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SUBSTRATE MANUFACTURING METHOD

Abstract

A substrate manufacturing method includes applying a laser beam of a wavelength transmittable through a material of a workpiece, thereby forming a peel-off layer inside the workpiece, and after the forming of the peel-off layer, with the peel-off layer as a starting point of separation, separating the workpiece, thereby manufacturing a substrate. In the forming of the peel-off layer, by alternately repeating moving the workpiece and a focusing point at which the laser beam is focused relative to each other along a first direction, in a state in which the focusing point is positioned inside the workpiece, and moving the workpiece and a position at which the focusing point is formed relative to each other along a second direction perpendicular to the first direction, the peel-off layer including first modified portions and second modified portions which are alternately lined up in the second direction is formed.

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Background/Summary

BACKGROUND OF THE INVENTION

Field of the Invention

[0001] The present invention relates to a substrate manufacturing method of manufacturing a substrate having a thickness smaller than that of a workpiece from the workpiece.

Description of the Related Art

[0002] Semiconductor devices are typically formed by use of a disc-shaped substrate. Also, the substrate is manufactured, for example, by cutting off a workpiece such as a cylindrical bulk called an ingot with use of a wire saw in such a manner as to separate a portion included in the workpiece having a predetermined thickness, from the workpiece (see, for example, Japanese Patent Laid-Open No. 2016-13929).

SUMMARY OF THE INVENTION

[0003] A substrate having a thickness of substantially 150 μm, for example, is used for formation of semiconductor devices. Also, a thickness of a wire saw is, for example, substantially 300 um. Hence, in a case in which the wire saw is used to manufacture a substrate from the workpiece, for example, 60% to 70% of the workpiece is discarded as debris therefrom, thereby causing reduction of its productivity.

[0004] In view of this circumstance, the present invention has an object of providing a substrate manufacturing method of being capable of enhancing the productivity of a substrate at a time of manufacturing, from a workpiece, the substrate thinner than the workpiece.

[0005] In accordance with an aspect of the present invention, there is provided a substrate manufacturing method of manufacturing a substrate from a workpiece, the substrate having a thickness smaller than that of the workpiece. The method includes applying, to the workpiece, a laser beam of a wavelength transmittable through a material of the workpiece, thereby forming a peel-off layer inside the workpiece, and separating the workpiece with the peel-off layer as a starting point of separation, after the forming of the peel-off layer, thereby manufacturing the substrate. In the forming of the peel-off layer, by alternately repeating moving the workpiece and a focusing point at which the laser beam is focused relative to each other along a first direction, in a state in which the focusing point is positioned inside the workpiece, and moving the workpiece and a position at which the focusing point is formed relative to each other along a second direction perpendicular to the first direction, the peel-off layer including first modified portions and second modified portions which are alternately lined up in the second direction is formed, the first modified portion is formed at a first focusing point at which a first laser beam having first output power is focused, and the second modified portion is formed at a second focusing point at which a second laser beam having a second output power greater than the first output power is focused.

[0006] Note that, preferably, in the applying of the laser beam, the original laser beam of a wavelength transmittable through the material of the workpiece may be split into the first laser beam and the second laser beam, and in a state in which the first focusing point and the second focusing point which are spaced apart from each other in the second direction are positioned inside the workpiece, the workpiece and each of the first focusing point and the second focusing point are moved relative to each other along the first direction. More preferably, in the applying of the laser beam, the first focusing point may move inside the workpiece in the first direction, while preceding the second focusing point.

[0007] In addition, cracks that develop from the first modified portion may be smaller than cracks that develop from the second modified portion. Alternatively, cracks may not develop from the first modified portion, but cracks may develop from the second modified portion.

[0008] Further, the substrate manufacturing method according to the present invention may further include, after the forming of the peel-off layer to be performed such that a modified portion that is closest to one end of the workpiece in the second direction becomes the second modified portion and a modified portion that is closest to another end thereof becomes the first modified portion, but before the separating, moving the workpiece and the second focusing point relative to each other along the first direction, in a state in which the second focusing point is positioned in such a manner overlapping with the first modified portion that is closest to the other end. Alternatively, in the substrate manufacturing method according to the present invention, the forming of the peel-off layer may be performed such that a modified portion which comes closest to each end of the workpiece in the second direction becomes the second modified portion.

[0009] According to the present invention, after the peel-off layer is formed inside the workpiece, by separating the workpiece with the peel-off layer as a starting point of separation, the substrate is manufactured. Hence, compared to a case in which the substrate is manufactured from the workpiece with use of the wire saw, productivity of the substrate can be enhanced.

[0010] The above and other objects, features and advantages of the present invention and the manner of realizing them will become more apparent, and the invention itself will best be understood from a study of the following description and appended claims with reference to the attached drawings showing a preferred embodiment of the invention.

