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

CROSS-REFERENCE TO RELATED APPLICATION

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

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

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.

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

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.

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.

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.

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.

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%.

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, 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 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 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

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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.

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.

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.

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.

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%.

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, 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 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 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

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

43. The method according to claim ~~3~~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 ~~about~~ 50 mm.

~~5~~4. The method according to claim 43, 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.

~~6~~5. The method according to claim 43, 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.

~~7~~6. The method according to claim ~~3~~1, wherein the nucleation promotion layer is a plate made of a material having a melting point higher than ~~about~~ 1400℃, 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.

~~8~~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 ~~about~~ 50%.

~~9~~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 ~~about~~ 70%.

~~10~~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 ~~about~~ 10 mm.

~~11~~10. The crystalline silicon ingot according to claim ~~10~~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.

~~12~~11. The crystalline silicon ingot according to claim ~~10~~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 ~~about~~ 50 mm.

~~11~~12. The crystalline silicon ingot according to claim ~~12~~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.

~~14~~13. The crystalline silicon ingot according to claim ~~10~~9, wherein the nucleation promotion layer is a plate made of a material having a melting point higher than ~~about~~ 1400℃, 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.

~~15~~14. The crystalline silicon ingot according to claim ~~10~~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 ~~about~~ 50%.

~~16~~15. The crystalline silicon ingot according to claim ~~10~~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 ~~about~~ 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 mm.

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℃, 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 40, wherein a slice sampled at the height of 100 mm below of the crystalline silicon ingot has a defect density of less than 5%.

44. The crystalline silicon ingot according to claim 40, wherein a slice sampled at the height of 150 mm below of the crystalline silicon ingot has a defect density of less than 10%.

45. The crystalline silicon ingot according to claim 40, wherein a slice sampled at the height of 250 mm below 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 mm.

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 claim 42-45, wherein the nucleation promotion layer is composed of a plurality of poly-Si chucks or mono-Si chucks.

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℃, 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 mm.

76. The poly-Si wafer according to claim 62, wherein the silicon grains have the average grain size of from 7.4 mm to 18.4 mm.

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

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℃, 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 mm.

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℃, 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 mm.

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℃, 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 40, wherein a slice sampled at the height of 100 mm below of the crystalline silicon ingot has a defect density of less than 5%.

44. The crystalline silicon ingot according to claim 40, wherein a slice sampled at the height of 150 mm below of the crystalline silicon ingot has a defect density of less than 10%.

45. The crystalline silicon ingot according to claim 40, wherein a slice sampled at the height of 250 mm below 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 mm.

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 claim 42-45, wherein the nucleation promotion layer is composed of a plurality of poly-Si chucks or mono-Si chucks.

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℃, 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 mm.

76. The poly-Si wafer according to claim 62, wherein the silicon grains have the average grain size of from 7.4 mm to 18.4 mm.

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