

Method for cutting a multiplicity of slices from workpieces by means of a wire saw during a sequence of cut-off operations

5 The invention relates to a method for cutting a multiplicity of slices from workpieces by means of a wire saw during a sequence of cut-off operations, wherein the wire saw comprises a wire array of moving wire sections of a saw wire and an actuating device, and the wire array is tensioned in a plane between two wire guide rollers, and wherein each of the two wire guide rollers is supported between a fixed bearing and a floating bearing. During each of the cut-off operations, the respective workpiece is fed by
10 means of the actuating device through the wire array along a feed direction perpendicular to a workpiece axis and perpendicular to the plane of the wire array in the presence of a working fluid and hard materials, which act abrasively on the workpiece.

15 Prior art/problems

Such a method for cutting a multiplicity of slices can be accomplished by means of lap slicing or grind slicing.

In the case of lap slicing, working fluid in the form of a slurry consisting of hard materials in a liquid carrier medium is fed to the working space formed between the
20 wire surface and the workpiece. In the case of lap slicing, material is removed by means of a three-body interaction involving the tool carrier (saw wire), the tool (abrasive) and the workpiece.

In the case of grind slicing, use is made of saw wire in whose surface hard materials are firmly bonded, and a working fluid is supplied which itself contains no abrasive
25 materials and acts as a cooling lubricant. In the case of grind slicing, material is removed by means of two body interaction involving a diamond-coated saw wire as a tool and the workpiece.

In the case of conventional wire saws, each of the wire guide rollers is provided in the
30 vicinity of each of its end faces with a bearing which is connected in a fixed manner to the machine frame and is referred to as a fixed bearing, and is provided in the vicinity of the opposite end face with a bearing which is movable in the axial direction of the wire guide roller relative to the machine frame and is referred to as a floating bearing.

There are known measures which aim to counteract the change in the arrangement of the wire array and the workpiece relative to one another during the cut-off operation in order to improve the plane parallelism of the main surfaces of the slices to be cut off.

5 US 5 377 568 discloses a method in which the position of a reference surface situated on the outside of the wire guide roller relative to the machine frame is measured, and a thermal length increase or length decrease in the wire guide roller is brought about by adjusting the temperature of the wire guide roller interior until the measured position change of the reference surface has been compensated again.

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WO 2013/079683 A1 discloses a method in which, first of all, the slice shapes obtained at various temperatures of the wire guide roller bearings are measured, and each of these shapes is stored with the respectively associated bearing temperature, and, in the follow-on cut, the bearing temperature which best matches the desired target shape is then selected.

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US 5 875 770 discloses a method in which the shape of slices from a cut is measured, a cut depth-dependent correction curve is calculated by forming the difference with respect to a desired ideal shape of the slices, and, in the following cut, the workpiece is moved in the axial direction relative to the wire array in accordance with this correction curve during the cut-off operation.

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Despite these measures, there continues to be a need for improvements, on the one hand because these measures have only a limited effect and, on the other hand, because the requirements in respect of flatness and plane parallelism of slices are becoming ever more demanding, especially in the semiconductor industry.

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It is the object of the present invention to make available slices whose shape matches a target shape as closely as possible.

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The object of the invention is achieved by a method for cutting a multiplicity of slices by means of a wire saw from workpieces during a sequence of cut-off operations divided into initial cuts and follow-on cuts, wherein the wire saw comprises a wire array of moving wire sections of a saw wire and an actuating device, and the wire

array is tensioned in a plane between two wire guide rollers, wherein each of the two wire guide rollers is supported between a fixed bearing and a floating bearing, the method comprising

5 during each of the cut-off operations, feeding the respective workpiece by means of the actuating device through the wire array along a feed direction perpendicular to a workpiece axis and perpendicular to the plane of the wire array in the presence of a working fluid and hard materials, which act abrasively on the workpiece, which comprises

10 during each of the cut-off operations, feeding the workpiece through the wire array with simultaneous axial movement of the floating bearings by adjusting the temperature of the fixed bearings with a cooling fluid in accordance with the specification of a first temperature profile, which specifies the temperature of the cooling fluid in dependence on a depth of cut and correlates with a first correction profile, which specifies the travel of the floating bearings in dependence on the depth
15 of cut; and

feeding the workpiece through the wire array while simultaneously moving the workpiece along the workpiece axis by means of an actuating element in accordance with the specification of a second correction profile, which specifies the travel of the workpiece, wherein the first and second correction profiles are opposed to a shape
20 deviation; and

determining the shape deviation during each of the cut-off operations and/or before each of the cut-off operations.