Description

BRIEF DESCRIPTION OF THE DRAWINGS
[0011] FIG. **1**A is a perspective view schematically illustrating an example of an ingot;
[0012] FIG. **1**B is a side view schematically illustrating the ingot depicted in FIG. **1**A;
[0013] FIG. **2** is a flowchart schematically indicating an example of a substrate manufacturing method;
[0014] FIG. **3** is a view schematically illustrating an example of a laser processing apparatus for forming a peel-off layer inside the ingot;
[0015] FIG. **4** is a flowchart schematically indicating a procedure performed at a time of forming the peel-off layer;
[0016] FIG. **5**A is a plan view schematically illustrating a manner in which the peel-off layer is formed inside the ingot;
[0017] FIG. **5**B is an enlarged longitudinal sectional view schematically illustrating part of the ingot formed with the peel-off layer therein;
[0018] FIG. **6**A is a side view schematically illustrating a manner in which a separating step is performed;
[0019] FIG. **6**B is a side view schematically illustrating the manner in which the separating step is performed; and
[0020] FIG. **7** is a flowchart schematically indicating another example of a substrate manufacturing method.
DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT
[0021] An embodiment of the present invention will be described with reference to the accompanying drawings. Note that the attached drawings are offered for easy understanding of the present invention and hence do not necessarily accurately reflect the products and/or methods implementing the present invention.
[0022] FIG. **1**A is a perspective view schematically illustrating an example of an ingot. FIG. **1**B is a side view schematically illustrating the ingot depicted in FIG. **1**A. Note that, in FIGS. **1**A and **1**B, crystal planes of a material of the ingot are also illustrated. In addition, in FIG. **1**B, crystal orientations of this material are also illustrated.
[0023] The material of an ingot **11** illustrated in FIGS. **1**A and **1**B is, for example, gallium oxide (β-Ga.sub.2O.sub.3) having a phase (hereinafter, simply referred to as “gallium oxide”). Gallium oxide has a wide-bandgap semiconductor with a bandgap of substantially 4.8 eV. Hence, gallium oxide is expected to be used as a material for a semiconductor device such as a power device.
[0024] Moreover, gallium oxide is a monoclinic crystal having such a crystal structure that an angle formed by a crystal orientation (a-axis) and a crystal orientation (c-axis) is 103.7° and an angle formed by a crystal orientation (b-axis) and each of the crystal orientation (a-axis) and the crystal orientation (c-axis) is 90°. Moreover, the ingot **11** depicted in FIGS. **1**A and **1**B has a front surface **11***a* and a back surface **11***b* that are in parallel with each other, and the front surface **11***a* and the back surface **11***b* each have a crystal plane {001} exposed therein (in this specification, for convenience, a plane that is exposed in the front surface **11***a* is called a crystal plane (**001**)).
[0025] Note that the ingot **11** is manufactured in such a manner that the crystal plane {001} is exposed in each of the front surface **11***a* and the back surface **11***b*. However, owing to a processing error or the like occurring in the manufacturing, a plane that is slightly inclined relative to the crystal plane {001} may be exposed in each of the front surface **11***a* and the back surface **11***b*. More specifically, in each of the front surface **11***a* and the back surface **11***b* of the ingot **11**, a plane that forms an angle of equal to or less than 1° with the crystal plane {001} may be exposed.
[0026] Further, a side surface **11***c* of the ingot **11** has two plane portions for representing a crystal orientation of the material of the ingot **11**, that is, a first orientation flat **13** and a second orientation flat **15**, formed thereon. Also, the first orientation flat **13** is longer than the second orientation flat **15** and is formed in such a manner as to be positioned at the crystal orientation as viewed from the center of the ingot **11**.
[0027] In addition, the second orientation flat **15** is formed in such a manner as to be positioned at the crystal orientation as viewed from the center of the ingot **11**. In other words, the second orientation flat **15** is formed serving as such a plane in which the crystal plane (**010**) is exposed. Hence, in the ingot **11**, the crystal plane (**100**) forms an obtuse angle of 103.7° with the front surface **11***a* or the back surface **11***b* and is orthogonal to

the second orientation flat **15**.

[0028] Note that the side surface **11***c* of the ingot **11** may not have one of or both the first orientation flat **13** and the second orientation flat **15** formed therein. In addition, the side surface **11***c* of the ingot **11** may have a cut-out portion (notch) for indicating the crystal orientation of the material of the ingot **11** formed therein, in place of the first orientation flat **13** and the second orientation flat **15**.

[0029] FIG. **2** is a flowchart schematically indicating one example of a substrate manufacturing method of manufacturing a substrate thinner than the ingot **11** serving as the workpiece, from the ingot **11**. In this method, first, a laser beam having a wavelength transmittable through the material of the ingot **11** is applied to the ingot **11**, thereby forming a peel-off layer inside the ingot **11** (peel-off layer forming step S**1**). Note that the peel-off layer is a layer which has modified portions in which a crystal structure of the material of the ingot **11** is disordered and cracks extending from the modified portions.

[0030] In the peel-off layer forming step S**1**, the modified portions in multiple columns are sequentially formed inside the ingot **11**. However, with use of a laser beam having a constant output power maintained, when the modified portions in multiple columns are sequentially formed from an edge of the ingot **11**, more specifically, when the modified portion positioned at the edge of the ingot **11** in a direction perpendicular to a direction in which each of the modified portions extends is first formed and the other modified portion is also formed in such a manner as to be adjacent to the previously formed modified portion in the relevant direction, greatly longer cracks may develop from the other modified portion that have been newly formed in the course of formation of the other modified portions.

[0031] More specifically, with use of the laser beam having a constant output power maintained, when the modified portions are formed in this order, internal stresses generated in the ingot **11** along with formation of the modified portions are applied to a newly formed modified portion, and as a result, cracks may overdevelop from the newly formed modified portion. In other words, when internal stresses accumulated along with formation of the modified portions becomes too large, greatly longer cracks may be formed from the newly formed modified portion in such a manner as to release the accumulated internal stresses.

[0032] In this case, the cracks develop to a region of the ingot **11** where formation of the cracks is not intended, causing difficulty in subsequent formation of desired modified portions at the relevant region. In addition, in this case, the proportion of the cracks developing along a thickness direction of the ingot **11** becomes large, causing possibility of lowering of productivity of the substrate at the time of manufacture of the substrate from the ingot **11**.

[0033] To address this problem, in the peel-off layer forming step S**1**, in order to prevent the cracks from excessively developing from the modified portions, the output power of the laser beam is adjusted, to thereby form multiple columns of modified portions inside the ingot **11**. More specifically, in the peel-off layer forming step S**1**, there is formed a peel-off layer including first modified portions and second modified portions which are lined up alternately in a direction perpendicular to a direction in which the modified portions extend.

[0034] Here, the first modified portion is formed at a focusing point (first focusing point) at which a laser beam (first laser beam) having a relatively small output power (first output power) is focused. Also, the second modified portion is formed at a focusing point (second focusing point) at which a laser beam (second laser beam) having a relatively large output power, that is, output power (second output power) larger than the first output power, is focused.

