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SUBSTRATE MANUFACTURING METHOD

Abstract

A substrate manufacturing method includes peel-off layer forming of forming a plurality of rows of peel-off layers inside a workpiece, and, after the peel-off layer forming, separating the workpiece with the plurality of rows of peel-off layers being used as separation initiating points, to manufacture substrates. The peel-off layer forming includes first processing of forming a plurality of rows of first peel-off layers each including a modified portion and each being spaced from one another, and second processing of, after the first processing, forming a plurality of rows of second peel-off layers each including a modified portion and a crack extending from the modified portion and each being located between a pair of adjacent first peel-off layers of the plurality of rows of first peel-off layers.

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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, from a workpiece using gallium oxide as the material, a substrate that is thinner than the workpiece.

Description of the Related Art

[0002] In gallium oxide (Ga.sub.2O.sub.3) which exhibits crystal polymorphism, the monoclinic β phase (β-Ga.sub.2O.sub.3) is the most stable phase. β-phase gallium oxide (hereinafter simply referred to as “gallium oxide”) is a wide gap semiconductor whose bandgap is approximately 4.8 eV. Hence, gallium oxide is expected to be used as the material of such semiconductor devices as power devices.

[0003] Semiconductor devices are typically formed with use of a disk-shaped substrate. This substrate is, for example, manufactured by slicing a workpiece with a wire saw in such a manner that a portion that is part of a workpiece such a cylindrical block called an ingot and that has a predetermined thickness is separated (see, for example, Japanese Patent Laid-open No. 2016-13929).

SUMMARY OF THE INVENTION

[0004] In forming semiconductor devices, for example, a substrate having a thickness of approximately 150 μm is used. Further, the wire saw to be used has a thickness of, for example, approximately 300 μm. Hence, when substrates are to be manufactured from a workpiece with use of the wire saw, for example, 60% to 70% of the workpiece is discarded as a cutting margin, leading to poor productivity.

[0005] In light of the abovementioned circumstance, an object of the present invention is to provide a substrate manufacturing method capable of improving the productivity of substrates at the time of manufacturing, from a workpiece using gallium oxide as the material, a substrate thinner than the workpiece.

[0006] In accordance with an aspect of the present invention, there is provided a substrate manufacturing method of manufacturing, from a workpiece using gallium oxide as a material, a substrate thinner than the workpiece, the method including peel-off layer forming of forming a plurality of rows of peel-off layers inside the workpiece, and separating, after the peel-off layer forming, the workpiece with the plurality of rows of peel-off layers being used as separation initiating points, to manufacture the substrate, in which the peel-off layer forming includes first processing of forming a plurality of rows of first peel-off layers each including a modified portion and each being spaced from one another, and second processing of, after the first processing, forming a plurality of rows of second peel-off layers each including the modified portion and a crack extending from the modified portion and each being located between a pair of adjacent first peel-off layers of the plurality of rows of first peel-off layers, in the first processing, alternately repeated are first laser beam applying of moving the workpiece and a focused spot of a laser beam having a wavelength transmittable through the gallium oxide relative to each other along a first direction in a state in which the focused spot is positioned inside the workpiece, and first indexing feeding of moving the workpiece and a position where the focused spot is to be formed relative to each other along a second direction perpendicular to the first direction, and, in the second processing, alternately repeated are second laser beam applying of moving the workpiece and the focused spot relative to each other along the first direction in a state in which the focused spot is positioned between the pair of adjacent first peel-off layers, and second indexing feeding of moving the workpiece and the position where the focused spot is to be formed relative to each other along the second direction.

[0007] Further, an output power level of the laser beam in the first laser beam applying may be set to be smaller than an output power level of the laser beam in the second laser beam applying, in the first processing, the plurality of rows of first peel-off layers each including the crack may be formed, and the crack included in each of the plurality of rows of first peel-off layers may be smaller than the crack included in each of the plurality of rows of second peel-off layers. In this case, preferably, the peel-off layer forming further includes, after the second processing, third laser beam applying of applying the laser beam to at least one of the plurality of rows of first peel-off layers such that the crack further extends.

[0008] Alternatively, an output power level of the laser beam in the first laser beam applying may be set to be smaller than an output power level of the laser beam in the second laser beam applying, and, in the first processing, the plurality of rows of first peel-off layers each not including the crack may be formed. In this case, preferably, the peel-off layer forming further includes, after the second processing, third laser beam applying of applying the laser beam to at least one of the plurality of rows of first peel-off layers such that the crack extends from the modified portion.

[0009] Alternatively, an output power level of the laser beam in the first laser beam applying may be set to be the same as an output power level of the laser beam in the second laser beam applying, and, in the first processing, the plurality of rows of first peel-off layers each including the crack may be formed. In this case, preferably, the peel-off layer forming further includes, after the second processing, third laser beam applying of applying the laser beam to at least one of the plurality of rows of first peel-off layers and/or at least one of the plurality of rows of second peel-off layers such that the crack further extends.

[0010] In addition, a depth of the focused spot from a face side of the workpiece in the first laser beam applying is preferably set to be the same as a depth of the focused spot from the face side in the second laser beam applying.

