WAFER AND METHOD, APPARATUS, DEVICE AND MEDIUM FOR IMPROVING ROUGHNESS THEREOF

CROSS-REFERENCE TO RELATED APPLICATION

[0001] The present disclosure claims a priority of Chinese Patent Application No. 202411435849.1filed in China on October 15, 2024, the entire contents of which are hereby incorporated by reference in their entireties.

TECHNICAL FIELD

[0002] The present disclosure relates to the field of semiconductor manufacturing technologies, and in particular, to a wafer and a method, an apparatus, a device and a medium for improving roughness thereof.

BACKGROUND

[0003] In the wafer manufacturing process, after a single crystal silicon ingot is prepared by the Czochralski process, the single crystal silicon ingot is sequentially processed through wire sawing, grinding, etching, lapping, chemical mechanical polishing (CMP), and cleaning to finally obtain a single crystal silicon wafer. For the single crystal silicon wafer, its surface profile is a key parameter for assessing its quality. Surface roughness is an important performance parameter among the wafer surface profile parameters.

[0004] According to the above processing procedures in the wafer manufacturing process, after the single crystal silicon ingot is cut by using a wire sawing equipment to obtain a bare wafer, the bare wafer already has an initial surface state, and subsequent processing procedures such as grinding, etching, lapping, CMP and cleaning only serve to gradually repair surface damage on the basis of the initial surface state. In view of this, if a single crystal silicon wafer with better surface roughness indicators is desired, it is necessary to start process optimization at the wire sawing stage, to improve the surface roughness of the bare wafer obtained from the wire sawing process, thereby improving the final surface roughness indicators of the single crystal silicon wafer.

[0005] Currently, no solution has been provided that optimizes the process at the wire sawing stage based on the surface roughness of the bare wafer obtained from this wire sawing process.

SUMMARY

[0006] The present disclosure provides a wafer and a method, apparatus, device and medium for improving roughness thereof; the roughness of a bare wafer obtained by wire sawing in a target wavelength range is taken as an evaluation index, and process parameters in a wire sawing process are adjusted through the index, thereby reducing the surface roughness of a wafer surface.

[0007] In a first aspect, the present disclosure provides a method for improving wafer roughness, the method includes:

[0008] detecting a roughness in a target wavelength range of a bare wafer obtained after a wire sawing process;

[0009] when the roughness is greater than or equal to a set roughness threshold, selecting a to-be-adjusted wire sawing parameter according to priorities of wire sawing parameters indicated by a fitting function between multiple wire sawing process parameters and the roughness in the target wavelength range.

[0010] In a second aspect, the present disclosure provides an apparatus for improving wafer roughness, the apparatus includes: a detection part, a comparison part, and a process improvement part; wherein

[0011] the detection part is configured to detect a roughness in a target wavelength range of a bare wafer obtained after a wire sawing process;

[0012] the comparison part is configured to compare the roughness with a set roughness threshold, and to trigger the process improvement part when the roughness is greater than or equal to the set roughness threshold;

[0013] the process improvement part is configured to select a to-be-adjusted wire sawing parameter according to priorities of wire sawing parameters indicated by a fitting function between multiple wire sawing process parameters and the roughness in the target wavelength range.

[0014] In a third aspect, the present disclosure provides a computing device, and the computing device includes: a processor and a memory; the processor is used to execute instructions stored in the memory to implement the method for improving wafer roughness as described in the first aspect.

[0015] In a fourth aspect, the present disclosure provides a computer readable storage medium, and the computer-readable storage medium includes at least one instruction stored thereon. The at least one instruction, when executed by a processor, causes the processor to implement the method for improving wafer roughness as described in the first aspect.

[0016] In a fifth aspect, the present disclosure provides a wafer, where the wafer is obtained through a wire sawing process improved by the method for improving wafer roughness as described in the first aspect, and the roughness in the target wavelength range is at least one of the following:

[0017] when the target wavelength range is 0 to 1.8 micrometer wavelength, the roughness is 0.01 nm to 1 nm;

[0018] when the target wavelength range is 1.8 micrometer wavelength to 22 micrometer wavelength, the roughness is 1 nm to 3 nm;

[0019] when the target wavelength range is 22 micrometer wavelength to 20 millimeter wavelength, the roughness is 3 nm to 30 nm.

[0020] The present disclosure provides a wafer and a method, an apparatus, a device and a medium for improving roughness thereof; the roughness of a bare wafer obtained by wire sawing in a target wavelength range is taken as an evaluation index, and when the roughness in the target wavelength range of the bare wafer obtained after a wire sawing process is greater than or equal to a set roughness threshold, a to-be-adjusted wire sawing parameter is selected based on priorities of the wire sawing parameters indicated by a fitting function between multiple wire sawing parameters and the roughness in the target wavelength range, and a roughness in the target wavelength range of ae bare wafer obtained from a subsequent wire sawing process is reduced by adjusting the selected wire sawing parameter.

BRIEF DESCRIPTION OF THE DRAWINGS

[0021] FIG. 1 is a schematic diagram of an exemplary multi-wire sawing equipment according to the present disclosure;

[0022] FIG. 2 is a schematic diagram of a cutting area in a wire sawing process according to the present disclosure;

[0023] FIG. 3 is a schematic flow chart of a method for improving wafer roughness according to the present disclosure;

[0024] FIG. 4 is a schematic flow chart of a process for detecting roughness in a target wavelength range according to the present disclosure;

[0025] FIG. 5 is a schematic diagram of a filter sliding on a wafer surface according to the present disclosure;

[0026] FIG. 6 is a schematic diagram of a divided analysis area according to the present disclosure;

[0027] FIG. 7 is a schematic diagram of an apparatus for improving wafer roughness according to the present disclosure;

[0028] FIG. 8 is a schematic diagram of another apparatus for improving wafer roughness according to the present disclosure; and

[0029] FIG. 9 is a schematic structural diagram of a computing device according to the present disclosure.

