

# US Patent & Trademark Office

## Patent Public Search | Text View

United States Patent  
Kind Code  
Date of Patent  
Inventor(s)

12383985  
B2  
August 12, 2025  
Gaab; Andreas Simon et al.

### Substrate cutting and separating systems and methods

#### Abstract

A method of forming a plurality of defects within a substrate with a laser beam focal line using a laser beam, each defect of the plurality of defects being a damage track within the substrate with a diameter of about 10 microns or less, the plurality of defects forming a contour line on the substrate. The substrate having a first surface and a second surface that is opposite from the first surface. The method further includes exerting (i) a first force on the first surface of the substrate at a location that is adjacent to the contour line and (ii) a second force on the second surface of the substrate at a location that is on the contour line. Additionally, the method includes breaking the substrate along the contour line and into a first substrate portion and a second substrate portion.

**Inventors:** Gaab; Andreas Simon (Grobenzell, DE), Gaona; Richard Anthony (Novato, CA), Haenel; Nicolai Martin (Bayern, DE), Humphrey; Dale (Santa Rosa, CA), Terbrueggen; Ralf Joachim (Bavaria, DE), Tyler; John Eric (Napa, CA)

**Applicant:** CORNING INCORPORATED (Corning, NY)

**Family ID:** 1000008750425

**Assignee:** Corning Incorporated (Corning, NY)

**Appl. No.:** 17/554357

**Filed:** December 17, 2021

#### Prior Publication Data

Document Identifier	Publication Date
US 20220193831 A1	Jun. 23, 2022

#### Related U.S. Application Data

us-provisional-application US 63248700 20210927  
us-provisional-application US 63128279 20201221

#### Publication Classification

**Int. Cl.:** B23K26/53 (20140101); B23K26/00 (20140101); B23K26/70 (20140101); B23K103/00 (20060101)

**U.S. Cl.:**

CPC B23K26/53 (20151001); B23K26/0006 (20130101); B23K26/70 (20151001); B23K2103/54 (20180801)

#### Field of Classification Search

**CPC:** B23K (2103/54); B23K (26/0006); B23K (26/0624); B23K (26/53); B23K (26/70); C03B (33/0222); C03B (33/033); H01L (21/67092); Y02P (40/57)

#### References Cited

##### U.S. PATENT DOCUMENTS

Patent No.	Issued Date	Patentee Name	U.S. Cl.	CPC
11773004	12/2022	Hackert	428/131	B23K 26/364
2005/0009301	12/2004	Nagai et al.	N/A	N/A
2011/0056922	12/2010	Ueki	N/A	N/A
2011/0136322	12/2010	Sato et al.	N/A	N/A
2013/0323469	12/2012	Abramov et al.	N/A	N/A
2017/0028505	12/2016	Hosseini et al.	N/A	N/A
2017/0243786	12/2016	Yoshino et al.	N/A	N/A
2018/0057390	12/2017	Hackert et al.	N/A	N/A
2020/0290918	12/2019	Basit et al.	N/A	N/A

**FOREIGN PATENT DOCUMENTS**

<b>Patent No.</b>	<b>Application Date</b>	<b>Country</b>	<b>CPC</b>
102218777	12/2010	CN	N/A
103079747	12/2012	CN	N/A
104736489	12/2014	CN	N/A
106102983	12/2015	CN	N/A
110722271	12/2019	CN	N/A
111183121	12/2019	CN	N/A
2011119548	12/2010	JP	N/A
2011212963	12/2010	JP	B28D 5/04
2015122402	12/2014	JP	N/A
2018519229	12/2017	JP	N/A
2020001072	12/2019	JP	N/A
10-2020-0002633	12/2019	KR	N/A
20200002633	12/2019	KR	N/A
2012/006736	12/2011	WO	N/A
2015/113026	12/2014	WO	N/A
2019/055751	12/2018	WO	N/A

**OTHER PUBLICATIONS**

Borghi et al., "M2 factor of Bessel-Gauss beams", Optics Letters, vol. 22, No. 5, 1997, pp. 262-264. cited by applicant  
 Siegman, "New developments in laser resonators", SPIE Symposium Series, vol. 1224, 1990, pp. 2-14. cited by applicant  
 International Search Report and Written Opinion of the International Searching Authority; PCT/US2021/061704; mailed on Apr. 20, 2022, 11 pages; European Patent Office. cited by applicant  
 Japanese Office action for Application No. 2023-537275, dated Dec. 5, 2024, 7 pages. cited by applicant  
 Chinese Office action for application No. 202180091814.9, dated May 16, 2025, 9 pages. cited by applicant

*Primary Examiner:* Jennison; Brian W

*Assistant Examiner:* Eckardt; Adam M

*Attorney, Agent or Firm:* Womble Bond Dickinson (US) LLP

**Background/Summary**

(1) This application claims the benefit of priority under 35 U.S.C. § 119 of U.S. Provisional Application Ser. No. 63/128,279 filed on Dec. 21, 2020 and U.S. Provisional Application Ser. No. 63/248,700 filed on Sep. 27, 2021, the content of which is relied upon and incorporated herein by reference in its entirety

**FIELD**

(1) The present disclosure generally relates to apparatuses and methods for cutting and separating substrates, and more particularly, to cutting and separating substrates using a laser beam and a breaker system.

**BACKGROUND**

(2) The area of laser processing of materials encompasses a wide variety of applications that involve cutting, drilling, milling, welding, melting, etc., of different types of materials. Among these processes, one that is of particular interest is cutting or separating different types of substrates comprised of such materials as glass, sapphire, or fused silica for thin film transistors (TFT) or display materials for electronic devices. The cutting or separating of the substrates conventionally requires a laser beam to form a scribe line along the substrate. Next, either a mechanical force or another laser is applied to the scribe line to cut or separate the substrate along the scribe line.

(3) However, such conventional systems often cause unwanted chipping or cracking in the substrate. Furthermore, such conventional systems can damage a coating applied to a surface of the substrate. Accordingly, a need exists to improve the cutting and separating of substrates using a laser beam.

**BRIEF SUMMARY**

(4) Therefore, what is needed is a system that cuts and separates a substrate without causing such chipping and cracking in the substrate. Furthermore, what is needed is a system that provides good edge quality with such a cutting and separating process. Embodiments of the present disclosure include a system that comprises a laser processing system and a substrate breaking system to precisely and accurately cut and separate a substrate. More specifically, the laser processing system uses a laser beam to precisely form a contour line in the substrate. The substrate breaking system then separates the substrate along the contour line without damaging the substrate or a coating applied thereon. Such produces an efficient and easy system to accurately cut and separate a substrate and to provide a cut substrate with enhanced edge quality. Furthermore, the system disclosed herein precisely cuts and separates the substrate while preventing any cracking or chipping of the substrate during the process.

(5) According to a first aspect, a method of forming a plurality of defects within a substrate with a laser beam focal line using a laser beam is disclosed, each defect of the plurality of defects being a damage track within the substrate with a diameter of about 10 microns or less, the plurality of defects forming a contour line on the substrate. The substrate has a first surface and a second surface that is opposite from the first surface. The method further comprises exerting (i) a first force on the first surface of the substrate at a location that is adjacent to the contour line and (ii) a second force on the second surface of the substrate at a location that is on the contour line. Additionally, the method comprises breaking the substrate along the contour line and into a first substrate portion and a second substrate portion.

(6) According to a second aspect a system is disclosed that comprises a laser processing system comprising a beam source configured to output a laser beam that is focused into a laser beam focal line and a substrate breaking system comprising a first set of breaker bars and a flexible membrane. The first set of breaker bars comprising a first breaker bar with a first edge, a second breaker bar with a second edge, and a third breaker bar with a third edge. The first breaker bar and the second breaker bar being disposed on a first side of the flexible membrane and the third breaker bar being disposed on a second side of the flexible membrane.

(7) Additional features and advantages of the processes and systems described herein will be set forth in the detailed description which follows, and in part will be readily apparent to those skilled in the art from that description or recognized by practicing the embodiments described herein, including the detailed description which follows, the claims, as well as the appended drawings.

(8) It is to be understood that both the foregoing general description and the following detailed description describe various embodiments and are intended to provide an overview or framework for understanding the nature and character of the claimed subject matter. The accompanying drawings are included to provide a further understanding of the various embodiments, and are incorporated into and constitute a part of this specification. The drawings illustrate the various embodiments described herein, and together with the description serve to explain the principles and operations of the claimed subject matter.

---

## Description

### BRIEF DESCRIPTION OF THE DRAWINGS

- (1) The embodiments set forth in the drawings are illustrative and exemplary in nature and not intended to limit the subject matter defined by the claims. The following detailed description of the illustrative embodiments can be understood when read in conjunction with the following drawings, where like structure is indicated with like reference numerals and in which:
- (2) FIG. 1 schematically depicts a system for cutting and separating a substrate, according to one or more embodiments described herein;
- (3) FIG. 2A schematically depicts a laser processing system of the system of FIG. 1, according to one or more embodiments described herein;
- (4) FIG. 2B schematically depicts the positioning of a laser beam focal line of the laser processing system of FIG. 1A, according to one or more embodiments described herein;
- (5) FIG. 2C schematically depicts an optical assembly of the laser processing system of FIG. 1A, according to one or more embodiments described herein;
- (6) FIG. 3A graphically depicts the relative intensity of laser pulses within an exemplary pulse burst vs. time, according to one or more embodiments described herein;
- (7) FIG. 3B graphically depicts the relative intensity of laser pulses vs. time within another exemplary pulse burst, according to one or more embodiments described herein;
- (8) FIGS. 4A-4C schematically depict a substrate breaking system, according to one or more embodiments described herein;
- (9) FIGS. 5A and 5B depict breaking bar sets of the substrate breaking system of FIGS. 4A-4C, according to one or more embodiments described herein;
- (10) FIG. 6 schematically depicts a substrate breaking system, according to one or more embodiments described herein;
- (11) FIGS. 7A-7C depict the substrate breaking system with a substrate, according to one or more embodiments described herein;
- (12) FIGS. 8A-8C depict a film of the substrate breaking system, according to one or more embodiments described herein;
- (13) FIG. 9 depicts a breaking procedure of the substrate breaking system, according to one or more embodiments described herein;
- (14) FIG. 10 depicts the substrate breaking system positioned on a substrate, according to one or more embodiments described herein;
- (15) FIGS. 11A-11C schematically depict a substrate breaking system, according to one or more embodiments described herein; and
- (16) FIG. 12 depicts a process for cutting and separating a substrate, according to one or more embodiments described herein.
- (17) The features and advantages of the present invention will become more apparent from the detailed description set forth below when taken in conjunction with the drawings, in which like reference characters identify corresponding elements throughout. In the drawings, like reference numbers generally indicate identical, functionally similar, and/or structurally similar elements. The drawing in which an element first appears is indicated by the leftmost digit(s) in the corresponding reference number.

