

Method and device for production of a crystal rod with reduced pendulum deflection during the pulling process

5 Technical field

The invention relates to a method of producing a single-crystal rod with reduced pendulum deflection, and to the production of wafers by further processing from semiconductor material. The invention further relates to a crystal pulling device and to the use of the crystal pulling
10 device for reduction of pendulum deflections. The invention finally relates to a computer program for reduction of pendulum deflections, and to a computer-readable medium on which this computer program is stored.

Prior art and technical problem

Primarily in the case of crystal pulling devices that are operated with a pulling device of the
15 cable pendulum device type, it is known that pendulum movements of the mass unit suspended from the pulling cable occur during the actual crystal pulling process (i.e. the growing crystal rod in particular), but also during process steps on the mass unit suspended from the pulling cable that precede or follow the actual crystal pulling process (i.e. those relating inter alia to the movement of the melt coverage, or other components of the crystal
20 pulling device, which have to be lifted for example). It may be the case here that a maximum pendulum deflection of the mass unit based on an axis of rest of the crystal pendulum takes on such great magnitudes that the mass unit, for example, collides with the crucible wall of the crucible of the crystal pulling device and causes corresponding damage to the crucible and in particular to the suspended mass unit, i.e., for example, to the crystal rod in the production
25 process or to components of the crystal pulling device.

With regard to the actual crystal pulling process, however, damage to the growing crystal rod occurs well before collision of the growing crystal rod with the crucible edge: even in the case of slight pendulum deflection, there are yield losses because the crystal no longer grows or is pulled out of the melt in a cylindrical fashion. Such crystal growth is naturally disadvantageous
30 and makes the crystal rod (section) produced unusable.

In order to enable crystal pulling even within the resonance frequency of the system, active control to counter pendulum movement is required.

A solution to this problem known from the prior art is active closed-loop control of the crystal pulling device by means of an "X-Y stage" beneath the rotary head of the cable, as described, for example, in DE 102009024472 A1. In this case, pendulum deflections during the pulling process are reduced by moving the rotary head of the cable across the X-Y stage correspondingly in transverse directions (in X direction and Y direction) to the height axis. However, the provision of such a movable X-Y stage beneath the rotary head of the cable to counteract pendulum deflections during the pulling process entails a complex set up in terms of construction and control technology.

The present invention is therefore based on the objective technical problem of providing, in a simple manner, in particular, a method and a device for production of a single-crystal rod with reduced pendulum deflection, which have the abovementioned disadvantages at least to a reduced degree, if at all, and which in particular do not require the provision of a movable X-Y stage beneath a rotary head of the cable to counteract or reduce pendulum deflections.

The object is achieved in a first aspect by a method of producing a single-crystal rod according to the features of claim 1, in a second aspect by a crystal pulling device according to the features of claim 9, in a third aspect by the use thereof for reduction of pendulum deflections according to claim 11, and finally in a fourth aspect by a computer program for reduction of pendulum deflections according to the features of claim 12. The invention further relates to a computer-readable medium according to claim 13 on which said computer program is stored. The invention finally relates, proceeding from the method of the invention or preferred variants thereof for production of a single-crystal rod with reduced pendulum deflection, to the production of wafers from semiconductor material by further processing according to claim 14.

The invention is based here on the technical teaching that it is possible in a simple manner and in particular without the additional construction setup just described to manufacture a crystal rod that has been pulled with reduced pendulum deflection on the crystal pulling device, in that a reduction, especially an attenuation, of the maximum pendulum deflection based on an axis of rest of the crystal pendulum that occurs during pulling is made exclusively via controlled, and especially continuous and variable, setting of the target pulling speed. In other words, the current invention has established that it is sufficient for effective reduction or

attenuation of pendulum deflection during pulling to match the target pulling speed in reaction to the current outcome of the pendulum deflection, and to conduct this in particular with reference to definable switching steps and following switching criteria (relating inter alia to the progression, variation and magnitude of the target pulling speed).

5 Description of the invention

In a first aspect, the invention therefore relates to a method of producing a single-crystal rod, especially of silicon, by means of a pulling device of a crystal pulling device, where the crystal pulling device, in particular the pulling device, defines a center of pendulum rotation D through which a defined axis of rest of the crystal pendulum runs essentially along a height axis.

- 10 During at least one pulling process, via actuation of the pulling device with the control device, an essentially gradually progressive single-crystal rod section with an associated essentially gradually progressive assigned single-crystal length is pulled here from a melt according to a settable, variable target pulling speed of the pulling device to give the single-crystal rod.

- What is envisaged here in accordance with the invention is that, during at least one phase of
- 15 the pulling process, such a controlled, variable setting of the target pulling speed is undertaken via controlled actuation of the pulling device via a control device in such a way that, after each change in the setting of the target pulling speed has been made, for the continuation of the pulling process, maximum pendulum deflections $\hat{\Delta}$ of the progressive single-crystal rod section based on the axis of rest of the crystal pendulum develop as a
- 20 function of the progressive pulling time and/or progressive single-crystal length, the magnitudes of which and/or differential magnitudes of which from successive magnitudes are reduced at least in phases, especially by comparison with magnitudes and/or differential magnitudes of maximum reference pendulum deflections $\hat{\Delta}_R$ that would develop alternatively to the pulling process in a reference pulling process, in each case with an identical
- 25 progressive pulling time and/or identical progressive single-crystal rod length on a progressive reference single-crystal rod section in which a reference single-crystal rod is being pulled according to a reference process-typical reference target pulling speed profile.

