TWO-BEAM LASER ANNEALING WITH IMPROVED TEMPERATURE PERFORMANCE

FIELD

[0001] The present disclosure relates generally to annealing as used in semiconductor manufacturing to fabricate integrated circuits, and in particular relates to laser annealing of semiconductor wafers using two laser beams having different wavelengths to improve the temperature performance of the annealing process.

BACKGROUND ART

[0002] Millisecond laser annealing, such as laser spike annealing (LSA), has been widely adopted in advanced semiconductor device fabrication because it offers an ultra-low thermal budget, high dopant activation and super-abrupt junctions. A key challenge to implementing this type of annealing on patterned wafers is the potential large within-chip temperature non-uniformities that can arise from spatial variations in the optical and thermal properties of the wafer surface caused by the features of the IC chip. These adverse effects are referred to in the art as "pattern density effects" or just "pattern effects."

[0003] In one example of LSA, an infrared laser directs a single annealing laser beam to the wafer surface at or near the Brewster angle of incidence and with a P-polarization to minimize reflections and thus any within-chip temperature non-uniformities due to pattern density effects. The infrared wavelength reduces optical interference effects from the patterns because of its relatively long wavelength (e.g., 10.6 microns) compared to the film thickness (e.g., on the order of 1 micron or less). The Brewster angle of incidence is known to be the angle of maximum absorption for a surface and acts to minimize difference in light absorption due to the IC chip features, including the various thin film stacks used in IC chip fabrication.

[0004] This single-beam approach works very well for many IC chip features and circuit layouts. However, for certain IC chip features and for layouts involving large features, temperature overshoots have been observed due to optical diffraction at the boundary between two adjacent regions that have different optical properties. This reduces the

maximum annealing temperature that can be used to activate the dopants in the adjacent regions.

[0005] FIG. 1 is a close-up cross-sectional view of a section of a prior art silicon wafer 10 having a wafer body 9 and a wafer surface 12. The wafer 10 of FIG. 1 includes a feature in the form of an oxide region (e.g., an oxide isolation pad) 16 formed in the wafer body 9 adjacent the wafer surface 12. The oxide region feature 16 defines an oxide-silicon interface 17 within the wafer body 9 and constitutes an example wafer structure or feature. FIG. 2 is a plot of normalized intensity vs. distance x (μm) from the interface 17. The plot shows the simulated optical intensity distribution in the section of the wafer 10 shown in FIG. 1 during single-beam laser annealing as performed according to the prior art. The simulation was performed using a P-polarized CO_2 laser beam LB (see FIG. 1) at a wavelength of 10.6 μm and incident upon the wafer surface 12 at an angle of incidence θ near the Brewster angle θ_B for a silicon substrate (i.e., $\theta \approx \theta_B \approx 75^o$). The intensity plot of FIG. 2 shows a relatively strong intensity oscillation in the wafer body 9 adjacent the interface 17. The periodicity of the oscillation depends on the angle of incidence θ of the laser beam LB, and is typically a fraction of the wavelength.

[0006] The corresponding temperature distribution in the wafer section is smoother than the intensity distribution due to thermal diffusion, with a typical heat diffusion length for millisecond laser annealing being about 100 μm. However, the temperature at the interface 17 is still higher than that of the rest of the wafer body 9. This temperature variation is referred to as edge temperature overshoot ΔT_{edge}. This temperature overshoot can lead to edge damage near features 16 formed in the wafer 10.

SUMMARY

[0007] Aspects of the disclosure include systems and methods for performing laser annealing using two laser beams having different wavelengths, while other aspects of the disclosure use two laser beams having the same wavelength but a different configuration, i.e., at least one of a different polarization, a different angle of incidence and a different plane of incidence. The systems and methods improve the temperature uniformity of the wafer surface during the annealing process. For wafers whose annealing temperature is limited by slip generation, the two-beam annealing systems and methods disclosed herein

can be used to increase the maximum annealing temperature that can be applied without causing slip.

[0008] Measurements performed on semiconductor wafers indicate that the wafer surface reflectivity can vary significantly as a function of wafer surface position as well as of the laser wavelength, polarization, angle of incidence and the incident plane orientation with respect to the features formed on the wafer surface. The two-wavelength annealing approach described herein can reduce and in some cases substantially compensate for reflectivity variations and thereby improve the anneal temperature uniformity even within individual IC chips.

[0009] The use of the systems and methods disclosed herein to improve within-chip temperature uniformity (as compared to conventional single-beam annealing approaches) is particularly useful when annealing wafers having devices formed with materials that cause high surface reflectivity at infrared wavelengths. In this case, the ratio of the intensities of the two laser beams can be optimized or can be varied as a function of wafer surface position to achieve a minimum optical absorption contrast, which in turn leads to improved anneal temperature uniformity.