[0035] Note that the first output power may be set to such a value allowing the cracks to develop from the first modified portion or set to such a value preventing the cracks from developing from the first modified portion. Even if the first output power is set to a value allowing the cracks to develop from the first modified portion, the first output power is smaller than the second output power, and accordingly, the cracks developing from the first modified portion are smaller than the cracks developing from the second modified portion.

[0036] In a case in which the peel-off layer is formed in this manner, it is possible to control a range in which the cracks developing from the second modified portion can be developed to a portion between a pair of adjacent first modified portions. Hence, in the peel-off layer forming step S**1**, it is possible to prevent the greatly longer cracks from developing from the second modified portion in the course of performing the peel-off layer forming step S**1**.

[0037] FIG. **3** is a view schematically illustrating an example of a laser processing apparatus for forming a peel-off layer inside the ingot **11**. Note that, in FIG. **3**, a direction indicated with an arrow X (X direction) and a direction indicated with an arrow Y (Y direction) are directions perpendicular to each other on a horizontal plane, and a direction (vertical direction) indicated with an arrow Z (Z direction) is perpendicular to each of the X direction and the Y direction. Also, in FIG. **3**, some of constituent components of the laser processing apparatus are illustrated in a block form.

[0038] A laser processing apparatus **2** illustrated in FIG. **3** includes a chuck table **4** having a circular holding surface that is substantially in parallel with the horizontal plane. The chuck table **4** is, for example, coupled with a suction mechanism having an ejector and the like (not illustrated), and a rotational mechanism having, for example, a pulley, a motor, and the like (not illustrated).

[0039] When the suction mechanism is operated, a suction force is applied to a space in the vicinity of the holding surface of the chuck table **4**. Hence, when the suction mechanism is operated in a state in which the ingot **11** is placed on the holding surface, the ingot **11** is held under suction on the holding surface of the chuck table **4**.

[0040] Moreover, when the rotational mechanism is operated, the chuck table **4** rotates with a straight line passing through the center of the holding surface and extending along the Z direction as a rotational axis. For example, the rotational mechanism causes the chuck table **4** to rotate such that the second orientation flat **15** of the ingot **11** held on the holding surface of the chuck table **4** is in parallel with the X direction.

[0041] In addition, above the chuck table **4**, a laser beam applying unit **6** is provided. The laser beam applying unit **6** has, as a laser medium, a laser oscillator **8** having neodymium-doped yttrium aluminum garnet (Nd:YAG) and the like, for example.

[0042] The laser oscillator **8** emits a laser beam (for example, a pulsed laser beam with a frequency of 30 kHz and a pulse width of 4 ns) of a wavelength (for example, 1064 nm or 1342 nm) passing through the material of the ingot **11** (for example, gallium oxide). The output power of this laser beam is adjusted by the attenuator **10**, and then, the laser beam is supplied to the splitting unit **12**.

[0043] The splitting unit **12** has a spatial light modulator and/or a diffraction optical element (DOE) including a liquid crystal phase control element which is referred to as a liquid crystal on silicon (LCOS), for example. Further, for example, the splitting unit **12** splits the laser beam (original laser beam) whose output power is adjusted by the attenuator **10** into a first laser beam LB**1** having a first output power and a second laser beam LB**2** having a second output power larger than the first output power.

[0044] Each of the laser beams LB**1** and LB**2** is reflected on a mirror **14** to be guided to a head **16**. The head **16** houses, for example, a focusing lens (not illustrated) which focuses each of the laser beams LB**1** and LB**2**. Each of the laser beams LB**1** and LB**2** which are focused by the focusing lens is emitted toward a side of the holding surface of the chuck table **4**, in short, directly below the head **16**, with a central region of a lower surface of the head **16** as an emitting region.

[0045] Note that a first focusing point P**1** at which the first laser beam LB**1** is focused and a second focusing point P**2** at which the second laser beam LB**2** is focused are identical with each other in position (height) of the Z direction, for example, but are different from each other in position of the Y direction. Moreover, both of the focusing points P**1** and P**2** may be identical with each other and may be different from each other in position of the X direction.

[0046] Further, the head **16** of the laser beam applying unit **6** and an optical system (for example, the mirror **14**) for guiding the laser beams LB**1** and LB**2** to the head **16** are coupled with, for example, a moving mechanism (not illustrated) including a ball screw and the like. When the moving mechanism is operated, an emitting region of each of the laser beams LB**1** and LB**2** is moved along the X direction, the Y direction, and/or the Z direction.

[0047] Also, in the laser processing apparatus **2**, when the moving mechanism is operated, the first focusing point P**1** at which the first laser beam LB**1** emitted from the head **16** to the side of the holding surface of the chuck table **4** is focused and the second focusing point P**2** at which the second laser beam LB**2** emitted from the head **16** to the side of the holding surface of the chuck table **4** is focused can be adjusted in position (coordinate) in the X direction, the Y direction, and/or the Z direction.

[0048] When the peel-off layer forming step S**1** is performed in the laser processing apparatus **2**, first, the ingot **11** is placed on the holding surface of the chuck table **4** such that the front surface **11***a* faces upward. Next, the suction mechanism is operated such that the ingot **11** is held under suction on the chuck table **4**.

[0049] Next, for example, in such a manner that the second orientation flat **15** is in parallel with the X direction, the rotational mechanism causes the chuck table **4** to rotate. That is, in such a manner that the crystal orientation of gallium oxide is in parallel with the X direction and the crystal orientation thereof is in parallel with the Y direction, the rotational mechanism causes the chuck table **4** to rotate.

[0050] Next, in such a manner that a linear region of the ingot **11** (for example, a linear region along the X direction positioned in the vicinity of the second orientation flat **15**) along the X direction positioned in the vicinity of one end of the Y direction is positioned along the X direction as viewed from the head **16**, in plan view, the moving mechanism moves the head **16** and the like along the X direction and/or the Y direction.

[0051] Next, the peel-off layer including the first modified portion formed by emitting the first laser beam LB**1** having the first output power and the second modified portion formed by emitting the second laser beam LB**2** having the second output power, the first modified portion and the second modified portion being alternately lined up in the Y direction, is formed inside the ingot **11**.

