[0040] FIG. 3 is a diagram illustrating a horizontal magnetic field being applied to a crucible 102 containing a melt 104 from which an ingot 113 is grown. The transition between the melt and the ingot is generally referred to as the crystal-melt interface 125 (alternatively the “ingot-melt” or “solid-melt” interface) and is typically non-linear, for example concave, convex or gull-winged relative to the melt surface 111. The two magnetic poles 129, 130 are placed in opposition to generate a magnetic field generally perpendicular to the ingot-growth direction and generally parallel to the melt surface 111. The magnetic poles 129, 130 may be a conventional electromagnet, a superconductor electromagnet, or any other suitable magnet for producing a horizontal magnetic field of the desired strength. Application of a horizontal magnetic field gives rise to Lorentz force along the axial direction, in a direction opposite of fluid motion, opposing forces driving melt convection. The convection in the melt is thus suppressed, and the axial temperature gradient in the ingot near the interface increases. The melt-ingot interface then moves upward to the ingot side to accommodate the increased axial temperature gradient in the ingot near the interface and the contribution from the melt convection in the crucible decreases. The horizontal configuration has the advantage of efficiency in damping a convective flow at the melt surface 111.

[0041] The magnetic poles 129, 130 may be cooled by circulating cooling fluid through the poles 129, 130. A ferrous shield 155 (FIG. 1) may surround the magnetic poles 129, 130 to reduce stray magnetic fields and to enhance the strength of the field produced.

[0042] In accordance with embodiments of the present disclosure, a position of the maximum gauss plane (“MGP”) during formation of a constant diameter portion of the silicon ingot is regulated in at least two stages of ingot growth. The MGP is characterized by the maximum magnitude of the horizontal component of the magnetic field and a zero vertical component along

via computer-executable instructions stored on non-transitory computer-readable media or medium.

[0062] The non-transitory memory 202 stores instructions that are executed by the processor 201 to configure the controller 108. In accordance with embodiments of the present disclosure, the controller 108 is configured to cause the translation device 160 to move the pair of magnetic poles 129, 130 to regulate a position of the maximum gauss plane during formation of a constant diameter portion of the silicon ingot in accordance with the embodiments described above. For example, the position of the maximum gauss plane may be regulated in the at least two stages of ingot growth with the position of the maximum gauss plane in the second stage being a position lower than the position of the maximum gauss plane during the first stage. The controller 108 may be configured to maintain the position of the maximum gauss plane in the at least two stages (and also including the optional intermediate stage) at the distances from the melt free surface in the embodiments described above. The controller 108 may be configured to maintain the position of the maximum gauss plane such that the various lengths of the first and second stages and the rate at which the magnet is lowered in the intermediate stage as described above may be achieved.

[0063] The controller 108 may be triggered to change the position of the magnetic poles in the various stages of ingot growth (e.g., to terminate the first stage and move to the intermediate stage or terminate the intermediate stage and move to the second stage) by the weight of the melt, the length of the ingot or by a timed control.

[0064] Compared to conventional methods and apparatus for producing single crystal silicon, the methods and apparatus of embodiments of the present disclosure have several advantages. By moving the magnetic poles

CLAIMS:

1. A method for producing a silicon ingot, the method comprising:

melting polycrystalline silicon in a crucible enclosed in a growth chamber to form a melt, the melt having a melt free surface;

generating a horizontal magnetic field within the growth chamber;

contacting a seed crystal with the melt;

withdrawing the seed crystal from the melt to form the silicon ingot; and

regulating a position of a maximum gauss plane during formation of a constant diameter portion of the silicon ingot in at least two stages of ingot growth, the at least two stages comprising:

a first stage corresponding to formation of the silicon ingot from a beginning of formation of the constant diameter portion of the silicon ingot up to an intermediate ingot length; and

a second stage corresponding to formation of the silicon ingot from at least the intermediate ingot length to a total length of the constant diameter portion; and

wherein regulating the position of the maximum gauss plane comprises maintaining the position of the maximum gauss plane in the second stage at a position lower than the position of the maximum gauss plane during the first stage.

2. The method as set forth in claim 1 wherein the at least two stages comprise an intermediate stage that corresponds to formation of the silicon ingot between the first stage and the second stage, wherein regulating the position of the maximum gauss plane comprises lowering the position of the maximum gauss plane from the position in the first stage to the position in the second stage during the intermediate stage.

3. The method as set forth in claim 1 or claim 2 wherein the position of the maximum gauss plane during the first stage is maintained to be above the melt free surface.

4. The method as set forth in claim 3 wherein the position of the maximum gauss plane during the second stage is maintained to be below the melt free surface.

5. The method as set forth in any one of claims 1 to 4 wherein the position of the maximum gauss plane is maintained at a position at least 20 mm above the melt free surface during the first stage or least 40 mm above the melt free surface, at least 60 mm above the melt free surface, from the melt free surface to 150 mm above the melt free surface, from 20 mm above the melt free surface to 150 mm above the melt free surface, or from 40 mm above the melt free surface to 150 mm above the melt free surface during the first stage.