DETAILED DESCRIPTION OF EMBODIMENTS

[0030] The technical solution of the present disclosure will be clearly and completely described hereinafter in conjunction with the accompanying drawings of the present disclosure.

[0031] Referring to FIG. 1, it shows an exemplary multi-wire sawing equipment 1 suitable for the technical solution of the present disclosure. The equipment may include a wire sawing unit 11 and a carrying unit 12. In some embodiments of the present disclosure, the wire sawing unit 11 may be located below the carrying unit 12 in the vertical direction. In embodiments not shown in the present disclosure, the wire sawing unit 11 may be located above the carrying unit 12 in the vertical direction, which will not be described in detail here.

[0032] The wire sawing unit 11 may include multiple wire spools 111, a sawing wire 112, and a wire sawing slurry supply unit 113, with the sawing wire 112 wound around the wire spools 111 to form an array composing of mutually parallel sawing wire segments. Bellow, with reference to FIG.1, a description is given with the number of wire spools 111 being two as an example. The two wire spools 111 are arranged opposite to each other with their axes parallel. The two wire sawing slurry supply units 113 are respectively located directly above the two wire spools 111, used for spraying wire sawing slurry onto the two wire spools 111 and the sawing wire 112. The wire sawing slurry can be a liquid medium in which abrasive particles are suspended.

[0033] The reciprocating motion direction of the wire spools 111 and the sawing wire 112 toward and away from the carrying unit 12 is shown by the solid arrow in FIG. 1, and the reciprocating motion speed can be exemplified as 5m/s to 18m/s. The carrying unit 12 is used for loading and fixing the silicon ingot S to be processed, and may include a base 121 and a middleware 122. The silicon ingot S to be processed is fixed to the base 121 via the middleware 122. For example, the silicon ingot to be processed can be adhered to the lower surface of the base 121 via its circumferential surface, thereby being fixed to the base 121.

[0034] For the multi-wire sawing equipment 1 shown in FIG. 1, the carrying unit 12 can be moved in the vertical direction toward the array of sawing wire segments to make the silicon ingot to be processed be closer to the array of sawing wire segments. After the array of sawing wire segments and the silicon ingot S to be processed come into contact with each other, the cutting of the silicon ingot S to be processed is realized by the movement of each sawing wire segment in the array along its extending direction and the feeding movement of the carrying unit 12 continuing in the vertical direction toward the array of sawing wire segments. It is to be noted that the present disclosure realizes the movement of the carrying unit 12 through a lifting device (not shown in the figure). It can be understood that those skilled in the art can also realize the movement of the carrying unit 12 in other ways according to practical needs and implementation scenarios, and the present disclosure will not be described in detail here.

[0035] A plurality of wire grooves 111A are opened on the circumferential surface of the wire spool 111 for guiding and fixing the sawing wire 112 to ensure that it maintains a stable tension and position during the cutting process. Generally, the wire grooves 111A are evenly distributed on the circumferential surface of the wire spool 111.

[0036] In the process of wire sawing based on the multi-wire sawing equipment 1 described above, the wire sawing slurry cannot be sprayed onto the middle part of the silicon ingot S to be processed, and the wire sawing slurry for this part can only be carried and transported by the sawing wire. Since the sawing wire can only operate in a limited space, and there is no strong adhesion between the wire sawing slurry and the sawing wire material, the wire sawing slurry attached to the sawing wire is very easily scraped off during the transportation of the sawing wire, which makes the content of the wire sawing slurry in the middle part of the silicon ingot S to be processed less than that in the edge part, and the insufficient content of the wire sawing slurry may lead to variation in cutting force along the cutting direction. Specifically, due to the lack of convective heat transfer and heat dissipation channels for the wire sawing slurry, more heat will accumulate in the middle part of the silicon ingot S to be processed and cannot be dissipated, which will cause thermal stress differences throughout the entire wafer, resulting in wafer deformation.

[0037] In addition, as the silicon ingot S to be processed is fed downwards, the change of the cutting area during the wire sawing process is a process of increasing and decreasing. Taking the cross-section of the silicon ingot to be processed shown in FIG. 2 as an example, as the silicon ingot S to be processed is fed downwards as indicated by the arrow, the cutting area gradually increases from a chord (dashed line) to a diameter and then decreases to a chord (dot-

dashed line). Based on FIG. 2, when the cutting area is a diameter, more heat accumulates inside the bare wafer, and there is a higher risk of thermal stress deformation.

[0038] Based on the above-mentioned content, the inventor found that: maintaining a constant cutting rate may not be an ideal wire sawing solution. The process parameters related to the cutting rate can be appropriately adjusted as the cutting area increases to allow for more sufficient heat dissipation inside the silicon ingot S to be processed, thereby improving the roughness of the bare wafer.

[0039] Based on this, referring to FIG. 3, it shows a method for improving wafer roughness provided by the present disclosure, the method includes steps S301 to S302.

[0040] Step S301: detecting a roughness in a target wavelength range of a bare wafer obtained after a wire sawing process.

