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## METHOD OF PROCESSING MONOCRYSTALLINE SILICON WAFER

### Abstract


A monocrystalline silicon wafer fabricated such that a particular crystal plane, e.g., a crystal plane (100), included in crystal planes {100} is exposed on each of face and reverse sides of the monocrystalline silicon wafer is irradiated with a laser beam along a first direction parallel to the particular crystal plane and inclined to a particular crystal orientation, e.g., a crystal orientation [010], included in crystal orientations <100> at an angle of 5° or less, thereby forming a peel-off layer that functions as separation initiating points between a part of the monocrystalline silicon wafer that belongs to the face side thereof and a part of the monocrystalline silicon wafer that belongs to the reverse side thereof.



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## Background/Summary

[0001] This is a continuation of U.S. patent application Ser. No. 17/821,556 filed Aug. 23, 2022, which claims the benefit of Japanese Patent Application No. 2021-140404, filed on Aug. 30, 2021.

BACKGROUND OF THE INVENTION

Field of the Invention

[0002] The present invention relates to a method of processing a monocrystalline silicon wafer by forming peel-off layers in the monocrystalline silicon wafer and then separating the monocrystalline silicon wafer along the peel-off layers that function as separation initiating points.

Description of the Related Art

[0003] Chips of semiconductor devices (hereinafter simply referred to as “devices”) are generally manufactured from a disk-shaped monocrystalline silicon wafer (hereinafter simply referred to as a “wafer”). Specifically, the wafer has a plurality of areas demarcated by a grid of projected dicing lines, and devices are formed respectively in face sides of the areas of the wafer. The wafer is divided into device chips along the projected dicing lines.

[0004] Some wafers have through-silicon vias (TSVs) for a purpose of producing highly integrated packages including a plurality of chips. Such packages allow electrodes included in different chips to be electrically interconnected through TSVs, for example.

[0005] A TSV is formed in a wafer according to the following sequence of steps. First, a groove is formed in a face side of a wafer. Then, a TSV is provided in the groove. Then, the face side of the wafer is affixed to a support wafer. Then, a reverse side of the wafer is ground until the TSV is exposed on the reverse side.

[0006] A wafer often has its outer circumferential region beveled for the purpose of preventing itself from chipping. When the reverse side of the wafer with the beveled outer circumferential region is ground until the thickness of the wafer is reduced to half or less, the reverse side of the outer circumferential region is shaped into something like a knife edge.

[0007] While the reverses side of the wafer is being ground in this manner, stresses tend to concentrate on the reverse side of the outer circumferential region, making the wafer likely to crack. As a result, a yield of chips from the wafer is liable to decrease. To avoid such problems, it has been proposed in the art to remove part of the face side of the outer circumferential region of the wafer, i.e., to perform generally-called edge trimming, before the reverse side of the wafer is ground (see, for example, JP 2007-158239A).

[0008] At a time the remainder of the reverse side of the wafer has been ground, the wafer has its outer circumferential side surface extending generally perpendicularly to the face and reverse sides of the wafer. Consequently, no stress concentration occurs on the reverse side of the outer circumferential region during the grinding of the wafer, making the wafer less likely to crack. As a consequence, the yield of chips from the wafer is prevented from decreasing.

[0009] However, in a case where the reverse side of the wafer is ground until TSVs are exposed on the reverse side of the wafer after the edge trimming, an amount of material ground off the wafer is large, and hence grindstones that are used to grind the wafer are worn to a large extent.

Accordingly, chips or packages fabricated from the wafer are likely to become costly, and the processing of the wafer is apt to be prolonged.

[0010] In view of the foregoing shortcomings, it has been proposed in the art to divide a wafer with a laser beam having a wavelength transmittable through the wafer (see, for example, JP 2020-136442A). According to the proposed process, the laser beam is applied to the wafer to form peel-off layers in the wafer while the focused spot of the laser beam is being positioned in the wafer, and the wafer is separated along the peel-off layers that function as separation initiating points.

[0011] According to the process, the laser beam is applied to an annular first region of the wafer that causes no irregular reflection of the laser beam, i.e., an annular region positioned radially inwardly of the beveled outer circumferential region. The applied laser beam forms in the wafer a peel-off layer that functions as separation initiating points, i.e., a hollow cylindrical peel-off layer, extending between a region of the wafer where devices are formed and the outer circumferential region of the wafer.

[0012] Then, the laser beam is applied again to a second region of the wafer that causes no irregular reflection of the laser beam, i.e., a circular region that is positioned radially inwardly of the beveled outer circumferential region. The applied laser beam forms a peel-off layer that functions as separation initiating points extending between the face and reverse sides of the wafer, i.e., a disk-shaped peel-off layer.

[0013] Then, external forces are exerted on the wafer to separate the wafer along the hollow cylindrical peel-off layer and the disk-shaped peel-off layer. In other words, the outer circumferential region of the wafer is separated from the region of the wafer where devices are formed, and the reverse side of the wafer is separated from the face side thereof.

[0014] In a case where the wafer is divided in the manner described above, the amount of material ground off the reverse side of the wafer until TSVs are exposed is reduced, and grindstones that are used to grind the wafer are worn to a reduced extent. Consequently, chips or packages fabricated from the wafer are prevented from becoming costly, and the processing of the wafer is prevented from being prolonged.

## SUMMARY OF THE INVENTION

[0015] The peel-off layers referred to above include a modified region where the crystal structure of monocrystalline silicon of the wafer is disrupted and cracks extending from the modified region. Specifically, when the laser beam is applied to the wafer, a modified region is formed in the wafer around the focused spot of the laser beam. Cracks extend from the modified region along certain crystal planes of monocrystalline silicon of the wafer.

[0016] Generally, monocrystalline silicon is likely to cleave along a particular crystal plane included in crystal planes {111}. For example, when a laser beam is applied to a wafer that is fabricated such that a particular crystal plane, e.g., crystal plane (100), included in crystal planes {100} is exposed on each of face and reverse sides of the wafer, along a crystal orientation, e.g., crystal orientation [011], parallel to the particular crystal plane, of a particular crystal orientation included in crystal orientations <110>, many cracks are developed from a modified region along a particular crystal plane, e.g., crystal plane (111), included in crystal planes {111}.

[0017] An acute angle formed between a particular crystal plane, e.g., crystal plane (100), included in crystal planes {100} and a particular crystal plane, e.g., crystal plane (111), included in crystal planes {111} of monocrystalline silicon is approximately 54.7°. Therefore, when the laser beam is applied to the wafer as described above, many cracks are developed from the modified region in a direction inclined at approximately 54.7° to the face side or the reverse side of the wafer.

[0018] In other words, if the direction in which the cracks are developed is resolved into a component parallel to the face and reverse sides of the wafer, i.e., a parallel component, and a component perpendicular to the face and reverse sides of the wafer, i.e., a perpendicular component, then the perpendicular component becomes larger than the parallel component. Consequently, when the laser beam is applied to the wafer to form a peel-off layer, i.e., a disk-shaped peel-off layer, as separation initiating points between the face and reverse sides of the wafer, the following problems tend to take place.

[0019] Since the parallel component of the direction in which the cracks are developed is relatively small, the interval between adjacent modified regions needs to be reduced in order to connect the adjacent modified regions with the cracks. For reducing the interval between the adjacent modified regions, it is necessary to increase a processing time, i.e., the time in which the laser beam is applied, required to form the disk-shaped peel-off layer.

[0020] Furthermore, inasmuch as the perpendicular component of the direction in which the cracks are developed is relatively large, the cracks are liable to develop from the disk-shaped peel-off layer toward the face side of the wafer, possibly breaking devices on the wafer. Though the probability that devices will be damaged may be reduced by forming a disk-shaped peel-off layer at a position sufficiently spaced from the face side of the wafer, this approach leads to an increase in the amount of material ground off the wafer in a subsequent wafer grinding process.

[0021] In view of the aforesaid difficulties, it is an object of the present invention to provide a method of processing a monocrystalline silicon wafer to reduce the processing time required to separate the wafer along a peel-off layer that has been formed in the wafer and also to lower the probability that devices on the wafer will be damaged.

