

METHOD AND SYSTEM FOR LASER PROCESSING A SEMICONDUCTOR SUBSTRATE

FIELD

[0001] The improvements generally relate to semiconductor substrate manufacturing and more specifically in the laser dicing of such semiconductor substrates.

BACKGROUND

[0002] A number of different semiconductor substrate dicing techniques exist in the art. Examples of such techniques include, but are not limited to, conventional saw dicing, laser dicing and the like. For example, saw dicing involves a rotating saw cutting a semiconductor substrate into desired substrate portions. It is known that saw dicing is often times preferable in situations where the semiconductor substrates are thicker. However, saw dicing's speed is generally limited to 250 mm/s, unless the quality of the cuts can be considerably affected. Moreover, laser dicing involves the irradiation of a narrowly focused laser beam along a given substrate path which weakens a region within the semiconductor substrate. The semiconductor substrate can then be broken or otherwise separated along the weakened region to form the desired substrate portions. Laser dicing is therefore an interesting option when greater dicing speeds are sought after. For thin substrates, only one pass of the laser beam may be enough to create a sufficiently weakened path whereas many subsequent passes may be required to form a weakened path for thicker substrates. In multi-pass dicing, it is known that the shallower passes aren't as challenging as the deeper passes since whenever the laser beam is focused at a bottom of the semiconductor substrate during a deep pass, a larger area of the substrate is exposed to the laser beam near a top surface of the semiconductor substrate. Such a large exposure area in turn causes the resulting cut to be larger in width, which can increase material loss and reduce overall throughput. In the meantime, the laser beam can also be clipped by some components in the substrate resulting in less energy being deposited into the focal region for dicing. As such, laser dicing can be found impractical or too slow for semiconductor substrates having thicknesses over 200 μm . Although existing semiconductor substrate dicing techniques are satisfactory to a certain degree, there still remains room for improvement.

SUMMARY

[0003] The existing laser dicing techniques typically involve the use of commonly available laser sources operating in the near-infrared region of the electromagnetic spectrum, and especially in the 800 nm to 1.5 μm range. However, it was found that in these regions of the electromagnetic spectrum, e.g., where the laser wavelengths are below or close to a bandgap wavelength of the semiconductor substrate, which can favor direct single photon absorption, self-limiting light-matter mechanisms typically impart an upper limit on the power of the laser beam. For instance, in applications where a Nd:YAG laser operating at 1064 nm was used to dice silicon, saturation was observed at as low as 1.5 W of laser average power. In some situations, using a laser power exceeding that limit can cause pre-focal plasma shielding and/or self-limiting effects preventing the laser beam to propagate passed a given depth within the semiconductor substrate. Additionally or alternately, using a saturating laser power can cause undesirable cracks to propagate around the weakened path and in turn increase its width. As the laser power is limited for a desired path width, the speed at which the passes can be performed is also limited. A solution to these challenges was found by exploring an unconventional pulsed laser source operating deeper in the infrared region of the electromagnetic spectrum, for instance from a wavelength greater than a bandgap wavelength of the semiconductor substrate and more specifically of 2.4 μm or more. At these greater wavelengths, it was found the impact of the undesirable self-limiting light-matter mechanisms described is greatly reduced, e.g., due to multiphoton absorption and multiple light-matter mechanisms scaling favorably with higher wavelength, thereby enabling laser dicing at greater speeds for thicker semiconductor substrates since modification length can be created with a more elongated profile and the laser power saturation threshold can be considerably increased.

[0004] In accordance with a first aspect of the present disclosure, there is provided a method for processing a semiconductor substrate, the semiconductor substrate having a bandgap wavelength, the method comprising: irradiating the semiconductor substrate with a mid-infrared pulsed laser beam, the mid-infrared pulsed laser beam having a central wavelength greater than the bandgap wavelength of the semiconductor substrate, the central wavelength of the mid-infrared pulsed laser beam being of 2.4 μm or greater, said irradiating including performing a relative movement between a focal point of the mid-infrared pulsed laser beam

and the semiconductor substrate, the movement causing the focal point of the mid-infrared pulsed laser beam to move along a path extending within the semiconductor substrate and forming a weakened region along the path, the semiconductor substrate separable into substrate portions upon exertion of a separating force on the semiconductor substrate.

[0005] Further in accordance with the first aspect of the present disclosure, the central wavelength can for example range between 2.4 μm and 5 μm .

[0006] Still further in accordance with the first aspect of the present disclosure, the central wavelength can for example be within 2.7 μm to 3.0 μm .

[0007] Still further in accordance with the first aspect of the present disclosure, the semiconductor substrate can for example be a monocrystalline silicon substrate.

[0008] Still further in accordance with the first aspect of the present disclosure, said irradiating can for example include a single pass of the focal point along the path, the single pass forming the weakened region.

[0009] Still further in accordance with the first aspect of the present disclosure, the mid-infrared pulsed laser beam can for example have a power of about 0.75 W or greater.

[0010] Still further in accordance with the first aspect of the present disclosure, the semiconductor substrate can for example be a silicon substrate.

[0011] Still further in accordance with the first aspect of the present disclosure, the semiconductor substrate can for example have a thickness ranging between about 200 and 1000 μm .

[0012] Still further in accordance with the first aspect of the present disclosure, the relative movement can for example be performed at an effective linear speed ranging between 10 and 45 mm/s.

[0013] Still further in accordance with the first aspect of the present disclosure, said irradiating can for example include more than one pass of the mid-infrared pulsed laser beam along the path to form the weakened region.

[0014] Still further in accordance with the first aspect of the present disclosure, said semiconductor substrate can for example have a first surface, a second surface opposite the first surface, and a thickness extending between the first surface and the second surface, said irradiating can for example be performed through the first surface.

[0015] Still further in accordance with the first aspect of the present disclosure, said irradiating can for example include one or more passes of the mid-infrared pulsed laser beam along the path to form the weakened region, in which a deepest one of the one or more passes can for example have a depth corresponding to about 75% of a thickness of the semiconductor substrate, preferably about 60% of the thickness of the semiconductor substrate, and most preferably about 50% of the thickness of the semiconductor substrate.

[0016] Still further in accordance with the first aspect of the present disclosure, the weakened region can for example have a first dimension extending along a plane of the semiconductor substrate and a second dimension extending perpendicularly to the plane of the semiconductor substrate, the second dimension ranging between 200 μm and 500 μm .

[0017] Still further in accordance with the first aspect of the present disclosure, the first dimension can for example be below 50 μm , preferably below 40 μm and most preferably below 30 μm .

[0018] Still further in accordance with the first aspect of the present disclosure, during the relative movement, a focal point of the mid-infrared pulsed laser beam can for example be located at a given depth from a surface of the semiconductor substrate, the given depth ranging between 200 μm and 500 μm .

[0019] Still further in accordance with the first aspect of the present disclosure, the method can for example further comprise applying the separating force to the semiconductor substrate, the semiconductor substrate separating into the substrate portions upon said applying, the substrate portions having a separation interface having at least one of a peak-to-peak roughness of about 30 μm or below and an RMS roughness of about 5 μm or below.

[0020] Still further in accordance with the first aspect of the present disclosure, the mid-infrared pulsed laser beam can for example include laser pulses having pulse durations in a nanosecond range.

[0021] Still further in accordance with the first aspect of the present disclosure, the mid-infrared pulsed laser beam can for example have laser pulses of pulse widths a picosecond range.

[0022] Still further in accordance with the first aspect of the present disclosure, the weakened region can for example be formed at a linear effective speed exceeding 40 mm/s, the linear effective speed defined as a total distance traveled by the focal point of the mid-infrared pulsed laser beam relative to the semiconductor substrate, the total distance encompassing one or more individual passes of the mid-infrared pulsed laser beam along the path, divided by a total period of time required to perform the one or more individual passes of the mid-infrared pulsed laser beam along the path.

[0023] Still further in accordance with the first aspect of the present disclosure, the laser pulses can for example have a pulse duration ranging between about 20 fs and 1 μ s.

[0024] Still further in accordance with the first aspect of the present disclosure, the relative movement can for example be performed at a linear effective speed ranging between about 20 mm/s and 2 m/s.

[0025] Still further in accordance with the first aspect of the present disclosure, the semiconductor substrate can for example have a thickness greater than 100 μ m, preferably greater than 300 μ m, and most preferably greater than 500 μ m.

[0026] Still further in accordance with the first aspect of the present disclosure, the mid-infrared pulsed laser beam can for example have a power of about 2 W or greater, more preferably above 5 W and most preferably of at least 10 W.

[0027] Still further in accordance with the first aspect of the present disclosure, the mid-infrared pulsed laser beam can for example be emitted by a fiber laser source.

[0028] It is noted that in this disclosure, the term “mid-infrared” is meant to encompass a region of the electromagnetic spectrum with wavelengths ranging between about 2.4 μm and 20 μm . A “mid-infrared laser beam” is thus meant to refer to a laser beam having a wavelength ranging between about 2.4 μm and 20 μm . A “mid-infrared laser source” is a laser source which can emit the mid-infrared laser beam.