[0010] Accordingly, aspects of the disclosure include systems and methods for performing laser annealing of a semiconductor wafer during integrated circuit (IC) chip manufacturing by combining first and second laser beams. The first laser beam is an infrared P-polarized laser beam incident upon the wafer surface at or near the Brewster angle θ_B of silicon (i.e., about 75 degrees). The first laser beam is a preheat laser beam that heats the wafer surface to an intermediate temperature that is typically within several hundred degrees centigrade or so of the target peak annealing temperature. The second laser beam can be an infrared, a visible, or a UV laser beam. The second laser beam can have the same infrared wavelength as the first laser beam but then must have a different configuration, i.e., at least one of a different polarization, a different angle of incidence and a different plane of incidence. If the second laser beam has a substantially different wavelength from the first laser beam, then it can have substantially the same beam configuration, i.e., lie in the same incident plane and have the same or close to the same incident angle. Of course, the second laser beam can also have a different wavelength and a different configuration from the first laser beam. The second laser beam can be incident upon the wafer surface

anywhere from near-normal incidence to a large angle, e.g., the Brewster's angle θ_B or beyond. The second laser beam is used to heat the wafer surface to an annealing temperature T_A, which in an example is just below the wafer melt temperature. In an example, the second laser beam increases the wafer surface temperature by between 200 °C and 800 °C. The first and second laser beams form respective first and second line images on the wafer surface. In an example, the first line image encompasses the second line image, i.e., the second line image falls within the first line image. The first and second line images move across the wafer surface in synchrony. Such movement can be accomplished by moving the wafer, by moving the line images, or by a combination of these two movements.

[0011] A second aspect of the disclosure is a method of combining two laser beams to improve the annealing temperature uniformity as described above, and further includes performing the annealing based on reflectivity maps at the preheat and anneal wavelengths and for the portion of the wafer surface to be annealed. Thus, the method includes measuring the reflectivity of at least a portion of the wafer surface for the respective preheat and anneal wavelengths λ_1 and λ_2 to obtain first and second reflectivity maps. Then, using the first and second reflectivity maps, the method also includes annealing the wafer surface using first and second laser beam intensities I_1 and I_2 that reduce the temperature variation in the wafer surface as compared to using a single laser beam for annealing. In an example, at least one of the first laser beam intensity I_1 and the second laser beam intensity I_2 is varied as a function of the wafer surface position in a manner that reduces or minimizes variations in the wafer surface temperature as compared to annealing the wafer surface with a single anneal laser beam.

[0012] The third aspect of the disclosure is a method of defining intensities I_1 and I_2 of the two laser beams to reduce or mitigate edge damage near large features or slip generations formed in the wafer surface. In an example, the intensity I_2 of the second laser beam is selected by performing experiments on test wafers over a range of second intensities and establishing the second intensity associated with a reduced or minimum amount of edge damage or a slip generation threshold temperature. The amount of edge damage or slip generation of the test wafers is determined by inspection, e.g., by optical microscope inspection.

[0013] Additional features and advantages of the disclosure are set forth in the detailed description that follows, and in part will be readily apparent to those skilled in the art from that description or recognized by practicing the embodiments as described herein, including the detailed description which follows, the claims, as well as the appended drawings. The claims constitute part of this specification, and are hereby incorporated into the detailed description by reference.

[0014] It is to be understood that both the foregoing general description and the following detailed description presented below are intended to provide an overview or framework for understanding the nature and character of the disclosure as it is claimed. The accompanying drawings are included to provide a further understanding of the disclosure, and are incorporated into and constitute a part of this specification. The drawings illustrate various embodiments of the disclosure, and together with the description serve to explain the principles and operations of the disclosure.

[0015] The claims set forth below constitute part of this specification and in particular are incorporated into and constitute part the Detailed Description set forth below.

BRIEF DESCRIPTION OF THE DRAWINGS

[0016] FIG. 1 is a close-up cross-sectional view of a section of a prior art silicon wafer that includes an oxide region formed in a wafer body and adjacent a wafer surface, and shows a scanned anneal laser beam passing over the wafer surface;

[0017] FIG. 2 is a plot of normalized intensity vs. the distance x (μm) into the wafer body from the oxide-silicon interface of FIG. 1, with the plot showing the simulated laser optical intensity distribution in the silicon section of the wafer body during laser annealing as performed according to the prior art, and also showing the edge overshoot temperature ΔT_{EDGE} that can cause edge damage to the wafer at the edge of the oxide region;

[0018] FIG. 3 is a schematic diagram of an example embodiment of a laser annealing system according to the disclosure;

[0019] FIG. 4A is a schematic elevated view of an example laser annealing system or an example wafer reflectivity measurement system, illustrating different configurations for the

preheat laser beam (first light beam–source system) and the anneal laser beam (second light beam–source system);

[0020] FIG. 4B is a schematic diagram based on FIG. 4A and shows the first and second incident planes for the preheat and anneal laser beams as defined by the X-Z plane and the Y-Z plane, respectively;

[0021] FIG. 5A is a plan schematic view of example idealized preheat and anneal line images as formed on the wafer surface;

[0022] FIG. 5B and FIG. 5C are schematic plots of example intensity profiles for the preheat and anneal line images as taken in the Y-direction (FIG. 5B) and X-direction (FIG. 5C);

[0023] FIG. 5D plots the wafer surface temperature T_S (°C) vs. time (milliseconds) and shows a typical wafer surface temperature profile generated by the preheat and anneal laser beams.

[0024] FIG. 5E is a plan view of an example wafer that includes a close-up inset illustrating an example region RW of the wafer surface that includes IC chips, and also a second close-up inset illustrating an example wafer feature (oxide regions) within the IC chip;

[0025] FIG. 6A and FIG. 6B are two-dimensional (x,y) gray-scale reflectivity maps of a portion of an example wafer surface as measured at the preheat wavelength λ_1 (FIG. 6A) and at the anneal wavelength λ_2 (FIG. 6B);

[0026] FIG. 7A and FIG. 7B are plots of reflectivity R vs. position x (mm)(i.e., one-dimensional reflectivity maps) based on the reflectivity maps FIG. 6A and FIG. 6B respectively, as taken along the white dashed lines A-A';

[0027] FIG. 8A and FIG. 8B are similar to FIG. 6A and FIG. 7A and show a two-dimensional (x,y) reflectivity map and a reflectivity vs. position plot (i.e., a one-dimensional

reflectivity map) taken at a central line based on a combination of an IR preheat wavelength of 10.6 microns and an anneal wavelength of 0.85 microns (850 nm);

[0028] FIG. 9 is a bar chart that compares the edge damage threshold temperatures T_{DT} (°C) observed in three different layout areas of a test wafer using conventional single-beam annealing (white bars) and using the two-beam annealing systems and methods disclosed herein (black bars); and

[0029] FIG. 10 is a plot of the slip threshold temperature as measured using conventional annealing and the two-beam laser annealing systems and methods disclosed herein.