The method can be configured as lap slicing or grind slicing. Depth of cut (doc)
25 denotes a length counter to the feed direction in the region of the entry cut into the workpiece as far as the exit cut from the workpiece.

Adjusting the temperature of the fixed bearings (referred to below as wire guide temperature control, WGTC) leads to contraction or expansion of the fixed bearings
30 and hence of the components thereof in the axial direction of the wire guide rollers, resulting in axial movement of the floating bearings and thus movement of the wire guide rollers relative to the workpiece.

Adjusting the temperature of the fixed bearings thus has the same effect qualitatively as moving the workpiece (referred to below as ingot positioning control, IPC) along the workpiece axis by means of an actuating element. The actuating element is preferably a piezoelectric actuator. The variables which bring about the respective travel are thus the temperature of the cooling fluid in the case of WGTC, and the
 5 signal used to drive the actuating element in the case of IPC.

According to the invention, both measures are provided to minimize any possible shape deviation. There are particular advantages associated with this approach. If the
 10 measures are used in combination, it is possible to achieve an amplitude (amount of travel) of movement of the wire guide rollers relative to the workpiece that is greater than the amplitude possible when using only one of the measures. The range within which the movement of the floating bearings and the workpiece is linearly dependent on the variable bringing about the movement is wider than the corresponding range
 15 available when using only one of the measures. From changing the variable that brings about the movement to the actual occurrence of the movement takes significantly more response time in the case of WGTC than in the case of IPC, especially if the actuating element is a piezoelectric actuator. Thus, the two measures have different control bandwidths. Accordingly, it is advantageous to counter
 20 comparatively high-frequency shape deviations, i.e. shape deviations that change with comparatively large gradients depending on the depth of cut, by means of IPC and comparatively low-frequency shape deviations by means of WGTC. Because of the different response times, control by IPC can be used to damp overshoot of control by WGTC. In addition, the control bandwidth of the combination of IPC and WGTC is
 25 larger than that of IPC or of WGTC. The combination of both measures makes it possible to achieve a larger travel per unit time, because the movement of the floating bearings and the workpiece is carried out by two independent actuators.

If the shape deviation is determined before a cut-off operation, the term shape
 30 deviation refers to the deviation of a shape profile of a slice or an average shape profile of slices from a reference shape profile.

If the shape deviation is determined during a cut-off operation, the term shape deviation refers to the deviation of the position of a line through the center of an

observed kerf or the deviation of the position of an average line representing a plurality of such lines from the position of a reference trajectory. This line and the reference trajectory would have the same position with respect to a common reference if the cut-off operation were completely trouble-free, i.e. without

5 unintentional axial movement of the wire guide rollers and/or axial movement of the workpiece. The common reference is a location in space that remains motionless, e.g. a location on the machine frame. If a plurality of kerfs is observed, the locations of the lines through the centers of the kerfs are averaged to give the location of an average line. Points at the same height of the line or the average line and the reference

10 trajectory represent a certain depth of cut. Accordingly, the distance of such a point on the line or on the average line from the corresponding point on the reference trajectory indicates the shape deviation at the depth of cut represented by the points.

Observation of one or more kerfs is preferably performed by irradiation with optical

15 radiation, IR radiation, X-rays, or γ -rays. In addition, mechanical scanning of the kerfs or inductive or capacitive measurement of the kerfs may also be considered.

The shape deviation is determined during each of the cut-off operations and/or before each of the cut-off operations.