[0029] In accordance with a second aspect of the present disclosure, there is provided a system for processing a semiconductor substrate, the semiconductor substrate having a bandgap wavelength, the system comprising: a frame having a substrate support receiving the semiconductor substrate; a mid-infrared laser source mounted to the frame and configured for emitting a mid-infrared laser beam having a central wavelength greater than the bandgap wavelength of the semiconductor substrate, the central wavelength of the mid-infrared pulsed laser beam being of 2.4 μm or greater; a scanning head optically coupled to the mid-infrared laser source, the mid-infrared laser source and the scanning head irradiating the semiconductor substrate with a focal point of the mid-infrared laser beam along a path extending within the semiconductor substrate and forming a weakened region along the path, the semiconductor substrate separable into substrate portions upon exertion of a separating force on the semiconductor substrate.

[0030] Further in accordance with the second aspect of the present disclosure, the mid-infrared laser source can for example be a mid-infrared fiber laser source.

[0031] Still further in accordance with the second aspect of the present disclosure, the mid-infrared fiber laser source can for example include an optical amplifier having: a length of fiber including low phonon energy glass, the length of fiber having a laser-active doped region doped with laser-active dopants; and a laser pump source adapted to pump the laser-active doped region of the length of fiber.

[0032] Still further in accordance with the second aspect of the present disclosure, the low phonon energy glass can for example be a fluoride glass.

[0033] All technical implementation details and advantages described with respect to a particular aspect of the present invention are self-evidently mutatis mutandis applicable for all other aspects of the present invention.

[0034] Many further features and combinations thereof concerning the present improvements will appear to those skilled in the art following a reading of the instant disclosure.

DESCRIPTION OF THE FIGURES

[0035] In the figures,

[0036] Fig. 1 is an oblique view of an example of a laser for processing a semiconductor substrate, shown with a mid-infrared pulsed laser beam moved along a path of the semiconductor substrate, in accordance with one or more embodiments;

[0037] Fig. 1A is an oblique view of the semiconductor substrate of Fig. 1, showing a weakened region extending along the path, in accordance with one or more embodiments;

[0038] Fig. 1B is an oblique view of substrate portions resulting from the separation of the semiconductor substrate of Fig. 1A along the weakened region, in accordance with one or more embodiments;

[0039] Fig. 1C is an enlarged view of the inset of Fig. 1, in accordance with one or more embodiments;

[0040] Fig. 2 is a graph showing different wavelength bands for the mid-infrared pulsed laser beam of Fig. 1, in accordance with one or more embodiments;

[0041] Fig. 3 is a flow chart of an example of a method for processing a semiconductor substrate, in accordance with one or more embodiments;

[0042] Fig. 4A is a top plan view of an example of a substrate portion separated using the method of Fig. 3, performed on a 675 μm thick silicon substrate with a single pass of a mid-infrared pulsed laser beam having a power of 0.75 W travelling at 40 mm/s, in accordance with one or more embodiments;

[0043] Fig. 4B is an enlarged view of Fig. 4A, in accordance with one or more embodiments;

[0044] Fig. 4C is a side elevation view of a separation edge of the substrate portion of Fig. 4A, showing a weakened region, in accordance with one or more embodiments;

[0045] Fig. 4D is an enlarged view of Fig. 4C, in accordance with one or more embodiments;

[0046] Fig. 5A is an oblique view of a separation edge of the substrate portion of Fig. 4A, showing a substantially perpendicular separation, in accordance with one or more embodiments;

[0047] Fig. 5B is a side elevation view of a separation edge of the substrate portion of Fig. 4A, showing a substantially perpendicular separation, in accordance with one or more embodiments;

[0048] Fig. 6A is a top plan view of an example of a semiconductor substrate having a weakened region made using the method of Fig. 3, performed on a 675 μm thick silicon substrate with a single pass of a mid-infrared pulsed laser beam having a wavelength of 2.8 μm and power of 0.75 W travelling at 10 mm/s, in accordance with one or more embodiments;

[0049] Fig. 6B is an enlarged view of a substrate portion resulting from the separation of the semiconductor substrate of Fig. 6A at the weakened region, in accordance with one or more embodiments;

[0050] Fig. 6C is a side elevation view of a separation edge of the substrate portion of Fig. 6A, showing the weakened region, in accordance with one or more embodiments;

[0051] Fig. 6D is an enlarged view of Fig. 6C, in accordance with one or more embodiments;

[0052] Fig. 7A is an oblique view of a separation edge of the substrate portion of Fig. 6A, showing a substantially perpendicular separation, in accordance with one or more embodiments;

[0053] Fig. 7B is a side elevation view of a separation edge of the substrate portion of Fig. 6A, showing a substantially perpendicular separation, in accordance with one or more embodiments;

[0054] Fig. 8A is a top plan view of an example of a semiconductor substrate having a weakened region made using the method of Fig. 3, performed on a 675 μm thick silicon substrate with two passes of a mid-infrared pulsed laser beam having a wavelength of 2.8 μm and a power of 0.75 W travelling at 60 mm/s, in accordance with one or more embodiments;

[0055] Fig. 8B is a top plan view of a substrate portion resulting from the separation of the semiconductor substrate of Fig. 8A, in accordance with one or more embodiments;

[0056] Fig. 8C is a top plan view of another substrate portion resulting from the separation of the semiconductor substrate of Fig. 8A, in accordance with one or more embodiments;

[0057] Fig. 8D is a side elevation view of a separation edge of the substrate portion of Fig. 8C, showing the weakened region, in accordance with one or more embodiments;

[0058] Fig. 8E is an enlarged view of Fig. 8D, in accordance with one or more embodiments;

[0059] Fig. 9A is an oblique view of a separation edge of the substrate portion of Fig. 8C, showing a substantially perpendicular separation, in accordance with one or more embodiments;

[0060] Fig. 9B is a side elevation view of a separation edge of the substrate portion of Fig. 8C, showing a substantially perpendicular separation, in accordance with one or more embodiments;

[0061] Fig. 10A is a top plan view of an example of a substrate portion having a weakened region made using the method of Fig. 3, performed on a 675 μm thick silicon substrate with two passes of a mid-infrared pulsed laser beam having a wavelength of 2.8 μm and a power of 0.75 W travelling at 80 mm/s, in accordance with one or more embodiments;

[0062] Figs. 10B and 10C are side elevation views of different separation edges of the substrate portion of Fig. 10A, in accordance with one or more embodiments;

[0063] Fig. 11 is a graph showing root mean square (RMS) roughness for separation edges of different substrate portions separated using the method of Fig. 3 with different parameter combinations, in accordance with one or more embodiments;

[0064] Fig. 12 is a graph showing peak-to-peak roughness for the substrate portions of Fig. 11, in accordance with one or more embodiments;

[0065] Fig. 13 is a graph showing a three-dimensional surface measurement profile of one of the substrate portions of Fig. 11, in accordance with one or more embodiments;

[0066] Fig. 14 is a graph showing the surface roughness of the separation edge of one of the substrate portions of Fig. 11, in accordance with one or more embodiments;

[0067] Fig. 15 is a side elevation view of a separation edge of a substrate portion made of gallium arsenide (GaAs) cut after formation of a weakened region therein using a mid-infrared pulsed laser beam, in accordance with one or more embodiments;

[0068] Fig. 16 is a side elevation view of a separation edge of a substrate portion made of indium phosphide (InP) cut after formation of a weakened region therein using a mid-infrared pulsed laser beam, in accordance with one or more embodiments; and

[0069] Fig. 17 is a schematic view of an example of a computing device of a controller, in accordance with one or more embodiments.

DETAILED DESCRIPTION

[0070] Fig. 1 shows an example of a system 100 for processing a semiconductor substrate 10 having a bandgap wavelength, in accordance with an embodiment. As depicted, the system 100 has a frame 102 in relation to which are positioned a substrate support 104, a mid-infrared pulsed laser source 106 and a scanning head 108. During processing, the substrate support 104 receives the semiconductor substrate 10. For instance, the semiconductor substrate 10 can be received, and maintain into position, on a top surface 104a of the substrate support 104. The mid-infrared pulsed laser source 106 is configured for emitting a mid-infrared pulsed laser beam 110 having a central wavelength greater than the bandgap wavelength of the semiconductor substrate. Moreover, the central wavelength of the mid-infrared pulsed laser

beam 110 is of 2.4 μm or greater. For instance, the wavelength of the mid-infrared pulsed laser beam 110 generally ranges between 2.4 μm and 5 μm , preferably between 2.5 μm and 4 μm , and most preferably between 2.7 μm and 3.0 μm . In some specific embodiments, the wavelength of the mid-infrared pulsed laser beam 110 is of about 2.8 μm .