[0011] According to the present invention, after a plurality of rows of first peel-off layers and a plurality of rows of second peel-off layers are formed inside a workpiece, the workpiece is separated with these peel-off layers being used as separation initiating points, and substrates are thus manufactured. This makes it possible to improve the productivity of substrates compared to the case in which substrates are manufactured from the workpiece with use of a wire saw.

[0012] 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

[0013] FIG. **1**A is a perspective view schematically illustrating an example of an ingot using gallium oxide as a material;

[0014] FIG. **1**B is a side elevational view schematically illustrating the ingot depicted in FIG. **1**A;

[0015] FIG. **2** is a flowchart schematically illustrating an example of a substrate manufacturing method;

[0016] FIG. **3** is a flowchart schematically illustrating an example of a peel-off layer forming step illustrated in FIG. **2**;

[0017] FIG. **4** is a perspective view schematically illustrating the manner of the peel-off layer forming step;

[0018] FIG. **5** is a flowchart schematically illustrating an example of a first processing step illustrated in FIG. **3**;
[0019] FIG. **6**A is a plan view schematically illustrating the manner of the first processing step;
[0020] FIG. **6**B is a longitudinal sectional view schematically illustrating, in an enlarged manner, part of the ingot obtained after the first processing step; FIG. **7** is a flowchart schematically illustrating an example of a second processing step illustrated in FIG. **3**;
[0021] FIG. **8**A is a plan view schematically illustrating the manner of the second processing step;
[0022] FIG. **8**B is a longitudinal sectional view schematically illustrating, in an enlarged manner, part of the ingot obtained after the second processing step;
[0023] FIG. **9**A is a side elevational view schematically illustrating the manner of a separating step illustrated in FIG. **2**;
[0024] FIG. **9**B is a side elevational view schematically illustrating the manner of the separating step illustrated in FIG. **2**; and
[0025] FIG. **10** is a flowchart schematically illustrating another example of the peel-off layer forming step illustrated in FIG. **2**.
DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT
[0026] An embodiment of the present invention will be described with reference to the attached drawings. Note that the attached drawings are provided for easy understanding of the present invention and do not necessarily reflect, in an accurate manner, the objects and/or methods in which the present invention is embodied.
[0027] FIG. **1**A is a perspective view schematically illustrating an example of an ingot using gallium oxide as the material, while FIG. **1**B is a side elevational view schematically illustrating the ingot depicted in FIG. **1**A. Note that FIGS. **1**A and **1**B also depict the crystal plane of gallium oxide included in the ingot. Moreover, FIG. **1**B also depicts the crystal orientation of gallium oxide.
[0028] Gallium oxide has a monoclinic crystal structure in which the angle formed between the crystal orientation [100] (a-axis) and the crystal orientation [001] (c-axis) is 103.7° and the angles formed between the crystal orientation [010] (b-axis) and the crystal orientation [100] (a-axis) and between the crystal orientation (b-axis) and the crystal orientation [001] (c-axis) are each 90°. The ingot illustrated in FIGS. **1**A and **1**B and denoted by **11** has a face side **11***a* and a reverse side **11***b* that are parallel to each other and on each of which a crystal plane {001} is exposed (here, for the sake of convenience, the plane exposed on the face side **11***a* is assumed to be the crystal plane (001)).
[0029] Note that, while the ingot **11** is so manufactured that the crystal plane {001} is exposed on each of the face side **11***a* and the reverse side **11***b*, a plane slightly inclined relative to the crystal plane {001} may be exposed on each of the face side **11***a* and the reverse side **11***b* due to processing errors or the like that occurs at the time of manufacture. Specifically, on each of the face side **11***a* and the reverse side **11***b* of the ingot **11**, a plane which forms an angle of 1° or less with the crystal plane {001} may be exposed.
[0030] On a side surface **11***c* of the ingot **11**, two flat portions for indicating the crystal orientation of gallium oxide, that is, a first orientation flat **13** and a second orientation flat **15**, are formed. The first orientation flat **13** is longer than the second orientation flat **15** and formed in such a manner as to be positioned at the crystal orientation [100] as viewed from the center of the ingot **11**.
[0031] The second orientation flat **15** is formed in such a manner as to be positioned at the crystal orientation [010] as viewed from the center of the ingot **11**. In other words, the second orientation flat **15** is so formed as to be a plane on 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 face side **11***a* or the reverse side **11***b* and is perpendicular to the second orientation flat **15**.
[0032] Note that, on the side surface **11***c* of the ingot **11**, one of or both the first orientation flat **13** and the second orientation flat **15** may not be formed. Further, in the side surface **11***c* of the ingot **11**, a cutout (notch) for indicating the crystal orientation of gallium oxide may be formed in place

of the first orientation flat **13** and the second orientation flat **15**.

[0033] FIG. **2** is a flowchart schematically illustrating an example of a substrate manufacturing method of manufacturing, from the ingot **11** used as a workpiece, a substrate thinner than the ingot **11**. In this method, first, a plurality of rows of peel-off layers are formed inside the ingot **11** (peel-off layer forming step S**1**). Note that each of the peel-off layers includes a modified portion in which the crystal structure of gallium oxide is disordered. Moreover, each of the peel-off layers may include a crack that extends from the modified portion.

