

APPARATUS AND METHOD FOR LASER MACHINING OF A SUBSTRATE

FIELD

[0001] Embodiments of the present disclosure relate to an apparatus and a method for laser
5 machining of a substrate. More specifically, embodiments described herein relate to an
apparatus and a method for efficient and exact laser machining of a substrate, particularly a
crystalline silicon (c-Si) substrate or a polymer composite substrate, particularly the
formation of via holes in the substrate.

10 BACKGROUND

[0002] There is an increasing demand for volume processing of substrates such as
crystalline silicon (c-Si) substrates, particularly c-Si wafers, or substrates including polymer-
based build-up films, such as Ajinomoto Build-up Films, in fields such as next-generation
PCB (printed circuit board) manufacturing, display manufacture, or solar cell
15 manufacturing. The substrates may be processed with laser machining methods, particularly
laser drilling and laser cutting, to achieve high processing volume and high accuracy.

[0003] Challenges arise when processing substrates with high precision at high speed and
therefore high laser energies. The substrates subject to the laser light incidence may become
hot or even locally melt in undesired locations. In such a situation, a high precision can no
20 longer be guaranteed. Even worse, in such a situation an ongoing laser exposure with
unchanged parameters may result in a poor drilling efficiency and quality. The drilling
process furthermore causes debris to be generated which might further disturb the exact
processing, leading to a reduced precision of the laser machining. For cost reasons, the
substrates are regularly thin and fragile and particularly susceptible to damage or breakage
25 which additionally increases the difficulty of the machining process.

[0004] In view of the above, new methods and apparatuses for laser machining of
substrates that overcome at least some of the problems in the art are beneficial.

[0005] SUMMARY

[0006] According to an aspect, an apparatus for hole drilling in a substrate is provided. The apparatus includes a laser system configured to apply a laser beam onto the substrate for removing material from a set of areas on the substrate by directing the laser beam onto
5 predefined positions corresponding to the set of areas on the substrate in a sequence. The sequence defines the order in which the areas are subjected to the laser beam. The apparatus further includes a ventilation system configured to produce a fluid flow along one or more sides of the substrate. The fluid flow is directed in a fluid flow direction. The apparatus further includes a controller configured to control the laser beam such that the laser beam is
10 sequentially positioned according to a first laser beam movement direction and a second laser beam movement direction with the laser beam being repeatedly directed onto each position corresponding to the set of areas at least three times. At least half of the subjected areas are allowed to cool for at least 50ms after each time an area from the set of areas is subjected to the laser beam. The angle between the first laser beam movement direction and
15 the fluid flow direction is defined as q_1 , the angle between the second laser movement beam direction and the fluid flow direction is defined as q_2 . Either

- both $\cos q_1$ and $\cos q_2$ are smaller than or equal to 0; or
- each of q_1 and q_2 is larger than 20° and smaller than 340° ; or
- either q_1 or q_2 is smaller than 20° , or larger than 340° , and the laser beam movement
20 is controlled such that the area which is subjected to the laser beam in the sequence is more than one area distant from the prior area subjected to the laser beam in the sequence.

[0007] According to an aspect, a method for drilling holes in a substrate is provided. The method includes applying a laser beam onto the substrate by directing the laser beam onto
25 predefined positions corresponding to a set of areas on the substrate in a sequence. The sequence defines the order in which the areas are subjected to the laser beam. The laser beam removes material from the set of areas. The method further includes producing, while applying the laser beam onto the substrate, a fluid flow along one or more sides of the substrate. The fluid flow is directed in a fluid flow direction. The applying of the laser beam

in a sequence includes sequentially positioning the laser beam according to a first laser beam movement direction and a second laser beam movement direction with the laser beam being repeatedly directed onto each position corresponding to the set of areas at least three times. At least half of the subjected areas are allowed to cool for at least 50ms after each time an
5 area from the set of areas is subjected to the laser beam. The angle between the first laser beam movement direction and the fluid flow direction is defined as q_1 , the angle between the second laser movement beam direction and the fluid flow direction is defined as q_2 .
Either

- both $\cos q_1$ and $\cos q_2$ are smaller than or equal to 0; or
 - 10 - each of q_1 and q_2 is larger than 20° and smaller than 340° ; or
 - q_1 or q_2 is smaller than 20° , or larger than 340° , and the laser beam movement is controlled such that the area which is subjected to the laser beam in the sequence is more than one area distant from the prior area subjected to the laser beam in the sequence.
- 15 [0008] According to aspects, the method and apparatus for drilling holes as disclosed herein consists of one or two first laser beam movement directions, and one or two second laser beam movement directions. In those aspects, the laser is not moved in another direction during the hole drilling process other than for auxiliary actions such as, but not limited to, moving the laser to a starting position or guiding the laser back to a pause position.
- 20 [0009] According to aspects, the direction of the laser beam movement is never in the same direction as the fluid flow direction except when the laser beam movement is controlled such that the area which is subjected to the laser beam directly before the laser beam movement is more than one area distant, in particular more than 5 areas distant, from the area subjected to the laser beam directly after the laser beam movement. In addition, according to aspects,
- 25 the angles between every direction in which the laser beam moves during the drilling process and the fluid flow direction is never smaller than 20° or larger than 340° except when the laser beam movement is controlled such that the area which is subjected to the laser beam directly before the laser beam movement is more than one area distant, in particular more

than 5 areas distant, from the area subjected to the laser beam directly after the laser beam movement.

[0010] Embodiments are also directed at apparatuses for carrying out the disclosed methods and include apparatus parts for performing each described method aspect. These
5 method aspects may be performed by way of hardware components, a computer programmed by appropriate software, by any combination of the two or in any other manner. Furthermore, embodiments according to the disclosure are also directed at methods for operating the described apparatus. The methods for operating the described apparatus include method aspects for carrying out every function of the apparatus.

