

CRYSTALLINE SILICON INGOT, METHOD OF FABRICATING THE SAME AND POLY-SI WAFER MADE THEREFROM

CROSS-REFERENCE TO RELATED APPLICATION

5 This utility application claims priority to Taiwan application serial number 100143484, filed Nov. 28, 2011, and Taiwan application serial number 101208779, filed May 10, 2012, which are incorporated herein by reference.

BACKGROUND OF THE INVENTION

1. Field of the invention

10 The invention relates to a crystalline silicon ingot and a fabricating method thereof, and particularly to a crystalline silicon ingot having a low bulk defect density and small-sized silicon grains at the bottom thereof by using a nucleation promotion layer and a fabricating method thereof.

2. Description of the prior art

15 Most of the solar cells produce a photovoltaic (PV) effect when absorbing sunlight. Currently, the solar cell is made of a silicon-based material, since for the most parts, silicon is the second most abundant and accessible element in the world. Also, silicon is cost-effective, nontoxic, and chemically stable, and becomes broadly used in semiconductor applications.

20 There are three kinds of silicon-based materials for fabricating solar cells, i.e., single-crystal silicon (mono-Si), polysilicon (poly-Si), and amorphous silicon (a-Si). Poly-Si is much less expensive than mono-Si when produced by Czochralski method

(CZ method) or floating zone method (FZ method), so it is usually used as a raw material of the solar cell due to the economic concern.

Conventionally, poly-Si for solar cells is fabricated by a common casting process. That is, it is prior art to produce poly-Si for solar cells by a casting process.

5 In brief, the poly-Si solar cell is fabricated by melting high purity silicon in a mold like quartz crucible, then cooling with a controlled solidification to form a poly-Si ingot, followed by slicing it into wafers that fit compactly into a PV cell module for further application. The ingot formed by the above process is in fact in the form of an aggregation of silicon crystals having random crystal orientations.

10 It's difficult to texture (roughen) the surface of the poly-Si chip due to the random crystal orientations of grains. Surface texturing can enhance the efficiency of the PV cell by reducing light reflection and thus increasing solar energy absorption on the surface of the cell. In addition, "kinks" that form in the boundaries between the grains of conventional multi-crystalline silicon tend to nucleate structural defects
15 in the form of clusters or lines of dislocations. These dislocations, and the impurities tended to be attracted by dislocations, are believed to cause a fast recombination of electrical charge carriers in a photovoltaic cell made from conventional multi-crystalline silicon, reducing the power output of the solar cell. Thus, the poly-Si PV cell usually has lower efficiency than the equivalent mono-Si PV cell, even a radial
20 distribution of defects exists in the latter manufactured by the current technique. However, because of the relatively simple fabricating process and lower cost for the poly-Si solar cell and also the effective defect passivation step in processing the solar cell, poly-Si is still more broadly used as the silicon source of the PV cell.

Currently, it has been developed that crystalline silicon ingot is fabricated using
25 a mono-Si seed layer and based on directional solidification, in which a large-sized, (100)-oriented mono-Si cubic is generally employed as a seed. Unfortunately, during the competition among the (100)-oriented grain and the random nucleation grain, the latter is prevailing. For maximizing the seeded crystalline volume in an ingot, the

current technique takes advantage of the boundaries in (111)-oriented silicon to surround the regions occupied by the (100)-oriented silicon seeds, thereby impeding successfully the growth of crystals having other orientations. In this way, a high quality ingot of mono-Si or bi-crystal silicon block may be obtained, in which the lifetime of the minority charge carriers is maximized in the resultant wafer employed for fabricating the high-performance solar cell. Herein, the term “single crystal silicon (mono-Si)” is referred to a bulk of mono-Si that has a single uniform crystal orientation throughout the bulk, while the term “bi-crystal silicon” is referred to a silicon bulk that has one uniform crystal orientation in or over 50% of the volume of the bulk, and has another uniform crystal orientation in the rest of the volume of the bulk. For example, such bi-crystal silicon may include a body of single crystal silicon having one crystal orientation next to another body of single crystal silicon having a different crystal orientation making up the balance of the volume of crystalline silicon. Additionally, conventional multi-crystalline silicon refers to crystalline silicon having cm-scale grain size distribution, with multiple randomly oriented crystals located within a body of silicon. However, the crystalline silicon ingot fabricated by the current technique described above where the expensive mono-Si is used as a seed is rather costly.

There are other techniques without using expensive mono-Si as a seed. Laterally grown crystals are spread over the bottom of the crucible by local undercooling first, and then columnar crystals are grown upwards. The large-sized silicon grains of thus obtained ingots have a low bulk defect density. Therefore, the solar cell made from silicon wafers sliced from the crystalline silicon ingot fabricated by the above techniques may have higher photoelectric conversion efficiency.

However, the above current techniques using poly-Si are only proved successful in the laboratory, while in an industrial level production, it's usually more difficult to perform the poly-Si casting by controlling the growth of the dendrites to be spread over the bottom of the crucible using local undercooling. Industrial-scale multi-crystalline silicon casting is affected by the heating uniformity of the crucible and the

entirety, which increases variance of the initial undercooling controlling. Therefore, the poly-Si at the bottom of the crucible tends to grow into a large-sized grain and the defect density in this area will become elevated. The defect density becomes higher rapidly as the large-sized grains proceed to grow, resulting in poor quality of the entire crystalline silicon ingot and the solar cell with reduced photoelectric conversion efficiency.

In addition, referring FIG. 1, the detected result of crystal orientations of current poly-Si ingots projected on a triangle composed of crystal orientations (001), (111) and (101) in a polar diagram of crystal geometry is schematically shown. FIG. 1 shows that the dominant orientations of current poly-Si ingots are between (112) and (315) and/or between (313) and (111). Herein, the term "dominant orientation" is referred to the group of crystal orientations that are present in a silicon ingot at a volume percentage of greater than 50%.