- What the method of the invention achieves in a simple manner is a reduction (or attenuation) of the maximum pendulum deflection based on the axis of rest of the crystal pendulum that
- 30 occurs within the at least one phase exclusively via controlled, and especially continuous, setting of the target pulling speed. This setting of the target pulling speed is preferably made via controlled actuation of the pulling device via that control device of the crystal pulling device

which is provided in generic crystal pulling devices in any case. All that changes is thus the actuation commands for controlled, variable setting of the target pulling speed, especially according to the switching criteria or switching steps described further down, without any need to provide further units for actuation on the crystal pulling device or in the environment of the crystal pulling device. In other words, the reduction in pendulum deflection according to the invention can be conducted on a conventional (generic) crystal pulling device, and by means of execution of the computer program of the invention (as described further down) by means of a computer device (comprising a processor unit) which is provided in generic methods and crystal pulling systems in any case.

- 10 The method of the invention overcomes the disadvantages described at the outset in conjunction with approaches to a solution cited in the prior art for reduction of pendulum deflections.

The reference pulling process means a comparative process (conducted separately from the method of the invention), i.e. one that is not being conducted (simultaneously) on the crystal pulling device at the moment of performance of the method of producing the single-crystal rod. It serves as a comparative process in the sense of a process of reference (POR) and enables quantification of the effect of the inventive reduction or attenuation of the maximum pendulum deflection. The reference process-typical reference target pulling speed profile preferably follows a process-typical progression of conventional crystal pulling systems.

- 20 The “essentially gradually progressive single-crystal rod section” in the context of the invention which is pulled out of the melt during the pulling process may also include temporary remelting processes. In other words, it is not absolutely necessary for the crystal rod to be constantly in the growing state.

What is meant by “at least in sections” in the context of the invention is that a reduction (by comparison with the reference pulling process) in the magnitudes and/or differential magnitudes thereof from successive magnitudes of the pendulum deflections Δ may in each case also develop solely in sections during the progressive pulling time and/or progressive single-crystal length. For example, it is possible that, by means of the method of the invention, a high reduction in differential magnitudes from successive magnitudes of the pendulum deflections Δ develops over a phase at the start of the pulling process (especially at the start of the phase of the pulling process) and, by contrast, a high reduction in the magnitudes of the pendulum deflections Δ per se (compared to the reference pulling process) is established

toward the middle or end of the pulling process (especially toward the middle or end of the phase of the pulling process). This influencing of the resulting deflection characteristics of the single-crystal rod section can then be achieved via controlled, variable setting of the target pulling speed (via corresponding actuation of the pulling device via the control device).

- 5 Because of the possibility of flexible configuration of the controlled setting of the target pulling speed, especially depending on a definable pendulum deflection trigger threshold value, there is a multitude of resultant further progression variants.

- 10 The method of the invention is suitable both for performance on a crystal pulling device with a pulling device of the cable pendulum device type and for performance on a crystal pulling device of the conventional CZ pulling device type with a framework unit. However, the particularly advantageous effects of the invention are manifested in particular in the case of performance on a crystal pulling device with a pulling device of the cable pendulum device type.

- 15 In preferred variants, the center of rotation D is defined by the pulling device and is spatially assigned thereto. In this case, in designs of the pulling device of the cable pendulum device type, the rotary head for the cable which is provided may be configured according to conventional designs of rotary cable heads, but without provision or interaction with an X-Y stage or other (physical) unit, and be driven in a conventional manner (via a drive unit in the form of a motor unit). In other words, no change in the construction or addition to the
20 construction of the rotary cable head is required for performance of the method of the invention.

- In a preferred variant, the center of rotation D during the pulling process dwells essentially at a fixed location, or performs essentially no relative movements. However, what is meant by “essentially” in this connection is that, for example, in the case of execution of the pulling
25 device in the manner of a cable pendulum device, the center of rotation D, as a result of the winding-up of the cable on the drum during the pulling process, may in this respect naturally give rise to a spatially variable location of the center of rotation D within certain limits since, in the case of certain designs, the point at which the pulling cable rolls off the drum will move during the windup of the pulling cable. However, this effect on the results of the determination
30 of pendulum deflection is negligible.

In particularly advantageous variants, it is preferably the case that the variable setting of the target pulling speed is made in reaction to the maximum pendulum deflection attaining or

going above or below a definable pendulum deflection trigger threshold value, which is in the range from 0 mm to 100.0 mm, preferably in the range from 0.1 mm to 10.0 mm, further preferably in the range from 0.5 mm to 3.0 mm.

Actuation in the context of the invention also encompasses closed-loop control and the steps
5 of closed-loop control, and the control device in the context of the invention also includes a closed-loop control unit designed to perform constant comparison with the definable threshold values, here in particular the at least one pendulum deflection trigger threshold value, and, depending on the result of the comparison, especially with reference to definable switching criteria and following definable switching steps, to set the target pulling speed in a controlled,
10 variable manner (or to keep it set at the current level for the moment).

The pendulum deflection trigger threshold value represents a measure of the magnitude of the crystal pendulum movement from which the active controlled variable setting of the target pulling speed should be undertaken; in other words, the deflection threshold from which the reduction or attenuation should be undertaken by appropriate actuation of the pulling device
15 via the control device with a definable target pulling speed.