DETAILED DESCRIPTION

[0030] Reference is now made in detail to various embodiments of the disclosure, examples of which are illustrated in the accompanying drawings. Whenever possible, the same or like reference numbers and symbols are used throughout the drawings to refer to the same or like parts. The drawings are not necessarily to scale, and one skilled in the art will recognize where the drawings have been simplified to illustrate the key aspects of the disclosure. In some of the Figures, Cartesian coordinates are provided for the sake of reference and are not intended as providing limitations on specific directions and orientations of the systems and methods described herein. The claims as set forth below are incorporated into and constitute part of this detailed description.

[0031] In the discussion below, the term "semiconductor substrate" and "wafer" are synonymous and used interchangeably. Likewise, the terms "semiconductor wafer surface" and "wafer surface" are synonymous and used interchangeably, with "wafer surface" being shorthand for "semiconductor wafer surface." The term "wafer" is shorthand for "semiconductor wafer" such as is used in the fabrication of integrated circuit devices. An exemplary wafer is a silicon wafer.

[0032] FIG. 3 is a schematic diagram of an example embodiment of a laser annealing system ("system") 100 according to the disclosure. FIG. 4A is a schematic elevated view of

example system 100. The system 100 of FIG. 4A can also be a wafer reflectivity measurement system 100RM, as discussed below.

[0033] With reference to FIG. 3, the system 100 includes a wafer stage 120 that operably supports a chuck 130 having an upper surface 132. The wafer stage 120 is configured to move in the X-Y plane and optionally in the Z-direction. The chuck upper surface 132 is configured to operably support a wafer 10 having a wafer body 9 and a planar surface 11 that operably supports a patterned wafer surface 12. The wafer surface 12 can have any pattern that is associated with the various stages of fabricating IC chips and IC chip features (see e.g., the example wafer features 16 in FIG. 5E, introduced and discussed below).

[0034] In an example, the chuck 130 is heated so that the wafer 10 can be preheated. The wafer stage 120 is operably connected to a stage controller 124, and the chuck 130 is operably connected to a chuck controller 134.

[0035] With reference to FIG. 3 and FIG. 4A, the system 100 also includes a first light beam–source system 150 that in an example is configured to generate a first light beam 168 having a first wavelength λ_1. In an example, the first light beam 168 is a laser beam having an intensity I_1 and is used to preheat the wafer surface 12 by raising a wafer surface temperature T_S to be in the range of from about 500 °C to about 1,100 °C, which is below the wafer anneal temperature T_A, in an example, about 1,300 °C.

[0036] In another example, the system 100 constitutes or is otherwise used as a reflectivity measurement system 100RM, and the first light beam 168 is narrow-band light centered at the IR processing wavelength for annealing and is used to measure a first reflectivity $R_1(x,y)$ of the wafer surface 12 at the first wavelength λ_1, as described below. As the discussion below is initially directed to laser annealing and later to reflectivity measurement, for convenience a first light beam–source system 150 is hereafter referred to as the preheat laser system 150 and the first light beam 168 is also referred to as the preheat laser beam 168.

[0037] An example preheat laser system 150 includes a preheat laser 160 and a preheat optical system 166 that defines a first optical axis A1. The preheat laser 160 can include a diode laser or a CO_2 laser, such as a continuous-wave (CW), P-polarized 10.6 micron CO_2

laser. The axis A1 can be oriented so that the preheat laser beam 168 is incident upon the wafer surface 12 at an incidence angle θ_1 that is in the range of from near normal (i.e., near 0 degrees) to a large oblique incident angle, such as the Brewster angle for silicon, or larger. In an example embodiment, the first optical axis A1 has an angle θ_1 that is substantially equal to the Brewster's angle for silicon, so that aforementioned pattern density effects from non-uniform optical absorption are reduced or minimized.

[0038] The preheat optical system 166 is configured to receive an initial preheat laser beam 162 and form therefrom the preheat laser beam 168. The preheat laser beam 168 travels generally along the first (preheat) optical axis A1 and forms a first (preheat) line image 170 at the wafer surface 12.

[0039] FIG. 5A is a plan schematic view of an example idealized preheat line image 170 as formed on the wafer surface 12. FIG. 5B and FIG. 5C are schematic plots of an example intensity profile 170P for the preheat line image 170 as taken in the Y-direction (FIG. 5B) and X-direction (FIG. 5C). The intensity profile 170P corresponds to that of the preheat laser beam 168 at the wafer surface 12 and defines the preheat line image 170, e.g., by virtue of the intensity being above a certain threshold intensity I_{TH}. The preheat line image 170 is shown as having a centerline or axis C1 in the long (i.e., Y) direction, which is perpendicular to the scan (i.e., X) direction. The preheat line image 170 is scanned in the X-direction at a velocity V_S as indicated by the large arrow in FIG. 5A.