### DETAILED DESCRIPTION

- (18) Reference will now be made in detail to embodiments of a system and processes for laser processing transparent workpieces examples of which are illustrated in the accompanying drawings. Whenever possible, the same reference numerals will be used throughout the drawings to refer to the same or like parts.
- (19) As used herein, “laser processing” comprises directing a laser beam onto and/or into a substrate. In some embodiments, laser processing further comprises translating the laser beam relative to the substrate, for example, along a contour line, along a modification line, or along another pathway. Examples of laser processing include using a laser beam to form a contour comprising a series of defects that extend into the substrate and using a laser beam to form a modification track in the substrate.
- (20) As used herein, “contour,” refers to a set of defects in a substrate formed by translating a laser along a line. As used herein, a contour refers to a virtual two dimensional shape or path in or on a substrate. Thus, while a contour itself is a virtual shape, the contour may be manifest, for example, by a fault line or a crack.
- (21) As used herein, “contour line,” denotes a linear, angled, polygonal or curved line on a surface of a substrate that defines the path traversed by the laser beam as it is moved within the plane of the substrate and that is created by the set of defects. A contour line defines a surface of desired separation in the substrate. A contour line may be formed by creating a plurality of defects in the substrate using various techniques, for example by directing a pulsed laser beam at successive points along the contour line.
- (22) As used herein, a “fault line” refers to a series of closely spaced defect lines extending along and approximating a contour.
- (23) As used herein, a “defect” refers to a region of modified material (e.g., a region of modified refractive index relative to the bulk material), void space, crack, scratch, flaw, hole, perforation or other deformities in the substrate. These defects may be referred to, in various embodiments herein, as defect lines or damage tracks. A defect line or damage track is formed by a laser beam directed onto a single position of the substrate, for a single laser pulse or multiple pulses at the same location. Translating the laser along the substrate results in multiple defect lines that form a contour line. For a line focus laser, the defect may have a linear shape.
- (24) As used herein, the phrase “beam cross section” refers to the cross section of a laser beam along a plane perpendicular to a beam propagation direction of the laser beam, for example, along an X-Y plane when the beam propagation direction is in a Z direction.
- (25) As used herein, “beam spot” refers to a cross section of a laser beam (e.g., a beam cross section) in the impingement surface, i.e., the surface of a substrate in closest proximity to the laser optics.
- (26) As used herein, “impingement surface” refers to the surface of a substrate in closest proximity to the laser optics.
- (27) As used herein, “upstream” and “downstream” refer to the relative position of two locations or components along a beam pathway with respect to a beam source. For example, a first component is upstream from a second component if the first component is closer to the laser optics along the path traversed by the laser beam than the second component.
- (28) As used herein, “laser beam focal line,” refers to pattern of interacting (e.g., crossing) light rays of a laser beam that form a linear, elongated focused region, parallel to an optical axis. The laser beam focal line comprises aberrated light rays that interact (e.g., cross) an optical axis of the laser beam at different positions along the optical axis. Furthermore, the laser beam focal lines described herein are formed using a quasi-non-diffracting beam, mathematically defined in detail below.
- (29) The phrase “transparent substrate,” as used herein, means a substrate formed from glass, glass-ceramic or other material which is transparent, where the term “transparent,” as used herein, means that the material has an optical absorption of less than 20% per mm of material depth, such as less than 10% per mm of material depth for the specified pulsed laser wavelength, or such as less than 1% per mm of material depth for the specified pulsed laser wavelength. Unless otherwise specified, the material has an optical absorption of less than about 20% per mm of material depth. Transparent substrates may comprise glass workpieces formed from glass compositions, such as borosilicate glass, soda-lime glass, aluminosilicate glass, alkali aluminosilicate, alkaline earth aluminosilicate glass, alkaline earth boro-aluminosilicate glass, fused silica, or crystalline materials such

as sapphire, silicon, silicon carbide, gallium arsenide, or combinations thereof. In some embodiments, the substrate may be strengthened via thermal tempering before or after laser processing the substrate. In some embodiments, the glass may be ion-exchangeable, such that the glass composition can undergo ion-exchange for glass strengthening before or after laser processing the substrate. For example, the substrate may comprise ion exchanged and ion exchangeable glass, such as Corning Gorilla® Glass available from Corning Incorporated of Corning, NY (e.g., code 2318, code 2319, and code 2320). Further, such ion exchanged glasses may have coefficients of thermal expansion (CTE) of from about 6 ppm/° C. to about 10 ppm/° C. Other exemplary transparent substrates comprise EAGLE XG® and CORNING LOTUS' available from Corning Incorporated of Corning, NY. Moreover, the substrate may comprise other components which are transparent to the wavelength of the laser, for example, crystals such as sapphire or zinc selenide.

(30) In an ion exchange process, ions in a surface layer of the substrate are replaced by larger ions having the same valence or oxidation state, for example, by partially or fully submerging the substrate in an ion exchange bath. Replacing smaller ions with larger ions causes a layer of compressive stress to extend from one or more surfaces of the substrate to a certain depth within the substrate, referred to as the depth of layer. The compressive stresses are balanced by a layer of tensile stresses (referred to as central tension) such that the net stress in the glass sheet is zero. The formation of compressive stresses at the surface of the glass sheet makes the glass strong and resistant to mechanical damage and, as such, mitigates catastrophic failure of the glass sheet for flaws which do not extend through the depth of layer. In some embodiments, smaller sodium ions in the surface layer of the substrate are exchanged with larger potassium ions. In some embodiments, the ions in the surface layer and the larger ions are monovalent alkali metal cations, such as Li<sup>+</sup> (when present in the glass), Na<sup>+</sup>, K<sup>+</sup>, Rb<sup>+</sup>, and Cs<sup>+</sup>. Alternatively, monovalent cations in the surface layer may be replaced with monovalent cations other than alkali metal cations, such as Ag<sup>+</sup>, Tl<sup>+</sup>, Cu<sup>+</sup>, or the like.

(31) Referring now to FIG. 1, system **10** is schematically depicted as comprising a laser processing system **100** and a substrate breaker system **200**. As discussed further below, the laser processing system **100** is configured to modify a substrate **160** by forming defects (e.g., damage tracks) in the substrate. Substrate breaker system **200** may then separate and break the substrate along a line formed by the defects. Such separates and breaks the substrate **160** into at least two portions. Thus, the combination of the laser processing system **100** and the substrate breaker system **200** together cut and separate a substrate into at least two portions.

(32) The substrate **160** (which may also be referred to as a “workpiece” or a “wafer”) may be a glass, glass-ceramic, or ceramic, exemplary materials of which are disclosed above. Thus, for example, the substrate **160** may be a transparent substrate. Alternatively, the substrate **160** is a semiconductor wafer or an amorphous substrate having a plurality of dies fabricated thereon. In some embodiments, the substrate **160** comprises a stack of substrates, which may be secured together with, for example, an adhesive or bonding. In some embodiments, the bonding may be via eutectic, anodic, or fusion bonding. The stack of substrates **160** may comprise one or more intermediate layers therein.

(33) The substrate **160** may have a thickness in a range of about 50 microns to about 10 mm, or from about 100 microns to about 5 mm, or from about 0.3 mm to about 3 mm.

(34) In some embodiments, substrate **160** may comprise a coating disposed thereon. Exemplary coatings include, for example metallic, conductive (e.g. ITO and organic conductive coatings) and/or polymeric coatings. In other embodiments the substrate **160** may contain macro- or nano-surface structures generated by, for example, etching and/or bonding processes. Exemplary surface structures include voids, openings, and channels. The coatings and/or surface structures may be within or form an intermediate layer between substrates **160** within a stack of the substrates **160**. In some embodiments, the substrate **160** comprises devices fabricated or disposed on the substrate **160**. The devices can be, for example, semiconductor devices, photonic devices, MEMS (micro electromechanical system) devices, or lenses. The substrate **160** may be in any shape including, for example, rectangular or circular shape. In some embodiments, the substrate **160** is a circular wafer.

(35) Referring now to FIGS. 2A and 2B, an exemplary substrate **160** is schematically depicted undergoing laser processing, according to the methods described herein, by laser processing system **100**. In particular, FIG. 2A schematically depicts the formation of a contour line **165** comprising a plurality of defects **172**, which may be used to separate the transparent workpieces **160**. The contour line **165** comprising the plurality of defects **172** may be formed by processing the transparent workpiece **160** with a laser beam **112**, which may comprise an ultra-short pulsed laser beam moving in a translation direction **101** along contour line **165**. The defects **172** may extend, for example, through the depth of the transparent workpiece **160**, and may, in this exemplary embodiment, be orthogonal to an impingement surface of the transparent workpiece **160**. Further, the laser beam **112** initially contacts the substrate **160** at an impingement location **115**, which is a specific location on the impingement surface. As depicted in FIGS. 2A and 2B, a first surface **162** of the substrate **160** comprises the impingement surface, however, it should be understood that in other embodiments, the laser beam **112** may instead initially irradiate a second surface **164** of the substrate **160**. Furthermore, FIG. 2A depicts that the laser beam **112** forms a beam spot **114** projected onto the first surface **162** of the substrate **160**.

(36) FIGS. 2A and 2B depict the laser beam **112** propagating along a beam pathway **111** and oriented such that the laser beam **112** may be focused into a laser beam focal line **113** within the substrate **160**, for example, using an aspheric optical element **120** (FIG. 2C), which may include, for example, an axicon and one or more lenses (e.g., a first lens **130** and a second lens **132**, as described below and depicted in FIG. 2C). The position of the laser beam focal line **113** may be controlled along the Z-axis and about the Z-axis. Further, the laser beam focal line **113** may have a length in a range of from about 0.1 mm to about 100 mm or in a range of from about 0.1 mm to about 10 mm. Various embodiments may be configured to have a laser beam focal line **113** with a length of about 0.1 mm, about 0.2 mm, about 0.3 mm, about 0.4 mm, about 0.5 mm, about 0.7 mm, about 1 mm, about 2 mm, about 3 mm, about 4 mm, or about 5 mm e.g., from about 0.5 mm to about 5 mm. Further, the laser beam focal line **113** may be a portion of a quasi-non-diffracting beam, as defined in more detail below.

(37) In operation, the laser beam **112** may be translated relative to the substrate **160** (e.g., in the translation direction **101**) along the contour line **165** to form the plurality of defects **172** of the contour line **165**. Directing or localizing the laser beam **112** into the substrate **160** generates an induced absorption within the substrate **160** and deposits enough energy to break chemical bonds in the substrate **160** at spaced locations along the contour line **165** to form the defects **172**. According to one or more embodiments, the laser beam **112** may be translated across the substrate **160** by motion of the substrate **160** (e.g., motion of a translation stage **190** coupled to the substrate **160**, as shown in FIG. 2C), motion of the laser beam **112** (e.g., motion of the laser beam focal line **113**), or motion of both the substrate **160** and the laser beam focal line **113**. By translating the laser beam focal line **113** relative to the substrate **160**, the plurality of defects **172** may be formed in the substrate **160**.

(38) In some embodiments, the defects **172** may generally be spaced apart from one another by a distance along the contour line **165** of from about 0.1 μm to about 500 μm, for example, about 1 μm to about 200 μm, about 2 μm to about 100 μm, about 5 μm to about 20 μm, or the like. For example, suitable spacing between the defects **172** may be from about 0.1 μm to about 50 μm, such as from about 5 μm to about 15 μm, from about 5 μm to about 12 μm, from about 7 μm to about 15 μm, or from about 7 μm to about 12 μm. In some embodiments, a spacing between adjacent defects **172** may be about 50 μm or less, 45 μm or less, 40 μm or less, 35 μm or less, 30 μm or less, 25 μm or less, 20 μm or less, 15 μm or less, 10 μm or less, or the like.

(39) As illustrated in FIG. 1A, the plurality of defects **172** of the contour line **165** extend into the substrate **160** and establish a path for crack propagation for separation of the substrate **160** into separate portions along the contour line **165**. Each defect **172** may extend through an entire thickness of the substrate **160** or for less than the entire thickness. The formation of the plurality of defects **172** may be referred to herein as a nano-perforation step due to the small size of the defects **172**. For example, each defect **172** may have a diameter of about 100 microns or less, or about 50 microns or less, or about 10 micron or less, or about 3 micron or less, or about 1 micron or less, or about 900 nm or less, or about 800 nm or less, or about 700 nm or less, or about 600 nm or less or about 500 nm or less, or about 400 nm or less, or in a range from about 200 nm to about 1 micron, or in a range from about 300 nm to about 800 nm. As discussed further below, the location of the plurality of defects **172** dictates where the glass substrate **160** will be separated during a subsequent breaking step.

(40) Forming the contour line **165** comprises translating the laser beam **112** relative to the substrate **160** (e.g., in the translation direction **101**) along the line **170** to form the plurality of defects **172** of the contour line **165**. According to one or more embodiments, the laser beam **112** may be translated across the substrate **160** by motion of the substrate **160**, motion of the laser beam **112** (e.g., motion of the laser beam focal line **113**), or motion of both the substrate **160** and the laser beam **112**, for example, using one or more translation stages **190** (FIG. 2C). By translating the laser beam focal line **113** relative to the substrate **160**, the plurality of defects **172** may be formed in the substrate **160**. Moreover, while the contour line **165** illustrated in FIG. 2A is linear, the contour line **165** may also be nonlinear (i.e., having a curvature). Curved contours may be produced, for example, by translating either the substrate **160** or laser beam focal line **113** with respect to the other in two dimensions instead of one dimension.