[0052] FIG. **4** is a flowchart schematically indicating a procedure performed at a time of forming such a peel-off layer. Also, FIG. **5**A is a plan view schematically illustrating a manner in which the peel-off layer is formed inside the ingot **11**, and FIG. **5**B is an enlarged longitudinal sectional view schematically illustrating part of the ingot **11** formed with the peel-off layer therein.

[0053] When a peel-off layer **17** illustrated in FIG. **5**B is formed, first, in a state in which the first focusing point P**1** at which the first laser beam LB**1** is focused and the second focusing point P**2** at which the second laser beam LB**2** is focused are positioned inside the ingot **11**, the ingot **11** and both of the focusing points P**1** and P**2** are moved relative to each other along the X direction (laser beam applying step S**11**).

[0054] More specifically, in the laser beam applying step S**11**, while both of the laser beams LB**1** and LB**2** are emitted from the head **16**, in such a manner that both of the focusing points P**1** and P**2** pass from one end of the ingot **11** to the other end thereof in the X direction at a predetermined speed (for example, 390 mm/s), the moving mechanism moves the head **16** and the like along the X direction. That is, with a direction parallel to the crystal orientation of gallium oxide as a scanning direction, both of the laser beams LB**1** and LB**2** are emitted to the ingot **11**.

[0055] At this time, both of the laser beams LB**1** and LB**2** are obtained by causing the original laser beam to be split such that respective positions of both of the focusing points P**1** and P**2** in the X direction, the Y direction, and the Z direction satisfy the following conditions, for example.

[0056] First, in the X direction, in such a manner that the first focusing point P**1** moves inside the ingot **11**, preceding the second focusing point P**2**, both of the focusing points P**1** and P**2** are positioned. That is, in the laser beam applying step S**11**, in a case in which the moving mechanism moves the head **16** and the like in the X direction, the focusing point P**1** is positioned on the X direction side as viewed from the focusing point P**2**.

[0057] In addition, both of the focusing points P**1** and P**2** are positioned such that both of the focusing points P**1** and P**2** are spaced apart from each other in the Y direction and the second focusing point P**2** is closer to one end of the ingot **11** (more specifically, is closer to the second orientation flat **15**) in the Y direction than the first focusing point P**1**. Moreover, both of the focusing points P**1** and P**2** are positioned at the same height in the Z direction.

[0058] In the laser beam applying step S**11**, the first modified portion **19***a* and the second modified portion **19***b* are formed inside the ingot **11** (more specifically, in two columns of linear regions each extending along the X direction). Note that the first modified portion **19***a* is formed at the first focusing point P**1** at which the first laser beam LB**1** is focused and the second modified portion **19***b* is formed at the second focusing point P**2** at which the second laser beam LB**2** is focused.

[0059] In addition, when the first modified portion **19***a* and the second modified portion **19***b* are formed inside the ingot **11**, a volume of the ingot **11** is expanded, and an internal stress is generated in the ingot **11**. This internal stress becomes greater in proportion to a size of each of the first modified portion **19***a* and the second modified portion **19***b*, that is, the output power of each of the laser beams LB**1** and LB**2**.

[0060] When the internal stress becomes great, cracks develop from each of the first modified portion **19***a* and the second modified portion **19***b* in such a manner as to release this internal stress. Hence, setting the output power of each of the laser beams LB**1** and LB**2** appropriately allows for control whether or not the cracks **21** develop from each of the first modified portion **19***a* and the second modified portion **19***b* and the size of the cracks **21**, to some extent.

[0061] For example, in the laser beam applying step S**11**, in such a manner causing cracks smaller than the cracks **21** developing from the second modified portion **19***b* to develop from the first modified portion **19***a*, the output power of each of the laser beams LB**1** and LB**2** is set. Alternatively, in the laser beam applying step S**11**, in such a manner developing the cracks **21** from the second modified portion **19***b* but preventing the cracks from developing from the first modified portion **19***a*, the output power of each of the laser beams LB**1** and LB**2** may be set. Note that, in FIG. **5**A and FIG. **5**B, for convenience, the peel-off layer **17** not including the cracks which develop from the first modified portion **19***a* is illustrated.