[0040] The preheat laser beam 168 typically has a Gaussian intensity profile in the scanning direction and a relatively flat top profile in the long (cross-scanning) direction. An example beam width W1 (defined at full width half maximum (FWHM) of the Gaussian profile) for the preheat laser beam 168 (and thus for the preheat line image 170) is in the range of from about 0.05 mm to about 2 mm. An example beam length L1 for the preheat laser beam 168 (and thus for the preheat line image 170) is typically in the range of from about 5 mm to about 20 mm. In an example, the scanning of the preheat laser beam 168 and its corresponding preheat line image 170 has an associated heat diffusion length (depth) into the wafer 10 in the range of from about 30 microns to about 500 microns.

[0041] With reference again to FIG. 3 and FIG. 4A, the system 100 also includes a second light beam-source system 250 that generates a second light beam 268. In an example, the

second light beam 268 is a second laser beam of intensity I_2 and is used to add heat to the preheated portion of the wafer surface 12 as caused by irradiation with the preheat laser beam 168 (and optionally heated chuck 130) so that a wafer surface temperature T_S locally rises and spikes at an anneal temperature T_A, which in an example is just below a wafer melt temperature T_{MELT}. The second light beam 268 is also referred to below as an anneal laser beam 268.

[0042] FIG. 5D plots the wafer surface temperature T_S (°C) vs. time (milliseconds) for a given position on the wafer surface 12, and shows a typical wafer surface temperature profile generated by the preheat laser beam 168 and the anneal laser beam 268 preheat as the beams pass over the position. The temperature T_0 is the base wafer surface temperature prior to the application of the preheat laser beam 168 or the anneal laser beam 268 to the wafer surface 12. T_{PH} is the preheat wafer surface temperature produced by the preheat laser beam 168, and ΔT_S is the surface temperature increase from the preheat wafer temperature T_{PH} to the anneal temperature T_A produced by the anneal laser beam 268. The data in the plot of FIG. 5D is based on the preheat laser beam 168 being wider in the scanning direction than the anneal laser beam 268. This serves to preheat the wafer to an intermediate (preheat) temperature T_{PH} before the anneal laser beam further heats the wafer surface to the anneal temperature T_A.

[0043] In another example, the second light beam 268 is a narrow-band light beam centered at processing a (second) wavelength λ_2 of the second light beam 268, and is used to measure a second reflectivity $R_2(x,y)$ of the wafer surface 12 at the second wavelength λ_2, as described below. As the discussion below is initially directed to laser annealing, the second light beam-source system 250 is hereafter referred to as an anneal laser system 250 and the at least one second light beam 268 is referred to as the anneal laser beam 268 unless otherwise noted.

[0044] In an example, the anneal laser system 250 includes an anneal laser 260 that generates an initial anneal laser beam 262. The second wavelength λ_2 of the second light beam 268 is referred to as the anneal wavelength, and can be any wavelength that can heat the wafer surface 12 after it has been preheated. Example anneal wavelengths include IR, visible or ultraviolet (UV) wavelengths.

[0045] The anneal laser system 250 also includes an anneal optical system 266 operably arranged relative to the anneal laser 260 along a second (anneal) optical axis A2. An example anneal optical system 266 includes a beam-shaping optical system 266A, a fold-mirror FM1, an adjustable aperture 267, a projection optical system 266B and optionally another fold mirror FM2. The anneal optical system 266 is configured to receive the initial anneal laser beam 262 from the anneal laser 260 and to form therefrom the anneal laser beam 268. The anneal laser beam 268 forms at the wafer surface 12 a second (anneal) line image 270 relative to the preheat line image 170 so that that the aforementioned annealing occurs. In an example embodiment, the second (anneal) optical axis A2 has an incident angle θ_2 to the wafer surface 12 at or near the Brewster angle for silicon, though any reasonable incident angle for the second optical axis A2 can be employed.

[0046] In an example, the intensity I_2 of the anneal laser beam 268 is selected to raise the temperature of the wafer surface 12 by between 200 °C and 800 °C, depending on the preheat temperature T_{PH}. In an example, the intensity I_2 raises the wafer surface temperature from the preheat wafer surface temperature T_{PH} up to the anneal temperature T_A, which in an example is just below the melting temperature of silicon.

[0047] FIG. 5A also includes a plan schematic view of an example idealized anneal line image 270 as formed on the wafer surface 12 relative to the preheat line image 170. FIG. 5B and FIG. 5C also include X-direction and Y-direction cross-sectional plots of an example intensity profile 270P for the anneal laser beam 268. The intensity profile 270P defines the anneal line image 270, e.g., by virtue of the intensity being above a threshold intensity I_{TH}. The anneal line image 270 has a length L2 in the Y-direction and a width W2 in the X-direction.

[0048] FIG. 5E is a plan view of an example wafer 10 that includes a close-up inset illustrating an example region RW of the wafer surface 12. The region RW includes a number of IC chips 15 spaced apart by gaps 13, e.g., a kerf region or a region used to form scribe lines for dicing the IC chips 15. Example wafer features 16 are also shown within one IC chip 15. The example wafer features 16 are shown by way of example as metallization lines within the IC chip 15, the metallization lines being oriented in the Y-direction.

[0049] The intensity profile 270P as taken along the scanning direction typically has a Gaussian form. In an example, the width W2 of the anneal line image 270 is defined by the FWHM of a Gaussian Y-directional cross-section of the intensity profile 270P. A typical width W2 is in the range of 50 microns to 500 microns. In an example, the length L2 of the anneal line image 270 is substantially the same as the length L1 of the preheat line image 170.