[0034] In the peel-off layer forming step S**1**, a plurality of rows of peel-off layers are formed one by one inside the ingot **11**. Yet, when the plurality of rows of peel-off layers are formed one by one from one end, that is, when one peel-off layer that is positioned at the end in a direction perpendicular to the direction in which the peel-off layers extend is formed first and the other peel-off layers are formed one by one in such a manner as to be adjacent to the peel-off layer formed immediately prior to the current one, an extremely long crack sometimes extends from the modified portion included in the peel-off layer while the peel-off layers are being formed.

[0035] Specifically, when the peel-off layers are formed in the order described above, internal stress generated in the ingot **11** in association with the formation of the modified portions included in the peel-off layers acts on the modified portion included in the newly formed peel-off layer, and a crack excessively extends from the newly formed modified portion, in some cases. In other words, when the internal stress accumulated in association with the formation of the modified portions becomes excessive, an extremely long crack is, in some cases, formed in the newly formed modified portion in order to collectively release the accumulated internal stress.

[0036] In this case, there is a possibility that the crack extends to a region of the ingot **11** in which formation of peel-off layers is not intended and makes it difficult to thereafter form desired peel-off layers in the region. Further, in this case, the components of the crack along the thickness direction of the ingot **11** may become greater and reduce the productivity of substrates when the substrates are to be formed from the ingot **11**.

[0037] As such, in the peel-off layer forming step S**1**, a plurality of rows of peel-off layers are formed inside the ingot **11** in such an order that cracks do not excessively extend from the modified portions. FIG. **3** is a flowchart schematically illustrating an example of the peel-off layer forming step S**1** in which a plurality of rows of peel-off layers are formed in such a manner.

[0038] In the peel-off layer forming step S**1**, first, a plurality of rows of first peel-off layers each including a modified portion and each being spaced from one another are formed (first processing step S**11**). After the first processing step S**11**, a plurality of rows of second peel-off layers each including a modified portion and a crack and each being located between a pair of adjacent first peel-off layers of the plurality of rows of first peel-off layers are formed (second processing step S**12**).

[0039] More specifically, in the peel-off layer forming step S**1**, after the plurality of rows of first peel-off layers are formed in such a manner that each region between each pair of adjacent first peel-off layers in the ingot **11** is left unprocessed (first processing step S**11**), the plurality of rows of second peel-off layers are each formed in the respective remaining plurality of rows of unprocessed regions (second processing step S**12**).

[0040] In this case, in the first processing step S**11**, the internal stress generated in the ingot **11** in association with the formation of the modified portions included in the first peel-off layers is less likely to act on the modified portion included in the newly formed first peel-off layer. Further, in the second processing step S**12**, the extendable range of the crack extending from the modified portion included in the second peel-off layer can be limited to the range between a pair of adjacent first peel-off layers.

[0041] Note that each of the first peel-off layers includes or does not include, for example, a crack smaller than the crack extending from the modified portion included in each of the second peel-off layers. Alternatively, each of the first peel-off layers may include a crack of substantially the same size as the crack extending from the modified portion included in each of the second peel-off layers.

[0042] FIG. **4** is a perspective view schematically illustrating the manner of the peel-off layer forming step S**1**. Note that, in FIG. **4**, a direction indicated by an arrow X (X direction) and a direction indicated by an arrow Y (Y direction) are directions perpendicular to each other on a horizontal plane, and a direction indicated by an arrow Z (Z direction) is a direction (vertical direction) perpendicular to the X direction and the Y direction.

[0043] The peel-off layer forming step S**1** is performed in a laser processing apparatus **2**. The laser processing apparatus **2** includes a chuck table **4** that has a circular holding surface substantially parallel to the horizontal plane and that is capable of holding the ingot **11** on this holding surface.

[0044] The chuck table **4** is coupled to a suction mechanism (not illustrated). This suction mechanism includes, for example, an ejector or the like. When the suction mechanism is operated, suction force acts in the space near 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**.

[0045] The chuck table **4** is also coupled to a rotation mechanism (not illustrated). The rotation mechanism includes, for example, a pulley, a motor, and the like. When the rotation mechanism is operated, the chuck table **4** rotates about a straight line passing through the center of the holding surface and extending along the Z direction as the rotational axis. For example, the rotation mechanism rotates the chuck table **4** such that the second orientation flat **15** of the ingot **11** held on the holding surface of the chuck table **4** becomes parallel to the X direction.

[0046] A head **8** of a laser beam application unit **6** is provided above the chuck table **4**. The head **8** is provided on a distal end portion of a cylindrical housing **10** extending along the Y direction. Note that the head **8** houses an optical system such as a condenser lens (for example, a condenser lens with a numerical aperture (NA) of 0.85) and a mirror, while the housing **10** includes an optical system such as a mirror and/or a lens.

[0047] A moving mechanism is coupled to a proximal end portion of the housing **10**. The moving mechanism includes, for example, a ball screw, a motor, and the like. When the moving mechanism is operated, the housing **10** moves along the X direction, the Y direction, and/or the Z direction. Further, the laser beam application unit **6** has, for example, a laser oscillator (not illustrated) including neodymium-yttrium-aluminum-garnet (Nd:YAG) or the like as a laser medium.

