

SINGLE CRYSTAL SILICON AND SILICON WAFER WITH CONTROLLABLE OXYGEN CONTENT, AND SINGLE CRYSTAL SILICON GROWTH METHOD AND SYSTEM

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims a priority of the Chinese patent application No. 202411201430.X filed on August 29, 2024, which is incorporated herein by reference in its entirety.

TECHNICAL FIELD

[0002] The present application relates to the field of silicon wafer manufacturing technology, and in particular, to single crystal silicon and a silicon wafer with a controllable oxygen content, a single crystal silicon growth method, and a single crystal silicon growth system.

BACKGROUND

[0003] In the field of semiconductor manufacturing, the fabrication of single crystal silicon is a basis for manufacturing a high-performance electronic element. A single crystal silicon growth technology, especially a Czochralski method for the single crystal silicon growth, is an important step for the semiconductor manufacturing.

[0004] Generally, a head of the single crystal silicon has a high oxygen content, and a tail thereof has a low oxygen content. A possible cause for this phenomenon lies in that, along with the growth of a crystal, a contact area between a quartz crucible and a silicon melt decreases gradually, and a thermal environment around a furnace body and the flow of the silicon melt change, so the oxygen content in the silicon melt changes. During the single crystal silicon growth, the oxygen content in the single crystal silicon may be affected by an excessive heating duration and the melt back caused by abnormalities in the crystal growth, so it is impossible to meet the customer

requirements and the product specification, and thereby the production capacity and the yield are adversely affected.

[0005] Based on the above, the present disclosure provides single crystal silicon and a silicon wafer with a controllable oxygen content, a single crystal silicon growth method, and a single crystal silicon growth system, so as to improve the relevant technology.

SUMMARY

[0006] An object of the present disclosure is to provide single crystal silicon and a silicon wafer with a controllable oxygen content, a single crystal silicon growth method, and a single crystal silicon growth system, so as to monitor an actual heating duration of a quartz crucible, adjust a control parameter set and a configuration parameter value of the control parameter set based on the actual heating duration, and control the distribution of oxygen in the single crystal silicon.

[0007] The object is achieved using the following technical solutions.

[0008] In a first aspect, the present disclosure provides a single crystal silicon growth method, including: obtaining an actual heating duration of a quartz crucible during the growth of single crystal silicon; determining a control parameter set and a configuration parameter value of the control parameter set based on a difference range in which a difference between the actual heating duration and a target heating duration lies, the control parameter set including a silicon rotation speed and/or a crucible rotation speed, and various control parameter sets corresponding to distinct difference ranges; and automatically configuring a corresponding control parameter based on the configuration parameter value of the control parameter set to allow an oxygen content deviation between an oxygen content of the single crystal silicon and a target oxygen content to be -10% to 10%.

[0009] In some embodiments of the present disclosure, the step of determining a control parameter set includes: in a case that the difference range in which the difference lies is a first difference range, taking the silicon rotation speed as a control

parameter item in the control parameter set; and in a case that the difference range in which the difference lies is a second difference range, taking the silicon rotation speed and the crucible rotation speed as control parameter items in the control parameter set. A minimum value of the second difference range is not smaller than a maximum value of the first difference range.

[0010] In some embodiments of the present disclosure, the step of determining a configuration parameter value of the control parameter set includes: with respect to each control parameter item, performing following steps: determining a correspondence between the configuration parameter value of the control parameter item and a target parameter value based on the difference range in which the difference lies. Various correspondences correspond to distinct difference ranges; and calculating the configuration parameter value of the control parameter based on the target parameter value of the control parameter item and the correspondence.

[0011] In some embodiments of the present disclosure, the correspondence is represented by a corresponding formula or a corresponding model.

[0012] In some embodiments of the present disclosure, the correspondence is represented by a corresponding formula, and one or more compensation coefficients in the corresponding formula are determined based on the difference range in which the difference lies.

[0013] In some embodiments of the present disclosure, the target parameter value of the control parameter is determined based on a length range in which a length of the single crystal silicon lies.

[0014] In some embodiments of the present disclosure, the single crystal silicon growth method further includes: dividing a growth process of the single crystal silicon into a plurality of growth stages based on a length range in which a length of the single crystal silicon lies; and at each growth stage, measuring the oxygen content of the single crystal silicon, and calculating the oxygen content deviation between the oxygen content of the single crystal silicon and the target oxygen content.

[0015] In a second aspect, the present disclosure provides in some embodiments a single crystal silicon growth system, including: a control module configured to implement the above-mentioned single crystal silicon growth method; a heating module configured to heat a quartz crucible containing a raw material; a silicon rotation module configured to rotate single crystal silicon; and a crucible rotation module configured to rotate the quartz crucible.

[0016] In some embodiments of the present disclosure, the control module includes: a data processing unit configured to obtain an actual heating duration of the quartz crucible during the growth of single crystal silicon, and determine a control parameter set and a configuration parameter value of the control parameter set based on a difference range in which a difference between the actual heating duration and a target heating duration lies, the control parameter set including a silicon rotation speed of the silicon rotation module and/or a crucible rotation speed of the crucible rotation module, and various control parameter sets corresponding to distinct difference ranges; and a system control unit configured to automatically configure a corresponding control parameter based on the configuration parameter value of the control parameter set to allow an oxygen content deviation between an oxygen content of the single crystal silicon and a target oxygen content to be -10% to 10%.

[0017] In some embodiments of the present disclosure, the data processing unit determines the control parameter set through: in a case that the difference range in which the difference lies is a first difference range, taking the silicon rotation speed as a control parameter item in the control parameter set; and in a case that the difference range in which the difference lies is a second difference range, taking the silicon rotation speed and the crucible rotation speed as control parameter items in the control parameter set. A minimum value of the second difference range is not smaller than a maximum value of the first difference range.

[0018] In a third aspect, the present disclosure further provides in some embodiments single crystal silicon with a controllable oxygen content. An oxygen content deviation between an oxygen content of the single crystal silicon and a target

oxygen content is -10% to 10%, and the single crystal silicon is fabricated using the above-mentioned single crystal silicon growth method or the above-mentioned single crystal silicon growth system.

[0019] In a fourth aspect, the present disclosure further provides in some embodiments a silicon wafer with a controllable oxygen content, the silicon wafer is obtained through machining single crystal silicon, an oxygen content deviation between an oxygen content of the single crystal silicon and a target oxygen content is -10% to 10%, and the single crystal silicon is fabricated using the above-mentioned single crystal silicon growth method or the above-mentioned single crystal silicon growth system.

[0020] The present disclosure provides the single crystal silicon and the silicon wafer with the controllable oxygen content, the single crystal silicon growth method and the system. The actual heating duration of the quartz crucible is monitored during the growth of the single crystal silicon, and the difference between the actual heating duration and the target heating duration is calculated. The corresponding control parameter set and the configuration parameter value of the control parameter set are determined based on the difference range in which the difference lies, and the control parameter set includes the silicon rotation speed and/or the crucible rotation speed. Various difference ranges correspond to distinct control parameter sets and various configuration parameter values thereof. The corresponding control parameter item is automatically adjusted based on the configuration parameter value of the control parameter item, so as to adjust a growth condition of the single crystal silicon, and ensure that the oxygen content deviation between the oxygen content of the single crystal silicon and the target oxygen content is -10% to 10%. In the embodiments of the present disclosure, the configuration parameter values are controlled using an automatic gain control logic during the growth of the crystal. Through monitoring the difference between the actual heating duration and the target heating duration, the control parameter items such as the silicon rotation speed and the crucible rotation speed are automatically adjusted in stages using a stepwise management mode, so as to

effectively control the distribution of oxygen in the single crystal silicon, ensure that the oxygen contents of the crystals fabricated using different heating durations are substantially the same, and ensure the product quality. In addition, through accurately controlling values of control parameter items, it is able to prevent the oxygen content of the single crystal silicon from being affected by an abnormality in the growth of the crystal and an excessive heating duration of the quartz crucible, reduce fluctuations and defects during the growth of the crystal, and improve the structural integrity and electrical performance of the crystal, thereby to improve the quality of the single crystal silicon. Through the automatic control, it is able to reduce the human interventions and uncertainty caused by manual operations, improve the production stability and consistency, reduce a time for adjustment and modification, and improve the production efficiency. Through real-time monitoring and dynamic adjustment, it is able to flexibly respond to any changes in single-factor variables and multi-factor variables, provide more optimization selections, and adapt to different changes in the production demands and the production conditions.