[0071] In this embodiment, the scanning head 108 is optically coupled to the mid-infrared pulsed laser source 106. As discussed in greater detail below, the mid-infrared pulsed laser source 106 and the scanning head 108 are operable to irradiate the semiconductor substrate 10 with a focal point 112 of the mid-infrared pulsed laser beam 110 along a path P extending within the semiconductor substrate 10. By doing so, a weakened region 114 is formed along the path P within the semiconductor substrate 10. The formation of the weakened region 114 may occur due to multiphoton absorption, which is enabled by the central wavelength of the mid-infrared pulsed laser beam being greater than the bandgap wavelength of the semiconductor substrate 10. The weakened region 114 can be provided in the form of crack regions extending from the volume where the focal point is focused and towards the surface, and these crack regions can join together as the focal point of the mid-infrared pulsed laser beam scans across the path within the semiconductor substrate. In the illustrated embodiment, the weakened path 114 can be formed by two passes of different depths of the mid-infrared pulsed laser beam 112 along the path P. The mid-infrared pulsed laser source 106 and the scanning head 108, or any other substrate moving apparatus (not shown) can be controlled by a controller 109.

[0072] As shown in the rectangular inset, the first one of the two passes is made by irradiating the focal point 112 of the mid-infrared pulsed laser beam 110 along the path P of the semiconductor substrate and at a depth of z_1 from a top surface 10a of the semiconductor substrate 10. The second pass is made by irradiating the focal point 112 along the path P at a depth of z_2 (in which $z_2 < z_1$) from the top surface 10a of the semiconductor substrate 10. However, in some other embodiments, only a single pass of the mid-infrared pulsed laser beam 110 can be sufficient to form the weakened region 114. Of course, more than two passes of the mid-infrared pulsed laser beam 110 can be required in some applications. Typically, the deepest passes are performed first to avoid obstructing the transmission of the mid-infrared pulsed laser beam. As a result of these passes, Fig. 1A shows a linear weakened region 114

running between opposite edges 10b and 10c of the semiconductor substrate 10. With such a weakened region 114, the semiconductor substrate 10 is separable into two or more substrate portions 10' when a separating force F is exerted on the semiconductor substrate 10, such as shown in Fig. 1B. In some embodiments, the separating force is a shearing force exerted at the weakened region and oriented perpendicularly to a plane of the semiconductor substrate. In some other embodiments, the separating force can be a pulling force, a twisting force, and the like. When the weakened region 114 is performed with the mid-infrared pulsed laser beam 110 disclosed herein, the separation edges 10d and 10e (i.e., the edges resulting from separating the semiconductor 10 into the substrate portions 10' at the weakened region 114) can have a satisfactory surface roughness, as discussed below.

Fig. 1C emphasizes another aspect of the disclosed method which can allow the deepest pass of the focal point of the mid-infrared pulsed laser beam to be farther from the back surface 10b than the typical stealth dicing laser beams operating in the 800 nm to 1.5 μm range. Indeed, as shown, the deepest pass is located at a depth of z_1 from the top surface 10a. Correspondingly, the spacing between that first pass and the back surface 10b is given by $T - z_1$, where T denotes the thickness of the substrate. With a focal point spaced-apart from the back surface 10b in this manner, and a given numeral aperture (i.e., the beam's conical shape), one would obtain a first street width sw_1 defined by the width of the top surface 10a of the semiconductor substrate exposed to the mid-infrared pulsed laser beam 110 during that deepest pass. In contrast, the dashed lines on the right-hand side of the semiconductor substrates illustrates a representation of a typical stealth dicing laser beam operating in the 800 nm to 1.5 μm range. Since those conventional laser sources are limited in the power that they can deliver within the semiconductor wafer, conventional stealth dicing techniques can require a significant number of passes of the focal point of the laser beam within the semiconductor wafer, and as a result requires some of these passes to be close to the back surface 10b. As shown, the focal point of the deepest pass would be located close to the back surface 10b, which for the given numerical aperture, would provide a second street width sw_2 which would be larger than the first street width sw_1 . Accordingly, it is noted that the use of the method and system disclosed herein can help reducing the street width associated with the formation of a weakened layer, as the deepest pass can be relatively farther from the back surface compared to existing stealth dicing techniques. For understanding purposes, the

deepest pass formed with conventional stealth dicing techniques is often at about 40 μm of the back surface of the semiconductor wafer. With the method and system disclosed herein, it was demonstrated that the deepest pass can be formed at a depth ranging between 100 μm and 300 μm and still achieve convenient separation at the weakened region. Accordingly, in some embodiments, a deepest one of the pass(es) of the mid-infrared pulsed laser beam has a depth corresponding to about 75% of the thickness T of the semiconductor substrate, preferably about 60% of the thickness T of the semiconductor substrate, and most preferably about 50% of the thickness T of the semiconductor substrate.

[0073] The fewer number of passes and the increased saturation power of the mid-infrared pulsed laser beam collectively speed the formation of the weakened region 114. In some embodiments, the weakened region 114 can be formed with an effective linear speed exceeding 40 mm/s, preferably 80 mm/s and most preferably 160 mm/s. The effective linear speed is defined as a total distance traveled by the focal point of the mid-infrared pulsed laser beam relative to the semiconductor substrate, the total distance encompassing one or more individual passes of the mid-infrared pulsed laser beam along the path, divided by a total period of time required to perform the one or more individual passes of the mid-infrared pulsed laser beam along the path. Broadly described, in an embodiment in which N individual passes of the focal point are performed to form a weakened region having a length L , the total distance traveled by the focal point is given by $N*L$, with L denoting the length of an individual pass as well as the length of the weakened region. The effective linear speed can thus be determined by dividing the total distance travelled by the focal point by the total time t required to performed all of the N individual passes, i.e., $V_{\text{effective}} = N*L/t$. It is understood that the effective linear speed is meant to encompass the potential movement of the semiconductor substrate and the potential movement of the focal point of the mid-infrared pulsed laser beam. For instance, if the semiconductor substrate is moving along a first direction at a first speed value, and the mid-infrared pulsed laser beam is moving along a second direction opposite the first direction, then the effective linear speed may be given by the addition of the first speed value and the second speed value.

[0074] The semiconductor substrate 10 can be a silicon substrate (Si), a silicon carbide (SiC) substrate, a gallium nitride (GaN) substrate, a gallium arsenide (GaAs) substrate, an indium

phosphide (InP), Silicon on insulator (SOI) substrate, Silicon Nitride (SiN) substrate, to name a few examples. Preferably, the semiconductor substrate 10 is a monocrystalline semiconductor substrate, a polycrystalline semiconductor substrate, an amorphous semiconductor substrate, or a combination thereof. Other suitable types of semiconductor substrate 10 will appear to the skilled reader. It is intended that although the semiconductor substrate 10 has a rectangular shape in the illustrated example, the semiconductor substrate 10 can have other shapes including, but not limited to, a circular shape such as a wafer shape, an ovoid shape, and the like.

[0075] It is noted that all semiconductor materials have their own bandgap energies and corresponding bandgap wavelengths tied together via Planck relation. The bandgap energy and the bandgap wavelength define at which wavelengths or photon energies the semiconductor material exhibits at least some transparency. It is intended that the mid-infrared pulsed laser beam is selected so that it has a central wavelength which is greater than the bandgap wavelength of the corresponding semiconductor substrate, and most preferably also above 2.4 μm or greater. Equivalently, the mid-infrared pulsed laser beam can have a photon energy which is below the bandgap energy of the semiconductor substrate. Having such a relation between the central wavelength and/or the bandgap energy of the mid-infrared pulsed laser beam and the bandgap wavelength of the semiconductor substrate can enable multiphoton absorption to occur.

[0076] For example, lead selenide (PbSe) has a direct band gap of 0.27 eV or 4.57 μm ; lead telluride (PbTe) has a direct band gap of 0.32 eV or 3.86 μm ; indium arsenide (InAs) has a direct band gap of 0.36 eV or 3.43 μm ; lead sulfide (PbS) has a direct band gap of 0.37 eV or 3.34 μm ; germanium (Ge) has an indirect band gap of 0.67 eV or 1.84 μm ; gallium antimonide (GaSb) has a direct band gap of 0.726 eV or 1.70 μm ; silicon (Si) has an indirect band gap of 1.12 eV or 1.1 μm ; indium phosphide (InP) has a direct band gap of 1.35 eV or 915 nm; gallium arsenide (GaAs) has a direct band gap of 1.441 eV or 857 nm; cadmium tellurite (CdTe) has a direct band gap of 1.5 eV or 823 nm; cadmium selenide (CdSe) has a direct band gap of 1.74 eV or 710 nm; aluminum arsenide (AlAs) has an indirect band gap of 2.12 eV or 583 nm; gallium phosphide (GaP) has an indirect band gap of 2.24 eV or 551 nm; cadmium sulfide (CdS) has a direct band gap of 2.42 eV or 510 nm; gallium nitride (GaN) has a direct band

gap of 3.4 eV or 363 nm; cubic zinc sulfide (ZnS) has a direct band gap of 3.54 eV or 349 nm; hexagonal zinc sulfide (ZnS) has a direct band gap of 3.91 eV or 316 nm; and aluminum nitride (AlN) has a direct band gap of 6.015 eV or 205 nm, to name a few examples.