SUMMARY OF THE INVENTION

In view of the forgoing problems, one scope of the invention is to provide a crystalline silicon ingot having a low bulk defect density and small-sized silicon grains at the bottom thereof and a method of fabricating the crystalline silicon ingot in which a nucleation promotion layer is used for facilitating the nucleation of silicon grains.

In addition, another scope of the invention is to provide a method of fabricating a crystalline silicon ingot having crystalline characteristics distinguishable from those of conventional crystalline silicon ingots.

In one aspect of the invention, a method of fabricating the crystalline silicon ingot includes the following steps. As a first step, a nucleation promotion layer is loaded onto a bottom of a mold where the mold itself defines a vertical direction. Next, a silicon source is provided on the nucleation promotion layer in the mold,

followed by heating the mold until the silicon source is melted into a silicon melt completely. Then, at least one thermal control parameter regarding the silicon melt is controlled to enable a plurality of silicon grains from the silicon melt to nucleate on the nucleation promotion layer and to grow in the vertical direction. As the final step,
5 the at least one thermal control parameter is proceed to be controlled for growing the plurality of the silicon grains in the vertical direction until entirety of the silicon melt is solidified to obtain the crystalline silicon ingot.

In one embodiment, the nucleation promotion layer functions to inhibit the increase of the defect density of the plurality of the silicon grains during the growth
10 process. The defect density's increment rate of thus obtained silicon crystalline ingot in the vertical direction ranges from 0.01%/mm to 10%/mm.

In one embodiment, the silicon grains that are immediately adjacent to the nucleation promotion layer have an average grain size of less than about 10 mm.

In one embodiment, the nucleation promotion layer is composed of a plurality of
15 crystal particles with irregular shape. Each of the crystal particles has a particle size of less than about 50 mm.

In one embodiment, the plurality of the crystal particles are poly-Si particles, mono-Si particles, single crystal silicon carbide or other crystal particles having a melting point higher than 1400°C and capable of facilitating nucleation.

20 In another embodiment, the nucleation promotion layer is a plate made of a material having a melting point higher than about 1400°C. The surface of the plate contacting the silicon melt has a roughness of 300 μm to 1000 μm to provide multiple nucleation sites for the plurality of the silicon grains.

In one embodiment, the dominant crystal orientations in the silicon grains
25 fabricated by the method of the invention are between (001) and (111), and a volume percentage of the silicon grains with the dominant crystal orientations is greater than

about 50%.

In one embodiment, a heater is located above the mold, and a directional solidification block is located below the mold. The at least one thermal control parameter may include a first temperature gradient from the heater to the mold, a
5 second temperature gradient from the bottom of the silicon melt to the top of the directional solidification block, a heat transfer flux and so on.

In another aspect of the invention, a method of fabricating the crystalline silicon ingot includes the following steps. As a first step, a nucleation promotion layer is loaded onto a bottom of a mold, wherein the nucleation promotion layer is formed by
10 jointing a plurality of crystal particles with irregular shape together and the mold itself defines a vertical direction. Next, a silicon source is provided on the nucleation promotion layer in the mold, followed by heating the mold until the silicon source is melted into a silicon melt completely. Then, at least one thermal control parameter regarding the silicon melt is controlled to enable a plurality of silicon grains from the
15 silicon melt to nucleate on the nucleation promotion layer and to grow in the vertical direction. As the final step, the at least one thermal control parameter is proceed to be controlled for growing the plurality of the silicon grains in the vertical direction until entirety of the silicon melt is solidified to obtain the crystalline silicon ingot.

Contrary to prior art where expensive mono-Si seeds and local undercooling are
20 involved to form silicon grains on the bottom of the crucible, the invention provides the silicon melt with dense nucleation sites by using the nucleation promotion layer with lower cost. A high-density grain distribution is achieved to inhibit the generation of a certain fast-grown orientations, thereby greatly decreasing the distribution ratio of large-sized silicon grains. Since the competition is much less
25 frequently occurred between small-sized grains during the growth process, and small-sized grains tend to grow upward in a generally single direction due to great denseness in grain population, the situation that the small-sized grains are overwhelmed by the large-sized grains is effectively diminished so that the columnar

crystals are allowed to grow completely. In addition, during the growth of the crystals, the grain boundaries distributed densely in the ingot of the invention by stress field thereof attract defects to agglomerate or to slip on the grain boundaries to release thermal stress. Accordingly, the increase of defects such as dislocation is hindered effectively, thereby leading to a better quality of the crystalline silicon ingot and a higher photoelectric conversion efficiency of the solar cell made therefrom. The crystalline silicon ingot made by the method of the invention silicon ingot has crystalline characteristics distinguishable from those of current crystalline silicon ingots.

The characteristics, realization and functions of the invention are disclosed in the following description with reference to the preferred exemplified embodiments and the accompanying drawings.

BRIEF DESCRIPTION OF THE APPENDED DRAWINGS

These and other features and advantages of the various embodiments disclosed herein will be better understood with respect to the following description and drawings, in which like reference numerals refer to like parts throughout, and in which:

FIG. 1 is a diagram schematically showing the detected result of crystal orientations of current poly-Si ingots projected on a triangle composed of crystal orientations (001), (111) and (101) in a polar diagram of crystal geometry;

FIGS. 2A-2D are schematically sectional views of a method of fabricating a crystalline silicon ingot according to one preferred embodiment of the invention;

FIG. 3 is a sectional view of a DSS crystal growth furnace according to one preferred embodiment of the invention in which a nucleation promotion layer loaded on the bottom of a mold is a plate;

FIG. 4 is a diagram showing a ratio of various crystal orientations in the crystalline silicon ingot fabricating by the method of the invention;

FIG. 5 is a diagram comparing the silicon grain size of the crystalline silicon ingot fabricated according to one preferred embodiment of the invention and the
5 conventional method;

FIG. 6 is a diagram showing comparison between the defect density of the crystalline silicon ingot fabricated by one preferred embodiment of the invention and that of the crystalline silicon ingot fabricated by conventional method;

FIG. 7 is a metallograph regarding the grain size at the bottom, middle, and top
10 of the crystalline silicon ingot of one preferred embodiment;

FIG. 8 is a metallograph regarding the grain size at the bottom, middle, and top of the conventional crystalline silicon ingot;

FIG. 9 is a bar graph showing the photoelectric conversion efficiency of the solar cell made from the bottom, middle, and top (about 250 mm vertically away
15 from the bottom) of the ingots A (of one preferred embodiment) and B (conventional one) for comparison;

FIG. 10 is a diagram showing the defect density variation along height of the crystalline silicon ingots fabricated by the method of the invention and by using mono-Si chucks with various particle sizes as the nucleation promotion layer.

