

CONTROL OF ANISOTROPIC DEFORMATION WITH DIRECTIONAL STRESS MODULATION FOR DEVICE MANUFACTURING

BACKGROUND

[0001] Modern semiconducting devices, such as processing units, memory devices, light detectors, solar cells, light-emitting semiconductor devices, devices that deploy complementary metal-oxide-semiconductor (CMOS) structures, and the like, are often manufactured on silicon wafers (or other suitable substrates). Wafers may undergo numerous processing operations, such as physical vapor deposition, chemical vapor deposition, etching, photo-masking, polishing, and/or various other operations. In a continuous effort to reduce the cost of semiconductor devices, multi-layer stacks of dies, insulating films, patterned and/or doped semiconducting films, and/or other features are often deposited on a single wafer, resulting in high aspect ratio devices, which are used, e.g., in 3D flash memory devices and other applications. Deposition, patterning, etching, polishing, etc., of stacks of multi-layered structures often result in significant stresses applied to the underlying wafers. Such stresses lead to both an out-of-plane distortion and an in-plane distortion of features supported by the wafers. These distortions result in misalignment of deposited features and can significantly degrade quality of manufactured devices.

BRIEF DESCRIPTION OF THE DRAWINGS

[0002] The present disclosure will be understood more fully from the detailed description given below and from the accompanying drawings of various embodiments of the disclosure.

[0003] **FIG. 1A** illustrates schematically a portion of a uniformly (e.g., parabolically) deformed substrate such that the stress tensor is isotropic $\sigma_{xx} \approx \sigma_{yy}$. **FIG. 1B** illustrates schematically a portion of a substrate having anisotropic (e.g., cylindrical) deformation such that the stress tensor is anisotropic $\sigma_{xx} > \sigma_{yy}$.

[0004] **FIGs. 2A–2L** show a substrate-wide view of a process of semiconductor manufacturing that uses directional patterns for stress mitigation, according to at least one embodiment.

[0005] **FIGs. 3A–F** illustrate schematically a process of correcting substrate deformation using a stress-mitigation beam applied to a stress compensation layer deposited on a back side of a substrate and partially shielded by a directional pattern, according to at least one embodiment.

[0006] FIG. 4 illustrates an example Zernike polynomial decomposition of one actual deformation (top left) of a substrate, in arbitrary units, into a paraboloid bow deformation (top right), a saddle deformation (bottom left), and a residual deformation, (bottom right), according to at least one embodiment.

[0007] FIG. 5 is a flowchart illustrating an example method of mitigation of anisotropic substrate stress and deformation using stress-compensation beams with directional patterns, in accordance with at least one embodiment.

[0008] FIG. 6 is a flowchart illustrating an example method of determining settings for beam irradiation, in accordance with at least one embodiment.

[0009] FIGs. 7A–7B illustrates schematically an irradiation system capable of performing irradiation of stress compensation layers, according to at least one embodiment.

[0010] FIG. 8 depicts a block diagram of an example computer system capable of supporting operations of the present disclosure, according to at least one embodiment.

SUMMARY

[0011] In one embodiment, disclosed is a method that includes forming, responsive to an anisotropic deformation of a substrate, a stress-compensation layer (SCL) on the substrate and subjecting the SCL to a stress-mitigation beam to induce a directionally-modulated pattern of stress in the SCL that causes mitigation of the anisotropic deformation of the substrate.

[0012] In another embodiment, disclosed is a system that includes a memory, and a processing device communicatively coupled to the memory. The processing device causes performance of operations that include forming, responsive to an anisotropic deformation of a substrate, an SCL on the substrate, and subjecting the SCL to a stress-mitigation beam to induce a directionally-modulated pattern of stress in the SCL that causes mitigation of the anisotropic deformation of the substrate.

[0013] In another embodiment, disclosed is a semiconductor manufacturing system that includes one or more chambers to deposit one or more films on a substrate, form, responsive to an anisotropic deformation, an SCL on the substrate, subject the SCL to a stress-mitigation beam to induce a directionally-modulated pattern of stress in the SCL that causes mitigation of the anisotropic deformation of the substrate.

DETAILED DESCRIPTION

[0014] Modern technology often aims to maximize chip area utilization by manufacturing three-dimensional devices with vertical stacks of multiple layers of semiconducting structures. For example, in NAND flash memory devices, lateral relative arrangement (CMOS near Array, or CnA) of memory cells (e.g., floating gate transistors) and peripheral transistors (e.g., CMOS circuitry used to support write/read operations OF memory cells) has mostly given way to a vertical arrangement (CMOS under Array, or CuA) in which peripheral CMOS circuitry is disposed below an array of memory cells. In many instances, semiconductor structures are manufactured in an anisotropic fashion, e.g., with multiple high, long (along the direction of wordlines), and narrow (along the direction of bitlines) stacks of memory cells manufactured (deposited and/or etched) on substrates. In one example of NAND flash memory device manufacturing, a stack of multiple alternating oxide (O) and nitride (N) layers (e.g., silicon oxide and silicon nitride layers, in one example) can be deposited on top of a silicon wafer. In another example of a three-dimensional (3D) Dynamic Random-Access Memory (DRAM) manufacturing, a stack of alternating $\text{Si}_{1-x}\text{Ge}_x$ (SiGe) alloy layers and silicon (e.g., epitaxial silicon) layers can be deposited on top of a silicon wafer. Depositing these and other high aspect ratio structures typically results in anisotropic stresses that cause substrates to become deformed (e.g., warped). For example, deposition of layers/films can cause an isotropic stress and the subsequent patterning (e.g., with word lines, bit lines, and/or the like) can increase or decrease stress differently along different directions resulting in anisotropic warping. Substrate deformation can lead to misalignment of manufactured features and result in substandard or inoperable devices. Correcting the anisotropic stresses and the resulting substrate deformations is an important but difficult task.

[0015] Stress mitigation may be achieved with deposition of a stress-compensation layer (SCL), which may be a film of a material that, being deposited on the back side or, in some instances, the front side of a substrate, introduces a stress that at least partially negates the stresses caused by patterning and other features placed on the front side of the substrate. Additional control of stresses in the substrate may be achieved with ion implantation into the SCL that modifies (typically, reduces) the amount of stress in the SCL by introducing substitutions and vacancies in the crystal structure of the SCL. SCLs can be quite efficient in correcting stresses that are uniform and isotropic, $\sigma_{xx} \approx \sigma_{yy}$, and result in parabolic warping but mitigating stresses that are anisotropic, $\sigma_{xx} \neq \sigma_{yy}$, remains a challenging problem and requires additional treatment of the SCL. **FIG. 1A** illustrates schematically a portion of a

uniformly (e.g., parabolically) deformed substrate 100 such that the stress tensor is isotropic $\sigma_{xx} \approx \sigma_{yy}$. Deformations of the type illustrated in **FIG. 1A** can be addressed using conventional techniques of SCL. **FIG. 1B** illustrates schematically a portion of a substrate 150 having anisotropic (e.g., cylindrical) deformation such that the stress tensor is anisotropic $\sigma_{xx} > \sigma_{yy}$, where y is the axis of the cylindrical deformation. Deformations of the type illustrated in **FIG. 1B** can be efficiently corrected using one or more techniques disclosed below.

[0016] Aspects and embodiments of the present disclosure address these and other challenges of the modern semiconductor manufacturing technology by providing for systems and techniques capable of correcting anisotropic substrate deformations. In one example embodiment, mitigation of anisotropic stresses, with substantially different σ_{xx} and σ_{yy} , can be achieved by creating spatial patterns of stress within the SCL, in which stress is modulated (e.g., on micron scale) along a particular direction while remaining largely constant along the other, perpendicular direction. Such anisotropic stress modulation, suitably chosen, in direction and magnitude, can compensate (or at least reduce significantly), the anisotropic stress caused by features patterned on the device side of the substrate. Anisotropic stress modulation in the SCL can be achieved using a number of techniques disclosed herein.

[0017] In one example embodiment, creating a pattern of stress modulation can be made by first growing, depositing, or otherwise forming a similarly patterned protective mask of variable thickness on the (initially) uniform SCL. The formed directional patterns can include line gratings (e.g., ridges and/or grooves) used for partial (local) shielding of SCL from the stress-mitigation beam. The grooves of the gratings allow access of the particles of the stress-mitigation beam to the underlying areas of the SCL (stress-mitigated areas), where stress is significantly modified, as a result. On the other hand, the ridges of the gratings can shield other areas of SCL (protected areas) where stresses remain unmitigated (or weakly mitigated). The grating defined by the mask enables the use of wide stress-mitigation beams with a cross-section significantly exceeding the width of the grooves/ridges and is henceforth referred to as mask-transfer patterning herein. Mask patterning does not impose strict requirements regarding the size of stress-mitigation beams and enables the use of wide beams. While mask transfer patterning has been illustrated with an ion-beam energy source, the same or similar result can be achieved with other energetic particles, such as photons from a laser source.