(41) In embodiments, the substrate **160** is further acted upon in a subsequent separating step to induce separation of the substrate **160** along the contour line **165**. As discussed further below, the subsequent separating step includes using the substrate breaker system **200** to apply a mechanical force to initiate and propagate a crack along the contour line **165**.

(42) Referring again to FIGS. 2A and 2B, the laser beam **112** used to form the defects **172** further has an intensity distribution  $I(X,Y,Z)$ , where  $Z$  is the beam propagation direction of the laser beam **112**, and  $X$  and  $Y$  are directions orthogonal to the direction of propagation, as depicted in the figures. The  $X$ -direction and  $Y$ -direction may also be referred to as cross-sectional directions and the  $X$ - $Y$  plane may be referred to as a cross-sectional plane. The intensity distribution of the laser beam **112** in a cross-sectional plane may be referred to as a cross-sectional intensity distribution.

(43) The laser beam **112** at the beam spot **114** or other cross sections may comprise a quasi-non-diffracting beam, for example, a beam having low beam divergence as mathematically defined below, by propagating the laser beam **112** (e.g., the laser beam **112**, such as a Gaussian beam, using a beam source **110**, such as a pulsed beam source) through an aspheric optical element **120**, as described in more detail below with respect to the optical assembly **103** depicted in FIG. 2C. Beam divergence refers to the rate of enlargement of the beam cross section in the direction of beam propagation (i.e., the  $Z$  direction). One example beam cross section discussed herein is the beam spot **114** of the laser beam **112** projected onto the transparent workpiece **160**. Example quasi-non-diffracting beams include Gauss-Bessel beams and Bessel beams.

(44) Diffraction is one factor that leads to divergence of laser beams **112**. Other factors include focusing or defocusing caused by the optical systems forming the laser beams **112** or refraction and scattering at interfaces. Laser beams **112** for forming the defects **172** of the contour line **165** may form laser beam focal lines **113** with low divergence and weak diffraction. The divergence of the laser beam **112** is characterized by the Rayleigh range  $Z_{sub.R}$ , which is related to the variance  $\sigma_{sup.2}$  of the intensity distribution and beam propagation factor  $M_{sup.2}$  of the laser beam **112**. Additional information on beam divergence can be found in the articles entitled “New Developments in Laser Resonators” by A.E. Siegman in SPIE Symposium Series Vol. 1224, p. 2 (1990) and “ $M_{sup.2}$  factor of Bessel-Gauss beams” by R. Borghi and M. Santarsiero in Optics Letters, Vol. 22(5), 262 (1997), the disclosures of which are incorporated herein by reference in their entirety. Additional information can also be found in the international standards ISO 11146-1:2005(E) entitled “Lasers and laser-related equipment—Test methods for laser beam widths, divergence angles and beam propagation ratios—Part 1: Stigmatic and simple astigmatic beams”, ISO 11146-2:2005(E) entitled “Lasers and laser-related equipment—Test methods for laser beam widths, divergence angles and beam propagation ratios—Part 2: General astigmatic beams”, and ISO 11146-3:2004(E) entitled “Lasers and laser-related equipment—Test methods for laser beam widths, divergence angles and beam propagation ratios—Part 3: Intrinsic and geometrical laser beam classification, propagation and details of test methods”, the disclosures of which are incorporated herein by reference in their entirety.

(45) Beam cross section is characterized by shape and dimensions. The dimensions of the beam cross section are characterized by a spot size of the beam. For a Gaussian beam, spot size is frequently defined as the radial extent at which the intensity of the beam decreases to  $1/e_{sup.2}$  of its maximum value, which is denoted as  $I_{vo}$ . The maximum intensity of a Gaussian beam occurs at the center ( $x=0$  and  $y=0$  (Cartesian) or  $r=0$  (cylindrical)) of the intensity distribution and radial extent used to determine spot size is measured relative to the center.

(46) Beams with axisymmetric (i.e. rotationally symmetric around the beam propagation axis  $Z$ ) cross sections can be characterized by a single dimension or spot size that is measured at the beam waist location as specified in Section 3.12 of ISO 11146-1:2005(E). For a Gaussian beam, the spot size is equal to  $w_{sub.o}$ , which corresponds to  $2\sigma_{sub.0}$ , or  $2\sigma_{sub.0y}$ . For an axisymmetric beam having an axisymmetric cross section, such as a circular cross section,  $\sigma_{sub.0x}=\sigma_{sub.0y}$ . Thus, for axisymmetric beams, the cross section dimension may be characterized with a single spot size parameter, where  $w_{sub.o}=2\sigma_{sub.0}$ . Spot size can be similarly defined for non-axisymmetric beam cross sections where, unlike an axisymmetric beam,  $\sigma_{sub.0x}\neq\sigma_{sub.0y}$ . Thus, when the spot size of the beam is non-axisymmetric, it is necessary to characterize the cross-sectional dimensions of a non-axisymmetric beam with two spot size parameters:  $w_{sub.ox}$  and  $w_{sub.oy}$  in the  $x$ -direction and  $y$ -direction, respectively, where

$$w_{sub.ox}=2\sigma_{sub.0x} \quad (1)$$

$$w_{sub.oy}=2\sigma_{sub.0y} \quad (2)$$

(47) Further, the lack of axial (i.e. arbitrary rotation angle) symmetry for a non-axisymmetric beam means that the results of a calculation of values of  $\sigma_{sub.0x}$  and  $\sigma_{sub.0y}$  will depend on the choice of orientation of the  $X$ -axis and  $Y$ -axis. ISO 11146-1:2005(E) refers to these reference axes as the principal axes of the power density distribution (Section 3.3-3.5) and in the following discussion we will assume that the  $X$  and  $Y$  axes are aligned with these principal axes. Further, an angle  $\phi$  about which the  $X$ -axis and  $Y$ -axis may be rotated in the cross-sectional plane (e.g., an angle of the  $X$ -axis and  $Y$ -axis relative to reference positions for the  $X$ -axis and  $Y$ -axis, respectively) may be used to define minimum ( $w_{sub.o,min}$ ) and maximum values ( $w_{sub.o,max}$ ) of the spot size parameters for a non-axisymmetric beam:

$$w_{sub.o,min}=2\sigma_{sub.0,min} \quad (3)$$

$$w_{sub.o,max}=2\sigma_{sub.0,max} \quad (4)$$

where  $2\sigma_{sub.0,min}=2\sigma_{sub.0x}(\phi_{sub.min,x})=2\sigma_{sub.0y}(\phi_{sub.min,y})$  and  $2\sigma_{sub.0,max}=2\sigma_{sub.0x}(\phi_{sub.max,x})=2\sigma_{sub.0y}(\phi_{sub.max,y})$ . The magnitude of the axial asymmetry of the beam cross section can be quantified by the aspect ratio, where the aspect ratio is defined as the ratio of  $w_{sub.o,max}$  to  $w_{sub.o,min}$ . An axisymmetric beam cross section has an aspect ratio of 1.0, while elliptical and other non-axisymmetric beam cross sections have aspect ratios greater than 1.0, for example, greater than 1.1, greater than 1.2, greater than 1.3, greater than 1.4, greater than 1.5, greater than 1.6, greater than 1.7, greater than 1.8, greater than 1.9, greater than 2.0, greater than 3.0, greater than 5.0, greater than 10.0, or the like.

(48) To promote uniformity of defects **172** in the beam propagation direction (e.g., depth dimension of the transparent workpiece **160**), a laser beam **112** having low divergence may be used. In one or more embodiments, laser beams **112** having low divergence may be utilized for forming defects **172**.

(49) Beams with Gaussian intensity profiles may be less preferred for laser processing to form defects **172** because, when focused to small enough spot sizes (such as spot sizes in the range of microns, such as about 1-5  $\mu\text{m}$  or about 1-10  $\mu\text{m}$ ) to enable available laser pulse energies to modify materials such as glass, they are highly diffracting and diverge significantly over short propagation distances. To achieve low divergence, it is desirable to control or optimize the intensity distribution of the pulsed laser beam to reduce diffraction. Pulsed laser beams may be non-diffracting or weakly diffracting. Weakly diffracting laser beams include quasi-non-diffracting laser beams. Representative weakly diffracting laser beams include Bessel beams, Gauss-Bessel beams, Airy beams, Weber beams, and Mathieu beams.

(50) For non-axisymmetric beams, the Rayleigh ranges  $Z_{sub.Rx}$  and  $Z_{sub.Ry}$  are unequal. The values of  $Z_{sub.Rx}$  and  $Z_{sub.Ry}$  will accordingly vary, and each will have a minimum value and a maximum value that correspond to the principal axes, with the minimum value of  $Z_{sub.Rx}$  being denoted as  $Z_{sub.Rx,min}$  and the minimum value of  $Z_{sub.Ry}$  being denoted  $Z_{sub.Ry,min}$  for an arbitrary beam profile  $Z_{sub.Rx,min}$  and  $Z_{sub.Ry,min}$  can be shown to be given by

$$(51) \quad Z_{Rx, \min} = \frac{4\pi\sigma_{0, \min}^2}{M_x^2 \lambda} \text{ and } (52)$$

$$Z_{Ry, \min} = \frac{4\pi\sigma_{0, \min}^2}{M_y^2 \lambda} (6)$$

(52) Since divergence of the laser beam occurs over a shorter distance in the direction having the smallest Rayleigh range, the intensity distribution of the laser beam **112** used to form defects **172** may be controlled so that the minimum values of Z.sub.Rx and Z.sub.Ry (or for axisymmetric beams, the value of Z.sub.R) are as large as possible. Since the minimum value Z.sub.Rx,min of Z.sub.Rx and the minimum value Z.sub.Ry,min of Z.sub.Ry differ for a non-axisymmetric beam, a laser beam **112** may be used with an intensity distribution that makes the smaller of Z.sub.Rx,min and Z.sub.Ry,min as large as possible when forming damage regions.

(53) In some embodiments, the smaller of Z.sub.Rx,min and Z.sub.Ry,min (or for axisymmetric beams, the value of Z.sub.R) is greater than or equal to 50  $\mu\text{m}$ , greater than or equal to 100  $\mu\text{m}$ , greater than or equal to 200  $\mu\text{m}$ , greater than or equal to 300  $\mu\text{m}$ , greater than or equal to 500  $\mu\text{m}$ , greater than or equal to 1 mm, greater than or equal to 2 mm, greater than or equal to 3 mm, greater than or equal to 5 mm, in the range from 50  $\mu\text{m}$  to 10 mm, in the range from 100  $\mu\text{m}$  to 5 mm, in the range from 200  $\mu\text{m}$  to 4 mm, in the range from 300  $\mu\text{m}$  to 2 mm, or the like.

(54) The values and ranges for the smaller of Z.sub.Rx,min and Z.sub.Ry,min (or for axisymmetric beams, the value of Z.sub.R) specified herein are achievable for different wavelengths to which the workpiece is transparent through adjustment of the spot size parameter w.sub.o,min defined in Equation (3). In some embodiments, the spot size parameter w.sub.o,min is greater than or equal to 0.25  $\mu\text{m}$ , greater than or equal to 0.50  $\mu\text{m}$ , greater than or equal to 0.75  $\mu\text{m}$ , greater than or equal to 1.0  $\mu\text{m}$ , greater than or equal to 2.0  $\mu\text{m}$ , greater than or equal to 3.0  $\mu\text{m}$ , greater than or equal to 5.0  $\mu\text{m}$ , in the range from 0.25  $\mu\text{m}$  to 10  $\mu\text{m}$ , in the range from 0.25  $\mu\text{m}$  to 5.0  $\mu\text{m}$ , in the range from 0.25  $\mu\text{m}$  to 2.5  $\mu\text{m}$ , in the range from 0.50  $\mu\text{m}$  to 10  $\mu\text{m}$ , in the range from 0.50  $\mu\text{m}$  to 5.0  $\mu\text{m}$ , in the range from 0.50  $\mu\text{m}$  to 2.5  $\mu\text{m}$ , in the range from 0.75  $\mu\text{m}$  to 10  $\mu\text{m}$ , in the range from 0.75  $\mu\text{m}$  to 5.0  $\mu\text{m}$ , in the range from 0.75  $\mu\text{m}$  to 2.5  $\mu\text{m}$ , or the like.