[0048] The laser oscillator generates a laser beam having a wavelength (for example, 1,064 nm) transmittable through gallium oxide (for example, a pulsed laser beam having a frequency of 30 kHZ and a pulse width of 4 ns). The laser beam, after being adjusted in an attenuator such that the output power level thereof has a predetermined value (for example, 0.1 to 2.0 W), is emitted directly downward from the head **8** via the optical systems housed in the housing **10** and the head **8**.

[0049] An imaging unit **12** capable of imaging the region immediately below it is provided on the lateral portion of the housing **10**. The imaging unit **12** includes, for example, a light source such as a light emitting diode (LED) that emits light of a wavelength transmittable through gallium oxide (for example, visible light), an objective lens, and an imaging element such as a charge coupled device (CCD) image sensor or a complementary metal oxide semiconductor (CMOS) image sensor.

[0050] 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 face side **11***a* faces upward. Next, the suction mechanism is operated such that the ingot **11** is held under suction on the holding surface of the chuck table **4**. Thereafter, the imaging unit **12** is operated such that an image of the face side **11***a* of the ingot **11** is formed.

[0051] Subsequently, with reference to the image, for example, the rotation mechanism rotates the chuck table **4** such that the second orientation flat **15** becomes parallel to the X direction. That is, the rotation mechanism rotates the chuck table **4** such that the crystal orientation [100] of gallium

oxide becomes parallel to the X direction and the crystal orientation [010] of gallium oxide becomes parallel to the Y direction.
[0052] Then, the moving mechanism moves the housing **10** along the X direction and/or the Y direction such that the region near one end of the ingot **11** in the Y direction (for example, the region near the second orientation flat **15**) is positioned in the X direction as viewed from the head **8** in plan view. Subsequently, the moving mechanism moves the housing **10** along the Z direction such that a focused spot P of the laser beam emitted from the head **8** is positioned at a predetermined depth from the face side **11***a* of the ingot **11** (for example, a depth of 300 μm from the face side **11***a*).
[0053] Next, the first processing step S**11** is performed. FIG. **5** is a flowchart schematically illustrating an example of the first processing step S**11**. FIG. **6**A is a plan view schematically illustrating the manner of the first processing step S**11**, while FIG. **6**B is a longitudinal section view schematically illustrating, in an enlarged manner, part of the ingot **11** obtained after the first processing step S**11**.
[0054] In the first processing step S**11**, first, the ingot **11** and the focused spot P of the laser beam are moved relative to each other along the X direction in a state in which the focused spot P is positioned inside the ingot **11** (first laser beam applying step S**111**).
[0055] Specifically, in the first laser beam applying step S**111**, while a laser beam is being emitted from the head **8**, the moving mechanism moves the housing **10** along the X direction such that the focused spot P of the laser beam passes from one end to the other end of the ingot **11** in the X direction at a predetermined speed (for example, 390 mm/s). That is, the laser beam is applied to the ingot **11** with the direction parallel to the crystal orientation [100] of gallium oxide being set as the scanning direction of the laser beam.
[0056] This forms, inside the ingot **11**, a modified portion **17** in which the crystal structure of gallium oxide is disordered with the focused spot P of the laser beam being the center. When the modified portion **17** is formed inside the ingot **11**, the volume of the ingot **11** expands, and internal stress is generated in the ingot **11**.
[0057] The internal stress becomes greater in proportion to the size of the modified portion **17**, i.e., the output power level of the laser beam. When the internal stress becomes greater, cracks extend from the modified portions **17** to release this internal stress. Hence, appropriately setting the output power level of the laser beam makes it possible to control whether or not to allow the cracks to extend from the modified portions **17** and the size of the cracks to a certain extent.
[0058] For example, when the modified portion **17** is to be formed but no crack is to be extended from the modified portion **17** in the first processing step S**11**, the output power level of the laser beam is, for example, set to 0.3 W. Further, when cracks of the same size as the cracks extending from the modified portions **17** formed in the second processing step S**12** are to be extended from the modified portions **17** in the first processing step S**11**, the output power level of the laser beam is, for example, set to 0.8 W. Alternatively, when cracks smaller than the cracks extending from the modified portions **17** formed in the second processing step S**12** are to be extended from the modified portions **17** in the first processing step S**11**, the output power level of the laser beam is, for example, set to 0.4 to 0.7 W.
[0059] Note that, in gallium oxide, the crystal plane (100) is most likely to be cleaved, followed by the crystal plane (001). Here, in the first laser beam applying step S**111**, the scanning direction of the laser beam is set to a direction which forms a large angle with the crystal plane (100) (specifically, the direction parallel to the crystal orientation [100]). In this case, the ingot **11** becomes less likely to be cleaved in the crystal plane (100) of gallium oxide. That is, in the first laser beam applying step S**111**, generation of cracks having greater components along the thickness direction of the ingot **11** is restrained.
[0060] When the focused spot P of the laser beam emitted from the head **8** passes the other end of the ingot **11** in the X direction, the first laser beam applying step S**111** is completed. With the first

laser beam applying step S**111** being performed in the manner described above, linear peel-off layers (first peel-off layers) **19** each including the modified portion **17** and a crack or including the modified portion **17** but not the crack are formed inside the ingot **11**. Note that FIGS. **6**A and **6**B illustrate the first peel-off layers **19** including no cracks for the sake of convenience.