BRIEF DESCRIPTION OF THE DRAWINGS

[0021] The present disclosure will be further described hereinafter in conjunction with the drawings and the specific embodiments.

[0022] Fig. 1 is a schematic view showing a single crystal silicon growth system according to an embodiment of the present disclosure;

[0023] Fig. 2 is a flow chart of a single crystal silicon growth method according to an embodiment of the present disclosure; and

[0024] Fig. 3 is another flow chart of the single crystal silicon growth method according to an embodiment of the present disclosure.

Reference Sign List

- | | |
|---|--------------------------|
| 1 | heating module |
| 2 | crucible rotation module |
| 3 | data processing unit |

- 4 system control unit
- 5 silicon rotation module

DETAILED DESCRIPTION

[0025] The technical solution in the embodiments of the present disclosure will be described hereinafter in a clear and complete manner in conjunction with the drawings. Obviously, the following embodiments merely relate to a part of, rather than all of, the embodiments of the present disclosure, and based on these embodiments, a person skilled in the art may, without any creative effort, obtain the other embodiments, which also fall within the scope of the present disclosure.

[0026] In the embodiments of the present disclosure, it should be appreciated that, such words as “first” and “second” are merely used to differentiate different components rather than to implicitly or explicitly indicate any relative importance or implicitly indicate the quantity of the indicated technical features. Hence, the features defined with “first” and “second” implicitly or explicitly include one or more features. In the embodiments of the present disclosure, such a phrase as “a plurality of” means that there are at least two or more components, unless otherwise specified.

[0027] A single crystal silicon growth process includes, for example, stacking, melting, dipping, necking, shoulder, over shoulder, body and tail process. Generally, oxygen in single crystal silicon mainly derives from a quartz crucible. The quartz crucible (SiO_2) is usually used for the growth of the single crystal silicon. The quartz crucible reacts with a silicon melt at a high temperature to generate a SiO gas, and the SiO gas is further dissolved in the silicon melt. Along with the growth of a crystal, a contact area between the quartz crucible and the silicon melt decreases gradually, and a thermal environment around a furnace body and the flow of the silicon melt change, so an oxygen content in the silicon melt changes, a head of the single crystal silicon has a high oxygen content, and a tail thereof has a low oxygen content. In addition, due to melt-back caused by repeated abnormality in the crystal growth and an excessive heating duration, the oxygen content is decreased significantly in an axial direction after

the growth of the crystal, so it is impossible to meet the specific requirements and the product specification, and thereby the production capacity and the yield are adversely affected.

[0028] To be specific, during the crystal growth, along with the progress of a lifting process, the contact area between the silicon melt and the quartz crucible gradually decreases, so generally such a phenomenon where the head of the single crystal silicon has a high oxygen content and the tail thereof has a low oxygen content occurs. Further, the oxygen content of the single crystal silicon is also affected by the melt back caused by the abnormality in the crystal growth and the excessive heating duration.

[0029] At first, a melt back operation is performed in a case of the abnormality in the crystal growth to ensure the quality of the crystal and reduce the loss, but it may lead to the re-distribution of the oxygen content in the crystal. A segregation coefficient (k) of oxygen in silicon is smaller than 1, so during the crystal growth, oxygen is diffused in a liquid phase more rapidly than in a solid phase, and it easily stays in the melt rather than to enter the crystal. Due to the melt back operation, after oxygen is diffused from the solid phase into the liquid phase again, the oxygen content is re-distributed in the melt. In a next growth process, due to the effect of the segregation coefficient, oxygen tends to stay in the melt, so the oxygen content in a newly-grown crystal is further reduced, and thereby the oxygen content in the newly-grown crystal is low.

[0030] Next, solubility and a diffusion coefficient of oxygen in the silicon melt are high, so oxygen may be dissolved in a high-temperature silicon melt in a better manner to rapidly achieve uniform distribution in the silicon melt. In other words, during the melt back operation, oxygen entering the melt again is rapidly, uniformly distributed in the melt. Due to the diffusion, oxygen is re-distributed in the entire melt, so the oxygen content in the melt increases within a short time period. In addition, due to the uniform distribution, the oxygen content is reduced relatively.

[0031] In addition, oxygen from the quartz crucible is present in the form of SiO gas at a high temperature, 98% of oxygen is taken away by an argon gas flow, and merely 2% of oxygen is further dissolved in the silicon melt in the form of SiO gas and thereby enters the crystal. Furthermore, the distribution and an overall level of the oxygen content are affected by the excessive heating duration. The excessive heating duration may lead to excessive volatilization of oxygen, and especially oxygen escapes from a surface of the crystal at a high-temperature region, so the entire oxygen content is reduced. During the regrowth of the crystal, oxygen is also taken away by the argon gas flow, so oxygen entering the melt is further reduced, and the oxygen content in the regrown crystal is further reduced. Moreover, oxygen is re-distributed in the crystal at a long-term high temperature, so the oxygen content in part of regions is further reduced.

[0032] The present disclosure will be described hereinafter in details.

[0033] In a conventional single crystal silicon growth method, in a case that an actual heating duration exceeds a target heating duration, oxygen is distributed in a crystal non-uniformly, and especially an oxygen content in an axial direction is relatively low, so it is difficult to meet the customer's requirement and the product specification. In the related art, it is difficult to accurately adjust relevant control parameters, so the product quality and the production efficiency are degraded. Hence, there is an urgent need to provide an improved single crystal silicon growth method, so as to automatically adjust the control parameters, optimize the distribution of oxygen, and ensure the quality of the single crystal silicon.

[0034] Referring to Figs. 1 to 3, Fig. 1 is a schematic view showing a single crystal silicon growth system according to an embodiment of the present disclosure, Fig. 2 is a flow chart of a single crystal silicon growth method according to an embodiment of the present disclosure, and Fig. 3 is another flow chart of the single crystal silicon growth method according to an embodiment of the present disclosure.

[0035] In order to improve the related art, as shown in Fig. 2, the present disclosure provides in some embodiments a single crystal silicon growth method, which includes Steps S101 to S103.

[0036] Step S101: obtaining an actual heating duration of a quartz crucible during the growth of single crystal silicon.

[0037] S102: determining a control parameter set and a configuration parameter value of the control parameter set based on a difference range in which a difference between the actual heating duration and a target heating duration lies. The control parameter set includes a silicon rotation speed and/or a crucible rotation speed, and various control parameter sets corresponding to distinct difference ranges are different.

[0038] S103: automatically configuring a corresponding control parameter based on the configuration parameter value of the control parameter set to allow an oxygen content deviation between an oxygen content of the single crystal silicon and a target oxygen content to be -10% to 10%.

[0039] For example, in a case that the oxygen content deviation between the oxygen content of the single crystal silicon and the target oxygen content is -10% to 10%, it means that a ratio of a difference (i.e., the oxygen content deviation) between the oxygen content of the single crystal silicon and the target oxygen content to the target oxygen content is within a range of -10% to 10%.