[0022] In accordance with an aspect of the present invention, there is provided a method of processing a monocrystalline silicon wafer fabricated such that a particular crystal plane included in crystal planes {**100**} is exposed on each of face and reverse sides of the monocrystalline silicon wafer, having a plurality of devices formed on the face side, and having a beveled outer circumferential region, by applying a laser beam having a wavelength transmittable through the monocrystalline silicon wafer while positioning a focused spot of the laser beam within the monocrystalline silicon wafer, thereby forming a peel-off layer within the monocrystalline silicon wafer, and thereafter separating the monocrystalline silicon wafer along the peel-off layer that functions as separation initiating points. The method includes an affixing step of affixing the face side of the monocrystalline silicon wafer to a face side of a support wafer, a first peel-off layer forming step of applying the laser beam from the reverse side of the monocrystalline silicon wafer to an annular first region of the monocrystalline silicon wafer that is positioned radially inwardly of the outer circumferential region of the monocrystalline silicon wafer, thereby forming a first peel-off layer that functions as separation initiating points between a region of the monocrystalline silicon wafer where the devices are formed and the outer circumferential region thereof, a second peel-off layer forming step of applying the laser beam from the reverse side of the monocrystalline silicon wafer to a second region of the monocrystalline silicon wafer that is positioned radially inwardly of the outer circumferential region of the monocrystalline silicon wafer, thereby forming a second peel-off layer that functions as separation initiating points between a part of the monocrystalline silicon wafer that belongs to the face side thereof and a part of the monocrystalline silicon wafer that belongs to the reverse side thereof, and a separating step of, after the affixing step, the first peel-off layer forming step and the second peel-off layer forming step, exerting external forces on the monocrystalline silicon wafer, thereby separating the monocrystalline silicon wafer along the first peel-off layer and the second peel-off layer as the separation initiating points. The second peel-off layer forming step includes a laser beam applying step of applying the laser beam to a straight region of the monocrystalline silicon wafer along a first direction included in the second region while moving the monocrystalline silicon wafer and the focused spot relatively to each other along the first direction that lies parallel to the particular crystal plane and is inclined to a particular crystal orientation included in crystal orientations <100> at an angle of 5° or less, and an indexing feed step of moving a position in the monocrystalline crystal wafer where the focused spot is formed by the applied laser beam along a second direction parallel to the particular crystal plane and perpendicular to the first direction. The laser beam applying step and the indexing feed step are repeatedly carried out to form the second peel-off layer.

[0023] It is preferable that the first peel-off layer forming step be carried out before the second peel-off layer forming step.

[0024] It is preferable that the second region be positioned radially inwardly of the first region.

[0025] It is preferable that the first peel-off layer forming step include the step of forming the first peel-off layer so as to terminate short of the reverse side of the monocrystalline crystal wafer.

[0026] It is preferable that the first peel-off layer forming step include the step of forming the first peel-off layer along a side surface of a truncated cone having a first bottom surface positioned near the face side of the monocrystalline crystal wafer and a second bottom surface smaller in diameter than the first bottom surface and positioned within the monocrystalline crystal wafer, by applying the laser beam such that the focused spot thereof is progressively closer to the face side of the monocrystalline crystal wafer toward the outer circumferential region thereof.

[0027] According to the present invention, a monocrystalline silicon wafer fabricated such that a particular crystal plane, e.g., a crystal plane (100), included in crystal planes {100} is exposed on each of face and reverse sides of the monocrystalline silicon wafer is irradiated with a laser beam along a first direction parallel to the particular crystal plane and inclined to a particular crystal orientation, e.g., a crystal orientation [010], included in crystal orientations <100> at an angle of 5° or less, thereby forming a peel-off layer, i.e., a second peel-off layer, that functions as separation initiating points between a part of the monocrystalline silicon wafer that belongs to the face side thereof and a part of the monocrystalline silicon wafer that belongs to the reverse side thereof.

[0028] In this case, cracks extending from modified areas include more cracks along a particular crystal plane, e.g., a crystal plane (101), included in crystal planes {n10}(n represents a natural number of 10 or less) than cracks along a particular crystal plane, e.g., a crystal plane (111), included in crystal planes {111}. The acute angle formed between the particular crystal plane included in the crystal planes {100} and the particular crystal plane included in the crystal planes {n10} is 450 or less.

[0029] According to the present invention, therefore, a component, parallel to the face and reverse sides of the wafer, of the direction in which the cracks are developed, i.e., a parallel component, is larger and a component of the direction perpendicular to the face and reverse sides of the wafer, i.e., a perpendicular component, is smaller than if a second peel-off layer is formed by irradiating a monocrystalline silicon wafer fabricated such that a particular crystal plane included in crystal planes {100} is exposed on each of face and reverse sides of the monocrystalline silicon wafer with a laser beam along a particular crystal orientation, e.g., a crystal orientation [011], parallel to the particular crystal plane and included in crystal orientations <110>.

[0030] According to the present invention, consequently, since the parallel component of the direction in which the cracks are developed is large, the intervals between adjacent modified areas are increased. As a result, the distance that the position in the monocrystalline crystal wafer is moved, i.e., an indexed distance, in the indexing feed step is increased, thereby shortening the processing time, i.e., a period of time in which the laser beam is applied, required to form the peel-off layer that functions as separation initiating points between the face and reverse sides of the wafer.

[0031] According to the present invention, moreover, since the perpendicular component of the direction in which the cracks are developed is small, cracks are less likely to be developed from the peel-off layer toward the face side of the wafer. Consequently, the probability that devices will be broken is lowered when the wafer is separated into the part of the wafer belonging to the face side and the part of the wafer belonging to the reverse side.

[0032] 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

[0033] FIG. **1**A is a plan view schematically illustrating a wafer by way of example;

[0034] FIG. **1**B is a cross-sectional view schematically illustrating the wafer by way of example;

[0035] FIG. **2** is a flowchart of a sequence of a method of processing a monocrystalline silicon wafer according to an embodiment of the present invention;

[0036] FIG. **3** is a cross-sectional view schematically illustrating a manner in which a face side of the wafer is affixed to a face side of a support wafer;

[0037] FIG. **4** is a perspective view schematically illustrating a laser processing apparatus by way of example;

[0038] FIG. **5** is a view, partly in block form, schematically illustrating the manner in which a laser beam emitted from a laser beam applying unit travels;

[0039] FIG. **6** is a side elevational view, partly in cross section, schematically illustrating the manner in which laser beams are applied to the wafer that is rotating;

[0040] FIG. **7** is a flowchart schematically illustrating a second peel-off layer forming step by way of example;

[0041] FIG. **8** is an enlarged fragmentary cross-sectional view schematically illustrating the manner in which laser beams are applied to the wafer that is moving along an X-axis direction;

[0042] FIG. **9** is an enlarged fragmentary cross-sectional view schematically illustrating adjacent peel-off layers formed within the wafer;

[0043] FIG. **10**A is a side elevational view, partly in cross section, schematically illustrating the manner in which the wafer is separated;

[0044] FIG. **10**B is a side elevational view, partly in cross section, schematically illustrating the manner in which the wafer is separated;

[0045] FIG. **11** is a side elevational view, partly in cross section, schematically illustrating the manner in which laser beams are applied to the wafer that is rotating;

[0046] FIG. **12** is a graph illustrating widths of peel-off layers formed within the wafer when laser beams are applied to straight regions extending along respective different crystal orientations;

[0047] FIG. **13** is a plan view schematically illustrating a modified wafer;

[0048] FIG. **14**A is a side elevational view, partly in cross section, schematically illustrating the manner in which a region of a wafer where a plurality of devices are formed and an outer circumferential region of the wafer are separated from each other;

[0049] FIG. **14**B is a side elevational view, partly in cross section, schematically illustrating the manner in which the region of the wafer where the plurality of devices are formed and the outer circumferential region of the wafer are separated from each other;

[0050] FIG. **15**A is a side elevational view, partly in cross section, schematically illustrating the manner in which face and reverse sides of the wafer are separated from each other; and

[0051] FIG. **15**B is a side elevational view, partly in cross section, schematically illustrating the manner in which the face and reverse sides of the wafer are separated from each other.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

[0052] A preferred embodiment of the present invention will be described below with reference to the accompanying drawings. FIG. **1**A schematically illustrates, in plan, a wafer, i.e., a monocrystalline silicon wafer, **11** by way of example, and FIG. **1**B illustrates, in cross section, the wafer **11** illustrated in FIG. **1**A. In FIG. **1**A, the crystal orientations of monocrystalline silicon that the wafer **11** is made of are also illustrated.

[0053] As illustrated in FIGS. **1**A and **1**B, the wafer **11** includes a cylinder of monocrystalline silicon where a particular crystal plane, e.g., a crystal plane (100) for the sake of convenience, included in crystal planes {100} is exposed on each of a face side **11***a* and a reverse side **11***b* thereof. In other words, the wafer **11** includes a cylinder of monocrystalline silicon where respective lines normal to the face and reverse sides **11***a* and **11***b*, i.e., a crystal axis, extend along the crystal orientation [100].

