

LASER SPIKE ANNEALING USING FIBER LASERS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of priority under 35 U.S.C. § 119(e) of U.S. Provisional Application Serial No. 61/920,655, filed on December 24, 2013, and which is incorporated by reference herein.

FIELD

[0002] The present disclosure relates to laser spike annealing, and in particular relates to laser spike annealing using fiber lasers.

[0003] The entire disclosure of any publication or patent document mentioned herein is incorporated by reference.

BACKGROUND

[0004] Laser annealing using a scanned laser beam offers an ultra-low thermal budget, a high dopant activation and super-abrupt junctions that are ideal for advanced semiconductor device fabrication. Consequently, most logic devices with minimum feature sizes below 45 nm, and many memory devices below 32 nm, now use some form of laser processing for one of several manufacturing steps, including source-drain activation, metal-silicon alloy formation, defect annealing, and the like.

[0005] One form of laser annealing uses pulsed lasers. Examples of pulsed laser annealing are described in WO 2001/071787 A1, U.S. Patent No. 6,365,476 and U.S. Patent No. 6,366,308. Typical semiconductor applications require an annealing time of 0.1 milliseconds to 10 milliseconds (ms). Since optical pulses from a pulsed laser have a much shorter time duration (e.g., nanoseconds to microseconds) than the required annealing time, many optical pulses are required for a given exposure. This leads to problems in annealing uniformity because of pulse-to-pulse power variations.

SUMMARY

[0006] An aspect of the disclosure is a method of performing laser spike annealing of a surface of a wafer. The method includes: generating with a plurality of fiber laser systems respective continuous-wave (CW) output radiation beams that partially overlap at the

surface of the wafer to form an elongate annealing image having a long axis and an annealing length L_A along the long axis; heating at least a region of the wafer to a pre-anneal temperature T_{PA} to define a pre-heat region; and scanning the elongate annealing image over the surface of the wafer and at least partially within (and in an example, entirely within) the pre-heat region in a direction substantially perpendicular to the long axis so that the elongate annealing image has a dwell time t_D in the range $100 \text{ ns} \leq t_D \leq 10 \text{ ms}$, or in another example $30 \text{ ns} \leq t_D \leq 10 \text{ ms}$, and raises the temperature of surface of the wafer to an annealing temperature T_A .

[0007] Another aspect of the disclosure is the method described above, wherein the annealing length L_A is in the range $3 \text{ mm} \leq L_A \leq 450 \text{ mm}$, or in another example $3 \text{ mm} \leq L_A \leq 30 \text{ mm}$.

[0008] Another aspect of the disclosure is the method described above, wherein the elongate annealing image has width W_A measured perpendicular to the long axis and wherein $25 \text{ microns} \leq W_A \leq 500 \text{ microns}$, or in another example $50 \text{ microns} \leq W_A \leq 500 \text{ microns}$.

[0009] Another aspect of the disclosure is the method described above, wherein the CW output radiation beam has an amount of optical power P_A in the range $100 \text{ W} \leq P_A \leq 10,000 \text{ W}$, or in another example $100 \text{ W} \leq P_A \leq 1,000 \text{ W}$,

[0010] Another aspect of the disclosure is the method described above, wherein the pre-anneal temperature T_{PA} is in the range $200^\circ\text{C} \leq T_{PA} \leq 600^\circ\text{C}$.

[0011] Another aspect of the disclosure is the method described above, wherein the anneal temperature T_A is either in the range $1,100^\circ\text{C} \leq T_A \leq 1,350^\circ\text{C}$ or in the range $T_A \geq 1,410^\circ\text{C}$.

[0012] Another aspect of the disclosure is the method described above, and further including: measuring a temperature distribution at the surface of the wafer; and adjusting an amount of power in at least one of the CW output radiation beams to improve an amount of uniformity in the temperature distribution.

[0013] Another aspect of the disclosure is the method described above, wherein the wafer has an edge, the elongate annealing image has an end, and further including either reducing an amount of power in or turning off the CW output radiation beam that forms the

end of the elongate annealing image prior to the elongate annealing image passing over the edge of the wafer.

[0014] Another aspect of the disclosure is the method described above, wherein the elongate annealing image is formed by between three and (up to) fifty CW output radiation beams (i.e., 3, 4, 5, 6, etc., up to 50 output radiation beams).

[0015] Another aspect of the disclosure is the method described above, wherein the CW output radiation beams define elongate images of length L that partially overlap along the long axis by an amount Δ , and wherein the amount of overlap $\Delta \geq 0.79 \cdot (L/2)$.

[0016] Another aspect of the disclosure is a method of optimizing an amount of uniformity of an annealing image using a measurement wafer having a surface. The method includes generating with a plurality of fiber laser systems respective continuous-wave (CW) output radiation beams that partially overlap at the surface of the measurement wafer to form an elongate annealing image having a long axis and a length L_A along the long axis. The method also includes detecting an amount of optical power reflected from the measurement wafer for each of the CW output radiation beams. The method also includes adjusting an amount of optical power in one or more of the CW output radiation beams to optimize an amount of uniformity of the elongate annealing image.