In particularly advantageous variants, it is preferably the case that, during the at least one phase of the pulling process, by means of a pendulum movement determination device, at least the progression of the current maximum pendulum deflection of the single-crystal rod section is determined as a function of the current pulling time and/or current single-crystal
20 length, wherein, by means of the pendulum movement determination device, the results of the determination are transmitted continuously to an indicator device for further use. Additionally or alternatively, the results of the determination are transmitted to a memory device for further use. The indicator device and the memory device are preferably part of a computer device comprising a processor unit. In particular, a current result is still transmitted to the control
25 device. The control device can variably set the target pulling speed in a controlled manner, especially according to at least one switching step and following at least one definable switching criterion (especially as described further down) when the current maximum pendulum deflection attains or goes below or above a definable pendulum deflection trigger threshold value.

30 In preferred variants, the pendulum movement determination device or components of the pendulum movement determination device, especially a processing device of the pendulum

movement determination device, is preferably physically assigned locally to a computer device (comprising a processor unit), and preferably integrated therein.

In principle, the progression of the current maximum pendulum deflection of the single-crystal rod section can be determined in any desired manner as a function of the current pulling time and/or the current single-crystal length. For example, this progression can be ascertained by means of a pendulum movement determination device in which the respective current result for the maximum pendulum deflection is determined via a measurement of weight. In particularly advantageous variants, however, it is preferably the case that a camera device of a pendulum movement determination device provided records at least one imaging region comprising at least one section of a circumferential edge between the progressive single-crystal rod section and the melt continuously as a function of time, and a processing device of the pendulum movement determination device, at least for the section of the circumferential edge, by means of computer-based image processing, determines the time-dependent absolute and relative location coordinates thereof (in other words, the relative location coordinates of the section of the currently deflected circumferential edge are reported in relation to the ideal position of the circumferential edge (i.e. in the middle of the axis of rest of the crystal pendulum)) and, on the basis of these absolute and relative location coordinates, determines at least one time-dependent and/or crystal length-dependent progression of the section of the circumferential edge of the crystal rod section in the manner of pendulum oscillations of the crystal rod section in relation to the axis of rest of the crystal pendulum and about the center of pendulum rotation D, and, for each pendulum oscillation n, determines the assigned period duration T, zero axis intercept time t and maximum pendulum deflection $\hat{A}$. It is preferably further the case that the processing device also determines at least the progression of the current maximum pendulum deflection of the single-crystal rod section as a function of the current pulling time and/or the current single-crystal length. Preferably, the respective current result of the (maximum) pendulum deflection for the assigned pendulum oscillation is determined proceeding from the timed absolute and relative location coordinates of the section of the deflected circumferential edge. The result is preferably reported in relation to the axis of rest of the crystal pendulum in a plane at right angles to the axis of rest of the crystal pendulum.

In particularly advantageous variants, it is preferably the case that, at least during the phase of the pulling process, the pulling device, actuated via the control device, undertakes the setting of the target pulling speed as a function of the current result for the maximum

pendulum deflection in accordance with at least one of the following switching steps and following a definable switching criterion:

- 5 I) According to a first switching criterion, a first switching step is executed preferably as follows: if the currently determined result for the maximum pendulum deflection $\hat{A}$ remains below a definable pendulum deflection trigger threshold value, a current set target pulling speed of the pulling device, which is especially a first or third target pulling speed, is kept essentially constant.
- 10 In other words, this switching criterion or this switching step corresponds to a state in which the active reduction or attenuation is not switched on provided that the currently determined result for the maximum pendulum deflection $\hat{A}$ remains below the definable pendulum deflection trigger threshold value.

15 Additionally or alternatively:

- 20 II) According to a second switching criterion, a second switching step is executed preferably as follows: as soon as the currently determined result for the maximum pendulum deflection $\hat{A}$ attains a definable pendulum deflection trigger threshold value, there is an essentially abrupt changeover from a target pulling speed which is especially a first or third target pulling speed to a definable target pulling speed interval which is limited by a second upper and/or a second lower target pulling speed, where the second upper target pulling speed is raised by a magnitude Δ_{v2o} in relation to the target pulling speed and the second lower target pulling speed is lowered by a magnitude Δ_{v2u} in relation to the target pulling speed, where the
- 25 target pulling speed is especially a first or third target pulling speed.

30 In other words, in the case of this switching criterion or this switching step, because of the attainment of the pendulum deflection trigger threshold value, the active reduction or attenuation is activated in the manner described proceeding from the previously inactive state.

Additionally or alternatively:

- 35 III) According to a third switching criterion, a third switching step is executed preferably as follows: if the currently determined result for the maximum pendulum

deflection $\hat{A}$ exceeds a definable pendulum deflection trigger threshold value, there is a continuous changeover essentially at each zero axis intercept time t of a pendulum movement of the crystal rod section in relation to the axis of rest of the crystal pendulum essentially abruptly between a second upper target pulling speed and a second lower target pulling speed, where the second upper target pulling speed has been raised by a magnitude Δ_{v2o} in relation to a target pulling speed and the second lower target pulling speed has been reduced by a magnitude Δ_{v2u} in relation to a target pulling speed, where the target pulling speed is especially a first or third target pulling speed.