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According to one embodiment, determination of the shape deviation is based on observing one or more kerfs, and two closed control loops are established. The first control loop responds to a control error, i.e. to a determined shape deviation, by means of WGTC, and the second control loop responds by means of IPC, wherein the

25 movement of the floating bearings and of the workpiece which is to be performed to rectify the shape deviation is carried out with the work divided between the loops. The floating bearings are moved by means of WGTC according to a first correction profile, which determines the travel of the floating bearings in dependence on the depth of cut. The temperature profile, which specifies the temperature of the coolant in

30 dependence on a depth of cut, correlates with the first correction profile. It is experimentally determined in advance what temperature change of the cooling fluid is required to bring about the specified travel of the floating bearing of the respective wire guide roller. The first correction profile determines, in dependence on the depth of cut, the proportion of travel that the floating bearings perform in order to reduce the

shape deviation. The workpiece is moved by means of IPC in accordance with a second correction profile. The second correction profile determines, in dependence on the depth of cut, the proportion of travel that the workpiece performs in order to reduce the shape deviation. The sum of both proportions corresponds to the travel
 5 required to reduce the determined shape deviation. The proportions of travel can be divided equally or differently.

According to another embodiment, the determination of the shape deviation is based on a comparison of an average shape profile of already cut-off slices with a reference
 10 shape profile, the comparison provides an overall correction profile which, even before a cut-off operation, determines what travel is necessary in dependence on the depth of cut in order to avoid the shape deviation which, in view of the comparison, would be expected without countermeasures. The overall correction profile is divided into the first and second correction profile, and this determines what proportions of travel are
 15 to be performed by means of WGTC and IPC. In this case, too, the proportions of travel can be divided equally or in some other ratio.

According to a further embodiment, the determination of the shape deviation is based on the observation of one or more kerfs and on a comparison of an average shape
 20 profile of already cut-off slices with a reference shape profile. The shape deviation that is determined by the observation of one or more kerfs is assigned the first or alternatively the second correction profile and the shape deviation that is determined by comparison of the average shape profile with the reference shape profile is assigned the second or alternatively the first correction profile. If therefore WGTC is
 25 used against a shape deviation for which the determination takes place during each of the cut-off operations, IPC is used against a shape deviation that is determined before each of the cut-off operations, or vice versa.

The surface of a slice is composed of the main surfaces and the edge surface. The
 30 main surfaces comprise the front side and the rear side of the slice. A slice can be measured by being arranged between a pair of sensors, as is customary in the case of warp measurement. Each of the sensors measures the distance of the facing main surface of the slice at measurement points. The measurement points can be distributed over the main surfaces or can lie along a diameter of the slice that deviates

by no more than $\pm 20^\circ$ from the feed direction. The measurement points preferably lie with position i along the diameter of the slice, to be specific counter to the feed direction, and therefore each measurement point is associated with a particular depth of cut. The density of the measurement points is preferably no less than 1 per cm, and

5 the distance between one measurement point and the nearest adjacent point is preferably the same for all the measurement points.

The shape profile of a slice is the line which connects the measurement points s_i , which are calculated at the positions i in accordance with the rule $s_i = D - (FD_i - BD_i)$,

10 where D is the distance between the sensors, FD_i is the distance between the upper sensor and the respective measurement point on the front side of the slice, and BD_i is the distance between the lower sensor and the respective measurement point on the rear side of the slice. It should be noted that the present invention can also be carried out using an alternative definition of the shape profile, as long as this alternative

15 definition encodes the shape of the slice in dependence on the depth of cut.