6. The method as set forth in any one of claims 1 to 5 wherein the position of the maximum gauss plane is maintained at a position at least 20 mm below the melt free surface during the second stage or least 40 mm below the melt free surface, at least 60 mm below the melt free surface, at least 80 mm below the melt free surface, at least 100 mm below the melt free surface, from the melt free surface to 200 mm below the melt free surface, from 20 mm below the melt free surface to 200 mm below the melt free surface, or from 20 mm below the melt free surface to 150 mm below the melt free surface during the second stage.

7. The method as set forth in any one of claims 1 to 6 wherein the at least two stages comprise an intermediate stage that corresponds to formation of the silicon ingot between the first stage and the second stage, wherein regulating the position of the maximum gauss plane comprises lowering the position of the maximum gauss plane from the position in the first stage to the position in the second stage during the intermediate stage, wherein the position of the maximum gauss plane is lowered below the melt free surface during the intermediate stage.

8. The method as set forth in any one of claims 1 to 7 wherein the at least two stages comprise an intermediate stage that corresponds to formation of the silicon ingot between the first stage and the second stage, wherein regulating the position of the maximum gauss plane comprises lowering the position of the maximum gauss plane from the position in the first stage to the position in the second stage during the

intermediate stage, wherein the position of the maximum gauss plane is lowered at least 40 mm over no more than 60% of the constant diameter portion, no more than 50% or no more than 40% of the constant diameter portion.

9. The method as set forth in any one of claims 1 to 7 wherein the at least two stages comprise an intermediate stage that corresponds to formation of the silicon ingot between the first stage and the second stage, wherein regulating the position of the maximum gauss plane comprises lowering the position of the maximum gauss plane from the position in the first stage to the position in the second stage during the intermediate stage, wherein the position of the maximum gauss plane is lowered at least 75 mm over no more than 60% of the constant diameter portion, no more than 50% or no more than 40% of the constant diameter portion.

10. The method as set forth in any one of claims 1 to 7 wherein the at least two stages comprise an intermediate stage that corresponds to formation of the silicon ingot between the first stage and the second stage, wherein regulating the position of the maximum gauss plane comprises lowering the position of the maximum gauss plane from the position in the first stage to the position in the second stage during the intermediate stage, wherein the position of the maximum gauss plane is lowered at least 100 mm over no more than 60% of the constant diameter portion, no more than 50% or no more than 40% of the constant diameter portion.

11. The method as set forth in any one of claims 1 to 7 wherein the at least two stages comprise an intermediate stage that corresponds to formation of the silicon ingot between the first stage and the second stage, wherein regulating the position of the maximum gauss plane comprises lowering the position of the maximum gauss plane from the position in the first stage to the position in the second stage during the intermediate stage, wherein the position of the maximum gauss plane is lowered at least 150 mm over no more than 60% of the constant diameter portion, no more than 50% or no more than 40% of the constant diameter portion.

12. The method as set forth in any one of claims 1 to 11 wherein a length of the first stage is at least 10% of the constant diameter portion, at least 20% of

the constant diameter portion, at least 10% and less than 50% of the constant diameter portion, or to at least 10% and less than 40% of the constant diameter portion.

13. The method as set forth in claim 12 wherein the first stage begins at a start of the constant diameter portion of the ingot.

14. The method as set forth in any one of claims 1 to 13 wherein a length of the second stage is at least 10% of the constant diameter portion, at least 20% of the constant diameter portion, at least 30% of the constant diameter portion, at least 10% and less than 50% of the constant diameter portion, or to at least 20% and less than 50% of the constant diameter portion.

15. The method as set forth in claim 14 wherein the second stage extends to a total length of the constant diameter portion of the ingot.

16. The method as set forth in any one of claims 1 to 15 wherein the position of the maximum gauss plane is constant during the first stage.

17. The method as set forth in any one of claims 1 to 15 wherein the position of the maximum gauss plane changes during the first stage.

18. The method as set forth in any one of claims 1 to 17 wherein the position of the maximum gauss plane is constant during the second stage.

19. The method as set forth in any one of claims 1 to 18 wherein the position of the maximum gauss plane changes during the second stage.

20. An ingot puller apparatus for manufacturing a single crystal silicon ingot, the ingot puller apparatus comprising:

a crucible for holding a silicon melt;

an ingot puller housing that defines a growth chamber for pulling a silicon ingot from the silicon melt, the crucible being disposed within the growth chamber;

a pair of magnetic poles disposed radially outward from the crucible; and

a translation device for moving the magnetic poles axially relative to the crucible.

21. The ingot puller apparatus as set forth in claim 20 wherein the translation device comprises:

a guide; and

a mount for moving each magnetic pole relative to the guide.

22. The ingot puller apparatus as set forth in claim 21 wherein the guide comprises a rail and the mount connects each magnetic pole to the rail.

23. The ingot puller apparatus as set forth in claim 21 or claim 22 comprising an actuator for moving the magnetic poles relative to the guide.