[0050] With reference again to FIG. 3 and FIG. 4A, the system 100 includes a first photodetector 280 arranged relative to the wafer surface 12 to detect a specularly reflected laser beam 168R that reflects from the wafer surface. The first photodetector 280 generates an electrical signal SD1 representative of the intensity of the detected reflected laser beam 168R. In an example photodetector 280 includes a cooled (e.g., thermal-electric cooled or liquid-nitrogen cooled) infrared detector.

[0051] The system 100 also includes a second photodetector 290 arranged to detect reflected or scattered light beam 268RS from the wafer surface 12. In an example, the second photodetector 290 includes an integrating sphere 292 and a photodiode 294 that is operably attached thereto and in optical communication with the interior of the integrating sphere 292. The second photodetector 290 generates an electrical signal SD2 representative of the intensity of the detected reflected and scattered light beam 268RS. Note that if a short wavelength anneal laser 260 is used to generate the anneal laser beam 268, the amount of scattering of the anneal laser beam 268 from the patterned wafer surface 12 may be significant. Hence, in an example, the integrating sphere 292 is employed to collect both the specular reflected and scattered laser light beam 268RS.

[0052] The system 100 further includes a system controller 300 electrically connected to the stage controller 124, the chuck controller 134, the preheat laser 160, the anneal laser 260, the adjustable aperture 267, and the first and second photodetectors 280 and 290. In an example, the system controller 300 comprises a computer or like machine that is adapted (e.g., via instructions such as software embodied in a computer-readable or machine-readable medium) to cause the controller to control the operation of the various components of the system 100. The system controller 300 includes a processor unit ("processor") 302 and a memory unit ("memory") 304. An example controller 300 is or

includes a computer with a processor and includes an operating system such as Microsoft WINDOWS or LINUX.

[0053] In an example embodiment, the processor 302 is or includes any processor or device capable of executing a series of software instructions and includes, without limitation, a general- or special-purpose microprocessor, finite state machine, controller, computer, central-processing unit (CPU), field-programmable gate array (FPGA) or digital signal processor. In an example embodiment, the processor is an Intel XEON or PENTIUM processor, or an AMD TURION or other in the line of such processors made by AMD Corp., Intel Corp. or another semiconductor processor manufacturer.

[0054] The memory 304 is operably connected to the processor 302. As used herein, the term "memory" refers to any processor-readable medium, including but not limited to RAM, ROM, EPROM, PROM, EEPROM, disk, floppy disk, hard disk, CD-ROM, DVD or the like, on which may be stored a series of instructions executable by the processor 302. In an example embodiment, the system controller 300 includes a disk drive 306 adapted to accommodate a removable processor-readable medium 308, such as CD-ROM, DVE, memory stick or like storage medium.

[0055] The laser annealing methods described herein may be implemented in various embodiments in a machine-readable medium (e.g., memory 304) comprising machine readable instructions (e.g., computer programs and/or software modules) for causing the system controller 300 to perform the annealing methods described herein by controlling the operation of system 100. In an example embodiment, the computer programs run on processor 302 out of memory 304.

[0056] The computer programs and/or software modules may comprise multiple modules or objects in order to perform the various methods of the present disclosure and to control the operation and function of the various components in the system 100 and in the reflectivity measurement system 100RM. The type of computer programming languages used for the code may range from procedural code-type languages to object-oriented languages. The files or objects need not have a one-to-one correspondence to the modules or method steps described. Further, the method and system may comprise combinations of

software, hardware and firmware. Firmware can be downloaded into processor 302 for implementing the various example embodiments disclosed herein.

Improved surface temperature uniformity

[0057] A benefit of using the two-beam laser annealing systems and methods disclosed herein is improved temperature uniformity of the wafer surface 12, which is achieved by mitigating the aforementioned adverse pattern density effects that among other things create a varying reflectivity over the wafer surface. As discussed above, for certain devices such as memory chips, the wafer surface 12 may comprise materials and features 16 involving high reflectivity at the long wavelengths associated with the preheat laser beam 168 and lower reflectivity at the short wavelengths associated with the anneal laser beam 268. Consequently, the preheat laser beam 168 and the anneal laser beam and 268 can be employed to reduce the optical absorption contrast, and hence provide a more uniform temperature distribution during the annealing process.

[0058] Embodiments of the methods of annealing disclosed herein include selecting intensities I_1 and I_2 of the preheat laser beam 168 and the anneal laser beam 268, respectively, based on the reflectivity properties of at least a portion of the wafer surface 12, to achieve improved uniformity in the annealing temperature over the wafer 10. In an example, the selection of intensities I_1 and I_2 is done in a manner that maximally reduces temperature variations in the wafer surface 12 during the annealing process.

[0059] In an example, the ratio $RI = I_1/I_2$ is used as a parameter for optimizing the annealing process to achieve a reduced or minimized temperature variation in the wafer surface 12 during the annealing process. In an example, intensities I_1 and I_2 are varied during scanning based on first and second reflectivity maps for at least a portion of the wafer surface 12. In an example, the variation is carried out over a scale that is at least the size of the anneal line image 268P, since the intensity of the anneal line image does not vary over its length. Generally, the frequency of any change in intensity I_1 and/or I_2 varies slowly relative to the spatial frequency of the wafer surface reflectivity at the preheat and anneal wavelengths λ_1 and λ_2.