[0062] In addition, as for gallium oxide, the crystal plane (**100**) is most likely to be cleaved, and the crystal plane (**001**) is second most likely to be cleaved. In this case, in the laser beam applying step S**11**, the scanning direction of both of the laser beams LB**1** and LB**2** is set to a direction in which an angle formed between the scanning direction of both of the laser beams LB**1** and LB**2** and the crystal plane (**100**) is larger (more specifically, set to a direction parallel to the crystal orientation) In this case, the ingot **11** is less likely to be cleaved on the crystal plane (**100**) of gallium oxide. That is, in the laser beam applying step S**11**, generation of cracks largely developing along the thickness direction of the ingot **11** is prevented.
[0063] When the first focusing point P**1** at which the first laser beam LB**1** emitted from the head **16** is focused and the second focusing point P**2** at which the second laser beam LB**2** emitted from the head **16** is focused pass through the other end of the ingot **11** in the X direction, the laser beam applying step S**11** is completed.
[0064] When the laser beam applying step S**11** is performed in this manner, the second modified portion **19***b* and the cracks **21** developing from the second modified portion **19***b* are formed at a linear region along the X direction positioned in the vicinity of the one end of the ingot **11** (more specifically, the second orientation flat **15**) in the Y direction, and the first modified portion **19***a* is formed at a linear region along the X direction positioned slightly farther than this region from the second orientation flat **15**.
[0065] Then, if the modified portion (more specifically, the first modified portion **19***a* or the second modified portion **19***b*) is not formed at each of the regions in the vicinity of both ends of the ingot **11** in the Y direction (step S**12**: NO), the ingot **11** and the positions at which both of the focusing points P**1** and P**2** are formed are moved relative to each other along the Y direction (moving step S**13**).
[0066] In the moving step S**13**, in plan view, in such a manner that the head **16** is positioned in the X direction as viewed from the linear region that is slightly farther from the second orientation flat **15** than the region in which the laser beam is previously applied, the moving mechanism moves the head **16** and the like by a predetermined distance (for example, 0.1 to 0.2 mm) along the Y direction. Note that this distance is set to a value twice greater than a center-to-center distance between both of the focusing points P**1** and P**2** in the Y direction, for example, in the laser beam applying step S**11**.
[0067] Next, with a direction opposite to the X direction as the scanning direction of both of the laser beams LB**1** and LB**2**, the laser beam applying step S**11** is performed. At this time, both of the laser beams LB**1** and LB**2** are obtained by causing the original laser beam to be split such that the positions of both of the focusing points P**1** and P**2** in the X direction, the Y direction, and the Z direction satisfy the abovementioned conditions, for example. Note that, in this laser beam applying step S**11**, since the direction opposite to the X direction is the scanning direction of both of the laser beams LB**1** and LB**2**, the focusing point P**1** is positioned on the side of the direction opposite to the X direction as viewed from the focusing point P**2**.
[0068] Moreover, until irradiation of the first laser beam LB**1** or the second laser beam LB**2** to a region in the vicinity of the other end of the ingot **11** (for example, a region farthest from the second orientation flat **15**) in the Y direction is completed, the moving step S**13** and the laser beam applying step S**11** are alternately repeated. That is, relative movement of the ingot **11** and the positions in which both of the focusing points P**1** and P**2** are formed along the Y direction and irradiation of both of the laser beams LB**1** and LB**2** to the ingot **11** with the X direction or the direction opposite thereto as the scanning direction are alternately repeated.
[0069] Then, when the modified portion (more specifically, the first modified portion **19***a* or the second modified portion **19***b*) is formed at each of the regions in the vicinity of both ends of the ingot **11** in the Y direction (step S**12**: YES), the peel-off layer forming step S**1** is completed.
[0070] Note that, in the abovementioned peel-off layer forming step S**1**, it is preferable that the peel-off layer **17** be formed in such a manner that the modified portion which is closest to not only the one end of the ingot **11** in the Y direction but also the other end thereof is the second modified portion **19***b*. In this case, it becomes easier to cause cracks **21** to develop to both ends of the ingot **11** in the Y direction, to thereby separate the ingot **11** in the separating step S**2** which will be described later.
[0071] In order to form such a peel-off layer **17**, for example, it is sufficient that, while a distance L between the one end to the other end of the ingot **11** in the Y direction is recognized, a distance D.sub.0 from the one end of the ingot **11** in the Y direction to the focusing point P**2** in the first round of the laser beam applying step S**11**, an interval I between both of the focusing points P**1** and P**2** in the Y direction in each round of the laser beam applying step S**11**, a distance D.sub.y by which the head **16** and the like move in the moving step S**13**, and the number of times of performance n in the laser beam applying step S**11** satisfy the following expression (1).
[00001][Expression1] $\{D_0+(n-1)D_Y\}<L<\{D_0+(n-1)D_Y+I\}\quad(1)$

[0072] More specifically, in a case in which the distance Do, the interval I, and the distance D.sub.y are set in the ratio of 1:2:4, it is sufficient that the distance D.sub.y and the number of times of performance n should be set in such a manner as to satisfy the following expression (2).

[00002][Expression2]

$$\left\{\frac{D_Y}{4}+(n-1)D_Y\right\}<L<\left\{\frac{D_Y}{4}+(n-1)D_Y+\frac{D_Y}{2}\right\} \text{.fwdarw. } \frac{4n-3}{4}D_Y<L<\frac{4n-1}{4}D_Y \text{ .fwdarw. } \frac{4L}{4n-1}<D_Y<\frac{4L}{4n-3} \quad (2)$$

[0073] Moreover, in a case in which the distance D.sub.0, the interval I, and the distance D.sub.y are set in the ratio of 1:1:2, it is sufficient that the distance D.sub.y and the number of times of performance n should be set in such a manner as to satisfy the following (3).

[00003][Expression3]

$$\left\{\frac{D_Y}{2}+(n-1)D_Y\right\}<L<\left\{\frac{D_Y}{2}+(n-1)D_Y+\frac{D_Y}{2}\right\} \text{.fwdarw. } \frac{2n-1}{2}D_Y<L<\text{nD}_Y \text{ .fwdarw. } \frac{L}{n}<D_Y<\frac{2L}{2n-1} \quad (3)$$

[0074] In addition, in a case in which the distance D.sub.0, the interval I, and the distance D.sub.Y are set in the ratio of 2:1:2, it is sufficient that the distance D.sub.y and the number of times of performance n should be set in such a manner as to satisfy the following expression (4).

[00004][Expression4]

$$\left\{D_Y+(n-1)D_Y\right\}<L<\left\{D_Y+(n-1)D_Y+\frac{D_Y}{2}\right\} \text{.fwdarw. nD}_Y<L<\frac{2n+1}{2}D_Y \text{ .fwdarw. } \frac{2L}{2n+1}<D_Y<\frac{L}{n} \quad (4)$$

[0075] Further, in the abovementioned peel-off layer forming step S**1**, irradiation of the first laser beam LB**1** to the ingot **11** and irradiation of the second laser beam LB**2** to the ingot **11** are performed in the same round of laser beam applying step S**11**, however, they may be performed in separate rounds of the laser beam applying step S**11**.

[0076] For example, in the peel-off layer forming step S**1**, after the laser beam applying step S**11** is performed in multiple times for forming all of the multiple columns of the first modified portions **19***a*, the laser beam applying step S**11** may be performed in multiple times for forming all of the multiple columns of the second modified portions **19***b*.

[0077] Alternatively, in the peel-off layer forming step S**1**, the first modified portion **19***a* and the second modified portion **19***b* may be formed alternately. For example, in the peel-off layer forming step S**1**, the laser beam applying step S**11** in which the X direction is set as the scanning direction of the second laser beam LB**2** and the abovementioned moving step S**13**, and the laser beam applying step S**11** in which the direction opposite to the X direction is set as the scanning direction of the first laser beam LB**1** and the abovementioned moving step S**13** may sequentially be repeated.