In other words, this switching criterion or switching step corresponds to a state in which the active reduction or attenuation is switched on or activated, and the reduction or attenuation is implemented in the manner described above for as long as the currently determined result of the maximum pendulum deflection $\hat{A}$ exceeds the definable pendulum deflection trigger threshold value.

Additionally or alternatively:

- IV) According to a fourth switching criterion, a fourth switching step is executed as follows: as soon as the currently determined result for the maximum pendulum deflection $\hat{A}$ goes below a definable pendulum deflection trigger threshold value,
- a. there is an essentially abrupt changeover from a second upper target pulling speed raised by a magnitude Δ_{v2o} in relation to a first or third target pulling speed to the first or third target pulling speed,
 - and/or
 - b. there is an essentially abrupt changeover from a second lower target pulling speed reduced by a magnitude Δ_{v2u} in relation to a first or third target pulling speed to a first or third target pulling speed.

In other words, in this switching criterion or this switching step, because the value goes below the pendulum deflection trigger threshold value proceeding from the state of active reduction or attenuation, there is a switch to the inactive state (i.e. the active reduction or attenuation is switched off).

“Essentially abrupt” also means that a ramp-like but steep, time-delayed rise by the magnitude Δ_{v2o} or drop by the magnitude Δ_{v2u} is possible, provided that the attenuation effect is sufficient.

It will be apparent that it is not absolutely necessary for the mode of function of the switching criterion or switching steps that exactly the maximum pendulum deflection or the axis of rest of the pendulum be used for the determination; provided that the period duration T of oscillation is in the high single-digit second range, the delay in signal processing or in
 5 intervention by the system is negligible.

In particularly advantageous variants, it is preferably the case that a definable pendulum deflection trigger threshold value is in the range from 0 mm to 100.0 mm, preferably in the range from 0.1 mm to 10.0 mm, further preferably in the range from 0.5 mm to 3.0 mm.

Additionally or alternatively, a definable, settable target pulling speed, especially according to
 10 at least one switching criterion as specified above, may be in the range from 0 mm/min to 10 mm/min, preferably in the range from 0.1 mm/min to 4 mm/min, further preferably from 0.5 mm/min to 3 mm/min.

Additionally or alternatively, a first and/or third target pulling speed, especially according to at least one switching criterion as specified above, may be in the range from 0 mm/min to 10
 15 mm/min, preferably in the range from 0.1 mm/min to 4 mm/min, further preferably from 0.5 mm/min to 3 mm/min.

In particularly advantageous variants, it is preferably the case that a magnitude Δ_{v2o} , which is a magnitude of the target pulling speed between a target pulling speed that is especially a first or third target pulling speed and a second upper target pulling speed, is settable within a
 20 range from 0.0001 mm/min to 3 mm/min, preferably from 0.001 mm/min to 0.1 mm/min. The magnitude Δ_{v2o} is preferably set in a constant manner over the at least one phase or settable in a variable manner within the range during the at least one phase.

Additionally or alternatively, a magnitude Δ_{v2u} , which is a magnitude of the target pulling speed between a target pulling speed that is especially a first or third target pulling speed and a
 25 second lower target pulling speed, is settable within a range from 0.0001 mm/min to 3 mm/min, preferably from 0.001 mm/min to 0.1 mm/min. The magnitude Δ_{v2u} here is preferably set in a constant manner over the at least one phase or settable in a variable manner within the range during the at least one phase.

In a further aspect, the invention relates to a crystal pulling device for production of a single-
 30 crystal rod with a pulling device, where the pulling device is designed, at least during a pulling

process, via actuation of the pulling device with a control device, to pull an essentially gradually progressive single-crystal rod section with an associated essentially gradually progressive assigned single-crystal length from a melt according to a settable, variable target pulling speed of the pulling device to give the single-crystal rod, where the crystal pulling
 5 device, preferably by means of the pulling device, defines a center of pendulum rotation D through which a defined axis of rest of the crystal pendulum runs essentially along a height axis.

According to the invention, the crystal pulling device, especially the control device of the crystal pulling device, is designed, at least during a phase of the pulling process, to undertake
 10 such a controlled variable setting of the target pulling speed via controlled actuation of the pulling device via the control device in such a way that, after each change in the setting of the target pulling speed has been made, for the continuation of the pulling process, maximum pendulum deflections $\hat{A}$ of the progressive single-crystal rod section based on the axis of rest of the crystal pendulum develop as a function of the progressive pulling time and/or
 15 progressive single-crystal length, the magnitudes of which and/or differential magnitudes of which from successive magnitudes are each reduced at least in phases, especially by comparison with magnitudes and/or differential magnitudes of maximum reference pendulum deflections $\hat{A}_R$ that would develop alternatively to the pulling process in a reference pulling process, in each case with an identical progressive pulling time and/or identical progressive
 20 single-crystal rod length on a progressive reference single-crystal rod section in which a reference single-crystal rod is being pulled according to a reference process-typical reference target pulling speed profile.

The crystal pulling device of the invention may be designed here either with a pulling device of the cable pendulum device type or with a pulling device of the conventional CZ pulling device
 25 type with a framework unit. However, the particularly advantageous effects of the invention are manifested particularly in the case of performance on a crystal pulling device having a pulling device of the cable pendulum device type.