[0041] In the present disclosure, the uniformity of the wafer surface profile is reflected in the height difference between each point on the wafer surface, and this height difference will present a phenomenon of height value fluctuation of each point on the wafer surface as a whole. Based on this understanding, the present disclosure views this fluctuation phenomenon from the perspective of a wave as being caused by the superposition of wave signals of different wavelengths. The smaller the wavelength of the wave signal, the smaller the regional size of the height value fluctuation phenomenon it represents; the larger the wavelength of the wave signal, the larger the regional size of the height value fluctuation phenomenon it represents.

[0042] On the basis of the above explanation, in order to evaluate or measure the roughness of a smaller area, the above fluctuation phenomenon can be filtered by the area size of the desired measurement roughness, thereby obtaining the wave signal data within the wavelength range corresponding to the area where the desired measurement roughness is obtained, and the roughness of the wafer under the standard of this area size can be calculated based on the wave signal data. In the present disclosure, the target wavelength range of from 22 micrometer wavelength to 20 millimeter wavelength is taken as an example.

[0043] Step S302: when the roughness is greater than or equal to a set roughness threshold, selecting a to-be-adjusted wire sawing parameter according to priorities of wire sawing parameters indicated by a fitting function between multiple wire sawing process parameters and the roughness in the target wavelength range, thereby reducing the roughness in the target wavelength range of the bare wafer obtained from a subsequent wire sawing process.

[0044] In the present disclosure, after detecting the roughness in the target wavelength range of the bare wafer that has completed the wire sawing process, it is possible to characterize

whether the roughness is good or not through a set roughness threshold. Taking the target wavelength range of 22 micrometer wavelength to 20 millimeter wavelength as an example, in some examples, the roughness threshold can be set to 25 nm. That is, when the roughness value in the target wavelength range of the bare wafer is greater than or equal to 25 nm, it means that the cutting ability of the multi-wire sawing equipment 1 has deteriorated seriously.

[0045] Specifically, the bare wafer obtained from the wire sawing process exhibits obvious periodic wire marks on a macroscopic scale, which can be regarded as an overall presentation of roughness on the wafer surface. Based on this understanding, it can be seen that these wire marks, like the roughness mentioned in the previous steps, can be expressed as a fluctuation phenomenon with amplitude, and this fluctuation phenomenon is also caused by the superposition of wave signals of different wavelengths.

[0046] Combining the structure and working principle of the multi-wire sawing equipment shown in FIG. 1, the inventor found that: this macroscopic presentation (i.e., wire marks) is related to the following wire sawing parameters used in the wire sawing process: the movement speed of the sawing wire's reciprocating motion, the cycle of the sawing wire's reciprocating motion and the feeding speed of the silicon ingot S to be processed. The degree of influence of the above three wire sawing parameters on the roughness in the target wavelength range of the bare wafer surface can be characterized by a fitting function. In the present disclosure, the fitting function is represented by a power function of the above three wire sawing parameters, for example, as shown in the following formula:

[0047] $$PV = K1 \times Vs^{a} \times Tr^{b} \times Vf^{c}$$

[0048] where, Vs represents the movement speed of the sawing wire's reciprocating motion, Tr represents the cycle of the sawing wire's reciprocating motion, Vf represents the feeding speed, and a, b, c are empirical coefficients in the fitting function, which respectively represent the degree of influence of their corresponding wire sawing parameters on the roughness, and K1 represents the fitting coefficient. In order to determine the empirical coefficients and fitting coefficients of the above fitting function, in some examples, the collected wire sawing parameters in a historical wire sawing process and the detected roughness in the target wavelength range of the bare wafer obtained from the historical wire sawing process are substituted into the above fitting function to determine the a, b, c and K1 in the fitting function.

[0049] In the present disclosure, $K1=6.2\times10^{-3}$, a= 0.529, b =1.445, c =0.873. Based on the specific values of the empirical coefficients a, b, c, it can be seen that: the cycle of the sawing

wire's reciprocating motion corresponding to the empirical coefficient b has the greatest influence on the roughness, followed by the feeding speed corresponding to the empirical coefficient c, and then the movement speed of the sawing wire's reciprocating motion corresponding to the empirical coefficient a. For the magnitude of the above influence, priorities are set for the movement speed of the sawing wire's reciprocating motion, the cycle of the sawing wire's reciprocating motion and the feeding speed, respectively. Specifically, the greater the influence, the higher the priority. Therefore, when the roughness exceeds the set roughness threshold, the wire sawing parameters are selected for adjustment according to the above priority, thereby reducing the roughness in the target wavelength range of the bare wafer obtained from a subsequent wire sawing process.

[0050] The technical solution shown in FIG. 3 takes the roughness in a target wavelength range of the bare wafer obtained by wire sawing as an evaluation index. When the roughness in the target wavelength range of the bare wafer that has completed the wire sawing process is greater than or equal to a set roughness threshold, a to-be-adjusted wire sawing parameter is selected based on the priority of the wire sawing parameters indicated by a fitting function between multiple wire sawing parameters and the roughness in the target wavelength range, and the roughness in the target wavelength range of the bare wafer obtained from a subsequent wire sawing process is reduced by adjusting the selected wire sawing parameter.

[0051] For the technical solution shown in FIG. 3, in some possible implementations, the fitting function can be obtained by fitting the collected wire sawing parameters in the historical wire sawing process and the detected roughness in the target wavelength range of the bare wafer obtained from the historical wire sawing process. The specific fitting process may include:

[0052] forming an initialized fitting function based on a product of a power function related to the movement speed of the sawing wire's reciprocating motion with the first empirical coefficient as an exponent, a power function related to the cycle of the sawing wire's reciprocating motion with the second empirical coefficient as an exponent, and a power function related to the feeding speed with the third empirical coefficient as an exponent;

[0053] in the historical wire sawing process, collecting historical wire sawing parameters and detecting the roughness in the target wavelength range of the bare wafer that has completed the historical wire sawing process;

[0054] substituting the historical wire sawing parameters and the roughness in the target wavelength range of the bare wafer that has completed the historical wire sawing process into

the fitting function to obtain the first empirical coefficient, the second empirical coefficient, and the third empirical coefficient in the fitting function.