[0078] However, in these cases, the number of times of performance in each of the laser beam applying step S**11** and the moving step S**13** which are performed in the peel-off layer forming step S**1** may generally double. Hence, in this case, throughput in the laser processing apparatus **2** is reduced.

[0079] In view of such a drawback, it is preferable that irradiation of the first laser beam LB**1** to the ingot **11** and irradiation of the second laser beam LB**2** to the ingot **11** be performed in the same round of the laser beam applying step S**11**.

[0080] Also, in the abovementioned peel-off layer forming step S**1**, although the laser beam applying step S**11** is performed such that the first focusing point P**1** at which the first laser beam LB is focused precedes the second focusing point P**2** at which the second laser beam LB**2** is focused inside the ingot **11** in the X direction, the laser beam applying step S**11** may be performed such that both of the focusing points P**1** and P**2** run side by side. That is, in the peel-off layer forming step S**1**, the laser beam applying step S**11** may be performed in a state in which positions of both of the focusing points P**1** and P**2** in the X direction match with each other.

[0081] However, in this case, the cracks **21** that largely obliquely develop in plan view may develop from the second modified portion **19***b*. That is, in this case, the cracks **21** may develop in such a manner as to cross a region of the ingot **11** where the first modified portion **19***a* is to be formed but the first modified portion **19***a* has not yet been formed. Hence, in this case, the first modified portion **19***a* is not formed as intended, and the thickness of the peel-off layer **17** that is formed inside the ingot **11** increases, thereby causing lowering of productivity in the manufacturing of the substrate from the ingot **11**.

[0082] In view of such a drawback, it is preferable that the laser beam applying step S**11** be performed such that the first focusing point P**1** precedes the second focusing point P**2** inside the ingot **11** in the X direction.

[0083] Moreover, in the abovementioned peel-off layer forming step S**1**, the direction parallel to the crystal orientation of gallium oxide (the X direction or the opposite direction thereto) is set as the scanning direction of both of the laser beams LB**1** and LB**2**. However, a direction that is not parallel to the crystal orientation of gallium oxide may be set as the scanning direction of both of the laser beams LB**1** and LB**2**.

[0084] Note that, however, when the scanning direction of both of the laser beams LB**1** and LB**2** is parallel to the crystal orientation of gallium oxide, the percentage of the cracks **21** that develop along the crystal plane (**100**) parallel to the crystal orientation may increase. In a case in which the percentage of the cracks **21** that develop along the crystal plane (**100**) increases, the thickness of the peel-off layer **17** that is formed inside the ingot **11** increases, resulting in lowering of the productivity in the manufacturing of a substrate from the ingot **11**.
[0085] In addition, in this case, the percentage of the cracks **21** that develop along the crystal plane (**001**), that is, the cracks **21** that develop in parallel to the front surface **11***a* of the ingot **11**, decreases, so that a width of the peel-off layer **17** (a length in a direction perpendicular to each of the thickness direction of the ingot **11** and the scanning direction of both of the laser beams LB**1** and LB**2**) formed inside the ingot **11** decreases. Hence, in this case, in the moving step S**13**, the distance by which the head **16** and the like move has to be reduced, causing lowering of the throughput in the laser processing apparatus **2**.
[0086] In view of these drawbacks, in order to enhance the productivity and the throughput in the manufacturing of a substrate from the ingot **11**, the scanning direction of both of the laser beams LB**1** and LB**2** is preferably set such that an angle formed between the scanning direction of both of the laser beams LB**1** and LB**2** and a straight line parallel to the crystal orientation of gallium oxide becomes greater, that is, the angle formed between the scanning direction of both of the laser beams LB**1** and LB**2** and the straight line parallel to the crystal orientation becomes smaller.
[0087] Moreover, in the abovementioned peel-off layer forming step S**1**, irradiation of both of the laser beams LB**1** and LB**2** to the ingot **11** may be performed along only one direction (for example, along the X direction). That is, in the peel-off layer forming step S**1**, irradiation of both of the laser beams LB**1** and LB**2** to the ingot **11** may be repeated in a condition that a direction opposite to the relevant one direction (for example, a direction opposite to the X direction) is not assigned to the scanning direction of both of the laser beams LB**1** and LB**2** but the relevant one direction is assigned to the scanning direction.
[0088] After the peel-off layer forming step S**1** is performed, with the peel-off layer **17** as a starting point of separation, the ingot **11** is separated, so that a substrate is manufactured (separating step S**2**). FIG. **6**A and FIG. **6**B are each a side view schematically illustrating a manner in which the separating step S**2** is performed. This separating step S**2** is performed by a separation apparatus **18**. The separation apparatus **18** includes a chuck table **20** having the same structure as that of the chuck table **4** depicted in FIG. **3**.
[0089] The chuck table **20** is coupled with a table-side suction mechanism (not illustrated). This table-side suction mechanism has, for example, a vacuum pump and the like. When the table-side suction mechanism is operated, a suction force is applied to a space in the vicinity of the holding surface of the chuck table **20**. Hence, when the table-side suction mechanism is operated in a state in which the ingot **11** is placed on the holding surface, the ingot **11** is held under suction on the holding surface of the chuck table **20**.
[0090] Above the chuck table **20**, a separation unit **22** is provided. The separation unit **22** has a suction plate **24** that has a plurality of suction ports formed in a lower surface thereof. The plurality of suction ports are communicated with a separation unit-side suction mechanism such as a vacuum pump through a suction path that is formed inside the suction plate **24**. When the separation unit-side suction mechanism is operated, a suction force is applied to a space in the vicinity of the lower surface of the suction plate **24**.
[0091] In addition, a vertical-direction-moving mechanism **26** is coupled with an upper surface of the suction plate **24**. The vertical-direction-moving mechanism **26** has, for example, a ball screw, a motor, and the like. When the vertical-direction-moving mechanism **26** is operated, the suction plate **24** moves along the vertical direction.
[0092] In the separation apparatus **18**, when the separating step S**2** is performed, first, in a state in which the chuck table **20** and the suction plate **24** are sufficiently apart from each other, in such a manner that the front surface **11***a* of the ingot **11** in which the peel-off layer **17** is formed faces upward, the ingot **11** is placed on the holding surface of the chuck table **20**. Next, the table-side suction mechanism is operated in such a manner that the ingot **11** is held under suction on the holding surface of the chuck table **20**.
[0093] Next, in such a manner as to bring the lower surface of the suction plate **24** into contact with the front surface **11***a* of the ingot **11**, the vertical-direction-moving mechanism lowers the suction plate **24** (see FIG. **6**A). Next, in such a manner that the front surface **11***a* side of the ingot **11** is sucked upward, the separation unit-side suction mechanism is operated. Next, in such a manner that the suction plate **24** is spaced apart from the chuck table **20**, the vertical-direction-moving mechanism **26** lifts the suction plate **24** (see FIG. **6**B).
[0094] Hence, such an external force that the front surface **11***a* side and the back surface **11***b* side of the ingot **11** are separated from each other is applied to the ingot **11**, and accordingly, the cracks **21** included in the