[0040] In some embodiments of the present disclosure, the above-mentioned single crystal silicon growth method is adapted to a control module of a single crystal silicon growth system, and the single crystal silicon growth system further includes a heating module, a silicon rotation module and a crucible rotation module. The heating module is configured to heat the quartz crucible containing a raw material, the silicon rotation module is configured to rotate the single crystal silicon, and the crucible rotation module is configured to rotate the quartz crucible.

[0041] In some embodiments of the present disclosure, the control parameter set further includes power of a heater.

[0042] The actual heating duration of the quartz crucible refers to an actual operating time of the heating module during the growth of the single crystal silicon, i.e., an accumulated duration of the heating module for heating the quartz crucible. For example, the target heating duration is a predetermined heating duration to ensure that

the oxygen content of the crystal meets the requirement. For example, the target heating duration is a minimum heating duration within which the oxygen content of the quartz crucible is not reduced obviously after the continuous operation. The target heating duration is obtained through one or more experiments, or predicted by a trained prediction model. For example, the control parameter set includes one or more control parameter items for adjusting the single crystal silicon growth, e.g., the silicon rotation speed and/or the crucible rotation speed. Different combinations of the control parameters are used to optimize the growth condition of the crystal. The silicon rotation speed refers to a rotation speed of the crystal (i.e., the single crystal silicon) during the single crystal silicon growth. The crucible rotation speed refers to a rotation speed of the quartz crucible during the single crystal silicon growth.

[0043] The silicon rotation speed and/or the crucible rotation speed are adjusted to optimize the distribution of the oxygen content in the single crystal silicon. Through adjusting the silicon rotation speed and/or the crucible rotation speed, it is able to change a shape of a crystal-melt interface, thereby to affect the distribution and the transmission of oxygen at the interface. An appropriate combination of the rotation speeds is used to maintain the stability of the interface, and provide the uniform oxygen content. Different combinations of the rotation speeds may change a convection mode in the melt. Appropriate convection is used to provide the uniform oxygen content, and prevent a local oxygen content from being too low. Due to the reaction of the quartz crucible with the silicon melt at a high temperature, oxygen enters the single crystal silicon, so through adjusting the control parameters such as the silicon rotation speed and the crucible rotation speed, it is able to effectively control a speed and an amount of oxygen entering the single crystal silicon, thereby to ensure that the oxygen content deviation between the oxygen content of the single crystal silicon and the target oxygen content is -10% to 10%.

[0044] During the single crystal silicon growth, a SiO gas is generated due to the reaction of the quartz crucible with the silicon melt at a high temperature, and the SiO gas is partially dissolved in the silicon melt and gradually enters the crystal during the

crystal growth. In the above-mentioned method, the actual heating duration of the quartz crucible is monitored in real time and compared with the target heating duration, and then the corresponding control parameter set (including the silicon rotation speed and/or the crucible rotation speed) is determined based on the difference between the actual heating duration and the target heating duration, so as to automatically adjust the control parameter during the growth. To be specific, different difference ranges correspond to different control parameter sets. The silicon rotation speed and the crucible rotation speed are accurately adjusted based on the difference between the actual heating duration and the target heating duration, so as to control the dissolution and diffusion of the SiO gas in the silicon melt. Along with the progress of the crystal growth, a contact area between the quartz crucible and the silicon melt gradually decreases, and a thermal environment and the flow of the silicon melt also change, so a fluctuation in the oxygen content is affected by these factors. Through adjusting the control parameters, it is able to reduce the influence caused by the fluctuation, and ensure that the oxygen content of the single crystal silicon tends to be uniform. In a case that there is an abnormality during the crystal growth or the melt back operation needs to be performed, in the above-mentioned method, the relevant control parameters are adjusted accurately to re-allocate the oxygen content in the silicon melt, so as to prevent the abnormal fluctuation in the oxygen content due to the melt back or long-term heating. A diffusion speed of oxygen in a liquid phase is rapid, and through adjusting the crucible rotation speed and the silicon rotation speed, it is able to accelerate or decelerate a distribution rate of oxygen, thereby to control the oxygen content. The system automatically configures the corresponding control parameters based on the configuration parameter value of the control parameter set, so that the oxygen content of the single crystal silicon is always maintained within -10% to 10% of the target oxygen content. Through the automatic control, it is able to not only reduce an error caused by human interventions, but also achieve the optimization based on a real-time growth condition, thereby to improve the production efficiency and the product quality.

[0045] In the above-mentioned method, through monitoring and adjusting the control parameters in real time, it is able to significantly reduce the fluctuation in the oxygen content of the single crystal silicon, and ensure that the oxygen content is within a predetermined target range. In a case that there is a large difference between the oxygen contents at different stages of the crystal growth, especially the oxygen contents of the head and the tail, it is able to achieve the time-based automatic gain control, balance the distribution of the oxygen content through automatically adjusting the relevant rotation speeds, and prevent the occurrence of the inconsistent performance of the crystal due to the non-uniform oxygen content. In a case that there is an abnormality during the crystal growth or the melt back operation needs to be performed, through the above-mentioned method, the re-distribution of the oxygen content is accurately controlled, so as to prevent the crystal quality from being adversely affected due to a too low or high oxygen content, and reduce the defective products and the production loss. Through the above-mentioned method, it is able to reduce the manual operations, improve the production stability and efficiency to adapt to different product requirements in a better manner, significantly improve the yield of the single crystal silicon, reduce the unqualified products during the production, improve the product consistency, and finally improve the overall production capacity.

[0046] In the embodiments of the present disclosure, the target oxygen content is not particularly defined, and it may be selected according to the practical need. For example, the target oxygen content is 8.5 ppma, 10 ppma, 11 ppma, 11.5 ppma, 12 ppma, or 14.5 ppma, where ppma represents Parts Per Million by Atomic, i.e., the quantity of atoms of a particular element in one million of atoms. For example, in a case that the oxygen content of the single crystal silicon is 10 ppma, it means that there are 10 oxygen atoms in one million of atoms.

[0047] In some embodiments of the present disclosure, the difference range of the difference is divided into a plurality of difference ranges in a stepwise management mode. For example, the difference range in which the difference lies is divided into $(-\infty, 0h]$, $(0h, 60h]$ and $(60h, 140h]$, or the difference range in which the difference lies

is divided into $(-\infty, 0h]$, $(0h, 30h]$, $(30h, 60h]$, $(60h, 100h]$ and $(100h, 140h]$, where h represents hour, and ∞ represents infinity great.

[0048] In the above-mentioned embodiments of the present disclosure, during the single crystal silicon growth, the actual heating duration is obtained in real time, and the difference between the actual heating duration and the target heating duration is calculated. The corresponding control parameter set and the configuration parameter value of the control parameter set, including the silicon rotation speed and/or the crucible rotation speed, are determined based on the difference range in which the difference lies, and the corresponding control parameter is automatically adjusted based on the configuration parameter values of the control parameter items, so as to adjust the growth condition of the single crystal silicon, and ensure that the oxygen content deviation between the oxygen content of the single crystal silicon and the target oxygen content is -10% to 10%.

[0049] In the above-mentioned embodiments of the present disclosure, the control parameters are controlled using an automatic gain control logic during the growth of the crystal. Through monitoring the difference between the actual heating duration and the target heating duration, the control parameters such as the silicon rotation speed and the crucible rotation speed are automatically adjusted in stages using a stepwise management mode, so as to effectively control the distribution of oxygen in the single crystal silicon, ensure that the oxygen contents of the crystals fabricated using different heating durations are substantially the same, and ensure the product quality. In addition, through accurately controlling the control parameters, it is able to prevent the oxygen content of the single crystal silicon from being affected by an abnormality in the growth of the crystal and an excessive heating duration of the quartz crucible, reduce fluctuations and defects during the growth of the crystal, and improve the structural integrity and electrical performance of the crystal, thereby to improve the quality of the single crystal silicon. Through the automatic control, it is able to reduce the human interventions and uncertainty caused by manual operations, improve the production stability and consistency, reduce a time for adjustment and modification,

and improve the production efficiency. Through real-time monitoring and dynamic adjustment, it is able to flexibly respond to any changes in single-factor variables and multi-factor variables, provide more optimization selections, and adapt to different changes in the production demands and the production conditions.