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BRIEF DESCRIPTION OF THE DRAWINGS

[0011] So that the manner in which the above recited features of the present disclosure can be understood in detail, a more particular description of the disclosure, briefly summarized above, may be had by reference to embodiments. The accompanying drawings relate to
15 embodiments of the disclosure and are described in the following:

FIG. 1 shows a schematic view of an apparatus for laser machining of a substrate according to embodiments described herein;

FIG. 2 shows a schematic view of an apparatus for laser machining of a substrate according to embodiments described herein;

20 FIG. 3 shows a schematic set of areas to be processed, and a laser beam movement between the areas in relation to a fluid flow;

FIG. 4 shows a schematic set of areas to be processed, and a laser beam movement between the areas in relation to a fluid flow;

25 FIG. 5 shows a schematic set of areas to be processed, and a laser beam movement between the areas in relation to a fluid flow;

FIG. 6 shows a schematic set of areas to be processed, and a laser beam movement between the areas in relation to a fluid flow;

FIG. 7 shows a schematic set of areas to be processed, and a laser beam movement between the areas in relation to a fluid flow;

5 FIG. 8 illustrates the angle q_1 and q_2 between the laser beam movement directions and the fluid flow direction;

DETAILED DESCRIPTION

[0012] Reference will now be made in detail to the various embodiments of the disclosure,
10 one or more examples of which are illustrated in the figures. Within the following description of the drawings, the same reference numbers refer to same components. Generally, only the differences with respect to individual embodiments are described. Each example is provided by way of explanation of the disclosure and is not meant as a limitation of the disclosure. Further, features illustrated or described as part of one embodiment can be used on or in
15 conjunction with other embodiments to yield yet a further embodiment. It is intended that the description includes such modifications and variations.

[0013] The application of the present disclosure particularly relates to the production of any type of multilayer electronic assembly, such as printed circuit boards (PCBs), semiconductor packaging, solar cells or photovoltaic cells, display devices, such as LCD,
20 OLED or microLED-based screens, or any type of device requiring high-precision handling of c-SI wafers or substrates including polymeric films with holes provided therein.

[0014] According to an aspect, the substrate may be a silicon-based substrate, such as a crystalline silicone (c-SI) substrate or wafer. The substrate can include structures, functional layers or devices provided on the substrate, such as semiconductor devices, dielectric layers,
25 doted layers, metal layers e.g. for providing electrical connections, or other structures commonly known in semiconductor manufacturing. The substrate can include polymer-based layers, such as dielectric films. The dielectric film can be a polymer film, such as a polymer composite film. Polymer-based layers can include films such as an Ajinomoto

Build-up film. The substrate can be provided on a carrying structure, e.g. the substrate can be a polymer film provided on a silicon-based carrying structure, and drilling a hole can include drilling a hole in the polymer film but not the underlying silicon-based carrying structure.

5 [0015] As understood herein, a hole may refer to a through-hole that goes through the complete thickness of the substrate. A hole as understood herein may alternatively or additionally refer to a blind hole. In particular, the holes as understood herein may refer to an array of holes. The holes can be configured for the formation of vias in the substrate. The holes can be configured for providing components therein. The holes can be configured for
10 modifying the mechanical, electrical or thermal characteristics of the substrate in a beneficial matter. The holes can be configured for allowing subsequent manufacturing operations including the holes.

[0016] According to aspects of the present disclosure, it is not envisaged to perform so-called percussion drills, i.e., to drill each hole in one action, such as a single laser exposure,
15 laser incidence or “shot” only. Rather, it is proposed to drill each hole in an iterative process. The iterative process as used herein can be understood in that each hole is repeatedly subjected to a laser beam, each time for a certain time period called “shot” herein. Each shot aims at removing material from the area that is subject to the laser beam. In terms of thickness of the substrate, the material removed may, for instance, correspond to not more
20 than 25% of the thickness of the substrate at the location of the area that is subjected to the laser beam, more particularly not more than 20% or even not more than 15%.

[0017] According to an aspect, the drilling process includes a laser system configured to apply a laser beam onto the substrate for removing material from a set of areas on the substrate. The laser system may include a laser light source including a laser emitter. The
25 laser light source can include a solid state laser, a diode-pumped laser, a pulsed laser, and/or an ultraviolet (UV) or an infrared laser such as a CO₂ laser. The laser light source may be chosen according to the substrate material, e.g. according to beneficial embodiments, the wavelength of the laser beam can have a high absorption in the substrate material. Particularly, for c-SI substrates, an infrared laser with a wavelength above 1,000 nm may be
30 chosen, and for polymer substrates, particularly ABF-based substrates, a UV laser with a wavelength below 400 nm may be chosen.

[0018] According to an aspect, the laser system may further include an optical assembly for focusing the laser light to form a laser beam. The laser beam may be a narrow beam with a high spatial coherence. The laser beam may be conical and/or focused on the substrate to provide a narrow exposure area, the narrow exposure area typically corresponding to the size, e.g. the diameter of a hole to be drilled, e.g. the narrow exposure area can have a diameter of 5 % to 90 % of the hole to be drilled, such as 20 % to 50 % or less than 40 %. According to an embodiment, an area to be subjected to the laser beam can have a shape with a circumference, and the laser beam can be directed onto predefined positions corresponding to the circumference of the areas.