[0077] Referring now to Fig. 2, it is noted that the semiconductor substrate of the photonic chip has a bandgap energy and corresponding bandgap wavelength defining an optical transmission window 33. The optical transmission window 33 can range between about 1 μm and about 25 μm , preferably between about 2.0 μm and about 20 μm and most preferably between about 2.5 μm and about 10 μm . For instance, in embodiments where the semiconductor substrate includes silicon having a bandgap wavelength of about 1.1 μm , the optical transmission window 33 can range between about 1.1 μm and about 15 μm . In such embodiments, the central wavelength of the mid-infrared pulsed laser beam can be selected to be greater than 2.4 μm . The optical transmission window typically exhibits transmittances ranging between about 1 %/cm and about 10 %/cm, for instance.

[0078] In view of the above, it is intended that the mid-infrared pulsed laser beam has a central wavelength extending at least partially or wholly within the optical transmission window 33 of the semiconductor substrate. For instance, the central wavelength of the mid-infrared pulsed laser beam can range between about 2.4 μm and about 20 μm , preferably between about 2.5 μm and about 10 μm and most preferably about between about 2.8 μm and about 3.4 μm , depending on the embodiment. As such, optical energy can be delivered within the photonic chip, e.g., including within the semiconductor substrate and/or proximate to the semiconductor substrate. In embodiments where the semiconductor includes silicon, it was found convenient to use a mid-infrared pulsed laser beam having a narrow spectral bandwidth (or central wavelength, equivalently) centered ranging between 2.8 and 3.2 μm , for instance.

[0079] The mid-infrared pulsed laser source 106 can be any type of laser source emitting a mid-infrared pulsed laser beam having a wavelength of 2.4 μm or greater. Examples of such mid-infrared laser sources 106 can include, but are not limited to, fiber laser sources in which the laser active region includes low-phonon energy glass doped with rare-earth ions, or combination thereof, such as erbium-doped fluoride glass (Er:Fl) sources and/or other rare-earth doped glass can be used including, but not limited to, dysprosium, holmium, praseodymium, thulium, periodically poled lithium niobate (PPLN) sources, optical parameter

oscillator (OPO) sources, optical parametric amplifier (OPA) sources (e.g., tunable OPA sources can cover the whole mid-infrared region of the electromagnetic spectrum in some embodiments), down-converted lasers (difference frequency generation (DFG), Optical parametric generation lasers), erbium-doped yttrium aluminum garnet crystal (Er:YAG) sources, erbium-doped yttrium scandium gallium garnet crystal (Er:crystal or Er:glass such as Er:YSGG) sources, quantum-cascade laser (QCL) sources, Cr:ZnSe/ZnS sources, to name a few examples. In embodiments where the mid-infrared laser source is a pulsed laser source, the mid-infrared pulsed laser beam can have laser pulses with pulse widths in the nanosecond range, in the picosecond range, or in the femtosecond range. The pulse energy can be in the microjoule range or in the nanojoule range, depending on the embodiment. The mid-infrared pulsed laser beam can include, continuous wave, a steady train of laser pulses, or bursts of pulses, depending on the embodiment.

[0080] Still referring to Fig. 2, these mid-infrared laser sources 106 can have their own respective emission wavelength bands. For instance, some Cr:crystal (such as Cr:ZnSe/ZnS) sources were found to emit a mid-infrared pulsed laser beam 110 having a wavelength of about 2.4 μm . These Cr:ZnSe/ZnS sources can be pulsed sources emitting laser pulses having pulse widths in the femtosecond range and pulse energies in the microjoule or nanojoule range. Another Cr:ZnSe/ZnS source was found to emit a mid-infrared pulsed laser beam 110 having a wavelength of about 2.5 μm , with pulse widths in the nanosecond range. An OPO source was found to emit a mid-infrared pulsed laser beam 110 having a wavelength of about 2.75 μm . Er:YSGG sources were found to emit a mid-infrared pulsed laser beam 110 having a wavelength of about 2.78 μm . These Er:YSGG sources can operate in the pulsed regime, with pulse widths in the microsecond range. Er:FL sources, were found to emit a mid-infrared pulsed laser beam 110 having a wavelength of about 2.8 μm . One of these Er:FL pulsed sources was found to have pulse widths in the femtosecond range, with energy pulses ranging from the nanojoule range to the microjoule range. Other Er:FL sources were found to emit a mid-infrared pulsed laser beam 110 having a wavelength of about 2.8 μm with pulse widths in the nanosecond range. An example PPLN source was found to emit a mid-infrared pulsed laser beam 110 having a wavelength of about 2.8 μm . Another diode-pumped OPO source was found to emit a mid-infrared pulsed laser beam 110 having a wavelength of about 2.8 μm with pulse widths in the nanosecond range. An OPA source was found to emit a mid-

infrared pulsed laser beam 110 having a wavelength of about 2.8 μm , with pulse widths in the femtosecond range and pulse energies in the microjoule range. Er:YAG sources were found to emit a mid-infrared pulsed laser beam 110 having a wavelength of about 2.94 μm . These Er:YAG sources can emit a mid-infrared pulsed laser beam with pulse widths in the nanosecond range. A fiber laser pumped OPO source was found to emit a mid-infrared pulsed laser beam 110 having a wavelength of about 3.0 μm , with pulse widths in the femtosecond range and pulse energies in the nanojoule range. Another OPA source was found to emit a mid-infrared pulsed laser beam 110 having a wavelength of about 3.0 μm , with pulse widths in the femtosecond range and pulse energies in the microjoule range. Generally speaking, the mid-infrared laser beam can have repetition rates from 1 Hz to 10 GHz. Some of these mid-infrared laser sources are free-space laser sources whereas others are fiber laser sources. Other mid-infrared laser source examples can be used as well with the systems and method described herein.

[0081] With respect to low phonon energy glass mid-infrared fiber laser sources, the mid-infrared pulsed laser source 106 can include an amplifier including a length of fiber made of a low phonon energy glass and having at least laser-active doped region doped with one or more laser-active dopants (e.g., erbium), and one or more than one pump laser adapted to generate one or more than one pump laser beam. The length of fiber can have a first end in which is launched a seed laser beam and a second end where the mid-infrared pulsed laser beam is outputted. In this disclosure, the expression "low phonon energy glass" is intended to encompass any glass having a maximum phonon energy lower than the phonon energy of silica-based glass, i.e., lower than 800 cm^{-1} . Fibers made of a low phonon energy glass generally have a transmittance window ranging in the mid-infrared (i.e., 2.4 μm to longer wavelengths), unlike fibers made of a high phonon energy glass, such as a silica-based glass, which rather exhibits a transmittance window only in a given portion of the near-infrared (e.g., up to 2.4 μm). Understandably, using a fiber made of a low phonon energy glass allows photons at wavelengths in the mid-infrared to propagate along the length of fiber, in contrast with fibers of a high phonon energy glass which instead prevent the propagation of these photons. In cases where the laser-active doped region is pumped in the near-infrared (e.g., erbium ions), the low phonon energy glass of the length of fiber has a transmittance window extending in the near-infrared. However, in some other cases, the laser-active doped region

is pumped in the mid-infrared so a transmittance window extending in the near-infrared can be omitted. Examples of low phonon energy glass includes fluoride-, chalcogenide-, chalcogenide- or telluride-based glass. In some circumstances, even some oxide glasses (e.g., tellurite-based glass) can be considered as a low phonon energy glass. For instance, in some embodiments, the low phonon energy glass is a zirconium fluoride glass having a composition including ZrF_4 such as ZBLAN (ZrF_4/HfF_4 , BaF_2 , LaF_3 , NaF , and AlF_3). In some other embodiments, the low phonon energy glass is an indium fluoride glass having a composition including SnF_4 . In alternate embodiments, the low phonon energy glass is an aluminum fluoride glass having a composition including AlF_3 . In further embodiments, the low phonon energy glass is a chalcogenide glass having a composition including As_2S_3 , As_2Se_3 , $AsTe$, $AsSSe$, $AsSTe$, $GaLaS$, $GeAsS$, $GeAsSe$ or the like. Any other suitable low phonon energy glass having a transmittance window in the mid-infrared can be used. Examples of such mid-infrared laser sources are described in U.S. Patent No. 10,084,287 B2. These mid-infrared laser sources can be purchased from Femtum Inc. (Canada), to list only an example manufacturer.

[0082] Referring back to Fig. 1, the mid-infrared pulsed laser source 106 is mounted to the frame 102. The mid-infrared pulsed laser source 106 can be directly mounted to the frame 102 in some embodiments, or indirectly mounted to the frame 102 via a supporting bracket 120 or the like. The scanning head 108 can be directly or indirectly mounted to the frame 102 as well. In this embodiment, the scanning head 108 is mounted to the frame 102 via a supporting bracket 120. More specifically, the scanning head 108 is configured to receive the mid-infrared pulsed laser beam 110 from the mid-infrared pulsed laser source 106 and to redirect its focal point 112 along a path P extending within the semiconductor substrate 10. The path P can be linear or arcuate, with a smooth and continuous or discontinuous segments, depending on the embodiment. In some other embodiments, the frame can have a first frame element to which is mounted the mid-infrared laser source, a second frame element to which is mounted the scanning head, and a third frame element to which is mounted the support. The first, second and third frame elements can be made integral to one another, or be mechanically independent from one another.