An average shape profile of slices is a shape profile obtained by averaging the shape profiles of a plurality of slices. A reference shape profile is a desired shape profile, preferably the shape profile of a slice which has completely flat and mutually parallel

20 main surfaces. The average shape profile is determined for slices which result from preferably at least 1 to 5 cut-off operations by means of the same wire saw, wherein these cut-off operations have immediately preceded the cut-off operation to be carried out by this wire saw. The selection of slices for the creation of the average shape profile can be slice-based or cut-based, or can include both. In the case of slice-based

25 selection, certain slices from a cut-off operation are used to determine the respective average shape profile by averaging, and others are excluded. For example, only those slices are taken into account in the averaging process that have a specific position in the workpiece, e.g. only every 15th to 25th slice along the workpiece axis. Another possibility for slice-based selection is the exclusion of slices with the largest and the

30 smallest deviation of the shape profile from the average shape profile of all slices in the cut-off operation (so-called trimmed mean). Alternatively, it is possible to exclude from averaging slices whose shape profile deviates from the average shape profile of all slices in the cut-off operation by more than 1 to 2 sigma. In a cut-based selection,

all slices from at least one cut-off operation are used to determine an average shape profile and all slices from at least one other cut-off operation are excluded from it.

5 The average shape profile of slices in a cut-off operation changes over the course of a sequence of cut-off operations. Changes are preferably used to evaluate the performance of the wire saw. They may indicate wear of the saw wire and/or the facing of the wire guide rollers or of any other component of the wire saw that is subject to wear. Preferably, therefore, a threshold for the shape deviation is defined which, when reached or exceeded, initiates maintenance activities (predictive
10 maintenance activities) instead of a further cut-off operation. Even before such a threshold is reached, such changes can be used as an occasion to take adjustment measures to counteract a deterioration of the work result due to wear. Such adjustment measures can be, for example, changing the composition and/or temperature of the working fluid and/or changing the wire speed and/or other process-
15 specific parameters.

Cut-off operations that take place after a change in the saw system represent a special case. Such a change in the saw system occurs, for example, when there is a change of wire guide rollers, mechanical adjustments to the wire saw, or changes in
20 physical or chemical properties of the working fluid. The first cut-off operations after a change of the saw system, the so-called initial cuts, preferably consist of 1 to 5 cut-off operations. For initial cuts, the shape deviation is preferably determined by comparing an average shape profile of slices with the reference shape profile, wherein the average shape profile of slices produced by the same wire saw in the course of one or
25 more initial cuts made before the saw system was changed is used.

A wire saw used in accordance with the invention comprises two or more wire guide rollers, for example three or four wire guide rollers. Adjustment of the temperature of the fixed bearings of the wire guide rollers can be limited to the two wire guide rollers
30 between which the wire array is tensioned, by means of which the workpiece is fed in.

The workpiece is preferably composed of a semiconductor material such as silicon, which is in a multicrystalline or monocrystalline state. The periphery of the cross section of the workpiece is square, rectangular or circular. In the case of a workpiece

of cylindrical shape, the workpiece axis extends through the center of the cylinder. The method according to the invention is suitable particularly for the production of round semiconductor wafers composed of monocrystalline silicon with a diameter of at least 200 mm, in particular at least 300 mm.

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Details of the invention are described below with reference to drawings.

Brief description of the figures

10 **Figure 1** shows schematically features of a wire saw that play a role in the use of the invention.

Figure 2 shows further details of the wire saw.

Figure 3 shows the course of a kerf through the workpiece and an envisaged course represented by a reference trajectory.

15 **Figure 4** shows the arrangement of a slice between two sensors for determining the shape deviation thereof before a cut-off operation.

Figure 5 shows the advantage obtained when the amplitudes of WGTC and IPC are added.

20 **Figure 6** shows the range within which an amplitude $\mathcal{A}$ of the movement is linearly dependent on the variable bringing about the movement.

Figure 7 shows an advantageous division of the overall correction profile between WGTC and IPC.

Figure 8 shows that a larger travel per unit time can be brought about by combining WGTC and IPC.

25 **Figure 9** shows how an advantageous division of the overall correction profile between WGTC and IPC damps the overshoot of the amplitude which would be observed if WGTC were used as the only measure.