(55) Non-diffracting or quasi-non-diffracting beams generally have complicated intensity profiles, such as those that decrease non-monotonically vs. radius. By analogy to a Gaussian beam, an effective spot size w.sub.o,eff can be defined for non-axisymmetric beams as the shortest radial distance, in any direction, from the radial position of the maximum intensity (r=0) at which the intensity decreases to 1/e.sup.2 of the maximum intensity. Further, for axisymmetric beams w.sub.o,eff is the radial distance from the radial position of the maximum intensity (r=0) at which the intensity decreases to 1/e.sup.2 of the maximum intensity. A criterion for Rayleigh range based on the effective spot size w.sub.o,eff for non-axisymmetric beams or the spot size w.sub.o for axisymmetric beams can be specified as non-diffracting or quasi-non-diffracting beams for forming damage regions using equation (7) for non-axisymmetric beams or equation (8) for axisymmetric beams:

$$(56) \quad \text{Smaller of } Z_{Rx, \min}, Z_{Ry, \min} > F_D \frac{\pi w_{0, \text{eff}}^2}{\lambda} (7)$$

$$Z_R > F_D \frac{\pi w_0^2}{\lambda} (8)$$

where F.sub.D is a dimensionless divergence factor having a value of at least 10, at least 50, at least 100, at least 250, at least 500, at least 1000, in the range from 10 to 2000, in the range from 50 to 1500, in the range from 100 to 1000. For a non-diffracting or quasi-non-diffracting beam, the smaller of Z.sub.Rx,min, Z.sub.Ry,min in Equation (7), over which the effective beam size doubles, is F.sub.D times the distance expected if a typical Gaussian beam profile were used. The dimensionless divergence factor F.sub.D provides a criterion for determining whether or not a laser beam is quasi-non-diffracting. As used herein, the laser beam **112** is considered quasi-non-diffracting if the characteristics of the laser beam satisfy Equation (7) or Equation (8) with a value of F.sub.D $\geq$ 10. As the value of F.sub.D increases, the laser beam **112** approaches a more nearly perfect non-diffracting state. Moreover, it should be understood that Equation (8) is merely a simplification of Equation (7) and as such, Equation (7) mathematically describes the dimensionless divergence factor F.sub.D for both axisymmetric and non-axisymmetric pulsed laser beams **112**.

(57) Referring now to FIG. 2C, an optical assembly **103** for producing a laser beam **112** that is quasi-non-diffracting and that forms the laser beam focal line **113** at the substrate **160** using the aspheric optical element **120** (e.g., an axicon **122**) is schematically depicted. The optical assembly **103** includes a beam source **110** that outputs the laser beam **112**, first lens **130** and second lens **132**. The beam source **110** may comprise any known or yet to be developed beam source **110** configured to output laser beams **112**, for example, pulsed laser beams or continuous wave laser beams. In some embodiments, the beam source **110** may output a laser beam **112** comprising a wavelength of, for example, 1064 nm, 1030 nm, 532 nm, 530 nm, 355 nm, 343 nm, or 266 nm, or 215 nm. Further, the laser beam **112** used to form defects **172** in the substrate **160** may be well suited for materials that are transparent to the selected pulsed laser wavelength.

(58) Further, the substrate **160** may be positioned such that the laser beam **112** output by the beam source **110** irradiates the substrate **160**, for example, after traversing the aspheric optical element **120** and thereafter, both the first lens **130** and the second lens **132**. An optical axis **102** extends between the beam source **110** and the substrate **160** (along the Z-axis in the embodiment depicted in FIG. 2C) such that when the beam source **110** outputs the laser beam **112**, the beam pathway **111** of the laser beam **112** extends along the optical axis **102**.

(59) Suitable laser wavelengths for forming defects **172** are wavelengths at which the combined losses of linear absorption and scattering by the substrate **160** are sufficiently low. In embodiments, the combined losses due to linear absorption and scattering by the substrate **160** at the wavelength are less than 20%/mm, or less than 15%/mm, or less than 10%/mm, or less than 5%/mm, or less than 1%/mm, where the dimension “/mm” means per millimeter of distance within the substrate **160** in the beam propagation direction of the laser beam **112** (e.g., the Z direction). Representative wavelengths for many glass substrates include fundamental and harmonic wavelengths of Nd.sup.3+ (e.g., Nd.sup.3+:YAG or Nd.sup.3+:YVO.sub.4 having fundamental wavelength near 1064 nm and higher order harmonic wavelengths near 532 nm, 355 nm, and 266 nm). Other wavelengths in the ultraviolet, visible, and infrared portions of the spectrum that satisfy the combined linear absorption and scattering loss requirement for a given substrate material can also be used.

(60) In operation, the laser beam **112** output by the beam source **110** may create multi-photon absorption (MPA) in the substrate **160**. MPA is the simultaneous absorption of two or more photons of identical or different frequencies that excites a molecule from one state (usually the ground state) to a higher energy electronic state (i.e., ionization). The energy difference between the involved lower and upper states of the molecule is equal to the sum of the energies of the involved photons. MPA, also called induced absorption, can be a second-order or third-order process (or higher order), for example, that is several orders of magnitude weaker than linear absorption. It differs from linear absorption in that the strength of second-order induced absorption may be proportional to the square of the light intensity, for example, and thus it is a nonlinear optical process.

(61) The perforation step that creates the contour line **165** (FIGS. 2A and 2B) may utilize the beam source **110** (e.g., a pulsed beam source such as an ultra-short pulse laser) in combination with the aspheric optical element **120**, the first lens **130**, and the second lens **132**, to irradiate the substrate **160** and generate the laser beam focal line **113**. The laser beam focal line **113** comprises a quasi-non-diffracting beam, such as a Gauss-Bessel beam or Bessel beam, as defined above, and may fully or partially perforate the substrate **160** to form defects **172** in the substrate **160**, which may form the contour line **165**. However, it is also contemplated that the laser beam focal line **113** is formed using a curve effect or filamentation. In embodiments in which the laser beam **112** comprises a pulsed laser beam, the pulse duration of the individual pulses is in a range of from about 1 femtosecond to about 200 picoseconds, such as from about 1 picosecond to about 100 picoseconds, 5 picoseconds to about 20 picoseconds, or the like, and the repetition rate of the individual pulses may be in a range from about 1 kHz to 4 MHz, such as in a range from about 10 kHz to about 3 MHz, or from about 10 kHz to about 650 kHz.

(62) Referring also to FIGS. 3A and 3B, in addition to a single pulse operation at the aforementioned individual pulse repetition rates, in embodiments comprising a pulsed laser beam, the pulses may be produced in pulse bursts **201** of two sub-pulses **201A** or more (such as, for example,

3 sub-pulses, 4 sub-pulses, 5 sub-pulses, 10 sub-pulses, 20 sub-pulses, or more per pulse burst, such as from 1 to 30 sub-pulses per pulse burst **201**, or from 5 to 20 sub-pulses per pulse burst **201**). While not intending to be limited by theory, a pulse burst is a short and fast grouping of sub-pulses that creates an optical energy interaction with the material (i.e. MPA in the material of the substrate **160**) on a time scale not easily accessible using a single-pulse operation. While still not intending to be limited by theory, the energy within a pulse burst (i.e. a group of pulses) is conserved. As an illustrative example, for a pulse burst having an energy of 100  $\mu\text{J}$ /burst and 2 sub-pulses, the 100  $\mu\text{J}$ /burst energy is split between the 2 pulses for an average energy of 50  $\mu\text{J}$  per sub-pulse and for a pulse burst having an energy of 100  $\mu\text{J}$ /burst and 10 sub-pulses, the 100  $\mu\text{J}$ /burst is split amongst the 10 sub-pulses for an average energy of 10  $\mu\text{J}$  per sub-pulse. Further, the energy distribution among the sub-pulses of a pulse burst does not need to be uniform. In fact, in some instances, the energy distribution among the sub-pulses of a pulse burst is in the form of an exponential decay, where the first sub-pulse of the pulse burst contains the most energy, the second sub-pulse of the pulse burst contains slightly less energy, the third sub-pulse of the pulse burst contains even less energy, and so on. However, other energy distributions within an individual pulse burst are also possible, where the exact energy of each sub-pulse can be tailored to effect different amounts of modification to the transparent workpiece **160**.

(63) While still not intending to be limited by theory, when the defects **172** of the one or more contours **170** are formed with pulse bursts having at least two sub-pulses, the force necessary to separate the substrate **160** along the contour line **165** (i.e. the maximum break resistance) is reduced compared to the maximum break resistance of a contour line **165** with the same spacing between adjacent defects **172** in an identical substrate **160** that is formed using a single pulse laser. For example, the maximum break resistance of a contour line **165** formed using a single pulse is at least two times greater than the maximum break resistance of a contour line **165** formed using a pulse burst having 2 or more sub-pulses. Further, the difference in maximum break resistance between a contour line **165** formed using a single pulse and a contour line **165** formed using a pulse burst having 2 sub-pulses is greater than the difference in maximum break resistance between a contour line **165** formed using a pulse burst having 2 sub-pulses and a pulse burst having 3 sub-pulses. Thus, pulse bursts may be used to form contour lines **165** that separate easier than contour lines **165** formed using a single pulse laser.

(64) Referring still to FIGS. 3A and 3B, the sub-pulses **201A** within the pulse burst **201** may be separated by a duration that is in a range from about 1 nsec to about 50 nsec, for example, from about 10 nsec to about 30 nsec, such as about 20 nsec. In other embodiments, the sub-pulses **201A** within the pulse burst **201** may be separated by a duration of up to 100 psec (for example, 0.1 psec, 5 psec, 10 psec, 15 psec, 18 psec, 20 psec, 22 psec, 25 psec, 30 psec, 50 psec, 75 psec, or any range therebetween). For a given laser, the time separation T.sub.p (FIG. 3B) between adjacent sub-pulses **201A** within a pulse burst **201** may be relatively uniform (e.g., within about 10% of one another). For example, in some embodiments, each sub-pulse **201A** within a pulse burst **201** is separated in time from the subsequent sub-pulse by approximately 20 nsec (50 MHz). Further, the time between each pulse burst **201** may be from about 0.25 microseconds to about 1000 microseconds, e.g., from about 1 microsecond to about 10 microseconds, or from about 3 microseconds to about 8 microseconds.

(65) In some of the exemplary embodiments of the beam source **110** described herein, the time separation T.sub.b (FIG. 3B) is about 5 microseconds for the beam source **110** outputting a laser beam **112** comprising a burst repetition rate of about 200 kHz. The laser burst repetition rate is related to the time T.sub.b between the first pulse in a burst to the first pulse in the subsequent burst (laser burst repetition rate=1/T.sub.b). In some embodiments, the laser burst repetition rate may be in a range of from about 1 kHz to about 4 MHz. In embodiments, the laser burst repetition rates may be, for example, in a range of from about 10 kHz to 650 kHz. The time T.sub.b between the first pulse in each burst to the first pulse in the subsequent burst may be from about 0.25 microsecond (4 MHz burst repetition rate) to about 1000 microseconds (1 kHz burst repetition rate), for example from about 0.5 microseconds (2 MHz burst repetition rate) to about 40 microseconds (25 kHz burst repetition rate), or from about 2 microseconds (500 kHz burst repetition rate) to about 20 microseconds (50 kHz burst repetition rate). The exact timing, pulse duration, and burst repetition rate may vary depending on the laser design, but short pulses (T.sub.d<20 psec and, in some embodiments, T.sub.d≤15 psec) of high intensity have been shown to work particularly well.