[0083] Fig. 3 shows a flow chart of an example method 300 for processing a semiconductor substrate 10 having a bandgap wavelength. The method 300 can be performed by the system 100 described with reference to Fig. 1.

[0084] At step 302, the semiconductor substrate is irradiated with a mid-infrared pulsed laser beam. The mid-infrared pulsed laser beam has a central wavelength which is greater than the bandgap wavelength of the semiconductor substrate, and which is also of 2.4 μm or greater. The step 302 of irradiating can include a step of performing a relative movement between a focal point of the mid-infrared pulsed laser beam and the semiconductor substrate. The relative movement causes the focal point of the mid-infrared pulsed laser beam to move along a path extending within the semiconductor substrate and by doing so forms a weakened region, for instance via multiphoton absorption, along the path.

[0085] It is understood that the weakened region can have a first dimension extending with a plane of the semiconductor substrate and which is perpendicular to the path, and a second dimension extending across the semiconductor substrate (and thus perpendicular to the first dimension). The more this width is small, the better, as it can result in a greater number of substrate portions for a corresponding semiconductor substrate. The second dimension is more akin to a depth along which the semiconductor material is weakened within the semiconductor substrate. The greater the second dimension, the better, as it can reduce the number of passes required for a given semiconductor wafer. For instance, in some embodiments, the second dimension d2 can range between 200 μm and 500 μm , whereas the first dimension d1 can be below 50 μm , preferably below 40 μm and most preferably below 30 μm . It is intended that these satisfactory ranges can be allowed only using the mid-infrared pulsed laser beam, with the range of pulse width disclosed herein, as no or almost no undesirable self-limiting light-matter interactions are produced as the mid-infrared pulsed laser beam propagates within the semiconductor substrate. In some situations, the intensity clamping phenomena occurs as well using mid-infrared pulsed laser beams, however the method described herein can form satisfactory weakened regions within the semiconductor substrate with a mid-infrared pulsed laser beam of lower peak-to-peak intensity, thereby not triggering the undesirable self-limiting light-matter interactions discussed above.

[0086] At step 304, a separating force is applied on the semiconductor substrate at the weakened region. The step 304 causes the semiconductor substrate to separate into substrate portions. The number of substrate portions is dictated by the shape of the weakened region formed within the semiconductor substrate. In some embodiments, the substrate portions have a separation interface having a peak-to-peak roughness of about 30 μm or below. Additionally or alternately, the substrate portions have a separation interface having an RMS roughness of about 5 μm or below.

[0087] In some embodiments, the step 302 of irradiating can include a single pass of the focal point of the mid-infrared pulsed laser beam along the path. However, in some other embodiments, the step 302 of irradiating can include two or more passes of the focal point of the mid-infrared pulsed laser beam along the path. The passes can be made at a similar depth from a top surface of the semiconductor substrate or at different depths, depending on the embodiment.

[0088] In some embodiments, the wavelength of the mid-infrared pulsed laser beam ranges between 2.4 μm and 5 μm , and is preferably of about 2.8 μm . In some embodiments, the mid-infrared pulsed laser beam is a pulsed laser beam. The pulse laser beam has laser pulses of pulse widths ranging either in the nanosecond range, the picosecond range, or the femtosecond range. For instance, the pulse width can range between 20 fs and 1 μs . In some embodiments, the laser pulses have a pulse energy ranging in the microjoule range or in the nanojoule region. More specifically, in some embodiments, the pulse energy of these laser pulses can be of about 50 μJ or greater. The mid-infrared pulsed laser beam can have a power of about 2 W or greater, more preferably above 5 W and most preferably of at least 10 W.

[0089] In one example embodiment, the mid-infrared pulsed laser beam had a power of about 0.75 W or greater and its focal point was made to travel at a linear speed ranging between 10 and 45 mm/s. With a single pass of the focal point along the path, a silicon substrate having a thickness ranging between about 200 and 1000 μm was sufficiently weakened to allow separate upon the application of a separating force at one or more appropriate location. Depending on the operating parameters, the semiconductor substrate can have a thickness greater than 100 μm , preferably greater than 300 μm , and most preferably greater than 500 μm . Based on the thickness of the semiconductor substrate, the number of passes, the output

power of the mid-infrared pulsed laser beam, the relative movement between the focal point and the semiconductor substrate can be performed at a linear speed of about 20 mm/s or above, most preferably above 200 mm/s and most preferably above 300 mm/s. In some embodiments, the linear speed can be up to 2 m/s. The depth at which the passes are made can range between about 200 μm and 600 μm . Although this embodiment involved the use of a 0.75 W power mid-infrared pulsed laser beam, more powerful mid-infrared laser sources can be used including, but not limited to, 5 W power mid-infrared laser sources, 20 W power mid-infrared laser sources, and the like.

[0090] Figs. 4A-4D show a substrate portion separated using the method of Fig. 3, performed on a 675 μm thick silicon substrate with a single pass of a mid-infrared pulsed laser beam having a power of 0.75 W travelling at 40 mm/s. Figs. 4A and 4B show a top plan view of the substrate portion with magnification factors of 4x and 20x, respectively. These figures show the quality of the separation as can be appreciated by the minor defects to the edge. As depicted, the enlarged view of Fig. 4B shows defects extending from 5.89 μm on a top surface of the substrate portion. With magnification factors of 4x and 20x, respectively, Figs. 4C and 4D show the weakened region resulting from the single pass of the mid-infrared pulsed laser beam. In this embodiment, the focal point of the mid-infrared pulsed laser beam was focused at a depth of 560 μm from the top surface of the semiconductor substrate. As depicted, the weakened region has a dimension extending along the thickness of the substrate portion. The dimension of the weakened region can be of about 350 μm , for instance. Figs. 5A and 5B show the perpendicularity of edges of the resulted separated substrate portion.

[0091] Figs. 6A-6D show a substrate portion separated using the method of Fig. 3, performed on a 675 μm thick silicon substrate with a single pass of a mid-infrared pulsed laser beam having a power of 0.75 W travelling at 10 mm/s. Fig. 6A shows a top view of the semiconductor substrate after the weakened region has been made, with a magnification factor of 4x. The weakened region is shown to have a first dimension d1 extending along the plane of the semiconductor substrate. Fig. 6B shows a substrate portion resulting from the separation of the semiconductor substrate of Fig. 6A with a magnification factor of 20x. Figs. 6C and 6D show the weakened region, with magnification factors of 4x and 20x, respectively, resulting from the single pass of the mid-infrared pulsed laser beam, with an emphasis of a second

dimension extending in an orientation parallel to the thickness of the semiconductor substrate and perpendicular to the top surface of the semiconductor substrate. In this embodiment, the focal point of the mid-infrared pulsed laser beam was focused at a depth of 448 μm from the top surface of the semiconductor substrate. Figs. 7A and 7B show the perpendicularity of some edges of the separated substrate portion of Fig. 6A. In some embodiments, the first and second dimensions d1 and d2 extend perpendicularly to one another, with the second dimension d2 ranging between 200 μm and 500 μm . The first dimension d1 can be below 50 μm , preferably below 40 μm and most preferably below 30 μm .

[0092] Figs. 8A-8E show a substrate portion separated using the method of Fig. 3, performed on a 675 μm thick silicon substrate with two passes of a mid-infrared pulsed laser beam having a wavelength of 2.8 μm and power of 0.75 W travelling at 60 mm/s. In this embodiment, the focal point of the mid-infrared pulsed laser beam was focused at a depth of 238 μm from the top surface for the first pass and a depth of 448 μm from the top surface for the second pass. Fig. 8A shows a top view of the semiconductor substrate within which the weakened region has been formed by the two passes of the mid-infrared pulsed laser beam. A dislocation is observed. Fig. 8B shows a first substrate portion bearing the dislocation of Fig. 8A. Fig. 8C shows another edge of the substrate portion. Figs. 8D and 8E show the weakened region resulting from the two passes of the mid-infrared pulsed laser beam after separation.

[0093] Figs. 10A-10C show a substrate portion separated using the method of Fig. 3, performed on a 675 μm thick silicon substrate with two passes of a mid-infrared pulsed laser beam having a wavelength of 2.8 μm and power of 0.75 W travelling at 80 mm/s. In this embodiment, the focal point of the mid-infrared pulsed laser beam was focused at a depth of 238 μm from the top surface for the second pass and a depth of 395 μm from the top surface for the first pass. Fig. 10A shows an edge of the substrate portion resulting from the separate at the weakened region. Figs. 10B and 10C show the weakened region resulting from the two passes of the mid-infrared pulsed laser beam after separation.