[0017] Another aspect of the disclosure is a method of performing laser spike annealing of a surface of a wafer. The method includes generating with a plurality of fiber laser systems respective continuous-wave (CW) output radiation beams that partially overlap at the surface of the wafer to form an elongate pre-annealing image having a long axis and a length L_A along the long axis. The method also includes heating at least a region of the wafer with the elongate pre-annealing image to a pre-anneal temperature T_{PA} to define a pre-heat region. The method also includes scanning a second laser beam that resides at least partially within the pre-heat region to raise the temperature of surface of the wafer to annealing temperature T_A .

[0018] Another aspect of the disclosure is the method described above, wherein the anneal temperature T_A is either in the range $1,100\text{ }^{\circ}\text{C} \leq T_A \leq 1,350\text{ }^{\circ}\text{C}$ or in the range $T_A \geq 1,410\text{ }^{\circ}\text{C}$.

[0019] Another aspect of the disclosure is the method described above, wherein the annealing temperature T_A is greater than the melt temperature of doped silicon.

[0020] Another aspect of the disclosure is a system for performing laser spike annealing of a wafer having a surface. The system includes a plurality of fiber laser systems that deliver respective output radiation beams that partially overlap at the surface of the wafer to form an annealing image; a wafer support assembly that supports the wafer and heats the wafer to a pre-anneal temperature T_{PA} and that moves the wafer relative to the annealing image so that the annealing image scans over the surface of the wafer with a dwell time t_D in the range $100 \text{ ns} \leq t_D \leq 10 \text{ ms}$, or in another example $30 \text{ ns} \leq t_D \leq 10 \text{ ms}$; and wherein the annealing image has an amount of optical power P_A in the range $10 \text{ W} \leq P_A \leq 1,000 \text{ W}$, or in another example $10 \text{ W} \leq P_A \leq 100 \text{ W}$, so that the temperature of surface of the wafer is raised from a pre-anneal temperature T_{PA} to an annealing temperature T_A during said scanning.

[0021] Another aspect of the disclosure is the system described above, wherein the pre-anneal temperature T_{PA} is in the range $200 \text{ }^\circ\text{C} \leq T_{PA} \leq 600 \text{ }^\circ\text{C}$.

[0022] Another aspect of the disclosure is the system described above, wherein the annealing temperature T_A is either in the range $1,100 \text{ }^\circ\text{C} \leq T_A \leq 1,350 \text{ }^\circ\text{C}$ or in the range $T_A \geq 1,410 \text{ }^\circ\text{C}$.

[0023] Another aspect of the disclosure is a system for performing laser spike annealing of a wafer having a surface. The system includes: a plurality of fiber laser systems that deliver respective output radiation beams that partially overlap at the surface of the wafer to form an annealing image; a pre-heat laser system that generates a pre-heat radiation beam that pre-heats a region of the surface of the wafer to a pre-anneal temperature T_{PA} ; a wafer support assembly that supports the wafer and that moves the wafer relative to the annealing image so that the annealing image scans over the surface of the wafer and at least partially within the pre-heat region with a dwell time of t_D in the range $100 \text{ ns} \leq t_D \leq 10 \text{ ms}$, or in another example $30 \text{ ns} \leq t_D \leq 10 \text{ ms}$, and wherein the annealing image has an amount of optical power P_A in the range $100 \text{ W} \leq P_A \leq 10,000 \text{ W}$, or in another example $100 \text{ W} \leq P_A \leq 1,000 \text{ W}$, so that the temperature of surface of the wafer is raised from the pre-anneal temperature T_{PA} to an annealing temperature T_A during said scanning.

[0024] Another aspect of the disclosure is the system described above, wherein the pre-anneal temperature T_{PA} is in the range $200 \text{ }^\circ\text{C} \leq T_{PA} \leq 600^\circ\text{C}$.

[0025] Another aspect of the disclosure is the system described above, wherein the annealing temperature T_A is either in the range $1,100\text{ }^{\circ}\text{C} \leq T_A \leq 1,350\text{ }^{\circ}\text{C}$ or in the range $T_A \geq 1,410\text{ }^{\circ}\text{C}$.

[0026] Another aspect of the disclosure is the system for performing laser spike annealing of a wafer having a surface. The system includes a plurality of fiber laser systems that deliver respective output radiation beams that partially overlap at the surface of the wafer to form a pre-annealing image that pre-heats a pre-heat region of the surface of the wafer to a pre-anneal temperature T_{PA} ; an annealing laser system that generates an annealing laser beam that at least partially overlaps the pre-heat region; a wafer support assembly that supports the wafer and that moves the wafer relative to the pre-annealing image so that the pre-annealing image scans over the surface of the wafer and at least partially within the pre-heat region with a dwell time of t_D in the range $30\text{ ns} \leq t_D \leq 10\text{ ms}$; and wherein the pre-annealing image has an amount of optical power P_A in the range $100\text{ W} \leq P_A \leq 10,000\text{ W}$ so that the temperature of surface of the wafer is raised from the pre-anneal temperature T_{PA} to an annealing temperature T_A during said scanning.

[0027] Another aspect of the disclosure is the system described above, wherein the pre-anneal temperature T_{PA} is in the range $200\text{ }^{\circ}\text{C} \leq T_{PA} \leq 600^{\circ}\text{C}$.

[0028] Another aspect of the disclosure is the system described above, wherein the annealing temperature T_A is either in the range $1,100\text{ }^{\circ}\text{C} \leq T_A \leq 1,350\text{ }^{\circ}\text{C}$ or in the range $T_A \geq 1,410\text{ }^{\circ}\text{C}$.