List of reference numerals employed

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- 1 wire guide roller
- 2 wire array
- 3 saw wire
- 4 workpiece

- 5 5 fixed bearing
- 6 6 floating bearing
- 7 7 machine frame
- 8 8 facing
- 5 9 channel
- 10 10 direction arrow
- 11 11 direction arrow
- 12 12 actuating device
- 13 13 kerf detector
- 10 14 data processing unit
- 15 15 actuating element
- 16 16 control unit
- 17 17 kerf
- 18 18 reference trajectory
- 15 19 upper sensor
- 20 20 lower sensor
- 21 21 slice

20 Detailed description of exemplary embodiments according to the invention

A wire saw suitable for carrying out the method according to the invention comprises a wire array 2 consisting of moving wire sections of a saw wire 3, which is tensioned in a plane between two wire guide rollers 1. During a cut-off operation, the workpiece 4

25 is fed through the wire array 2 along a feed direction perpendicular to a workpiece axis and perpendicular to the plane of the wire array 2 by means of an actuating device 12. In the course of this operation, the wire guide rollers 1 tensioning the wire array 2, and the workpiece 4, are each moved in an axial direction in accordance with direction arrows 10 and 11, respectively, in dependence on a first and a second

30 correction profile. The first and the second correction profile counter a shape deviation determined before or during a cut-off operation. To determine the shape deviation during the cut-off operation, there is a kerf detector 13 for observing kerfs and a data processing unit 14 for creating the first and the second correction profile. The data processing unit 14 transmits to an actuating element 15 a control signal which, in

35 dependence on the depth of cut, brings about a movement of the workpiece 4 in

accordance with the second correction profile in the direction along the workpiece axis indicated by the direction arrow 11.

As shown in figure 2, the wire guide roller 1 is mounted between a fixed bearing 5 and a floating bearing 6. The fixed bearing 5 and the floating bearing 6 are supported on a machine frame 7. The wire guide roller 1 has a facing 8 that is provided with grooves, in which the saw wire 3 runs. The fixed bearing 5 comprises a channel 9, through which a cooling fluid for adjusting the temperature of the fixed bearing 5 is passed. If the temperature of the fluid is increased, the thermal expansion of the fixed bearing 5 brings about an axial movement of the wire guide roller 1 in the direction of the floating bearing 6, and the floating bearing 6 moves outward in the direction, indicated by direction arrow 10, of the axis of the wire guide roller 1 relative to the machine frame 7. If the temperature of the cooling fluid is reduced, a movement of the wire guide roller 1 and of the floating bearing 6 in the opposite direction is brought about. The temperature of the cooling fluid is specified in dependence on the depth of cut by a temperature profile, which correlates with the first correction profile. A control unit 16, which is connected to a heat exchanger and a pump, ensures that the fluid passed through the fixed bearing 5 has the temperature required by the respective temperature profile when a certain depth of cut is reached. The data processing unit 14 transmits to the control unit 16 the temperature profile, which brings about a movement of the floating bearings in accordance with the first correction profile.

Figure 3 shows the course of a kerf 17 through the workpiece 4 and an envisaged course represented by a reference trajectory 18. The respective deviation of the line through the center of the kerf from the reference trajectory corresponds to the overall correction profile, which is divided in the form of the first and the second correction profile between WGTC and IPC.

Figure 4 shows the arrangement of a slice between two sensors 19, 20 for determining a shape deviation thereof before a cut-off operation. The sensors 19, 20 measure the distance FD_i of the upper sensor 19 from the front side of the slice 21 and the distance BD_i of the lower sensor 20 from the rear side of the slice 21 at certain positions i along the diameter of the slice 21 in the feed direction in accordance with certain depths of cut. The shape profile of the slice is the line which connects the measured values s_i calculated in accordance with the rule $s_i = D - (FD_i - BD_i)$, where D denotes the distance between the sensors. The shape deviation of the

slice is obtained by comparing the shape profile of the slice with a reference shape profile. The deviation from the reference shape profile in dependence on the depth of cut corresponds to the overall correction profile, which is divided between WGTC and IPC in the form of the first and the second correction profile.

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Figure 5 shows the advantage obtained when the amplitudes of WGTC and IPC are added. If the overall correction profile requires a travel of amplitude A of the order of the dashed line, it would not be possible for this travel to be accomplished by means of WGTC or IPC individually since the achievable travel with the respective individual measure is not sufficient. Only the combination of WGTC and IPC makes this possible.