[0094] Fig. 11 shows a graph showing RMS roughness for different substrate portions obtained using different combinations of parameters. All these samples were obtained by performing the method of Fig. 3 on a 675 μm thick silicon substrate with a given number of

passes of a mid-infrared pulsed laser beam having a wavelength of 2.8 μm and power of 0.75 W travelling at a given speed. The other parameters are summarized in Table 1 below:

Sample #	Number of passes; and depth of the passes (μm from the top surface)	Speed for each of the passes (mm/s)
1	3; with $z_3=175$, $z_2=367,5$, $z_1=560$	$v_1=v_2=v_3=40$
2	2; $z_2=238$, $z_1=448$	$v_1=v_2=60$
3	2; $z_2=238$, $z_1=448$	$v_1=v_2=40$
4	1; $z_1=560$	$v_1=40$
5	1; $z_1=560$	$v_1=30$
6	2; $z_2=238$, $z_1=560$	$V_1=100$, $v_2=40$
7	2; $z_2=175$, $z_1=560$	$v_1=v_2=100$
8	1; $z_1=560$	$v_1=10$

[0095] Table 1 – Processing parameters for forming the weakened region

[0096] Fig. 12 is a graph showing peak-to-peak roughness for the samples presented in Table 1. Fig. 13 is a graph showing a three-dimensional surface measurement profile for substrate portion sample #6 whereas Fig. 14 is a graph showing surface roughness of the separation edge for substrate portion sample #2. In this latter figure, the peak-to-peak roughness was measured to be about 10 μm and the RMS roughness was measured to be about 2 μm .

[0097] As discussed above, it was found that for each pass of the focal point of the mid-infrared pulsed laser beam within the semiconductor substrate, the weakened region formed therewithin can have a length (or a height) that is considered significant, especially when compared to the weakened region lengths achievable with laser beams having a wavelength

in the conventional 800 nm to 1.5 μm range. The reasons explaining why the mid-infrared pulsed laser beam disclosed herein can mark weakened region along greater lengths at each pass of the mid-infrared pulsed laser beam have yet to be confirmed. However, the following paragraphs provides different key physical aspects, which when taken individually or collectively, can explain why the mid-infrared pulsed laser beam and the conventional near-infrared laser beam perform so differently in the context of semiconductor dicing. Although the following explanation involve a 2.8 μm wavelength and a silicon substrate, it is believed that similar explanations can apply to any wavelength of 2.4 μm or greater, and/or substrates of any semiconductor materials.

[0098] It was found that for wavelengths below or close to the bandgap wavelength of about 1.1 μm for silicon, the interaction between nanosecond laser pulses and silicon would be limited to a single photon ionization process. Accordingly, the substrate weakening would be limited by the penetration depth of a single photon, i.e., the depth at which a single photon would be absorbed by the silicon substrate. For wavelengths of about 1.2 μm or above, the interaction between nanosecond laser pulses and silicon would be a multiphoton ionization process, as the silicon material is transparent to the laser beam. As such, there would be no theoretical limit as to where the mid-infrared pulsed laser beam can be focused within the thickness of the semiconductor substrate. As a result, a crack can be formed anywhere within the semiconductor substrate, allowing deeper and/or longer weakened regions where desired. However, it is noted that there are practical limits when considering laser beam propagation inside a semiconductor substrate, such as the top surface dicing width should be greater than the input laser beam diameter, to name one example consideration.

[0099] Fig. 15 shows an example of a GaAs substrate 10' within which a weakened region has been formed using the mid-infrared pulsed laser beam 1510 discussed above, in accordance with an experiment. In this specific experiment, the mid-infrared pulsed laser beam 1510 was directed through a top surface 1510a of the GaAs substrate 10'. As shown, the path along which the focal point of the mid-infrared pulsed laser beam 1510 has been directed included only one pass. That pass was parallel to a back surface 1510b of the GaAs substrate 10'. In this specific embodiment, the GaAs substrate 10' had a thickness of about 300 μm whereas the depth of the first pass was about at 250 μm from the top surface 1510a

or about 50 μm of the back surface 1510b. Under these operating parameters, the weakened region was sufficient to allow the GaAs substrate 10' to be easily separated into GaAs substrate portions. In this experiment, the formation of the weakened region was performed at an effective linear speed of 200 mm/s and included 4 passes of the focal point of the mid-infrared pulsed laser beam.

[00100] Moreover, it was found that when nanosecond pulses with photon energy smaller than the silicon's band gap interact with silicon, the dominant ionization process would be avalanche ionization. In such a process, the seed free electrons are provided by way of multiphoton ionization. Once the seed electrons are promoted from the valence band to the conduction band, they can experience inverse bremsstrahlung heating / free-carrier absorption and impact ionization which would finally lead to avalanche ionization. If the exponential growth of the electron density due to avalanche ionization reaches the critical electron density, it can induce crack formation within the silicon substrate.

[00101] The above-mentioned theoretical explanations as to why a mid-infrared pulsed laser beam at 2.8 μm can produce longer cracks via 3-photon ionization process than conventional wavelength range (between 1.1 μm and 2.2 μm) via 2-photon ionization process are detailed below.

[00102] One key physical aspect is higher ponderomotive energy. Once the electron is free to the conduction band, it can gain energy from the oscillating laser field:

[00103]
$$U_p = \frac{e^2 E^2}{4m_e \omega^2} = \frac{2e^2}{c\epsilon_0 m_e} \cdot \frac{I}{4\omega^2}; \quad (1)$$

[00104] where U_p denotes the ponderomotive energy, and ω denotes the laser frequency. In the context of the above application, the ponderomotive energy can be given by:

[00105]
$$U_p = 9.33 \cdot I(10^{14} \text{W/cm}^2) \cdot \lambda(\text{cm})^2; \quad (2)$$

[00106] As can be understood from equation (2), the ponderomotive energy is proportional to laser intensity I and to the square of laser wavelength λ . Note that the 2.8 μm laser wavelength would induce a 3-photon ionization process, which can require higher laser

intensity for initializing multiphoton ionization, thus the electron can gain much higher ponderomotive energy due to higher intensity and longer wavelength.

[00107] Another key physical aspect relates to higher electron heating rate. Indeed, as the ponderomotive energy gained by the electron can transfer to kinetic energy, this can lead to higher electron collision rate and thus higher electron heating rate:

$$[00108] \quad \frac{dn_e}{dt} \approx \frac{e^2 E^2}{2m_e \omega^2} \cdot v_e = 2U_p v_e \propto I \lambda^2 \quad (3).$$

[00109] Note that equation (3) is for ionization in gas, as ionization equations within silicon could not be timely found. However, equation (3) gives a rough understanding as to how these parameters can interact within one another in the context of semiconductor materials.

[00110] Another key physical aspect would relate to lower laser intensity threshold for avalanche ionization. It was found that the inverse square wavelength scaling can allow laser beams with longer wavelengths to drive avalanche ionization at lower laser intensity:

$$[00111] \quad I_{th} = \frac{N \epsilon_{ion} c^3 \epsilon_0 m_e}{4 \pi^2 \tau_p e^2 v_e} \cdot \frac{1}{\lambda^2}; \quad (4).$$

[00112] Again, equation (4) is for ionization in gas, as ionization equations within silicon could not be timely found. Note that equation (3) is for ionization in gas, as ionization equations within silicon could not be timely found. However, equation (3) gives a rough understanding as to how these parameters can interact within one another in the context of semiconductor materials. Since the 2.8 μm laser wavelength required higher laser intensity to initialize the multiphoton ionization as compared to the 2-photon ionization process, that means that when the 2.8 μm laser beam interacts with silicon, which has higher laser intensity and longer wavelength, the avalanche ionization is much more efficient than the others with wavelengths between 1.1 μm and 2.2 μm .

[00113] Another key phenomenon happening at the same time is that as the temperature increase within the semiconductor, the bandgap energy is shrinking, known as band gap closure. Since that during the pulse interaction within the semiconductor the local

temperature is elevated to very high temperatures, the bandgap wavelength is shifting towards the longer wavelengths. Thus the remainder of the pulse is now «seeing» a semiconductor with evolving optical, thermo-mechanical and electronic properties. The band gap closure leads to enhanced pre-focal self-limiting effects at lower near infrared wavelength compared to higher mid-infrared wavelength. As the bandgap properties evolve due to spatio-temporal temperature evolution during the focal volume of the laser pulse, so do the one-photon, two-photon, and three-photon absorption coefficients as well. In general, mid-IR wavelengths help solve or avoid the detrimental self-limiting effects (induced 1-photon or induced 2-photon or so forth leading to plasma shielding) of band gap closure.