[0029] Additional features and advantages are set forth in the Detailed Description that follows, and in part will be readily apparent to those skilled in the art from the description or recognized by practicing the embodiments as described in the written description and claims hereof, as well as the appended drawings. It is to be understood that both the foregoing general description and the following Detailed Description are merely exemplary, and are intended to provide an overview or framework to understand the nature and character of the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0030] The accompanying drawings are included to provide a further understanding, and are incorporated in and constitute a part of this specification. The drawings illustrate one or more embodiment(s), and together with the Detailed Description serve to explain principles and operation of the various embodiments. As such, the disclosure will become more fully understood from the following Detailed Description, taken in conjunction with the accompanying Figures, in which:

[0031] FIG. 1 is a schematic diagram of an example laser spike annealing (LSA) system according to the disclosure and that can be used to carry out the methods disclosed herein;

[0032] FIG. 2 is a close-up view of an example LSA system showing an example of a fiber laser system;

[0033] FIG. 3 is a close-up view of an example modulator in the form of an acousto-optic modulator, which forms a standing acoustic-wave grating;

[0034] FIG. 4A is a close-up view of an example elongate image formed by the continuous-wave output radiation beam intersecting the surface of the wafer;

[0035] FIG. 4B is a plot of the intensity I (normalized units) as a function of position coordinate x/L for an example elongate image formed by a Gaussian intensity output radiation beam;

[0036] FIG. 5 is a top-down view of a surface of the wafer illustrating how multiple elongate images can be partially overlapped in the long direction (X-direction) to form a combined image referred to herein as an “annealing image”;

[0037] FIG. 6A is a plot of the intensity profile $I_A(x/L)$ of an annealing formed by combining seven elongate images using an offset $\Delta = L/2$;

[0038] FIGS. 6B and 6C are similar to FIG. 6A but for respective offsets $\Delta = 0.9 \cdot (L/2)$ and $\Delta = 0.79 \cdot (L/2)$;

[0039] FIG. 7A is a top-down view of a wafer that shows an example annealing image as made up of individual elongate images that overlap in the long direction, where the annealing image is scanned relative to the surface of the wafer in the direction indicated by arrow AR;

[0040] FIG. 7B is similar to FIG. 7A, but wherein the annealing image crosses a portion of the edge of the wafer and the endmost elongate image is turned off or reduced in intensity to avoid causing edge damage to the wafer;

[0041] FIGS. 7C and 7D are similar to FIG. 7B, and show the annealing image continuing to cross the edge of the wafer while the endmost elongate image is turned off or reduced in intensity, which reduces the size of the annealing image as it is scanned over the edge of the wafer;

[0042] FIG. 8A is similar to FIG. 2 and illustrates an example embodiment of the LSA system wherein a pre-heat laser system that generates a pre-heat radiation beam is used to pre-heat the surface of the wafer;

[0043] FIGS. 8B and 8C are top-down views of the surface of the wafer of FIG. 8A showing two examples of the pre-heat region and the annealing image, with FIG. 8B showing the annealing image entirely within the pre-heat region and FIG. 8C showing the annealing image partially within the pre-heat region;

[0044] FIG. 9A is a schematic diagram that illustrates an example LSA system wherein the laser system made up of fiber laser systems forms a pre-annealing image used to pre-heat surface of the wafer to form the pre-heated region, and a second laser system is used to form the annealing image; and

[0045] FIG. 9B is similar to FIG. 8B and shows the pre-heat region formed by the pre-annealing image, along with the annealing image formed by the second laser system of the example LSA system of FIG. 9A.

DETAILED DESCRIPTION

[0046] 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.

[0047] The claims as set forth below are incorporated into and constitute part of this Detailed Description.

[0048] Cartesian coordinates are shown in some of the Figures for the sake of reference and are not intended to be limiting as to direction or orientation.

[0049] FIG. 1 is a schematic diagram of an example laser spike annealing (LSA) system 10 according to the disclosure. The LSA system 10 includes a laser system 12 and a wafer support assembly 14. The wafer support assembly 14 includes a chuck 20 having a surface 22 that supports a semiconductor substrate ("wafer") 30 having a surface 32. In an example, the chuck 20 is configured to generate heat to heat the wafer 30 up to a pre-anneal temperature T_{PA} , e.g., in the range from 200 °C to 600 °C. The chuck 20 is shown as connected to a chuck controller 26 that is used to control the temperature of chuck 20.

[0050] The chuck 20 resides upon a movable stage 40. The movement of movable stage 40 is controlled by a stage controller 46 that is operably connected to the movable stage 40.

[0051] The laser system 12 includes one or more fiber laser systems 50. FIG. 2 is a close-up view of an example LSA system 10 showing an example of fiber laser system 50. Each fiber laser system 50 includes a fiber laser 52 having a length of fiber section 53. In an example, each fiber laser 52 emits initial radiation (initial radiation beam) 54 having a wavelength λ of about 2 μm , e.g., $1.8 \mu\text{m} \leq \lambda \leq 2.1 \mu\text{m}$. An example fiber laser 52 is a Thulium-based fiber laser, such as available from IPG Photonics Corp, Oxford, Massachusetts. In an example, between two and fifty fiber laser systems 50 can be used (i.e., 2, 3, 4...50 fiber laser systems 50), and in a more specific example, between three and six fiber laser systems 50 can be used (i.e., 3, 4, 5 or 6 fiber laser systems 50).