(66) The burst repetition rate may be in a range of from about 1 kHz to about 2 MHz, such as from about 1 kHz to about 200 kHz. Bursting or producing pulse bursts **201** is a type of laser operation where the emission of sub-pulses **201A** is not in a uniform and steady stream but rather in tight clusters of pulse bursts **201**. The pulse burst laser beam may have a wavelength selected based on the material of the substrate **160** being operated on such that the material of the substrate **160** is substantially transparent at the wavelength. The average laser power per burst measured at the material may be at least about 40  $\mu\text{J}$  per mm of thickness of material. For example, in embodiments, the average laser power per burst may be from about 40  $\mu\text{J}/\text{mm}$  to about 2500  $\mu\text{J}/\text{mm}$ , or from about 500  $\mu\text{J}/\text{mm}$  to about 2250  $\mu\text{J}/\text{mm}$ . In a specific example, for 0.5 mm to 0.7 mm thick Corning EAGLE XG® substrate, pulse bursts of from about 300  $\mu\text{J}$  to about 600  $\mu\text{J}$  may cut and/or separate the substrate, which corresponds to an exemplary range of about 428  $\mu\text{J}/\text{mm}$  to about 1200  $\mu\text{J}/\text{mm}$  (i.e., 300  $\mu\text{J}/0.7\text{ mm}$  for 0.7 mm EAGLE XG® glass and 600  $\mu\text{J}/0.5\text{ mm}$  for a 0.5 mm EAGLE XG® glass).

(67) The energy required to modify the substrate **160** is the pulse energy, which may be described in terms of pulse burst energy (i.e., the energy contained within a pulse burst **201** where each pulse burst **201** contains a series of sub-pulses **201A**), or in terms of the energy contained within a single laser pulse (many of which may comprise a burst). The pulse energy (for example, pulse burst energy) may be from about 25  $\mu\text{J}$  to about 750  $\mu\text{J}$ , e.g., from about 50  $\mu\text{J}$  to about 500  $\mu\text{J}$ , or from about 50  $\mu\text{J}$  to about 250  $\mu\text{J}$ . For some glass compositions, the pulse energy (e.g., pulse burst energy) may be from about 100  $\mu\text{J}$  to about 250  $\mu\text{J}$ . However, for display or TFT glass compositions, the pulse energy (e.g., pulse burst energy) may be higher (e.g., from about 300  $\mu\text{J}$  to about 500  $\mu\text{J}$ , or from about 400  $\mu\text{J}$  to about 600  $\mu\text{J}$ , depending on the specific glass composition of the substrate **160**).

(68) While not intending to be limited by theory, the use of a laser beam **112** comprising a pulsed laser beam capable of generating pulse bursts is advantageous for cutting and separating materials, for example glass materials. In contrast with the use of single pulses spaced apart in time by the repetition rate of the single-pulsed laser, the use of a burst sequence that spreads the pulse energy over a rapid sequence of pulses within the burst allows access to larger timescales of high intensity interaction with the material than is possible with single-pulse lasers. The use of pulse bursts (as opposed to a single pulse operation) increases the size (e.g., the cross-sectional size) of the defects **172**, which facilitates the connection of adjacent defects **172** when separating substrate **160** along the one or more contour lines **165**, thereby minimizing unintended crack formation. Further, using a pulse burst to form defects **172** increases the randomness of the orientation of cracks extending outward from each defect **172** into the bulk material of the substrate **160** such that individual cracks extending outward from defects **172** do not influence or otherwise bias the separation of the contour line **165** such that separation of the defects **172** follows the contour line **165**, minimizing the formation of unintended cracks.

(69) Referring again to FIG. 2C, the aspheric optical element **120** is positioned within the beam pathway **111** between the beam source **110** and the substrate **160**. In operation, propagating the laser beam **112**, e.g., an incoming Gaussian beam, through the aspheric optical element **120** may alter the laser beam **112** such that the portion of the laser beam **112** propagating beyond the aspheric optical element **120** is quasi-non-diffracting, as described above. The aspheric optical element **120** may comprise any optical element comprising an aspherical shape. In some embodiments, the aspheric optical element **120** may comprise a conical wavefront producing optical element, such as an axicon lens, for example, a negative refractive axicon lens, a positive refractive axicon lens, a reflective axicon lens, a diffractive axicon lens, a programmable spatial light modulator axicon lens (e.g., a phase axicon), or the like.

(70) In some embodiments, the aspheric optical element **120** comprises at least one aspheric surface whose shape is mathematically described as:  $z' = (\text{cr.sup.2}/1) + (1 - (1 + k)(\text{c.sup.2r.sup.2})).\text{sup.1}/2 + (\text{a.sub.1r} + \text{a.sub.2r.sup.2} + \text{a.sub.3r.sup.3} + \text{a.sub.4r.sup.4} + \text{a.sub.5r.sup.5} + \text{a.sub.6r.sup.6} + \text{a.sub.7r.sup.7} + \text{a.sub.8r.sup.8} + \text{a.sub.9r.sup.9} + \text{a.sub.10r.sup.10} + \text{a.sub.11r.sup.11})$  where  $z'$  is the surface sag of the aspheric surface,  $r$  is the distance between the aspheric surface and the optical axis **102** in a radial direction (e.g., in an X-direction or a Y-direction),  $c$  is the surface curvature of the aspheric surface (i.e.  $\text{c.sub.i} = 1/\text{R.sub.i}$ , where  $R$  is the surface radius of the aspheric surface),  $k$  is the conic constant, and coefficients  $\text{a.sub.i}$  are the first through the twelfth order aspheric coefficients or higher order aspheric

coefficients (polynomial aspheres) describing the aspheric surface, at least one example embodiment, the aspheric optical element **120** includes the following coefficients a.sub.1-a.sub.7, respectively: -0.085274788; 0.065748845; 0.077574995; -0.054148636; 0.022077021; -0.0054987472; 0.0006682955; and the aspheric coefficients a.sub.8-a.sub.12 are 0. In this embodiment, the at least one aspheric surface has the conic constant  $k=0$ . However, because the a.sub.1 coefficient has a nonzero value, this is equivalent to having a conic constant  $k$  with a non-zero value. Accordingly, an equivalent surface may be described by specifying a conic constant  $k$  that is non zero, a coefficient a.sub.1 that is non-zero, or a combination of a nonzero  $k$  and a non-zero coefficient a.sub.1. Further, in some embodiments, the at least one aspheric surface is described or defined by at least one higher order aspheric coefficients a.sub.2-a.sub.12 with non-zero value (i.e., at least one of a.sub.2, a.sub.3, . . . , a.sub.12 $\neq$ 0). In one example embodiment, the aspheric optical element **120** comprises a third-order aspheric optical element such as a cubically shaped optical element, which comprises a coefficient a.sub.3 that is non-zero.

(71) In some embodiments, when the aspheric optical element **120** comprises an axicon **122** (as depicted in FIG. 2C), the axicon **122** may have a laser output surface **126** (e.g., conical surface) having an angle of about 1.2°, such as from about 0.5° to about 5°, or from about 1° to about 1.5°, or even from about 0.5° to about 20°, the angle measured relative to a laser input surface **124** (e.g., flat surface) upon which the laser beam **112** enters the axicon **122**. Further, the laser output surface **126** terminates at a conical tip. Moreover, the aspheric optical element **120** includes a centerline axis **125** extending from the laser input surface **124** to the laser output surface **126** and terminating at the conical tip. In other embodiments, the aspheric optical element **120** may comprise a waxicon, a spatial phase modulator such as a spatial light modulator, or a diffractive optical grating. In operation, the aspheric optical element **120** shapes the incoming laser beam **112** (e.g., an incoming Gaussian beam) into a quasi-non-diffracting beam, which, in turn, is directed through the first lens **130** and the second lens **132**.

(72) Referring still to FIG. 2C, the first lens **130** is positioned upstream the second lens **132** and may collimate the laser beam **112** within a collimation space **134** between the first lens **130** and the second lens **132**. Further, the second lens **132** may focus the laser beam **112** into the substrate **160**, which may be positioned at an imaging plane **104**. In some embodiments, the first lens **130** and the second lens **132** each comprise plano-convex lenses. When the first lens **130** and the second lens **132** each comprise plano-convex lenses, the curvature of the first lens **130** and the second lens **132** may each be oriented toward the collimation space **134**. In other embodiments, the first lens **130** may comprise other collimating lenses and the second lens **132** may comprise a meniscus lens, an asphere, or another higher-order corrected focusing lens.

(73) Now referring to FIG. 4A, an exemplary substrate breaker system **200** applies a mechanical force to the substrate **160** to separate the substrate **160** along the contour line **165**. Thus, substrate breaker system **200** separates the substrate **160** into at least two portions along the contour line **165**.

(74) As shown in FIG. 4A, substrate breaker system **200** comprises a plurality of breaker bars **220**, which are each configured to apply a mechanical force to the substrate **160**. As discussed further below, one or more of the breaker bars **220** can comprise a different length from one or more other breaker bars **220**. In some embodiments, the breaker bars **220** are arranged into a plurality of sets of breaker bars (for example, wherein each set includes three individual breaker bars of the plurality of breaker bars **220**). FIG. 4A, for example, shows a first set of breaker bars **251** that comprises a first breaker bar **222**, a second breaker bar **224**, and a third breaker bar **226**. It is noted that the plurality of breaker bars **220** comprise at least the first, second, and third breaker bars **222**, **224**, **226**. In the embodiment of FIG. 4A, the first set of breaker bars **251** comprises three breaker bars. First and second breaker bars **222**, **224** are positioned on a first side of the substrate **160** (such as first surface **162**, as shown in FIG. 2A), and third breaker bar **226** is positioned on a second side of the substrate **160** (such as second surface **164**, as shown in FIG. 2A). However, it is also contemplated that the first and second breaker bars **222**, **224** may be positioned on second surface **164** of the substrate **160** and that the third breaker bar **226** may be positioned on first surface **162** of the substrate **160**.

(75) The first and second breaker bars **222**, **224** can move laterally such that the breaker bars can move toward and away from each other. Furthermore, the third breaker bar **226** can also move laterally relative to the first and second breaker bars **222**, **224**. Therefore, the third breaker bar **226** may be positioned in the middle between the first and second breaker bars **222**, **224**. Such also allows the breaker bars to each be placed in an exact location relative to the contour line **165**, as discussed further below.

(76) The plurality of breaker bars **220** each comprise an edge **225** with a sharp point, sharp line, rounded edge, or tapered edge for pressing on the substrate **160** to separate the substrate along the contour line **165**. Thus, edge **225** is in contact with the substrate **160** during the separating process. As shown in FIG. 4A, in some embodiments, the edge **225** of the third breaker bar **226** is disposed on and along the contour line **165** and the edge **225** of the first and second breaker bars **222**, **224** are disposed adjacent to but outside of the contour line **165**. Thus, the edge **225** of the first and second breaker bars **222**, **224** may be spaced a distance from the contour line **165** during the separating step. The distance between the edge **225** of the first breaker bar **222** and the contour line **165** may be the same or different from the edge **225** of the second breaker bar **224** and the contour line **165**. Furthermore, the first and second breaker bars **222**, **224** apply a downward pressure on the substrate **160** (according to FIG. 4A) and the third breaker bar **226** applies an upward pressure on the substrate **160** (according to FIG. 4A) in order to separate the substrate **160** along the contour line **165**. However, it is noted that the terms “downward” and “upward” as used herein are merely used to depict the relative difference in pressure application and may vary depending on the orientation of the system **200**.

(77) The edges **225** of the first, second, and third breaker bars **222**, **224**, **226** can be formed of the same or different materials, can comprise the same or different edge angles (for example, an angle of the sharp point or taper at the edge **225**), and have the same or different lengths and widths. The edges **225** provide minimum surface contact with the substrate **160** and provide a maximum force to a surface of the substrate **160** (e.g., surface **162** and/or surface **164**). In some embodiments, the edges **225** may be a knife, blade, or sharp tip. In other embodiments, the edges **225** may have a tapered round edge.