[0018] In other embodiments, mask transfer patterning does not need to be deployed as the patterning is achieved by using stress-mitigation beams with high (e.g., micron or sub-micron) spatial resolution. For example, a narrow-spot laser beam can be directed to a pattern of spatial locations where stress is to be decreased (or, in some instances, increased). The narrow-spot beam can be a beam focused by one or more optical elements and scanned across the surface of the substrate, e.g., along the directions of the patterns, with a suitably chosen speed and intensity to deliver a target dose of photons to the target regions of the SCL. In some embodiments, a cylindrical lens (or other similar optics, e.g., cylindrical mirror) may be used to form a line beam that can illuminate, for a predetermined period of time, a linear target region before shifting to a next linear target region, and so on. The size of the beam can control the width of the regions where the stress is affected (e.g., reduced) while the length of the shift can determine the widths of the regions where the stress remains largely intact. While maskless direct-write patterning of the grating has been illustrated herein with a laser source of energetic photons, the same or a similar result can be accomplished by other techniques of delivering energetic particles to the SCL, e.g., ions, electrons, etc.

[0019] In some embodiments, instead of using a single narrow laser beam, or several such beams in parallel, an array of a multiple (e.g., two, four, ten, or more) light-emitting diodes, e.g., laser diodes, can be used to direct light (e.g., using any suitable focusing and/or collimating optics) to a corresponding number of target regions. In other embodiments, one or several laser beams (e.g., wide laser beams) can direct incident light to one or more diffractive optical elements (DOEs) that direct the light along multiple paths towards the target areas on the SCL. The parameters of a DOE (e.g., pitch of the grating), the distance from the light source to the DOE, the distance from the DOE to the substrate, etc., can be selected such that the diffracted rays strike the SCL at the desired regions where the constructive interference from multiple elements of the DOE ensures narrow illumination. Similarly, regions located between the target regions may receive little light, as a result of the destructive interference.

[0020] In some embodiments, the beam of photons can be a high-intensity beam that results in an ablation (or partial ablation) or annealing of the target regions and reduction in the local stress. In other embodiments, the beam of photons can be a lower-intensity beam with the wavelength selected to ensure a single-photon absorption with subsequent thermal excitation of phonons resulting in curing of the SCL material and the increase or decrease of the local stress.

[0021] The stress-mitigation beam can include matter particles (e.g., ions, electrons), electromagnetic waves (e.g., UV light, visible light, infrared light, etc.), and/or a suitable combination thereof. The stress-mitigation beam can strike the SCL and change the bonding network of the SCL. For example, an ion beam of low energy can interact with surface atoms of the SCL, e.g., removing some of the surface atoms, effectively implementing etching of surface regions of the SCL. The effectiveness of such etching can be controlled by a choice of ion species/radicals/ambient gasses. In another example, an ion beam of high energy can deposit ions inside the SCL. Ions and/or photons of the beam can break bonds of the bonding network (or crystal lattice) of the SCL forming vacancies therein, and can further cause annealing due to local heating, UV curing, and/or other effects. Substitution defects and/or vacancies created by the particles of the stress-mitigation beam modify (e.g., reduce) stress in the SCL and, through the SCL, in the substrate. The intensity and/or dose (the intensity integrated over time) of the stress-mitigation beam can vary with a location within the SCL and can be determined (e.g., simulated, modeled, etc.) in a way that maximally relieves the stress in the SCL (and, further, in the substrate). This causes the combination of the substrate, the deposited layers/films, and the SCL to flatten and facilitates precise alignment of features that are patterned on the substrate, etched in one or more stacks of layers, and/or the like, and improves quality of the manufactured devices. The intensity/doses of irradiation can be determined based on measured deformation of the substrate (with layers/films/mask deposited thereon), e.g., using various optical measurement techniques. Multiple techniques can then be used to determine optimal intensity and/or dose of the stress-mitigation beam, such as Monte Carlo simulations, influence function computations, and/or other techniques, as disclosed below.

[0022] Various techniques of implementing patterns of alternating lower-stress and higher-stress regions disclosed herein cause the substrate to experience a compensating anisotropic deformation that mitigates the anisotropic pattern caused by the feature patterning on the device side of the wafer.

[0023] Advantages of the disclosed embodiments include but are not limited to correcting deformations of anisotropic substrate shapes in semiconductor manufacturing for more accurate alignment of features manufactured on substrates, improved uniformity of layers/masks formed on substrates, better handling of wafers during processing, and/or the like.

[0024] A “wafer,” as used herein, refers to any substrate or material surface formed on a substrate upon which film processing is performed during a fabrication process. For example,

a wafer surface on which processing can be performed includes materials such as silicon, silicon oxide, silicon nitride, strained silicon, silicon on insulator, carbon doped silicon oxides, amorphous silicon, doped silicon, germanium, gallium arsenide, glass, sapphire, plastic, and any other materials such as metals, metal nitrides, metal alloys, and other conductive materials, depending on the application. Wafers include, without limitation, semiconductor wafers. Wafers may be exposed to a pretreatment process to polish, etch, reduce, oxidize, hydroxylate, anneal, UV cure, e-beam cure and/or bake the substrate surface. In addition to film processing directly on the surface of the wafer itself, any of the film processing steps disclosed may also be performed on an underlayer formed on the wafer as disclosed in more detail below, and the term “wafer surface” is intended to include such underlayer as the context indicates. Thus, for example, where a film/layer or partial film/layer has been deposited onto a wafer surface, the exposed surface of the newly deposited film/layer becomes the wafer surface. In some embodiments, wafers have a thickness in the range of 0.25 mm to 1.5 mm, or in the range of 0.5 mm to 1.25 mm, in the range of 0.75 mm to 1.0 mm, or more. In some embodiments, wafers have a diameter of about 10 cm, 20 cm, 30 cm, or more.

[0025] FIGs. 2A–2H show a substrate-wide view of a process of semiconductor manufacturing that uses directional patterns for stress mitigation, according to at least one embodiment. FIG. 2A shows a substrate 202, which can be a bare wafer or a wafer with one or more features patterned thereon (e.g., source lines of NAND devices). In some embodiments, substrate 202 can undergo any additional treatment, such as annealing. A stack 206 of one or more films can be deposited on substrate 202. Stack 206 can include uniform (unpatterned) or patterned films. For example, a target pattern 208 can be created within at least some of films of stack 206, e.g., using photolithography and/or other techniques. Stack 206 can further include chip boundaries, area boundaries, slits, channels, and/or any other applicable features. As illustrated in FIG. 2B, a frontside protection layer 209 can be deposited to protect stack 206.

[0026] FIG. 2C illustrates an SCL 210 deposited or otherwise formed on the back side of substrate 202. Although, for the sake of illustration, FIG. 2C illustrates backside SCL deposition, in other embodiments, the SCL can be formed on the front side, e.g., on top of stack 206 and target pattern 208. (In some embodiments, the SCL can later be removed, after stress mitigation. In other embodiments, the SCL can remain in place while the substrate 202 can be thinned from the back side with additional features deposited on the exposed—thorough the back side—stack 206 of films.) With the back side of substrate 202 facing up, as

shown in **FIG. 2D**, a suitable directional patterned mask 212 can be manufactured on the SCL 210. (For simplicity, **FIGs. 2D–2H** do not depict frontside protection layer 209.) “Directional pattern,” as used herein, refers to any pattern having characteristic length scale(s) of associated features along one direction substantially exceeding, e.g., by factor 3, 5, 10, or more, a characteristic length of the features along the other direction. An example directional pattern can include diffraction gratings with a pitch of 10 nm – 100 μm or more and length of lines of 10 μm – 1 cm or more. In some embodiments, the directional patterned mask 212 can be made of a different material than SCL 210. For example, directional patterns can be or include a photoresist mask deposited on SCL 210. In some embodiments, the directional patterned mask 212 can be made of the same material as SCL 210. In some embodiments, the directional pattern can include raised portions 212-1 (e.g., ridges, protrusions, elevations, etc.) and recessed portions 212-2 (e.g., trenches, grooves, ruts, dips, etc.).

[0027] Directional patterned mask 212 can be formed using a variety of techniques. In some embodiments, e.g., where ion stress-mitigation beams are used, an ion mask can be placed on SCL 210, e.g., using suitable deposition techniques, growth techniques, spin-coating techniques, and/or the like. The ion mask material can subsequently be covered with a photoresist layer. In some embodiments, the mask material can first be covered with one or more dielectric anti-reflective coating (DARC) layers, bottom anti-reflective coating (BARC) layers with the photoresist placed on top of the DARC/BARC layers. The photoresist can be shielded with a photomask having a target pattern that is to be transferred to the ion mask to form directional patterned mask 212. The areas of the photoresist unprotected by the photomask are then exposed to light, e.g., using UV light, visible light, infrared light, and/or the like. The photoresist is then developed by removing the photomask and the exposed (or unexposed, depending on a specific type of photoresist) areas of the photoresist. The remaining, after development, portions of the photomask are then used during etching to protect portions of the ion mask that become the directional patterned mask 212. The remaining portions of the photoresist can be removed by ashing or similar techniques. In some embodiments, directional patterned mask 212 may be formed using contact printing (contact lithography) techniques, in which the photomask is pressed against the photoresist.

[0028] In other embodiments, e.g., where photon stress-mitigation beams are used, the photomask may be used directly as the directional patterned mask 212 and can be removed following application of the stress-mitigation beam.

[0029] As illustrated in **FIG. 2E**, the directional patterned mask 212 and SCL 210 can be subjected to irradiation by a stress-mitigation beam 218. Stress-mitigation beam 218 can be generated by a suitable collimating and focusing column 220. As illustrated in **FIG. 2F** for a portion of the substrate 202, the directional patterned mask 212 modulates the amount of radiation that reaches SCL 210. For example, the portions of SCL 210 that are located below raised portions 212-1 of directional patterned mask 212 (protected areas) may be shielded to a higher degree than the portions of SCL 210 that are located below recessed portions 212-2 (stress-mitigated areas). In some embodiments, instead of being bombarded by ions of the stress-mitigation beam 218, the SCL 210 can be exposed, for a predetermined period of time, to a plasma environment.