[0052] In an example, each fiber laser 52 operates in single mode, i.e., it generates a single-mode initial radiation beam 54. In an example, the initial radiation beam 54 has a power of up to about 200 W. In an example embodiment, the fiber lasers 52 are configured so that the wavelengths λ of adjacent fiber lasers 52 differ by a few nanometers to avoid speckle effects at the surface 32 of the wafer 30. In the example LSA system 10 of FIG. 1, some or all of fiber laser systems 50 are operably supported by a support member 55, e.g., a mounting plate, operably arranged relative to the wafer support assembly 14. In one example, the support member 55 is movable relative to the wafer support assembly 14,

while in another example it is stationary. In an example, the output power of each fiber laser 52 can be directly modulated via a laser controller, which in an example is schematically represented by a controller 90 introduced and discussed below.

[0053] Each fiber laser system 50 includes an optical system 60 that receives the initial radiation beam 54 and generates an output radiation beam 64. The output radiation beams 64 from the plurality of fiber laser systems 50 collectively form a combined output radiation beam 64C, as discussed below. In an example, the optical system 60 includes, in order from fiber section 53, a collimating lens 72, a (radiation) modulator 74, and a cylindrical optical system 80 (see FIG. 2) that in an example includes first and second cylindrical lenses 82 and 84 having respective optical powers in orthogonal planes. In an example embodiment illustrated in FIG. 1, the second cylindrical lens 84 is formed as a single element that is shared by some or all of the fiber laser systems 50.

[0054] The cylindrical optical system 80 serves to take a generally symmetric Gaussian collimated radiation beam 54C from the collimating lens 72 and expand it in one direction and then bring it to a focus in the orthogonal direction so that the resulting output radiation beam 64 forms an elongate image 102 on surface 32 of the wafer 30 (see FIG. 4A). The elongate image 102 has a long axis a_L . In an example, some or all of the elements that make up the optical system 60 are formed from fused silica.

[0055] The LSA system 10 also includes a controller 90 that in an example embodiment is operably connected to the wafer support assembly 14, and in particular to the chuck controller 26 and the stage controller 46 to control the heating of chuck 20 and the scanning movement of movable stage 40 as discussed below. In an example, the controller 90 is also connected to the laser system 12, and in particular to the fiber laser systems 50 to control the activation of fiber lasers 52 and to control the amount of power in the initial radiation beam 54, as discussed below. An example controller 90 comprises a computer. The controller 90 is generally programmable with instructions embodied in a computer-readable medium that cause the controller 90 to control the operation of LSA system 10. The controller 90 can comprise or otherwise include one or more computers, processors, microcontrollers, microcomputers, programmable logic controllers, application-specific integrated circuits and other programmable circuits.

[0056] In an example of the operation of LSA system 10, the controller 90 causes fiber lasers 52 to emit the initial radiation beam 54, which travels through the fiber section 53 and emerges from the fiber section 53 as a divergent beam. The divergent initial radiation beam 54 is received by the collimating lens 72, which serves to form the aforementioned collimated radiation beam 54C. The collimated radiation beam 54C is then received by the modulator 74. As mentioned above, the controller 90 can be used to modulate the output power of fiber lasers 52.

[0057] FIG. 3 is a close-up view of an example modulator 74 in the form of an acousto-optic modulator, which forms a standing acoustic-wave grating (“grating”) 76. The acoustic-wave grating 76 serves to diffract the collimated radiation beam 54C into a 0th-order radiation beam 54C0 and a 1st-order radiation beam 54C1. By adjusting the amplitude of the acoustic-wave grating 76, the amount of power in the 0th-order and 1st-order radiation beams 54C0 and 54C1 can be adjusted. In an example, the 1st-order radiation beam 54C1 continues to the cylindrical optical system 80 while the 0th-order radiation beam 54C0 is directed to a beam dump BD. The modulator 74 can be driven at high frequencies (e.g., in the MHz range) that are significantly shorter than the thermal diffusion time of silicon. This allows for using the modulator 74 to control the power in each output radiation beam 64 to compensate for any temperature gradients that occur in the surface 32 of the wafer 30.

[0058] In an example embodiment, the modulator 74 is not employed and the fiber laser 52 is modulated directly, e.g., via a laser controller, which as noted above can be the controller 90. This direct modulation approach of the fiber lasers 52 can be used especially when the velocity of movable stage 40 is slow enough to allow for modulation to be performed using feedback via the laser controller.

[0059] In an example embodiment of the operation of LSA system 10 as illustrated in FIG. 2, the wafer 30 to be processed is replaced by a measurement wafer 30M that is used to calibrate the power output of each fiber laser system 50. To perform the calibration, each fiber laser system 50 is activated to generate its corresponding output radiation beam 64. The measurement wafer 30M has a surface 32M configured to direct a select amount of output radiation beam 64 as measurement radiation 64M to a photodetector 120 arranged relative to the measurement wafer 30M.