10 [0019] According to an aspect, the laser system can include a laser beam orientating assembly. The laser beam orientating assembly can include one or more laser beam orientating mirrors. A surface of the laser beam orientating mirror could be polygonal. The laser beam orientating mirror may be movable, in particular rotatable. For instance, by directing the laser beam towards the laser beam orientating mirror at a first side of the laser beam orientating mirror, the laser beam may be directed to the substrate at a first area to be drilled. Once the laser beam orientating mirror is moved, turned, or pivoted, the laser beam might hit the laser beam orientating mirror at a second side which causes the laser beam to jump to the second area of the substrate to be drilled.

[0020] According to an aspect, the drilling process typically includes predefined positions on the substrate corresponding to the set of areas to be drilled in a predefined order, such as a sequence, particularly a sequence defining positions corresponding to the set of areas on the substrate to be drilled. An apparatus for drilling the areas can include a controller. The controller may be configured to control the laser movement beam according to the sequence, where the laser is only shot at the areas to be drilled. The region between the areas not designed to be drilled is not subjected to the laser beam. This can be done, for instance, by supplying a controllable laser beam orientating mirror, such as a mirror included in a galvanometric assembly, particularly a two-axis galvanometric assembly, such as a dual axis scanning galvo system.

[0021] According to an aspect, the laser beam orientating mirror may have a reflective surface that reflects the laser beam and directs the laser beam to a desired location on the substrate. The desired location on the substrate can be a first position, and the laser beam

orientating mirror can be controlled to direct the laser beam to the first position and subsequently be controlled to direct the laser beam to a second position, which can be a desired location on the substrate. The transition between the first position and the second position may be fast and include a jumping of the laser beam between the first position and
5 the second position. Particularly, the laser beam orientating mirror may be configured for enabling a fast transition between multiple positions, e.g. a transition from the first position to the second position may occur at a frequency of 0.1 to 100 kHz, 0.5 to 50 kHz or 1 to 30 kHz.

[0022] In addition or alternatively, according to an aspect, the laser beam orientating
10 mirror may be configured for moving the laser beam continuously over the substrate, particularly an area of the substrate including the set of areas to be drilled. Continuously may include different speeds of the movement. The laser beam may be continuous. The laser beam may be repeatedly blocked by a shutter to avoid laser incidence in, for instance, the region between the areas to be drilled. The shutter may be controlled by the controller as
15 described herein. The shutter may be controlled such that the predefined positions on the substrate corresponding to the set of areas can be drilled. In particular, the shutter may be controlled such that the region between the areas to be drilled is not exposed to laser light. Instead of the shutter or in addition to the shutter, the laser beam may be pulsed, e.g. by operating the shutter as described above, and/or by providing a laser light source configured
20 for pulsed operation, such as a pulsed laser. According to an aspect, a laser light source configured for pulsed operation may include a laser light source configured for Q-switching, i.e. including a Q-switch, such as an active or a passive Q-switch, and/or a laser light source including an acousto-optic modulator to pulse the laser.

[0023] According to an aspect, in typical embodiments described herein, an array of holes
25 may be produced in the substrate, the array consisting of n rows and m columns with n and m being integer numbers. Consequently, a number of m times n holes in total have to be drilled. In further embodiments, the array can include not drilling a set of holes in the n - m substrate. The array may have, by design, “missing” holes or sections. An array may include several sub-arrays, the sub-arrays being definable as n - m arrays. According to embodiments,
30 complex patterns may be formed, based on a number of sub-arrays, the sub-arrays being arrays as described herein.

[0024] According to an aspect, the device and method described herein are configured for processing a substrate to produce a set of holes, i.e. process areas on the substrate, including at least 1,000 areas, particularly at least 10,000 areas, or at least 100,000 areas.

[0025] According to an aspect, a single array of holes can be produced in the substrate.

5 According to an embodiment, several arrays of holes can be produced in the substrate. An array of holes can include a set of areas. A substrate can be processed to include several arrays of holes, i.e. several sets of areas, such as at least 2 sets, at least 4 sets, at least 6 sets or at least 10 sets. According to aspects of the present disclosure, the holes of a first array may be drilled until they are completed, and subsequently the holes of a second array may
10 be drilled until they are completed (and so on in the case of even more arrays, e.g. in the case of at least 4 arrays).

[0026] Producing several arrays of holes can include producing an array of holes in a first section of the substrate as described herein, moving the substrate in relation to the apparatus, and producing a subsequent array of holes in a second section of the substrate. According to
15 embodiments, the apparatus can include a substrate support, such as a susceptor, holder, working table or the like configured for providing the substrate thereon and moving the substrate in relation to the apparatus, e.g. after a set of areas is processed, such as a two-axis work table or a rotary work table. According to embodiments, instead of moving the substrate, the substrate can remain stationary during processing, and laser system can be
20 repositioned such that the laser system is moved in relation to the substrate or the apparatus.

[0027] Subsequently producing several arrays of holes can particularly be beneficial in cases where the workable area or “field of view” of the laser system is smaller than the total substrate area to be processed. In one example, the laser system can have a “field of view”
25 corresponding to the area which can be processed by the laser system, with the set of areas lying within the field of view. The field of view can be at least 50 mm by 50 mm, at least 100 mm by 100 mm, at least 165 mm by 165 mm or even at least 250 mm by 250 mm.

[0028] According to an aspect, in embodiments, the laser beam is directed at each position corresponding to an area to be drilled at least three times, or even at least five times or even
30 at least ten times. The drilling process may particularly be designed in a way that the number

of shots causes the holes to have the predefined depth in the substrate. In particular, the predefined depth may be the substrate thickness. In this case, the drilling process is designed such that the number of shots is predefined such that through-holes are produced.