[0030] As further illustrated in **FIG. 2F**, in some embodiments, an additional coating layer 222 can be deposited between SCL 210 and directional patterned mask 212, e.g., one or more anti-reflective coating (ARC) layers or adhesion-promoting materials, such as Hexamethyldisilazane (HMDS) or similar layers. Stress-mitigation beam 218 can then be applied to directional patterned mask 212. In some embodiments, stress mitigation beam 218 can be a high-energy ion beam depositing ions inside directional patterned mask 212. In some embodiments, stress mitigation beam 218 can be a low-energy ion beam mitigating stress by etching regions of SCL 210 exposed by recessed portions 212-2 of directional patterned mask 212.

[0031] **FIG. 2G** is a cross-sectional view of an example non-limiting geometry of directional patterned mask 212, according to one embodiment. The directional patterned mask 212 illustrated in **FIG. 2F** has the form of a grating that includes a set of rectangular (or near rectangular) raised portions of height T , e.g., 100 nm–10 μm , and separated by trenches of width W , e.g., 100 nm–100 μm . A period of grating P (pitch) can be 200 nm – 200 μm , or any other suitable value. In some embodiments, height T can be significantly larger than a residual height, $T \gg R$.

[0032] **FIG. 2H** illustrates the portion of the wafer from **FIG. 2F** after irradiation by stress-mitigation beam 218. As depicted schematically in **FIG. 2H**, higher-stress regions 231 of SCL 210 (indicated with darker shading), which were shielded from stress mitigation beam 218, may have more residual stress than lower-stress regions 232 (indicated with lighter shading), which received higher exposure to stress mitigation beam 218. Directional patterned mask 212 and/or coating layer 222 can then be removed, e.g., dissolved, polished, or evaporated after irradiation. Application of stress-mitigation beam 218 causes a stress in

SCL 210 to decrease, resulting in the flattening of the structure (reduced deformation). The reduction of stress in SCL 210 also causes the stress in substrate 202 and/or stack 206 to be reduced.

[0033] As a result of operations illustrated in **FIGs. 2A–2G**, a spatially modulated directional patterned structure (illustrated in **FIG. 2H**) is formed in SCL 210 where higher-stress regions 231 are interspaced with lower-stress regions of 232 using a deposited directional patterned mask 212 that non-uniformly shields selected areas of SCL 210 from stress mitigation beam 218. This enables the use of stress-mitigation beam 218 with a wide cross-sectional area.

[0034] In some embodiments, e.g., as illustrated with **FIGs. 2I–2K** the same (or similar) spatially modulated pattern of stress can be formed in SCL 210 without deposition of directional patterned mask 212. For example, this can be achieved using a narrow cross-sectional stress mitigation beam 218, e.g., a beam generated by a UV curing laser can be used to form narrow-pitch pattern of high stress/low stress regions in SCL 210 directly, without depositing directional patterned mask 212 or some other mask.

[0035] As illustrated in **FIG. 2I**, a narrow-spot laser beam 240, generated by laser source 242 can be directed to a pattern of spatial locations where stress is to be decreased, e.g., in the instances, of an ablation treatment or annealing treatment, or increased (e.g., in the instances of a curing treatment). Annealing should be understood as quasi-equilibrium heating and subsequent cooling of the material of the SCL that changes physical and/or chemical structure of the material. Ablation should be understood as a fast, e.g., of a femtosecond-scale duration, non-equilibrium heating of the material of the SCL that causes at least partial destruction of atomic or molecular bonds and/or a partial removal of the material. Curing should be understood as any photon-assisted (e.g., using UV photons) transformation of physical or chemical properties of the material of the SCL, e.g., hardening of the material.

[0036] Laser source 242 can be a gas laser, a semiconductor laser, a laser diode, or some other suitable source of light. The narrow-spot beam 240 can be a beam focused or collimated by one or more optical elements (not explicitly shown in **FIG. 2I**) and scanned across the surface of the substrate, e.g., as illustrated with the sequence of the arrows. The intensity of laser beam 240 and the speed of scanning, e.g., determined by a beam dwell time at each of the locations where the laser beam 240 is applied, can be chosen to deliver a target dose of photons to desired regions of the SCL. More specifically, laser beam 240 can be used to form (via photon irradiation) lower-stress regions 232 in the instances of ablation/annealing or higher-stress regions 231 in the instances of curing. In some embodiments, laser source 242

can be moved relative to stationary substrate 202 while in other embodiments, laser source 242 can remain stationary while substrate 202 is moved relative to laser source 242.

[0037] In some embodiments, as illustrated in **FIG. 2J**, a cylindrical lens 250 (or other similar optics) can be used to focus (photon) stress-mitigation beam 218 to a narrow line-like region on SCL 210 to form a lower-stress region 232 (or a higher-stress region, in some embodiments). The line-like region can be illuminated for a predetermined amount of time before stress-mitigation beam 218 is shifted to illuminate the next region, and so on. The size of the beam at the narrowest point (focal point of cylindrical lens 250) controls the width of the regions where the stress is affected (e.g., reduced) while the length of the shift determines the widths of the regions where the stress remains largely intact.

[0038] In some embodiments, as illustrated in **FIGs. 2K–L**, instead of illumination by a single narrow (e.g., focused) laser beam, multiple beams can be deployed in parallel. More specifically, as depicted in **FIG. 2K**, an array 260 of multiple (e.g., two or more) light-emitting sources 262, e.g., laser diodes, can be used to direct light beams 264 (e.g., using any suitable focusing and/or collimating optics) to a corresponding number of individual target regions in parallel. In some embodiments, the array 260 of light-emitting sources 262 can be mounted on the same circuit board 266 (or multiple circuit boards). In some embodiments, the number of light-emitting sources 262 can be large enough to cover the entire width of substrate 202. In other embodiments, the number of light-emitting sources 262 in the array 260 can be sufficient to cover a portion of the width of substrate 202 with the entire width of substrate 202 covered by moving the array 260 across the surface of SCL 210. In some embodiments, the array 260 can be a two-dimensional array of light-emitting sources 262, e.g., a rectangular array, a hexagonal array, a circular array, and/or the like. In some embodiments, the array 260 can be a linear array of light-emitting sources 262. Scanning of substrate 202 can be performed by moving light-emitting sources 262 of the array 260 along the lines of the stress patterns being formed within SCL 210.

[0039] In some embodiments, as depicted in **FIG. 2L**, one or more diffractive optical elements (DOEs) 270 can be placed in the direction of one or more beams 272. DOE 270 can cause constructive interference of beams 272 to produce multiple diffracted beams 274 directed towards target areas of SCL 210. In some embodiments, beams 272 can be implemented via a single (or several) wide beam(s) while diffracted beams 274 can be narrow beams having micron-size width at the points where diffracted beams 274 strike SCL 210. In some embodiments, beams 272 can be formed using a TEM₀₀ electromagnetic wave. In some embodiments, DOE 270 can include a diffraction grating, a hologram, a spatial light

modulator, a deformable mirror, and/or other optical elements capable of producing multiple narrow beams from an incident (narrow or wide) beam. DOE 270 can be used in conjunction with other optical elements, e.g., focusing and/or collimating lenses, mirrors, polarizers, filters, and/or the like. In some embodiments, beams 272 can be delivered to DOE 270 over air or using one or more optical fibers or waveguides. Parameters of DOE 270, e.g., the pitch of diffraction grating(s), a distance from the light source to DOE 270, a distance from DOE 270 to the surface of SCL 210, and/or the like can be selected (in view of the wavelength of light) to ensure that the diffracted beams 274 strike SCL 210 at the desired regions. Although **FIG. 2L** illustrates an example embodiment where diffracted beams 274 are normally incident on SCL 210, in other embodiments, diffracted beams 274 can strike SCL 210 at some other angle of incidence, e.g., 30 degrees, 45 degrees, 60 degrees, and/or the like.

[0040] The type of a material of SCL 210, the thickness d of this material, the wavelength λ of photons, in the examples of **FIGs. 2I–2L** (and/or **FIG. 2E**, in the instances where a photon beam is deployed) can be selected in view of the dependence $\delta(\lambda)$ of the material's penetration depth δ (optical thickness). More specifically, a thickness D of the SCL 210 can be selected to be larger than the penetration depth δ : $D > \delta(\lambda)$, so that the stress-mitigation beam does not penetrate into underlying structures (e.g., substrate 202, features of stack 206, and/or the like). Similarly, the sources of light can be selected having the wavelength λ , e.g., 1064 nm, 532 nm, 355 nm, and/or the like, that is within the range of efficient absorption (rather than transparency) of the material of SCL 210. This ensures that the photons are absorbed within the target regions of SCL 210 and do not go (in substantial amounts) through the thickness of SCL 210.

[0041] Prior to irradiating SCL 210 with a stress-mitigation beam, the amount of stress in the wafer (and films that can be deposited thereon) can be determined by measuring a profile $h(\vec{r})$ of the wafer. The profile $h(\vec{r})$ can refer to the vertical coordinate of the top surface of the SCL or wafer/stack of films (if the measurement is performed prior to SCL deposition). In some instances, stress in the wafer can be uniform and isotropic, $\sigma_{xx} \approx \sigma_{yy}$. In some instances, stress in the wafer can be anisotropic, $\sigma_{xx} \neq \sigma_{yy}$. Certain feature patterns can result in stresses that are compressive along one direction, e.g., $\sigma_{xx} > 0$, and tensile along a perpendicular direction, $\sigma_{yy} < 0$, resulting in saddle-shaped wafers.

