surface (as depicted in Figure 3) may have an amount of bow of about 75 μm, and thus would not be suitable for association with a receiving substrate. The formation of at least one strained transitional layer in accordance with the embodiments described herein can advantageously decrease the amount of bow, thereby making the donor workpiece suitable for association with a receiving substrate.

[0052] Additionally, the implantation generally penetrates the workpiece to a constant distance from the workpiece surface. Formation of at least one strained

transitional layer can advantageously affect the uniformity of the depth of the implant that creates the area of weakness, which penetrates the workpiece a constant distance from the surface, is substantially more planar without workpiece bow and warp. The strained active layer 16 may thereby help to concentrate the implanted species (e.g., hydrogen) around the region of weakness 40 and can thereby lead to lower surface roughness after splitting, which may enhance the effects of a subsequent etch (e.g., a selective etch) designed to remove residual SiGe from the receiving substrate 44. In certain embodiments, the position of the strained transitional layer 16 and the energy of the implantation are selected such that the implanted species (e.g., hydrogen) concentrate around the position of the strained transitional layer 16.

[0053] In certain embodiments, the at least one strained transitional layer exists in an integrated circuit, for example and without limitation after being cut from a workpiece processed in accordance with certain embodiments described herein. As an example, in certain embodiments an integrated circuit comprises a substrate, a relaxed buffer layer including a graded portion formed on the substrate, and at least one strained transitional layer within the graded portion of the relaxed buffer layer. In some embodiments, for example when the strained transitional layer is transferred by SSOI, portions of the relaxed buffer layer and/or the stained transitional layers may be removed (e.g., by etchback, polishing, etc.) before further processing of the workpiece.

[0054] Defects in traditional relaxed buffer layers can lead to threading dislocation densities (TDD) of between about $10^4/cm^2$ and $10^5/cm^2$ in the relaxed buffer layers. In certain embodiments, the at least one strained transitional layer described herein helps to reduce TDD proximate to a top surface of the relaxed buffer layer to less than $10^4/cm^2$. In some embodiments, the at least one strained transitional layer helps to reduce TDD proximate to a top surface of the relaxed buffer layer by about an order of magnitude (e.g., to below about $4\times10^3/cm^2$). For example, depositing three strained transitional layers within a relaxed buffer layer comprising $Si_{0.8}Ge_{0.2}$ on a 300 mm wafer can lead to TDD below approximately $10^4/cm^2$ in the relaxed buffer layer. In another example, depositing two strained transitional layers within a relaxed buffer layer comprising $Si_{0.8}Ge_{0.2}$ on a 200 mm wafer can lead to TDD below approximately $10^4/cm^2$ in the relaxed buffer layer. It will be appreciated that a strained active layer deposited over a relaxed buffer layer with a low TDD can result in a strained active layer with a substantially similar level of defectivity if the strained active layer is less than about its

critical thickness. For example, depositing a strained active layer over a relaxed buffer layer comprising $Si_{0.8}Ge_{0.2}$ and three strained transitional layers on a 300 mm wafer can lead to TDD below approximately $10^4/cm^2$ in the strained active layer. In another example, depositing a strained active layer over a relaxed buffer layer comprising $Si_{0.8}Ge_{0.2}$ and two strained transitional layers on a 200 mm wafer can lead to TDD below approximately $10^4/cm^2$ in the strained active layer. Therefore, the insertion of strained transitional layers may also be useful to reduce defects in workpieces that are not detrimentally bowed and/or warped (e.g., workpieces with low germanium concentrations).

[0055] Although this invention has been disclosed in the context of certain preferred embodiments and examples, it will be understood by those skilled in the art that the present invention extends beyond the specifically disclosed embodiments to other alternative embodiments and/or uses of the invention and obvious modifications and equivalents thereof. In addition, while several variations of the invention have been shown and described in detail, other modifications, which are within the scope of this invention, will be readily apparent to those of skill in the art based upon this disclosure. It is also contemplated that various combinations or sub-combinations of the specific features and aspects of the embodiments may be made and still fall within the scope of the invention. It should be understood that various features and aspects of the disclosed embodiments can be combined with, or substituted for, one another in order to form varying modes of the disclosed invention. Thus, it is intended that the scope of the present invention herein disclosed should not be limited by the particular disclosed embodiments described above, but should be determined only by a fair reading of the claims that follow.