The crystal pulling device of the invention can achieve the advantages analogously to the method of the invention described in detail above, and so reference is made to the above
 30 observations to avoid repetition. In general, the invention has been described primarily using the features of the method according to the invention or according to its preferred variants. It will be apparent that these features (in conjunction with their described advantages) of the preferred variants of the method are equally applicable to preferred variants of the crystal

pulling devices, where the individual device components of the crystal pulling device are then designed accordingly in order to implement the associated method steps. In order to avoid repetition, reference is therefore made to the full scope of the observations above, and it is stated here in summary that, in preferred variants of the crystal pulling device, the pulling device is preferably designed, during at least one pulling process, via the pulling device, to pull an essentially gradually progressive single-crystal rod section with an associated essentially gradually progressive assigned single-crystal length from a melt according to a settable, variable target pulling speed of the pulling device to give the single-crystal rod by the method of the invention described or according to one or more of its preferred described variants of the method.

In a further aspect, the invention relates to the use of the crystal pulling device (according to the invention or according to one or more of its preferred described variants) for reduction of pendulum deflections of a mass unit suspended from a pulling device. In other words, the use of the crystal pulling device is suitable for general performance of a working method for reduction of pendulum deflections of a mass unit suspended from a pulling device (as described by way of introduction, for example melt coverage inter alia).

In a further aspect, the invention relates to a computer program comprising commands which, when the program is executed by a computer device (comprising a processor unit), cause the latter, by means of the control device of the crystal pulling device according to the invention (or according to its variants described above), to specifically actuate the pulling device thereof for the production of a crystal rod with reduced pendulum deflections by the production method of the invention (or according to its variants described above). The invention further relates to a computer-readable medium on which this computer program is stored.

Brief description of the figures

Figure 1 shows a schematic section through a crystal pulling device 100 with a pulling device of the cable pendulum device type and schematically illustrates a pendulum deflection at a circumferential edge of a current crystal rod section during the pulling process of the invention.

Figure 2 illustrates the effect of attenuation of the maximum pendulum deflection for a phase during the pulling process ZP1 compared to the process of record (POR) over the progressive single-crystal rod length.

Figure 3 shows a detail view of a section during the phase of the pulling process ZP1 (without POR comparison) in which the active attenuation is switched on and off, following definable switching steps and switching criteria I to IV.

Preferred working example

The crystal pulling device 100 is designed to implement a method of producing a single-crystal rod of silicon and comprises a pulling device 110. The pulling device 110 is designed, during a pulling process ZP1, via actuation of the pulling device 110 by means of a control device 120, to pull an essentially gradually progressive single-crystal rod section with an associated essentially gradually progressive assigned single-crystal length from a melt according to an adjustable, variable target pulling speed of the pulling device 110 to give the single-crystal rod.

The pulling device 110 of the crystal pulling device 100 is designed as a cable pendulum device. The pulling device 110 here defines a center of pendulum rotation D, through which a defined axis of rest of the crystal pendulum runs essentially along a height axis H. During the pulling process, the crystal rod section oscillates about the center of pendulum rotation D (or suspension point) in the manner of pendulum vibrations in relation to the axis of rest of the crystal pendulum. Figure 1 shows a schematic of a current maximum pendulum deflection (assigned to a pendulum oscillation) at a current circumferential edge of a current deflected crystal rod section during the pulling process ZP1.

The fundamental setup of the crystal pulling device 100 corresponds to a conventional crystal pulling device and is additionally configured with the specific configuration of the control device for controlled actuation of the control device or controlled setting of the target pulling speed for operation under reduced pendulum deflection. There is therefore no detailed discussion of conventional components of a crystal pulling device.

The control device 120 is designed, during a phase of the pulling process ZP1, to make such a controlled, variable setting of the target pulling speed v_s via controlled actuation of the pulling device 110 such that, after each change in the setting of the target pulling speed has

been made, for the continuation of the pulling process, maximum pendulum deflections $\hat{A}$ of the progressive single-crystal rod section based on the axis of rest of the crystal pendulum develop as a function of the progressive pulling time and progressive single-crystal length, the magnitudes of which are reduced, by comparison with magnitudes that would develop

5 alternatively to the pulling process in a reference pulling process (process of record, POR), see figure 2, in each case with an identical progressive pulling time and identical progressive single-crystal rod length on a progressive reference single-crystal rod section in which a reference single-crystal rod is being pulled according to a reference process-typical reference target pulling speed profile. Specifically, the reduction (in the sense of attenuation) of the

10 maximum pendulum deflection based on the axis of rest of the crystal pendulum that occurs within the phase is made exclusively via controlled (continuous) setting of the target pulling speed. This effect of attenuation, by comparison with the POR, is shown in figure 2 for a period during the pulling process ZP1 versus the progressive single-crystal rod length.

Determination of the progression of the current pendulum deflection during the pulling process

15 ZP1:

In order to ascertain the progression of the current pendulum deflection, a pendulum movement determination device 130 is provided. A camera device 131 of the pendulum movement determination device 130 records at least one imaging region comprising at least one section of a circumferential edge UK between the progressive single-crystal rod section

20 and the melt continuously as a function of time. A portion of the circumferential edge UK is indicated as a dot in the schematic section diagram in figure 1. Also provided is a processing device 132 of the pendulum movement determination device 130, which, at least for the section of the circumferential edge, using means of computer-based image processing, determines the time-dependent location coordinates thereof and, on the basis of these

25 location coordinates, determines a time-dependent and crystal length-dependent progression (of the section) of the circumferential edge of the crystal rod section in the manner of pendulum oscillations of the crystal rod section in relation to the axis of rest of the crystal pendulum and about the center of pendulum rotation D, and, for each pendulum oscillation n, determines the assigned period duration T, zero axis intercept time t and maximum pendulum

30 deflection $\hat{A}$. Finally, the processing device 132 determines the progression of the current maximum pendulum deflection of the single-crystal rod section as a function of the current pulling time and the current single-crystal length.