[0060] For example, the surface 32M of measurement wafer 30M may have a select amount of surface roughness designed to cause a select or otherwise known amount of scattering of output radiation beam 64 when forming measurement radiation 64M. The calibration power measurements for the fiber laser systems 50 as performed by the photodetector 120 are embodied in photodetector signals SD provided to the controller 90. The controller 90 processes the photodetector signals SD and adjusts the respective modulators 74 accordingly (e.g., via a modulator control signal SM) so that each output radiation beam 64 delivers substantially the same amount of optical power or a select amount of power to the surface 32 of the wafer 30 to be processed. In another example, the modulator control signal SM is directed to the fiber lasers 52 so that the controller 90 acts a laser controller that controls the output power of each fiber laser 52.

[0061] In an example, the photodetector 120 comprises a multichannel pyrometer that can be used during the normal operation of LSA system 10 to control the power distribution in the combined output radiation beam 64C, as described below.

[0062] The 1st-order radiation beam 54C1 is received by the cylindrical optical system 80, which as discussed above forms the output radiation beam 64 that has an elongate direction and focused, narrower direction. The output radiation beams 64 from the fiber laser systems 50 are directed to the surface 32 of the wafer 30 in a manner that results in the formation of respective elongate images 102, wherein adjacent elongate images partially overlap.

[0063] FIG. 4A is a close-up view of an example elongate image 102 formed by the output radiation beam 64 intersecting the surface 32 of the wafer 30. The elongate image 102 has a width W in the narrow direction (Y-direction) and a length L in the elongate direction (X-direction) that defines the long axis a_L . In an example, with the width W and the length L are defined by a threshold intensity contour of a Gaussian intensity distribution that defines the elongate image 102. FIG. 4B is a plot of the intensity I (normalized units) as a function of position coordinate x/L for an example elongate image 102 formed by a Gaussian intensity output radiation beam 64 whose profile can be described by the equation

$$I(x) = \exp \{-2 \cdot (x/L)^2\},$$

In an example, the length L is defined by the $1/e^2$ intensity contour, as shown in FIG. 4B.

[0064] FIG. 5 is a top-down view of the surface 32 of the wafer 30 illustrating how multiple elongate images 102 can be partially overlapped in the long direction (X-direction) to form a combined image, referred to as annealing image 102A. The annealing image 102A has a long axis A_L , a length L_A (referred to as the “annealing length”) measured in the direction of the long axis A_L , and a width W_A measured in the direction perpendicular to the long axis A_L . The offset in the long direction between adjacent images is denoted Δ . The intensity profile $I_A(x)$ of annealing image 102A can be expressed as:

$$I_A(x) = \sum \exp \{ -2 \cdot [(x - \Delta \cdot n) / L]^2 \},$$

where n is a number parameter relating to the (integer) number of combined elongate images 102, and the offset Δ is measured relative to the center of the annealing image 102A. The annealing image 102A has an overall length L_A , which in an example is defined by the $1/e^2$ intensity contour of annealing image 102A. An example range on the length L_A is given by $3 \text{ mm} \leq L_A \leq 30 \text{ mm}$. An example range on the width W_A is $50 \text{ microns} \leq W_A \leq 500 \text{ microns}$ or in another example $25 \text{ microns} \leq W_A \leq 500 \text{ microns}$.

[0065] FIG. 6A is a plot of the intensity profile $I_A(x/L)$ of annealing image 102A formed by combining seven elongate images 102. The number parameter n ranges from -3 to +3 in the above expression for $I_A(x)$, and the offset $\Delta = L/2$.

[0066] FIGS. 6B and 6C are similar to FIG. 6A but for $\Delta = 0.9 \cdot (L/2)$ and $\Delta = 0.79 \cdot (L/2)$. As the value of the offset Δ gets smaller, the overall intensity of annealing image 102A increases and its overall length L_A decreases.

[0067] In an example embodiment, the annealing image 102A has an amount of optical power P_A in the range from $100 \text{ W} \leq P_A \leq 10,000 \text{ W}$ or in another example, $100 \text{ W} \leq P_A \leq 1,000 \text{ W}$.

[0068] In an example, the uniformity of annealing image 102A is judged by thermal emission E from the wafer 30, which is very sensitive to the variation of the temperature, which in turn is proportional to the power density: $\delta(E)/E \approx (10^{-\alpha}) \cdot \delta(T)/T$, where $11 < \alpha < 15$. An acceptable uniformity of the intensity profile is therefore given by substantially uniform distribution in the flat portion of the intensity profile. Usually, the existence of visible modulations in intensity leads to unacceptable variations of the temperature of the wafer 30. Of the intensity profiles $I_A(x)$ of annealing image 102A shown in FIGS. 6A through 6C, the

intensity profile of FIG. 6C has acceptable uniformity while those of FIGS. 6A and 6B do not for most annealing applications. Thus, in an example, the offset $\Delta \leq 0.79 \cdot (L/2)$ is used to obtain a suitably uniform intensity profile and thus substantially uniform wafer heating.

[0069] Once the annealing image 102A is formed, it is scanned over surface 32 of the wafer 30 to perform laser spike annealing of the surface 32 of the wafer 30, e.g., to enhance dopant diffusion in semiconductor devices (not shown) supported by the wafer 30. The scanning of annealing image 102A is accomplished in one example embodiment by the controller 90 directing the stage controller 46 to move the movable stage 40 so that surface 32 of the wafer 30 moves relative to the annealing image 102A. The movement of the wafer 30 is performed such that the dwell time t_D of the annealing image 102A at a given point on the surface 32 of the wafer 30 that is scanned is in the range $30 \text{ ns} \leq t_D \leq 10 \text{ ms}$ or in another example $100 \text{ ns} \leq t_D \leq 10 \text{ ms}$.