[0061] When the first peel-off layers **19** are not formed in each of the regions near both ends of the ingot **11** in the Y direction (step S**112**: NO), the ingot **11** and the position where the focused spot P is to be formed are moved relative to each other along the Y direction (first index feeding step S**113**). In the first index feeding step S**113**, the moving mechanism moves the housing **10** by a predetermined index amount (for example, 0.1 to 0.2 mm) along the Y direction such that the head **8** is positioned in the X direction as viewed from a region slightly farther from the second orientation flat **15** than the region to which the laser beam has most recently been applied, in plan view.

[0062] Next, with the opposite direction of the X direction being set as the scanning direction of the laser beam, the first laser beam applying step S**111** is performed. Further, the first index feeding step S**113** and the first laser beam applying step S**111** are alternately repeated until the application of the laser beam is completed for the region near the other end of the ingot **11** in the Y direction (for example, the region farthest from the second orientation flat **15**).

[0063] In other words, relative movement of the position where the focused spot P of the laser beam is to be formed and the ingot **11** along the Y direction and application of the laser beam to the ingot **11** with the X direction or the opposite direction of the X direction being set as the scanning direction of the laser beam are alternately repeated. When the first peel-off layers **19** are formed in each of the regions near both ends of the ingot **11** in the Y direction (step S**112**: YES), the first processing step S**11** is completed.

[0064] After the first processing step S**11**, the second processing step S**12** is performed. FIG. **7** is a flowchart schematically illustrating an example of the second processing step S**12**. FIG. **8**A is a plan view schematically illustrating the manner of the second processing step S**12**, while FIG. **8**B is a longitudinal sectional view schematically illustrating, in an enlarged manner, part of the ingot **11** obtained after the second processing step S**12**.

[0065] In the second processing step S**12**, first, the ingot **11** and the focused spot P of the laser beam are moved relative to each other along the X direction in a state in which the focused spot P is positioned between a pair of adjacent first peel-off layers **19** (second laser beam applying step S**121**).

[0066] Specifically, in the second laser beam applying step S**121**, while a laser beam is being emitted from the head **8**, the moving mechanism moves the housing **10** along the X direction such that the focused spot P of the laser beam passes from one end to the other end of the ingot **11** in the X direction at a predetermined speed (for example, 390 mm/s). That is, a laser beam is applied to the ingot **11** with the direction parallel to the crystal orientation [100] of gallium oxide being set as the scanning direction of the laser beam.

[0067] Further, in the second laser beam applying step S**121**, the output power level of the laser beam is set to a value (for example, 0.8 W) that allows a crack **21** to extend from the modified portion **17**. As a result, the modified portion **17** and the crack **21** are formed between a pair of adjacent first peel-off layers **19**.

[0068] When the focused spot P of the laser beam emitted from the head **8** passes the other end of the ingot **11** in the X direction, the second laser beam applying step S**121** is completed. Performing the second laser beam applying step S**121** in the manner described above forms a linear peel-off layer (second peel-off layer) **23**, which includes the modified portion **17** and the crack **21**, between the pair of adjacent first peel-off layers **19**.

[0069] If the second peel-off layer **23** is not formed in any of the regions between the plurality of rows of first peel-off layers **19** (that is, the plurality of rows of unprocessed regions) (step S**122**: NO), the ingot **11** and the position where the focused spot P is to be formed are moved relative to each other along the Y direction (second index feeding step S**123**). In the second index feeding step S**123**, the moving mechanism moves the housing **10** along the Y direction by a predetermined index amount (for example, 0.1 to 0.2 mm) such that the head **8** is positioned in the X direction as viewed from an unprocessed region adjacent to a region that is between a pair of adjacent first peel-off layers **19** and to which the laser beam has most recently been applied.

[0070] Next, with the opposite direction of the X direction being set as the scanning direction of the laser beam, the second laser beam applying step S**121** is performed. Further, the second index feeding step S**123** and the second laser beam applying step S**121** are alternately repeated until the application of laser beam is completed for every region between the plurality of rows of first peel-off layers **19**.

[0071] That is, relative movement of the position where the focused spot P of the laser beam is to be formed and the ingot **11** along the Y direction and application of the laser beam to the ingot **11** with the X direction or the opposite direction of the X direction being set as the scanning direction of the laser beam are alternately repeated. When the second peel-off layer **23** is formed in every region between the plurality of rows of the first peel-off layers **19** (step S**122**: YES), the second processing step S**12** is completed, that is, the peel-off layer forming step S**1** is completed.

[0072] Note that, in the abovementioned peel-off layer forming step S**1** (specifically, the first processing step S**11** and the second processing step **12**), the direction (the X direction or the opposite direction thereof) parallel to the crystal orientation [100] of gallium oxide is set as the scanning direction of the laser beam, but a direction that is not parallel to the crystal orientation [100] may be set as the scanning direction of the laser beam.