[0042] In some embodiments, a vertical profile of wafer deformation $z = h(\vec{r})$ can be measured using optical metrology (e.g., optical interferometry) techniques. In some embodiments, wafer deformation $z = h(\vec{r})$ can be measured after a stack of layers/films is

deposited on the wafer. The wafer profile $h(\vec{r})$ can then be represented via a number of parameters that qualitatively and quantitatively characterize geometry of the wafer deformation, e.g., a set of Zernike (or a similar set of) polynomials, $h(\vec{r}) = \sum_j A_j Z_j(\vec{r})$. Consecutive coefficients $A_1, A_2, A_3, A_4 \dots$ represent weights of specific geometric features (elemental deformations) of the wafer described by the corresponding Zernike polynomials $Z_j(\vec{r})$. In some embodiments, a material of SCL 210 can be selected based on the sign of a paraboloid bow coefficient A_4 . In some embodiments, selection of a thickness d of SCL 210 can be made based on a value of the paraboloid bow coefficient A_4 . SCL 210 can be deposited using any suitable deposition techniques including physical vapor deposition (e.g., sputtering), chemical vapor deposition (e.g., plasma-assisted deposition), epitaxy, exfoliation, and/or the like. Deposition can be performed at room temperature or at temperatures different from room temperature (e.g., at an elevated temperature). As illustrated in **FIGs. 3A–3E** below, thickness d of SCL 210 can be selected to overcorrect the wafer deformation to some degree. The overcorrection can be chosen in conjunction with a type of stress-mitigation beam 218 (e.g., ion implants, photons, electrons, etc.), a type of implant species, energy, and dose to ensure maximum effect from the stress mitigation. Stress in the combined structure of the wafer, films, and the SCL can then be modified by stress-mitigation beam 218 that strikes SCL 210 and changes its crystal structure. Substitution defects and/or vacancies created by the beam mitigate (e.g., reduce) stress in SCL 210 and can reduce the degree of stress overcorrection caused by deposition of SCL 210. This leads to flattening of substrate 202.

[0043] **FIGs. 3A–F** illustrate schematically a process of correcting wafer deformation using a stress-mitigation beam applied to a stress compensation layer deposited on a back side of a wafer and partially shielded by a directional pattern, according to at least one embodiment. **FIG. 3A** depicts a substrate 202 having a deformation, which can include a paraboloid bow deformation (with negative coefficient $A_4 < 0$, as illustrated) and can further include other deformations, such as saddle deformation, residual deformation, etc. The wafer's front side 302 can support any number of features, e.g., deposition and/or etching patterns, a stack of layers/films, and/or any other structures. **FIG. 3B** illustrates deposition of an SCL 210 on the back side 304 of substrate 202. In some embodiments, SCL 210 can include layers of multiple materials. In some embodiments, a material of SCL 210 can be selected in view of the sign of coefficient A_4 . For example, for a negative bow, $A_4 < 0$, SCL 202 can be selected to have a compressive stress (as illustrated in **FIGs. 3B–3E**). For silicon

wafers, such a film can be a silicon nitride (Si_3N_4) film but can also be a film of some other material. Conversely, for a positive bow, $A_4 > 0$, SCL 210 can be selected to have a tensile stress (not shown in **FIGs. 3B–3F**). SCL 210 can be deposited using any suitable deposition techniques including physical vapor deposition (e.g., sputtering), chemical vapor deposition (e.g., plasma-assisted deposition), epitaxy, exfoliation, and/or the like. Deposition can be performed at room temperature or at temperatures different from room temperature (e.g., at an elevated temperature). In some embodiments, a thickness d of SCL 210 can be selected to overcorrect the wafer deformation to some degree, e.g., as illustrated in **FIG. 3C** where a positive paraboloid bow is overcorrected to a negative paraboloid bow. The thickness-dependent paraboloid bow correction $A_{corr}(d)$ changes wafer deformation from $h(r, \phi)$ to $h_{corr}(r, \phi)$:

$$h_{corr}(r, \phi) = h(r, \phi) + A_{corr}(d) \cdot Z_4(r, \phi).$$

[0044] The degree of overcorrection can be chosen in conjunction with a type and parameters (e.g., energy, dose, etc.) of a specific stress-mitigation beam to be used on SCL 210. The overcorrection can make the combined structure of substrate 202 and SCL 210 susceptible to further control of stress (and thus control of deformation of the wafer $h_{corr}(r, \phi)$).

[0045] As illustrated in **FIG. 3D**, SCL 210 can be used in conjunction with a directional patterned mask 212 that provides a local shielding of SCL 210 from a stress-mitigation beam 218. As illustrated in **FIG. 3E**, collimating and focusing column 220 can generate stress-mitigation beam 218 that strikes SCL 210 and changes its elastic properties, e.g., by creating vacancies, breaking crystal bonds, depositing ions, and/or via any other applicable mechanisms. Stress-mitigation beam 218 can carry photons, electrons, silicon ions, phosphorus ions, argon ions, neon ions, xenon ions, krypton ions, and/or the like. In some embodiments, the energy and type of ions in stress-mitigation beam 218 can be selected to limit the implanted ions to the volume of SCL 210 without allowing the ions to reach substrate 202 (and/or any layers/films deposited on substrate 202). Ions that lodge in SCL 210 create substitution defects therein. Additionally, the ions leave a trail of vacancy defects along paths of propagation in SCL 210. The substitution defects and/or vacancies mitigate (e.g., reduce) stress in SCL 210 and can reduce the degree of stress overcorrection caused by the SCL deposition. This causes the combination of substrate 202 and SCL 210 to flatten.

[0046] In some embodiments, the number of ions ΔN_i deposited per small area $\Delta A = \Delta x \Delta y$ (or the total amount of photon energy applied to this area) of substrate 202 can be

determined using simulations (performed as described in more detail below) based on the local value of the corrected deformation $h_{corr}(r, \phi)$, which may include a saddle deformation, a residual deformation, and the part of the paraboloid bow deformation $A_{corr}(d) + A_4$ that has been overcorrected by the deposition of SCL 210. The target local density $n(x, y) = \Delta N_i / \Delta x \Delta y$ of the ions can be delivered by controlling the scanning velocity v of stress-mitigation beam 218. In some embodiments, stress-mitigation beam 218 has a profile that can be approximated with a Gaussian function, e.g., the ion flux $j(\rho) = j_0 \exp(-x^2/a^2 - y^2/b^2)$, where x and y are Cartesian coordinates, j_0 is the maximum ion flux at the center of the beam, and a and b are characteristic spreads of the beam along the x -axis and y -axis, respectively. Correspondingly, a point that is located at distance y from the path of the center of the beam receives an ion dose that includes the following number of ions:

$$\frac{\Delta N_i}{\Delta x \Delta y} = \frac{j_0}{v} \int_{-\infty}^{\infty} dx e^{-x^2/a^2 - y^2/b^2} = \frac{j_0 \sqrt{\pi}}{va} e^{-y^2/b^2}.$$

Correspondingly, by reducing the scanning velocity v , the number of ions received by various regions of SCL 210 can be increased, and vice versa. Additionally, stress-mitigation beam 218 can perform multiple scans with different offsets y so that various points of SCL 210 receive multiple doses of ions with different factors e^{-y^2/b^2} that can average to a target dose. For example, after n passes of stress-mitigation beam 218, each made with a respective velocity v_k at a different distance y_k from the center of the beam to the area $\Delta x \Delta y$, the total dose of ions (or amount of electromagnetic radiation) received by this area will be

$$n(x, y) = \left. \frac{\Delta N_i}{\Delta x \Delta y} \right|_{total} = j_0 \sqrt{\pi} \sum_{k=1}^n \frac{e^{-y_k^2/b^2}}{av_k}.$$

[0047] As illustrated in **FIG. 3F**, the alternating pattern of stress-mitigated areas and protected areas formed in SCL 210 by the stress-mitigation beam and directional patterned mask 212 results in a significant mitigation of cylindrical deformation of substrate 202, but can further mitigate saddle and residual deformations.

[0048] In some embodiments, the intensity and/or total amount of irradiation per various areas of the SCL can be determined using simulations, e.g., Monte Carlo simulations. The Monte Carlo simulations can be performed for a film made of the actual SCL material(s) and having a specific thickness d . An initial Monte Carlo simulation can be performed for

specific baseline (default) conditions of the particle irradiation (e.g., default settings of an ion implantation apparatus). The baseline conditions can include a default type of particles, a default energy of the particles, a default dose of particles to be applied to the SCL (e.g., a default velocity of scanning and a default scanning pattern), and the like. The baseline conditions can subsequently be modified (e.g., optimized) using the Monte Carlo simulations. The Monte Carlo simulations can use calibration data collected (measured) for actual particle irradiation performed for various ion/photon/electron energies, types of ions, types and materials of SCL(s), angles of particle incidence on the films, and/or the like.

[0049] In some embodiments, the implantation map $n(\vec{r})$ can be computed using an influence function $G(\vec{r}; \vec{r}')$ that characterizes a response (e.g., deformation) at a point $\vec{r}$ of the wafer as caused by a point-like force applied at another point $\vec{r}'$ of the wafer. In some embodiments, the influence function $G(\vec{r}; \vec{r}')$, also known as the Green's function, can be determined from computational simulations or from analytical calculations. In some embodiments, the influence function can be determined from one or more experiments, which can include performing ion implantation into a film deposited on a reference wafer.