[0050] In order to automatically adjust the control parameter set based on t between the actual heating duration and the target heating duration and optimize the distribution of the oxygen content, in some embodiments of the present disclosure, the step of determining a control parameter set includes: in a case that the difference range in which the difference lies is a first difference range, taking the crucible rotation speed as a control parameter items in the control parameter set; and in a case that the difference range in which the difference lies is a second difference range, taking the silicon rotation speed and the crucible rotation speed as control parameter items in the control parameter set. A minimum value of the second difference range is not smaller than a maximum value of the first difference range.

[0051] In some embodiments of the present disclosure, the method further includes: in a case that the difference range in which the difference lies is a third difference range, automatically configuring the silicon rotation speed based on a target parameter value of the silicon rotation speed, and automatically configuring the crucible rotation speed based on a target parameter value of the crucible rotation speed.

[0052] For example, the first difference range includes (0h, 30h] and (30h, 60h], i.e., the first difference range is divided into these two difference ranges. The second difference range includes (60h, 100h] and (100h, 140h], i.e., the second difference range is divided into these two difference ranges. The third difference range includes $(-\infty, 0h]$, i.e., in a case that the actual heating duration is smaller than or equal to the target heating duration, the target parameter values of the silicon rotation speed and the crucible rotation speed are directly used to automatically configure the corresponding control parameters (i.e., the silicon rotation speed and the crucible rotation speed), so a control mode is simple and effective.

[0053] For example, in a case that the difference range in which the difference lies is (0h, 30h] or (30h, 60h], the crucible rotation speed C/R is taken as the control parameter item in the control parameter set. In a case that the difference range in which the difference lies is (60h, 100h] or (100h, 140h], the crucible rotation speed C/R and the silicon rotation speed S/R are taken as the control parameter items in the control parameter set.

[0054] Different difference ranges correspond to different control policies, so as to always maintain the stable oxygen content in the crystal. In the above-mentioned embodiments of the present disclosure, in a case that the difference ΔT is within the first difference range (e.g., (0h, 30h] or (30h, 60h]), merely the crucible rotation speed (C/R) is taken as the control parameter items; and in a case that the difference ΔT is within the second difference range (e.g., (60h, 100h] or (100h, 140h]), both the crucible rotation speed (C/R) and the silicon rotation speed (S/R) are taken as the control parameter items. Through the stepwise management mode, the control parameter set is automatically configured, so as to accurately control the oxygen content, and ensure that the oxygen content deviation between the oxygen content of the single crystal silicon and the target oxygen content is -10% to 10%. Through the above-mentioned single crystal silicon growth method, the silicon rotation speed and the crucible rotation speed are automatically adjusted in stages, so as to control the distribution of oxygen in the single crystal silicon more accurately, and ensure the more uniform oxygen content. In the method, the control parameter is flexibly adjusted based on different difference ranges, so as to reduce the fluctuation in the oxygen content during the crystal growth, and improve the quality of the single crystal silicon. Through an automatic gain control mode, it is able to reduce the human interventions, optimize a control policy, improve the production efficiency, and reduce a computational burden and control complexity, thereby to meet the customer's requirement on the product specification and quality in a better manner.

[0055] In a case that the difference between the actual heating duration and the target heating duration is small, merely the crucible rotation speed C/R is adjusted. In a

case that the difference is large, both the crucible rotation speed C/R and the silicon rotation speed S/R are adjusted simultaneously. Through the stage-based control policy, it is able to perform a control process more flexibly. In a case that the difference is small, merely one control parameter (the crucible rotation speed) is adjusted, and the control mode is relatively simple and easily implemented. In a case that the difference is large, a plurality of control parameters (the silicon rotation speed and the crucible rotation speed) needs to be taken into consideration. Along with an increase in the difference, the control policy is changed from single-parameter adjustment to multi-parameter adjustment, and this stepwise adjustment mode is adapted to different differences between the heating durations in a better manner, so as to ensure the control accuracy. Hence, in a case that the difference is small, merely the crucible rotation speed is adjusted, so as to reduce an adjustment frequency and adjustment complexity of the system, reduce the control cost, and reduce unnecessary complex operations. In a case that merely one control parameter is adjusted, the computational burden is small and a system response is rapid, so it is able to rapidly adapt to the difference between the heating durations within a small range, and improve the entire control efficiency. In a case that the difference is large, the silicon rotation speed and the crucible rotation speed are adjusted simultaneously, so as to optimize the distribution of the oxygen content, and ensure the control accuracy. Through the stage-based control policy, it is able to improve the operating efficiency of the system while ensuring a control effect. The control policy is dynamically adjusted based on the difference range in which the difference lies between the actual heating duration and the target heating duration, so as to respond to different production situations flexibly, and ensure that the high-quality single crystal silicon is obtained under various conditions. Through the control method, it is able to not only control the oxygen content, but also reduce the system complexity and the operating cost while improving the production efficiency, thereby to enable the entire single crystal silicon growth process to be more economical and efficient.

[0056] For a conventional single crystal silicon growth method, in a case of controlling the oxygen content, there is no elaborate control policy with respect to

different difference ranges. In addition, the computational burden is large, and the control efficiency is low, so it is not adapted to a complex growth process. In some embodiments of the present disclosure, the determining the configuration parameter value of the control parameter set includes: with respect to each control parameter, performing following steps: determining a correspondence between the configuration parameter value and a target parameter value of the control parameter based on the difference range in which the difference lies, various correspondences corresponding to distinct difference ranges; and calculating the configuration parameter value of the control parameter based on the target parameter value of the control parameter and the correspondence.

[0057] In some embodiments of the present disclosure, the correspondence is represented by a corresponding formula or a corresponding model.

[0058] The configuration parameter values refer to specific values for configuring the control parameters obtained through calculation or calibration, and these values are used to achieve a desired control object. The target parameter value refers to a reference value for the control parameter, so as to ensure that the single crystal silicon growth process meets the practical need. The correspondence refers to a mathematical relationship between the configuration parameter value and the target reference value of the control parameter, e.g., the correspondence is represented in the form of a corresponding formula or a corresponding model. Considering the influence caused by the difference, the corresponding formula or corresponding model is determined based on the difference range in which the difference lies. In the embodiments of the present disclosure, the corresponding model is not particularly defined, e.g., it may be a deep learning model.

[0059] In order to determine the configuration parameter value of the control parameter, the configuration parameter value is calculated based on the correspondence between the configuration parameter value and the target parameter value, i.e., the corresponding formula or the corresponding model, and the target parameter value, so

as to ensure that the configuration parameter value of the control parameter meets the requirement on the growth process.

[0060] In some embodiments of the present disclosure, the correspondence is represented by a corresponding formula, and one or more compensation coefficients in the corresponding formula are determined based on the difference range in which the difference lies.

[0061] For example, the corresponding formula is a mathematical expression for calculating the configuration parameter value of the control parameter during the single crystal silicon growth. The compensation coefficients in the corresponding formula are used to flexibly adjust the parameter value based on an actual difference. The compensation coefficients are coefficients in the corresponding formula, and they are used to adjust the control parameter to adapt to the difference between the actual heating duration and the target heating duration. The compensation coefficient varies with the difference range in which the difference lies, so as to perform the control in a more accurate manner.