[0055] For the above implementation, exemplary specific implementation details may include:

[0056] First, a fitting function is expressed by a power function of the above three wire sawing parameters as follows:

[0057] $PV = K1 \times Vs^{a} \times Tr^{b} \times Vf^{c}$

[0058] where, Vs represents the movement speed of the sawing wire's reciprocating motion in the historical wire sawing parameters, Tr represents the cycle of the sawing wire's reciprocating motion in the historical wire sawing parameters, Vf represents the feeding speed in the historical wire sawing parameters, and a, b, c are empirical coefficients in the fitting function, which respectively represent the degree of influence of their corresponding wire sawing parameters on the roughness, and K1 represents the fitting coefficient.

[0059] Next, the above fitting function is logarithmically transformed to obtain the logarithmically transformed fitting function as shown in the following formula:

[0060] $\log(PV) = \log(K1) + a\log(Vs) + b\log(Tr) + c\log(Vf)$

[0061] Then, by using the historical wire sawing parameters collected in the historical wire sawing process and the detected roughness in the target wavelength range of the bare wafer that has completed the historical wire sawing process, the empirical coefficients and fitting coefficients in the above logarithmically transformed fitting function are calculated by a least square method to obtain a fitting function suitable for the technical solution shown in FIG. 3.

[0062] Through the above process of obtaining the fitting function, K1=6.2×10^{-3}, a= 0.529, b =1.445, and c =0.873 can finally be obtained. According to the above empirical coefficients, it can be known that the cycle of the sawing wire's reciprocating motion has the greatest influence on the roughness, followed by the feeding speed, and then the movement speed of the sawing wire's reciprocating motion.

[0063] In the present disclosure, some historical wire sawing parameters and the corresponding roughness in the range from 22 micrometer wavelength to 20 millimeter wavelength of the bare wafers that has completed historical wire sawing processes are shown in Table 1 below.

Vf（mm/min）	Vs（m/s）	Tr（s）	roughness in the target wavelength range
3	15	80	38.1

3	15	65	28.2
3	15	40	14
2	15	40	9.8
1.5	15	40	7.6
1.5	12	40	6.8
1.5	8	40	5.5

Table 1

[0064] In the present disclosure, when the target wavelength range is 1.8 micrometer wavelength to 22 micrometer wavelength, based on the aforementioned process of obtaining the fitting function, $K1=4.4\times10^{-3}$, a= 0.659, b =1.217, and c =0.887 can be obtained. According to the above empirical coefficients, it can also be known that the cycle of the sawing wire's reciprocating motion has the greatest influence on the roughness, followed by the feeding speed, and then the movement speed of the sawing wire's reciprocating motion. In the present disclosure, some historical wire sawing parameters and the corresponding roughness in the range from 1.8 micrometer wavelength to 22 micrometer wavelength of the bare wafer that has completed the historical wire sawing process are shown in Table 2 below.

Vf（mm/min）	*Vs*（m/s）	*Tr*（s）	roughness in the target wavelength range
3	15	40	6.2
3	15	30	4.4
3	15	20	2.7
2	15	20	1.9
1.5	15	20	1.4
1.5	12	20	1.2
1.5	8	20	1.0

Table 2

[0065] In the present disclosure, when the target wavelength range is 0 to 18 micrometer wavelength, based on the aforementioned process of obtaining the fitting function, $K1=6.7\times10^{-3}$, a= 0.813, b =1.105, and c =0.971 can be obtained. According to the above empirical coefficients, it can also be known that the cycle of the sawing wire's reciprocating motion has the greatest influence on the roughness, followed by the feeding speed, and then the movement speed of the sawing wire's reciprocating motion. In the present disclosure, some historical wire sawing parameters and the corresponding roughness in the range from 0 to 22 micrometer

wavelength of the bare wafer that has completed the historical wire sawing process are shown in Table 3 below.

Vf（mm/min）	*Vs*（m/s）	*Tr*（s）	roughness in the target wavelength range
1.5	8	20	1.5
1.5	8	15	1.1
1.5	8	10	0.7
1	8	10	0.5
0.7	8	10	0.3
0.7	6	10	0.3
0.7	4	10	0.2

Table 3

[0066] In the above Tables 1, 2 and 3, the conclusion about the degree of influence of the cycle of the sawing wire's reciprocating motion, the feeding speed, and the movement speed of the sawing wire's reciprocating motion on the roughness can also be verified from the variation of the roughness with the changes of Vf, Vs, and Tr.

[0067] For the technical solution shown in FIG. 3, in some possible implementations, as shown in FIG. 4, the process of detecting the roughness in a target wavelength range of a bare wafer that has completed the wire sawing process described in step S301 can include steps S3011 to S3013.

[0068] Step S3011: for each sampling point on a surface of the bare wafer, obtaining an original measurement data of a wafer surface height at each sampling point through a single-point measurement solution.

[0069] For this implementation, specifically, a single-point measurement solution is a solution where only one sampling point's measurement data can be measured in one measurement process. In some examples, a contact measurement solution can be used, for example, using a probe to make contact with the bare wafer surface and move horizontally on the wafer surface. With this horizontal movement, the height difference of the bare wafer surface will cause the probe to generate a longitudinal displacement. This longitudinal displacement is sensed by a displacement sensor and the sensed longitudinal displacement value is converted into the height data of the bare wafer surface, that is, the original measurement data regarding the wafer surface height. In other examples, non-contact

measurement solutions such as capacitive measurement, laser focus measurement, etc., can also be used.