[0050] In some embodiments, wafer deformation $h(\vec{r}) = h_{quad}(\vec{r}) + h_{res}(\vec{r})$ can be represented (decomposed) as a combination of a quadratic $h_{quad}(\vec{r})$ and residual (non-quadratic) $h_{res}(\vec{r})$ contributions. The quadratic deformation can include a parabolic (paraboloid) part $h_{par}(r)$, which has the complete axial symmetry, and a saddle part $h_{saddle}(\vec{r})$. The thickness d of SCL 210 can be computed (or empirically determined) in such a way that the SCL is to apply a desired target stress to the wafer. To eliminate a non-uniform saddle deformation, SCL 210 can be of such thickness/material that turns the saddle deformation into a cylindrical deformation having a definite sign throughout the area of the wafer. The uniform-sign cylindrical deformation (as well as a residual higher-order non-quadratic deformation) can then be mitigated with irradiation by a stress-mitigation beam. In some embodiments, a cylindrical decomposition is not unique and can be either positive (upward-facing cylindrical deformation) or negative (downward-facing cylindrical deformation). Both decompositions can be analyzed and a decomposition that enables a more effective stress mitigation can be selected. For example, a decomposition that is characterized by a smaller parabolic bow deformation can be selected. The parabolic bow deformation can be mitigated using a choice of SCL 210 (e.g., type and thickness) while the remaining cylindrical deformation (and the higher-order residual deformation) can be addressed by appropriately selected ion or photon irradiation doses $n(\vec{r})$.

[0051] In some embodiments, mitigation of a cylindrical deformation or a saddle deformation can include identifying principal axes (directions) of the cylinder/saddle and a magnitude of the cylindric/saddle deformation and directing the stress-mitigation beam into appropriately selected edge regions of the SCL. For example, individual edge regions to which the beam is directed can have a width that is at or below 30% of a diameter of the wafer. Residual higher-order (ripple) deformations can then be mitigated with further irradiation into the area of the SCL.

[0052] Some of these techniques will now be described in more detail. In one embodiment, a vertical profile of wafer deformation $z = h(\vec{r})$ can be measured using optical metrology techniques. For example, an interferogram of the profile $h(\vec{r})$ can be obtained using optical interferometry measurements. The wafer profile $h(\vec{r})$ can then be represented via a number of parameters that qualitatively and quantitatively characterize geometry of the wafer deformation. In some embodiments, a set of Zernike (or a similar set of) polynomials may be used to represent the wafer profile,

$$h(\vec{r}) = \sum_j A_j Z_j(\vec{r}),$$

where the planar radius-vector $\vec{r} = (r, \phi)$ may be represented as the radial coordinate r and the polar angle ϕ within the (average) plane of the wafer. Consecutive coefficients $A_1, A_2, A_3, A_4 \dots$ represent weights of specific geometric features (elemental deformations) of the wafer described by the corresponding Zernike polynomials $Z_1(r, \phi), Z_2(r, \phi), Z_3(r, \phi), Z_4(r, \phi) \dots$. (Herein, the Noll indexing scheme for the Zernike polynomials is being referenced.) The first three coefficients are of less interest as they describe a uniform shift of the wafer (coefficient A_1 , associated with the $Z_1(r, \phi) = 1$ polynomial), a deformation-free x -tilt that amounts to a rotation around the y -axis (coefficient A_2 , associated with the $Z_2(r, \phi) = 2r \cos \phi$ polynomial), and a deformation-free x -tilt that amounts to a rotation around the x -axis (coefficient A_3 , associated with the $Z_3(r, \phi) = 2r \sin \phi$ polynomial) that can be eliminated by a realignment of the coordinate axes. The fourth coefficient A_4 is associated with $Z_4(r, \phi) = \sqrt{3} (2r^2 - 1)$ and characterizes an isotropic paraboloid deformation (“bow”). The fifth A_5 and the sixth A_6 coefficients are associated with $Z_5(r, \phi) = \sqrt{6} r^2 \sin 2\phi$ and $Z_6(r, \phi) = \sqrt{6} r^2 \cos 2\phi$ polynomials, respectively, and characterize a saddle-type deformation. The A_5 coefficient characterizes a saddle shape that curves up ($A_5 > 0$) or down ($A_5 < 0$) along the diagonal $y = x$ and curves down ($A_5 > 0$) or

up ($A_5 < 0$) along the diagonal $y = -x$. The A_6 coefficient characterizes a saddle shape that curves up ($A_6 > 0$) or down ($A_6 < 0$) along the x -axis and curves down ($A_6 > 0$) or up ($A_6 < 0$) along the y -axis. The higher coefficients A_7 , A_8 , etc., characterize progressively faster variations of the wafer deformation $h(r, \phi)$ along the radial direction, along the azimuthal direction, or both and collectively represent a residual deformation, $h_{res}(r, \phi) = h(r, \phi) - \sum_{j=4}^6 A_j Z_j(r, \phi)$. **FIG. 4** illustrates an example Zernike polynomial decomposition 400 of one actual deformation $h(r, \phi)$ (top left) of a wafer, in arbitrary units, into a paraboloid bow deformation $A_4 Z_4(r, \phi)$ (top right), a saddle deformation $A_5 Z_5(r, \phi) + A_6 Z_6(r, \phi)$ (bottom left), and a residual deformation, $h_{res}(r, \phi)$ (bottom right), according to at least one embodiment.

[0053] **FIG. 5** is a flowchart illustrating an example method 500 of mitigation of anisotropic substrate stress and deformation using stress-compensation beams with directional patterns, in accordance with at least one embodiment. Method 500 can be performed using a semiconductor manufacturing system that includes one or more processing chambers, e.g., deposition chamber(s), plasma chamber(s), etching chamber(s), polishing chamber(s), film removal chamber(s), beam irradiation chamber(s), optical inspection chamber(s), and/or the like. The processing chambers can be connected to one or more transfer chambers, which can be equipped with robot(s) to handle substrates, e.g., moving substrates into and out of processing chambers. The transfer chamber can further be connected to a load-lock chamber (Front-End Interface) that can be coupled to one or more Front Opening Unified Pod carriers that hold bare substrates, processed substrates, partially processed substrates, and/or the like. Operations performed by the semiconductor manufacturing system, including any, some or all operations of method 500, can be performed responsive to instructions issued by a suitable computing device having a processing logic and memory to store the instructions.

[0054] At block 510, method 500 can include preparing a substrate, including but not limited to obtaining a bare substrate, preprocessing the bare substrate, e.g., polishing the substrate, removing stains and/or residue from the substrate, and/or the like, and/or performing any number of similar operations. At block 520, method 500 can continue with depositing one or more films/layers on the substrate. The layers can include a layer of conducting features, e.g., source lines to be used as part of memory cell (transistor) circuitry. In some embodiments, the layers can further include multiple alternating Nitride and Oxide layers to be used as hosts of memory cells and separations between memory cells. In some

embodiments, the layers can include alternating silicon and silicon-germanium alloy layers. At block 530, method 500 includes obtaining optical inspection data, e.g., by measuring the shape of the substrate, e.g., a displacement of a surface (e.g., the top surface) of a substrate as a function of some in-plane coordinates, e.g., polar coordinates $z = h(r, \phi)$, Cartesian coordinates, $z = h(x, y)$, or any other suitable coordinates. At block 540, method 500 includes decomposition of the determined shape over a suitable set of polynomials, e.g., Zernike polynomials, and obtaining a set of polynomial expansion coefficients, $\{A_j\} = (A_1, A_2, A_3), A_4, A_5, A_6, A_7, \dots$, each coefficient in the set characterizing a degree of presence of a particular elemental geometric shape in the substrate's deformation.

[0055] In some embodiments, method 500 can include a decision-making block 550 to select a type of SCL to be used with the substrate. For example, a decision at block 550 can be made based on the coefficient that determines a degree of parabolicity of the deformation, e.g., coefficient A_4 . If the substrate is curved downwards (towards the back side of the substrate), $A_4 < 0$, a compressive SCL can be selected for the back side deposition at block 550. If $A_4 > 0$, a tensile SCL can be selected for back side deposition. Operations of block 550 can also include determining a type of a material for the SCL to be deposited and a thickness d of the SCL. In some embodiments, this determination can be made based on multiple expansion coefficients (more than just the paraboloid bow coefficient A_4) from the set $\{A_j\}$ or the full profile $h(r, \phi)$. In one specific non-limiting example, the thickness d can be determined as follows. First, a target paraboloid deformation $\tilde{A}_4$ can be determined that is sufficient to overcompensate for the measured substrate deformation, e.g., for $h(r, \phi) < 0$, the following condition can be satisfied:

$$\tilde{A}_4 Z_4(\rho, \phi) + h(r, \phi) \equiv (\tilde{A}_4 + A_4) Z_4(\rho, \phi) + A_5 Z_5(\rho, \phi) + A_6 Z_6(\rho, \phi) + \dots > 0.$$

In other words, the target paraboloid deformation $\tilde{A}_4$ can be chosen sufficiently large to compensate for the paraboloid deformation (A_4), saddle deformation (A_5 and A_6) and the residual deformation (A_7 , and higher coefficients). In some embodiments, the target paraboloid deformation $\tilde{A}_4$ can be selected with at least an excess magnitude A_E over the minimum needed to overcompensate for the substrate deformation, e.g.,

$$\tilde{A}_4 Z_4(\rho, \phi) + h(r, \phi) > A_E Z_4(\rho, \phi).$$

The excess magnitude A_E can be empirically selected and can depend on the specific material used for the SCL.