24. The ingot puller apparatus as set forth in claim 23 wherein the actuator comprises a pneumatic or hydraulic cylinder, a rack and pinion, a pulley or gear train with a ball screw.

25. The ingot puller apparatus as set forth in claim 23 or claim 24 comprising a motor for powering the actuator.

26. The ingot puller apparatus as set forth in any one of claims 20 to 25 comprising a controller including a processor and a non-transitory memory storing instructions executed by the processor to configure the controller, the controller configured to cause the translation device to move the pair of magnetic poles to regulate a position of a maximum gauss plane during formation of a constant diameter portion of the silicon ingot in at least two stages of ingot growth, the at least two stages comprising:

a first stage corresponding to formation of the silicon ingot from a beginning of formation of the constant diameter portion of the silicon ingot up to an intermediate ingot length; and

a second stage corresponding to formation of the silicon ingot from at least the intermediate ingot length to a total ingot length.

27. The ingot puller apparatus as set forth in claim 26 wherein the controller is configured to maintain the position of the maximum gauss plane in the

second stage at a position lower than the position of the maximum gauss plane during the first stage.

28. The ingot puller apparatus as set forth in claim 27 wherein the controller is configured to maintain the position of the maximum gauss plane at least 20 mm above a melt free surface during the first stage or least 40 mm above the melt free surface, at least 60 mm above the melt free surface, from the melt free surface to 150 mm above the melt free surface, from 20 mm above the melt free surface to 150 mm above the melt free surface, or from 40 mm above the melt free surface to 150 mm above the melt free surface during the first stage.

29. The ingot puller apparatus as set forth in claim 27 or claim 28 wherein the controller is configured to maintain the position of the maximum gauss plane at least 20 mm below the melt free surface during the second stage or least 40 mm below the melt free surface, at least 60 mm below the melt free surface, at least 80 mm below the melt free surface, at least 100 mm below the melt free surface, from the melt free surface to 200 mm below the melt free surface, from 20 mm below the melt free surface to 200 mm below the melt free surface, or from 20 mm below the melt free surface to 150 mm below the melt free surface during the second stage.

30. The ingot puller apparatus as set forth in any one of claim 26 to 29 wherein the at least two stages comprise an intermediate stage that corresponds to formation of the silicon ingot between the first stage and the second stage, wherein the controller is configured to lower the position of the maximum gauss plane from the position in the first stage to the position in the second stage during the intermediate stage, and wherein the controller is configured to lower the maximum gauss plane below the melt free surface during the intermediate stage.

31. The ingot puller apparatus as set forth in any one of claims 26 to 30 wherein the at least two stages comprise an intermediate stage that corresponds to formation of the silicon ingot between the first stage and the second stage, wherein the controller is configured to lower the position of the maximum gauss plane from the position in the first stage to the position in the second stage during the intermediate

stage, and wherein the controller is configured to lower the maximum gauss plane at least 40 mm over no more than 60% of the constant diameter portion, no more than 50% or no more than 40% of the constant diameter portion.

32. The ingot puller apparatus as set forth in any one of claims 26 to 30 wherein the at least two stages comprise an intermediate stage that corresponds to formation of the silicon ingot between the first stage and the second stage, wherein the controller is configured to lower the position of the maximum gauss plane from the position in the first stage to the position in the second stage during the intermediate stage, and wherein the controller is configured to lower the maximum gauss plane at least 75 mm over no more than 60% of the constant diameter portion, no more than 50% or no more than 40% of the constant diameter portion.

33. The ingot puller apparatus as set forth in any one of claims 26 to 30 wherein the at least two stages comprise an intermediate stage that corresponds to formation of the silicon ingot between the first stage and the second stage, wherein the controller is configured to lower the position of the maximum gauss plane from the position in the first stage to the position in the second stage during the intermediate stage, and wherein the controller is configured to lower the maximum gauss plane at least 100 mm over no more than 60% of the constant diameter portion, no more than 50% or no more than 40% of the constant diameter portion.

34. The ingot puller apparatus as set forth in any one of claims 26 to 30 wherein the at least two stages comprise an intermediate stage that corresponds to formation of the silicon ingot between the first stage and the second stage, wherein the controller is configured to lower the position of the maximum gauss plane from the position in the first stage to the position in the second stage during the intermediate stage, and wherein the controller is configured to lower the maximum gauss plane at least 150 mm over no more than 60% of the constant diameter portion, no more than 50% or no more than 40% of the constant diameter portion.

35. The ingot puller apparatus as set forth in any one of claims 26 to 34 wherein the controller is configured to maintain a length of the first stage to be at least 10% of the constant diameter portion, at least 20% of the constant diameter portion, at

least 10% and less than 50% of the constant diameter portion, or to at least 10% and less than 40% of the constant diameter portion.

36. The ingot puller apparatus as set forth in any one of claims 26 to 35 wherein the controller is configured to maintain a length of the second stage to be at least 10% of the constant diameter portion, at least 20% of the constant diameter portion, at least 30% of the constant diameter portion, at least 10% and less than 50% of the constant diameter portion, or to at least 20% and less than 50% of the constant diameter portion.