through a beam-redirecting element that is activated in synchrony with the laser source, wherein $p_s \leq \delta$; and forming from the deflected light beam a line image at an image plane.

[0024] Another aspect of the disclosure is the method described above, wherein $\delta \leq 100$ μm.

[0025] Another aspect of the disclosure is the method described above, wherein forming the line image includes passing the deflected light beam through a knife-edge aperture while imaging the knife-edge aperture onto the image plane with a relay optical system.

[0026] Another aspect of the disclosure is the method described above, wherein the micro-scale intensity variations have RMS value, and wherein the RMS value of the micro-scale intensity variations in the deflected light beam as measured at the knife-edge aperture is decreased by at least a factor of between 1.5X and 5X as compared to an undeflected laser beam as measured at the knife-edge aperture.

[0027] Another aspect of the disclosure is the method described above, wherein the light pulses have a repetition rate of f_{rep}, and wherein imparting the time-varying spatial deflection δ includes driving the beam-redirecting element at a repetition rate f_{a_rep} that is equal to or a harmonic of the repetition rate of the light pulses.

[0028] Another aspect of the disclosure is the method described above, wherein the beam-redirecting element is either acoustic-based or electro-optic based.

[0029] Another aspect of the disclosure is a method of reducing micro-scale intensity variations when performing laser annealing of a semiconductor wafer with a line image. The method includes: directing along an optical axis a first laser beam having light pulses and first micro-scale intensity variations; imparting to each light pulse in the first laser beam a time-varying angular deflection relative to the optical axis, thereby smearing out each light pulse over an amount of spatial deflection δ to form a second laser beam having second micro-scale intensity variations that are less than the first micro-scale intensity variations; and using the second laser beam to form the line image.

[0030] Another aspect of the disclosure is the method as described above, wherein the first micro-scale intensity variations have a root-mean square (RMS) value, and wherein the RMS value of the micro-scale intensity variations in the second laser beam is decreased by at least a factor of between 1.5X and 5X as compared to the first laser beam.

[0089] FIG. 8 is a plot of the simulated peak-to-valley modulation M (normalized to the modulation value with no rotation) as a function of rotation angle φ (degrees) for such hypothetical distribution. There is drastic reduction in the simulated peak-to-valley modulation M with rotation as compared to no rotation. Thus, in an example embodiment, the laser annealing system 10 includes a single beam-redirecting element 30 that is rotated about the optical axis A1 by a rotation angle φ, which in an example is optimized to minimize the simulated peak-to-valley modulation M, which is one way to characterize the micro-scale intensity variations.

[0090] FIG. 9 is a plot of intensity counts (normalized to the average) versus position (mm) for experimental results obtained for an example laser annealing system 10 according to FIG. 2 for both a deflected laser beam (i.e., deflected light pulses) and a non-deflected laser beam (i.e., non-deflected light pulses). The data for the deflected laser beam is offset by 1 from the no-deflection data for ease of illustration. The AOD beam-redirecting element 30 was an AOM. The AOD(AOM) repetition rate (frequency) f_{a_rep} and the laser pulse frequency f_{rep} were both 10kHz. The AOD(AOM) bandwidth Δf_a was about 100 MHz. The other system parameters used were similar to those used in connection with the plot of FIG. 6. The intensity counts were taken from a cross-section of the beam profile image captured by a high-resolution CMOS image sensor placed at the image plane IP. The lighter portions of the beam profile image correspond to the non-deflected beam while the darker portions correspond to the deflected beam.

[0091] The data show about a 3X reduction in beam intensity modulation. The actual modulation reduction depends on the nature of the interference pattern. As discussed above, a typical interference pattern involves intensity modulation with different spatial periodicities. In general, the reduction will be most effective for the micro-scale intensity variations with periodicities $p_s < \delta$ and less effective for the micro-scale intensity variations with periodicities $p_s > \delta$. As discussed above, a typical modulation reduction in the micro-scale intensity variations is 1.5X or greater, e.g., 2X to 5X. For the non-deflected beam profile shown in FIG.. 9, model calculations predict a reduction of about 3X in modulation using spatial deflection δ, which consistent with experimental results.

[0092] 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

What is claimed is:

1. A method of reducing micro-scale intensity variations when forming a line image used to perform laser annealing of a semiconductor substrate, comprising:

a) directing a laser beam along an optical axis, wherein the laser beam has a wavelength λ and includes light pulses having a temporal pulse length τ in the range from 10 nanoseconds to 10 microseconds;

b) imparting to each light pulse a varying angular deflection relative to the optical axis to cause each light pulse to be smeared out over an amount of spatial deflection δ sufficient to reduce the micro-scale intensity variations in the laser beam by a factor of at least 1.5X root-mean square (RMS) as compared to no angular deflection, and wherein $\delta \leq$ 100 microns; and

c) using the laser beam formed in act b) to form the line image.

2. The method according to claim 1, wherein act b) of imparting the varying angular deflection includes either passing the laser beam through or reflecting the laser beam off of a beam-redirecting element.

3. The method according to claim 2, wherein the beam-redirecting element includes either an acousto-optic modulator or an electro-optic modulator.

4. The method according to claim 1, wherein the micro-scale intensity variations have a modulation period p_s in the range $\lambda/4 \leq p_s \leq 40\lambda$, and wherein $\delta \geq p_s$.

5. The method according to claim 4, wherein the micro-scale intensity variations have a modulation period p_s in the range $\lambda/2 \leq p_s \leq 20\lambda$.

6. The method according claim 1, further comprising performing beam conditioning of the laser beam either before or after imparting the varying angular deflection to the light pulses in the laser beam.