(78) The plurality of breaker bars **220** (including the edges **225** of each) can be formed of one or more hard materials for easily machining, such as metal, in particular stainless steel, or one or more softer materials for better flatness conformality, such as hard plastic. The length of the breaker bars **220** in embodiments is equal to or greater than the length of the contour line **165** in the substrate **160**. In some embodiments, the length of the breaker bars exceeds about the length of the contour line **165** by about 10% or greater, or about 20% or greater, or about 30% or greater, or about 40% or greater of the length of the contour line **165**. Thus, if the contour line **165** has a length of 400 mm, the length of a breaker bar is about 440 mm.

(79) During the breaking processes disclosed herein, only the edge **225** of each breaker bar **220** contacts the substrate **160**, thus reducing any damage to the substrate **160**. In embodiments in which the substrate **160** comprises a coating (either on one or both of the first surface **162** and the second surface **164**), only the edge **225** of each breaker bar **220** oriented directly to the coating contacts the coating, thus reducing any damage to the coating. The edges **225** may each have a very narrow tip, with a diameter ranging from about 100 microns to about 300 microns, or about 150 microns to about 25 microns.

(80) As also shown in FIG. 4A, substrate **160** is disposed on a support **260**. As discussed further below, the support **260** secures and holds the substrate **160** during the separating and cutting processes using the substrate breaker system **200**. Additionally, the support **260** may also secure and hold the substrate **160** during the laser modification step using the laser processing system **100**. In the embodiments that include the support **260**, the edge **225** of the third breaker bar **226** may contact the support **260** (rather than the substrate **160**) during the separating step and the first and second breaker bars **222**, **224** may contact the substrate **160** directly. In other embodiments that include the support **260**, the first and second breaker bars **222**, **224** may contact the support **260** (rather than the substrate **160**) and the third breaker bar **226** may contact the substrate **160** directly.

(81) The plurality of breaker bars **220** are each secured to system **200** using, for example, one or more base members **230**. For example, in the embodiment of FIG. 4A, the first breaker bar **222** is secured with a first base member **232**, the second breaker bar **224** is secured with a second base member **234**, and the third breaker bar **226** is secured with a third base member **236**. Furthermore, each breaker bar **220** may comprise one or more holes **240** for attachment to the base members **230**.

(82) FIG. 4B shows an enlarged view of the breaker bars **220** of FIG. 4A. Additionally, FIG. 4C shows an enlarged view of the breaker bars **220** of



FIG. 4A secured to the base members 230.

(83) As discussed above, FIGS. 4A-4C show a first set of breaker bars 251 that comprise three breaker bars (222, 224, 226). It is also contemplated that system 200 comprises more than one set of breaker bars. It is also contemplated that each set of breaker bars may comprise more or less than three breaker bars. FIGS. 5A and 5B show embodiments wherein system 200 comprises more than one set of breaker bars used to separate a circular substrate 160. For example, as shown in FIGS. 5A and 5B, system 200 may comprise a plurality of sets of breaker bars (e.g., sets 251, 252, 253, 354, 255, 256). Each set comprises three breaker bars, such as first, second, and third breaker bars 222, 224, 226 as discussed above.

(84) In some embodiments, the breaker bars of the different sets of breaker bars may comprise different lengths. For example, as shown in FIG. 5B, the breaker bars of the first set of breaker bars 251 may comprise the longest length and may be disposed at or near a centerline of the substrate 160. If the substrate 160 forms a shape other than the circle depicted in FIG. 5B, the longest breaker bar set would be disposed at the contour line 165 with the longest extension. The breaker bars of the third set of breaker bars 253, as shown in FIGS. 5A and 5B, may be shorter in length than the breaker bars of the first set of breaker bars 251. Furthermore, the third set of breaker bars 253 may be positioned at an intermediate region of the substrate 160, for example between the centerline and an edge of the substrate 160. The breaker bars of the sixth set of breaker bars 256 may be shorter in length than the breaker bars of both the first and third set of breaker bars 251, 253. Furthermore, the sixth set of breaker bars 256 may be positioned at an edge portion (or close to the edge portion) of the substrate 160. In some embodiments, the breaker bars of the sixth set of breaker bars 256 may include the breaker bars with the shortest lengths of all of the breaker bars.

(85) The plurality of breaker bars 220 may have different lengths depending on the size of the substrate 160. For example, the breaker bars 220 may each have a length of about 420 mm or less, or about 400 mm or less, or about 330 mm or less, or about 310 mm or less, or about 300 mm or less. Additionally or alternatively, the length of each breaker bar 220 may be about 300 mm or greater, or about 310 mm or greater, or about 330 mm or greater, or about 400 mm or greater, or about 420 mm or greater. In some embodiments, the length is in a range from about 300 mm to about 420 mm. Furthermore, one or more breaker bars 220 may differ from one or more other breaker bars 220 by a length of about 50 mm to about 80 mm, or about 55 mm to about 75 mm, or about 60 mm to about 70 mm.

(86) FIG. 6 illustrates a configuration for system 200 according to some embodiments. As shown in FIG. 6, the system comprises multiple sets of breaker bars, as disclosed above, with breaker bars of various lengths. Furthermore, the plurality of breaker bars 220 are disposed on a first rotating member 270 and on a second rotating member 275. More specifically, the top breaker bars (e.g., 222, 224) are disposed on the first rotating member 270 and the bottom breaker bars (e.g., 226) are disposed on the second rotating member 275. Each rotating member 270, 275 rotates in order to position a different set of breaker bars into position to separate and cut the substrate. For example, the first and second rotating members 270, 275 may first be rotated to position the first set of breaker bars 251 into position to separate and cut the substrate along a first contour line 165. Thus, the first and second breaker bars 22, 224 of the first set are positioned on top of the substrate 160 and adjacent to the first contour line 165 and the third breaker bar 226 of the first set is positioned on the bottom of the substrate 165 such that the edge 225 of the third breaker bar 226 is positioned on and along the first contour line 165 (as discussed above). The first set of breaker bars 251 may then apply pressure to the substrate 160 to separate the substrate along the first contour line 165.

(87) Next, both the first and second rotating members 270, 275 may be rotated in order to position, for example, the third set of breaker bars 253 into position to separate the substrate along a second contour line 165. For example, the second contour line may be shorter in length than the first contour line and may require the breaker bars of the third set with the relatively shorter lengths. In another embodiment, the breaker bars of the third set 253 may have a different edge 225 (for example, a different tapered angle at the edge) than the breaker bars of the first set 251. Therefore, the first and second rotating members 270, 275 may be rotated to position the first and second breaker bars 222, 224 of the third set adjacent to the second contour line 165 and the third breaker bar 226 of the third set on the bottom of the substrate 165 such that the edge 225 of the third breaker bar 226 is positioned on and along the second contour line 165 (as discussed above). The third set of breaker bars 253 may then apply pressure to the substrate 160 to separate the substrate along the second contour line 165.

(88) First rotating member 270 may rotate in a first rotating direction 271 and second rotating member 275 may rotate in a second rotating direction 276. First and second rotating directions 271, 276 may be in the same or different directions. Furthermore, first rotating member 270 may rotate simultaneously with second rotating member 275, such that they rotate together under the same control. It is also contemplated that first rotating member 270 rotates independently and separate from second rotating member 275.

(89) In the embodiment of FIG. 6, first and second rotating members 270, 275 each form a pentagon in cross-section so that five set of breaker bars (251-255) are positioned on the rotating members. More specifically, each set of breaker bars is positioned on a face (side) of the pentagon. However, it is also contemplated that first and second rotating members 270, 275 may comprise other shapes and configurations. For example, the first and second rotating members 270, 275 may each form a square in cross-section such that four sets of breaker bars are positioned on the rotating members. In other embodiments, the first and second rotating members 270, 275 each form a triangle in cross-section such that three sets of breaker bars are positioned on the rotating members. It is also noted that other shapes and configurations may be used, as are well-known in the art.

(90) As shown in FIG. 6, system 200 may further comprise a positioning assembly 300 configured to position the substrate 160 and/or the plurality of breaker bars 220. Although the positioning assembly 300 is shown in the embodiment of FIG. 6, it is noted that the positioning assembly 300 can be used with the other embodiments disclosed herein and is not limited to this embodiment. The positioning assembly 300 comprises a base 310 configured to support the assembly. Furthermore, the positioning assembly 300 comprises a linear positioning table 320 and a rotational table 330 that are configured to move and position the substrate 160 and the support 260. More specifically, the linear positioning table 320 is configured to move the substrate 160 and the support 260 in lateral X, Y, and Z directions (e.g., up, down, into the page, and out of the page). The rotational table 330 is configured to rotate the substrate 160 and the support 260 about either of the X axis, the Y axis, or the Z axis. For example, the rotational table 330 can rotate the substrate 160 so that a left end of the substrate 160 is higher than a right end of the substrate 160.

(91) The positioning assembly 300 may further comprise a frame 340 for securing the support 260 on the system 200. The frame 340 can secure the support 260 using, for example, a magnetic element, a vacuum ring, or any other well-known attachment mechanisms.

(92) The positioning assembly 300 may be a part of or may encompass the translation stage 190, as discussed above with reference to the laser processing system 100.

(93) The linear positioning table 320 and rotational table 330 move the substrate 160 and the support 260 relative to the first rotating member 270 and to the second rotating member 275. Additionally or alternatively, the positioning system 300 may further comprise an assembly to position and move the first rotating member 270 and/or the second rotating member 275 relative to the substrate 160 and to the support 260. Additionally, as also discussed above, the breaker bars 220 in a specific set may move closer and further from each other to be precisely positioned relative to a contour line 165. For example, as shown in FIG. 6, first and second breaker bars 222, 224 may be moved closer together and further from each other along the lateral X-axis direction.

(94) The positioning assemblies disclosed herein can be precision mechanisms that provide precisely controlled movements by, for example, motors. The assemblies may further include a camera to facilitate the alignment and positioning of the substrate 160 relative to the first and second rotating members 270, 275. The camera can also facilitate the alignment and positioning of the breaker bars 220 relative to the contour line 165. For example, the camera can enable the edges 225 of the breaker bars 220 to be precisely aligned relative to the contour lines 165 on the substrate.

(95) The system can include a controller to automatically perform the breaking operation. The controller includes a processor and a memory in communication with the processor. The memory can be configured to store at least a portion of the information about the relative positioning of the components. In some embodiments of the present invention, the controller can be an integral part of the system. The controller can also be an add-on component for the system.

(96) In some embodiments, substrate **160** comprises a plurality of dies fabricated thereon. For example, the substrate **160** may be a semiconductor wafer, a glass substrate, or an amorphous substrate having the plurality of dies fabricated thereon. To prevent damage to the fabricated devices, the plurality of breaker bars **220** only contacts the surface of the substrate **160** in the “non-sensitive areas” between the dies. For example, as shown in FIGS. 7A-7C substrate **160** comprises a semiconductor **400** with a plurality of dies **410** fabricated therein. A network of channels **420** is formed between the dies **410** and form the “non-sensitive areas” between the dies **410**. System **200** is arranged such that the edges **225** of the plurality of breaking bars **220** only contact the channels **420** and do not contact the dies **410**. Thus, in these embodiments, the laser processing system **100** produces the contour lines **165** only along and in the channels **420** and not within the dies **410**. The plurality of breaking bars **220**, therefore, do not damage the sensitive materials within the dies **410** when separating and cutting the semiconductor.

(97) FIG. 7C (which is a cross-section of FIG. 7B along line B-B) shows an example in which the first set of breaking bars **251** is positioned relative to a contour line **165**. In this embodiment, the contour line **165** is positioned along a first channel **420'** that separates two dies **410**. The first and second breaking bars **222**, **224** are positioned on channels **420''** adjacent to the two separate dies **410** such that the first and second breaking bars **222**, **224** are separated from the contour line **165** by the two separate dies **410**. The third breaking bar **226** is positioned on and along the contour line **165** on a bottom surface of the semiconductor **400**.

(98) It is also noted that the adjacent channels **420''** may also comprise a contour line **165** formed therein. For example, as shown in FIG. 7C, one of the adjacent channels **420''** has a second contour line **165'** disposed therein. In such embodiments, the second breaking bar **222**, when positioned in the adjacent channel **420''** to separate the substrate along the contour line **165**, should not contact the second contour line **165'**. After the system **200** separates the substrate along the contour line **165**, at least one of the system **200** or the substrate may be moved to position the components to separate the substrate along the second contour line **165'**.