[0060] In another example, intensities I_1 and I_2 are kept constant and represent a best-choice of intensities for the particular reflectivity maps in terms of reducing or minimizing

the variation in the wafer surface temperature during the annealing process. An example of this best-choice method is illustrated in FIG. 8A and FIG. 8B as discussed below.

[0061] The reflectivity of at least a portion of the wafer surface 12 can be measured using the system 100 as described above using the preheat laser beam 168 and the anneal laser beam 268. More generally, the reflectivity of at least a portion of the wafer surface 12 can be measured using the reflectivity measurement system 100RM (or a similarly configured system) that utilizes the first and second light beam 168 and 268 as either laser or non-laser (e.g., lamp-generated) beams that have the same wavelengths as the preheat and anneal wavelengths λ_1 and λ_2, which are used to anneal the wafer 10. The discussion below is directed to the measurement of the reflectivity of the wafer surface 12 using the preheat and anneal laser beams 168 and 268 by way of example. The typical laser power used for establishing the first and second reflectivity maps over at least a portion of the wafer surface 12 at the preheat and anneal wavelengths λ_1 and λ_2 need not be as high as the annealing power, and can be in the milliwatt range.

[0062] With reference to FIG. 4B, in an example, the preheat laser beam 168 and the anneal laser beam 268 reside in respective first and second incident planes IP1 and IP2 that are perpendicular to each other. In particular, the first incident plane IP1 is defined by the X-Z plane and the second incident plane IP2 is defined by the Y-Z plane. The reflected first light beam 168R is detected by the first photodetector 280 along a specular reflection path. The reflected and scattered laser light beam 268RS is collected by the second photodetector 290. The system controller 300 controls the wafer stage 120 to effectuate X-Y scanning in a defined area of the wafer surface 12 that in an example covers an integer number of the IC chips 15. The detector signals SD1 and SD2 from the respective photodetectors 280 and 290 are generated as a function of the (x,y) wafer coordinates and are provided to the system controller 300. By knowing the respective intensities I_1 and I_2 of the first light beam 168 and the second light beam 268, and by measuring the respective reflected intensities I_1' and $I_2'$of the reflected first light beam 168R and the reflected and scattered laser light beam 268RS, the reflectivity at a given x-y location on the wafer surface 12 can be determined, e.g., by the processor 302.

[0063] Thus, reflectivity data is collected from the wafer surface 12 as a function of x-y coordinates to create reflectivity maps $R_1(x,y)$ and $R_2(x,y)$ of at least a portion of the wafer

surface 12. In an example, a calibrated wafer having a high reflectivity for the wavelengths associated with the first and second light beams 168 and 268, such as a metal-coated silicon wafer, is used to calibrate the reflectivity measurements. As discussed above, the reflectivity mapping of the wafer surface 12 can be carried out in an actual LSA annealing system or in a separate metrology system such as the measurement system 100RM.

[0064] FIG. 6A and FIG. 6B are contour plots of reflectivity that represent reflectivity maps of an example wafer surface 12 as measured at the preheat wavelength λ_1 (FIG. 6A) and anneal wavelength λ_2 (FIG. 6B). FIG. 7A and FIG. 7B are reflectivity plots as a function of position for the contour plots of FIG. 6A and FIG. 6B taken along the lines A-A'. The lower reflectivity region at the preheat wavelength λ_1 shows a higher reflectivity at the anneal wavelength λ_2, indicating that the combination of the two wavelengths can partially compensate for the variation in the reflectivity of the wafer surface 12.

[0065] FIG. 8A and FIG. 8B are similar to FIG. 6A and FIG. 7A and show the reflectivity map and cutline for when the first and second light beams 168 and 268 are used. The ratio RI of the two laser beam intensities I_1 and I_2 is chosen to give the most uniform absorption. For this application, it is desirable that the first and second light beams 168 and 268 have a similar size at the wafer surface 12 so that the annealing time from each laser does not differ significantly.

[0066] In an example embodiment, the optimal intensity ratio $RI = I_1/I_2$ is determined by minimizing the within-chip temperature distribution during annealing. This can be estimated based on the following equation for the wafer surface temperature:

$$T_S(x,y) = s_1 \cdot A_1(x,y) \cdot I_1 + s_2 \cdot A_2(x,y) \cdot I_2$$

[0067] The variables s_1 and s_2 are coefficients that represent the sensitivity of the wafer temperature to the absorbed intensity. These coefficients can be determined by annealing un-patterned silicon wafers and monitoring the temperature as a function of absorbed laser intensity.

[0068] The parameters A_1 and A_2 are the absorption distributions as calculated from the measured reflectivity maps R_1 and R_2 via the relationships:

$$A_1(x,y) = 1 - R_1(x,y)$$

$$A_2(x,y) = 1 - R_2(x,y),$$

where R_1 and R_2 are the reflectivity maps as measured according to the methods described above. When the integrating sphere 292 is used, the measured reflectivity map also includes the scattering contributions.

[0069] In the above example, the second light beam 268, which has a different wavelength than the first light beam 168, was used to generate an absorption distribution that partially compensates for the absorption variation associated with the first light beam. Since optical absorption also varies with the angle of incidence, polarization and orientation of the incident plane with respect to the features 16 on the wafer surface 12 (e.g., the IC chip circuit layout), the second light beam 268 with either a) the same wavelength and at least one or more of a different angle of incidence, polarization and incident plane orientation or b) a different wavelength and either the same or different orientation, can be employed to improve absorption uniformity and thus anneal temperature uniformity.