7. The method according to claim 1, wherein forming the line image includes passing a deflected laser beam through a relay optical system.

8. The method according to claim 1, wherein the micro-scale intensity variations occur in two orthogonal directions, and wherein act b) is performed using a beam-redirecting element that is oriented at an angle relative to the optical axis such that the micro-scale intensity variations are reduced in the two orthogonal directions.

9. A laser annealing system for annealing a surface of a semiconductor substrate with a line image formed by a laser beam, comprising:

a laser system that emits a laser beam having light pulses, with each light pulse having a wavelength λ and a temporal width τ, and wherein the laser beam includes an intensity profile having a first amount of micro-scale intensity variations with a modulation period p_s in the range from $\lambda/4$ to 40λ;

a beam-redirecting element arranged to receive the light pulses and for each light pulse causes a time-varying amount of spatial deflection δ of the laser beam, wherein $p_s \leq \delta \leq 100$ μm, thereby forming a deflected light beam with a second amount of micro-scale intensity variations that is less than the first amount of micro-scale intensity variations;

a relay optical system configured to receive the deflected light beam and form therefrom the line image at an image plane where the surface of the semiconductor substrate resides; and

a controller operably connected to the beam-redirecting element and to the laser system, the controller configured to synchronize the emission of the light pulses from the laser system with the operation of the beam-redirecting element to perform said time-varying amount of spatial deflection δ for each light pulse.

10. The laser annealing system according to claim 9, wherein the beam-redirecting element includes an acousto-optic deflector or an electro-optic deflector.

11. The laser annealing system according to claim 9 wherein the micro-scale intensity variations of the first amount has a modulation period p_s in the range $\lambda/2 \leq p_s \leq 20\lambda$.

12. The laser annealing system according to claim 9, wherein the relay optical system has a 1:1 magnification.

13. The laser annealing system according to claim 9, wherein $\lambda = 532$ nm.

14. The laser annealing system according to claim 9, further comprising a knife-edge aperture through which the deflected light beam passes and that defines a length of the line image.

15. The laser annealing system according to claim 9, wherein the second amount of micro-scale intensity variations is less than the first amount of micro-scale intensity variations by a factor of at least 1.5X root-mean square (RMS).

16. A method of reducing micro-scale intensity variations in a laser beam used for laser annealing of a semiconductor wafer, comprising:

generating from a laser source a laser beam having a wavelength λ and including light pulses, wherein the laser beam has an amount of the micro-scale intensity variations with a modulation period p_s between $\lambda/4$ and 40λ;

imparting a time-varying spatial deflection δ to each light pulse to form a deflected light beam by passing each light pulse through a beam-redirecting element that is activated in synchrony with the laser source, wherein $p_s \leq \delta$; and

forming from the deflected light beam a line image at an image plane.

17. The method according to claim 16, wherein $\delta \leq 100$ μm.

18. The method according to claim 16, wherein forming the line image includes passing the deflected light beam through a knife-edge aperture while imaging the knife-edge aperture onto the image plane with a relay optical system.

19. The method according to claim 18, wherein the micro-scale intensity variations have a root-mean square (RMS) value, and wherein the RMS value of the micro-scale intensity variations in the deflected light beam as measured at the knife-edge aperture is decreased

by at least a factor of between 1.5X and 5X as compared to an undeflected laser beam as measured at the knife-edge aperture.

20. The method according to claim 16, wherein the light pulses have a repetition rate of f_{rep}, and wherein imparting the time-varying spatial deflection δ includes driving the beam-redirecting element at a repetition rate f_{a_rep} that is equal to or a harmonic of the repetition rate of the light pulses.

21. The method according to claim 16, wherein the beam-redirecting element is either acoustic-based or electro-optic based.

22. A method of reducing micro-scale intensity variations when performing laser annealing of a semiconductor wafer with a line image, comprising:

directing along an optical axis a first laser beam having light pulses and first micro-scale intensity variations;

imparting to each light pulse in the first laser beam a time-varying angular deflection relative to the optical axis, thereby smearing out each light pulse over an amount of spatial deflection δ to form a second laser beam having second micro-scale intensity variations that are less than the first micro-scale intensity variations; and

using the second laser beam to form the line image.

23. The method according to claim 22, wherein the first micro-scale intensity variations have a root-mean square (RMS) value, and wherein the RMS value of the micro-scale intensity variations in the second laser beam is decreased by at least a factor of between 1.5X and 5X as compared to the first laser beam.

24. The method according to claim 22, wherein the first micro-scale intensity variations have a modulation period p_s, and wherein $p_s \leq \delta$.

25. The method according to claim 24, wherein the first laser beam has a wavelength λ and $\lambda/4 \leq p_s \leq 40\lambda$.

26. The method according to claim 22, wherein $\delta \leq 100$ µm.

27. The method according to claim 1, wherein act b) of imparting the varying angular deflection includes passing the laser beam through a beam-redirecting element including an acousto-optic modulator, the acousto-optic modulator having a driver including voltage controlled oscillator and a radio-frequency amplifier, wherein the laser beam is deflected by the acousto-optic modulator by a deflection angle $\Delta\theta a = \lambda \cdot \Delta fa/Va$, where Δfa is the radio-frequency modulation bandwidth of the radio-frequency amplifier, and Va is the acoustic velocity of the acousto-optic modulator, wherein the deflection angle $\Delta\theta a$ is thus proportional to the radio- frequency frequency modulation, which in turn is proportional to the variation of the input voltage of the voltage controlled oscillator embodied by a control signal from a controller.

28. The method according to claim 16, wherein beam conditioning of the laser beam is performed before imparting the time-varying spatial deflection to the each light pulses in the laser beam.