(99) FIGS. 8A-8C illustrate a configuration of the support **260** according to embodiments disclosed herein. As shown in FIG. 8A, support **260** may comprise a frame **510** attached to a flexible membrane **520**. The flexible membrane **520** may be a film, tape, sheet, or belt. In some embodiments, the flexible membrane **520** is stretched over the frame **510**. The frame **510** may be the frame **340** discussed above with reference to FIG. 6 or part of the frame **340**. As shown in FIG. 8B, the substrate **160** may be disposed on a top surface of the flexible membrane **520**. Furthermore, as discussed further below, the contour lines **165** may be formed on the substrate **160** before or after mounting the substrate **160** on the support **260**.

(100) Flexible membrane **520** may comprise a polymeric material such as, for example, polyvinyl chloride (PVC) or poly olefin. In some embodiments, the material of flexible membrane **520** comprises silicon. In other embodiments, the material of flexible membrane **520** is free of silicon, which may advantageously reduce any contamination of the flexible membrane **520**. Furthermore, the material of flexible membrane **520** may be resistant to the laser beam **112** such that it is not damaged by the laser beam. In further embodiments, the material of the flexible membrane **520** may be UV-insensitive.

(101) The flexible membrane **520** may be sufficiently elastic to bend and stretch during the separating and/or cutting steps of substrate **160**. For example, the flexible membrane **520** may be configured to bend and stretch upward and/or downward (in the embodiment of FIG. 4A) when first, second, and third breaker bars **222**, **224**, **226** apply pressure on the substrate **160** to break the substrate **160** along the contour line **165**. In some embodiments, flexible membrane **520** has an elasticity of about 150% or greater in horizontal and/or vertical directions of the membrane, or about 160% or greater in horizontal and/or vertical directions, or about 200% or greater in horizontal and/or vertical directions. In some embodiments the elasticity in the horizontal direction may be different from the elasticity in the vertical direction. In some embodiments, the elasticity is about 150% in a horizontal direction and 170% in a vertical direction, or about 160% in a horizontal direction and about 200% in a vertical direction. Furthermore the elasticity may comprise a tensile strength of about 2 kg/25 mm or greater, or about 3 kg/25 mm or greater. In some embodiments, the tensile strength in the horizontal direction may be different from the tensile strength in the vertical direction. For example, the tensile strength in a horizontal direction may be about 3 kg/25 mm and the tensile strength in a vertical direction may be about 3 km/25 mm.

(102) A total thickness T of the flexible membrane **520** may about 50 microns or greater, or about 60 microns or greater, or about 70 microns or greater, or about 80 microns or greater, or about 90 microns or greater, or about 100 microns or greater, or about 110 microns or greater, or about 120 microns or greater, or about 140 microns or greater, or about 160 microns or greater, or about 180 microns or greater, or about 200 microns or greater, or about 220 microns or greater, or about 240 microns or greater, or about 260 microns or greater. Additionally or alternatively, the thickness T of flexible membrane **520** may be about 280 microns or less, or about 260 microns or less, or about 240 microns or less, or about 220 microns or less, or about 200 microns or less, or about 180 microns or less, or about 160 microns or less, or about 140 microns or less, or about 120 microns or less, or about 110 microns or less, or about 100 microns or less, or about 90 microns or less, or about 80 microns or less, or about 70 microns or less. In some embodiments, the thickness T of flexible membrane **520** is in a range from about 50 microns to about 300 microns, or from about 80 microns to about 270 microns, or from about 90 microns to about 180 microns. For example, the thickness T may be about 80 microns, or about 95 microns, or about 98 microns, or about 130 microns, or about 168 microns, or about 268 microns.

(103) As shown in FIG. 8C, in some embodiments, the flexible membrane **520** may comprise a base layer **522** and an adhesive layer **524**. Substrate **160** may be secured to adhesive layer **524** of the flexible membrane **520**. The base layer **522** may comprise the polymeric materials disclosed above. The adhesive layer **524** may comprise, for example, rubber and/or acrylic. In one embodiment, an adhesion of adhesive layer **524** is about 34 g/25 mm.

(104) The base layer **522** may have a thickness ranging from about 70 microns to about 200 microns, or about 80 microns to about 180 microns, or about 100 microns to about 160 microns. In some embodiments, the thickness of the base layer **522** is about 70 microns, or about 80 microns, or about 115 microns, or about 125 microns

(105) The adhesive layer **524** may have a thickness ranging from about 5 microns to about 100 microns, or about 10 microns to about 90 microns, or about 15 microns to about 80 microns. In some embodiments, the thickness of the adhesive layer **524** is about 10 microns, or about 14, or about 15 microns. The thickness of the adhesive layer **524** may be smaller than the thickness of the base layer **522**.

(106) The flexible membrane **520** may comprise a backing film (not shown) formed of, for example, PET. In some embodiments, the backing film forms an anti-static layer. The backing film may have a thickness of about 10 microns or greater, or about 20 microns or greater, or about 25 microns or greater. The backing film can be applied to the base layer **522**, the adhesive layer **524** or both. Furthermore, the backing film may enable a reduction of adhesion after UV curing to release separated pieces of the substrate.

(107) The base layer **522** and the adhesive layer **524** may each be comprised of one unitary layer or a plurality of independent layers. For example, the layers **522** and/or **524** may each be formed of a laminate structure formed of a plurality of sub-layers. The sub-layers of each of **522** and/or **524** may be formed of the same or different materials.

(108) When system **200** breaks the substrate **160** along the contour line **165**, the substrate **160** may break into a first portion and a second portion. For example, as shown in FIG. 9, breaker bars **222**, **224**, **226** of system **200** break the substrate **160** into a first portion **161** and a second portion **163**. More specifically, the first breaker bar **222** and the second breaker bar **224** apply a downward force on the substrate **160** and on the support **260**. Furthermore, the third breaker bar **226** applies an upward force on the substrate **160** and on the support **260**. Such force by the breaker bars **222**, **224**, **226** causes the substrate **160** to break along the contour line **165** and separate into the first portion **161** and the second portion **163**. During this breaking procedure, the substrate **160** remains attached to the support **260**. Therefore, as shown in FIG. 9, for example, the flexible membrane **520** of the support **260** bends upward with the movement of the first and second portions **161**, **163** of the substrate **160**. As discussed above, the flexible membrane **520** has sufficient elasticity to bend and flex with the movement of the first and second portions **161**, **163**. Such allows the substrate **160** to remain attached and secured to the flexible membrane **520** during the breaking procedure. This prevents the first and second portions **161**, **163** from chipping or cracking during the breaking procedure. For example, by remaining secured to the flexible membrane **520**, the first and second

portions **161**, **163** do not strike into each other after the breaking procedure, which could cause chipping or cracking of the portions. Furthermore, by remaining secured to the flexible membrane **520**, the first and second portions **161**, **163** are prevented from inadvertently falling downward, such as to the ground.

(109) In some embodiments, the first breaker bar **222** applies a first force **F** on the substrate **160** at a location **X** that is adjacent to the contour line **165**. The third breaker bar **226** applies a second force **F** on the substrate **160** at location **Y** that is on or along the contour line **165**. Furthermore, the second breaker **224** applies a third force **F** on the substrate **160** at a location **Z** that is adjacent to the contour line **165**. The locations **X** and **Z** may be spaced from the contour line **165** by a distance that is sufficient to bend and break the substrate **160** but close enough not to overlap with the contour line **165**. In some embodiments, the locations **X** and **Z** are spaced a distance of about 25 microns or greater from the contour line **165**, or about 30 microns or greater, or about 35 microns or greater. It is also noted that the location **X** may be spaced a different length from the contour line **165** than the location **Z**. The first, second, and third forces **F** are sufficient to exceed the break resistance of the substrate **160** at the contour line **165** and, thus, break the substrate along the contour line **165**. In some embodiments, the first force **F** is equal to the third force **F**. It is further noted that in the embodiments that include the flexible membrane **520**, the first, second, and third forces **F** are also applied to the flexible tape **520**.

(110) The substrate **160** may be secured to the flexible membrane **520** either before or after the laser processing step using laser processing system **100**. Therefore, in some embodiments, the substrate **160** is secured to the flexible membrane **520** before the laser processing step. Laser beam **112** then passes along beam pathway **111** to form the plurality of defects **172**, which form contour line **165**, while the substrate **160** is secured to the flexible membrane **520**. Therefore, the laser beam **112** also passes through the flexible membrane **520** when forming the plurality of defects **172**. In these embodiments, the flexible membrane **520** is formed of a material such that it is not damaged by the laser beam **112**. In other embodiments, laser processing system **100** first forms the plurality of defects **172** of the contour line **165** and then, after the formation of the contour line **165**, the substrate **160** is attached to the flexible membrane **520**.

(111) In some embodiments, the plurality of defects **172** may be enlarged prior to the breaking step using breaking system **200**. For example, the defects **172** may be exposed to an etching solution, such as, for example, **HF** or **KOH**, or an ion-exchange process.

(112) FIG. **10** illustrates an exemplary configuration of five sets of breaker bars **251**, **252**, **253**, **254**, **255** of a breaking system **200** according to embodiments disclosed herein. In this embodiment, the substrate **160** is positioned on the flexible membrane **520** of the support **260**. As discussed above, the breaker bars of the different sets (**251**, **252**, **253**, **254**, **255**) have different lengths. Therefore, for example, the breaker bars of the fifth set **255** are the shortest while the breaker bars of the first set **251** are the longest. The different lengths of the breaker bars may be suitable to break the substrate **160** along different portions of the substrate **160** corresponding to different lengths (e.g., diameters) of the substrate **160**. For example, the first set of breaker bars **251** breaks the substrate **160** along contour lines **165** within a first region **A**, where the substrate **160** has the largest diameter (and, thus, the largest contour lines **165**). The fifth set of breaker bars **255** breaks the substrate **160** along contour lines **165** within fifth regions **E**, where the substrate **160** has the smallest diameter. Furthermore, the second set of breaker bars **252** breaks the substrate along contour lines **165** within second regions **B**, the third set of breaker bars **253** breaks the substrate along contour lines **165** within third regions **C**, and the fourth set of breaker bars **254** breaks the substrate along contour lines **165** within fourth regions **D**. It is noted that the diameter of the fifth regions **E** is smaller than the diameter of the fourth regions **D**, the diameter of the fourth regions **D** is smaller than the diameter of the third regions **C**, the diameter of the third regions **C** is smaller than the diameter of the second regions **B**, and the diameter of the second regions **B** is smaller than the diameter of the first region **A**.

(113) FIG. **11A** illustrates another embodiment of breaker system **200** in which the first breaker bars **222** are positioned on a first rotating member **272**, the second breaker bars **224** are positioned on a second rotating member **274**, and the third breaker bars **226** are positioned on a third rotating member **276**. As discussed above, the rotating members **272**, **274**, **276** can be rotated to, for example, move a first set of breaker bars into position to break the substrate **160** along a first contour line **165**. The rotating members **272**, **274**, **276** can further be rotated to, for example, move a second set of breaker bars into position to break the substrate along a second contour line **165**.

(114) As further shown in FIGS. **11A** and **11B**, the first and second rotating members **272**, **274** can move in the lateral **X**-axis direction with respect to each other (and with respect to the third rotating member **276**). Such movement of the first and second rotating members **271**, **272** provides exact positioning of the breaker bars with regard to the contour line **165**. The second rotating member **274** may comprise cavities **273** between each breaker bar disposed thereon. The cavities **273** provide clearance and space for the first and second rotating members **272**, **274** to move in close proximity without contacting each other.

(115) FIG. **11C** shows a perspective view of a portion of the breaker system **200** according to embodiments disclosed herein. In particular, FIG. **11C** shows the second breaker bars **224** positioned on the second rotating member **274**. As discussed above, these second breaker bars **224** are each part of a different breaker bar set with different lengths. Therefore, for example, the second breaker bar **224'** may be part of a first set and may have the longest length of all the second breaker bars. The second breaker bar **224''** may be part of a second set and may have the shortest length of all the second breaker bars. Furthermore, the second breaker bar **224'''** may have a longer length than second breaker bar **224''** but shorter than second breaker bar **224'**. The second breaker bar **224''''** may have a longer length than second breaker bar **224''** and **224'''** but shorter than second breaker bar **224'**.