20 DETAILED DESCRIPTION OF THE INVENTION

FIGS. 2A-2D are schematically sectional views of a method of fabricating a crystalline silicon ingot according to one preferred embodiment of the invention.

As shown in FIG. 2A, a crystal growth furnace 1 substantially according to DSS

(directional solidification system) (referred to as the “DSS furnace” hereinafter) is employed to carry out the fabricating of the invention. The DSS furnace 1 includes a body 10, a heat insulating cage 12 having an upper insulating cover 122 and a lower insulating plate 124, a directional solidification block 18 within the heat insulating cage 12, at least one support column 19 supporting the directional solidification block 18, a base 17 on the directional solidification block 18, a mold 16 within the base 17, a heater 14 above the mold 16 and an inert gas duct 11 traversing the body 10 and the heat insulating cage 12.

In practice, the mold 16 may be a quartz crucible. The directional solidification block 18 may be made of graphite. The base 17 may be made of graphite. The inert gas duct 11 is configured to introduce argon (Ar) gas into the heat insulating cage 12.

As shown in FIG. 2A, the method of the invention begins with loading a nucleation promotion layer 2 onto the bottom of the mold 16 which defines a vertical direction V , followed by providing a silicon source 30 on the nucleation promotion layer 2 in the mold 16. The mold 16 containing the nucleation promotion layer 2 and the silicon source 30 is placed in the base 17.

Next, the mold 16 is heated until the silicon source 30 is melted down into a silicon melt 32 completely, as shown in FIG. 2B.

Then, at least one thermal control parameter regarding the silicon melt 32 is controlled to enable a plurality of silicon grains 34 to nucleate from the silicon melt 32 on the nucleation promotion layer 2 and to grow in the vertical direction V , as shown in FIG. 2C. In one embodiment, the silicon grains 34 nucleate from the silicon melt 32 on the nucleation promotion layer 2, and grow to have an average grain size of two to three-fold larger are grown in the vertical direction V . The growth multiple of average grain size of silicon grains is calculated by the following formula:

S_f/S_i ; where S_i indicates average grain size of nucleated silicon grains 34, S_f indicates average grain size of nucleate and then grown silicon grains 34.

The at least one thermal control parameter includes a heat transfer flux. As shown in FIG. 2C, during the crystal growth process, in the DSS furnace 1, as the
5 upper insulating cover 122 moves upward slowly, a gap is thus formed in the closed space secured initially by the heat insulating cage 12. The heat transfer flux will be created since the gap becomes a medium for heat exchange between the inside and the outside of the heat insulating cage 12

As the final step, as shown in FIG. 2D, the at least one thermal control
10 parameter is proceeded to be controlled subsequently for growing the plurality of the silicon grains 34 in the vertical direction V until entirety of the silicon melt 32 is solidified. Thus is obtained the silicon crystalline ingot 3.

In one embodiment, the nucleation promotion layer 2 also functions to inhibit the increase of the defect density of the plurality of the silicon grains 34 during the
15 growth process. The defect density's increment rate of thus obtained silicon crystalline ingot 3 in the vertical direction V ranges from 0.01%/mm to 10%/mm determined by the following formula:

$$(D_{x2}-D_{x1})/(x2-x1)$$

where $x1$ and $x2$ indicate respectively two different levels in the vertical direction of
20 the ingot, and D_{x1} and D_{x2} indicate respectively the defect densities of the ingot in the tangent planes taken at levels $x1$ and $x2$.

Even small-sized silicon grains can inhibit the increment rate effectively. In the ingot 3 of the invention, there is a higher possibility for the small-sized silicon grains (<10 mm) to appear in the center of the bottom, while around the side or corner of
25 the bottom of the ingot, only a smaller number of the small-sized silicon grains (<10 mm) appear. It is found that the ratio of area occupied by the small-sized silicon

grains in a tangent plane along the vertical direction V affects the growth rate and the increment rate of the defect density of the grains.

In one embodiment, the silicon grains 34 those are immediately adjacent to the nucleation promotion layer 2 have an average grain size of less than about 10 μm .

5 In one embodiment, the nucleation promotion layer 2 is composed of a plurality of crystal particles 22 with irregular shape, each of which has a particle size of less than about 50 μm .

10 In one embodiment, the plurality of the crystal particles 22 may be poly-Si particles, mono-Si particles, single crystal silicon carbide or other crystal particles having a melting point higher than 1400°C and capable of facilitating nucleation. In an example, the plurality of the crystal particles 22 may be commercially available poly-Si or mono-Si chips or chunks that cost much less significantly than the mono-Si seeds. Next, the poly-Si or mono-Si chips or chunks are spread over the bottom of the mold 16 to form a nucleation promotion layer 2 as shown in FIG. 2A. During the
15 process that the silicon source 30 is melted down into the silicon melt 32 completely with the poly-Si or mono-Si chips filled as the nucleation promotion layer 2, as shown in FIG. 2B, portions of the poly-Si or mono-Si chips or chunks are melted and the others are not melted. For preventing the poly-Si or mono-Si chips or chunks from being completely melted, an opening is maintained between the upper
20 insulating cover 122 and the lower insulating plate 124 as shown in FIG. 2B to facilitate the heat dissipation of the lower part of the mold 16.