peel-off layer **17** further develop. As a result, with the peel-off layer **17** as a starting point of separation, the ingot **11** is separated, so that a substrate **23** is manufactured. As above, the separating step S**2** is completed, that is, the method of manufacturing the substrate indicated in FIG. **2** is completed.

[0095] In the method of manufacturing the substrate indicated in FIG. **2**, after the peel-off layer **17** is formed inside the ingot **11**, the ingot **11** is separated with the peel-off layer **17** as a starting point of separation, whereby the substrate **23** is manufactured. As a result, compared to a case in which a substrate **23** is manufactured from the ingot **11** with use of the wire saw, it is possible to enhance the productivity of the substrate **23**.

[0096] Note that the abovementioned details are merely one mode of the present invention, and the present invention is not limited the abovementioned details. For example, in the peel-off layer forming step S**1** according to the present invention, it is sufficient that the ingot **11**, the first focusing point P**1** at which the first laser beam LB**1** is focused, and/or the second focusing point P**2** at which the second laser beam LB**2** is focused be moved relative to each other, and hence, a structure therefor is not limited to any particular one.

[0097] More specifically, the peel-off layer forming step S**1** may be performed in a laser processing apparatus in which a moving mechanism that causes the chuck table **4** to move along each of the X direction, the Y direction, and/or the Z direction is provided.

[0098] Alternatively, the peel-off layer forming step S**1** may be performed with use of a laser processing apparatus in which a scanning optical system that can change the direction(s) of the first laser beam LB**1** and/or the second laser beam LB**2** emitted from the head **16** is provided in the laser beam applying unit **6**. Note that the scanning optical system includes, for example, a galvanoscanner, an acousto-optic deflector (AOD), a polygon mirror, and/or the like.

[0099] Moreover, in the separating step S**2** according to the present invention, as an external force for manufacturing the substrate **23**, ultrasonic vibration may be applied to the ingot **11**. That is, in the separating step S**2**, in place of or prior to application of such an external force that the front surface **11***a* side and the back surface **11***b* side of the ingot **11** are separated from each other, ultrasonic vibration may be applied to the front surface **11***a* side of the ingot **11**.

[0100] In addition, in a case in which the peel-off layer forming step S**1** is performed such that a modified portion that is closest to the one end of the ingot **11** in the Y direction (more specifically, the second orientation flat **15**) is the second modified portion **19***b* and that a modified portion that is closest to the other end of the ingot **11** in the Y direction is the first modified portion **19***a*, the substrate manufacturing method according to the present invention may include a step of reinforcing a region in the vicinity of the other end of the ingot **11** as a starting point of separation after the peel-off layer forming step S**1** but before the separating step S**2**.

[0101] That is, the substrate manufacturing method according to the present invention may include a step of facilitating separation of the ingot **11** in the separating step S**2**, by, for example, developing the cracks **21** to the other end of the ingot **11** in the Y direction. FIG. **7** is a flowchart schematically indicating one example of the substrate manufacturing method including such a step described above.

[0102] In this method, after the peel-off layer forming step S**1** but before the separating step S**2**, by positioning the second focusing point P**2** in such a manner overlapping with the first modified portion **19***a* that is closest to the other end of the ingot **11** in the Y direction, the ingot **11** and the second focusing point P**2** are moved relative to each other along the X direction (final laser beam applying step S**3**).

[0103] The final laser beam applying step S**3** is performed as in the laser beam applying step S**11** described above, for example, except that the first laser beam LB**1** is not emitted from the head **16** but the second laser beam LB**2** only is emitted.

[0104] More specifically, first, in such a manner that the first modified portion **19***a* that is closest to the other end of the ingot **11** is positioned in the X direction as viewed from the head **16**, in plan view, the moving mechanism moves the head **16** and the like along the X direction and/or the Y direction. Then, in such a manner that the focusing point P**2** passes from the one end of the ingot **11** in the X direction to the other end thereof as a predetermined speed, while the second laser beam LB**2** is emitted from the head **16**, the moving mechanism moves the head **16** and the like along the X direction.

[0105] Alternatively, the final laser beam applying step S**3** may be performed as in the laser beam applying step S**11** described above, also including a point that both the first laser beam LB**1** and the second laser beam LB**2** are emitted from the head **16**. In other words, the final laser beam applying step S**3** may be performed as in the laser beam applying step S**11** described above, except that it is performed such that the focusing point P**1** does not pass the inner side of the ingot **11**.