[0054] Though the wafer **11** is fabricated such that the crystal plane (100) is exposed on each of the face and reverse sides **11***a* and **11***b*, each of the face and reverse sides **11***a* and **11***b* may be slightly inclined to the crystal plane (100) due to processing errors, etc. introduced at the time of the fabrication of the wafer **11**. Specifically, an acute angle formed between each of the face and reverse sides **11***a* and **11***b* and the crystal plane (100) may be 1° or less.

[0055] In other words, the crystal axis of the wafer **11** may extend along such a direction that an acute angle formed between the direction and the crystal orientation [100] is 1° or less. The wafer **11** has a notch **13** defined in a side surface **11***c* thereof, and the center of the wafer **11** is positioned on a particular crystal orientation, e.g., a crystal orientation [011] for the sake of convenience, included in crystal orientations <110> as viewed from the notch **13**.

[0056] The wafer **11** includes a plurality of areas demarcated by a plurality of intersecting projected dicing lines. Devices **15** such as integrated circuits (ICs), large-scale-integration (LSI) circuits, semiconductor memories, or complementary-metal-oxide-semiconductor (CMOS) image sensors are formed on the face side **11***a* in the respective areas.

[0057] The face side **11***a* of the wafer **11** may have grooves defined therein where TSVs are to be provided. The wafer **11** that is disk-shaped, for example, has a beveled outer circumferential region. In other words, the wafer **11** has an outer circumferential side surface **11***c* that is curved so as to be projected outwardly. The outer circumferential region of the wafer **11** is free of devices **15**. A region of the wafer **11** where the devices **15** are formed, i.e., a device region, is disposed radially inwardly of and surrounded by the outer circumferential region.

[0058] FIG. **2** is a flowchart of the sequence of a method of processing a monocrystalline silicon wafer according to the present embodiment. According to the method, a laser beam having a wavelength transmittable through the wafer **11** is applied to the wafer **11** while positioning the focused spot of the laser beam within the wafer **11**, forming peel-off layers in the wafer **11**, and then the wafer **11** is divided along the peel-off layers that function as division initiating points.

[0059] Specifically, according to the method, the face side **11***a* of the wafer **11** is affixed to a face side of a support wafer (an affixing step S**1** illustrated in FIG. **2**). FIG. **3** schematically illustrates, in cross section, the manner in which the face side **11***a* of the wafer **11** is affixed to the face side, denoted by **17***a*, of the support wafer, denoted by **17**. The support wafer **17** to which the wafer **11** is to be affixed is of the same shape as the wafer **11**.

[0060] As with the wafer **11**, the support wafer **17** may be made of monocrystalline silicon and may have a plurality of devices formed on the face side **17***a* thereof. An adhesive **19** such as an acryl adhesive or an epoxy adhesive, for example, is disposed on the face side **17***a* of the support wafer **17**.

[0061] In the affixing step S**1**, while a reverse side **17***b* of the support wafer **17** is being supported, the face side **11***a* of the wafer **11** is pressed against the face side **17***a* of the support wafer **17** through the adhesive **19** interposed therebetween. The face side **11***a* of the wafer **11** is thus affixed to the face side **17***a* of the support wafer **17**, making up a laminated wafer.

[0062] Then, peel-off layers are formed in the wafer **11** by a laser processing apparatus. FIG. **4** schematically illustrates by way of example in perspective the laser processing apparatus, denoted by **2**, that is used to form peel-off layers in the wafer **11**. In FIG. **4**, X-axis directions, or leftward and rightward directions, indicated by the arrow X and Y-axis directions, or forward and rearward directions, indicated by the arrow Y extend perpendicularly to each other in a horizontal plane, and Z-axis directions, or upward and downward directions, indicated by an arrow Z extend vertically perpendicularly to the X-axis directions and the Y-axis directions.

[0063] As illustrated in FIG. **4**, the laser processing apparatus **2** has a base **4** that supports various components thereof. A horizontal moving mechanism **6** is disposed on an upper surface of the base

**4**. The horizontal moving mechanism **6** has a pair of Y-axis guide rails **8** fixed to the upper surface of the base **4** and extending along the Y-axis directions.

[0064] The horizontal moving mechanism **6** also includes a Y-axis movable plate **10** slidably mounted on the Y-axis guide rails **8** for sliding movement therealong. A screw shaft **12** extending along the Y-axis directions is disposed between the Y-axis guide rails **8**. An electric motor **14** for rotating the screw shaft **12** about its central axis is coupled to an end, i.e., a front end, of the screw shaft **12**.

[0065] A nut, not illustrated, that contains a number of balls rollingly movable in a helical groove defined in the outer surface of the screw shaft **12** is operatively threaded over the screw shaft **12**, thereby a ball screw is constructed. When the electric motor **14** is energized to rotate the screw shaft **12** about its central axis, the balls roll in the helical groove and circulate through the nut, causing the nut to move along one of the Y-axis directions at a time.

[0066] The nut is fixed to a lower surface of the Y-axis movable plate **10**. Therefore, when the screw shaft **12** is rotated about its central axis by the electric motor **14**, the nut and the Y-axis movable plate **10** are moved along one of the Y-axis directions at a time. A pair of X-axis guide rails **16** are fixed to an upper surface of the Y-axis movable plate **10** and extend along the X-axis directions.

[0067] An X-axis movable plate **18** is slidably mounted on the X-axis guide rails **16** for sliding movement therealong. A screw shaft **20** extending along the X-axis directions is disposed between the X-axis guide rails **16**. An electric motor **22** for rotating the screw shaft **20** about its central axis is coupled to an end of the screw shaft **20**.

[0068] A nut, not illustrated, that contains a number of balls rollingly movable in a helical groove defined in the outer surface of the screw shaft **20** is operatively threaded over the screw shaft **20**, thereby a ball screw is constructed. When the electric motor **22** is energized to rotate the screw shaft **20** about its central axis, the balls roll in the helical groove and circulate through the nut, causing the nut to move along one of the X-axis directions at a time.

[0069] The nut is fixed to a lower surface of the X-axis movable plate **18**. Therefore, when the screw shaft **20** is rotated about its central axis by the electric motor **22**, the nut and the X-axis movable plate **18** are moved along one of the X-axis directions at a time.

[0070] A cylindrical table base **24** is rotatably disposed on an upper surface of the X-axis movable plate **18**. A holding table **26** for holding thereon the laminated wafer referred to above is mounted on an upper portion of the table base **24**. The holding table **26** has a circular upper surface as a holding surface lying parallel to the X-axis directions and the Y-axis directions, for example. The holding surface is provided by a porous plate **26***a* that is exposed upwardly.

[0071] The table base **24** has a lower portion coupled to a rotary actuator, not illustrated, such as an electric motor. When the rotary actuator is energized, it rotates the holding table **26** about its central axis extending along a straight line through the center of the holding surface parallel to the Z-axis directions. When the horizontal moving mechanism **6** is actuated, the holding table **26** is moved along the X-axis directions and/or the Y-axis directions.

[0072] The porous plate **26***a* is held in fluid communication with a suction source, not illustrated, such as a vacuum pump through a fluid channel, not illustrated, defined in the holding table **26**. When the suction source is actuated, it generates a negative pressure that is transmitted through the fluid channel to a space near the holding surface.

[0073] A support structure **30** having a side surface generally parallel to the Y-axis directions and the Z-axis directions is disposed on a rear area of the base **4** behind the horizontal moving mechanism **6**. A vertical moving mechanism **32** is disposed on the side surface of the support structure **30**. The vertical moving mechanism **32** has a pair of Z-axis guide rails **34** fixed to the side surface of the support structure **30** and extending along the Z-axis directions.

[0074] The vertical moving mechanism **32** also includes a Z-axis movable plate **36** slidably mounted on the Z-axis guide rails **34** for sliding movement therealong. A screw shaft, not illustrated, extending along the Z-axis directions is disposed between the Z-axis guide rails **34**. An electric motor **38** for rotating the screw shaft about its central axis is coupled to an end, i.e., an upper end, of the screw shaft.

[0075] A nut, not illustrated, that contains a number of balls rollingly movable in a helical groove defined in the outer surface of the screw shaft is operatively threaded over the screw shaft, thereby a ball screw is constructed. When the electric motor **38** is energized to rotate the screw shaft about its central axis, the balls roll in the helical groove and circulate through the nut, causing the nut to move along one of the Z-axis directions at a time.