25 In another embodiment, as shown in FIG. 3, the nucleation promotion layer 2 may be a plate 24 made of a material having a melting point higher than about 1400 °C such as high purity graphite, silicon, or ceramic materials like aluminum oxide, silicon carbide, silicon nitride, aluminum nitride. The surface of the plate 24 contacting the silicon melt 32 has a roughness of 300 μm to 1000 μm to provide multiple nucleation sites for the plurality of the silicon grains 34. Particularly, like

reference numerals in FIG. 3 indicate like parts in FIG. 2C having substantially the same structure and function.

Referring back to FIGS. 2A-2D, the heater 14 is located above the mold 16, and the directional solidification block 18 is located below and in indirect contact with the mold 16. The thermal control parameters may be, for example, a first temperature gradient from the heater 14 to the mold 16, a second temperature gradient from the bottom of the silicon melt 20 to the top of the directional solidification block 18, or a heat transfer flux. In practice, the first temperature gradient has to be controlled below $0.4^{\circ}\text{C}/\text{cm}$, which could be achieved by for example increasing the distance from the heater 14 to the mold 16 or controlling the heater 14 at the set point of less than 1410°C . The second temperature gradient has to be controlled above $17^{\circ}\text{C}/\text{cm}$, which could be achieved by for example increasing the thickness of the directional solidification block 18. Also, the heat transfer flux has to be controlled larger than $37000\text{ W}/\text{m}^2$ by for example adjusting the rising speed of the upper insulating cover 122 to 3 cm/hr or more.

In another preferred embodiment, the method of fabricating the crystalline silicon ingot is disclosed as follows. First, a nucleation promotion layer 2 is loaded onto the bottom of the mold 16. The nucleation promotion layer 2 is formed by jointing multiple crystal particles 22 with irregular shape. The mold 16 itself defines a vertical direction V . In practice, the nucleation promotion layer 2 is obtained by cutting the lower part of another crystalline silicon ingot fabricated with the method of the invention. In this way, the nucleation promotion layer 2 may be recovered for subsequent uses.

Next, a silicon source 30 is provided in the mold 16 and placed on the nucleation promotion layer 2.

Afterwards, the mold 16 is heated until the silicon source 30 is melted completely into a silicon melt 32. Subsequently, at least one thermal control

parameter regarding the silicon melt 32 is controlled to enable a plurality of silicon grains 34 to nucleate from the silicon melt 32 on the nucleation promotion layer 2 and to grow in the vertical direction V . In one embodiment, the silicon grains 34 nucleate from the silicon melt 32 on the nucleation promotion layer 2, and grow to
5 have an average grain size of two to three-fold larger are grown in the vertical direction V .

At last, the at least one thermal control parameter is proceeded to be controlled for growing the plurality of the silicon grains 34 in the vertical direction V until entirety of the silicon melt 32 is solidified. Thus is obtained the silicon crystalline
10 ingot 3.

In one embodiment, the nucleation promotion layer 2 also functions to inhibit the increase of the defect density of the plurality of the silicon grains 34 during the growth process. The defect density's increment rate of thus obtained silicon crystalline ingot 3 in the vertical direction V ranges from 0.01%/mm to 10%/mm.

15 In one embodiment, the silicon grains 34 that are immediately adjacent to the nucleation promotion layer 2 have an average grain size of less than about 10 mm.

In one embodiment, the nucleation promotion layer 2 is composed of a plurality of crystal particles 22 with irregular shape, each of which has a particle size of less than about 50 mm.

20 The dominant crystal orientations in the silicon grains fabricated by the method of the invention are between (001) and (111), and a volume percentage of the silicon grains with the dominant crystal orientations is greater than about 50%.

The crystalline silicon ingot of the invention has a bottom and defines a vertical direction. The crystal silicon ingot of the invention includes a plurality of silicon
25 grains growing in a vertical direction and a nucleation promotion layer on the bottom. Also, in the ingot, the silicon grains those are immediately adjacent to the nucleation

promotion layer have an average grain size of less than about 10 mm. Further, the defect density's increment rate of thus obtained silicon crystalline ingot in the vertical direction ranges from 0.01%/mm to 10%/mm.

5 In one preferred embodiment, the nucleation promotion layer is composed of a plurality of crystal particles with random geometry, each of which has a grain size of less than about 50 mm.

10 In another preferred embodiment, the plurality of the crystal particles may be poly-Si particles, mono-Si particles, single crystal silicon carbide or other crystal particles having a melting point higher than 1400°C and capable of facilitating nucleation.

15 In yet another preferred embodiment, the nucleation promotion layer may be a plate made of a material having a melting point higher than about 1400°C such as high purity graphite, silicon, or ceramic materials like aluminum oxide, silicon carbide, silicon nitride, aluminum nitride. The interface between the plate and the silicon melt has a roughness of 300 μm to 1000 μm to provide multiple nucleation sites for the plurality of the silicon grains.

20 Referring to FIG. 4, crystalline geometric analysis of the crystalline silicon ingot fabricating by the method of the invention is conducted in an EBSD (electron back-scattered diffraction) way, and a ratio of various crystal orientations in the silicon grains the crystalline silicon ingot is shown in FIG. 4.

FIG. 4 indicates that the dominant crystal orientations in the silicon grains fabricated according to a preferred embodiment of the method of the invention are between (001) and (111), and a volume percentage of the silicon grains with the dominant crystal orientations is greater than about 70%.