[0029] According to an aspect, in embodiments, the number of times the laser is directed
5 onto the set of areas is a function of the substrate thickness depending on the substrate material, i.e. a thin substrate may be exposed to less pulses or shots than a thick substrate. The number of times the laser is directed onto the set of areas can be larger than a tenth of the substrate thickness in micrometers. In a first example, the laser is repeatedly directed onto an area of a silicon substrate with a thickness of 100 μm or less at least 5 times. In a
10 second example, the laser is repeatedly directed onto an area of a silicon substrate with a thickness of 1000 μm or more at least 200 times. In a third example, the laser is repeatedly directed onto an area of a polymer film or polymer composite film substrate with a thickness of 100 μm or less at least 20 times. In a fourth example, the laser is repeatedly directed onto an area of a polymer film or polymer composite film substrate with a thickness of 1000 μm
15 or more at least 400 times. In the examples, a through-hole is obtained.

[0030] According to an aspect, at least half of the subjected areas are allowed to cool for at least 50 ms after each time an area from the set of areas is subjected to the laser beam, particularly before the area is again subjected to the laser beam. The area can be allowed to cool for at least 60 ms, for at least 80 ms, or for at least 100 ms, or even for at least 500 ms.
20 According to embodiments, each area of the subjected areas is allowed to cool. In a beneficial example, the area is allowed to cool while another area is processed, particularly, the set of areas can be continuously processed while an individual area in the set of areas is allowed to cool.

[0031] According to an aspect, in embodiments, the method for drilling and the controller
25 configured to control the laser beam are designed such that all holes of the substrate are equal in size (e.g. measured as diameter) and/or depth. "Equal" in this context can be understood as a theoretic equality that shall include deviations in practice due to, for instance, slightly varying material properties of the substrate or the like.

[0032] By repeatedly directing the laser beam onto each position corresponding to the set
30 of areas several times and allowing the area to cool after being subjected to the laser beam,

the uniformness and positioning of the resulting holes can be improved. Furthermore, localized heating of the substrate can be avoided, which can result in higher uniformity between holes at the edges of the set of areas and holes in the center of the set of areas.

[0033] It was experimentally observed that in some cases, debris produced while
5 subjecting an area to the laser beam may interfere with the drilling operation of adjacent areas under some conditions, e.g. by scattering or absorbing the laser light in an undesired manner. This can limit the obtainable speed or quality of the drilling operation. Such undesired effects can be overcome by aspects of the apparatus and method herein described in further detail.

10 [0034] According to an aspect, a ventilation system is provided. The ventilation system is configured to produce a fluid flow along one or more sides of the substrate. The one or more sides of the substrate typically include a face of the substrate, particularly the face of the substrate including the set of areas to be drilled. The fluid flow is directed in a fluid flow direction. The fluid flow can be unidirectional, i.e. the fluid can, for each area of the set of
15 areas, flow in a substantially identical direction.

[0035] According to an aspect, the fluid flow may include a gas such as air, an inert gas or mixtures thereof. The gas may be chosen according to the properties of the substrate or the laser beam. In an example, the gas may be devoid of oxygen to prevent oxidation or combustion of the substrate or debris, or the creation of ozone when a low-wavelength laser
20 beam is used. The gas may be dried to reduce infrared absorption of the gas, particularly when an infrared laser beam is used. The gas may include nitrogen. The gas may include a noble gas, such as helium or argon. The ventilation system may include a circulation system to recirculate the fluid flow.

[0036] According to an aspect, an apparatus may include an enclosure. The enclosure can
25 enclose the laser system, the substrate support and/or the substrate. The enclosure can include ports for substrate loading and unloading, such as a load-lock chamber or a door. The enclosure can be configured for providing the fluid flow, and for maintaining the fluid composition, i.e. for enclosing a gas as described above. The enclosure can include a gas inlet and a gas outlet. The gas inlet and the gas outlet can be fluidly connected to the

ventilation system, particularly for providing the fluid flow within the enclosure. The enclosure can form a part of the ventilation system.

[0037] According to an aspect, the fluid flow can be laminar or substantially laminar. Laminar, in the context of this disclosure, can be defined as a fluid flowing without substantially turbulent characteristics. Laminar, in the context of this disclosure, can further be understood as a flow without substantial lateral mixing between volumes comprising the flow, such as the volumes of the flow as defined by the spacing between the areas of the set of areas for each area, e.g. along the spatial dimensions defining the face of the substrate, or all spatial dimensions, particularly the volume of the fluid flow adjacent to the face of the substrate, particularly the volume including the space up to 2 mm above the face of the substrate. The fluid flow may include non-laminar portions in areas not adjacent to the face of the substrate.

[0038] The flow can have a flow-rate or velocity of more than 1 m/s in the volume comprising the space of 1 mm to 2 mm above the one or more sides of the substrate, or more than 2 m/s, such as 2 to 5 m/s, or more than 5 m/s, such as more than 10 m/s. The fluid flow volume may be expressed in terms of cubic feet per minute (CFM), with an apparatus designed for processing 100 mm by 100 mm substrates typically having a fluid flow volume of at least 100 CFM, particularly more than 200 CFM.

[0039] According to an aspect, the fluid flow carries away at least a portion of the debris produced when subjecting an area to the laser beam. The debris can include solids or a gas, or mixtures with substantially gas-like properties, such as ionized gas, aerosols or vapors, such as suspended particles and/or evaporated substrate material produced by the substrate during the laser exposure. Carrying away the debris can include carrying away the debris before again subjecting the area to the laser beam. Carrying away the debris can include carrying the debris in the direction of the fluid flow, and, in some cases, over other areas of the set of areas. It can be beneficial to not subject areas to the laser beam while debris from other areas is present above an area, as is described in further detail herein.