[0062] In the embodiments of the present disclosure, the target parameter value of each control parameter is not particularly defined, and an appropriate value may be selected based on a length range in which a length of the single crystal silicon lies, and device performance and the product requirements during the actual production process. For example, the target parameter value of the crucible rotation speed (i.e., a target crucible rotation C/R Target) is within a range of 0.2 Revolutions Per Minute (RPM) to 1.1 RPM, and the target parameter value of the silicon rotation speed (i.e., a target silicon rotation speed S/R Target) is within a range of 6 RPM to 16 RPM. For furnaces having different product specification and made of different thermal insulation materials, the target parameter values of the silicon rotation speed and the crucible rotation speed are different.

[0063] An automatic configuration process of the control parameters will be described illustratively hereinafter. As shown in Fig. 3, it is presumed that a single crystal silicon growth system is used for the continuous production during the single

crystal silicon growth. After obtaining the single crystal silicon (e.g., an ingot) in a previous growth process, an oxygen content of the single crystal silicon is measured and recorded. In a current single crystal silicon growth process, the actual heating duration (i.e., T_x) of the quartz crucible is monitored and compared with the target heating duration (i.e., T_0). The target heating duration T_0 is a minimum heating duration within which the oxygen content of the quartz crucible is not reduced obviously. It is presumed that the difference range in which the difference lies ΔT (e.g., 10h) between the actual heating duration T_x and the target heating duration T_0 is (0h, 30h] and the crucible rotation speed C/R is taken as the control parameter in the control parameter set, and at this time, the control parameter set includes one control parameter, where $\Delta T = T_x - T_0$. Next, the correspondence (e.g., the corresponding formula) between the configuration parameter value of the crucible rotation speed C/R (i.e., a set crucible rotation speed C/R_{set}) and the target parameter value (i.e., a target crucible rotation speed C/R_{target}) is obtained based on the difference range (i.e., (0h, 30h]), and it is presumed that the corresponding formula is $C/R_{set} = C/R_{target} \times (1 + c_1)$, where c_1 represents a compensation coefficient for the crucible rotation speed corresponding to the difference range (0h, 30h]. Presumed that c_1 is 15%, the corresponding formula between the configuration parameter value and the target parameter value of the crucible rotation speed is $C/R_{set} = C/R_{target} \times (1 + 15\%)$. Then, the configuration parameter value of the crucible rotation speed is calculated based on the target parameter value (e.g., 0.94 RPM) of the crucible rotation speed and the corresponding formula through $C/R_{set} = 0.94 \text{ RPM} \times (1 + 15\%) = 1.08 \text{ RPM}$.

[0064] Similarly, it is presumed that the difference range in which the difference lies ΔT (e.g., 50h) between the actual heating duration T_x and the target heating duration T_0 is (30h, 60h] and the crucible rotation speed C/R is taken as the control parameter item in the control parameter set, and at this time, the control parameter set includes one control parameter item. Next, the correspondence (e.g., the corresponding formula) between the configuration parameter value of the crucible rotation speed C/R (i.e., a set crucible rotation speed C/R_{set}) and the target parameter value (i.e., a target

crucible rotation speed C/R_{target}) is obtained based on the difference range (i.e., (30h, 60h]), and it is presumed that the corresponding formula is $C/R_{\text{set}}=C/R_{\text{target}}\times(1+c_2)$, where c_2 represents a compensation coefficient for the crucible rotation speed corresponding to the difference range (30h, 60h]. Presumed that c_2 is 25%, the corresponding formula between the configuration parameter value and the target parameter value of the crucible rotation speed is $C/R_{\text{set}}=C/R_{\text{target}}\times(1+25\%)$. Then, the configuration parameter value of the crucible rotation speed is calculated based on the target parameter value (e.g., 0.94 RPM) of the crucible rotation speed and the corresponding formula through $C/R_{\text{set}}=0.94 \text{ RPM}\times(1+25\%)=1.18 \text{ RPM}$.

[0065] It is presumed that the difference range in which the difference lies ΔT (e.g., 80h) between the actual heating duration T_x and the target heating duration T_0 is (60h, 100h] and the crucible rotation speed C/R and the silicon rotation speed S/R are taken as the control parameters in the control parameter set, and at this time, the control parameter set includes two control parameters. Next, the correspondence (e.g., the corresponding formula) between the configuration parameter value of the crucible rotation speed C/R (i.e., a set crucible rotation speed C/R_{set}) and the target parameter value (i.e., a target crucible rotation speed C/R_{target}) is obtained based on the difference range (i.e., (60h, 100h]), and it is presumed that the corresponding formula is $C/R_{\text{set}}=C/R_{\text{target}}\times(1+c_3)$, where c_3 represents a compensation coefficient for the crucible rotation speed corresponding to the difference range (60h, 100h]. Presumed that c_2 is 30%, the corresponding formula between the configuration parameter value and the target parameter value of the crucible rotation speed is $C/R_{\text{set}}=C/R_{\text{target}}\times(1+30\%)$. Then, the configuration parameter value of the crucible rotation speed is calculated based on the target parameter value (e.g., 0.94 RPM) of the crucible rotation speed and the corresponding formula through $C/R_{\text{set}}=0.94 \text{ RPM}\times(1+30\%)=1.22 \text{ RPM}$. In addition, the correspondence (e.g., the corresponding formula) between the configuration parameter value of the silicon rotation speed S/R (i.e., a set silicon rotation speed S/R_{set}) and the target parameter value (i.e., a target silicon rotation speed S/R_{target}) is obtained based on the difference range (i.e., (60h, 100h]), and it is presumed that the

corresponding formula is $S/R_{\text{set}}=S/R_{\text{target}}\times(1-s_1)$, where s_1 represents a compensation coefficient for the silicon rotation speed corresponding to the difference range (60h, 100h]. Presumed that s_1 is 15%, the corresponding formula between the configuration parameter value and the target parameter value of the silicon rotation speed is $S/R_{\text{set}}=S/R_{\text{target}}\times(1-15\%)$. Then, the configuration parameter value of the silicon rotation speed is calculated based on the target parameter value (e.g., 16 RPM) of the silicon rotation speed and the corresponding formula through $S/R_{\text{set}}=16 \text{ RPM}\times(1-15\%)=13.6 \text{ RPM}$.

[0066] It is presumed that the difference range in which the difference lies ΔT (e.g., 120h) between the actual heating duration T_x and the target heating duration T_0 is (100h, 140h] and the crucible rotation speed C/R and the silicon rotation speed S/R are taken as the control parameters in the control parameter set, and at this time, the control parameter set includes two control parameters. Next, the correspondence (e.g., the corresponding formula) between the configuration parameter value of the crucible rotation speed C/R (i.e., a set crucible rotation speed C/R_{set}) and the target parameter value (i.e., a target crucible rotation speed C/R_{target}) is obtained based on the difference range (i.e., (100h, 140h]), and it is presumed that the corresponding formula is $C/R_{\text{set}}=C/R_{\text{target}}\times(1+c_4)$, where c_4 represents a compensation coefficient for the crucible rotation speed corresponding to the difference range (100h, 140h]. Presumed that c_4 is 35%, the corresponding formula between the configuration parameter value and the target parameter value of the crucible rotation speed is $C/R_{\text{set}}=C/R_{\text{target}}\times(1+35\%)$. Then, the configuration parameter value of the crucible rotation speed is calculated based on the target parameter value (e.g., 0.94 RPM) of the crucible rotation speed and the corresponding formula through $C/R_{\text{set}}=0.94 \text{ RPM}\times(1+35\%)=1.27 \text{ RPM}$. In addition, the correspondence (e.g., the corresponding formula) between the configuration parameter value of the silicon rotation speed S/R (i.e., a set silicon rotation speed S/R_{set}) and the target parameter value (i.e., a target silicon rotation speed S/R_{target}) is obtained based on the difference range (i.e., (100h, 140h]), and it is presumed that the corresponding formula is $S/R_{\text{set}}=S/R_{\text{target}}\times(1-s_2)$, where s_2 represents a compensation

coefficient for the silicon rotation speed corresponding to the difference range (100h, 140h]. Presumed that s_1 is 15%, the corresponding formula between the configuration parameter value and the target parameter value of the silicon rotation speed is $S/R_{\text{set}} = S/R_{\text{target}} \times (1 - 15\%)$. Then, the configuration parameter value of the silicon rotation speed is calculated based on the target parameter value (e.g., 16 RPM) of the silicon rotation speed and the corresponding formula through $S/R_{\text{set}} = 16 \text{ RPM} \times (1 - 15\%) = 13.6 \text{ RPM}$.