[0076] The nut is fixed to a reverse side of the Z-axis movable plate **36**. Therefore, when the screw shaft is rotated about its central axis by the electric motor **38**, the nut and the Z-axis movable plate **36** are moved along one of the Z-axis directions at a time.

[0077] A support block **40** is fixed to a face side of the Z-axis movable plate **36**. The support block **40** supports a portion of a laser beam applying unit **42**. FIG. **5** schematically illustrates, partly in block form, the manner in which a laser beam LB emitted from the laser beam applying unit **42** travels. Some of the components of the laser beam applying unit **42** are illustrated as functional blocks.

[0078] The laser beam applying unit **42** has a laser oscillator **44** mounted on the base **4**. The laser oscillator **44** has Nd:YAG or the like as a laser medium and emits the laser beam LB that has a wavelength of 1342 nm, for example, transmittable through the wafer **11**. The laser beam LB is a pulsed laser beam having a frequency of 60 kHz, for example.

[0079] The laser beam LB emitted from the laser oscillator **44** has its output power level adjusted by an attenuator **46** and is then supplied to a spatial optical modulator **48**. The spatial optical modulator **48** branches the adjusted laser beam LB into a plurality of laser beams LB. Specifically, the spatial optical modulator **48** branches the laser beam LB whose output power level has been adjusted by the attenuator **46** into a plurality of laser beams LB having respective focused spots that will be positioned in the wafer **11** at different positions, i.e., coordinates, in a plane parallel to the X-axis directions and the Y-axis directions, i.e., an XY coordinate plane, and/or at different positions, i.e., heights, in the Z-axis directions, for example.

[0080] The laser beams LB emitted from the spatial optical modulator **48** are applied to and reflected by a mirror **50** to travel to an applying head **52**. The applying head **52** houses therein a condensing lens, not illustrated, for converging the laser beams LB. The laser beams LB converged by the condensing lens are emitted toward the holding surface of the holding table **26**.

[0081] As illustrated in FIG. **4**, the applying head **52** is mounted on a front end of a cylindrical housing **54**. The support block **40** is fixed to a rear side surface of the housing **54**. An image capturing unit **56** is fixed to a front side surface of the housing **54**.

[0082] The image capturing unit **56** includes an image capturing device including, for example, a light source such as a light-emitting diode (LED), an objective lens, a charge-coupled device (CCD) image sensor, or a complementary-metal-oxide-semiconductor (CMOS) image sensor, etc.

[0083] When the vertical moving mechanism **32** is actuated, the laser beam applying unit **42** and the image capturing unit **56** are moved along one of the Z-axis directions at a time. The components referred to above of the laser processing apparatus **2** are enclosed in a cover, not illustrated, mounted on the base **4**. A touch panel **58** is disposed on a front surface of the cover.

[0084] The touch panel **58** includes an input device such as an electrostatic-capacitance or resistive-film touch sensor and a display device such as a liquid crystal display or an organic electroluminescence (EL) display. The touch panel **58** functions as a user interface.

[0085] The laser processing apparatus **2** forms peel-off layers in the wafer **11** according to the following sequence, for example. First, the laminated wafer is placed on the holding table **26** such that the center of the reverse side **17*b*** of the support wafer **17** of the laminated wafer and the center of the holding surface of the holding table **26** are aligned with each other. Then, the suction source that is fluidly connected to the porous plate **26*a*** is actuated to hold the laminated wafer under suction on the holding table **26**.

[0086] Next, the image capturing unit **56** captures an image of the reverse side **11***b* of the wafer **11** of the laminated wafer. Then, on the basis of the captured image, the horizontal moving mechanism **6** is actuated to position the applying head **52** of the laser beam applying unit **42** directly above a region of the wafer **11** slightly radially inwardly of the outer circumferential region thereof.

[0087] On the basis of the captured image, the rotary actuator coupled to the lower portion of the table base **24** may be energized to make the crystal orientation [010] of monocrystalline silicon of the wafer **11** parallel to the X-axis directions and also to make the crystal orientation [001] thereof parallel to the Y-axis directions.

[0088] Thereafter, the laser beam applying unit **42** is energized to apply the branched laser beams LB from the applying head **52** to an annular first region of the wafer **11** that is positioned radially inwardly of the outer circumferential region thereof, thereby forming a first peel-off layer functioning as separation initiating points between the region of the wafer **11** where the devices **15** are formed and the outer circumferential region thereof (a first peel-off layer forming step S**2** illustrated in FIG. **2**).

[0089] In the first peel-off layer forming step S**2**, while the laser beams LB are being applied to the annular first region of the wafer **11** positioned radially inwardly of the outer circumferential region thereof, the holding table **26** that is holding the wafer **11** through the support wafer **17** interposed therebetween is rotated about its central axis. FIG. **6** schematically illustrates, in side elevation, partly in cross section, the manner in which the laser beams LB are applied to the wafer **11** that is rotating.

[0090] Specifically, in the first peel-off layer forming step S**2**, the laser beams LB branched such that they will form a plurality of, e.g., two to ten, respective focused spots at different positions in the Z-axis directions, i.e., heights, in the wafer **11** are applied to the wafer **11**.

[0091] These focused spots include a lowest focused spot positioned at a height slightly higher than the face side **11***a* of the wafer **11** and a highest focused spot positioned at a height intermediate between the face and reverse sides **11***a* and **11***b* of the wafer **11**. The focused spots are disposed at respective positions, i.e., heights, that are spaced at equal intervals, e.g., ranging from 5 to 15 μm, in the wafer **11** along the Z-axis directions.

[0092] The laser beams LB thus applied form modified areas **21** around the respective focused spots in the wafer **11** where the crystal structure of the material of the wafer **11** is disrupted and cracks **23** developed from each of the modified areas **21** so as to interconnect adjacent pairs of modified areas **21**.

[0093] The modified areas **21** and the cracks **23** developed from the modified areas **21** jointly make up a peel-off layer in the wafer **11**. Then, while the laser beams LB are being applied to the wafer **11**, the rotary actuator coupled to the lower portion of the table base **24** is energized to cause the holding table **26** holding the laminated wafer to make one revolution about its central axis.

[0094] As a result, a peel-off layer, i.e., a first peel-off layer, is formed in the wafer **11** between the region of the wafer **11** where the devices **15** are formed and the outer circumferential region thereof. The first peel-off layer is of a hollow cylindrical shape along a side surface of a cylinder having a lower bottom surface positioned near the face side **11***a* of the wafer **11** and an upper bottom surface positioned within the wafer **11**, for example.

[0095] Then, the laser beams LB are applied to a second region of the wafer **11** that is positioned radially inwardly of the outer circumferential region thereof, thereby forming a second peel-off layer functioning as separation initiating points between the face and reverse sides **11***a* and **11***b* of the wafer **11** (a second peel-off layer forming step S**3** illustrated in FIG. **2**). FIG. **7** is a flowchart schematically illustrating the second peel-off layer forming step S**3** by way of example.

[0096] In the second peel-off layer forming step S**3**, the laser beams LB are applied to a straight region of the wafer **11** that extends along the crystal orientation [010] of monocrystalline silicon of the wafer **11** (a laser beam applying step S**31** illustrated in FIG. **7**). In a case where the laminated wafer is held on the holding table **26** such that the crystal orientation [010] lies parallel to the X-axis directions, for example, the laser beams LB are applied to the wafer **11** while the holding table **26** is being moved along one of the X-axis directions at a time.

[0097] FIG. **8** schematically illustrates, in side elevation, partly in cross section, the manner in which the laser beams LB are applied to the wafer **11** that is being moved along one of the X-axis directions at a time. In the laser beam applying step S**31**, the laser beams LB branched such that they will form a plurality of, e.g., two to ten, respective focused spots at different positions in the Y-axis directions, i.e., coordinates, in the wafer **11** are applied to the wafer **11**.

[0098] These focused spots are positioned at the same height as the highest modified area **21** of those modified areas **21** included in the first peel-off layer described above. Furthermore, the focused spots are disposed at respective positions, i.e., coordinates, that are spaced at equal intervals, e.g., ranging from 5 to 15 μm, in the wafer **11** along the Y-axis directions.

[0099] In the second peel-off layer forming step S**3**, as with the first peel-off layer forming step S**2**, the laser beams LB thus applied form modified areas **21** and cracks **23** developed from each of the modified areas **21** in the wafer **11**. Then, while the laser beams LB are being applied to the wafer **11**, the horizontal moving mechanism **6** is actuated to move the holding table **26** holding the laminated wafer along one of the X-axis directions at a time.