(116) Furthermore, FIG. **11C** shows a rod **280** upon which the second rotating member **274** is mounted. The first and third rotating members **272**, **276** may also be mounted on similar rods for rotation. Although the embodiment of FIG. **11C** includes the breaker bars having different lengths, this feature is not limited to the embodiment of FIG. **11C**. Instead, as discussed above, the different sized breaker bars may be used with any of the embodiments disclosed herein.

(117) FIG. **12** illustrates a process **400** according to the embodiments disclosed herein. In step **410**, the process **400** comprises forming one or more defects **172** in substrate **160**. As discussed above, the defects **172** may be formed using the laser beam **112**, and the defects **172** may together form a contour line **165**. During the formation of the defects **172**, the substrate **160** may or may not be disposed on flexible membrane **520** of support **260**. In step **420**, a set of breaker bars is positioned on the substrate **160** in relation to the contour line **165**. More specifically, in some embodiments, two top breaker bars (of a first set) are positioned on a top surface of the substrate **160** and adjacent to the contour line and a bottom breaker bar (of the first set) is positioned on a bottom surface of the substrate **160** and on the contour line **165**. In step **430**, the breaker bars apply pressure (force) to the substrate **160** to separate the substrate **160** along the contour line **165**. Thus, the substrate **160** is separated into two separate portions (step **440**). During these separation steps, the substrate **160** may be positioned and secured on the flexible membrane **520** so that the separated portions of the substrate **160** do not chip or crack.

(118) It is noted that during the formation of the defects **172** in the substrate **160** (step **410** of process **400**), the substrate **160** remains intact and is not separated into two portions. Thus, there is no material removal or mechanical force present during this step. Instead, the substrate **160** is separated (by the mechanical force of the breaker bars **220**) only during steps **430** and **440** of process **400**. Therefore, embodiments of the present disclosure comprise forming a plurality of defects **172** within a substrate **160** to form a contour line **165** while the substrate **160** is attached to a flexible membrane **520** and before the substrate **165** is separated into different portions.

(119) As disclosed above, the laser processing system **100** provides a highly controlled system in which the contour line **165** is produced with a high degree of control and specificity. Furthermore, the breaking system **200** is able to precisely control the locations of the breaker bars **220** to separate the substrate **160** only along the contour line **165**. Therefore, the cutting and separating of the substrate **160** can be controlled to achieve a very precise and accurate cutting line. Furthermore, by first forming the contour line **165** and then separating the substrate along the contour line **165**, the breaking force required to separate the substrate **160** is much lower than in traditional systems, which leads to improved edge quality. In particular any chipping at the cut edge of the substrate **160** may be about 80 microns or less, or about 50 microns or less, or about 20 microns or less.

(120) Embodiments of the present disclosure also allow for the breaker bars **220** to be positioned at locations that do not interfere with any sensitive materials on the substrate **160**. Furthermore, embodiments of the present disclosure provide a system that can cut and separate substrates with very low coefficient of thermal expansion (CTE) values and/or very small aspect ratios (e.g., substrates that are very thin and wide). In some embodiments, the glass substrate **160** is formed of HPFS glass with a CTE value of about 0.4 ppm/° C. or less. In other embodiments, the glass substrate **160** is Eagle XG glass with a CTE of about 3.5 ppm/° C. or less. Therefore, system **10** can be used with a greater variety of substrates than traditional systems.

(121) Additionally, the embodiments of the present disclosure cut and break a substrate while not damaging any coating applied on the substrate. Embodiments of the present disclosure are also able to cut and separate substrates with very large thicknesses.

(122) While various embodiments have been described herein, they have been presented by way of example, and not limitation. It should be apparent that adaptations and modifications are intended to be within the meaning and range of equivalents of the disclosed embodiments, based on the teaching and guidance presented herein. It therefore will be apparent to one skilled in the art that various changes in form and detail can be made to the embodiments disclosed herein without departing from the spirit and scope of the present disclosure. The elements of the embodiments presented herein are not necessarily mutually exclusive, but may be interchanged to meet various situations as would be appreciated by one of skill in the art.

(123) Embodiments of the present disclosure are described in detail herein with reference to embodiments thereof as illustrated in the accompanying drawings, in which like reference numerals are used to indicate identical or functionally similar elements. References to “one embodiment,” “an embodiment,” “some embodiments,” “in certain embodiments,” etc., indicate that the embodiment described may include a particular feature, structure, or characteristic, but every embodiment may not necessarily include the particular feature, structure, or characteristic. Moreover, such phrases are not necessarily referring to the same embodiment. Further, when a particular feature, structure, or characteristic is described in connection with an embodiment, it is submitted that it is within the knowledge of one skilled in the art to affect such feature, structure, or characteristic in connection with other embodiments whether or not explicitly described.

(124) The examples are illustrative, but not limiting, of the present disclosure. Other suitable modifications and adaptations of the variety of conditions and parameters normally encountered in the field, and which would be apparent to those skilled in the art, are within the spirit and scope of the disclosure.

(125) The term “or,” as used herein, is inclusive; more specifically, the phrase “A or B” means “A, B, or both A and B.” Exclusive “or” is designated herein by terms such as “either A or B” and “one of A or B,” for example.

(126) The indefinite articles “a” and “an” to describe an element or component means that one or at least one of these elements or components is present. Although these articles are conventionally employed to signify that the modified noun is a singular noun, as used herein the articles “a” and “an” also include the plural, unless otherwise stated in specific instances. Similarly, the definite article “the,” as used herein, also signifies that the modified noun may be singular or plural, again unless otherwise stated in specific instances.

(127) As used in the claims, “comprising” is an open-ended transitional phrase. A list of elements following the transitional phrase “comprising” is a non-exclusive list, such that elements in addition to those specifically recited in the list may also be present. As used in the claims, “consisting essentially of” or “composed essentially of” limits the composition of a material to the specified materials and those that do not materially affect the basic and novel characteristic(s) of the material. As used in the claims, “consisting of” or “composed entirely of” limits the composition of a material to the specified materials and excludes any material not specified.

(128) The term “wherein” is used as an open-ended transitional phrase, to introduce a recitation of a series of characteristics of the structure.

(129) Where a range of numerical values is recited herein, comprising upper and lower values, unless otherwise stated in specific circumstances, the range is intended to include the endpoints thereof, and all integers and fractions within the range. It is not intended that the scope of the claims be limited to the specific values recited when defining a range. Further, when an amount, concentration, or other value or parameter is given as a range, one or more preferred ranges or a list of upper preferable values and lower preferable values, this is to be understood as specifically disclosing all ranges formed from any pair of any upper range limit or preferred value and any lower range limit or preferred value, regardless of whether such pairs are separately disclosed. Finally, when the term “about” is used in describing a value or an end-point of a range, the disclosure should be understood to include the specific value or end-point referred to. Whether or not a numerical value or end-point of a range in the specification recites “about,” the numerical value or end-point of a range is intended to include two embodiments: one modified by “about,” and one not modified by “about.”

(130) As used herein, the term “about” means that amounts, sizes, ranges, formulations, parameters, and other quantities and characteristics are not and need not be exact, but may be approximate and/or larger or smaller, as desired, reflecting tolerances, conversion factors, rounding off, measurement error and the like, and other factors known to those of skill in the art.

(131) The present embodiment(s) have been described above with the aid of functional building blocks illustrating the implementation of specified functions and relationships thereof. The boundaries of these functional building blocks have been arbitrarily defined herein for the convenience of the description. Alternate boundaries can be defined so long as the specified functions and relationships thereof are appropriately performed.

(132) It is to be understood that the phraseology or terminology used herein is for the purpose of description and not of limitation. The breadth and scope of the present disclosure should not be limited by any of the above-described exemplary embodiments, but should be defined in accordance with the following claims and their equivalents.

## Claims

1. A method comprising: forming a plurality of defects within a first channel of a plurality of channels of a substrate with a laser beam focal line using a laser beam, the plurality of channels being disposed between dies within the substrate, each defect of the plurality of defects being a damage track within the first channel of the substrate with a diameter of about 10 microns or less, and the plurality of defects forming a contour line in the first channel of the substrate, the substrate having a first surface and a second surface that is opposite from the first surface; exerting (i) a first force on the first surface of the substrate within a second channel of the plurality of channels at a location that is adjacent to the contour line and a second force on the second surface of the substrate at a location that is on the contour line; breaking the substrate along the contour line and into a first substrate portion and a second substrate portion; and further comprising exerting a third force on the first surface of the substrate within a third channel of the plurality of the channels at a location that is adjacent to the contour line and at an opposite side of the contour line than the first force.

2. The method of claim 1, wherein the third force is equal to the first force.

3. The method of claim 1, further comprising exerting the first force with a first breaker bar, the first breaker bar only contacting the substrate at an edge of the breaker bar.

4. The method of claim 1, wherein the substrate is disposed on a flexible membrane, the method further comprising exerting the second force on the flexible membrane and on the second surface of the substrate.

5. The method of claim 4, wherein the flexible membrane bends and flexes due to the exertion of at least one of the first force and the second force.

6. The method of claim 4, wherein the flexible membrane is comprised of a polymeric material.

7. The method of claim 4, wherein the flexible membrane has a thickness of about 50 microns to about 300 microns.

8. The method of claim 4, wherein the flexible membrane has an elasticity of about 120% or more in a horizontal direction of the flexible membrane and about 120% or more in a vertical direction of the flexible membrane.

9. The method of claim 1, wherein the diameter of the damage track is about 5 microns or less.

10. The method of claim 1, wherein the substrate is comprised of a glass substrate, a glass-ceramic substrate, or a semiconductor wafer.
11. The method of claim 1, further comprising: forming a second plurality of defects within the substrate with the laser beam, each defect of the second plurality of defects being a damage track within the substrate with a diameter of about 10 microns or less, the second plurality of defects forming a second contour line on the substrate; and exerting (i) a fourth force on the first surface of the substrate at a location that is adjacent to the second contour line and (ii) a fifth force on the second surface of the substrate at a location that is on the second contour line; and breaking the substrate along the second contour line and into a third substrate portion and a fourth substrate portion.
12. A system comprising: a laser processing system comprising a beam source configured to output a laser beam that is focused into a laser beam focal line; and a substrate breaking system comprising a first set of breaker bars and a flexible membrane, the first set of breaker bars comprising a first breaker bar with a first edge, a second breaker bar with a second edge, and a third breaker bar with a third edge, and the first breaker bar and the second breaker bar being disposed on a first side of the flexible membrane and the third breaker bar being disposed on a second side of the flexible membrane, and the flexible membrane comprising a base layer and an adhesive layer such that a thickness of the adhesive layer is less than a thickness of the base layer.
13. The system of claim 12, further comprising a second set of breaker bars comprising a first breaker bar, a second breaker bar, and a third breaker bar, wherein: the first breaker bar of the second set of breaker bars has a shorter length than the first breaker bar of the first set of breaker bars, the second breaker bar of the second set of breaker bars has a shorter length than the second breaker bar of the first set of breaker bars, the third breaker bar of the second set of breaker bars has a shorter length than the third breaker bar of the first set of breaker bars.
14. The system of claim 13, further comprising a first rotating member, the first breaker bar and the second breaker bar being disposed on the first rotating member.
15. The system of claim 12, wherein the first breaker bar and the second breaker bar are disposed on a single side of the first rotating member.
16. The system of claim 12, further comprising a second rotating member, the third breaker bar being disposed on the second rotating member.
17. The system of claim 12, wherein the flexible membrane is comprised of a polymeric material.
18. The system of claim 17, wherein the flexible membrane has a thickness of about 50 microns to about 300 microns.
19. The system of claim 12, wherein the flexible membrane has an elasticity of about 120% or more in a horizontal direction of the flexible membrane and about 120% or more in a vertical direction of the flexible membrane.
-