WHAT IS CLAIMED IS:

1. A semiconductor workpiece comprising:

a substrate;

a relaxed buffer layer including a graded portion formed on the substrate, the buffer layer comprising silicon germanium having a concentration of germanium increasing from the substrate to a top surface of the buffer layer; and

at least one strained transitional layer within the graded portion of the relaxed buffer layer, the at least one strained transitional layer having a concentration of germanium lower than the concentration of germanium in the buffer layer above and below the at least one strained transitional layer such that the at least one strained transitional layer reduces an amount of workpiece bow relative to the relaxed buffer layer without at least one strained transitional layer, the workpiece bow being due to differential coefficient of thermal expansion (CTE) contraction of the relaxed buffer layer relative to CTE contraction of the substrate.

2. The workpiece of Claim 1, wherein the at least one strained transitional layer counters stresses in the workpiece due to differential coefficient of thermal expansion (CTE) contraction of the relaxed buffer layer relative to CTE contraction of the substrate.

3. The workpiece of Claim 1, wherein the strained transitional layer is between 1 and 10 nm thick.

4. The workpiece of Claim 1, wherein the strained transitional layer is between 6 and 8 ran thick.

5. The workpiece of Claim 1, wherein the strained transitional layer comprises strained silicon.

6. The workpiece of Claim 1, wherein the strained transitional layer comprises strained silicon germanium.

7. The workpiece of Claim 1, wherein the relaxed buffer layer comprises silicon and germanium, wherein a highest germanium concentration in the relaxed buffer layer is between 15% and 45%, and wherein the graded portion of the relaxed buffer layer comprises:

a first portion of the relaxed buffer layer formed on the substrate, a germanium concentration in the first portion of the relaxed buffer layer higher at an upper surface

away from the substrate than at a lower surface , wherein the lower surface of the first portion is closer to the substrate than the upper surface of the first portion;

a first strained transitional layer formed on the surface of the first portion of the relaxed buffer layer away from the substrate; and

a second portion of the relaxed buffer layer formed on the first strained transitional layer, a germanium concentration in the second portion of the relaxed , buffer layer higher at an upper surface away from the first strained transitional layer than at a lower surface , wherein the lower surface of the second portion is closer to the first strained transitional layer than the upper surface of the second portion.8. The workpiece of Claim 7, wherein the graded portion of the relaxed buffer layer further comprises:

a second strained transitional layer formed on the surface of the second portion of the relaxed buffer layer away from the substrate; and

a third portion of the relaxed buffer layer formed on the second strained transitional layer, a germanium concentration in the third portion of the relaxed buffer layer higher at an upper surface away from the second strained transitional layer than at a lower surface , wherein the lower surface of the third portion is closer to the second strained transitional layer than the upper surface of the third portion.

9. The workpiece of Claim 7, wherein a highest germanium concentration in the relaxed buffer layer is between 25% and 35%.

10. The workpiece of Claim 9, comprising two to three strained transitional layers within the graded portion of the relaxed buffer layer.

11. The workpiece of Claim 7, wherein a highest germanium concentration in the relaxed buffer layer is between 35% and 45%.

12. The workpiece of Claim 11, comprising three to five strained transitional layers within the graded portion of the relaxed buffer layer.

13. The workpiece of Claim 1, further comprising a strained active layer formed on the relaxed buffer layer.

14. The workpiece of Claim 1, wherein the relaxed buffer layer comprises a region of weakness, the region of weakness configured to facilitate splitting of the workpiece.

15. A method of manufacturing a semiconductor workpiece, the method comprising:

providing a substrate;

depositing a relaxed buffer layer on the substrate by flowing reactants comprising silicon precursors and germanium precursors, the buffer layer comprising silicon germanium having a concentration of germanium increasing from the substrate to a top surface of the buffer layer;

during depositing the relaxed buffer layer, depositing at least one strained transitional layer by pausing flowing the germanium precursors while continuing to flow the silicon precursors; and

cooling the workpiece, wherein the at least one strained transitional layer has a concentration of germanium lower than the concentration of germanium in the buffer layer above and below the at least one strained transitional layer such that the at least one strained transitional layer reduces an amount of workpiece bow due to differential coefficient of thermal expansion (CTE) contraction of the relaxed buffer layer relative to CTE contraction of the substrate during cooling relative to a relaxed buffer layer without at least one strained transitional layer.

16. The method of Claim 15, wherein the at least one strained transitional layer counters stresses in the workpiece due to differential coefficient of thermal expansion (CTE) contraction of the relaxed buffer layer relative to CTE contraction of the substrate during cooling.