[0056] Once the target paraboloid deformation $\tilde{A}_4$ has been determined, the thickness d of the SCL can be selected using a calibration data that tabulates or otherwise defines a function $d = f(\tilde{A}_4)$. In some embodiments, the function $f(\tilde{A}_4)$ can be a non-linear function. In some embodiments, the function $f(\tilde{A}_4)$ can be a linear function, $d = \alpha \tilde{A}_4$, with a coefficient of proportionality α determined based on mathematical modeling of elastic equations for specific SCL material(s), using empirical calibration, or any combination thereof. In some embodiments, thickness d of the SCL is selected to make deformation $h_{corr}(r, \phi)$ of a uniaxial type (e.g., cylindrical) after SCL deposition.

[0057] In some embodiments, the polynomial decomposition of the shape can be used to identify the axes of anisotropy of the substrate, e.g., based on the saddle coefficients A_5, A_6 .

[0058] Operations of block 560 can determine parameters for a directionally-modulated pattern of stress to be created in the SCL and further determine how such a pattern of stress can be achieved, e.g., using a directionally-modulated mask on the SCL in conjunction with a stress-mitigation beam of ion or by inducing such a pattern with directionally-modulated exposure to a stress-mitigation beam of photons. More specifically, a processing device performing operations of block 560 can first determine an orientation of the axes of cylindrical deformation relative to the substrate, e.g., a direction of the y -axis in **FIG. 1B**. For example, a cylindrical deformation can be identified as a combination of a parabolic deformation (described by coefficient A_4) and saddle deformation (described by coefficients A_5, A_6).

[0059] The direction of the axis can then be used as the axis of the directionally-modulated pattern of stress in the SCL (e.g., the direction along the ridges and/or trenches in **FIGs. 2D–2E**, direction of higher-stress region 232 in **FIG. 2J**, and/or the like). In those instances where the directionally-modulated pattern of stress in the SCL is achieved using a directionally-modulated mask formed on the SCL (e.g., as illustrated in **FIGs. 2D–2G**), operations of block 560 can determine a mask pattern period (pitch) P , trench width W , pattern thickness T , and/or the like. Determining these parameters can be accomplished using modeling, simulations, solving the elasticity equations (e.g., using a finite difference analysis), or by any other suitable techniques. A given anisotropic substrate deformation, e.g., deformation $h_{corr}(r, \phi)$ measured or predicted to occur after deposition of SCL of a given thickness d , can be corrected using more than a single set of the parameters. For example, increasing (decreasing) trench width W for a given period P and pattern thickness T can result in decreased/increased stiffness of the SCL (e.g., in the direction perpendicular to the axis of

the pattern), since the size of the protected areas in the SCL is decreased/increased. Similarly, decreased/increased stiffness of the SCL can be achieved by decreasing/increasing pattern thickness T for given period P and trench width W . Increasing resolution by decreasing period P (for a given ratio W/P) can result in a more uniform stress mitigation whereas increasing period P can facilitate stress modulations of higher amplitude (e.g., larger difference between the maximum and minimum stress).

[0060] Operations of block 560 can include determining an optimal directionally-modulated pattern of stress in the SCL that achieves the maximum mitigation of the substrate deformation. Operations of block 560 can also include determining a directionally-modulated pattern of stress that is practically achievable as the best approximation to the optimal pattern, given the available stress-mitigation beam species (particles), spatial resolution, energy, and/or other characteristics of the stress-mitigation beam.

[0061] At block 570, the SCL of the selected thickness d (of a fixed thickness) can be formed on the back side of the substrate. In some embodiments, SCL can be deposited on the front side of the substrate. In some embodiments, the SCL can be pre-processed (e.g., cleaned, annealed, etc.) before or after the SCL is deposited or otherwise formed on the substrate.

[0062] At block 580, a directionally-modulated mask can be formed on the SCL, e.g., in the instances where an ion stress-mitigation beam is deployed. In those instances where the stress-mitigation beam is a photon beam, operations of block 580 need not be performed. Forming the directionally-modulated mask can be performed by spin coating a photoresist, optical photolithography, imprint lithography, developing the photoresist, and/or other suitable techniques. In some embodiments, digital lithography techniques can be used instead of (or in addition to) contact printing. Optical lithography can include (but need not be limited to) contact photolithography (e.g., with a photoresist making a direct contact with the substrate), proximity photolithography (e.g., with a photoresist separated by a small gap from the substrate), and/or projection photolithography (e.g., with an optical element, such as a lens, positioned within the gap between the photoresist and the substrate).

[0063] At block 590, method 500 can include determining (e.g., computing) local dose maps for irradiation of the SCL/directional pattern. In some embodiments, the dose maps can be computed in view on the expansion coefficients A_5 , A_6 (to compensate for the saddle deformation) and A_7 , A_8 ... (to compensate for the residual deformation). At block 595, method 500 can continue with irradiating the SCL/directional pattern (e.g., according to the

computed irradiation doses) with a stress-mitigation beam to reduce the amount of stress in the substrate/films/mask structure and flatten the structure. The stress-mitigation beam can include ions, photons, electrons, and/or any combination thereof. Method 500 can further include various additional operations, as prescribed by the manufacturing specification, such as covering the SCL with ARC/photoresist layers, removing the remnants of the directional pattern, and/or performing any other suitable operations. In some embodiments, after the SCL is deposited, a shape of the substrate with the deposited SCL can be re-measured and the new expansion coefficients $\{A_j\}$ can be determined before parameters of the directional pattern are determined.

[0064] Multiple variations of method 500 are within the scope of this disclosure. In some embodiments, subjecting the SCL to the stress-mitigation beam can include forming a directionally-modulated mask on the SCL, which includes a plurality of raised portions, and/or a plurality of recessed portions (e.g., as shown in **FIGs. 2D** and **2F**), and illuminating the directionally-modulated mask by a stress-mitigation beam (e.g., as shown in **FIGs. 2E**). In some embodiments, subjecting the SCL to the stress-mitigation beam can include illuminating, by one or more beams of light, a plurality of locations of the SCL (e.g., as shown in **FIGs. 2I–2L**). The one or more beams of light can be generated using one or more lasers (e.g., as shown in **FIGs. 2I**), laser diodes (e.g., as shown in **FIG. 2K**), light-emitting diodes, and/or the like. In some embodiments, the one or more beams of light are produced (e.g., directed) using a diffraction optical element (e.g., as shown in **FIG. 2L**). In some embodiments, the one or more beams of light can be focused, onto the SCL, using one or more cylindrical lenses (e.g., as shown in **FIG. 2J**). In some embodiments, illuminating the plurality of locations of the SCL can include causing a relative motion of the one or more beams of light and the SCL. In some embodiments, the stress-mitigation beam has a cross-section that is more than 0.1 mm, and a period of the directionally-modulated pattern of stress in the SCL is less than 10 microns.

[0065] **FIG. 6** is a flowchart illustrating an example method 600 of determining settings for beam irradiation, in accordance with at least one embodiment. Method 600 can be performed as part of blocks 530–590 of method 500. At block 610, method 600 can include identifying some or all of a parabolic deformation (e.g., Zernike coefficients A_4), saddle deformation (e.g., Zernike coefficients A_5 , A_6), and the residual deformation (e.g., Zernike coefficients A_7 , $A_8 \dots$) of a substrate, e.g., using profilometry measurements.

[0066] At block 620, method 600 can continue with computing irradiation doses $n(\vec{r})$ for the SCL deposited on the substrate. Operations of block 620 can include one or more techniques for determining $n(\vec{r})$. In some embodiments, irradiation doses $n(\vec{r})$ can be computed using Monte Carlo simulations. In some embodiments, irradiation doses $n(\vec{r})$ can be computed using cylindrical decomposition of $h_{WF}(\vec{r})$, e.g., a decomposition of a saddle shape deformation into a parabolic deformation and a cylindrical deformation.

[0067] In some embodiments, irradiation doses $n(\vec{r})$ can be computed (and then applied at block 595) for selected edge regions of the SCL. For example, if the axis of cylindrical deformation, is the y -axis (as in FIG. 1B), the edge regions can be regions located within some vicinity of points $x = \pm R, y = 0$, where R is the radius of the substrate. Irradiation doses $n(\vec{r})$ near other regions (e.g., near the center of the substrate) can be significantly lower and/or zero, in some embodiments. In some embodiments, the edge regions of the SCL have a width that is at or below 30% of a diameter of the substrate. In some embodiments, the edge regions of the SCL can be exposed to a spatially uniform dose of particles of the stress-mitigation beam, a radially-varying dose of particles of the stress-mitigation beam, or an azimuthally-varying dose of particles of the stress-mitigation beam. In some embodiments, irradiation doses $n(\vec{r})$ can be spread out more uniformly across the area of the substrate, e.g., can be non-zero both near the edges and near the middle of the substrate. In some embodiments, irradiation doses $n(\vec{r})$ can be uniform (constant) throughout the area of the substrate while the uniformity of stress-mitigation is achieved by the deposited protective pattern having spatially-varying parameters (e.g., width W , period P , thickness T , etc.).