[0070] FIG. 7A is a top-down view of the wafer 30 and the surface 32 of the wafer 30, along with an edge 34 of the wafer 30, and shows the annealing image 102A as made up of the individual elongate images 102 that overlap in the long direction. FIG. 7A also shows the direction of movement of the annealing image 102A relative to the surface 32 of the wafer 30, as indicated by arrow AR. The annealing image 102A moves (scans) in a direction perpendicular to its long axis A_L , i.e., moves in the Y-direction when its long axis is in the X-direction, as shown in FIG. 7A.

[0071] An advantage of forming the annealing image 102A from multiple elongate images 102 is that the annealing image 102A can be tailored or otherwise adjusted by changing the individual elongate images 102. This adjustment can be performed even during scanning of the annealing image 102A. FIG. 7B is similar to FIG. 7A and illustrates an example where one edge 103E of the annealing image 102A crosses over the edge 34 of the wafer 30. To avoid causing damage to the edge 34 of the wafer 30 from the power in the annealing image 102A, the endmost elongate image 102 (denoted 102E) is turned off or is reduced in power or intensity so that the annealing image 102A does not irradiate the edge 34 of the wafer 30 (or does not irradiate the edge 34 of the wafer 30 with substantial power or intensity). This process of turning off or reducing the power or intensity in the endmost elongate image 102E can continue, as illustrated in FIGS. 7C and 7D as the annealing image 102A continues over its scan path and continues to cross over the edge 34 of the wafer 30.

Ultimately, there is only one elongate image 102 left that makes up the annealing image 102A.

[0072] FIG. 8A is similar to FIG. 2 and illustrates an example embodiment of LSA system 10 wherein a pre-heat laser system 200 that generates a pre-heat radiation beam 202 is used to pre-heat the surface 32 of the wafer 30. As illustrated in the close-up view of FIG. 8B, the pre-heat radiation beam 202 serves to create a pre-heated region 202R on the surface 32 of the wafer 30, which serves to increase the absorption of output radiation beam 64 at the surface 32 of the wafer 30. In an example, the pre-heat (pre-anneal) temperature T_{PA} of pre-heated region 202R is in the range from 200 °C to 600 °C. The annealing image 102A, which resides at least partially within the pre-heated region 202R, then brings the temperature of surface 32 of the wafer 30 up from the pre-anneal temperature T_{PA} to an annealing temperature T_A , which in an example is in the range from 1,100 to 1,350 °C for a non-melt annealing process and is greater than the melting temperature of doped silicon (e.g., about 1,410 °C) for a melt annealing process.

[0073] In the example of FIG. 8B, the pre-heated region 202R moves along with the annealing image 102A, as indicated by arrows AR1 and AR2. Examples of performing laser annealing using a pre-heat radiation beam 202 are disclosed in U.S. Pre-Grant Publication No. US2012/0111838 (the '838 publication). FIG. 8C shows an example similar to FIG. 8B but wherein the edges 103E of anneal image 102A lie outside the pre-heated region 202R. The arrangement of FIG. 8C provides a way of avoiding annealing with intensity non-uniformities or gradual intensity drop-offs that might arise at or near the edges 103E of annealing image 102A.

[0074] An aspect of the disclosure is the use of annealing image 102A to pre-heat surface 32 of the wafer 30 and to perform LSA using another annealing beam in a manner similar to that shown in FIGS. 8A and 8B and as described in the '838 publication. FIG. 9A is a schematic diagram that illustrates an example LSA system 10 that includes the laser system 12 that forms the annealing image 102A, which is now used to pre-heat the surface 32 of the wafer 30 to form the pre-heated region 202R. In this capacity, the annealing image 102A is referred to as pre-annealing image 102PA. The LSA system 10 of FIG. 9A also includes a second laser system 312 that generates an annealing laser beam 364 that forms an annealing image 402A on the surface 32 of the wafer 30, as shown in the tow-down

close-up view of FIG. 9B. The annealing laser beam 364 can be a continuous-wave (CW) laser beam or a pulsed laser beam.

The annealing laser beam 364, which resides at least partially within the pre-heated region 202R, serves to bring the surface 32 of the wafer 30 from the pre-anneal temperature T_{PA} up to an annealing temperature T_A , which in an example is in the range from 1,100 °C to 1,350 °C (i.e., $1,100\text{ °C} \leq T_A \leq 1,350\text{ °C}$) for a non-melt annealing process and is greater than the melting temperature of doped silicon (e.g., about 1,410 °C) for a melt annealing process. In another example, $1,100\text{ °C} \leq T_A \leq 1,300\text{ °C}$.

[0075] The various embodiments of LSA system 10 disclosed herein have a number of advantages. One advantage is that the fiber lasers 52 are tunable so that the wavelength λ of adjacent fiber lasers 52 can be detuned from one another by a few nanometers. This property can be used to make their initial radiation beams 54 substantially incoherent relative to one another to avoid adverse coherent-light effects, such as speckle that forms from reflection from the surface 32 of the wafer 30. Another advantage is that the fiber lasers 52 have high reliability, high efficiency, low cost and take up less room than other types of lasers. Also, because the fiber lasers 52 operate in single mode, the initial output beam 54 has a relatively clean Gaussian profile and so can be processed using a simple optical system 60. This in turn allows for a reasonably high optical system throughput, e.g., about 70%. Consequently, a 200 W initial radiation beam 54 can result in an output radiation beam 64 that delivers 140 W to the surface 32 of the wafer 30.