The pendulum movement determination device 130 continuously transmits the results of the determination to an indicator device 210 for further use. In addition, the results of the determination are transmitted to a memory device 220 for further use. The indicator device and the memory device are part of a computer device 200 comprising a processor unit 201. A current result is additionally transmitted to the control device 120 and, when the currently determined result of the maximum pendulum deflection attains or exceeds or goes below a definable pendulum deflection trigger threshold value PAS, the control device 120 sets the target pulling speed v_s in a variable and controlled manner according to at least one switching step or following a definable switching criterion, as described hereinafter.

10 Description of the controlled setting of the target pulling speed v_s during the pulling process ZP1:

With reference to figure 2 and in particular figure 3, for the single-crystal rod to be produced on the crystal pulling device 100, the target pulling speed v_s is set continuously and variably in reaction when the current result of the maximum pendulum deflection attains or exceeds or goes below a definable pendulum deflection trigger threshold value PAS, which has a value of 1.5 mm in the present working example.

Figure 3 shows a detailed view of a section during the phase of pulling process ZP1 in which the active attenuation is switched on and off according to definable switching steps and following switching criteria I to IV, which will now be described: depending on the current size of the maximum pendulum deflection ascertained by comparison with the pendulum deflection trigger threshold value PAS, during the phase of the pulling process ZP1, the setting of the target pulling speed is made according to one of the following switching steps, or the setting is made following a definable switching criterion (by correspondingly actuating the pulling device 110 via the control device 120):

- 25 I) According to a first switching criterion, a first switching step is executed as follows: if the currently determined result for the maximum pendulum deflection $\hat{A}$ remains below the pendulum deflection trigger threshold value PAS, a current set first target pulling speed of the pulling device 110 is kept essentially constant.
- 30 II) According to a second switching criterion, a second switching step is executed as follows: as soon as the currently determined result for the maximum pendulum deflection $\hat{A}$ attains the pendulum deflection trigger threshold value PAS, there is

an essentially abrupt changeover from the first target pulling speed to a definable target pulling speed interval which is limited by a second upper and a second lower target pulling speed, where the second upper target pulling speed is raised by a magnitude Δ_{v2o} in relation to the first target pulling speed and the second lower target pulling speed is lowered by a magnitude Δ_{v2u} in relation to the first target pulling speed.

III) According to a third switching criterion, a third switching step is executed as follows: if the currently determined result for the maximum pendulum deflection $\hat{A}$ exceeds the pendulum deflection trigger threshold value PAS, there is a continuous changeover essentially at each zero axis intercept time t of a pendulum movement of the crystal rod section in relation to the axis of rest of the crystal pendulum essentially abruptly between the second upper target pulling speed and the second lower target pulling speed, where the second upper target pulling speed has in turn been raised by a magnitude Δ_{v2o} in relation to the first target pulling speed and the second lower target pulling speed has been reduced by a magnitude Δ_{v2u} in relation to the first target pulling speed.

IV) According to a fourth switching criterion, a fourth switching step is executed as follows: as soon as the currently determined result for the maximum pendulum deflection $\hat{A}$ goes below the pendulum deflection trigger threshold value PAS, there is an essentially abrupt changeover from the second upper target pulling speed or from the second lower target pulling speed (depending on the current state before the changeover) to the first target pulling speed.

The effect of the “active” attenuation of the pendulum deflection according to the switching criteria by comparison with the POR is apparent in figure 2. The progressions are shown as a function of the progressive single-crystal length. In the present working example, the first target pulling speed is at a value of 0.525 mm/min and the magnitude Δ_{v2o} and the magnitude Δ_{v2u} at a size of 0.04 mm/min. In addition, figures 2 and 3 also show the progression of the current actual pulling speed v_i [mm/min] established in the system in reaction to the defined target pulling speed. Figure 3 shows a detailed view of the progression from figure 2, which includes all four steps or switching criteria I to IV.

The crystal rod produced with reduced pendulum deflection is then removed from the crystal pulling device 100 and subjected to a continuation of the process for production of a wafer from semiconductor material, comprising the following steps:

- sawing the single-crystal rod into thin wafers,
- 5 • chemical and mechanical further treatment of the thin wafers of semiconductor material, where the further treatment comprises the further treatment step of edge rounding, lapping, cleaning, and polishing.

The method described is generally suitable for reduction of pendulum deflections of a mass unit suspended from a pulling device.

- 10 Additionally provided in the working example is a computer program comprising commands which, when the program is executed by a computer device 200 (comprising a processor), cause the latter, by means of the control device 120 of the crystal pulling device 100, to specifically actuate the pulling device 110 thereof for the production of the crystal rod with reduced pendulum deflections by the production method described. This computer program is
- 15 stored on a computer-readable medium 300.

