CLAIMS

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

withdrawing a seed crystal from a melt comprising an amount of melted silicon in a crucible to form the silicon ingot, the crucible enclosed in a vacuum chamber containing a cusped magnetic field; and

regulating at least one process parameter, wherein regulating the at least one process parameter comprises regulating a crystal rotation rate, wherein the at least one process parameter is regulated in at least two stages, the at least two stages comprising:

a first stage corresponding to formation of the silicon ingot up to an intermediate ingot length; and

a second stage corresponding to formation of the silicon ingot from the intermediate ingot length to the total ingot length;

wherein regulating the crystal rotation rate during the first stage comprises regulating the crystal rotation rate to 12 rpm during the first stage;

wherein regulating the crystal rotation rate during the second stage comprises:

decreasing the crystal rotation rate over time from 12 rpm at the end of the first stage to 8 rpm when the silicon ingot length reaches 950 mm; and

maintaining the crystal rotation rate at 8 rpm during formation of the silicon ingot between an intermediate ingot length of 950 mm and the total ingot length.

2. The method of claim 1, wherein regulating the at least one process parameter comprises regulating a crucible rotation rate between 1.3 rpm and 2.2 rpm during the first stage, and between 0.5 rpm and 1.7 rpm during the second stage.

3. The method of claim 1, wherein regulating at least one process parameter comprises regulating a crucible rotation rate to 1.7 rpm during the first stage, and between 0.5 rpm and 1.7 rpm during the second stage.

4. The method of claim 1, wherein regulating the at least one process parameter during the second stage comprises regulating a magnetic field strength during the second stage to 150% of the magnetic field strength during the first stage.

5. The method of claim 1, wherein:

regulating the at least one process parameter comprises regulating, during the first stage, a magnetic field strength to a strength between 0.02 and 0.05 Tesla at an edge of the silicon ingot at a melt-solid interface, and regulating the magnetic field strength to a strength between 0.05 and 0.12 Tesla at a wall of the crucible; and

regulating the at least one process parameter during the second stage comprises regulating the magnetic field strength to a strength between 0.03 and 0.075 Tesla at the edge of the silicon ingot at the melt-solid

interface, and regulating the magnetic field strength to a strength between 0.075 and 0.18 Tesla at the wall of the crucible.

6. The method of claim 1, further comprising controlling a plurality of additional process parameters during the first and second stages, the plurality of additional process parameters comprising at least one of a heater power, a melt to reflector gap, a seed lift, a pull speed, an inert gas flow, an inert gas pressure, and a cusp position, wherein controlling the plurality of additional process parameters during the first and second stages comprises, for each parameter of the plurality of additional process parameters, controlling the parameter to be substantially the same during the first and second stages.

7. The method of claim 1, further comprising controlling a plurality of additional process parameters during the first and second stages, the plurality of additional process parameters comprising at least one of a heater power, a melt to reflector gap, a seed lift, a pull speed, an inert gas flow, an inert gas pressure, and a cusp position, wherein controlling the plurality of additional process parameters during the first and second stages comprises, for each parameter of the plurality of additional process parameters, controlling the parameter to be substantially the same during the first and second stages.

8. A crystal growing system for producing a silicon ingot, the system comprising

a vacuum chamber;

a crucible disposed within the vacuum chamber, the crucible rotatable about an axis of symmetry, and configured to hold a melt including molten silicon;

a pull shaft movable along the axis of symmetry and rotatable about the axis of symmetry, and configured to hold a seed crystal;

at least one magnet to generate a controllable cusped magnetic field within the crucible;

a control unit comprising a processor and a memory, the memory storing instruction that, when executed by the processor, cause the processor to:

withdraw the seed crystal from a melt in the crucible to form the silicon ingot; and

regulate at least one process parameter, wherein the at least one process parameter is regulated in at least two stages, the at least two stages comprising:

a first stage corresponding to formation of the silicon ingot up to an intermediate ingot length; and

a second stage corresponding to formation of the silicon ingot from the intermediate ingot length to the total ingot length;

wherein the instruction, when executed by the processor, cause the processor to regulate the at least one process parameter by reducing a crystal rotation rate

relative to the crystal rotation rate during the first stage.