[0076] In addition, the output wavelength λ of nominally (i.e., about) 2 μm is substantially larger than the size of features on the surface 32 of the wafer 30, so that adverse wafer pattern effects that can cause heating uniformity are mitigated. Also, the 2 μm output wavelength λ of the fiber lasers 52 and the tunability of this output wavelength λ allows for LSA system 10 to be tuned to avoid select absorption bands of process gasses that may reside adjacent surface 32 of the wafer 30. For example, ammonia has a strong absorption band right around 2 μm , and the fiber laser wavelength λ can be tuned slightly away from this absorption band wavelength.

[0077] It will be apparent to those skilled in the art that various modifications to the preferred embodiments of the disclosure as described herein can be made without

departing from the spirit or scope of the disclosure as defined in the appended claims.

Thus, the disclosure covers the modifications and variations provided they come within the scope of the appended claims and the equivalents thereto.

What is claimed is:

1. A method of performing laser spike annealing of a surface of a wafer, comprising:

generating with a plurality of fiber laser systems respective continuous-wave (CW) output radiation beams that form elongate images that partially overlap end-to-end at the surface of the wafer to form an elongate annealing image having a long axis and a length L_A along the long axis, wherein each elongate image has a Gaussian intensity profile with a length L as measured along the long axis and defined by a $1/e^2$ intensity contour, and wherein the partial overlap between adjacent elongate images is defined by a center-to-center offset $\Delta \leq 0.79 \cdot (L/2)$;

heating at least a region of the wafer to a pre-anneal temperature T_{PA} to define a pre-heat region; and

scanning the elongate annealing image over the surface of the wafer and at least partially within the pre-heat region in a direction substantially perpendicular to the long axis so that the elongate annealing image has a dwell time t_D in the range $30 \text{ ns} \leq t_D \leq 10 \text{ ms}$ and raises the temperature of surface of the wafer to an annealing temperature T_A .

2. The method according to claim 1, wherein the length L_A is in the range $3 \text{ mm} \leq L_A \leq 450 \text{ mm}$.

3. The method according to claim 1, wherein the elongate annealing image has width W_A measured perpendicular to the long axis, and wherein $25 \text{ microns} \leq W_A \leq 500 \text{ microns}$.

4. The method according to claim 1, wherein the CW output radiation beam has an amount of optical power P_A in the range $100 \text{ W} \leq P_A \leq 10,000 \text{ W}$.

5. The method according to claim 1, wherein the pre-anneal temperature T_{PA} is in the range $200^\circ\text{C} \leq T_{PA} \leq 600^\circ\text{C}$.

6. The method of claim 5, wherein the anneal temperature T_A is either in the range $1,100\text{ }^{\circ}\text{C} \leq T_A \leq 1,350\text{ }^{\circ}\text{C}$ or in the range $T_A \geq 1,410\text{ }^{\circ}\text{C}$.
7. The method according to claim 1 further comprising:
measuring a temperature distribution at the surface of the wafer; and
adjusting an amount of power in at least one of the CW output radiation beams to improve an amount of uniformity in the temperature distribution.
8. The method according to claim 1, wherein the wafer has an edge, the elongate annealing image has an end-most elongate image, and further comprising either reducing an amount of power in or turning off the CW output radiation beam that forms the end-most elongate annealing image prior to the end-most elongate image of the annealing image passing over the edge of the wafer.
9. The method according to claim 1, wherein the elongate images of the elongate annealing image are formed by between three and fifty CW output radiation beams.
10. A method of optimizing an amount of uniformity of an annealing image using a measurement wafer having a surface, comprising:
generating with a plurality of fiber laser systems respective continuous-wave (CW) output radiation beams that form respective elongate images that partially overlap end-to-end at the surface of the measurement wafer to form an elongate annealing image having a long axis and a length L_A along the long axis, wherein each elongate image has a Gaussian intensity profile with a length L as measured along the long axis and defined by a $1/e^2$ intensity contour, and wherein the partial overlap between adjacent elongate images is defined by a center-to-center offset $\Delta \leq 0.79 \cdot (L/2)$;
detecting an amount of optical power reflected from the measurement wafer for each of the CW output radiation beams; and

adjusting an amount of optical power in one or more of the CW output radiation beams to optimize an amount of uniformity of the elongate annealing image.

11. A method of performing laser spike annealing of a surface of a wafer, comprising:

generating with a plurality of fiber laser systems respective continuous-wave (CW) output radiation beams that form respective elongate beams that partially overlap end-to-end at the surface of the wafer to form an elongate pre-annealing image having a long axis and a length L_A along the long axis, each elongate image has a Gaussian intensity profile with a length L as measured along the long axis and defined by a $1/e^2$ intensity contour, and wherein the partial overlap between adjacent elongate images is defined by a center-to-center offset $\Delta \leq 0.79 \cdot (L/2)$;

heating at least a region of the wafer with the elongate pre-annealing image to a pre-anneal temperature T_{PA} to define a pre-heat region; and

scanning a second laser beam that resides at least partially within the pre-heat region to raise the temperature of surface of the wafer to an annealing temperature T_A .