[0040] According to an aspect, the laser beam as described herein typically has a first movement direction and a second movement direction. The movement direction can be understood as the direction of the movement between a first area and a second area, the areas

being areas subsequently subjected to the laser beam. The laser beam may be inactive during the movement defining the movement direction, i.e. when the laser beam is moved from a first position to a second position according to the movement direction, areas not intended to be subjected to the laser beam may be crossed, and the laser beam may be turned off, e.g. by means of the shutter. The laser beam movement direction can be defined in relation to the surface of the substrate, i.e. the movement direction can be a movement direction along a two-dimensional plane, the plane being formed by the face of the substrate having the set of areas to be drilled provided thereon. Similarly, the fluid flow direction can be a direction of the fluid flow in relation to a plane as defined by the substrate.

10 [0041] According to an aspect, the first movement direction and the second movement direction can be a movement direction of the laser beam between areas of the set of areas. The areas, particularly the areas defining a first laser beam movement direction, can be adjacent. The first movement direction and the second movement direction may be different, e.g. have an angle therebetween along the plane as defined by the substrate. In typical
15 embodiments, the angle between the first movement direction and the second movement direction may be $+90^\circ$ and/or -90° . Areas of the set of areas can be adjacent if the area can be reached without crossing other areas of the set of areas. Areas of the set of areas can be adjacent if the areas have the closest spacing within the set of areas. Adjacent, in the context of this disclosure, should not be understood as requiring a contacting of the areas, i.e.
20 adjacent areas can be physically spaced apart.

[0042] According to aspects, the first movement direction may change during the drilling process at least once, in embodiments a plurality of times. In particular, the first movement direction may be in a specific direction for a first number of areas, and be in the opposite direction for a second number of areas. According to aspects, the second movement direction
25 may change during the drilling process at least once, in embodiments a plurality of times. In particular, the second movement direction may be in a specific direction for a first number of areas, and be in the opposite direction for a second number of areas.

[0043] According to an aspect, the movement direction, particularly the second movement direction, can be a movement direction of the laser beam between non-adjacent areas of the
30 set of areas under some conditions, as defined in detail below. Areas of the set of areas can be non-adjacent if the area can be reached only by crossing, directly or indirectly, other areas

of the set of areas. Areas of the set of areas can be non-adjacent if the areas have other areas spaced between the non-adjacent areas that are adjacent and/or areas that are closer to any of the non-adjacent areas than the non-adjacent areas are to each other.

[0044] Areas, including closely spaced areas, can be non-adjacent if a laser beam movement in the direction of one area to the subsequent area would allow the laser beam movement to reach another area before the subsequent area. Areas can be non-adjacent if the laser beam movement is such that the area which is subject to the laser beam in the sequence after the laser is moved by the laser beam movement is more than one area distant, more than five areas distant, particularly at least more than 10 areas distant from a prior area subjected to the laser beam in the sequence.

[0045] According to an aspect, the angle between the first laser beam movement direction and the fluid flow direction is defined as q_1 , and the angle between the second laser beam movement direction and the fluid flow direction is defined as q_2 . For example, if a laser beam movement direction is parallel to the fluid flow, the angle is 0° . If a laser beam movement direction is opposite to the fluid flow, the angle is 180° . If a laser beam movement direction is orthogonal to the fluid flow, the angle is 90° or 270° . In embodiments, the apparatus and method described herein can be achiral with respect to the definition of q_1 and q_2 , thus, an angle of 90° and 270° may be equivalent and/or the value space may be defined by angles ranging from 0° to 180° . By defining the sequence of areas to be subjected to the laser beam and/or performing the hole drilling according to a defined relation between q_1 and q_2 , the debris of each area can be carried away such that the debris does not interfere with subsequently subjected areas. Beneficial embodiments including preferred ranges and examples for q_1 and q_2 are described in further detail below.

[0046] Referring now to the figures, the general aspects discussed above are described in further detail and in relation to embodiments.

[0047] Fig. 1 is a schematic illustration of an apparatus according to an embodiment of the present disclosure. The laser 100 emits a laser beam 120. The laser beam may be emitted directly onto the substrate 110. Generally and not limited to this set-up, an actuator (not shown) may be provided for moving the laser. Moving may include translational movements and/or rotational movements. In the embodiment of Fig. 1 as illustrated, the laser beam is

directed to a beam director 105. The beam director 105 may in particular include one or more mirrors and/or one or more lenses for guiding the laser beam, such as to have the laser beam follow the predefined sequence. Additionally or alternatively, the beam director may include a shutter. The shutter is typically controlled by the controller to block the laser beam during
5 blocking times, and to allow the laser beam to pass during irradiation times. In particular, a shutter may block the laser beam so as to avoid that the substrate is subjected to the laser beam outside the areas to be drilled.

[0048] According to embodiments, the shutter may be controlled such that the shutter blocks the laser beam between two shots. For instance, a first shot may be applied to the
10 substrate at a position on the substrate corresponding to an area to be drilled. The laser beam may subsequently be blocked by the shutter, and the laser beam may be directed to a second area to be drilled thereafter while the shutter no longer blocks the laser beam. As used herein, the control of the shutter may be aligned with the control of the laser beam movement.

[0049] The substrate 110 may rest on a substrate support 115. The substrate support may
15 be movable. In other embodiments, the substrate support may be fixed. The apparatus of the present disclosure may include a substrate mover, such as a gripper, to position the substrate on the substrate support. The substrate support may include underpressure suction units configured to apply underpressure to the substrate's bottom so as to guarantee that the substrate is fully at rest despite the laser machining.

20 [0050] The apparatus of the present disclosure may additionally include the ventilation system 125. As illustrated, the ventilation system produces a fluid flow 15. The fluid flow 15 as discussed in the present disclosure is typically oriented parallel to the substrate support surface and/or the substrate. The fluid flow is supposed to produce a flow 15 that transports or carries away debris that is produced during the laser machining. In particular, the present
25 disclosure provides the benefit that the control of the laser movement is designed in relation to the fluid flow direction so as to optimize the drilling process and to guarantee that debris produced during the drilling of an area does not negatively affect the drilling of another area, such as a neighboring or adjacent area.