25 As shown in FIG. 4, the silicon grains of the crystalline silicon ingot of the

invention include at least three crystal orientations which include (112), (113) and (115). In a slice (poly-Si wafer) sampled above the bottom of the crystalline silicon ingot, the volume percentage of the silicon grains with the crystal orientations (112), (113) and (115) is greater than 45%. In addition, in a slice (poly-Si wafer) sampled above the bottom of the crystalline silicon ingot, the volume percentage of the silicon grains with the crystal orientation (112) is between 25% and 30%. Further, the crystal orientations of the silicon grains further include (113) and (115), and the volume percentage of the silicon grains with the crystal orientations (113) and (115) is between 20% and 35%.

As shown in FIG. 4, other than (112), (113) and (115), the crystal orientations of the silicon grains further include (001) and (111). In addition, in a slice (poly-Si wafer) sampled above the bottom of the crystalline silicon ingot, the volume percentage of the silicon grains with the crystal orientations (112), (113), (115), (001) and (111) is greater than 50%. Further, in a slice (poly-Si wafer) sampled above the bottom of the crystalline silicon ingot, the volume percentage of the silicon grains with the crystal orientations (112), (113), (115), (001) and (111) is greater than 70%. In addition, other than (112), (113), (115), (001) and (111), the crystal orientations of the silicon grains further include (313), (101) and (315).

As shown in FIG. 4, in a slice (poly-Si wafer) sampled above the bottom of the crystalline silicon ingot, the volume percentage of the silicon grains with the crystal orientation (112) is greater than that of the silicon grains with any of the crystal

orientations (001), (111), (113) and (115). In addition, in a slice (poly-Si wafer) sampled above the bottom of the crystalline silicon ingot, the volume percentage of the silicon grains with the crystal orientation (001) is less than that of the silicon grains with any of the crystal orientations (111), (112), (113) and (115). In addition, 5 in a slice (poly-Si wafer) sampled above the bottom of the crystalline silicon ingot, the volume percentage of the silicon grains with the crystal orientation (112) is greater than that of the silicon grains with any of the crystal orientations (113) or (115). In addition, in a slice (poly-Si wafer) sampled above the bottom of the crystalline silicon ingot, the volume percentage of the silicon grains with the crystal 10 orientation (111) is greater than that of the silicon grains with any of the crystal orientation (113). Further, in a slice (poly-Si wafer) sampled above the bottom of the crystalline silicon ingot, the volume percentage of the silicon grains with the crystal orientation (115) is greater than that of the silicon grains with any of the crystal orientation (113). In addition, in a slice (poly-Si wafer) sampled above the bottom of 15 the crystalline silicon ingot, the volume percentage of the silicon grains with the crystal orientation (115) is greater than that of the silicon grains with any of the crystal orientation (111).”

FIGS. 5' and 6 are respectively diagrams showing the relationships of the average grain size and the defect density (in defect area ratio, %) with respect to the

level of the ingot between the crystalline silicon ingot A of one preferred embodiment and the crystalline silicon ingot B fabricated by the conventional method. From data for ingot A in FIG. 5, it is noted that the average grain size during initial stage is about 7.4 mm, and the average grain size during final stage is about 18.4 mm. Therefore the final average grain size is about 2.49 ($=18.4/7.4$) of the initial average grain size, which is between 2 and 3. That is to say the average grain size increasing two to three-fold larger in the vertical direction. FIG. 6 particularly shows the defect area ratios around the corner, sidewall, and center of both the ingots A and B.

As shown in FIG. 5, a slice (poly-Si wafer) sampled at the height of from 50 mm to 100 mm of the crystalline silicon ingot has the average grain size of from 7.4 mm to 13 mm. In addition, a slice (poly-Si wafer) sampled at the height of from 100 mm to 200 mm of the crystalline silicon ingot has the average grain size of from 13 mm to 17.6 mm. Further, a slice (poly-Si wafer) sampled at the height of from 200 mm to 250 mm of the crystalline silicon ingot has the average grain size of from 17.6 mm to 18.4 mm. It is evident that the average grain size of the silicon grains of the crystalline silicon ingot of the invention increases from the bottom region in the vertical direction. In other words, in some embodiments, a slice (poly-Si wafer) of the crystalline silicon ingot has the average grain size of less than 10 mm. In some embodiments, a slice (poly-Si wafer) of the crystalline silicon ingot has the average grain size of from 7.4 mm to 18.4 mm.

As shown in FIG. 6, it is evident that a slice (poly-Si wafer) sampled at the height of from 150 mm to 250 mm of the crystalline silicon ingot has a defect density of less than 15%. In addition, a slice (poly-Si wafer) sampled at the height of 100mm

below of the crystalline silicon ingot has a defect density of less than 5%. Further, a slice (poly-Si wafer) sampled at the height of 150 mm below of the crystalline silicon ingot has a defect density of less than 10%. Furthermore, a slice (poly-Si wafer) sampled at the height of 250 mm below of the crystalline silicon ingot has a defect density of less than 15%.”

FIG. 7 is a metallograph of the grain size at the bottom, middle, and top (about 250 mm vertically away from the bottom) of the ingot A of one preferred embodiment, while FIG. 8 is a metallograph of the grain size at the bottom, middle, and top (about 250 mm vertically away from the bottom) of the ingot B. The ingots A and B in the case have a height of 250 mm.

FIG. 9 is a bar graph showing the photoelectric conversion efficiency of the solar cell made from the bottom, middle, and top (about 250 mm vertically away from the bottom) of the ingots A and B for comparison. As shown in FIG. 9, the photoelectric conversion efficiency of the solar cell made from the ingot A ranging from 17.41%-17.56% is higher than that made from the ingot B ranging from 16.70%-17.10% by about 0.6%. Besides, the solar cells made from the bottom, middle, and top of the ingot have relatively approximate photoelectric conversion efficiencies, which is of great commercial value and beneficial to the cell manufacturer.