Claims

1. A method of producing a single-crystal rod, especially of silicon, by means of a pulling device (110) of a crystal pulling device (100), where the crystal pulling device (100) defines a center of pendulum rotation D through which a defined axis of rest of the crystal pendulum runs essentially along a height axis,
 wherein, during at least one pulling process, via actuation of the pulling device (110) with a control device (120), an essentially gradually progressive single-crystal rod section with an associated essentially gradually progressive assigned single-crystal length is pulled from a melt according to a settable, variable target pulling speed of the pulling device (110) to give the single-crystal rod,

wherein,

- during at least one phase of the pulling process, such a controlled, variable setting of the target pulling speed is undertaken via controlled actuation of the pulling device (110) via the control device (120) in such a way that, after each change in the setting of the target pulling speed has been made, for the continuation of the pulling process, maximum pendulum deflections of the progressive single-crystal rod section based on the axis of rest of the crystal pendulum develop as a function of the progressive pulling time and/or progressive single-crystal length, the magnitudes of which and/or differential magnitudes of which from successive magnitudes are reduced at least in phases, especially by comparison with magnitudes and/or differential magnitudes of maximum reference pendulum deflections that would develop alternatively to the pulling process in a reference pulling process, in each case with an identical progressive pulling time and/or identical progressive single-crystal rod length on a progressive reference single-crystal rod section in which a reference single-crystal rod is being pulled according to a reference process-typical reference target pulling speed profile.

2. The method as claimed in claim 1, wherein the reduction, especially attenuation, of the maximum pendulum deflection based on the axis of rest of the crystal pendulum that occurs within the at least one phase is made exclusively via controlled, and especially continuous, setting of the target pulling speed,
 and/or

the variable setting of the target pulling speed is made in reaction to the current result for the maximum pendulum deflection attaining or going above or below a definable pendulum deflection trigger threshold value which is in the range of 0 mm to 100.0 mm, preferably in the range of 0.1 mm to 10.0 mm, further preferably in the range of 0.5 mm to 3.0 mm.

3. The method as claimed in claim 1 or 2, wherein

a camera device (131) of a pendulum movement determination device (130) records at least one imaging region comprising at least one section of a circumferential edge between the advancing single-crystal rod section and the melt continuously as a function of time, and

a processing device (132) of the pendulum movement determination device (130), at least for the section of the circumferential edge, using means of computer-based image processing, determines the time-dependent location coordinates thereof and, on the basis of these location coordinates, determines at least one time-dependent and/or crystal length-dependent progression of the section of the circumferential edge of the crystal rod section by way of pendulum oscillations of the crystal rod section in relation to the axis of rest of the crystal pendulum and about the center of pendulum rotation D, and for each pendulum oscillation n determines the assigned period duration T, zero axis intercept time t and the maximum pendulum deflection $\hat{A}$, and

the processing device (132) also ascertains at least the progression of the current maximum pendulum deflection of the single-crystal rod section as a function of the current pulling time and/or the current single-crystal length.

4. The method as claimed in claim 3, wherein,

by means of the pendulum movement determination device (130), in a continuous manner, the results of the determination are transmitted to an indicator device (210) for further use and/or the results of the determination are transmitted to a memory device (220) for further use, wherein the indicator device (210) and the memory device (220) are part of a computer device (200) comprising a processor unit (201), and the current result of the determination of maximum pendulum deflection is transmitted to the control device (120) and, if the current result for the maximum pendulum deflection attains or goes above or below a definable pendulum deflection trigger threshold value, the control device (120) sets the target pulling speed variably and in a

controlled manner, especially in accordance with at least one switching step and following at least one definable switching criterion.

5. The method as claimed in any of the preceding claims, wherein,
 - 5 at least during the phase of the pulling process, the pulling device (110), actuated via the control device (120), undertakes the setting of the target pulling speed as a function of the current result for the maximum pendulum deflection, especially ascertained by the method and by means of the pendulum movement determination device as claimed in claim 3 or 4, in accordance with at least one of the following
 - 10 switching steps and following a definable switching criterion:
 - i according to a first switching criterion, a first switching step is executed as follows: if the currently determined result for the maximum pendulum deflection $\hat{A}$ remains below a definable pendulum deflection trigger threshold value, a current set
 - 15 target pulling speed of the pulling device, which is especially a first or third target pulling speed, is kept essentially constant,
 - and/or
 - ii according to a second switching criterion, a second switching step is executed as follows: as soon as the currently determined result for the maximum pendulum
 - 20 deflection $\hat{A}$ attains a definable pendulum deflection trigger threshold value, there is an essentially abrupt changeover from a target pulling speed which is especially a first or third target pulling speed to a definable target pulling speed interval which is limited by a second upper and/or a second lower target pulling speed, where the second upper target pulling speed is raised by a magnitude Δ_{v2o} in relation to the target pulling speed and the second lower target pulling speed is lowered by a magnitude Δ_{v2u} in relation to the target pulling speed, where the target pulling speed is especially a first or third target pulling speed,
 - 25 and/or
 - iii according to a third switching criterion, a third switching step is executed as follows: if the currently determined result for the maximum pendulum deflection $\hat{A}$ exceeds a definable pendulum deflection trigger threshold value, there is a continuous changeover essentially at each zero axis intercept time t of a pendulum movement of the crystal rod section in relation to the axis of rest of the crystal pendulum essentially abruptly between a second upper target pulling speed and a second lower target
 - 30 pulling speed, where the second upper target pulling speed has been raised by a magnitude Δ_{v2o} in relation to a target pulling speed and the second lower target pulling
 - 35 pulling speed, where the second upper target pulling speed has been raised by a magnitude Δ_{v2o} in relation to a target pulling speed and the second lower target pulling