[0051] As exemplarily illustrated with respect to Fig. 2, the apparatus may include an
30 enclosure. The ventilation system 125 may be provided outside the enclosure. An inlet

opening 130, such as the channels shown in Fig. 2, may be provided that guide the fluid flow into the enclosure. The substrate may be provided inside the enclosure. The enclosure may furthermore include an outlet opening 135 to allow the fluid flow to exit the enclosure. In alternative embodiments, the ventilation system is provided within the enclosure.

5 Furthermore, in embodiments that can be combined with any of the previously described embodiments, a fluid flow suction system may be provided. The fluid flow suction system may be configured to suck in the fluid flow provided by the ventilation system. In this way, a closed fluid flow may be provided that may be particularly optimized in removing debris and the like from the substrate. The outlet opening 135 may be connected by a fluid transport
10 system, such as a circulatory system, to the ventilation system 125 to allow the recirculation of the fluid. Filters may be provided for filtering debris from the fluid after exiting the outlet opening 135.

[0052] According to an aspect, the sequence for directing the laser beam onto the substrate for removing material from the areas of the set of areas is defined so as to fulfill either of the
15 following three conditions:

1.) Both $\cos q_1$ and $\cos q_2$ are smaller than or equal to 0. In other words, q_1 or q_2 both are in a range between 90° and 270° . The first or second laser beam movement direction can, in relation to the fluid flow direction, lie within this range, i.e. the movement direction can be orthogonal to the fluid flow or be a direction which has, in addition to the orthogonal
20 movement, a movement component which is opposite to the fluid flow direction. In one example, this condition is fulfilled if one of the first laser movement direction and the second laser movement direction is opposite to the fluid flow direction and/or wherein one of the first laser movement direction and the second laser movement direction is perpendicular to the fluid flow direction.

25 2.) each of q_1 and q_2 is larger than 20° and smaller than 340° ; or

3.) q_1 , or q_2 , is smaller than 20° , or larger than 340° , and the laser beam movement is controlled such that the area which is subjected to the laser beam in the sequence is more than one area distant from the prior area subjected to the laser beam in the sequence. In this condition, the laser beam movement direction has a movement component which coincides
30 with the flow direction. Adjacent areas may be subjected to the debris of the prior area

subjected to the laser beam, however, distant areas may be unaffected. In beneficial examples, this condition is only chosen for one of the first laser beam movement direction or the second laser beam movement direction. In beneficial examples, this condition is only chosen when alternative movement directions, e.g. according to conditions 1.) or 2.), are
5 unavailable, or if the movement according to condition 3.) allows several subsequent operations according to conditions 1.) or 2.).

[0053] In the following, several example sequences for the laser movement shall be discussed with reference to the figures.

[0054] As exemplarily illustrated in the Figures 3 to 7, the circles 10 represent the areas
10 that are supposed to be drilled. In order to not overload the figures, only a few of these circles are denoted explicitly by the reference number 10. The flow as provided by the present disclosure has the direction as indicated by the arrow 15 in the figures. The first laser beam movement direction is generally depicted as a solid line, and the second laser beam movement direction is generally depicted as a dotted line, however, this shall not be regarded
15 as a limitation, and exceptions from this convention become clear in the examples that follow. According to a general aspect, which can be included in or combined with all embodiments described herein, the first laser beam movement direction can be a direction of a movement of the laser beam between adjacent areas, and/or the second laser beam movement direction can be a direction of a movement of the laser beam between non-
20 adjacent areas.

[0055] Referring now to Fig. 3, a set of areas on a substrate according to an embodiment is shown. For ease of illustration, the following figures show set of areas that include fewer areas as compared to the applications of the present disclosure. The set of areas as illustrated is provided as a 4 by 8 array. Each area of the set of areas is subjected multiple times to the
25 laser beam according to a sequence of shots. A fluid flow 15 is provided, having a direction as indicated by the arrow. The sequence can begin e.g. in the bottom left area 20. The following areas are subsequently subjected to the laser beam along a line 1, i.e. the first laser beam movement direction, represented as a solid line, having an angle α_1 of 90° relative to the fluid flow direction and thus fulfilling condition 1.).

[0056] When the bottom right area is reached, the laser beam is moved in a second laser beam movement direction (dotted line) to reach the leftmost area of the next line of areas. The second laser beam movement direction 2 has an angle q_2 of 260° relative to the fluid flow direction and thus fulfills condition 1.).

- 5 [0057] The operations are repeated until the top right area 25 is reached, after which the second laser beam movement direction 2 is adjusted to return the laser beam to the bottom left area 20. The second laser beam movement direction 2 for this movement in relation to the fluid flow direction q_2 is 300° , thus, neither conditions 1.) or 2.) are fulfilled. However, the top right area is several areas distant from the bottom left area, thus, condition 3.) is
10 fulfilled.

- [0058] Referring now to Fig. 4, a set of areas according to an embodiment is shown. The set of areas may be the set of areas described in relation to Fig. 3, thus, only the differences in the positioning of the laser beam are described. The sequence can begin e.g. in the bottom right area 20. The following areas (illustrated in the lowermost line) are subsequently
15 subjected to the laser beam along a line, i.e. the first laser beam movement direction 1, represented as a solid line, having an angle q_1 of 270° relative to the fluid flow direction and thus fulfilling condition 1.).