[0068] In some embodiments, irradiation doses $n(\vec{r})$ can be computed using an influence function $G(\vec{r}; \vec{r}')$, also known as the Green's function, which characterizes a response (e.g., deformation) of the substrate at a point $\vec{r}$ of the substrate as caused by a point-like force applied at a point $\vec{r}'$ of the substrate. In some embodiments, the influence function $G(\vec{r}; \vec{r}')$ can be determined from computational simulations or analytical calculations. In some embodiments, the influence function can be determined from one or more experiments, which can include performing ion implantation into a film deposited on a reference substrate. In some embodiments, a combination of multiple techniques of determining the influence function $G(\vec{r}; \vec{r}')$ can be used.

[0069] As a way of example, the Monte Carlo simulations for a structure (e.g., substrate with films and an SCL deposited thereon) can be performed for specific materials of the structure (e.g., silicon substrate, stack of films, and/or the like) and for a specific thickness of

the structure. An initial Monte Carlo simulation can be performed for baseline (default) conditions of beam irradiation (e.g., default settings of an ion implantation apparatus or a light-emitting apparatus). The baseline conditions can include a default type of particles (ions, photons, electrons), a default energy of particles, a default dose of particles to be directed to the SCL (e.g., a default velocity of scanning and a default scanning pattern), and the like.

[0070] In some embodiments, various techniques of irradiation dose computations can use calibration data 622 collected for actual irradiation performed for various types of the irradiation beams, energies of the irradiation beams, types and materials of structures being irradiated, angles of beam incidence on the structures, and/or the like. In some embodiments, calibration data 622 can be statistically preprocessed. For example, various measurements can be collected for multiple substrate/films/SCL materials, types of particles, angles of incidence, and/or other parameters. The statistically processed measurements can be stored (e.g., in a memory of a processing device performing computation of the irradiation doses) in the form of probability distributions of various quantities, including but not limited to:

- distribution of the density of ion implantation with depth for different ion types, ion energies, angles of incidence;
- distribution of the number of vacancies produced at different depths (per unit of length of travel of the ions) for different types of irradiation particles (ions, photons, electrons), particle energies, and angles of incidence;
- distribution of stresses created by irradiation beams for different beam intensities and durations; and/or the like.

[0071] Performing irradiation dose computations of block 620 can include sampling from the stored distributions and identifying a likelihood that a target stress mitigation will be achieved with the default settings of conditions of beam irradiation of a SCL of a given type and thickness. Method 600 can include several verification operations designed to determine whether the target stress can be achieved without detrimentally affecting properties of the substrate/films. For example, at block 625, method 600 can include verifying if the penetration depth of the selected (e.g., default) type of particles is sufficient. For example, the penetration depth is to be at least a certain fraction of the thickness of the SCL, e.g., 20%, 30%, 50%, 80%, or more of that thickness. In some embodiments the penetration depth can be up to 100% of the thickness. If the energy is insufficient, method 600 can include checking, at block 630, if the irradiation beam source is capable of outputting particles of a

higher energy. If higher energies are available, method 600 can continue with increasing the energy of the particles (block 640) and repeating irradiation dose computations of block 620 for the increased energy. If the maximum energy of the irradiation beam source has already been reached, method 600 can continue with replacing (at block 650) ions with ions of a different type (e.g., if an ion beam is used for irradiation), e.g., replacing Silicon ions with Boron, Carbon, Fluorine, etc., ions, and repeating Monte Carlo simulations for the ions of the new type.

[0072] At block 655, method 600 can include verifying whether the number of expected formed vacancies is sufficient. To verify sufficiency, method 600 can assess stress mitigation caused by formed vacancies. In one embodiment, method 600 can begin at some value of stress in the SCL, e.g., -3.0 GPa or some other suitable value (negative sign indicating compressive stress) and use beam irradiation to mitigate this stress towards a neutral point, 0.0 GPa at various locales of the SCL.

[0073] If the number of vacancies is insufficient, method 600 can include increasing a dose of particles (at block 660) and repeating irradiation dose computations of block 620 for the increased dose.

[0074] At block 665, method 600 can include verifying that the vacancies are going to be placed within a target depth, e.g., the thickness d of the film or a certain fraction of the film, such as $0.8 d$, $0.7 d$, $0.5 d$, or some other value empirically set to prevent particles from penetrating into the substrate/films and affecting properties of the substrate/films. If the vacancies are to be formed at depths that exceed the target depth, method 600 can include (at block 670) increasing an angle of incidence (e.g., by tilting the irradiation beam) to keep vacancies (as well as substitution impurities) to a shallower region of the SCL.

[0075] Blocks 620–670 can be repeated multiple times until irradiation dose computations of block 620 are determined to be sufficient that the desired stress mitigation can be achieved, e.g., that the reduction in the tensile stress of the SCL is such that the deformation of the substrate is eliminated or at least reduced to an acceptable tolerance. The final settings for SCL irradiation (block 680) determined from irradiation dose computations can then be used for irradiation of the SCL with the stress-mitigation beam (at block 570).

[0076] **FIG. 7A** illustrates schematically an irradiation system 700 capable of performing irradiation of stress compensation layers, according to at least one embodiment. Irradiation system 700 can include collimating and focusing column 220 of **FIG. 1**. Irradiation system 700 can further include a beam source 702 for producing a source beam 704. Beam source 702 can include a chamber for generating ions (e.g., a plasma chamber), a light source

for generating photons (e.g., a laser, laser diode, lamp, etc.), a heated filament for producing electrons, and/or any other source for the particles of a type deployed in specific stress-mitigation techniques of the instant disclosure. Beam source 702 can be powered by a power element 706 and can include an extraction electrode assembly (not shown). Irradiation system 700 can include a mass spectrometer 708 (e.g., in the instances where beam source 702 produces charged particles, such as electrons or ions) and a collimating and focusing column 220. Collimating and focusing column 220 can direct stress-mitigation beam 218 to substrate 202. Substrate 202 can be supported by a support stage 712. In some embodiments, support stage 712 and substrate 202 can remain stationary during irradiation of substrate 202 by stress-mitigation beam 218 while components of irradiation system 700 can be repositioned relative to substrate 202. In some embodiments, irradiation system 700 can be stationary while support stage 712 can reposition substrate 202. In some embodiments, stress-mitigation beam 218 can have intensity (e.g., light intensity) that is modulated by changing intensity of beam source 702 and/or placing a partially absorbing or partially reflecting material at some location between beam source 702 and substrate 202. This enables delivery of local irradiation doses $n(x, y)$ to various locations of substrate 202. Scanning with stress-mitigation beam 218 can occur along multiple directions, e.g., along x -axis and along y -axis according to any suitable predetermined pattern, e.g., back-and forth along x -axis, in a spiral pattern, and so on. In various embodiments, stress-mitigation beam 218 can be scanned with a frequency of several Hz, tens of Hz, hundreds of Hz, thousands of Hz, or more.

[0077] Operations of irradiation system 700 can be controlled by a controller 714, which can include any suitable computing device, microcontroller, or any other processing device having a processor, e.g., a central processing unit (CPU), a field-programmable gate array (FPGA), an application-specific integrated circuit (ASIC), and/or the like, and a memory device, e.g., a random-access memory (RAM), read-only memory (ROM), flash memory, and/or the like or any combination thereof. Controller 714 can control operations of power element 706, support stage 712, and/or various other components and modules of irradiation system 700. Controller 714 can include a stress-mitigation module 716 capable of performing simulations that determine a target intensity of stress-mitigation beam 218 to be used to mitigate various wafer deformations. In some embodiments, as illustrated in **FIG. 7B**, support stage 712 can impart a tilt, e.g., in one or two spatial directions to substrate 202 to change an angle of incidence of stress-mitigation beam 218 relative to substrate 202. In some

embodiments, instead of tilting substrate 202, controller 714 can cause a tilt of stress-mitigation beam 218 relative to substrate 202.

[0078] FIG. 8 depicts a block diagram of an example computer system 800 capable of supporting operations of the present disclosure, according to at least one embodiment. In various illustrative examples, example computer system 800 may be or include controller 714 of FIG. 7. Example computer system 800 may be connected to other computer systems in a LAN, an intranet, an extranet, and/or the Internet. Computer system 800 may operate in the capacity of a server in a client-server network environment. Computer system 800 may be a personal computer (PC), a set-top box (STB), a server, a network router, switch or bridge, or any device capable of executing a set of instructions (sequential or otherwise) that specify actions to be taken by that device. Further, while only a single example computer system is illustrated, the term “computer” shall also be taken to include any collection of computers that individually or jointly execute a set (or multiple sets) of instructions to perform any one or more of the methods discussed herein.

[0079] Example computer system 800 may include a processing device 802 (also referred to as a processor or CPU), a main memory 804 (e.g., read-only memory (ROM), flash memory, dynamic random access memory (DRAM) such as synchronous DRAM (SDRAM), etc.), a static memory 806 (e.g., flash memory, static random access memory (SRAM), etc.), and a secondary memory (e.g., a data storage device 818), which may communicate with each other via a bus 830.

[0080] Processing device 802 represents one or more general-purpose processing devices such as a microprocessor, central processing unit, or the like. More particularly, processing device 802 may be a complex instruction set computing (CISC) microprocessor, reduced instruction set computing (RISC) microprocessor, very long instruction word (VLIW) microprocessor, processor implementing other instruction sets, or processors implementing a combination of instruction sets. Processing device 802 may also be one or more special-purpose processing devices such as an application specific integrated circuit (ASIC), a field programmable gate array (FPGA), a digital signal processor (DSP), network processor, or the like. In accordance with one or more aspects of the present disclosure, processing device 802 may include a processing logic 826 configured to execute instructions (e.g., instructions 822) implementing example method 500 of mitigation of anisotropic wafer stress and deformation using stress-compensation beams with directional pattern and/or method 600 of determining settings for beam irradiation.