[0073] Yet, when the scanning direction of the laser beam becomes parallel to the crystal orientation [010] of gallium oxide, the ratio of cracks **21** that extend along the crystal plane (100) parallel to the crystal orientation [010] may increase. When the ratio of the cracks **21** that extend along the crystal plane (100) increases, the thickness of each of the peel-off layers **19** and **23** (especially, the second peel-off layers **23**) formed inside the ingot **11** increases, leading to reduced productivity when substrates are to be manufactured from the ingot **11**.

[0074] Further, in this case, since the ratio of the cracks **21** that extend along the crystal plane (001), that is, the cracks **21** that extend in parallel with the face side **11***a* of the ingot **11**, decreases, the width (the length in the direction perpendicular to each of the thickness direction of the ingot **11** and the scanning direction of the laser beam) of each the peel-off layers **19** and **23** (especially, each the second peel-off layers **23**) formed inside the ingot **11** becomes smaller. Hence, in this case, there is no choice but to reduce the index amount described above, resulting in lower throughput in the laser processing apparatus **2**.

[0075] In view of these points, in order to improve the productivity and throughput at the time of manufacturing substrates from the ingot **11**, the scanning direction of the laser beam is preferably set such that the angle formed between the scanning direction and a straight line parallel to the crystal orientation [010] of gallium oxide becomes large, that is, the angle formed between the scanning direction and a straight line parallel to the crystal orientation [100] becomes small.

[0076] Further, in the peel-off layer forming step S**1** described above, the depth of the focused spot P of the laser beam from the face side **11***a* of the ingot **11** is maintained to be constant, but this depth may be changed in mid-course. For example, in the peel-off layer forming step S**1**, the depth of the focused spot from the face side **11***a* in the first laser beam applying step S**111** and the depth of the focused spot from the face side **11***a* in the second laser beam applying step S**121** may be different.

[0077] Yet, the crack **21** that is included in the second peel-off layer **23** formed in the second laser beam applying step S**121** more easily extends toward the first peel-off layer **19**. Hence, when the two depths are different, the thickness of each second peel-off layer **23** formed inside the ingot **11** increases, and lowers the productivity at the time of manufacturing substrates from the ingot **11**. In light of this situation, it is preferable that the two depths be set to be the same in order to improve the productivity at the time of manufacturing substrates from the ingot **11**.

[0078] Further, in the abovementioned peel-off layer forming step S**1**, the laser beam may be applied to the ingot **11** only along one direction (for example, the X direction). That is, in the peel-off layer forming step S**1**, without the opposite direction of the one direction (for example, the opposite direction of the X direction) being set as the scanning direction of the laser beam, application of the laser beam to the ingot **11** with the one direction being set as the scanning direction of the laser beam may be repeated.

[0079] After the peel-off layer forming step S**1**, with the plurality of rows of peel-off layers **19** and **23** being used as separation initiating points, the ingot **11** is separated, and substrates are manufactured (separating step S**2**). FIGS. **9**A and **9**B are each a side elevational view schematically illustrating the manner of the separating step S**2**. The separating step S**2** is performed in a separating apparatus **14**. The separating apparatus **14** includes a chuck table **16** having a structure similar to that of the chuck table **4** illustrated in FIG. **4**.

[0080] The chuck table **16** is coupled to a table-side suction mechanism (not illustrated). The table-side suction mechanism includes, for example, a vacuum pump and the like. When the table-side suction mechanism is operated, suction force acts in a space near a holding surface of the chuck table **16**. 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 **16**.

[0081] A separating unit **18** is provided above the chuck table **16**. The separating unit **18** includes a suction plate **20** which has a lower surface in which a plurality of suction ports are formed. The plurality of suction ports communicate with a separating unit-side suction mechanism such as a vacuum pump via a suction channel formed inside the suction plate **20**. When the separating unit-side suction mechanism is operated, suction force acts in a space near the lower surface of the suction plate **20**.

[0082] Further, a vertical direction moving mechanism **22** is coupled to an upper surface of the suction plate **20**. The vertical direction moving mechanism **22** includes, for example, a ball screw, a motor, and the like. When the vertical direction moving mechanism **22** is operated, the suction plate **20** moves along the vertical direction.

[0083] When the separating step S**2** is performed in the separating apparatus **14**, first, the ingot **11** in which the plurality of rows of peel-off layers **19** and **23** are formed is placed on the holding surface of the chuck table **16** such that the face side **11***a* faces upward, in a state in which the chuck table **16** and the suction plate **20** are sufficiently spaced from each other. Next, the table-side suction mechanism is operated such that the ingot **11** is held under suction on the holding surface of the chuck table **16**.

[0084] Subsequently, the vertical direction moving mechanism **22** lowers the suction plate **20** such that the lower surface of the suction plate **20** comes into contact with the face side **11***a* of the ingot **11** (see FIG. **9**A). Thereafter, the separating unit-side suction mechanism is operated such that the face side **11***a* of the ingot **11** is sucked toward the upper side. Then, the vertical direction moving mechanism **22** raises the suction plate **20** such that the suction plate **20** is spaced from the chuck table **16** (see FIG. **9**B).