- [0059] When the bottom left area is reached, the laser beam is moved in a second laser beam movement direction 2 to reach the leftmost area of the next line of areas. The second
20 laser beam movement direction is opposite to the fluid flow direction and therefore has an angle q_1 of 180° relative the fluid flow direction and thus fulfills condition 1.).

- [0060] The following areas along the line are subsequently subjected to the laser beam as before, however with the first laser beam direction 1 being adjusted to move in the opposite direction to the previous first laser movement direction, represented as a solid line, having
25 an angle q_1 of 90° relative to the fluid flow direction and thus fulfilling condition 1.).

[0061] The operations are repeated until the top right area 25 is reached, after which the second laser beam movement direction is adjusted to return the laser beam to the bottom right area. The second laser beam movement direction 2 for this movement is identical to the fluid flow direction, and therefore q_2 is 0° . For such a situation, neither conditions 1.)

nor 2.) are fulfilled. However, the top right area 25 is several areas distant from the bottom right area 20, thus, condition 3.) is fulfilled. It should be noted that the transition from area 25 to area 20 is depicted in Fig. 4 as a curved line for reasons of intelligibility only, i.e. the transition may be performed according to a straight line between area 25 and 20. The debris
5 from the drilling of the area denoted with reference number 25, however, does not jeopardize the further drilling operation after this movement in the second laser beam movement direction along the angle $q_2=0^\circ$ because, in practice, the area where the laser is located after this movement (denoted with reference number 20° in Fig. 4) is at least 10 areas, more specifically at least 20 areas away from the area before this movement. In addition, the
10 transition between area 25 and 20 may be performed slowly or in a delayed manner to ensure that any debris produced by the processing of area 25 has been cleared by the fluid flow so as to not interfere with the processing of area 20.

[0062] Referring now to Fig. 5, a set of areas according to an embodiment is shown. The set of areas may be the set of areas described in relation to Fig. 3 or 4. Only the differences
15 to the embodiment described in relation to Fig. 3 or 4 shall be discussed. The sequence begins with the processing of area 20 in the top left corner of the set of areas. After the first line of areas has been processed, the laser beam is moved in a second laser beam movement direction to the leftmost area of the next line. The angle q_2 is 250° , thus fulfilling condition 2.). Furthermore, the area is several areas distant from the prior area, thus fulfilling condition
20 3.). The return transition from area 25 to area 20 has a second laser beam movement direction with an angle q_2 of 150° , thus fulfilling condition 1.).

[0063] Referring now to Fig. 6, a set of areas according to an embodiment is shown. The set of areas may be a set of areas as described in relation to Fig. 3 to 5, thus, only the differences in the positioning of the laser beam are described. The sequence can begin e.g.
25 in the bottom right area 20. The following four areas are subsequently subjected to the laser beam along a line, i.e. the first laser beam movement direction, represented as a solid line, having an angle q_1 of 180° relative to the fluid flow direction and thus fulfilling condition 1.).

[0064] When the top right area is reached, the laser beam is moved in a second laser beam
30 movement direction to reach the bottommost area of the next line of areas. The second laser beam movement direction has an angle q_2 of 345° relative to the fluid flow direction, thus,

neither conditions 1.) or 2.) are fulfilled. However, the top right area 25 is several areas distant from the bottom right area 20, thus, condition 3.) is fulfilled. In practice, the distance is at least 10 areas, specifically more than 20 areas or even more than 30 areas.

[0065] The operations are repeated until the top left area 25 is reached, after which the
5 second laser beam movement direction is adjusted to return the laser beam to the bottom right area 20. The angle for this movement q_2 is 60° , thus fulfilling condition 2.). Furthermore, the area is several areas distant from the prior area, thus fulfilling condition 3.).

[0066] Referring now to Fig. 7, a set of areas according to an embodiment is shown. The
10 set of areas is provided as a 4 by 6 array. The processing operation begins at area 20, which is provided at the bottom line of areas in the array, and moves outward along a first direction with an angle q_1 of 270° until the outermost area is reached. The first direction of movement of the laser beam fulfills condition 1.). The laser beam is then moved in the laser beam movement direction q_2 of 90° to reach an area in the line of areas in the array adjacent to
15 starting area 20. It should be noted that the transition along the second direction is depicted in Fig. 7 as a curved line for reasons of intelligibility only, i.e. the transition may be performed according to a straight line. Thus, the second direction of movement of the laser beam fulfills condition 1.).

[0067] After the transition, the direction of the first laser beam movement direction q_1 is
20 adjusted to 90° and the areas of the line of areas in the array are processed until the outermost area is reached. Then, a transition into the next line of areas in the array of areas is performed with a second laser beam movement direction having an angle q_2 of 110° , thus fulfilling condition 1.).

[0068] The operations are repeated until the top right area 25 is reached, after which the
25 second laser beam movement direction is adjusted to return the laser beam to the bottom left area 20. The second laser beam movement direction for this movement in relation to the fluid flow direction q_2 is 300° , thus, neither conditions 1.) or 2.) are fulfilled. However, the top right area is several areas distant from the bottom left area, thus, condition 3.) is fulfilled.

- [0069] Directing the laser beam according to the described embodiments, particularly embodiments fulfilling either of the conditions 1.) to 3.) described above, a high-speed processing of the set of areas can be achieved, while simultaneously allowing each area of the set of areas to cool for at least 50 ms while the subsequent areas are processed according to the predefined sequence. Furthermore, the debris produced while performing the laser working is carried away by the fluid flow in a direction according to the fluid flow, while each laser shot is unaffected by the debris. Consequently, no unnecessary waiting times between laser shots need to be introduced, while maintaining a high processing quality otherwise not obtainable by known processes.
- 10 [0070] Fig. 8 aims to illustrate the angles q_1 and q_2 . Where the arrow 15 stands for the fluid flow direction, the further arrow between the areas 20 may represent the first laser beam movement direction or the second laser beam movement direction. The angle between the first or second laser beam movement direction (denoted as “1/2” in Fig. 8) and the fluid flow direction is denoted with 200, and would be 270° in the present example of Fig. 8.
- 15 [0071] While the foregoing is directed to embodiments of the disclosure, other and further embodiments of the disclosure may be devised without departing from the basic scope thereof, and the scope thereof is determined by the claims that follow.