17. The method of Claim 15, wherein depositing the relaxed buffer layer comprises depositing silicon and germanium in an epitaxial deposition reactor, wherein a highest germanium concentration in the relaxed buffer layer is between 15% and 25%, and wherein depositing the relaxed buffer layer comprises:

depositing a first portion of the relaxed buffer layer by flowing silicon and germanium precursors, a germanium concentration in the first portion of the relaxed buffer layer increasing as the first portion of the relaxed buffer layer is deposited;

after depositing the first portion of the relaxed buffer layer, depositing a first strained transition layer by pausing flowing the germanium precursors; and

after depositing the first strained transition layer, depositing a second portion of the relaxed buffer layer by resuming flowing the germanium precursors, a germanium concentration in the second portion of the relaxed buffer layer increasing as the second portion of the relaxed buffer layer is deposited.

18. The method of Claim 17, wherein depositing the relaxed buffer layer further comprises:

after depositing the second portion of the relaxed buffer layer, depositing a second strained transition layer by pausing flowing the germanium precursors; and

after depositing the second strained transition layer, depositing a third portion of the relaxed buffer layer by resuming flowing the germanium precursors, a germanium concentration in the third portion of the relaxed buffer layer increasing as the third portion of the relaxed buffer layer is deposited.

19. The method of Claim 17, wherein a highest germanium concentration in the relaxed buffer layer is between 25% and 35%.

20. The method of Claim 19, wherein depositing the relaxed buffer layer comprises depositing two to three strained transitional layers.

21. The method of Claim 17, wherein a highest germanium concentration in the relaxed buffer layer is between 35% and 45%.

22. The method of Claim 21, wherein depositing the relaxed buffer layer comprises depositing three to five strained transitional layers.

23. The method of Claim 15, wherein the at least one strained transitional layer reduces a threading dislocation density at a top surface of the relaxed buffer layer to less than $10^4/cm^2$.

24. A method of manufacturing a semiconductor workpiece, the method comprising:

providing a substrate;

depositing a first portion of a relaxed buffer layer comprising silicon germanium on the substrate by flowing silicon precursors and germanium precursors while increasing a germanium concentration in the growing first portion of the relaxed buffer layer;

after depositing the first portion of the relaxed buffer layer, pausing flowing the germanium precursors while continuing to flow the silicon precursors to deposit at least one strained transitional layer; and

after pausing flowing the germanium precursors, depositing a second portion of the relaxed buffer layer by resuming flowing the germanium precursors and increasing a germanium concentration in the growing second portion of the relaxed

buffer layer, wherein the at least one strained transitional layer has a concentration of germanium lower than the concentration of germanium in the buffer layer above and below the at least one strained transitional layer such that the at least one strained transitional layer reduces an amount of workpiece bow relative to a relaxed buffer layer without the at least one strained transitional layer, the workpiece bow being due to differential coefficient of thermal expansion (CTE) contraction of the relaxed buffer layer relative to CTE contraction of the substrate..

25. The method of Claim 24, wherein a duration of pausing flowing the germanium precursors is between 0.1 and 10 seconds.

26. The method of Claim 24, wherein a duration of pausing flowing the germanium precursors is a time for a rotatable susceptor holding the workpiece to rotate at least once.

27. The method of Claim 24, wherein pausing flowing the germanium precursors comprises depositing strained silicon.

28. The method of Claim 27, wherein the deposited strained silicon is between 1 and 10 nm thick.

29. The method of Claim 27, wherein the deposited strained silicon is between 6 and 8 nm thick.

30. The workpiece of Claim 1, wherein the at least one strained transitional layer has a germanium concentration of 0%.

31. The workpiece of Claim 15, wherein the at least one strained transitional layer has a germanium concentration of 0%.

32. The workpiece of Claim 24, wherein the at least one strained transitional layer has a germanium concentration of 0%.

33. The workpiece of Claim 1, wherein the germanium concentration in a portion of the relaxed buffer layer at a bottom surface of the strained transitional layer is the same as the germanium concentration in a portion of the relaxed buffer layer at a top surface of the strained transitional layer.

34. The workpiece of Claim 15, wherein the germanium concentration in a portion of the relaxed buffer layer at a bottom surface of the strained transitional layer is the same as the germanium concentration in a portion of the relaxed buffer layer at a top surface of the strained transitional layer.

35. The workpiece of Claim 24, wherein the germanium concentration in a portion of the relaxed buffer layer at a bottom surface of the strained transitional layer is the same as the germanium concentration in a portion of the relaxed buffer layer at a top surface of the strained transitional layer.

36. The workpiece of Claim 1, wherein the germanium concentration change from the relaxed buffer layer to the strained transitional layer is immediate.

37. The workpiece of Claim 15, wherein the germanium concentration change from the relaxed buffer layer to the strained transitional layer is immediate.

38. The workpiece of Claim 24, wherein the germanium concentration change from the relaxed buffer layer to the strained transitional layer is immediate.