[0085] As a result, such external force that separates the face side **11***a* and the reverse side **11***b* of the ingot **11** from each other is applied to the ingot **11**, and the cracks **21** included in the plurality of rows of peel-off layers **19** and **23** further extend. Consequently, the ingot **11** is separated with the plurality of rows of peel-off layers **19** and **23** being used as separation initiating points, and substrates **25** are manufactured. This completes the separating step S**2**, that is, the substrate manufacturing method illustrated in FIG. **2**.

[0086] In the substrate manufacturing method illustrated in FIG. **2**, after the plurality of rows of first peel-off layers **19** and the plurality of rows of second peel-off layers **23** are formed inside the ingot **11**, the ingot **11** is separated with these peel-off layers **19** and **23** being used as separation initiating points, and the substrates **25** are manufactured. This can improve the productivity of substrates **25** compared to manufacturing the substrates **25** from the ingot **11** with use of a wire saw.

[0087] Note that the details described above represent one mode of the present embodiment, the present invention is not limited to the details described above. For example, in the peel-off layer forming step S**1** according to the present invention, it is sufficient if the ingot **11** and the focused spot P of the laser beam can be moved relative to each other, and the structure therefor is not limited to any specific kind.

[0088] More specifically, the peel-off layer forming step S**1** may be performed in a laser processing apparatus provided with a moving mechanism that moves the chuck table **4** along each of the X direction, the Y direction, and/or the Z direction.

[0089] Alternatively, the peel-off layer forming step S**1** may be performed in a laser processing apparatus in which a scanning optical system capable of changing the direction of the laser beam emitted from the head **8** is provided in the laser beam application unit **6**. Note that the scanning optical system includes, for example, a galvanoscanner, an acousto-optic device (AOD), and/or a polygon mirror.

[0090] Further, the peel-off layer forming step S**1** according to the present invention may include a step that reinforces the plurality of rows of peel-off layers **19** and **23** as separation initiating points, after the second processing step S**12**. FIG. **10** is a flowchart schematically illustrating an example of the peel-off layer forming step S**1** including such a step.

[0091] In this peel-off layer forming step S**1**, a laser beam is applied to at least one of the plurality of rows of first peel-off layers **19** after the second processing step S**12** (third laser beam applying step S**13**).

[0092] The third laser beam applying step S**13** is, for example, performed in the same manner as the first laser beam applying step S**111** described above. Alternatively, the third laser beam applying step S**13** may be performed in the same manner as the first processing step S**11** described above. That is, in the third laser beam applying step S**13**, a laser beam may be applied to only one of the plurality of rows of first peel-off layers **19**, or a laser beam may be applied to all of the plurality of rows of first peel-off layers **19**.

[0093] Further, in the third laser beam applying step S**13**, a laser beam may be applied selectively to the plurality of rows of first peel-off layers **19**. For example, in the third laser beam applying step S**13**, a laser beam may be applied to the even-numbered or odd-numbered first peel-off layer **19** when the plurality of rows of first peel-off layers **19** are counted in an ascending order from the one located on one end to the one located on the other end. Alternatively, in the third laser beam applying step S**13**, a laser beam may be applied to every k-th first peel-off layer **19** (k is a natural number of three or more) when the first peel-off layers **19** are similarly counted in an ascending order.

[0094] When the first processing step S**11** is performed such that the first peel-off layers **19** including the cracks **21** are formed, the third laser beam applying step S**13** may be performed to further extend the cracks **21** included in the first peel-off layers **19**. Alternatively, when the first processing step S**11** is performed such that the first peel-off layers **19** including no cracks **21** are formed, the third laser beam applying step S**13** may be performed to extend the cracks **21** from the modified portions **17** included in the first peel-off layers **19**.

[0095] The peel-off layer forming step S**1** illustrated in FIG. **10** is preferable in such respects that the ingot **11** can easily be separated in the separating step S**2**, compared to the peel-off layer forming step S**1** illustrated in FIG. **3**. In contrast, the peel-off layer forming step S**1** illustrated in FIG. **3** is preferable in such respects that the throughput in the laser processing apparatus **2** can be improved, compared to the peel-off layer forming step S**1** illustrated in FIG. **10**.

[0096] Note that, when the first processing step S**11** is performed such that the first peel-off layers **19** including cracks **21** of the same size as the cracks **21** included in the second peel-off layers **23**