9. The system of claim 8, wherein the memory stores instruction that, when executed by the processor, cause the processor to regulate the at least one process parameter by regulating the crystal rotation rate ranges between 8 rpm to 14 rpm during the first stage and regulating the crystal rotation rate ranges between 6 rpm to 8 rpm during the second stage.

10. The system of claim 8, wherein the memory stores instruction that, when executed by the processor, cause the processor to regulate the at least one process parameter by:

regulating the crystal rotation rate to 12 rpm during the first stage; and

decreasing the crystal rotation rate over time from 12 rpm at the end of the first stage to 8 rpm when the silicon ingot length reaches 950 mm; and

maintaining the crystal rotation rate at 8 rpm during formation of the silicon ingot between the intermediate ingot length of 950 mm and the total ingot length.

11. The system of claim 8, wherein the memory stores instruction that, when executed by the processor, cause the processor to regulate the at least one process parameter by regulating a crucible rotation rate between 1.3 rpm and 2.2 rpm during the first stage, and between 0.5 rpm and 1.7 rpm during the second stage.

12. The system of claim 8, wherein the memory stores instruction that, when executed by the processor, cause the processor to regulate the at least one process parameter by regulating a crucible rotation rate to 1.7 rpm during the first stage, and between 0.5 rpm and 1.7 rpm during the second stage.

13. The system of claim 8, wherein the memory stores instruction that, when executed by the processor, cause the processor to regulate the at least one process parameter by regulating a magnetic field strength during the second stage to 150% of the magnetic field strength during the first stage.

14. The system of claim 8, wherein the memory stores instruction that, when executed by the processor, cause the processor to regulate the at least one process parameter by:

regulating, during the first stage, a magnetic field strength to a strength between 0.02 and 0.05 Tesla at an edge of the silicon ingot at a melt-solid interface, and to a strength between 0.05 and 0.12 Tesla at a wall of the crucible; and

regulating, during the second stage, the magnetic field strength to a strength between 0.03 and 0.075 Tesla at the edge of the silicon ingot at the melt-solid interface, and to a strength between 0.075 and 0.18 Tesla at the wall of the crucible.

15. The system of claim 8, further wherein the memory stores further instruction that, when executed by the processor, cause the processor to control a plurality of additional process parameters during the first and second stages.

16. The system of claim 15, wherein the plurality of additional process parameters comprise at least one of a heater power, a melt to reflector gap, a seed lift, a pull speed, an inert gas flow, an inert gas pressure, and a cusp position.

17. The system of claim 16, wherein the memory stores instruction that, when executed by the processor, cause the processor, for each parameter of the plurality of additional process parameters, to control the process parameter to be substantially the same during the first and second stages.

18. A crystal growing system for producing a silicon ingot, the system comprising

a vacuum chamber;

a crucible disposed within the vacuum chamber, the crucible rotatable about an axis of symmetry, and configured to hold a melt including molten silicon;

a pull shaft movable along the axis of symmetry and rotatable about the axis of symmetry, and configured to hold a seed crystal;

at least one magnet to generate a controllable cusped magnetic field within the crucible;

a control unit comprising a processor and a memory, the memory storing instruction that, when executed by the processor, cause the processor to:

withdraw the seed crystal from a melt in the crucible to form the silicon ingot; and

regulate at least one process parameter, wherein regulating the at least one process parameter comprises regulating a crucible rotation rate, wherein the at least one process parameter is regulated in at least two stages, the at least two stages comprising:

a first stage corresponding to formation of the silicon ingot up to an intermediate ingot length; and

a second stage corresponding to formation of the silicon ingot from the intermediate ingot length to the total ingot length; and

wherein the instruction, when executed by the processor, cause the processor to regulate the crucible rotation rate by reducing a crucible rotation rate relative to the crucible rotation rate during the first stage.

19. The system of claim 18, wherein the memory stores instruction that, when executed by the processor, cause the processor to regulate the at least one process parameter by regulating the crucible rotation rate to 1.7 rpm during the first stage, and between 0.5 rpm and 1.7 rpm during the second stage.