[0070] By way of example, consider the case where the wafer surface 12 has the IC chips 15 whose layout has the features 16 with metal grating lines running in both x and y directions. The features 16 that have grating lines parallel to the light incident plane (assuming p-polarization) will have a higher reflectivity than those perpendicular to the incident plane. In this case, the second light beam 268 can have the same wavelength, angle of incidence and polarization as the first light beam 168, but with an incident plane that is orthogonal to that of the first light beam.

[0071] The respective intensities I_1 and I_2 of the first and second light beams 168 and 268 can also be optimized to reduce the edge temperature overshoot and therefore improve the edge damage threshold. FIG. 9 is a bar chart that compares the edge damage threshold temperatures T_{DT} (in °C) observed in three different layout areas A, B and C of a test wafer using conventional single-beam annealing (white bars) and using the two-beam annealing systems and methods disclosed herein (black bars). The two-beam annealing systems and methods provide about a 40 °C improvement in damage threshold temperature T_{DT} over the prior art single-beam annealing method (i.e., $\Delta T_{DT} \approx 40$ °C as shown in the chart).

[0072] An added benefit of using the two-beam annealing systems and methods disclosed herein to preheat the wafer surface 12 is a reduced temperature ramping rate and reduced thermal gradient, which can be used to reduce slip generation in silicon substrate 10. FIG. 10 is a plot of the slip threshold temperature T_{slip} (°C) vs. the relative temperature T_{PH} of the preheat laser beam 168, including the case "none" where no preheat laser beam was employed. The laser annealing experiments were performed on bare silicon wafers implanted with boron (implant dose: $2x10^{15}cm^{-2}$; energy: 5keV). The slip thresholds were determined by optical microscope inspection. A significant improvement in slip threshold temperature T_{slip} is observed relative to the "none" case (i.e., prior-art single-beam annealing) for increasing the preheat temperature T_{PH}.

Annealing methods

[0073] Once the first and second wafer surface reflectivity maps $R_1(x,y)$ and $R_2(x,y)$ of the wafer 10 are established as described above, the methods disclosed herein include annealing the wafer using the system 100 by selecting the preheat and anneal laser beam intensities I_1 and I_2 based on the first and second reflectivity maps so that temperature non-uniformities of the annealing process are reduced as compared to prior art single-beam annealing.

[0074] Thus, with reference again to FIG. 3 and the system 100 therein, in an example system controller 300 sends a first control signal S1 to the preheat laser 160, which in response thereto generates initial preheat laser beam 162. This initial preheat laser beam 162 is received by the preheat optical system 166, which forms therefrom the preheat laser beam 168 of intensity I_1. The preheat laser beam 168 travels generally along first optical axis A1 and forms the preheat line image 170 at the wafer surface 12.

[0075] The system controller 300 also sends a second control signal S2 to the anneal laser 260, which in response thereto generates initial anneal laser beam 262. This initial anneal laser beam 262 is received by the anneal optical system 266, which forms therefrom the anneal laser beam 268 having intensity I_2. The anneal laser beam 268 forms the anneal line image 270 relative to the preheat line image 170 so that the aforementioned local wafer surface annealing occurs.

[0076] The system controller 300 also sends a third control signal S3 to the stage controller 124 to move (scan) the wafer 10 relative to the preheat and anneal line images 170 and 270. In an example where the chuck 130 provides wafer preheating, the system controller 300 may also send a fourth control signal S4 to the chuck controller 134 to initiate the wafer preheating process. The system controller 300 optionally sends a fifth control signal S5 to the adjustable aperture 267 to optionally set the length L2 and width W2 of the anneal line image 270. As discussed above, in one example, the preheat and anneal intensities I_1 and I_2 remain constant as the wafer surface 12 is annealed. In another example, at least one of preheat intensity I_1 and anneal intensity I_2 is varied during the scanning of the preheat and anneal laser beams 168 and 268 based on the first and second reflectivity maps $R_1(x,y)$ and $R_2(x,y)$ as stored in the system controller 300. In an example, the modulation of at least one of preheat intensity I_1 and anneal intensity I_2 is based on an average of the reflectivity measurements in each of the reflectivity maps $R_1(x,y)$ and $R_2(x,y)$.

[0077] The dwell time t_D of the preheat line image 170 is given by the ratio of line-image width W1 to scanning velocity V_S. In an example, the dwell time t_D is in the range of 100 microseconds (μs) ≤ t_D ≤ 20 millisecond (ms).

[0078] In the above discussion, the first laser beam 168 has a long wavelength, is oriented substantially at the Brewster angle of incidence and is used as a preheat beam while the second laser beam has a shorter wavelength, or a similar wavelength but different configuration, and is used as the anneal laser beam. Other embodiments of the disclosure include using the long-wavelength laser beam as the anneal laser beam and the short-wavelength laser beam as the preheat beam.

[0079] It will be apparent to those skilled in the art that various modifications and variations can be made to the present disclosure without departing from the spirit and scope of the disclosure. Thus it is intended that the present disclosure cover the modifications and variations of this disclosure provided they come within the scope of the appended claims and their equivalents.

What is claimed is:

1. A method of annealing a semiconductor substrate having a patterned surface and a melt temperature, comprising:

measuring, for a portion of the patterned wafer surface, first and second reflectivity maps at respective first and second wavelengths;

using the first and second reflectivity maps, defining first and second intensities of first and second laser beams having the first and second wavelengths, respectively, that will reduce an amount of surface temperature variation when the first and second laser beams irradiate the portion of the patterned surface during annealing of the semiconductor substrate as compared to annealing the portion of the patterned wafer surface using only one of the first and second laser beams; and

irradiating the portion of the patterned surface to anneal the semiconductor substrate without melting the substrate using the first and second laser beams having the first and second intensities, respectively.