[0070] Step S3012: based on original measurement data of all sampling points on the surface of the bare wafer, for each sampling point, obtaining a wave signal of each sampling point in the target wavelength range through a filter corresponding to the target wavelength range.

[0071] In this implementation, after the measurement of each sampling point on the surface of the bare wafer is completed through the aforementioned single-point measurement solution, the original measurement data of all sampling points can reflect the height difference between each sampling point, which can be regarded as a three-dimensional fluctuation phenomenon from the entire wafer surface. For this fluctuation phenomenon, the amplitude of the wave signals of different wavelengths that are superimposed to form this fluctuation phenomenon can be used to represent the height difference within the area corresponding to the wavelength size. Taking the target wavelength range from 22 micrometer wavelength to 20 millimeter wavelength as an example, the upper wavelength limit is 20 mm, and the lower wavelength limit is 22 μm. Taking the target wavelength range from 0 to 1.8 micrometer wavelength as an example, the upper wavelength limit is 1.8 μm, and the lower wavelength limit is 0. Taking the target wavelength range of 1.8 micrometer wavelength to 22 micrometer wavelength as an example, the upper wavelength limit is 22 μm, and the lower wavelength limit is 1.8 μm.

[0072] In some examples, in order to obtain the wave signal of each sampling point in the target wavelength range, in the specific implementation process of step S3012, first, a low-pass filter function is first used to filter out the wave signals with wavelengths higher than the upper wavelength limit from the fluctuation phenomenon, then a high-pass filter function is used to filter out the wave signals lower than the lower wavelength limit, and finally the wave signals within the target wavelength range are obtained.

[0073] Specifically, taking the above filter as a circular filter as an example, and the circular filter is composed of a double Gaussian filter function. Among them, the first Gaussian filter function GLP1 can be a Gaussian low-pass filter function whose low-pass filtering range covers the upper limit of the target wavelength range; the second Gaussian filter function GLP2 can be a Gaussian low-pass filter function whose low-pass filtering range covers the lower limit of the target wavelength range, and a high-pass filter function is obtained by (1-GLP2). Based on the aforementioned first Gaussian filter function and second Gaussian filter function, the circular filter GDHP can be expressed as GDHP= GLP1(1-GLP2). In the present disclosure, using the aforementioned example of the circular filter as shown in FIG. 5, the circular filter

indicated by the arrow can be slid across the bare wafer surface according to the sampling points, and the original measurement data of the sampling point at the center of the circular filter and other sampling points covered by the action range of the circular filter are used to filter through the circular filter to obtain the wave signal of each sampling point in the target wavelength range.

[0074] It is to be noted that as the wafer surface approaches the edge, the morphological changes become more drastic. In order to accurately capture the drastic morphological changes, when the sampling points are close to the edge of the wafer surface, the action range of the corresponding circular filter should be smaller than the action range of the circular filter corresponding to the sampling point close to the center of the wafer surface, that is, as the sampling point gradually moves away from the center of the wafer, the action range of the corresponding filter should decrease, or be called shrink. Therefore, the radius of the action range of the filter is determined by the distance between the sampling point and the center of the bare wafer.

[0075] In the present disclosure, a critical distance is set to determine whether the sampling point is close to the center of the wafer surface or close to the edge of the wafer surface. When the distance from the sampling point to the center of the bare wafer is less than or equal to the critical distance, the radius of the action range of the filter is the first radius; when the distance from the sampling point to the center of the bare wafer is greater than the critical distance, the radius of the action range of the filter is the second radius; where, both the first radius and the second radius are determined by the upper limit of the target wavelength range, and the first radius is greater than the second radius.

[0076] Based on the above example, specifically, the way of shrinking can be stepwise, that is, when the distance between the sampling point and the center of the bare wafer is greater than the critical distance, the second radius is fixedly set to a value smaller than the first radius; it can also be gradient, that is, the second radius gradually decreases as the sampling point moves away from the center of the bare wafer. Specifically, when the distance between the sampling point and the center of the bare wafer is greater than the critical distance, the second radius is a fixed value smaller than the first radius, or the second radius is negatively correlated with the distance between the sampling point and the center of the bare wafer.

[0077] Step S3013: determining the roughness in the target wavelength range of the bare wafer based on a statistical value of amplitudes of the wave signals of all sampling points in the target wavelength range.

[0078] For the above implementation, after obtaining the wave signals of all sampling points in the target wavelength range through filtering, in some examples, determining the roughness in the target wavelength range of the bare wafer based on the statistical value of the amplitude of the wave signals of all sampling points in the target wavelength range includes:

[0079] dividing the bare wafer into a plurality of analysis areas;

[0080] calculating a range of the amplitude of the wave signals in the target wavelength range for each analysis area based on the amplitude values of the wave signals of the sampling points in each analysis area in the target wavelength range**;**

[0081] determining an average of the ranges of the amplitudes of the wave signals in all analysis areas within the target wavelength range as the roughness of the bare wafer in the target wavelength range.

[0082] For the above example, as shown in FIG. 6, after the edge area of the wafer surface is removed according to edge exclusion (EE), the remaining area is divided according to a set size, such as a 10 mm × 10 mm square area, so that complete analysis areas that can present a complete square and incomplete analysis areas that are at the edge of the remaining area after the edge area is removed according to EE and cannot present a complete square can be obtained. These two analysis areas together constitute the analysis areas in the aforementioned implementation.