are formed, a laser beam may be applied to at least one of the plurality of rows of second peel-off layers **23** in place of or in addition to at least one of the plurality of rows of first peel-off layers **19**.
[0097] Further, in the separating step S**2** according to the present invention, ultrasonic vibrations may be applied to the ingot **11** as the external force for manufacturing substrates **25**. Specifically, in the separating step S**2**, ultrasonic vibrations may be applied to the face side **11***a* of the ingot **11**, in place of or prior to applying such external force that separates the face side **11***a* and the reverse side **11***b* of the ingot **11** from each other.
[0098] The workpiece to be used in the substrate manufacturing method according to the present invention may be an ingot manufactured in such a manner that a crystal plane (for example, the crystal plane (100)) other than the crystal plane {001} of gallium oxide is exposed on the face side.
[0099] Alternatively, the workpiece to be used in the substrate manufacturing method according to the present invention may, for example, be a bare wafer having a thickness twice or more but five times or less the thickness of the substrate to be manufactured. Note that this bare wafer is, for example, manufactured by separating the ingot in the same manner as that described above. In this case, the substrate **25** can be expressed as being manufactured by the abovementioned method being repeated twice.
[0100] As another alternative, the workpiece to be used in the substrate manufacturing method according to the present invention may be a device wafer manufactured by semiconductors devices being formed on one side of the bare wafer. In this case, laser beams are preferably applied to the device wafer from a side of the device wafer where no semiconductor devices are formed, so as to avoid adverse effects on the semiconductor devices.
[0101] Other structures, methods, and the like according to the embodiment described above can appropriately be modified within the scope of object of the present invention.
[0102] 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, from a workpiece using gallium oxide as a material, a substrate thinner than the workpiece, the method comprising: peel-off layer forming of forming a plurality of rows of peel-off layers inside the workpiece; and separating, after the peel-off layer forming, the workpiece with the plurality of rows of peel-off layers being used as separation initiating points, to manufacture the substrate, wherein the peel-off layer forming includes first processing of forming a plurality of rows of first peel-off layers each including a modified portion and each being spaced from one another, and second processing of, after the first processing, forming a plurality of rows of second peel-off layers each including the modified portion and a crack extending from the modified portion and each being located between a pair of adjacent first peel-off layers of the plurality of rows of first peel-off layers, in the first processing, alternately repeated are first laser beam applying of moving the workpiece and a focused spot of a laser beam having a wavelength transmittable through the gallium oxide relative to each other along a first direction in a state in which the focused spot is positioned inside the workpiece, and first indexing feeding of moving the workpiece and a position where the focused spot is to be formed relative to each other along a second direction perpendicular to the first direction, and, in the second processing, alternately repeated are second laser beam applying of moving the workpiece and the focused spot relative to each other along the first direction in a state in which the focused spot is positioned between the pair of adjacent first peel-off layers, and second indexing feeding of moving the workpiece and the position where the focused spot is to be formed relative to each other along the second direction.

2. The substrate manufacturing method according to claim 1, wherein an output power level of the laser beam in the first laser beam applying is set to be smaller than an output power level of the laser beam in the second laser beam applying, in the first processing, the plurality of rows of first peel-off layers each including the crack are formed, and the crack included in each of the plurality of rows of first peel-off layers is smaller than the crack included in each of the plurality of rows of second peel-off layers.
3. The substrate manufacturing method according to claim 2, wherein the peel-off layer forming further includes, after the second processing, third laser beam applying of applying the laser beam to at least one of the plurality of rows of first peel-off layers such that the crack further extends.
4. The substrate manufacturing method according to claim 1, wherein an output power level of the laser beam in the first laser beam applying is set to be smaller than an output power level of the laser beam in the second laser beam applying, and, in the first processing, the plurality of rows of first peel-off layers each not including the crack are formed.
5. The substrate manufacturing method according to claim 4, wherein the peel-off layer forming further includes, after the second processing, third laser beam applying of applying the laser beam to at least one of the plurality of rows of first peel-off layers such that the crack extends from the modified portion.
6. The substrate manufacturing method according to claim 1, wherein an output power level of the laser beam in the first laser beam applying is set to be the same as an output power level of the laser beam in the second laser beam applying, and, in the first processing, the plurality of rows of first peel-off layers each including the crack are formed.
7. The substrate manufacturing method according to claim 6, wherein the peel-off layer forming further includes, after the second processing, third laser beam applying of applying the laser beam to at least one of the plurality of rows of first peel-off layers and/or at least one of the plurality of rows of second peel-off layers such that the crack further extends.
8. The substrate manufacturing method according to claim 1, wherein a depth of the focused spot from a face side of the workpiece in the first laser beam applying is set to be the same as a depth of the focused spot from the face side in the second laser beam applying.
9. The substrate manufacturing method according to claim 2, wherein a depth of the focused spot from a face side of the workpiece in the first laser beam applying is set to be the same as a depth of the focused spot from the face side in the second laser beam applying.
10. The substrate manufacturing method according to claim 3, wherein a depth of the focused spot from a face side of the workpiece in the first laser beam applying is set to be the same as a depth of the focused spot from the face side in the second laser beam applying.
11. The substrate manufacturing method according to claim 4, wherein a depth of the focused spot from a face side of the workpiece in the first laser beam applying is set to be the same as a depth of the focused spot from the face side in the second laser beam applying.
12. The substrate manufacturing method according to claim 5, wherein a depth of the focused spot from a face side of the workpiece in the first laser beam applying is set to be the same as a depth of the focused spot from the face side in the second laser beam applying.
13. The substrate manufacturing method according to claim 6, wherein a depth of the focused spot from a face side of the workpiece in the first laser beam applying is set to be the same as a depth of the focused spot from the face side in the second laser beam applying.
14. The substrate manufacturing method according to claim 7, wherein a depth of the focused spot from a face side of the workpiece in the first laser beam applying is set to be the same as a depth of the focused spot from the face side in the second laser beam applying.