CLAIMS

1. An apparatus for hole drilling in a substrate, comprising:

a laser system configured to apply a laser beam onto the substrate for removing material from a set of areas on the substrate by directing the laser beam onto predefined
5 positions corresponding to the set of areas on the substrate in a sequence, the sequence defining the order in which the areas are subjected to the laser beam,

a ventilation system configured to produce a fluid flow along one or more sides of the substrate, the fluid flow being directed in a fluid flow direction;

a controller configured to control the laser beam such that the laser beam is
10 sequentially positioned according to a first laser beam movement direction and a second laser beam movement direction with the laser beam being repeatedly directed onto each position corresponding to the set of areas at least three times, with at least half of the subjected areas being allowed to cool for at least 50 ms after each time an area from the set of areas is subjected to the laser beam, wherein the angle between the first laser beam
15 movement direction and the fluid flow direction is defined as q_1 , the angle between the second laser beam movement direction and the fluid flow direction is defined as q_2 ;

wherein either

both $\cos q_1$ and $\cos q_2$ are smaller than or equal to 0; or

each of q_1 and q_2 is larger than 20° and smaller than 340° ; or

20 either q_1 or q_2 is smaller than 20° , or larger than 340° , and the laser beam movement is controlled such that the area which is subjected to the laser beam in the sequence is more than one area distant from the prior area subjected to the laser beam in the sequence.

25 2. The apparatus according to claim 1, wherein the second laser movement is such that the area which is subject to the laser beam in the sequence after the laser is moved by

the second movement is more than five areas, particularly at least more than 10 areas distant from a prior area subjected to the laser beam in the sequence.

3. The apparatus according to claims 1 or 2, wherein the areas have a shape with a
5 circumference, and wherein the laser beam is directed onto predefined positions corresponding to the circumference of the areas.

4. The apparatus according to any of the preceding claims, wherein one of the first
laser beam movement direction and the second laser beam movement direction is opposite
10 to the fluid flow direction and/or wherein one of the first laser movement direction and the second laser movement direction is perpendicular to the fluid flow direction.

5. The apparatus according to any of the preceding claims, wherein the set of areas
include at least 1,000 areas, particularly at least 10,000 areas, and more particularly at least
15 100,000 areas.

6. The apparatus according to any of the preceding claims, wherein the fluid flow
includes one or more from the group consisting of an inert gas, in particular helium or argon,
and nitrogen.
20

7. The apparatus according to any of the preceding claims, wherein the fluid flow is a
unidirectional laminar flow with a flow-rate of more than 1 m/s in the volume comprising
the space of 1 mm to 2 mm above the one or more sides of the substrate.

25 8. The apparatus according to any of the preceding claims, wherein the substrate is a
silicon substrate or a substrate comprising a polymer film or a polymer composite film.

9. The apparatus according to any of the preceding claims, wherein the apparatus
further comprising an enclosure, the enclosure including a gas inlet and a gas outlet.
30

10. A method for drilling holes in a substrate, comprising:

applying a laser beam onto the substrate by directing the laser beam onto predefined positions corresponding to a set of areas on the substrate in a sequence, the sequence defining the order in which the areas are subjected to the laser beam, the laser beam removing material from the set of areas;

- 5 producing, while applying the laser beam onto the substrate, a fluid flow along one or more sides of the substrate, the fluid flow being directed in a fluid flow direction;

applying the laser beam in a sequence including:

- sequentially positioning the laser beam according to a first laser beam movement direction and a second laser beam movement direction with the laser beam being repeatedly
10 directed onto each position corresponding to the set of areas at least five times, with at least half of the subjected areas being allowed to cool for at least 50 ms after each time an area from the set of areas is subjected to the laser beam, wherein the angle between the first laser beam movement direction and the fluid flow direction is defined as q_1 , the angle between the second laser beam movement direction and the fluid flow direction is defined as q_2 ;

- 15 wherein either

both $\cos q_1$ and $\cos q_2$ are smaller than or equal to 0; or

each of q_1 and q_2 is larger than 20° and smaller than 340° ; or

- either q_1 or q_2 is smaller than 20° , or larger than 340° , and the laser beam movement is controlled such that the area which is subjected to
20 the laser beam in the sequence is more than one area distant from the area subjected to the laser beam directly prior in the sequence.

11. The method according to claim 10, wherein the method includes carrying away, by the fluid flow, at least a portion of a debris produced when subjecting an area of the set of
25 areas to the laser beam.

12. The method according to claims 10 or 11, wherein the method includes carrying away, by the fluid flow, at least a portion of one of the group of: an ionized gas, an aerosol,

or an evaporated substrate material produced when subjecting an area of the set of areas to the laser beam.

13. The system or method according to any of the preceding claims, wherein the
5 substrate includes one or more sets of areas.

14. The system or method according to any of the preceding claims, wherein the
number of times the laser is directed onto the set of areas is a function of the substrate
thickness depending on the substrate material, wherein the number of times is larger than a
10 tenth of the substrate thickness in micrometers.

15. The system or method according to any of the preceding claims, wherein each of the
subjected areas is allowed to cool for at least 50 ms, or wherein at least half of the subjected
areas is allowed to cool for at least 50 to 100 ms, or for at least 100 ms.