12. The method according to claim 11, wherein the annealing temperature T_A is in the range $1,100\text{ }^\circ\text{C} \leq T_A \leq 1,350\text{ }^\circ\text{C}$.

13. The method according to claim 11, wherein the annealing temperature T_A is greater than the melt temperature of doped silicon.

14. A system for performing laser spike annealing of a wafer having a surface, comprising:

a plurality of fiber laser systems that deliver respective output radiation beams that form respective images that partially overlap end-to-end at the surface of the wafer to form an annealing image, wherein each elongate image has a Gaussian intensity profile with a length L as measured along the long axis and

defined by a $1/e^2$ intensity contour, and wherein the partial overlap between adjacent elongate images is defined by a center-to-center offset $\Delta \leq 0.79 \cdot (L/2)$;

a wafer support assembly that supports the wafer and heats the wafer to a pre-anneal temperature T_{PA} and that moves the wafer relative to the annealing image so that the annealing image scans over the surface of the wafer with a dwell time of t_D in the range $30 \text{ ns} \leq t_D \leq 10 \text{ ms}$; and

wherein the annealing image has an amount of optical power P_A in the range $10 \text{ W} \leq P_A \leq 1,000 \text{ W}$ so that the temperature of surface of the wafer is raised from a pre-anneal temperature T_{PA} to an annealing temperature T_A during said scanning.

15. The system according to claim 14, wherein the pre-anneal temperature T_{PA} is in the range $200^\circ\text{C} \leq T_{PA} \leq 600^\circ\text{C}$.

16. The system according to claim 14, wherein the annealing temperature T_A is either in the range $1,100^\circ\text{C} \leq T_A \leq 1,350^\circ\text{C}$ or in the range $T_A \geq 1,410^\circ\text{C}$.

17. A system for performing laser spike annealing of a wafer having a surface, comprising:

a plurality of fiber laser systems that deliver respective output radiation beams that form respective elongate images that partially overlap end-to-end at the surface of the wafer to form an annealing image, wherein each elongate image has a Gaussian intensity profile with a length L as measured along the long axis and defined by a $1/e^2$ intensity contour, and wherein the partial overlap between adjacent elongate images is defined by a center-to-center offset $\Delta \leq 0.79 \cdot (L/2)$;

a pre-heat laser system that generates a pre-heat radiation beam that pre-heats a region of the surface of the wafer to a pre-anneal temperature T_{PA} ;

a wafer support assembly that supports the wafer and that moves the wafer relative to the annealing image so that the annealing image scans over the surface of the wafer and at least partially within the pre-heat region with a dwell time of t_D in the range $30 \text{ ns} \leq t_D \leq 10 \text{ ms}$; and

wherein the annealing image has an amount of optical power P_A in the range $100\text{ W} \leq P_A \leq 10,000\text{ W}$ so that the temperature of surface of the wafer is raised from the pre-anneal temperature T_{PA} to an annealing temperature T_A during said scanning.

18. The system according to claim 17, wherein the pre-anneal temperature T_{PA} is in the range $200\text{ }^\circ\text{C} \leq T_{PA} \leq 600\text{ }^\circ\text{C}$.

19. The system according to claim 17, wherein the annealing temperature T_A is either in the range $1,100\text{ }^\circ\text{C} \leq T_A \leq 1,350\text{ }^\circ\text{C}$ or in the range $T_A \geq 1,410\text{ }^\circ\text{C}$.

20. A system for performing laser spike annealing of a wafer having a surface, comprising:

a plurality of fiber laser systems that deliver respective output radiation beams that form elongate images that partially overlap end-to-end at the surface of the wafer to form a pre-annealing image that pre-heats a pre-heat region of the surface of the wafer to a pre-anneal temperature T_{PA} , wherein each elongate image has a Gaussian intensity profile with a length L as measured along the long axis and defined by a $1/e^2$ intensity contour, and wherein the partial overlap between adjacent elongate images is defined by a center-to-center offset $\Delta \leq 0.79 \cdot (L/2)$;

an annealing laser system that generates an annealing laser beam that at least partially overlaps the pre-heat region;

a wafer support assembly that supports the wafer and that moves the wafer relative to the pre-annealing image so that the pre-annealing image scans over the surface of the wafer and at least partially within the pre-heat region with a dwell time of t_D in the range $30\text{ ns} \leq t_D \leq 10\text{ ms}$; and

wherein the pre-annealing image has an amount of optical power P_A in the range $100\text{ W} \leq P_A \leq 10,000\text{ W}$ so that the temperature of surface of the wafer is raised from the pre-anneal temperature T_{PA} to an annealing temperature T_A during said scanning.

21. The system according to claim 20, wherein the pre-anneal temperature T_{PA} is in the range $200\text{ }^{\circ}\text{C} \leq T_{PA} \leq 600\text{ }^{\circ}\text{C}$.

22. The system according to claim 20, wherein the annealing temperature T_A is either in the range $1,100\text{ }^{\circ}\text{C} \leq T_A \leq 1,350\text{ }^{\circ}\text{C}$ or in the range $T_A \geq 1,410\text{ }^{\circ}\text{C}$.