[0067] As mentioned hereinabove, in a case that ΔT is not greater than 60h, the crucible rotation speed C/R is adjusted to improve the oxygen content. This is because, within a short heating duration, it is mainly necessary to control the uniform distribution of oxygen in the crystal, so as to prevent a too low local oxygen concentration. All of c_1 to c_4 are greater than 0, and it means that the crucible rotation speed increases. Through increasing the crucible rotation speed, it is able to increase the convection of the melt, and facilitate the uniform distribution of oxygen. An appropriate crucible rotation speed is used to maintain a stable crystal-melt interface, and facilitate the uniform absorption of oxygen.

[0068] In a case that ΔT is greater than 60h and smaller than or equal to 140h, in addition to the crucible rotation speed C/R , the silicon rotation speed S/R is further optimized. This is because, within a long heating duration, oxygen may escape and be re-distributed more obviously, and the oxygen content needs to be improved through control. At this time, on one hand, the silicon rotation speed is adjusted to facilitate the uniform distribution of oxygen, and on the other hand, the crucible rotation speed is increased to increase the convection of the melt to further facilitate the uniform distribution and absorption of oxygen. Through adjusting both the silicon rotation speed and the crucible rotation speed, it is able to control the escape and re-distribution of oxygen more effectively, thereby to ensure the uniform distribution of the oxygen content in the axial direction.

[0069] In some embodiments of the present disclosure, the target parameter value of the control parameter is determined based on a length range in which a length of the single crystal silicon lies.

[0070] In other words, a growth process of the single crystal silicon is divided into a plurality of growth stages based on the length range in which the length of the single crystal silicon lies, different length ranges correspond to different growth stages, and different growth stages correspond to different target parameter values. It is presumed that the growth process of the single crystal silicon includes n growth stages, where n is a positive integer. In Fig. 3, an n^{th} body growth corresponds to an n^{th} growth stage.

[0071] In some embodiments of the present disclosure, the method further includes: dividing a growth process of the single crystal silicon into a plurality of growth stages based on a length range in which a length of the single crystal silicon lies; and at each growth stage, measuring the oxygen content of the single crystal silicon, and calculating the oxygen content deviation between the oxygen content of the single crystal silicon and the target oxygen content.

[0072] For example, a correspondence between the length range in which the length of the single crystal silicon lies and the target parameter value of the control parameter is stored in the form of a data table. In actual use, the target parameter value of the control parameter corresponding to the length range is determined through looking up the target parameter value in the data table. For example, in a case that the length range in which the length of the single crystal silicon lies is 0 mm to 300 mm, the target parameter value C/R_{target} of the crucible rotation speed is 0.94 RPM, and the target parameter value S/R_{target} of the silicon rotation speed is 16 RPM. In a case that the length range in which the length of the single crystal silicon lies is 300 mm to 600 mm, the target parameter value C/R_{target} of the crucible rotation speed is 0.58 RPM, and the target parameter value S/R_{target} of the silicon rotation speed is 10 RPM. In a case that the length range in which the length of the single crystal silicon lies is 600 mm to 900 mm, the target parameter value C/R_{target} of the crucible rotation speed is 0.22 RPM,

and the target parameter value S/R_{target} of the silicon rotation speed is 6 RPM. In a case that the length range in which the length of the single crystal silicon lies is 900 mm to 1200 mm, the target parameter value C/R_{target} of the crucible rotation speed is 0.64 RPM, and the target parameter value S/R_{target} of the silicon rotation speed is 6 RPM. In a case that the length range in which the length of the single crystal silicon lies is 1200 mm to 1500 mm, the target parameter value C/R_{target} of the crucible rotation speed is 1.06 RPM, and the target parameter value S/R_{target} of the silicon rotation speed is 6 RPM.

[0073] In the actual single crystal silicon growth, with respect to each growth stage, the oxygen content of the single crystal silicon and the oxygen content deviation between the oxygen content and the target oxygen content are measured as follows.

[0074] At a first growth stage, in a case that the length range in which the length of the single crystal silicon lies is 0 mm to 300 mm: in a case that the difference range in which the difference lies ΔT between the heating durations is (0h, 30h], the oxygen content deviation is 0.11 ppma; in a case that the difference range in which the difference lies ΔT is (30h, 60h], the oxygen content deviation is 0.12 ppma; in a case that the difference range in which the difference lies ΔT is (60h, 100h], the oxygen content deviation is 0.22 ppma; and in a case that the difference range in which the difference lies ΔT is (100h, 140h], the oxygen content deviation is 0.46 ppma.

[0075] At a second growth stage, in a case that the length range in which the length of the single crystal silicon lies is 300 mm to 600 mm: in a case that the difference range in which the difference lies ΔT between the heating durations is (0h, 30h], the oxygen content deviation is 0.11 ppma; in a case that the difference range in which the difference lies ΔT is (30h, 60h], the oxygen content deviation is 0.12 ppma; in a case that the difference range in which the difference lies ΔT is (60h, 100h], the oxygen content deviation is 0.23 ppma; and in a case that the difference range in which the difference lies ΔT is (100h, 140h], the oxygen content deviation is 0.45 ppma.

[0076] At a third growth stage, in a case that the length range in which the length of the single crystal silicon lies is 600 mm to 900 mm: in a case that the difference range in which the difference lies ΔT between the heating durations is (0h, 30h], the oxygen

content deviation is 0.10 ppma; in a case that the difference range in which the difference lies ΔT is (30h, 60h], the oxygen content deviation is -0.10 ppma; in a case that the difference range in which the difference lies ΔT is (60h, 100h], the oxygen content deviation is 0.15 ppma; and in a case that the difference range in which the difference lies ΔT is (100h, 140h], the oxygen content deviation is 0.39 ppma.

[0077] At a fourth growth stage, in a case that the length range in which the length of the single crystal silicon lies is 900 mm to 1200 mm: in a case that the difference range in which the difference lies ΔT between the heating durations is (0h, 30h], the oxygen content deviation is 0.07 ppma; in a case that the difference range in which the difference lies ΔT is (30h, 60h], the oxygen content deviation is -0.07 ppma; in a case that the difference range in which the difference lies ΔT is (60h, 100h], the oxygen content deviation is 0.38 ppma; and in a case that the difference range in which the difference lies ΔT is (100h, 140h], the oxygen content deviation is 0.62 ppma.

[0078] At a fifth growth stage, in a case that the length range in which the length of the single crystal silicon lies is 1200 mm to 1500 mm: in a case that the difference range in which the difference lies ΔT between the heating durations is (0h, 30h], the oxygen content deviation is 0.07 ppma; in a case that the difference range in which the difference lies ΔT is (30h, 60h], the oxygen content deviation is -0.07 ppma; in a case that the difference range in which the difference lies ΔT is (60h, 100h], the oxygen content deviation is 0.16 ppma; and in a case that the difference range in which the difference lies ΔT is (100h, 140h], the oxygen content deviation is 0.37 ppma.