[0106] Moreover, the workpiece used in the substrate manufacturing method according to the present invention may be an ingot manufactured such that a crystal plane other than the crystal plane {001} of gallium oxide (for example, the crystal plane (**100**)) is exposed in the front surface.
[0107] In addition, the workpiece used in the substrate manufacturing method according to the present invention may be a bare wafer having a thickness twice greater than and five-fold less than that of a substrate manufactured, for example. Note that the bare wafer is manufactured by separating the ingot **11**, as in the method described above, for example. In this case, it can also be said that the substrate **23** is manufactured by repeating twice the method described above.
[0108] Alternatively, the workpiece used in the substrate manufacturing method according to the present invention may be a device wafer manufactured by forming semiconductor devices on one surface of this bare wafer. In this case, it is preferable that the laser beam be applied to the device wafer from a side on which semiconductor devices of the device wafer are not formed, in order to prevent an adverse effect on the semiconductor devices.
[0109] In addition, materials of the workpiece used in the substrate manufacturing method according to the present invention is not limited to gallium oxide. For example, the workpiece may be a single crystal made of silicon (Si), silicon carbide (Sic), gallium nitride (GaN), lithium tantalate (LiTaO.sub.3:LT), or lithium niobate (LiNbO.sub.3:LN).
[0110] Other structures, methods, and the like according to the abovementioned embodiment can be implemented by appropriately being modified within a scope not departing from the object of the present invention.
[0111] The present invention is not limited to the details of the above described preferred embodiment. The scope of the invention is defined by the appended claims and all changes and modifications as fall within the equivalence of the scope of the claims are therefore to be embraced by the invention.

Claims

1. A substrate manufacturing method of manufacturing a substrate from a workpiece, the substrate having a thickness smaller than that of the workpiece, the method comprising: applying, to the workpiece, a laser beam of a wavelength transmittable through a material of the workpiece, thereby forming a peel-off layer inside the workpiece; and separating the workpiece with the peel-off layer as a starting point of separation, after the forming of the peel-off layer, thereby manufacturing the substrate, wherein, in the forming of the peel-off layer, by alternately repeating moving the workpiece and a focusing point at which the laser beam is focused relative to each other along a first direction, in a state in which the focusing point is positioned inside the workpiece, and moving the workpiece and a position at which the focusing point is formed relative to each other along a second direction perpendicular to the first direction, the peel-off layer including first modified portions and second modified portions which are alternately lined up in the second direction is formed, the first modified portion is formed at a first focusing point at which a first laser beam having first output power is focused, and the second modified portion is formed at a second focusing point at which a second laser beam having a second output power greater than the first output power is focused.
2. The substrate manufacturing method according to claim 1, wherein, in the applying of the laser beam, the original laser beam of a wavelength transmittable through the material of the workpiece is split into the first laser beam and the second laser beam, and in a state in which the first focusing point and the second focusing point which are spaced apart from each other in the second direction are positioned inside the workpiece, the workpiece and each of the first focusing point and the second focusing point are moved relative to each other along the first direction.
3. The substrate manufacturing method according to claim 2, wherein, in the applying of the laser beam, the first focusing point moves inside the workpiece in the first direction, while preceding the second focusing point.
4. The substrate manufacturing method according to claim 1, wherein cracks that develop from the first modified portion are smaller than cracks that develop from the second modified portion.
5. The substrate manufacturing method according to claim 1, wherein cracks do not develop from the first modified portion, but cracks develop from the second modified portion.
6. The substrate manufacturing method according to claim 1, further comprising: after the forming of the peel-off layer to be performed such that a modified portion that is closest to one end of the workpiece in the second direction becomes the second modified portion and a modified portion that is closest to another end

thereof becomes the first modified portion, but before the separating, moving the workpiece and the second focusing point relative to each other along the first direction, in a state in which the second focusing point is positioned in such a manner overlapping with the first modified portion that is closest to the other end.

7. The substrate manufacturing method according to claim 2, further comprising: after the forming of the peel-off layer to be performed such that a modified portion that is closest to one end of the workpiece in the second direction becomes the second modified portion and a modified portion that is closest to another end thereof becomes the first modified portion, but before the separating, moving the workpiece and the second focusing point relative to each other along the first direction, in a state in which the second focusing point is positioned in such a manner overlapping with the first modified portion that is closest to the other end.

8. The substrate manufacturing method according to claim 3, further comprising: after the forming of the peel-off layer to be performed such that a modified portion that is closest to one end of the workpiece in the second direction becomes the second modified portion and a modified portion that is closest to another end thereof becomes the first modified portion, but before the separating, moving the workpiece and the second focusing point relative to each other along the first direction, in a state in which the second focusing point is positioned in such a manner overlapping with the first modified portion that is closest to the other end.

9. The substrate manufacturing method according to claim 4, after the forming of the peel-off layer to be performed such that a modified portion that is closest to one end of the workpiece in the second direction becomes the second modified portion and a modified portion that is closest to another end thereof becomes the first modified portion, but before the separating, moving the workpiece and the second focusing point relative to each other along the first direction, in a state in which the second focusing point is positioned in such a manner overlapping with the first modified portion that is closest to the other end.

10. The substrate manufacturing method according to claim 5, after the forming of the peel-off layer to be performed such that a modified portion that is closest to one end of the workpiece in the second direction becomes the second modified portion and a modified portion that is closest to another end thereof becomes the first modified portion, but before the separating, moving the workpiece and the second focusing point relative to each other along the first direction, in a state in which the second focusing point is positioned in such a manner overlapping with the first modified portion that is closest to the other end.

11. The substrate manufacturing method according to claim 1, wherein the forming of the peel-off layer is performed such that a modified portion which comes closest to each end of the workpiece in the second direction becomes the second modified portion.

12. The substrate manufacturing method according to claim 2, the forming of the peel-off layer is performed such that a modified portion which comes closest to each end of the workpiece in the second direction becomes the second modified portion.

13. The substrate manufacturing method according to claim 3, the forming of the peel-off layer is performed such that a modified portion which comes closest to each end of the workpiece in the second direction becomes the second modified portion.

14. The substrate manufacturing method according to claim 4, wherein the forming of the peel-off layer is performed such that a modified portion which comes closest to each end of the workpiece in the second direction becomes the second modified portion.

15. The substrate manufacturing method according to claim 5, the forming of the peel-off layer is performed such that a modified portion which comes closest to each end of the workpiece in the second direction becomes the second modified portion.