[0083] It is to be noted that the wave signals in the target wavelength range at all sampling points on the wafer surface include all information that can characterize the surface profile (i.e., roughness) of the wafer surface in the size area corresponding to the target wavelength range. This information can be characterized by statistical values of the amplitude, such as the average, extremum, extremum under a set size area ratio, range, variance, standard deviation, median, mode, etc. as mentioned in the aforementioned technical solution.

[0084] In the present disclosure, taking the range as an example, the statistical value of the amplitude of the wave signals in the target wavelength range for each analysis area is defined as the range of the amplitude values of the wave signals at the sampling points and interpolation points in each analysis area in the target wavelength range; correspondingly, the roughness of the bare wafer in the target wavelength range is the average of the ranges of the amplitude values of the wave signals of all analysis areas in the target wavelength range.

[0085] Based on the above technical solutions and specific embodiments, the wafer obtained through the wire sawing process improved by the method for improving wafer roughness described above has a roughness in the target wavelength range of at least one of the following:

[0086] when the target wavelength range is 0 to 1.8 micrometer wavelength, the roughness is 0.01 nm to 1 nm;

[0087] when the target wavelength range is 1.8 micrometer wavelength to 22 micrometer wavelength, the roughness is 1 nm to 3 nm;

[0088] when the target wavelength range is 22 micrometer wavelength to 20 millimeter wavelength, the roughness is 3 nm to 30 nm.

[0089] Based on the same inventive concept as the aforementioned technical solution, referring to FIG. 7, it shows an apparatus 70 for improving wafer roughness, the apparatus 70 includes: a detection part 701, a comparison part 702, and a process improvement part 703.

[0090] The detection part 701 is configured to detect a roughness in a target wavelength range of a bare wafer obtained after a wire sawing process;

[0091] The comparison part 702 is configured to compare the roughness with a set roughness threshold, and to trigger the process improvement part 703 when the roughness is greater than or equal to the set roughness threshold;

[0092] The process improvement part 703 is configured to select a to-be-adjusted wire sawing parameter based on a priority of the wire sawing parameters indicated by a fitting function between multiple wire sawing process parameters and the roughness in the target wavelength range, thereby reducing the roughness in the target wavelength range of the bare wafer obtained from a subsequent wire sawing process.

[0093] In some examples, the multiple wire sawing parameters include: a reciprocating motion speed of a sawing wire, the cycle of the sawing wire's reciprocating motion, and a feeding speed;

[0094] accordingly, the fitting function is represented by a product of power functions regarding the movement speed of the sawing wire's reciprocating motion, the cycle of the sawing wire's reciprocating motion and the feeding speed, respectively.

[0095] In some examples, referring to FIG. 8, the apparatus 70 also includes: a fitting part 704, configured to:

[0096] form an initialized fitting function based on the product of a power function related to the movement speed of the sawing wire's reciprocating motion with the first empirical coefficient as an exponent, a power function related to the cycle of the sawing wire's reciprocating motion with the second empirical coefficient as an exponent, and a power function related to the feeding speed with the third empirical coefficient as an exponent;

[0097] in a historical wire sawing process, collect historical wire sawing parameters and detect the roughness in the target wavelength range of the bare wafer that has completed the historical wire sawing process;

[0098] substitute the historical wire sawing parameters and the roughness in the target wavelength range of the bare wafer that has completed the historical wire sawing process into the fitting function to obtain the first empirical coefficient, the second empirical coefficient, and the third empirical coefficient in the fitting function.

[0099] In some examples, the fitting part 704 is configured to:

[00100] logarithmically transform the fitting function to obtain a logarithmically transformed fitting function;

[00101] use the historical wire sawing parameters and the detected roughness in the target wavelength range of the bare wafer that has completed the historical wire sawing process to calculate the first empirical coefficient, the second empirical coefficient, and the third empirical coefficient in the fitting function by a least square method.

[00102] In some examples, the detection part 701 is configured to:

[00103] for each sampling point on the surface of the bare wafer, obtain an original measurement data regarding a wafer surface height at each sampling point through a single-point measurement solution;

[00104] based on the original measurement data of all sampling points on the surface of the bare wafer, obtain the wave signal of each sampling point in the target wavelength range through a filter corresponding to the target wavelength range for each sampling point;

[00105] determine the roughness in the target wavelength range of the bare wafer based on the statistical value of the amplitude of the wave signals of all sampling points in the target wavelength range.

[00106] In some examples, the filter is a circular filter and is composed of a double Gaussian filter function;

[00107] the radius of the action range of the filter is determined by the distance between the sampling point and the center of the bare wafer, and when the distance from the sampling point to the center of the bare wafer is less than or equal to a critical distance, the radius of the action range of the filter is a first radius; when the distance from the sampling point to the center of the bare wafer is greater than the critical distance, the radius of the action range of the filter is a second radius; where, both the first radius and the second radius are determined by the upper limit of the target wavelength range, and the first radius is greater than the second radius.

[00108] In some examples, the detection part 701 is configured to:

[00109] divide the bare wafer into a plurality of analysis areas;

[00110] calculate the range of the amplitude of the wave signals in the target wavelength range for each analysis area based on the amplitude values of the wave signals of the sampling points in each analysis area in the target wavelength range**;**

[00111] determine the average of the ranges of the amplitudes of the wave signals in all analysis areas within the target wavelength range as the roughness of the bare wafer in the target wavelength range.

[00112] In some examples, when the target wavelength range is 0 to 1.8 micrometer wavelength, the roughness threshold is 1 nm;

[00113] when the target wavelength range is 1.8 micrometer wavelength to 22 micrometer wavelength, the roughness threshold is 3 nm;

[00114] when the target wavelength range is 22 micrometer wavelength to 20 millimeter wavelength, the roughness threshold is 25 nm.