20. The system of claim 18, wherein the memory stores instruction that, when executed by the processor,

cause the processor to regulate the at least one process parameter by:

regulating the crucible rotation rate to 1.7 rpm during the first stage; and

decreasing the crucible rotation rate over time from 1.7 rpm at the end of the first stage to 0.5 rpm when the silicon ingot length reaches 950 mm; and

maintaining the crucible rotation rate at 0.5 rpm during formation of the silicon ingot between the intermediate ingot length of 950 mm and the total ingot length.

21. The system of claim 18, wherein the memory stores instruction that, when executed by the processor, cause the processor to regulate the at least one process parameter by regulating a magnetic field strength during the second stage to 150% of the magnetic field strength during the first stage.

22. The system of claim 18, wherein the memory stores instruction that, when executed by the processor, cause the processor to regulate the at least one process parameter by:

regulating, during the first stage, a magnetic field strength to a strength between 0.02 and 0.05 Tesla at an edge of the silicon ingot at a melt-solid interface, and to a strength between 0.05 and 0.12 Tesla at a wall of the crucible; and

regulating, during the second stage, the magnetic field strength to a strength between 0.03 and 0.075 Tesla

at the edge of the silicon ingot at the melt-solid interface, and to a strength between 0.075 and 0.18 Tesla at the wall of the crucible.

23. The system of claim 18, further wherein the memory stores further instruction that, when executed by the processor, cause the processor to control a plurality of additional process parameters during the first and second stages, the plurality of additional process parameters comprising at least one of a heater power, a melt to reflector gap, a seed lift, a pull speed, an inert gas flow, an inert gas pressure, and a cusp position.

24. The system of claim 23, wherein the memory stores instruction that, when executed by the processor, cause the processor, for each parameter of the plurality of additional process parameters, to control the process parameter to be substantially the same during the first and second stages.

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

withdrawing a seed crystal from a melt comprising an amount of melted silicon in a crucible to form the silicon ingot, the crucible enclosed in a vacuum chamber containing a cusped magnetic field; and

regulating at least one process parameter, wherein the at least one process parameter is regulated in at least two stages, the at least two stages comprising:

a first stage corresponding to formation of the silicon ingot up to an intermediate ingot length; and

a second stage corresponding to formation of the silicon ingot from the intermediate ingot length to the total ingot length;

wherein the first stage is an intermediate growth stage and the second stage is a late body growth stage, and wherein a transition from the intermediate growth stage to the late body growth stage is identified by determining the depth of the melt within the crucible or by determining that less than about 50% of the initial mass of the melt is left in the crucible;

wherein regulating the at least one process parameter during the second stage comprises at least one of:

reducing a crystal rotation rate relative to the crystal rotation rate during the first stage;

reducing a crucible rotation rate relative to the crucible rotation rate during the first stage; and

increasing a magnetic field strength relative to the magnetic field strength during the first stage.

26. The method of claim 25, wherein regulating the at least one process parameter comprises regulating the crystal rotation rate ranges between 8 rpm to 14 rpm during the first stage and regulating the crystal rotation rate ranges between 6 rpm to 8 rpm during the second stage.

27. The method of claim 25, wherein:

regulating the at least one process parameter comprises regulating the crystal rotation rate to 12 rpm during the first stage; and

regulating the at least one process parameter during the second stage comprises:

decreasing the crystal rotation rate over time from 12 rpm at the end of the first stage to 8 rpm when the silicon ingot length reaches 950 mm; and

maintaining the crystal rotation rate at 8 rpm during formation of the silicon ingot between an intermediate ingot length of 950 mm and the total ingot length.

28. The method of claim 25, wherein regulating the at least one process parameter comprises regulating the crucible rotation rate between 1.3 rpm and 2.2 rpm during the first stage, and between 0.5 rpm and 1.7 rpm during the second stage.

29. The method of claim 25, wherein regulating at least one process parameter comprises regulating the crucible rotation rate to 1.7 rpm during the first stage, and between 0.5 rpm and 1.7 rpm during the second stage.