It is obvious from FIGS. 5-9 that for the ingot B, the silicon grains are large and has lower defect density at the bottom of the crucible, whereas the defect density increases rapidly as the silicon grains proceed to grow. Hence, the crystalline silicon ingot thus obtained has a poor quality on the whole, and the photoelectric conversion efficiency of the solar cell made therefrom is lower without doubt. On the contrary, in fabricating the ingot A, the nucleation promotion layer is introduced as effective and dense nucleation sites for the silicon melt to significantly diminish the

distribution ratio of the large-sized silicon grains. Since the competition is much less frequently occurred between small-sized grains during the growth process, and small-sized grains tend to grow upward in a generally single direction due to great denseness in grain population, the situation that the small-sized grains are
5 overwhelmed by the large-sized grains is effectively reduced so that the columnar crystals are allowed to grow completely. In addition, during the growth of the crystals, the grain boundaries distributed densely in the ingot A contribute to concentrate defects by stress field, or the defects can slip on the grain boundaries to release thermal stress. Accordingly, the increase of defects such as dislocation is
10 hindered effectively, thereby leading to a better quality of the entire crystalline silicon ingot and a higher photoelectric conversion efficiency of the solar cell made therefrom.

Referring to FIG. 10, the defect density variation along height of the crystalline silicon ingots fabricated by the method of the invention and by using mono-Si chucks
15 with various particle sizes as the nucleation promotion layer is shown. The used mono-Si chucks include mono-Si chucks of less than 10 mm, mono-Si chucks of 7 ~ 20 mm, and mono-Si chucks of 10 ~40 mm. Similarly, the defect densities in FIG. 10 are presented by defect areas. It is obvious from FIG. 10 that the defect densities are all less in the crystalline silicon ingots fabricated according to the invention and
20 by using aforesaid mono-Si chucks.

From the above description of the invention, it is manifest that various techniques can be used for implementing the concepts of the invention without departing from the scope thereof. Moreover, while the invention has been described with specific reference to certain embodiments, a person of ordinary skills in the art
25 would recognize that changes can be made in form and detail without departing from the spirit and the scope of the invention. The described embodiments are to be considered in all respects as illustrative and not restrictive. It is intended that the scope of the invention is defined by the appended claims.

What is claimed is:

1. A method of fabricating a crystalline silicon ingot, comprising the steps of:
 - (a) loading a nucleation promotion layer onto a bottom of a mold, the mold itself defining a vertical direction;
 - (b) providing a silicon source on the nucleation promotion layer in the mold;
 - (c) heating the mold until the silicon source is melted into a silicon melt completely;
 - (d) controlling at least one thermal control parameter regarding the silicon melt continually to enable a plurality of silicon grains from the silicon melt to nucleate on the nucleation promotion layer and to grow in the vertical direction; and
 - (e) continuously controlling the at least one thermal control parameter to enable the silicon grains to continuously grow in the vertical direction until entirety of the silicon melt is solidified to obtain the crystalline silicon ingot, wherein the silicon grains that are immediately adjacent to the nucleation promotion layer have an average grain size of less than 10 mm.
2. The method according to claim 1, wherein an increment rate of the defect density of the silicon crystalline ingot in the vertical direction ranges from 0.01%/mm to 10%/mm.
3. The method according to claim 1, wherein the nucleation promotion layer is composed of a plurality of crystal particles with irregular shape, each of which has a particle size of less than 50 mm.

4. The method according to claim 3, wherein the plurality of the crystal particles comprise one selected from the group consisting of a poly-Si particle, a mono-Si particle, and a single crystal silicon carbide.
5. The method according to claim 3, wherein the plurality of the crystal particles comprise a poly-Si particle or a mono-Si particle, and in step (c), the portions of the crystal particles are melted.
6. The method according to claim 1, wherein the nucleation promotion layer is a plate made of a material having a melting point higher than 1400°C, and the surface of the plate contacting the silicon melt has a roughness of 300 μm to 1000 μm for providing the plurality of the silicon grains with multiple nucleation sites.
7. The method according to claim 1, wherein dominant crystal orientations in the silicon grains are between (001) and (111), and a volume percentage of the silicon grains with the dominant crystal orientations is greater than 50%.
8. The method according to claim 1, wherein dominant crystal orientations in the silicon grains are between (001) and (111), and a volume percentage of the silicon grains with the dominant crystal orientations is greater than 70%.
9. A crystalline silicon ingot having a bottom and defining a vertical direction, characterized in that:

the crystalline silicon ingot comprises a plurality of silicon grains grown in the vertical direction and a nucleation promotion layer on the bottom, wherein the silicon grains that are adjacent to the nucleation promotion layer have an average grain size of less than 10 mm.
10. The crystalline silicon ingot according to claim 9, wherein an increment rate of defect density of the silicon crystalline ingot in the vertical direction ranges from 0.01%/mm to 10%/mm.

11. The crystalline silicon ingot according to claim 9, wherein the nucleation promotion layer is composed of a plurality of crystal particles with irregular shape, each of which has a particle size of less than 50 μm .
12. The crystalline silicon ingot according to claim 11, wherein the plurality of the crystal particles include one selected from the group consisting of a poly-Si particle, a mono-Si particle, and a single crystal silicon carbide.
13. The crystalline silicon ingot according to claim 9, wherein the nucleation promotion layer is a plate made of a material having a melting point higher than 1400°C , and the surface of the plate contacting the silicon melt has a roughness of 300 μm to 1000 μm for providing the plurality of the silicon grains with multiple nucleation sites.
14. The crystalline silicon ingot according to claim 9, wherein dominant crystal orientations in the silicon grains are between (001) and (111), and a volume percentage of the silicon grains with the dominant crystal orientations is greater than 50%.
15. The crystalline silicon ingot according to claim 9, wherein dominant crystal orientations in the silicon grains are between (001) and (111), and a volume percentage of the silicon grains with the dominant crystal orientations is greater than 70%.
16. A crystalline silicon ingot having a bottom and defining a vertical direction, characterized in that:

the crystalline silicon ingot comprises a plurality of silicon grains grown in the vertical direction and a nucleation promotion layer on the bottom, wherein the silicon grains that are adjacent to the nucleation promotion layer have an average grain size increasing in the vertical direction and

have at least three crystal orientations.