[0100] As a result, a peel-off layer **25** is formed in a straight region along the X-axis directions that is included in the second region of the wafer **11** that is positioned radially inwardly of the outer circumferential region thereof. Many of the cracks **23** included in the peel-off layer **25** extend along a crystal plane (k01) (k represents an integral number except 0 whose absolute value is 10 or less). Specifically, when the laser beams LB are applied to the wafer **11** in the manner described above, the cracks **23** are likely to extend along the following crystal planes.

[00001] $(101), (201), (301), (401), (501), (601), (701), (801), (901), (1001)$ [Math. 1]

$(\bar{1}01), (\bar{2}01), (\bar{3}01), (\bar{4}01), (\bar{5}01), (\bar{6}01), (\bar{7}01), (\bar{8}01), (\bar{9}01), (\overline{10}01)$ [Math. 2]

[0101] The angle formed between the crystal plane (100) exposed on the face side and reverse sides **11***a* and **11***b* of the wafer **11** and the crystal plane (k01) is 450 or less. Therefore, if the direction in which the cracks **23** are developed is resolved into a component parallel to the face and reverse sides **11***a* and **11***b* of the wafer **11**, i.e., a parallel component, and a component perpendicular to the face and reverse sides **11***b* of the wafer **11**, i.e., a perpendicular component, then the parallel component becomes equal to or larger than the perpendicular component.

[0102] Then, the holding table **26** is moved along the crystal orientation [001] of monocrystalline silicon of the wafer **11** (an indexing feed step S**32** illustrated in FIG. **7**). For example, in a case where the laminated wafer is held on the holding table **26** such that the crystal orientation [001] of monocrystalline silicon of the wafer **11** lies parallel to the Y-axis directions, for example, the holding table **26** is moved along one of the Y-axis directions.

[0103] Then, the laser beam applying unit **42** and the horizontal moving mechanism **6** are operated to form a peel-off layer **25** in a straight region in the wafer **11** that lies parallel to the straight region where the peel-off layer **25** has already been formed. In other words, the laser beam applying step S**31** is performed again. FIG. **9** schematically illustrates, in cross section, adjacent peel-off layers **25** formed in the wafer **11** according to the laser beam applying step S**31** performed two times.

[0104] In this case, the laser beams LB form a peel-off layer **25**, i.e., a peel-off layer **25-2**, in the wafer **11** that lies parallel to the peel-off layer **25**, i.e., a peel-off layer **25-1**, formed in a first cycle of the laser beam applying step S**31**, and spaced from the peel-off layer **25-1** in one of the Y-axis directions. Furthermore, the indexing feed step S**32** and the laser beam applying step S**31** are repeatedly carried out to form peel-off layers **25** entirely in the second region of the wafer **11** that is positioned radially inwardly of the outer circumferential region thereof, i.e., in the second region from one end to the other along the Y-axis directions.

[0105] If the peel-off layers **25** have been formed entirely in the second region of the wafer **11** that is positioned radially inwardly of the outer circumferential region thereof (a step S**33** illustrated in FIG. **7**: YES), then the second peel-off layer forming step S**3** is completed. As a consequence, a peel-off layer, i.e., a second peel-off layer, is formed between the face and reverse sides **11***a* and **11***b* of the wafer **11**. The second peel-off layer is of a disk shape extending along an upper bottom surface of a cylinder that has a side surface extending along the first peel-off layer describe above, for example.

[0106] According to the method illustrated in FIG. **2**, after the first peel-off layer forming step S**2** and the second peel-off layer forming step S**3** have been carried out, external forces are exerted on the wafer **11** to separate the wafer **11** along the first peel-off layer and the second peel-off layer that function as separation initiating points (a separating step S**4**).

[0107] FIGS. **10**A and **10**B each schematically illustrates, in side elevation, partly in cross section, the manner in which the wafer **11** is separated. The separating step S**4** is carried out using a separating apparatus **60** illustrated in FIGS. **10**A and **10**B. As illustrated in FIGS. **10**A and **10**B, the separating apparatus **60** has a holding table **62** for holding thereon the laminated wafer including the wafer **11** in which the first peel-off layer and the second peel-off layer have been formed.

[0108] The holding table **62** has a circular upper surface as a holding surface that is provided by a porous plate, not illustrated, that is exposed upwardly. The porous plate is held in fluid communication with a suction source, not illustrated, such as a vacuum pump through a fluid channel, not illustrated, defined in the holding table **62**. When the suction source is actuated, it generates a negative pressure that is transmitted through the fluid channel to a space near the holding surface.

[0109] The separating apparatus **60** also includes a separating unit **64** disposed above the holding table **62**. The separating unit **64** has a cylindrical support rod **66** whose upper portion is coupled to a ball-screw-type lifting and lowering mechanism, not illustrated, for example. When the ball-screw-type lifting and lowering mechanism is actuated, it selectively lifts and lowers the separating unit **64**.

[0110] The support rod **66** has a lower end fixed centrally to an upper portion of a disk-shaped grip claw base **68**. A plurality of grip claws **70** that are spaced at generally equal intervals circumferentially around the grip claw base **68** are mounted on a lower surface of an outer circumferential region of the grip claw base **68**. The grip claws **70** have respective plate-shaped vertical bars **70***a* extending downwardly.

[0111] The vertical bars **70***a* have respective upper end portions coupled to an actuator such as an air cylinder housed in the grip claw base **68**. When the actuator is operated, it moves the grip claws **70** radially inwardly or outwardly of the grip claw base **68**. The grip claws **70** also have respective plate-shaped claw points **70***b* extending from respective inner side surfaces of lower ends of the vertical bars **70***a* toward the center of the grip claw base **68**. The claw points **70***b* are progressively thinner toward the center of the grip claw base **68**.

[0112] The separating apparatus **60** carries out separating step S**4** according to the following sequence, for example. First, the laminated wafer is placed on the holding table **62** such that the center of the reverse side **17***b* of the support wafer **17** of the laminated wafer that includes the wafer **11** where the first peel-off layer and the second peel-off layer have been formed and the center of the holding surface of the holding table **62** are aligned with each other.

[0113] Then, the suction source that is fluidly connected to the porous plate exposed as the holding surface is actuated to hold the laminated wafer under suction on the holding table **62**. Next, the actuator housed in the grip claw base **68** is operated to position the grip claws **70** radially outwardly of the grip claw base **68**.

[0114] Then, the lifting and lowering mechanism is actuated to position the tips of the claw points **70***b* of the respective grip claws **70** at the same height as the adhesive **19** of the laminated wafer. Next, the actuator in the grip claw base **68** is operated to bring the claw points **70***b* radially inwardly into contact with the laminated wafer. Thereafter, the lifting and lowering mechanism is actuated to lift the claw points **70**_b_ (see FIG. **10**A).

[0115] The claw points **70**_b_ as they are lifted exert upward external forces on the outer circumferential region of the wafer **11**, i.e., external forces along one of the thicknesswise directions of the wafer **11**. Under the external forces thus exerted, the cracks **23** included in the first peel-off layer and/or the second peel-off layer are developed, separating the region of the wafer **11** where the devices are formed and the outer circumferential region thereof from each other and also separating a part of the wafer **11** belonging to the face side **11**_a_ and a part of the wafer **11** belonging to the reverse side **11**_b_ from each other (see FIG. **10**B).

[0116] According to the method illustrated in FIG. **2**, when the laser beams LB are applied to the wafer **11** fabricated such that the crystal plane (100) is exposed on each of the face and reverse sides **11**_a_ and **11**_b_ of the wafer **11**, along the crystal orientation [010], a peel-off layer, i.e., a second peel-off layer, that functions as separation initiating points between the face and reverse sides **11**_a_ and **11**_b_ of the wafer **11** is formed in the wafer **11**.

[0117] In this case, the cracks **23** extending from the modified areas **21** include many cracks **23** along the crystal plane (k01) (k represents an integral number except 0 whose absolute value is 10 or less). The acute angle formed between the crystal plane (100) and the crystal plane (k01) of the monocrystalline crystal is 450 or less. According to the method, therefore, the component of the direction in which the cracks **23** are developed that is parallel to the face and reverse sides **11**_a_ and **11**_b_ of the wafer **11**, i.e., the parallel component, becomes equal to or larger than the component perpendicular to the face and reverse sides **11**_a_ and **11**_b_ of the wafer **11**, i.e., the perpendicular component.