30. The method of claim 25, wherein regulating the at least one process parameter during the second stage comprises regulating the magnetic field strength during the second stage to 150% of the magnetic field strength during the first stage.

31. The method of claim 25, wherein:

regulating the at least one process parameter comprises regulating, during the first stage, the magnetic field strength to a strength between 0.02 and 0.05 Tesla at an edge of the silicon ingot at a melt-solid interface, and regulating the magnetic field strength to a strength between 0.05 and 0.12 Tesla at a wall of the crucible; and

regulating the at least one process parameter during the second stage comprises regulating the magnetic field strength to a strength between 0.03 and 0.075 Tesla at the edge of the silicon ingot at the melt-solid interface, and regulating the magnetic field strength to a strength between 0.075 and 0.18 Tesla at the wall of the crucible.

32. A crystal growing system for producing a silicon ingot, the system comprising:

a vacuum chamber;

a crucible disposed within the vacuum chamber, the crucible rotatable about an axis of symmetry, and configured to hold a melt including molten silicon;

a pull shaft movable along the axis of symmetry and rotatable about the axis of symmetry, and configured to hold a seed crystal;

at least one magnet to generate a controllable cusped magnetic field within the crucible;

a control unit comprising a processor and a memory, the memory storing instruction that, when executed by the processor, cause the processor to:

withdraw the seed crystal from a melt in the crucible to form the silicon ingot; and

regulate at least one process parameter, wherein the at least one process parameter is regulated in at least two stages, the at least two stages comprising:

a first stage corresponding to formation of the silicon ingot up to an intermediate ingot length; and

a second stage corresponding to formation of the silicon ingot from the intermediate ingot length to the total ingot length;

wherein the first stage is an intermediate growth stage and the second stage is a late body growth stage, and wherein a transition from the intermediate growth stage to the late body growth stage is identified by determining the depth of the melt within the crucible or by determining that less than about 50% of the initial mass of the melt is left in the crucible;

wherein the instruction, when executed by the processor, cause the processor to regulate the at least one process parameter by at least one of:

reducing a crystal rotation rate relative to the crystal rotation rate during the first stage;

reducing a crucible rotation rate relative to the crucible rotation rate during the first stage; and

increasing a magnetic field strength produced by the at least one magnet relative to the magnetic field strength produced by the at least one magnet during the first stage.

33. The system of claim 32, wherein the memory stores instruction that, when executed by the processor, cause the processor to regulate the at least one process parameter by regulating the crystal rotation rate ranges between 8 rpm to 14 rpm during the first stage and regulating the crystal rotation rate ranges between 6 rpm to 8 rpm during the second stage.

34. The system of claim 32, wherein the memory stores instruction that, when executed by the processor, cause the processor to regulate the at least one process parameter by:

regulating the crystal rotation rate to 12 rpm during the first stage; and
decreasing the crystal rotation rate over time from 12 rpm at the end of the first stage to 8 rpm when the silicon ingot length reaches 950 mm; and

maintaining the crystal rotation rate at 8 rpm during formation of the silicon ingot between the intermediate ingot length of 950 mm and the total ingot length.

35. The system of claim 32, wherein the memory stores instruction that, when executed by the processor, cause the processor to regulate the at least one process parameter by regulating a crucible rotation rate between 1.3 rpm and 2.2 rpm during the first stage, and between 0.5 rpm and 1.7 rpm during the second stage.

36. The system of claim 32, wherein the memory stores instruction that, when executed by the processor,

cause the processor to regulate the at least one process parameter by regulating a crucible rotation rate to 1.7 rpm during the first stage, and between 0.5 rpm and 1.7 rpm during the second stage.

37. The system of claim 32, wherein the memory stores instruction that, when executed by the processor, cause the processor to regulate the at least one process parameter by regulating a magnetic field strength during the second stage to 150% of the magnetic field strength during the first stage.

38. The system of claim 32, further wherein the memory stores further instruction that, when executed by the processor, cause the processor to control a plurality of additional process parameters during the first and second stages.