[00114] Another key phenomenon is related to the square scaling of the free-carrier absorption (FCA), as can be defined by the equation immediately herebelow. When the free carrier absorption is stronger, the probability of direct absorption increases which increases the electron temperature. Since there's an interplay between excitation and deexcitation mechanisms, a higher free-carrier absorption is believed to enhance impact and avalanche ionization, thus elevating the average energy of the whole free-electron population, which in turn can lead to stronger energy deposition into the lattice, thus helping on the crack formation.

$$\Delta\alpha = \left(\frac{e^3 \lambda^2}{4\pi^2 c^3 \epsilon_0 n} \right) \left[\frac{\Delta N_e}{m_{ce}^{*2}} + \frac{\Delta N_h}{m_{ch}^{*2}} \right]. \quad (5).$$

[00115] Another key physical aspect involves lower critical electron density. Indeed, the inverse square wavelength scaling allows crack formation to be initialized at lower electron density for longer wavelengths:

$$n_c = \frac{\epsilon_0 m_e}{e^2} \omega^2 = \frac{4\pi^2 c^2 \epsilon_0 m_e}{e^2} \cdot \frac{1}{\lambda^2}. \quad (6)$$

[00117] A further key physical aspect relates to the longer Rayleigh length. The size ω_0 of the focal point and the Rayleigh length Z_R are dictated by:

$$[00118] \quad \omega_0 = \frac{2\lambda f}{\pi D}, \text{ and } (7)$$

[00119]
$$Z_R = \frac{\pi \omega_0^2}{\lambda} = \frac{4 \lambda f^2}{\pi D^2}. \quad (8)$$

[00120] Although 2-photon ionization has relatively longer interaction zone than 3-photon ionization, the interaction between the nanosecond laser and silicon is governed by the avalanche ionization. This means that as soon as free electrons are generated through multiphoton ionization induced by part of the rising edge of the pulse, the avalanche ionization can take over for the rest of the pulse. A longer Rayleigh length combined with much more efficient avalanche ionization due to higher ponderomotive energy, higher electron heating rate, lower intensity required for driving avalanche ionization and lower critical electron density for crack formation allow longer cracks to form for lasers with longer wavelength. As such, mid-infrared pulsed laser beam can advantageously be used to form weakened regions of greater lengths (i.e., higher heights, greater second dimensions) than the conventional 0.8 μm to 2.4 μm range.

[00121] The following paragraphs show other exemplary results that have been obtained using the methods and systems presented in this disclosure. As will be shown, satisfactory dicing has been achieved using a mid-infrared pulsed laser beam having a central wavelength greater than the bandgap wavelength of the semiconductor substrate. In most embodiments, the central wavelength of the mid-infrared pulsed laser beam has been of 2.4 μm or greater. The type of semiconductor substrate was varied from one experiment to another. For instance, p-type silicon substrates, unknown-type silicon substrates, silicon-on-insulator (SOI) substrates, low resistance semiconductor substrates, and other than silicon semiconductor substrates, such as indium phosphide semiconductor substrates, have been tested. The following parameters are presented as indicative purposes only, as other parameters could have been modified and still achieve successful dicing using the mid-infrared pulsed laser beam.

[00122] In a first set of experiments, p-type silicon substrates having a thickness of 680 μm have been successfully processed to form weakened regions allowing separation into substrate portions. In this first set of experiments, the pulse energy of the mid-infrared laser beam was 74 μJ and its focal length was 25 mm. In embodiments where two passes of the mid-infrared laser beam were made, a first pass was performed at a depth of 153.4 μm and a

second pass was performed at a shallower depth of 76.7 μm from the surface. In these cases, effective linear speeds of 40 mm/s or 60 mm/s were used. At both these speeds, the results were satisfactory as the p-type silicon substrates could be easily separated into substrate portions following the application of a sufficient force at the weakened regions. In another experiment, only one pass of the mid-infrared laser beam was made at a depth of 150 μm from the surface with an effective linear speed of 30 mm/s. In this case, too, a sufficiently weakened region has been successfully formed.

[00123] In a second set of experiments, unknown-type silicon substrates having a thickness of 730 μm have been successfully processed to form weakened regions allowing separation into substrate portions. In this second set of experiments, the pulse energy of the mid-infrared laser beam was 76 μJ and its focal length was 25 mm. In an experiment, two passes of the mid-infrared laser beam, with a first pass at a depth of 143 μm from the surface and a second pass at a shallower depth of 108 μm from the surface. In these cases, an effective linear speed of 40 mm/s was used. In another experiment, two passes of the mid-infrared laser beam, a first pass at a depth of 162 μm from the surface and a second pass at a shallower depth of 108 μm from the surface, were made at a linear effective speed of 40 mm/s. In these cases, sufficiently weakened regions have been successfully formed. One could even notice that, prior to separation, the weakened region could be observed on a face of the substrates. In some embodiments, such weakened regions had a street width as low as 0.58 μm .

[00124] In a third set of experiments, an unknown-type silicon substrate having a thickness of 1060 μm has been successfully processed to form a weakened region allowing separation into substrate portions. In this experiment, the pulse energy of the mid-infrared laser beam was 74 μJ and its focal length was 25 mm. In this embodiment, four passes of the mid-infrared laser beam were made at an effective linear speed of 10 mm/s. The first pass was performed at a depth of 260 μm from the surface, the second pass was performed at a depth of 208 μm from the surface, the third pass was performed at a depth of 156 μm from the surface, and the final, fourth pass was performed at a depth of 104 μm from the surface. A successful weakened region could be formed using these parameters as well.

[00125] In a fourth set of experiments, silicon-on-insulator substrates having a silicon layer thickness of 400 μm and a silicon dioxide layer thickness of 7 μm have been successfully processed to form weakened regions allowing separation into substrate portions. In these experiments, the pulse energy of the mid-infrared laser beam was 74 μJ and its focal length was 25 mm. In an experiment, three passes of the mid-infrared laser beam (the first one at 240 μm from the surface, the second one at a depth of 200 μm from the surface, and the third one at a depth of 100 μm from the surface) were made at an effective linear speed of 40 mm/s. In yet another experiment, two passes of the mid-infrared laser beam, with a first pass at 255 μm from the surface and a second pass at 216 μm from the surface, were made at an effective linear speed of 40 mm/s. In both cases, sufficiently weakened regions were obtained, thereby allowing dicing of the silicon-on-insulator substrates.

[00126] In a fifth set of experiments, unknown-type silicon substrates having a thickness of 400 μm have been successfully processed to form weakened regions allowing separation into substrate portions. In these experiments, the pulse energy of the mid-infrared laser beam was 74 μJ and its focal length was 25 mm. In an experiment, two passes of the mid-infrared laser beam, with a first pass at a depth of 90 μm from the surface and a second pass at a depth of 70 μm from the surface, were made at linear effective speeds of 40 mm/s and 60 mm/s. In another experiment, a single pass of the mid-infrared laser beam, at a depth of 78 μm from the surface, was made at an effective linear speed of 40 mm/s. Successful weakened regions could be formed using these parameters as well.

[00127] In a sixth set of experiments, low resistance (10-20mOhm.cm) semiconductor substrates having a thickness of 500 μm have been successfully processed to form weakened regions allowing separation into substrate portions. In these experiments, the pulse energy of the mid-infrared laser beam was 74 μJ and its focal length was 25 mm. In an experiment, two passes of the mid-infrared laser beam, with a first pass at a depth of 100 μm and a second pass at a depth of 80 μm from the surface, were made at an effective linear speed of 40 mm/s. In another experiment, a single pass of the mid-infrared laser beam, at a depth of 80 μm from the surface, was made at an effective linear speed of 40 mm/s. In these two cases, sufficiently weakened regions have been successfully formed.

[00128] In a seventh set of experiments, low resistance (5-10 mOhm.cm) semiconductor substrates having a thickness of 100 μm have been successfully processed to form weakened regions allowing separation into substrate portions. In these experiments, the pulse energy of the mid-infrared laser beam was 13 μJ and its focal length was 12.5 mm. In an experiment, a single pass of the mid-infrared laser beam, at a depth of 20 μm from the surface, was made at effective linear speeds of 20 mm/s and 30 mm/s. Here again, sufficiently weakened regions have been successfully formed.

[00129] In an eighth set of experiments, indium phosphide (InP) semiconductor substrates having a thickness of 630 μm have been successfully processed to form weakened regions allowing separation into substrate portions. For instance, in an experiment, two passes of the mid-infrared laser beam were made at an effective linear speed of 1 mm/s. In this case, the two passes of the laser were made from different faces of the InP semiconductor substrates. More specifically, a first pass has been made from a front face of the InP semiconductor substrates whereas a second pass has been made from a back face of the InP semiconductor substrates. Each pass of the mid-infrared laser beam 1610 was made at 140 μm from the corresponding face, such as shown in Fig. 16. In this experiment, the InP semiconductor substrates could be weakened sufficiently along the weakened regions to allow proper separation.

[00130] Although some specific parameters have been presented in the experiments above, those are meant to be exemplary only. Indeed, other parameters, other semiconductor substrates, or substrates having other (e.g., narrower, greater) thicknesses, can also be used in conjunction with the methods and systems described herein.