[0079] As can be seen from the above, at each growth stage of the single crystal silicon growth, even in a case that the difference ranges of the differences ΔT between the actual heating duration and the target heating duration are different, a maximum value of the calculated oxygen content deviation is -0.10 ppma and a maximum value thereof is 0.62 ppma. The ratio of the oxygen content deviation between the oxygen content of the single crystal silicon and the target oxygen content to the target oxygen content is within a range of -10% to 10%, and the oxygen content deviation is also

always within a deviation range of the target oxygen content (e.g., [-0.25ppma, 0.75ppma]).

[0080] In addition, it is found that, in a case that the difference range in which the difference lies ΔT between the heating durations is (0h, 30h] and c_1 is greater than 15% or smaller than 15%, the calculated oxygen content deviation is greater than ± 0.3 ppma. In a case that the difference range in which the difference lies ΔT between the heating durations is (30h, 60h] and c_2 is greater than 25% or smaller than 25%, the calculated oxygen content deviation is greater than ± 0.3 ppma. In a case that the difference range in which the difference lies ΔT between the heating durations is (60h, 100h], c_3 is greater than 30% or smaller than 30% and s_1 is greater than 15% or smaller than 15%, the calculated oxygen content deviation is greater than ± 0.4 ppma, and defects may occur for the crystal. In a case that the difference range in which the difference lies ΔT between the heating durations is (100h, 140h], c_4 is greater than 35% or smaller than 35% and s_2 is greater than 15% or smaller than 15%, the calculated oxygen content deviation is greater than ± 0.7 ppma. The expression “ ± 0.3 ppma” refers to a range of [-0.3ppma, 0.3ppma], and the other similar expressions have a similar meaning, which will not be particularly defined herein.

[0081] During the growth of large-size single crystal silicon, based on the experiences, in order to ensure that a product result corresponding to original control parameters does not change, especially in order to maintain the interface stability, usually the compensation coefficient for the crucible rotation speed is not greater than 40%. In order to improve the oxygen content of the crystal and provide the crystal with excellent lattice stacking quality, usually the compensation coefficient for the silicon rotation speed is not greater than 15%.

[0082] Through the above-mentioned single crystal silicon growth method, during the single crystal silicon growth, the difference ΔT between the actual heating duration T_x of the quartz crucible and the target heating duration T_0 is monitored and managed in a stepwise manner, so as to perform automatic gain control over the control parameter for the crystal growth. The control parameter is adjusted for the stepwise

management on ΔT , so that the oxygen contents of the single crystal silicon corresponding to different values of ΔT are at a substantially same level. The control parameters corresponding to the stepwise management include different combinations of the silicon rotation speeds and the crucible rotation speeds, so as to provide more selections for the optimization of the oxygen content based on the single-factor variables and the multi-factor variables.

[0083] The above-mentioned single crystal silicon growth method is used to optimize the distribution of the oxygen content in the single crystal silicon, especially in the axial direction. To be specific, the actual heating duration is obtained in real time, and the control parameter is dynamically adjusted based on the difference between the actual heating duration and the target heating duration, so as to form a closed-loop control system. This system rapidly responds to any change in a process condition to perform the real-time adjustment, so as to prevent the occurrence of hysteresis and inaccuracy in a conventional static control method, and ensure that the oxygen content deviation between the oxygen content of the single crystal silicon and the target oxygen content is -10% to 10%. Through this real-time adjustment mechanism, it is able to accurately control the oxygen content, and prevent the non-uniform oxygen content caused by a change in the heating duration.

[0084] A difference-based hierarchical control policy is adopted, and the silicon rotation speed and the crucible rotation speed are adjusted based on the difference. Through the elaborate control policy, in a case that the difference is small, it is able to reduce the control complexity and prevent overadjustment. In a case that the difference is large, it is able to perform the adjustment more extensively, thereby to ensure the control accuracy and stability. Through the difference-based hierarchical control policy, it is able to improve not only the control efficiency but also the control accuracy, thereby to prevent the occurrence of any unnecessary fluctuation caused by the overadjustment.

[0085] The single crystal silicon growth process is divided into a plurality of growth stages based on the length range in which the length of the single crystal silicon

lies, and different length ranges correspond to different target parameter values, so that the configuration parameter values calculated based on the target parameter values are different too. Though the hierarchical control method based on the lengths of the single crystal silicon, different length ranges correspond to different target parameter values of the control parameter and different target oxygen contents, so it is able to control each growth stage in a more targeted manner. In the method, with respect to different stages of the single crystal silicon growth process, the optimization is performed in a targeted manner, so as to ensure the uniform distribution of the oxygen content at each growth stage.

[0086] The single crystal silicon growth process is divided into the plurality of growth stages, the oxygen content of the single crystal silicon is measured at each growth stage, and the relevant control parameters are allowed to be further optimized in the subsequent automatic gain control process based on the oxygen content deviation between the measured oxygen content and the target oxygen content.

[0087] Hence, in the above-mentioned single crystal silicon growth method, through the combination of real-time monitoring, elaborate control policy, stage-based optimization and dynamic adjustment, it is able to optimize the distribution of the oxygen content of the single crystal silicon, especially in the axial direction, thereby to improve the quality and the production efficiency of the single crystal silicon.

[0088] As shown in Fig. 1, the present disclosure further provides in some embodiments a single crystal silicon growth system, which includes a control module, a heating module 1, a silicon rotation module 5 and a crucible rotation module 2. The control module is configured to implement the above-mentioned method. The heating module 1 is configured to heat a quartz crucible for receiving a raw material, the silicon rotation module 5 is configured to rotate single crystal silicon, and the crucible rotation module 2 is configured to rotate the quartz crucible.

[0089] In some embodiments of the present disclosure, the control module includes a data processing unit 3 and a system control unit 4. The data processing unit 3 is configured to obtain an actual heating duration of the quartz crucible during the

growth of single crystal silicon, and determine a control parameter set and a configuration parameter value of the control parameter set based on a difference range in which a difference between the actual heating duration and a target heating duration lies. The control parameter set includes a silicon rotation speed of the silicon rotation module 5 and/or a crucible rotation speed of the crucible rotation module 2, and the control parameter sets corresponding to distinct difference ranges are different. The system control unit 4 is configured to automatically configure a corresponding control parameter based on the configuration parameter value of the control parameter set to allow an oxygen content deviation between an oxygen content of the single crystal silicon and a target oxygen content to be -10% to 10%.

[0090] In the above-mentioned embodiments of the present disclosure, the control module of the single crystal silicon growth system is designed as a split-type, and it includes the data processing unit 3 and the system control unit 4. The data processing unit 3 focuses on data processing, e.g., obtaining the actual heating duration, comparing the actual heating duration with the target heating duration, determining the corresponding control parameter set, and calculating the configuration parameter value of the relevant control parameter. The system control unit 4 receives the control parameter set and the configuration parameter value from the data processing unit 3, and automatically configures the control parameter of relevant hardware of the single crystal silicon growth system, e.g., adjusts the silicon rotation speed of the silicon rotation module 5 and the crucible rotation speed of the crucible rotation module 2, so as to ensure that the oxygen content deviation between the oxygen content of the single crystal silicon and the target oxygen content is -10% to 10%. The data processing unit 3 and the system control unit 4 designed in a split-type are adopted. The data processing unit 3 is dedicated for optimizing the processing speed and efficiency, so as to achieve high-speed data processing and instant parameter decision-making. The system control unit 4 rapidly receives an output of the data processing unit 3, and adjusts the operation of the single crystal silicon growth system in real time, so as to reduce the delay, and improve the response speed of the entire system. Through the split-type design, each

unit is allowed to focus on its core function, so as to prevent functions of the modules from overlapping with each other and reduce any potential conflict, thereby to improve the stability and reliability of the system. In addition, through this design, it is able to facilitate the upgrade and maintenance in future. For example, the data processing unit 3 may be upgraded individually to use a more advanced data processing algorithm, rather than to re-design the entire control module. Through rapidly adjusting and accurately controlling growth parameters, it is able for the system to fabricate the high-quality single crystal silicon material efficiently, and reduce the defective products and the production cost.