2. The method according to claim 1, further comprising:

configuring the first and second laser beams in corresponding first and second incident planes, respectively.

3. The method according to claim 2, further comprising scanning the first and second laser beams relative to the portion of the patterned surface.

4. The method according to claim 3, further comprising:

the first intensity being sufficient to preheat the portion of the patterned wafer surface to a preheat temperature that is below the melt temperature and less than an anneal temperature that is below the melt temperature; and

the second intensity being sufficient to heat the patterned surface from the preheat temperature up to the anneal temperature.

5. The method according to claim 1, wherein the first wavelength is infrared and the second wavelength is different from the first wavelength.

6. The method according to claim 1, further comprising:
the first laser beam defining a preheat line image at the patterned surface;
the second laser beam defining an anneal line image at the patterned surface; and
wherein the anneal line image falls entirely within the preheat line image.

7. The method according to claim 6, further comprising providing one of the preheat line image and the at least one anneal line image to have a length that corresponds to a size of a region of the patterned surface.

8. The method according to claim 1, further comprising varying at least one of the first and second intensities during the irradiating of the portion of the patterned surface.

9. The method according to claim 1, wherein the portion of the patterned surface includes a wafer feature, and wherein the first and second intensities are further defined to minimize at least one of i) edge damage associated with the wafer feature and ii) wafer slip.

10. The method according to claim 1, wherein the second laser beam increases the wafer surface temperature to an anneal temperature, wherein the amount of wafer surface temperature increase is in the range of between 200 °C and 800 °C.

11. The method according to claim 10, wherein the anneal temperature is about 1,300 °C.

12. The method according to claim 1, wherein the first laser beam raises the surface temperature to be in the range from about 500 °C to about 1,100 °C.

13. A method of non-melt annealing a semiconductor substrate having a patterned surface and a melt temperature, comprising:

scanning at least one first laser beam over the patterned surface, the at least one first laser beam being configured in a first incidence plane and having a first wavelength and a first intensity that heats the patterned surface to a preheat temperature that is below the melt temperature and less than an anneal temperature; and

scanning at least one second laser beam over the patterned surface and relative to the first laser beam, the at least one second laser beam being configured in a second incidence plane and having a second wavelength and a second intensity that heats the patterned surface from the preheat temperature up to the anneal temperature; and

selecting the first and second intensities to achieve the anneal temperature while minimizing at least one of edge damage and slip generation.

14. The method according to claim 13, wherein the first wavelength is infrared and the second wavelength is different from the first wavelength.

15. The method according to claim 13, further comprising:

the first laser beam defining a preheat line image at the patterned surface;

the second laser beam defining an anneal line image at the patterned surface; and

wherein the anneal line image falls entirely within the preheat line image.

16. The method according to claim 15, further comprising providing one of the preheat line image and the at least one anneal line image to have a length that corresponds to a size of a region of the patterned surface.

17. The method according to claim 13, further comprising varying at least one of the first and second intensities of the first and second laser beams during the scanning of the first and second laser beams.

18. The method according to claim 13, wherein the second laser beam increases the patterned surface temperature to the anneal temperature, wherein the amount of patterned surface temperature increase is in the range of between 200 °C and 800 °C.

19. The method according to claim 18, wherein the anneal temperature is about 1,300 °C.

20. The method according to claim 13, wherein the first laser beam raises the patterned surface temperature to be in the range from about 500 °C to about 1,100 °C.

21. A method of annealing a semiconductor substrate having a patterned surface and a melt temperature, comprising:

measuring, for a portion of the patterned wafer surface, first and second reflectivity maps at respective first and second wavelengths;

using the first and second reflectivity maps, defining first and second intensities of first and second laser beams having the first and second wavelengths, respectively, that minimizes an amount of surface temperature variation; and

irradiating the portion of the patterned surface to anneal the semiconductor substrate without melting the substrate using the first and second laser beams having the first and second intensities, respectively.

22. A system for laser annealing a semiconductor wafer having a patterned surface with first and second reflectivity maps at respective first and second wavelengths and an anneal temperature that is below a melt temperature of the wafer, comprising:

a first laser system configured to generate a first laser beam having the first wavelength and a first intensity and scan the first laser beam over the patterned surface in a first incident plane to heat the patterned surface to a preheat temperature;

a second laser system configured to generate a second laser beam having the second wavelength and a second intensity and scan the second laser beam over the patterned surface in a second incident plane relative to the first incident plane of the first laser beam, the second laser beam being configured to heat the patterned surface from the preheat temperature to the anneal temperature; and

wherein the first and second intensities are selected based on the first and second reflectivity maps to reduce an amount of surface temperature variation during the scanning of the first and second laser beams as compared to annealing the wafer surface with only the second laser beam.

23. The system according to claim 22, further comprising:

the first laser beam defining a preheat line image at the patterned surface;

the second laser beam defining an anneal line image at the patterned surface; and

the first and second laser systems being configured so that the anneal line image resides entirely within the preheat line image.

24. The system according to claim 22, further comprising a controller operably arranged to vary at least one of the first and second intensities when the first and second laser beams are scanned.

25. The system according to claim 22, wherein the first wavelength is an infrared wavelength and the second wavelength is different from the first wavelength.

26. The system according to claim 22, further comprising the second intensity being sufficient to increase the patterned surface temperature up to the anneal temperature, wherein the amount of patterned surface temperature increase is in the range of between 200 °C and 800 °C.