speed has been reduced by a magnitude Δ_{v2u} in relation to a target pulling speed,
where the target pulling speed is especially a first or third target pulling speed,

and/or

iv according to a fourth switching criterion, a fourth switching step is executed as
follows: as soon as the currently determined result for the maximum pendulum
deflection $\hat{A}$ goes below a definable pendulum deflection trigger threshold value,

there is an essentially abrupt changeover from a second upper target pulling
speed raised by a magnitude Δ_{v2o} in relation to a first or third target pulling
speed to the first or third target pulling speed,

or

an essentially abrupt changeover from a second lower target pulling speed
reduced by a magnitude Δ_{v2u} in relation to the first or third target pulling speed
to a first or third target pulling speed.

6. The method as claimed in any of the preceding claims, wherein
a definable pendulum deflection trigger threshold value is in the range from 0 mm to
100.0 mm, preferably in the range from 0.1 mm to 10.0 mm, further preferably in the
range from 0.5 mm to 3.0 mm,
and/or
a definable settable target pulling speed and/or a first target pulling speed and/or third
target pulling speed, especially according to at least one switching step and following a
definable switching criterion, is in the range from 0 mm/min to 10 mm/min.
7. The method as claimed in any of the preceding claims, wherein
a magnitude Δ_{v2o} which is a target pulling speed magnitude between a target pulling
speed which is especially a first or third target pulling speed and a second upper target
pulling speed is settable within the range from 0.0001 mm/min to 3 mm/min, preferably
from 0.001 mm/min to 0.1 mm/min,
and/or
a magnitude Δ_{v2u} which is a target pulling speed magnitude between a target pulling
speed which is especially a first or third target pulling speed and a second lower target
pulling speed is settable within the range from 0.0001 mm/min to 3 mm/min, preferably
from 0.001 mm/min to 0.1 mm/min.
8. The method as claimed in any of the preceding claims, wherein

the method is conducted on a crystal pulling device (100) with a pulling device of the cable pendulum device type,

or

the method is conducted on a crystal pulling device (100) with a pulling device of the conventional CZ pulling device type with a framework unit.

9. A crystal pulling device for production of a single-crystal rod with a pulling device (110), where the pulling device (110) is designed, at least during a pulling process, via actuation of the pulling device (110) with a control device (120), to pull an essentially gradually progressive single-crystal rod section with an associated essentially gradually progressive assigned single-crystal length from a melt according to a settable, variable target pulling speed of the pulling device to give the single-crystal rod,

where the crystal pulling device, preferably by means of the pulling device (110), defines a center of pendulum rotation D through which a defined axis of rest of the crystal pendulum runs essentially along a height axis,

wherein

the crystal pulling device (100), especially the control device (120) of the crystal pulling device (100), is designed, during at least one phase of the pulling process, to undertake such a controlled variable setting of the target pulling speed via controlled actuation of the pulling device via the control device (120) in such a way that, after each change in the setting of the target pulling speed has been made, for the continuation of the pulling process, maximum pendulum deflections of the progressive single-crystal rod section based on the axis of rest of the crystal pendulum develop as a function of the progressive pulling time and/or progressive single-crystal length, the magnitudes of which and/or differential magnitudes of which from successive magnitudes are each reduced at least in phases, especially by comparison with magnitudes and/or differential magnitudes of maximum reference pendulum deflections that would develop alternatively to the pulling process in a reference pulling process, in each case with an identical progressive pulling time and/or identical progressive single-crystal rod length on a progressive reference single-crystal rod section in which a reference single-crystal rod is being pulled according to a reference process-typical reference target pulling speed profile.
10. The crystal pulling device as claimed in claim 9, wherein the crystal pulling device (100) executes the method as claimed in any of claims 1 to 8.

11. The use of the crystal pulling device as claimed in claim 9 for reduction of pendulum deflections of a mass unit suspended from a pulling device (110).
- 5 12. A computer program comprising commands which, when the program is executed by a computer device (200) comprising a processor unit (201), cause the latter, by means of the control device (120) of the crystal pulling device (100) as claimed in claim 9 or 10, to specifically actuate the pulling device (110) thereof for the production of a crystal rod with reduced pendulum deflections by the production method as claimed in any of
10 claims 1 to 8.
13. A computer-readable medium on which the computer program as claimed in claim 12 is stored.
14. A process for producing a wafer of semiconductor material from a single-crystal rod
15 that has been produced with reduced pendulum deflection by a method of producing a single-crystal rod as claimed in any of claims 1 to 8, followed at least by the following steps proceeding from the end of the method of producing the single-crystal rod:
- sawing the single-crystal rod into thin wafers,
 - 20 • subjecting at least one of the thin wafers of semiconductor material to chemical and/or mechanical further processing, where the further processing includes at least one further treatment step from edge rounding, lapping, cleaning, polishing, depositing an oxide layer, epitaxial growth of a single-crystal layer, especially silicon layer, or an SiGe layer or a GaN layer.
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