17. The crystalline silicon ingot according to claim 16, wherein the average grain size increasing two to three-fold larger in the vertical direction.
18. The crystalline silicon ingot according to claim 16, wherein a slice sampled at the height of from 50 mm to 100 mm of the crystalline silicon ingot has the average grain size of from 7.4 mm to 13 mm.
19. The crystalline silicon ingot according to claim 16, wherein a slice sampled at the height of from 100 mm to 200 mm of the crystalline silicon ingot has the average grain size of from 13 mm to 17.6 mm.
20. The crystalline ingot according to claim 16, wherein a slice sampled at the height of from 200 mm to 250 mm of the crystalline silicon ingot has the average grain size of from 17.6 mm to 18.4 mm.
21. The crystalline ingot according to claim 16, wherein the silicon grains that are adjacent to the nucleation promotion layer have an average grain size of less than 10 mm.
22. The crystalline silicon ingot according to claim 16, wherein a slice sampled at the height of from 150 mm to 250 mm of the crystalline silicon ingot has a defect density of less than 15%.
23. The crystalline silicon ingot according to claim 16, wherein a slice sampled at the height of 100 mm below of the crystalline silicon ingot has a defect density of less than 5%.
24. The crystalline silicon ingot according to claim 16, wherein a slice sampled at the height of 150 mm below of the crystalline silicon ingot has a defect density of less than 10%.

25. The crystalline silicon ingot according to claim 16, wherein a slice sampled at the height of 250 mm below of the crystalline silicon ingot has a defect density of less than 15%.
26. The crystalline silicon ingot according to any of claims 16-25, wherein in a slice sampled at the bottom above, the volume percentage of the silicon grains with the crystal orientation (112) is between 25% and 30%.
27. The crystalline silicon ingot according to any of claims 16-25, wherein the at least three crystal orientations comprise (112), (113) and (115).
28. The crystalline silicon ingot according to claim 27, wherein in a slice sampled at the bottom above, the volume percentage of the silicon grains with the crystal orientation (112) is greater than that of the silicon grains with the crystal orientations (113) or (115).
29. The crystalline silicon ingot according to claim 27, wherein in a slice sampled at the bottom above, the volume percentage of the silicon grains with the crystal orientation (115) is greater than that of the silicon grains with the crystal orientations (113).
30. The crystalline silicon ingot according to claim 27, wherein in a slice sampled at the bottom above, the volume percentage of the silicon grains with the crystal orientations (112), (113) and (115) is greater than 45%.
31. The crystalline silicon ingot according to claim 27, wherein the at least three crystal orientations further comprise (001) and (111).
32. The crystalline silicon ingot according to claim 31, wherein in a slice sampled at the bottom above, the volume percentage of the silicon grains with the crystal orientation (111) is greater than that of the silicon grains with the crystal orientations (113).

33. The crystalline silicon ingot according to claim 31, wherein in a slice sampled at the bottom above, the volume percentage of the silicon grains with the crystal orientations (112), (113), (115), (001) and (111) is greater than 50%.
34. The crystalline silicon ingot according to claim 31, wherein in a slice sampled at the bottom above, the volume percentage of the silicon grains with the crystal orientations (112), (113), (115), (001) and (111) is greater than 70%.
35. The crystalline silicon ingot according to claim 31, wherein in a slice sampled at the bottom above, the volume percentage of the silicon grains with the crystal orientation (112) is greater than that of the silicon grains with any of the crystal orientations (001), (111), (113) and (115).
36. The crystalline silicon ingot according to claim 31, wherein in a slice sampled at the bottom above, the volume percentage of the silicon grains with the crystal orientation (115) is greater than that of the silicon grains with the crystal orientation (111).
37. The crystalline silicon ingot according to claim 31, wherein in a slice sampled at the bottom above, the volume percentage of the silicon grains with the crystal orientation (001) is less than that of the silicon grains with any of the crystal orientations (111), (112), (113) and (115).
38. The crystalline silicon ingot according to any of claims 17-26, wherein the nucleation promotion layer is composed of a plurality of crystal particles with irregular shape, each of which has a particle size of less than 50 nm.
39. The crystalline silicon ingot according to claim 38, wherein the plurality of the crystal particles comprise one selected from the group consisting of a poly-Si particle, a mono-Si particle, and a single crystal silicon carbide.

40. The crystalline silicon ingot according to any of claims 17-26, wherein the nucleation promotion layer is composed of a plurality of poly-Si chucks or mono-Si chucks.
41. The crystalline silicon ingot according to any of claims 17-26, wherein the nucleation promotion layer is a plate made of a material having a melting point higher than about 1400°C, and the surface of the plate contacting the silicon grains has a roughness of 300 μm to 1000 μm for providing the plurality of the silicon grains with multiple nucleation sites.
42. A crystalline silicon ingot having a bottom and defining a vertical direction, characterized in that:
- the crystalline silicon ingot comprises a plurality of silicon grains grown in the vertical direction, a nucleation promotion layer on the bottom and a bottom region above the bottom, wherein the silicon grains have at least three crystal orientations, a slice sampled at the height of from 150 mm to 250 mm of the crystalline silicon ingot has a defect density of less than 15%.
43. The crystalline silicon ingot according to claim 42, wherein a slice sampled below 100 mm of the height of the crystalline silicon ingot has a defect density of less than 5%.
44. The crystalline silicon ingot according to claim 42, wherein a slice sampled below 150 mm of the height of the crystalline silicon ingot has a defect density of less than 10%.
45. The crystalline silicon ingot according to claim 42, wherein a slice sampled below 250 mm of the height of the crystalline silicon ingot has a defect density of less than 15%.