39. The system of claim 38, wherein the plurality of additional process parameters comprise at least one of a heater power, a melt to reflector gap, a seed lift, a pull speed, an inert gas flow, an inert gas pressure, and a cusp position.

40. The system of claim 39, wherein the memory stores instruction that, when executed by the processor, cause the processor, for each parameter of the plurality of additional process parameters, to control the process parameter to be substantially the same during the first and second stages.

41. A crystal growing system for producing a silicon ingot, the system comprising:

a vacuum chamber;

a crucible disposed within the vacuum chamber, the crucible rotatable about an axis of symmetry, and configured to hold a melt including molten silicon;

a pull shaft movable along the axis of symmetry and rotatable about the axis of symmetry, and configured to hold a seed crystal;

at least one magnet to generate a controllable cusped magnetic field within the crucible;

a control unit comprising a processor and a memory, the memory storing instruction that, when executed by the processor, cause the processor to:

withdraw the seed crystal from a melt in the crucible to form the silicon ingot; and

regulate at least one process parameter, wherein regulating the at least one process parameter comprises regulating a crucible rotation rate, wherein the at least one process parameter is regulated in at least two stages, the at least two stages comprising:

a first stage corresponding to formation of the silicon ingot up to an intermediate ingot length; and

a second stage corresponding to formation of the silicon ingot from the intermediate ingot length to the total ingot length;

wherein the first stage is an intermediate growth stage and the second stage is a late

body growth stage, and wherein a transition from the intermediate growth stage to the late body growth stage is identified by determining the depth of the melt within the crucible or by determining that less than about 50% of the initial mass of the melt is left in the crucible;

wherein the instruction, when executed by the processor, cause the processor to regulate the crucible rotation rate by reducing a crucible rotation rate relative to the crucible rotation rate during the first stage.

42. The system of claim 41, wherein the memory stores instruction that, when executed by the processor, cause the processor to regulate the at least one process parameter by regulating the crucible rotation rate between 1.3 rpm and 2.2 rpm during the first stage, and between 0.5 rpm and 1.7 rpm during the second stage.

43. The system of claim 41, wherein the memory stores instruction that, when executed by the processor, cause the processor to regulate the at least one process parameter by regulating the crucible rotation rate to 1.7 rpm during the first stage, and between 0.5 rpm and 1.7 rpm during the second stage.

44. The system of claim 41, wherein the memory stores instruction that, when executed by the processor, cause the processor to regulate the at least one process parameter by:

regulating the crucible rotation rate to 1.7 rpm during the first stage; and
decreasing the crucible rotation rate over time from 1.7

rpm at the end of the first stage to 0.5 rpm when the silicon ingot length reaches 950 mm; and

maintaining the crucible rotation rate at 0.5 rpm during formation of the silicon ingot between the intermediate ingot length of 950 mm and the total ingot length.

45. The system of claim 41, wherein the memory stores instruction that, when executed by the processor, cause the processor to regulate the at least one process parameter by regulating a magnetic field strength during the second stage to 150% of the magnetic field strength during the first stage.

46. The system of claim 41, wherein the memory stores instruction that, when executed by the processor, cause the processor to regulate the at least one process parameter by:

regulating, during the first stage, a magnetic field strength to a strength between 0.02 and 0.05 Tesla at an edge of the silicon ingot at a melt-solid interface, and to a strength between 0.05 and 0.12 Tesla at a wall of the crucible; and

regulating, during the second stage, the magnetic field strength to a strength between 0.03 and 0.075 Tesla at the edge of the silicon ingot at the melt-solid interface, and to a strength between 0.075 and 0.18 Tesla at the wall of the crucible.

47. The system of claim 41, further wherein the memory stores further instruction that, when executed by the processor, cause the processor to control a plurality of additional process parameters during the first and second stages, the plurality of additional process parameters comprising at least one of a heater power, a melt to reflector gap, a seed lift, a pull speed, an inert gas flow, an inert gas pressure, and a cusp position.

48. The system of claim 47, wherein the memory stores instruction that, when executed by the processor, cause the processor, for each parameter of the plurality of additional process parameters, to control the process parameter to be substantially the same during the first and second stages.