[00115] It is to be noted that, for the specific implementation of the functions configured for each “part” in the above-mentioned apparatus, reference can be made to the implementation and examples of the corresponding steps in the aforementioned method for improving wafer roughness, which will not be repeated here.

[00116] Referring to FIG. 9, which shows a block diagram of the structure of a computing device provided in an exemplary embodiment of the present disclosure. In some examples, the computing device 90 may be at least one of several devices such as a smartphone, a smartwatch, a desktop computer, a laptop computer, a virtual reality terminal, an augmented reality terminal, a wireless terminal, and a portable knee-top computer. The computing device 90 has a communication function and can access a wired network or a wireless network. The computing device 90 can broadly refer to one of a plurality of terminals, and those skilled in the art can know that the number of the above-mentioned terminals can be more or fewer. In some examples, the computing device 90 can receive data based on the wired network or wireless network it accesses. It can be understood that the computing device 90 undertakes the calculation and processing work of the technical solution of the present disclosure, which is not limited by the present disclosure.

[00117] As shown in FIG. 9, the computing device in the present disclosure can include one or more of the following components: a processor 910 and a memory 920.

[00118] Optionally, the processor 910 uses various interfaces and lines to connect various parts within the entire computing device, and executes various functions of the computing device and processes data by running or executing instructions, programs, code sets or instruction sets stored in the memory 920, and by calling data stored in the memory 920. Optionally, the processor 910 may be implemented in at least one of the following hardware forms: Digital Signal Processing (DSP), Field-Programmable Gate Array (FPGA), and Programmable Logic Array (PLA). The processor 1110 may integrate a combination of one or more of a Central Processing Unit (CPU), a Graphics Processing Unit (GPU), a Neural-network Processing Unit (NPU), and a baseband chip. Among them, the CPU mainly handles the operating system, user interface, and applications, etc.; the GPU is responsible for the rendering and drawing of content to be displayed on the touch display screen; the NPU is used to implement Artificial Intelligence (AI) functions; and the baseband chip is used to handle wireless communications. It can be understood that the above-mentioned baseband chip may also not be integrated into the processor 910, but may be implemented separately by a single chip.

[00119] The memory 920 may include a Random Access Memory (RAM) or a Read-Only Memory (ROM). Optionally, the memory 920 includes a non-transitory computer-readable storage medium. The memory 920 can be used to store instructions, programs, code, code sets, or instruction sets. The memory 920 may include a program storage area and a data storage area, wherein the program storage area can store instructions for implementing an operating system, instructions for implementing at least one function (such as touch function, sound playback function, image playback function, etc.), instructions for implementing the aforementioned various method embodiments, etc.; the data storage area can store data created according to the use of the computing device, etc.

[00120] In addition, those skilled in the art can understand that the structure of the computing device shown in the above figure does not constitute a limitation on the computing device. The computing device may include more or fewer components than shown, or a combination of certain components, or a different arrangement of component. For example, the computing device may also include a display screen, a camera assembly, a microphone, a speaker, a radio frequency circuit, an input unit, sensors (such as an accelerometer, an angular velocity sensor, a light sensor, etc.), an audio circuit, a WiFi module, a power supply, a Bluetooth module, and other components, which will not be described in detail herein.

[00121] An embodiment of the present disclosure further provides a computer readable storage medium storing at least one instruction, wherein the at least one instruction is used for being

executed by a processor to implement the method for improving wafer roughness as described in the above various embodiments.

[00122] An embodiment of the present disclosure further provides a computer program product, which includes computer instructions stored in a computer readable storage medium; a processor of a computing device reads the computer instructions from the computer readable storage medium, and the processor executes the computer instructions, so that the computing device executes the method for improving wafer roughness provided in the various optional implementations of the above aspects.

[00123] The present disclosure also provides a wafer, which is obtained through the wire sawing process improved by the method for improving wafer roughness described in the above technical solution, and the roughness in the target wavelength range is at least one of the following:

[00124] when the target wavelength range is 0 to 1.8 micrometer wavelength, the roughness is 0.01 nm to 1 nm;

[00125] when the target wavelength range is 1.8 micrometer wavelength to 22 micrometer wavelength, the roughness is 1 nm to 3 nm;

[00126] when the target wavelength range is 22 micrometer wavelength to 20 millimeter wavelength, the roughness is 3 nm to 30 nm.

[00127] Those skilled in the art should be able to realize that in the above one or more examples, the functions described in the embodiments of the present disclosure can be implemented by hardware, software, firmware, or any combination thereof. When implemented using software, these functions can be stored in a computer readable medium or transmitted as one or more instructions or codes on a computer readable medium. Computer readable media include computer storage media and communication media, where communication media include any media that facilitates the transmission of a computer program from one place to another. The storage medium can be any available medium that can be accessed by a general-purpose or special-purpose computer.

[00128] It is to be noted that the technical solutions recorded in the present disclosure can be arbitrarily combined without conflict.

[00129] The above description is merely a specific embodiment of the present disclosure, but the protection scope of the present disclosure is not limited thereto. Any changes or substitutions that can be easily conceived by a person skilled in the art within the technical scope disclosed in the present disclosure should be included in the scope of protection of the

present disclosure. Therefore, the protection scope of the present disclosure should be subject to the protection scope of the claims.