[0081] Example computer system 800 may further comprise a network interface device 808, which may be communicatively coupled to a network 820. Example computer system 800 may further comprise a video display 810 (e.g., a liquid crystal display (LCD), a touch screen, or a cathode ray tube (CRT)), an alphanumeric input device 812 (e.g., a keyboard), a cursor control device 814 (e.g., a mouse), and an acoustic signal generation device 816 (e.g., a speaker).

[0082] Data storage device 818 may include a computer-readable storage medium (or, more specifically, a non-transitory computer-readable storage medium) 824 on which is stored one or more sets of executable instructions 822. In accordance with one or more aspects of the present disclosure, executable instructions 822 may comprise executable instructions implementing example method 500 of mitigation of anisotropic wafer stress and deformation using stress-compensation beams with directional pattern and/or method 600 of determining settings for beam irradiation.

[0083] Executable instructions 822 may also reside, completely or at least partially, within main memory 804 and/or within processing device 802 during execution thereof by example computer system 800, main memory 804 and processing device 802 also constituting computer-readable storage media. Executable instructions 822 may further be transmitted or received over a network via network interface device 808.

[0084] While the computer-readable storage medium 824 is shown in **FIG. 8** as a single medium, the term “computer-readable storage medium” should be taken to include a single medium or multiple media (e.g., a centralized or distributed database, and/or associated caches and servers) that store the one or more sets of operating instructions. The term “computer-readable storage medium” shall also be taken to include any medium that is capable of storing or encoding a set of instructions for execution by the machine that cause the machine to perform any one or more of the methods described herein. The term “computer-readable storage medium” shall accordingly be taken to include, but not be limited to, solid-state memories, and optical and magnetic media.

[0085] Some portions of the detailed descriptions above are presented in terms of algorithms and symbolic representations of operations on data bits within a computer memory. These algorithmic descriptions and representations are the means used by those skilled in the data processing arts to most effectively convey the substance of their work to others skilled in the art. An algorithm is here, and generally, conceived to be a self-consistent sequence of steps leading to a desired result. The steps are those requiring physical manipulations of physical quantities. Usually, though not necessarily, these quantities take

the form of electrical or magnetic signals capable of being stored, transferred, combined, compared, and otherwise manipulated. It has proven convenient at times, principally for reasons of common usage, to refer to these signals as bits, values, elements, symbols, characters, terms, numbers, or the like.

[0086] It should be borne in mind, however, that all of these and similar terms are to be associated with the appropriate physical quantities and are merely convenient labels applied to these quantities. Unless specifically stated otherwise, as apparent from the following discussion, it is appreciated that throughout the description, discussions utilizing terms such as “identifying,” “determining,” “storing,” “adjusting,” “causing,” “returning,” “comparing,” “creating,” “stopping,” “loading,” “copying,” “throwing,” “replacing,” “performing,” or the like, refer to the action and processes of a computer system, or similar electronic computing device, that manipulates and transforms data represented as physical (electronic) quantities within the computer system's registers and memories into other data similarly represented as physical quantities within the computer system memories or registers or other such information storage, transmission or display devices.

[0087] Examples of the present disclosure also relate to an apparatus for performing the methods described herein. This apparatus may be specially constructed for the required purposes, or it may be a general purpose computer system selectively programmed by a computer program stored in the computer system. Such a computer program may be stored in a computer readable storage medium, such as, but not limited to, any type of disk including optical disks, CD-ROMs, and magnetic-optical disks, read-only memories (ROMs), random access memories (RAMs), EPROMs, EEPROMs, magnetic disk storage media, optical storage media, flash memory devices, other type of machine-accessible storage media, or any type of media suitable for storing electronic instructions, each coupled to a computer system bus.

[0088] The methods and displays presented herein are not inherently related to any particular computer or other apparatus. Various general purpose systems may be used with programs in accordance with the teachings herein, or it may prove convenient to construct a more specialized apparatus to perform the required method steps. The required structure for a variety of these systems will appear as set forth in the description below. In addition, the scope of the present disclosure is not limited to any particular programming language. It will be appreciated that a variety of programming languages may be used to implement the teachings of the present disclosure.

[0089] It is to be understood that the above description is intended to be illustrative, and not restrictive. Many other embodiment examples will be apparent to those of skill in the art upon reading and understanding the above description. Although the present disclosure describes specific examples, it will be recognized that the systems and methods of the present disclosure are not limited to the examples described herein, but may be practiced with modifications within the scope of the appended claims. Accordingly, the specification and drawings are to be regarded in an illustrative sense rather than a restrictive sense. The scope of the present disclosure should, therefore, be determined with reference to the appended claims, along with the full scope of equivalents to which such claims are entitled.

CLAIMS

What is claimed is:

1. A method comprising:
forming, responsive to an anisotropic deformation of a substrate, a stress-compensation layer (SCL) on the substrate; and
subjecting the SCL to a stress-mitigation beam to induce a directionally-modulated pattern of stress in the SCL, wherein the directionally-modulated pattern of stress in the SCL causes mitigation of the anisotropic deformation of the substrate.
2. The method of claim 1, wherein the stress-mitigation beam comprises at least one of: a beam of ions, a beam of photons, or a beam of electrons.
3. The method of claim 1, wherein subjecting the SCL to the stress-mitigation beam comprises:
forming a directionally-modulated mask on the SCL, wherein the directionally-modulated mask comprises at least one of:
a plurality of raised portions, or
a plurality of recessed portions; and
illuminating the directionally-modulated mask by the stress-mitigation beam.
4. The method of claim 3, wherein forming the directionally-modulated mask on the SCL comprises:
depositing a mask on the SCL; and
forming one or more directional features on the mask on the SCL using at least one of:
contact photolithography,
proximity photolithography,
projection photolithography,
imprint lithography, or
digital lithography.
5. The method of claim 1, wherein subjecting the SCL to the stress-mitigation beam comprises:

illuminating, by one or more beams of light, a plurality of locations of the SCL.

6. The method of claim 5, wherein the one or more beams of light are generated using at least one of:

- one or more lasers,
- one or more laser diodes, or
- one or more light-emitting diodes.

7. The method of claim 6, wherein the one or more beams of light are further generated using a diffraction optical element.

8. The method of claim 6, wherein the one or more beams of light are focused, onto the SCL, using one or more cylindrical lenses.

9. The method of claim 5, wherein illuminating the plurality of locations of the SCL comprises causing a relative motion of the one or more beams of light and the SCL.

10. The method of claim 1, wherein the stress-mitigation beam has a cross-section that is more than 0.1 mm, and wherein a period of the directionally-modulated pattern of stress in the SCL is less than 10 microns.

11. The method of claim 1, further comprising:
obtaining optical inspection data characterizing a profile of the anisotropic deformation of the substrate; and
determining, using the optical inspection data, at least one of:
the anisotropic deformation of the substrate, or
settings of the stress-mitigation beam.

12. The method of claim 11, wherein the settings for the stress-mitigation beam comprise one or more of:
a type of particles of the stress-mitigation beam,
an energy of the particles of the stress-mitigation beam, or
an angle of incidence of the particles of the stress-mitigation beam.

13. The method of claim 11, wherein obtaining the optical inspection data characterizing the profile of the anisotropic deformation of the substrate comprises obtaining a polynomial decomposition of the profile of the anisotropic deformation of the substrate.
14. A system comprising:
a memory; and
a processing device communicatively coupled to the memory, wherein the processing device causes performance of operations comprising:
forming, responsive to an anisotropic deformation of a substrate, a stress-compensation layer (SCL) on the substrate; and
subjecting the SCL to a stress-mitigation beam to induce a directionally-modulated pattern of stress in the SCL, wherein the directionally-modulated pattern of stress in the SCL causes mitigation of the anisotropic deformation of the substrate.
15. The system of claim 14, wherein subjecting the SCL to the stress-mitigation beam comprises:
forming a directionally-modulated mask on the SCL, wherein the directionally-modulated mask comprises at least one of:
a plurality of raised portions, or
a plurality of recessed portions; and
illuminating the directionally-modulated mask by the stress-mitigation beam.
16. The system of claim 14, wherein subjecting the SCL to the stress-mitigation beam comprises:
illuminating, by one or more beams of light, a plurality of locations of the SCL.
17. The system of claim 16, wherein the one or more beams of light are generated using at least one of:
one or more lasers,
one or more laser diodes, or
one or more light-emitting diodes.
18. The system of claim 16, wherein the one or more beams of light are further generated using a diffraction optical element.

19. The system of claim 16, wherein the operations further comprise:
obtaining optical inspection data characterizing a profile of the anisotropic deformation of the substrate; and
determining settings of the stress-mitigation beam using the optical inspection data.
20. A semiconductor manufacturing system comprising:
one or more processing chambers to:
deposit one or more films on a substrate;
form, responsive to an anisotropic deformation, a stress-compensation layer (SCL) on the substrate; and
subject the SCL to a stress-mitigation beam to induce a directionally-modulated pattern of stress in the SCL, wherein the directionally-modulated pattern of stress in the SCL causes mitigation of the anisotropic deformation of the substrate.