[0118] According to the method, therefore, the intervals between the adjacent modified areas **21** are increased. As a result, the distance that the holding table **26** is moved, i.e., an indexed distance, in the indexing feed step S**32** is increased, thereby shortening the processing time, i.e., a period of time in which the laser beams LB are applied, required to form the peel-off layers **25** in the wafer **11** that function as separation initiating points between the face and reverse sides **11**_a_ and **11**_b_ of the wafer **11**.

[0119] According to the method, moreover, cracks **23** are less likely to be developed from the peel-off layer **25** toward the face side **11**_a_ of the wafer **11**. Consequently, the probability that devices **15** will be broken is lowered when the wafer **11** is separated into the part of the wafer **11** belonging to the face side **11**_a_ and the part of the wafer **11** belonging to the reverse side **11**_b_.

[0120] The method described above represents an aspect of the present invention, and the present invention is not limited to the above method. According to the present invention, for example, after the first peel-off layer and the second peel-off layer have been formed in the wafer **11**, the face side **11**_a_ of the wafer **11** may be affixed to the face side **17**_a_ of the support wafer **17**. According to the present invention, in other words, the affixing step S**1** may be carried out after the first peel-off layer forming step S**2** and the second peel-off layer forming step S**3**.

[0121] Moreover, the structure of a laser processing apparatus that can be used in the present invention is not limited to the structure of the laser processing apparatus **2** described above. According to the present invention, for example, the present invention may be reduced to practice using a laser processing apparatus having a horizontal moving mechanism for moving the applying head **52** of the laser beam applying unit **42**, etc. along the X-axis directions and/or the Y-axis directions.

[0122] According to the present invention, in other words, the holding table **26** for holding the laminated wafer including the wafer **11** and the applying head **52** of the laser beam applying unit **42** for emitting the laser beams LB may be relatively moved respectively along the X-axis directions and the Y-axis directions. There is no limitation on the structure for moving the holding table **26** and the applying head **52** in that manner.

[0123] According to the present invention, moreover, the first peel-off layer forming step S**2** and the second peel-off layer forming step S**3** may be carried out in any sequence. According to the present invention, in other words, the first peel-off layer forming step S**2** may be carried out after the second peel-off layer forming step S**3** has been carried out.

[0124] However, if the disk-shaped second peel-off layer is formed in the wafer **11** in the second peel-off layer forming step S**3**, then it may be impossible or difficult to newly form a peel-off layer in the wafer **11** in a region closer to the face side **11***a* of the wafer **11** than the second peel-off layer.

[0125] According to the present invention, therefore, it is preferable to carry out the second peel-off layer forming step S**3** after the first peel-off layer forming step S**2** has been carried out. This sequence makes it possible to form reliably in the wafer **11** a peel-off layer, i.e., a first peel-off layer, that functions as separation initiating points between the region of the wafer **11** where the devices **15** are formed and the outer circumferential region thereof.

[0126] According to the present invention, alternatively, it is preferable for the second region of the wafer where the second peel-off layer is formed to be positioned radially inwardly of the first region of the wafer **11** where the first peel-off layer is formed. The second region positioned radially inwardly of the first region allows the first peel-off layer to be formed reliably in the wafer **11** even if the first peel-off layer forming step S**2** is carried out after the second peel-off layer forming step S**3** has been carried out.

[0127] According to the present invention, in the first peel-off layer forming step S**2**, the first peel-off layer may be formed that functions as separation initiating points between the region of the wafer **11** where the devices **15** are formed and the outer circumferential region thereof. The first peel-off layer is not limited to any particular shape. For example, the first peel-off layer may be of a shape extending along a side surface of a cylinder having a lower bottom surface positioned near the face side **11***a* of the wafer **11** and an upper bottom surface positioned near the reverse side **11***b* of the wafer **11**.

[0128] Specifically, the first peel-off layer may be formed in the wafer **11** so as to extend through the face and reverse sides **11***a* and **11***b* of the wafer **11**. In a case where the first peel-off layer is of such a shape, the outer circumferential region of the wafer **11** may possibly be scattered around as offcuts in the separating step S**4**. In the first peel-off layer forming step S**2** according to the present invention, therefore, the first peel-off layer should preferably be formed so as to terminate short of the reverse side **11***b* of the wafer **11**.

[0129] Furthermore, the first peel-off layer may be of a shape extending along a side surface of a truncated cone having a lower bottom surface, i.e., a first bottom surface, positioned near the face side **11***a* of the wafer **11** and an upper bottom surface, i.e., a second bottom surface, positioned within the wafer **11** and smaller in diameter than the lower bottom surface. The first peel-off layer of such a shape may be formed by applying the laser beams LB to the wafer **11** such that their focused spots are progressively closer to the face side **11***a* of the wafer **11** toward the outer circumferential region thereof.

[0130] FIG. **11** schematically illustrates, in side elevation, partly in cross section, the manner in which the laser beams LB are applied to the wafer **11** that is rotating in order to form first peel-off layer of such a shape. Specifically, for forming such a first peel-off layer, the laser beams LB are applied to the wafer **11** for forming a plurality of, e.g., eight, focused spots that are spaced at intervals of 10 μm in the wafer **11** in both radial directions thereof perpendicular to the Z-axis directions and thicknesswise directions thereof along the Z-axis directions.

[0131] The laser beams LB thus applied develop modified areas **21** around the respective focused spots in the wafer **11** where the crystal structure of the material of the wafer **11** is disrupted. The modified areas **21** are arranged in a straight array radially of the wafer **11** as viewed in plan. The straight array of the modified areas **21** is inclined to the face side **11***a* of the wafer **11** at an acute angle of 45°.

[0132] The angle formed between the straight array of the modified areas **21** and the face side **11***a* of the wafer **11** is not limited to 45°. Stated otherwise, the laser beams LB may be applied to the wafer **11** such that they develop their respective focused spots in the wafer **11** that are spaced at intervals in radial directions thereof and at intervals in thicknesswise directions thereof, the intervals in the radial directions being different from the intervals in the thicknesswise directions.

[0133] Cracks **23** extend from each of the modified areas **21** so as to interconnect adjacent modified areas **21** in each pair. The modified areas **21** and the cracks **23** extending from each of the modified areas **21** jointly form a peel-off layer in the wafer **11**.

[0134] Then, while the laser beam applying unit **42** is being energized, the rotary actuator coupled to the lower portion of the table base **24** is operated to rotate the holding table **26** that is holding the laminated wafer thereon by at least one revolution.

[0135] As a result, a peel-off layer, i.e., a first peel-off layer, is formed in a first region of the wafer **11** that is positioned slightly radially inwardly of the outer circumferential region thereof, the first peel-off layer extending along a side surface of a truncated cone that has a lower bottom surface positioned near the face side **11***a* of the wafer **11** and an upper bottom surface positioned within the wafer **11**.

[0136] When the first peel-off layer is thus formed, the probability that a side surface of the region where the devices **15** are formed that is newly exposed by dividing the wafer **11** on the separating apparatus **60** described above and an inner side surface of the outer circumferential region of the wafer **11** will contact each other is low. In this case, furthermore, cracks **23** tend to be developed in directions from the first peel-off layer along the side surface of the truncated cone.

[0137] In this case, moreover, the probability that cracks **23** will be developed toward devices **15** is low, preventing devices **15** from being broken. With the first peel-off layer thus formed, it is easy to fabricate chips from a region of the face side **11***a* of the wafer **11** near the outer circumferential region thereof. Therefore, the number of chips that can be fabricated from the wafer **11** is increased.

[0138] According to the present invention, in the first peel-off layer forming step S**2**, the laser beams LB may be applied to the wafer **11** while the horizontal moving mechanism **6** and the vertical moving mechanism **32** are being actuated in addition to or instead of the rotary actuator coupled to the lower portion of the table base **24**. In other words, the laser beams LB may be applied to the wafer **11** while not only the wafer **11** is being rotated, but also the coordinates of the focused spots of the laser beams LB in the XY coordinate plane and the heights of the focused spots are being changed.

[0139] According to the present invention, in the first peel-off layer forming step S**2**, the laser beams LB may be applied to the wafer **11** in a plurality of cycles such that their focused spots are positioned at identical or close locations. In this case, the modified areas **21** included in the produced peel-off layer become larger in size and the cracks **23** included in the produced peel-off layer are extended further. Consequently, the wafer **11** can be separated more easily in the separating step S**4**.

[0140] According to the present invention, in the first peel-off layer forming step S**2**, the laser beams LB may be applied to the wafer **11** such that adjacent ones of the modified areas **21** are not interconnected by cracks **23** but interconnected directly. In this case, since the shape of the peel-off layer can be determined independently of the shape of the cracks **23** extending from the modified areas **21**, the wafer **11** can be processed stably.