46. The crystalline silicon ingot according to any of claims 42-45, wherein a slice sampled above the bottom has the plurality of silicon grains with the crystal orientation (112) and the volume percentage of from 25% to 30%.
47. The crystalline silicon ingot according to any of claims 42-45, wherein the at least three crystal orientations comprise (112), (113) and (115).
48. The crystalline silicon ingot according to claim 47, wherein in a slice sampled at the bottom above, the volume percentage of the silicon grains with the crystal orientation (112) is greater than that of the silicon grains with the crystal orientations (113) or (115).
49. The crystalline silicon ingot according to claim 47, wherein in a slice sampled at the bottom above, the volume percentage of the silicon grains with the crystal orientation (115) is greater than that of the silicon grains with the crystal orientations (113).
50. The crystalline silicon ingot according to claim 47, wherein in a slice sampled at the bottom above, the volume percentage of the silicon grains with the crystal orientations (112), (113) and (115) is greater than 45%.
51. The crystalline silicon ingot according to claim 47, wherein the at least three crystal orientations further comprise (001) and (111).
52. The crystalline silicon ingot according to claim 51, wherein in a slice sampled at the bottom above, the volume percentage of the silicon grains with the crystal orientations (112), (113), (115), (001) and (111) is greater than 50%.
53. The crystalline silicon ingot according to claim 51, wherein in a slice sampled at the bottom above, the volume percentage of the silicon grains with the crystal orientations (112), (113), (115), (001) and (111) is greater than 70%.

54. The crystalline silicon ingot according to claim 51, wherein in a slice sampled at the bottom above, the volume percentage of the silicon grains with the crystal orientation (112) is greater than that of the silicon grains with any of the crystal orientations (001), (111), (113) and (115).
55. The crystalline silicon ingot according to claim 51, wherein in a slice sampled at the bottom above, the volume percentage of the silicon grains with the crystal orientation (115) is greater than that of the silicon grains with the crystal orientations (111).
56. The crystalline silicon ingot according to claim 51, wherein in a slice sampled at the bottom above, the volume percentage of the silicon grains with the crystal orientation (111) is greater than that of the silicon grains with the crystal orientations (113).
57. The crystalline silicon ingot according to claim 51, wherein in a slice sampled at the bottom above, the volume percentage of the silicon grains with the crystal orientation (001) is less than that of the silicon grains with any of the crystal orientations (111), (112), (113) and (115).
58. The crystalline silicon ingot according to any of claims 42-45, wherein the nucleation promotion layer is composed of a plurality of crystal particles with irregular shape, each of which has a particle size of less than 50 μm .
59. The crystalline silicon ingot according to claim 58, wherein the plurality of the crystal particles comprise one selected from the group consisting of a poly-Si particle, a mono-Si particle, and a single crystal silicon carbide.
60. The crystalline silicon ingot according to any of claims 42-45, wherein the nucleation promotion layer is composed of a plurality of poly-Si chunks or mono-Si chunks.

61. The crystalline silicon ingot according to any of claims 42-45, wherein the nucleation promotion layer is a plate made of a material having a melting point higher than about 1400°C, and the surface of the plate contacting the silicon grains has a roughness of 300 μm to 1000 μm for providing the plurality of the silicon grains with multiple nucleation sites.
62. A poly-Si wafer, characterized in that:
- the poly-Si wafer comprises a plurality of silicon grains having at least three crystal orientations which include (113) and (115), the volume percentage of the silicon grains with the crystal orientations (113) and (115) is between 20% and 35%.
63. The poly-Si wafer according to claim 62, wherein the volume percentage of the silicon grains with the crystal orientation (115) is greater than that of the silicon grains with the crystal orientations (113).
64. The poly-Si wafer according to claim 62, wherein the crystal orientations of the plurality of silicon grains further include (112), and the volume percentage of the silicon grains with the crystal orientation (112) is between 25% and 30%.
65. The poly-Si wafer according to claim 62, wherein the crystal orientations of the plurality of silicon grains further include (112).
66. The poly-Si wafer according to claims 64 or 65, wherein the volume percentage of the silicon grains with the crystal orientations (112), (113) and (115) is greater than 45%.
67. The poly-Si wafer according to claims 64 or 65, wherein the volume percentage of the silicon grains with the crystal orientation (112) is greater than that of the silicon grains with the crystal orientations (113) or (115).

68. The poly-Si wafer according to claims 64 or 65, wherein the crystal orientations of the plurality of silicon grains further include (001) and (111).
69. The poly-Si wafer according to claim 68, wherein the volume percentage of the silicon grains with the crystal orientation (111) is greater than that of the silicon grains with the crystal orientations (113).
70. The poly-Si wafer according to claim 68, wherein the volume percentage of the silicon grains with the crystal orientations (112), (113), (115), (001) and (111) is greater than 50%.
71. The poly-Si wafer according to claim 68, wherein the volume percentage of the silicon grains with the crystal orientations (112), (113), (115), (001) and (111) is greater than 70%.
72. The poly-Si wafer according to claim 68, wherein the volume percentage of the silicon grains with the crystal orientation (112) is greater than that of the silicon grains with any of the crystal orientations (001), (111), (113) and (115).
73. The poly-Si wafer according to claim 68, wherein the volume percentage of the silicon grains with the crystal orientation (115) is greater than that of the silicon grains with the crystal orientations (111).
74. The poly-Si wafer according to claim 68, wherein the volume percentage of the silicon grains with the crystal orientation (001) is less than that of the silicon grains with any of the crystal orientations (111), (112), (113) and (115).
75. The poly-Si wafer according to claim 62, wherein the silicon grains have an average grain size of less than 10 nm.
76. The poly-Si wafer according to claim 62, wherein the silicon grains have the average grain size of from 7.4 nm to 18.4 nm.

77. The poly-Si wafer according to claim 62, wherein the silicon grains have a defect density of less than 15%.