What is claimed is:

1. A method for improving wafer roughness, comprising:

detecting a roughness in a target wavelength range of a bare wafer obtained after a wire sawing process;

when the roughness is greater than or equal to a set roughness threshold, selecting a to-be-adjusted wire sawing parameter according to priorities of wire sawing parameters indicated by a fitting function between multiple wire sawing process parameters and the roughness in the target wavelength range.

2. The method according to claim 1, wherein the multiple wire sawing parameters include: a movement speed of a sawing wire's reciprocating motion, a cycle of the sawing wire's reciprocating motion and a feeding speed of a silicon ingot to be processed;

the fitting function is expressed as a product of power functions of the movement speed of the sawing wire's reciprocating motion, the cycle of the sawing wire's reciprocating motion and the feeding speed of the silicon ingot to be processed, respectively.

3. The method according to claim 1, wherein the method further comprises:

forming an initialized fitting function based on a product of a power function of the movement speed of the sawing wire's reciprocating motion with a first empirical coefficient as an exponent, a power function of the cycle of the sawing wire's reciprocating motion with a second empirical coefficient as an exponent, and a power function of the feeding speed with a third empirical coefficient as an exponent;

in a historical wire sawing process, collecting historical wire sawing parameters and detecting roughness in the target wavelength range of a bare wafer obtained after the historical wire sawing process;

substituting the historical wire sawing parameters and the roughness in the target wavelength range of the bare wafer the historical wire sawing process into the fitting function to obtain the first empirical coefficient, the second empirical coefficient, and the third empirical coefficient in the fitting function.

4. The method according to claim 3, wherein the substituting the historical wire sawing parameters and the roughness in the target wavelength range of the bare wafer obtained after the historical wire sawing process into the fitting function to obtain the first empirical coefficient, the second empirical coefficient, and the third empirical coefficient in the fitting function, comprises:

performing logarithmic transformation on the fitting function to obtain a logarithmically transformed fitting function;

substituting the historical wire sawing parameters and the roughness in the target wavelength range of the bare wafer obtained after the historical wire sawing process into the logarithmically transformed fitting function to calculate the first empirical coefficient, the second empirical coefficient and the third empirical coefficient via the method of least squares.

5. The method according to claim 1, wherein the detecting a roughness in a target wavelength range of a bare wafer obtained after a wire sawing process, comprises:

for each sampling point on a surface of the bare wafer, obtaining an original measurement data of a wafer surface height at each sampling point through a single-point measurement solution;

based on original measurement data of all sampling points on the surface of the bare wafer, for each sampling point, obtaining a wave signal of each sampling point in the target wavelength range through a filter corresponding to the target wavelength range; and

determining the roughness in the target wavelength range of the bare wafer based on a statistical value of amplitudes of the wave signals of all sampling points in the target wavelength range.

6. The method according to claim 5, wherein the filter is a circular filter and is composed of a double Gaussian filter function;

the filter has an action range with a radius determined by a distance between the sampling point and a center of the bare wafer; when the distance from between sampling point and the center of the bare wafer is less than or equal to a critical distance, the radius of the action range of the filter is a first radius; when the distance between the sampling point and the center of the bare wafer is greater than the critical distance, the radius of the action range of the filter is a second radius; both the first radius and the second radius are determined by an upper limit of the target wavelength range, and the first radius is greater than the second radius.

7. The method according to claim 5, wherein the determining the roughness in the target wavelength range of the bare wafer based on a statistical value of amplitudes of the wave signals of all sampling points in the target wavelength range, comprises:

dividing the bare wafer into a plurality of analysis areas;

calculating a range of amplitudes of wave signals in the target wavelength range for each analysis area based on amplitude values of wave signals in the target wavelength range of sampling points in each analysis area;

determining an average of the ranges of the amplitudes of the wave signals in the target wavelength range of all analysis areas as the roughness of the bare wafer in the target wavelength range.

8. The method according to any one of claims 1 to 7, wherein when the target wavelength range is 0 to 1.8 micrometer wavelength, the roughness threshold is 1 nm;

when the target wavelength range is 1.8 micrometer wavelength to 22 micrometer wavelength, the roughness threshold is 3 nm;

when the target wavelength range is 22 micrometer wavelength to 20 millimeter wavelength, the roughness threshold is 25 nm.

9. An apparatus for improving wafer roughness, comprising: a detection part, a comparison part, and a process improvement part; wherein

the detection part is configured to detect a roughness in a target wavelength range of a bare wafer obtained after a wire sawing process;

the comparison part is configured to compare the roughness with a set roughness threshold, and to trigger the process improvement part when the roughness is greater than or equal to the set roughness threshold;

the process improvement part is configured to select a to-be-adjusted wire sawing parameter according to priorities of wire sawing parameters indicated by a fitting function between multiple wire sawing process parameters and the roughness in the target wavelength range.

10. A computing device, comprising: a processor and a memory; wherein the processor is used to execute instructions stored in the memory to implement the method for improving wafer roughness according to any one of claims 1 to 8.

11. A computer readable storage medium, comprising at least one instruction stored thereon; wherein the at least one instruction, when executed by a processor, causes the processor to implement the method for improving wafer roughness according to any one of claims 1 to 8.

12. A wafer, wherein the wafer is obtained through a wire sawing process improved by the method according to any one of claims 1 to 8, and the roughness in the target wavelength range is at least one of the following:

when the target wavelength range is 0 to 1.8 micrometer wavelength, the roughness is 0.01 nm to 1 nm;

when the target wavelength range is 1.8 micrometer wavelength to 22 micrometer wavelength, the roughness is 1 nm to 3 nm;

when the target wavelength range is 22 micrometer wavelength to 20 millimeter wavelength, the roughness is 3 nm to 30 nm.