[00131] Referring now to Fig. 17, the controller 109 shown in Fig. 1 can be provided as a combination of hardware and software components. The hardware components can be implemented in the form of a computing device 1700, an example of which is described with reference to Fig. 17. The computing device 1700 can have a processor 1702, a memory 1704, and I/O interface 1706. Instructions 1708 for performing the methods disclosed herein, e.g., controlling the scanning head, controlling the movement of the focal spot of the mid-infrared pulsed laser beam, generating coordinates of the areas to be irradiated, can be stored on the memory 1704 and accessible by the processor 1702.

[00132] The processor 1702 can be, for example, a general-purpose microprocessor or microcontroller, a digital signal processing (DSP) processor, an integrated circuit, a field-programmable gate array (FPGA), a reconfigurable processor, a programmable read-only memory (PROM), a programmable logic controller (PLC), or any combination thereof.

[00133] The memory 1704 can include a suitable combination of any type of computer-readable memory that is located either internally or externally such as, for example, random-access memory (RAM), read-only memory (ROM), compact disc read-only memory (CDROM), electro-optical memory, magneto-optical memory, erasable programmable read-only memory (EPROM), and electrically-erasable programmable read-only memory (EEPROM), Ferroelectric RAM (FRAM) or the like.

[00134] Each I/O interface 1706 enables the computing device 1700 to interconnect with one or more input devices, such as mouse(s), keyboard(s), sensor(s), or with one or more output devices such as monitor(s), external memory system(s), accessible network(s).

[00135] Each I/O interface 1706 enables the controller to communicate with other components, to exchange data with other components, to access and connect to network resources, to server applications, and perform other computing applications by connecting to a network (or multiple networks) capable of carrying data including the Internet, Ethernet, plain old telephone service (POTS) line, public switch telephone network (PSTN), integrated services digital network (ISDN), digital subscriber line (DSL), coaxial cable, fibre optics, satellite, mobile, wireless (e.g., Wi-Fi, WiMAX), SS7 signaling network, fixed line, local area network, wide area network, and others, including any combination of these.

[00136] The computing device 1700 and any software application that can be run by the computing device 1700 are meant to be examples only. Other suitable embodiments of the controller can also be provided, as it will be apparent to the skilled reader.

[00137] As can be understood, the examples described above and illustrated are intended to be exemplary only. For instance, the methods and systems described herein can be used in the manufacturing of any photonic device including, but not limited to, microelectromechanical systems (MEMS), silicon photonics, photonic integrated circuits,

silicon-based bio-MEMS and genomic microarrays, water-sensitive cantilevers and other fragile membrane devices, non-homogeneous multiproduct wafers including non-traditional polygons such as hexagons and octagons, small die applications (e.g., <1mmx1mm square), and the like. The methods and systems described herein can be used to cut substrates of any type of semiconductor material including, but not limited to, InP, SiC, Si, SiN, GaN, InGaAs, CdTe, Ge, SiGe, silicon-on-insulator, and the like. The methods and systems described herein can be used to cut any type of crystalline structure including, but not limited to, <100> crystalline structure, <110> crystalline structure, <111> crystalline structure, monocrystalline structure, polycrystalline structure, to name a few examples. Each pass of the focal point of the mid-infrared pulsed laser beam can be moved at a respective speed. It is intended that the relative movement between the focal point of the mid-infrared pulsed laser beam and the semiconductor can include, a movement of the semiconductor wafer, a movement of the focal point of the mid-infrared pulsed laser beam, or a combination of both depending on the embodiment. The semiconductor substrate can be received on a 3D motorized translation platform. For semiconductor substrates, the field of view of the scanning head may be very limited. As such, translation stages are preferably used. The scanning head is not necessary. Indeed, in some other embodiments, a focal lens and/or a microscope objective can be used for focusing the mid-infrared pulsed laser beam within the semiconductor substrate (which would be moved by the translation stage(s)). The scope is indicated by the appended claims.

WHAT IS CLAIMED IS:

1. A method for processing a semiconductor substrate, the semiconductor substrate having a bandgap wavelength, the method comprising:

irradiating the semiconductor substrate with a mid-infrared pulsed laser beam, the mid-infrared pulsed laser beam having a central wavelength greater than the bandgap wavelength of the semiconductor substrate, the central wavelength of the mid-infrared pulsed laser beam being of 2.4 μm or greater, said irradiating including performing a relative movement between a focal point of the mid-infrared pulsed laser beam and the semiconductor substrate, the movement causing the focal point of the mid-infrared pulsed laser beam to move along a path extending within the semiconductor substrate and forming a weakened region along the path, the semiconductor substrate separable into substrate portions upon exertion of a separating force on the semiconductor substrate.

2. The method of claim 1 wherein the central wavelength ranges between 2.4 μm and 5 μm .

3. The method of claim 1 wherein the central wavelength is within 2.7 μm to 3.0 μm .

4. The method of any one of claims 1 to 3 wherein the semiconductor substrate is a monocrystalline silicon substrate.

5. The method of any one of claims 1 to 4 wherein said irradiating consisting of a single pass of the focal point along the path, the single pass forming the weakened region.

6. The method of claim 5 wherein at least one of: the mid-infrared pulsed laser beam having a power of about 0.75 W or greater; the semiconductor substrate being a silicon substrate; the semiconductor substrate having a thickness ranging between about 200 and 1000 μm ; and the relative movement being performed at a linear effective speed ranging between 10 and 45 mm/s.

7. The method of any one of claims 1 to 6 wherein said irradiating includes more than one pass of the mid-infrared pulsed laser beam along the path to form the weakened region.

8. The method of any one of claims 1 to 7 wherein the weakened region has a first dimension extending along a plane of the semiconductor substrate and a second dimension extending perpendicularly to the plane of the semiconductor substrate, the second dimension ranging between 200 μm and 500 μm .

9. The method of claim 8 wherein the first dimension is below 50 μm , preferably below 40 μm and most preferably below 30 μm .

10. The method of any one of claims 1 to 9 wherein, during the relative movement, the focal point of the mid-infrared pulsed laser beam is located at a given depth from a surface of the semiconductor substrate, the given depth ranging between 200 μm and 500 μm .

11. The method of any one of claims 1 to 10 further comprising: applying the separating force to the semiconductor substrate, the semiconductor substrate separating into the substrate portions upon said applying, the substrate portions having a separation interface having at least one of: a peak-to-peak roughness of about 30 μm or below, and a RMS roughness of about 5 μm or below.

12. The method of any one of claims 1 to 11 wherein the mid-infrared pulsed laser beam has laser pulses of pulse widths in a nanosecond range.

13. The method of any one of claims 1 to 12 wherein the mid-infrared pulsed laser beam includes laser pulses having pulse durations in a picosecond range.

14. The method of any one of claims 1 to 13 wherein the weakened region is formed at a linear effective speed exceeding 40 mm/s, the linear effective speed defined as a total distance traveled by the focal point of the mid-infrared pulsed laser beam relative to the semiconductor substrate, the total distance encompassing one or more individual passes of the mid-infrared pulsed laser beam along the path, divided by a total period of time

required to perform the one or more individual passes of the mid-infrared pulsed laser beam along the path.

15. The method of any one of claims 1 to 14 wherein the laser pulses have a pulse duration ranging between about 20 fs and 1 μ s.

16. The method of any one of claims 1 to 15 wherein the relative movement is performed at a linear effective speed ranging between about 20 mm/s and 2 m/s.

17. The method of any one of claims 1 to 16 wherein the semiconductor substrate has a thickness greater than 100 μ m, preferably greater than 300 μ m, and most preferably greater than 500 μ m.

18. The method of any one of claims 1 to 17 wherein the mid-infrared pulsed laser beam has a power of about 2 W or greater, more preferably above 5 W and most preferably of at least 10 W.

19. The method of any one of claims 1 to 18 wherein the mid-infrared pulsed laser beam is emitted by a fiber laser source.

20. A system for processing a semiconductor substrate, the semiconductor substrate having a bandgap wavelength, the system comprising:

- a frame having a substrate support receiving the semiconductor substrate;

- a mid-infrared laser source mounted to the frame and configured for emitting a mid-infrared laser beam having a central wavelength greater than the bandgap wavelength of the semiconductor substrate, the central wavelength of the mid-infrared pulsed laser beam being of 2.4 μ m or greater;

- a scanning head optically coupled to the mid-infrared laser source, the mid-infrared laser source and the scanning head irradiating the semiconductor substrate with a focal point of the mid-infrared laser beam along a path extending within the semiconductor substrate and forming a weakened

region along the path, the semiconductor substrate separable into substrate portions upon exertion of a separating force on the semiconductor substrate.

21. The system of claim 20 wherein the mid-infrared laser source is a mid-infrared fiber laser source.

22. The system of claim 21 wherein the mid-infrared fiber laser source includes an optical amplifier having: a length of fiber including low phonon energy glass, the length of fiber having a laser-active doped region doped with laser-active dopants; and a laser pump source adapted to pump the laser-active doped region of the length of fiber.

23. The system of claim 22 wherein the low phonon energy glass is a fluoride glass.