[0141] According to the present invention, in the second peel-off layer forming step S**3**, the region of the wafer **11** to which the laser beams LB are applied in the laser beam applying step S**31** of the second peel-off layer forming step S**3** is not limited to the straight region of the wafer **11** that extends along the crystal orientation [010] of monocrystalline silicon of the wafer **11**. In the laser beam applying step S**31**, for example, the laser beams LB may be applied to a straight region that extends along the crystal orientation [001].

[0142] When the laser beams LB are applied to the wafer **11** in the manner described above, the cracks **23** are likely to extend along the following crystal planes.

[00002] $(110), (210), (310), (410), (510), (610), (710), (810), (910), (1\underline{0}10)$ [Math . 3]

$(\bar{1}10), (\bar{2}10), (\bar{3}10), (\bar{4}10), (\bar{5}10), (\bar{6}10), (\bar{7}10), (\bar{8}10), (\bar{9}10), (\bar{1}\underline{0}10)$ [Math . 4]

[0143] According to the present invention, furthermore, the laser beams LB may be applied to a straight region of the wafer **11** that extends along a direction slightly inclined to the crystal orientation [010] or the crystal orientation [001]. This alternative will be described below with reference to FIG. **12**.

[0144] FIG. **12** is a graph illustrating the widths of peel-off layers formed within the wafer **11** when the laser beams LB are applied to straight regions extending along respective different crystal orientations, i.e., the lengths of the peel-off layers in a direction perpendicular to the direction along which the straight regions extend. The horizontal axis of the graph represents the angles, as viewed in plan, formed between the direction in which straight regions, i.e., reference regions, perpendicular to the crystal orientation [011] extend and straight regions, i.e., measurement regions, as measurement objects.

[0145] Specifically, in a case where the horizontal axis of the graph represents an angle of 45°, a straight region along the crystal orientation [001] becomes a measurement object. Similarly, in a case where the horizontal axis of the graph represents an angle of 135°, a straight region along the crystal orientation [010] becomes a measurement object. The vertical axis of the graph represents values obtained by dividing the widths of peel-off layers formed in measurement regions by applying the laser beams LB to the measurement regions by the widths of peel-off layers formed in reference regions by applying the laser beams LB to the reference regions.

[0146] As illustrated in FIG. **12**, the widths of peel-off layers are wide when the angle formed between the direction in which the reference regions extend and the direction in which the measurement regions extend is in the range from 40° to 50° or from 130° to 140°. In other words, the widths of peel-off layers are wide when the laser beams LB are applied to not only straight regions along the crystal orientation [001] or the crystal orientation [010], but also straight regions along a direction inclined to these crystal orientations at an angle of 5° or less.

[0147] According to the present invention, consequently, in the laser beam applying step S**31** of the second peel-off layer forming step S**3**, the laser beams LB may be applied to straight regions along a direction inclined at 5° or less, as viewed in plan, to the crystal orientation [001] or the crystal orientation [010].

[0148] In the laser beam applying step S**31**, more specifically, the laser beams LB may be applied to straight regions along a direction, i.e., a first direction, parallel to the crystal plane, i.e., the crystal plane (100), that is exposed on the face and reverse sides **11***a* and **11***b* of the wafer **11**, among particular crystal planes included in the crystal planes {100} and inclined to a particular crystal orientation, i.e., the crystal orientation [001] or the crystal orientation [010], included in the crystal orientations <100> at an angle of 5° or less.

[0149] When the laser beam applying step S**31** is carried out, the indexing feed step S**32** is carried out by moving positions in the wafer **11** where the focused spots are formed by the applied laser beams LB along a direction, i.e., a second direction, parallel to the crystal plane, i.e., the crystal plane (100), that is exposed on the face and reverse sides **11***a* and **11***b* of the wafer **11**, among particular crystal planes included in the crystal planes {100} and perpendicular to the first direction.

[0150] According to the present invention, moreover, in the second peel-off layer forming step S**3**, the laser beam applying step S**31** and the indexing feed step S**32** may be carried out repeatedly again after the peel-off layers **25** have been formed entirely in the second region of the wafer **11** that is positioned radially inwardly of the outer circumferential region thereof, i.e., in the second region from one end to the other along the Y-axis directions (step S**33**: YES).

[0151] Specifically, the laser beams LB for forming a peel-off layer **25** may be applied again to the second region of the wafer **11** where the peel-off layer **25** has already been formed. In this case, the densities of the modified areas **21** and the cracks **23** included in the peel-off layers **25** are increased. The increased densities make it easy to separate the wafer **11** in the separating step S**4**.

[0152] According to the present invention, in the second peel-off layer forming step S**3**, the laser beam applying step S**31** may be carried out again after the laser beam applying step S**31** and before the indexing feed step S**32**. In other words, the laser beams LB for forming a peel-off layer **25** may be applied again to the straight region where the peel-off layer **25** has already been formed. In this case, as is the case with the above alternative, it becomes easy to separate the wafer **11** in the separating step S**4**.

[0153] According to the present invention, in the separating step S**4**, ultrasonic waves may be applied to the wafer **11** prior to the separating of the wafer **11** in which the first peel-off layer and the second peel-off layer have been formed. In this case, inasmuch as the cracks **23** included in the first peel-off layer and the second peel-off layer are developed, the wafer **11** can be separated more easily.

[0154] According to the present invention, in the separating step S**4**, the wafer **11** may be separated using an apparatus other than the separating apparatus **60**. For example, according to the present invention, in the separating step S**4**, after the region of the wafer **11** where the devices **15** are formed and the outer circumferential region thereof have been separated from each other, the wafer **11** may be separated into the part of the wafer **11** belonging to the face side **11***a* and the part of the wafer **11** belonging to the reverse side **11***b*.

[0155] An example of the separating step S**4** described above will be described below with reference to FIGS. **13**, **14**A, **14**B, **15**A, and **15**B. FIG. **13** schematically illustrates, in plan, a wafer **11** to be used in such the separating step S**4**. Prior to the affixing step S**1** described above, a plurality of recesses **11***d* are formed in the outer circumferential region of the wafer **11**, the recesses **11***d* extending radially of the wafer **11**.

[0156] The recesses **11***d* are spaced at generally equal intervals circumferentially around the wafer **11**, except where the notch **13** is defined. Each of the recesses **11***d* has a portion positioned radially inwardly of the wafer **11** and extending to the first peel-off layer to be formed in the first peel-off layer forming step S**2**.

[0157] The first peel-off layer formed in the wafer **11** is of a shape extending along a side surface of a cylinder having a lower bottom surface positioned near the face side **11***a* of the wafer **11** and an upper bottom surface positioned near the reverse side **11***b* of the wafer **11**. Specifically, the first peel-off layer is formed in the wafer **11** so as to extend through the face and reverse sides **11***a* and **11***b* of the wafer **11**.

[0158] The recesses **11***d* are formed by a known cutting apparatus when it cuts the wafer **11**, for example. Alternatively, the recesses **11***d* may be formed by a known laser processing apparatus when it applies a laser beam to the wafer **11** for performing laser ablation.

[0159] The wafer **11** may alternatively have, rather than the recesses **11***d*, a plurality of peel-off layers defined in the outer circumferential region thereof and extending radially of the wafer **11**. These peel-off layers are formed in the same process as the process of forming the first peel-off layers and the second peel-off layers described above, for example.

[0160] FIGS. **14**A and **14**B schematically illustrate in side elevation, partly in cross section, the manner in which the region of the wafer **11** illustrated in FIG. **13** where the devices **15** are formed and the outer circumferential region thereof are separated from each other. The wafer **11** is separated in this manner using an expanding apparatus **72** illustrated in FIGS. **14**A and **14**B.

[0161] The expanding apparatus **72** has a hollow cylindrical drum **74** that is fixed in position. A support unit **76** is disposed around the drum **74**. The support unit **76** has an annular support base **78** surrounding an upper end portion of the drum **74**. A plurality of clamps **80** are disposed on the support base **78** and spaced at generally equal intervals circumferentially around the support base **78**.

[0162] A plurality of air cylinders are disposed beneath the support base **78** and spaced at generally equal intervals circumferentially around the support base **78**. The air cylinders have respective piston rods **82** whose upper ends are fixed to a lower portion of the support base **78**. Therefore, in the expanding apparatus **72**, when the air cylinders are actuated, they selectively lift and lower the support base **78** and the clamps **80** with the piston rods **82**.