[0091] In some embodiments of the present disclosure, the data processing unit 3 determines the control parameter set through: in a case that the difference range in which the difference lies is a first difference range, taking the silicon rotation speed as a control parameter in the control parameter set; and in a case that the difference range in which the difference lies is a second difference range, taking the silicon rotation speed and the crucible rotation speed as control parameters in the control parameter set. A minimum value of the second difference range is not smaller than a maximum value of the first difference range.

[0092] In some embodiments of the present disclosure, the data processing unit 3 determines the configuration parameter value of the control parameter set through: with respect to each control parameter, performing following processings: determining a correspondence between the configuration parameter value and a target parameter value of the control parameter based on the difference range in which the difference lies, various correspondences corresponding to distinct difference ranges; and calculating the configuration parameter value of the control parameter based on the target parameter value of the control parameter and the correspondence.

[0093] In some embodiments of the present disclosure, the correspondence is represented by a corresponding formula or a corresponding model.

[0094] In some embodiments of the present disclosure, the correspondence is represented by a corresponding formula, and one or more compensation coefficients in

the corresponding formula are determined based on the difference range in which the difference lies.

[0095] In some embodiments of the present disclosure, the target parameter value of the control parameter is determined based on a length range in which a length of the single crystal silicon lies.

[0096] In some embodiments of the present disclosure, the data processing unit 3 is further configured to: divide a growth process of the single crystal silicon into a plurality of growth stages based on a length range in which a length of the single crystal silicon lies; and at each growth stage, measure the oxygen content of the single crystal silicon, and calculate the oxygen content deviation between the oxygen content of the single crystal silicon and the target oxygen content .

[0097] The present disclosure further provides in some embodiments single crystal silicon with a controllable oxygen content. An oxygen content deviation between an oxygen content of the single crystal silicon and a target oxygen content is -10% to 10%, and the single crystal silicon is fabricated using the above-mentioned method or system.

[0098] The present disclosure further provides in some embodiments a silicon wafer with a controllable oxygen content. The silicon wafer is obtained through machining single crystal silicon, an oxygen content deviation between an oxygen content of the single crystal silicon and a target oxygen content is -10% to 10%, and the single crystal silicon is fabricated using the above-mentioned method or system.

[0099] It should be further appreciated that, the above embodiments have been described in a progressive manner, and the same or similar contents in the embodiments have not been repeated, i.e., each embodiment has merely focused on the difference from the others. Especially, the product embodiments are substantially similar to the method embodiments, and thus have been described in a simple manner.

[00100] Unless otherwise defined, any technical or scientific term used herein shall have the common meaning understood by a person of ordinary skills. Such words as “first” and “second” used in the specification and claims are merely used to

differentiate different components rather than to represent any order, number or importance. Similarly, such words as “one” or “one of” are merely used to represent the existence of at least one member, rather than to limit the number thereof. Such words as “include” or “including” intends to indicate that an element or object before the word contains an element or object or equivalents thereof listed after the word, without excluding any other element or object. Such words as “connect/connected to” or “couple/coupled to” may include electrical connection, direct or indirect, rather than to be limited to physical or mechanical connection. Such words as “on”, “under”, “left” and “right” are merely used to represent relative position relationship, and when an absolute position of the object is changed, the relative position relationship will be changed too.

[00101] It should be appreciated that, in the case that such an element as layer, film, region or substrate is arranged “on” or “under” another element, it may be directly arranged “on” or “under” the other element, or an intermediate element may be arranged therebetween.

[00102] In the above description, the features, structures, materials or characteristics may be combined in any embodiment or embodiments in an appropriate manner.

[00103] The above are merely the preferred embodiments of the present disclosure, but shall not be construed as limiting the scope of the present disclosure. Any person skilled in the art may make modifications and substitutions without departing from the spirit of the present disclosure, and these modifications and substitutions shall also fall within the scope of the present disclosure. Hence, the scope of the present disclosure shall be subject to the scope defined by the appended claims.

What is claimed is:

1. A single crystal silicon growth method, comprising:

obtaining an actual heating duration of a quartz crucible during the growth of single crystal silicon;

determining a control parameter set and a configuration parameter value of the control parameter set based on a difference range in which a difference between the actual heating duration and a target heating duration lies, wherein the control parameter set comprises a silicon rotation speed and/or a crucible rotation speed, and various control parameter sets corresponding to distinct difference ranges; and

automatically configuring a corresponding control parameter based on the configuration parameter value of the control parameter set to allow an oxygen content deviation between an oxygen content of the single crystal silicon and a target oxygen content to be -10% to 10%.

2. The single crystal silicon growth method according to claim 1, wherein the step of determining a control parameter set comprises:

in a case that the difference range in which the difference lies is a first difference range, taking the crucible rotation speed as a control parameter item in the control parameter set; and

in a case that the difference range in which the difference lies is a second difference range, taking the silicon rotation speed and the crucible rotation speed as control parameter items in the control parameter set, wherein a minimum value of the second difference range is not smaller than a maximum value of the first difference range.

3. The single crystal silicon growth method according to claim 1, wherein the step of determining a configuration parameter value of the control parameter set comprises:

with respect to each control parameter item, performing following steps:

determining a correspondence between the configuration parameter value of the control parameter item and a target parameter value based on the difference range in which the difference lies, wherein various correspondences corresponding to distinct difference ranges; and

calculating the configuration parameter value of the control parameter item based on the target parameter value of the control parameter and the correspondence.

4. The single crystal silicon growth method according to claim 3, wherein the correspondence is represented by a corresponding formula or a corresponding model.

5. The single crystal silicon growth method according to claim 3, wherein the correspondence is represented by a corresponding formula, and one or more compensation coefficients in the corresponding formula are determined based on the difference range in which the difference lies.

6. The single crystal silicon growth method according to claim 3, wherein the target parameter value of the control parameter is determined based on a length range in which a length of the single crystal silicon lies.

7. The single crystal silicon growth method according to claim 1, further comprising:

dividing a growth process of the single crystal silicon into a plurality of growth stages based on a length range in which a length of the single crystal silicon lies; and

at each growth stage, measuring the oxygen content of the single crystal silicon, and calculating the oxygen content deviation between the oxygen content of the single crystal silicon and the target oxygen content.

8. A single crystal silicon growth system, comprising:

a control module, configured to implement the single crystal silicon growth method according to any one of claims 1 to 7;

a heating module, configured to heat a quartz crucible containing a raw material;

a silicon rotation module, configured to rotate single crystal silicon; and

a crucible rotation module, configured to rotate the quartz crucible.

9. Single crystal silicon with a controllable oxygen content, wherein an oxygen content deviation between an oxygen content of the single crystal silicon and a target oxygen content is -10% to 10%, and the single crystal silicon is fabricated using the single crystal silicon growth method according to any one of claims 1 to 7 or the single crystal silicon growth system according to claim 8.

10. A silicon wafer with a controllable oxygen content, wherein the silicon wafer is obtained through machining single crystal silicon, an oxygen content deviation between an oxygen content of the single crystal silicon and a target oxygen content is -10% to 10%, and the single crystal silicon is fabricated using the single crystal silicon growth method according to any one of claims 1 to 7 or the single crystal silicon growth system according to claim 8.