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Figure 6 shows that, in the range B2 with the rest position B1, the amplitude $\mathcal{A}$ of the movement is linearly dependent on the variable (input, I) bringing about the movement. Outside this range, deviations from linear behavior occur, resulting in Δ errors. By combining WGTC and IPC, the range B2 in which the overall system reacts linearly is increased.

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Figure 7 shows an advantageous division of the overall correction profile between WGTC and IPC, which consists of counteracting low-frequency shape deviations by means of WGTC and the first correction profile and high-frequency shape deviations by means of IPC and the second correction profile. For this purpose, use is preferably made of a crossover, which, by means of a low-pass filter (LP) and a high-pass filter (HP), assigns low-frequency portions of the shape deviation to correction by means of WGTC and high-frequency portions of the shape deviation to correction by means of IPC.

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Figure 8 shows that by means of the combination of WGTC and IPC a larger total amplitude $A_2 + A_1$ per unit time Δt can be achieved because the movement of the floating bearings and the workpiece is carried out by two independent actuators. When using WGTC or IPC alone, only one amplitude of A_1 and A_2 , respectively, is possible in this time unit.

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Figure 9 shows how an advantageous division of the overall correction profile between WGTC and IPC damps the overshoot of the amplitude A over time t (right-

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hand diagram) which would be observed if WGTC were used as the only measure (left-hand diagram).

5 The above description of illustrative embodiments is to be understood as being exemplary. The disclosure made thereby enables a person skilled in the art, on the one hand, to understand the present invention and the advantages associated therewith and also comprises, on the other hand, alterations and modifications to the described structures and methods that are obvious within the understanding of a person skilled in the art.

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Claims

1. A method for cutting a multiplicity of slices by means of a wire saw from workpieces during a sequence of cut-off operations divided into initial cuts and follow-on cuts,
 5 wherein the wire saw comprises a wire array of moving wire sections of a saw wire and an actuating device, and the wire array is tensioned in a plane between two wire guide rollers, wherein each of the two wire guide rollers is supported between a fixed bearing and a floating bearing, the method comprising
 during each of the cut-off operations, feeding the respective workpiece by
 10 means of the actuating device through the wire array along a feed direction perpendicular to a workpiece axis and perpendicular to the plane of the wire array in the presence of a working fluid and hard materials, which act abrasively on the workpiece, which comprises
 during each of the cut-off operations, feeding the workpiece through the wire
 15 array with simultaneous axial movement of the floating bearings by adjusting the temperature of the fixed bearings with a cooling fluid in accordance with the specification of a temperature profile, which specifies the temperature of the cooling fluid in dependence on a depth of cut and correlates with a first correction profile, which specifies the travel of the floating bearings in dependence on the depth of cut;
 20 and
 feeding the workpiece through the wire array while simultaneously moving the workpiece along the workpiece axis by means of an actuating element in accordance with the specification of a second correction profile, which specifies the travel of the workpiece, wherein the first and second correction profiles are opposed to a shape
 25 deviation; and
 determining the shape deviation during each of the cut-off operations and/or before each of the cut-off operations.

2. The method as claimed in claim 1, wherein the shape deviation is measured during
 30 each of the cut-off operations by comparing the position of a line through the center of at least one kerf with the position of a reference trajectory.

3. The method as claimed in claim 1, wherein the shape deviation is determined by a comparison of an average shape profile of already cut-off slices with a reference shape profile before each of the cut-off operations.
- 5 4. The method as claimed in claim 3, wherein the average shape profile is determined by averaging shape profiles of selected slices, the selection being made in a slice-based, cut-based, or slice-based and cut-based manner.
- 10 5. The method as claimed in claim 3 or claim 4, wherein the already cut-off slices originate from at least 1 to 5 cut-off operations that directly preceded the respective cut-off operation.
- 15 6. The method as claimed in any one of claims 1 to 5, wherein a maintenance measure is initiated instead of the respective cut-off operation if the shape deviation determined before the respective cut-off operation reaches or exceeds a defined threshold.