[0163] For separating the region of the wafer **11** illustrated in FIG. **13** where the devices **15** are formed and the outer circumferential region thereof from each other, the annular frame **29** is affixed to a circumferential region of a surface of a disk-shaped expansion tape **27**, and the reverse side **11***b* of the wafer **11** is affixed to a central region of the surface of the disk-shaped expansion tape **27**. There is now formed a frame unit including the laminated wafer where the wafer **11** and the support wafer **17** are affixed to each other and the annular frame **29** integrally combined with the laminated wafer.

[0164] Then, the air cylinders are actuated to position an upper surface of the support base **78** flush with an upper end of the drum **74**. Then, the annular frame **29** is placed on the support base **78** with the expansion tape **27** interposed therebetween. In other words, the frame unit with the support wafer **17** facing upwardly is placed on the support base **78**.

[0165] Then, the annular frame **29** is fixed in position by the clamps **80** (see FIG. **14**A). Then, the air cylinders are actuated to lower the annular frame **29** fixed in position by the clamps **80**. The central region of the expansion tape **27** is expanded radially of the wafer **11** as much as the annular frame **29** is lowered.

[0166] At this time, forces directed radially outwardly of the wafer **11** act on the wafer **11** affixed to the expansion tape **27**. As a result, the region of the wafer **11** where the devices **15** are formed and the outer circumferential region thereof are separated from each other along the first peel-off layer (see FIG. **14**B).

[0167] FIGS. **15**A and **15**B schematically illustrate in side elevation, partly in cross section, the manner in which the part of the wafer **11** illustrated in FIG. **14**B belonging to the face side **11***a* and the part of the wafer **11** belonging to the reverse side **11***b* are separated from each other. The wafer **11** is separated in this manner using a separating apparatus **84** illustrated in FIGS. **15**A and **15**B. The separating apparatus **84** has a holding table **86** for holding thereon the laminated wafer including the wafer **11** illustrated in FIG. **14**B.

[0168] The holding table **86** has a circular upper surface as a holding surface that is provided by a porous plate, not illustrated, that is exposed upwardly. The porous plate is held in fluid communication with a suction source, not illustrated, such as a vacuum pump through a fluid channel, not illustrated, defined in the holding table **86**. When the suction source is actuated, it generates a negative pressure that is transmitted through the fluid channel to a space near the holding surface.

[0169] The separating apparatus **84** also includes a separating unit **88** disposed above the holding table **86**. The separating unit **88** has a cylindrical support rod **90** whose upper portion is coupled to a ball-screw-type lifting and lowering mechanism, not illustrated, for example. When the ball-screw-type lifting and lowering mechanism is actuated, it selectively lifts and lowers the separating unit **88**.

[0170] The support rod **90** has a lower end fixed centrally to an upper portion of a disk-shaped suction plate **92**. The suction plate **92** has a plurality of suction ports, not illustrated, defined in a lower surface thereof and held in fluid communication with a suction source, not illustrated, such as a vacuum pump through a fluid channel, not illustrated, defined in the suction plate **92**. When the suction source is actuated, it generates a negative pressure that is transmitted through the fluid channel to a space near the lower surface of the suction plate **92**.

[0171] For separating the part of the wafer **11** illustrated in FIG. **14**B belonging to the face side **11***a* and the part of the wafer **11** belonging to the reverse side **11***b* from each other, the laminated wafer including the wafer **11** is removed the expansion tape **27**. Then, the laminated wafer is placed on the holding table **86** such that the center of the reverse side **17***b* of the support wafer **17** of the laminated wafer and the center of the holding surface of the holding table **86** are aligned with each other.

[0172] Then, the suction source that is fluidly connected to the porous plate of the holding table **86** is actuated to hold the laminated wafer under suction on the holding table **86**. Then, the lifting and lowering mechanism is actuated to lower the separating unit **88** to bring the lower surface of the suction plate **92** into contact with the reverse side **11***b* of the wafer **11**.

[0173] Then, the suction source that is fluidly connected to the suction ports in the suction plate **92** is actuated to attract the reverse side **11***b* of the wafer **11** to the lower surface of the suction plate **92** under a negative pressure acting through the suction ports. Then, the lifting and lowering mechanism is actuated to lift the separating unit **88** to space the suction plate **92** away from the holding table **86** (see FIG. **15**A).

[0174] At this time, forces directed upwardly thicknesswise of the wafer **11** act on the wafer **11** in which the reverse side **11***b* is held on the suction plate **92** by the negative pressure acting through the suction ports. As a result, the part of the wafer **11** belonging to the face side **11***a* and the part of the wafer **11** belonging to the reverse side **11***b* are separated from each other along the second peel-off layer functioning as separation initiating points (see FIG. **15**B).

[0175] The structure, method, etc. according to the above embodiment may be changed or modified appropriately without departing from the scope of the present invention.

[0176] 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 method of processing a monocrystalline silicon wafer fabricated such that a particular crystal plane included in crystal planes {100} is exposed on each of face and reverse sides of the monocrystalline silicon wafer, having a beveled outer circumferential region, by applying a laser beam having a wavelength transmittable through the monocrystalline silicon wafer while positioning a focused spot of the laser beam within the monocrystalline silicon wafer, thereby forming a peel-off layer within the monocrystalline silicon wafer, and thereafter separating the monocrystalline silicon wafer along the peel-off layer that functions as separation initiating points, the method comprising: a first peel-off layer forming step of applying the laser beam from the reverse side of the monocrystalline silicon wafer to an annular first region of the monocrystalline silicon wafer that is positioned radially inwardly of the outer circumferential region of the monocrystalline silicon wafer, thereby forming a first peel-off layer that functions as separation initiating points when the outer circumferential region is separated from the monocrystalline silicon wafer; a second peel-off layer forming step of applying the laser beam from the reverse side of the monocrystalline silicon wafer to a second region of the monocrystalline silicon wafer that is positioned radially inwardly of the outer circumferential region of the monocrystalline silicon wafer, thereby forming a second peel-off layer that functions as separation initiating points between a part of the monocrystalline silicon wafer that belongs to the face side thereof and a part of the monocrystalline silicon wafer that belongs to the reverse side thereof; and a separating step of, after the first peel-off layer forming step and the second peel-off layer forming step, exerting external forces on the monocrystalline silicon wafer, thereby separating the monocrystalline silicon wafer along the first peel-off layer and the second peel-off layer as the separation initiating points, wherein the second peel-off layer forming step includes a laser beam applying step of applying the laser beam to a straight region of the monocrystalline silicon wafer along a first direction included in the second region while moving the monocrystalline silicon wafer and the focused spot relatively to each other along the first direction that lies parallel to the particular crystal plane, and an indexing feed step of moving a position in the monocrystalline crystal wafer where the focused spot is formed by the applied laser beam along a second direction parallel to the particular crystal plane and perpendicular to the first direction, and the laser beam applying step and the indexing feed step are repeatedly carried out to form the second peel-off layer.

**2**. The method according to claim 1, wherein the first direction is inclined to a particular crystal orientation included in crystal orientations <100> at an angle of 5° or less.

**3**. The method according to claim 1, wherein the monocrystalline silicon wafer has a plurality of devices formed on the face side thereof.

**4**. The method according to claim 1, further comprising an affixing step of, before the first peel-off layer forming step and the second peel-off layer forming step, affixing the face side of the monocrystalline silicon wafer to a face side of a support wafer.

**5**. The method according to claim 4, wherein the support wafer has a plurality of devices formed on the face side thereof.

**6**. The method according to claim 1, wherein the first peel-off layer includes a plurality of modified areas each of which is positioned between the face side of the monocrystalline silicon wafer and the second peel-off layer in thicknesswise directions of the monocrystalline silicon wafer and whose positions in the thicknesswise directions are different from each other.

**7**. The method according to claim 1, wherein the first peel-off layer forming step is carried out before the second peel-off layer forming step.

**8**. The method according to claim 1, wherein the second region is positioned radially inwardly of the first region.

**9**. The method according to claim 1, wherein the first peel-off layer forming step includes the step of forming the first peel-off layer so as to terminate short of the reverse side of the monocrystalline crystal wafer.

**10**. The method according to claim 1, wherein the first peel-off layer forming step includes the step of forming the first peel-off layer along a side surface of a truncated cone having a first bottom surface positioned near the face side of the monocrystalline crystal wafer and a second bottom surface smaller in diameter than the first bottom surface and positioned within the monocrystalline crystal wafer, by applying the laser beam such that the focused spot thereof is progressively closer to the face side of the monocrystalline crystal wafer toward the outer circumferential region thereof.