FIG. 2, the volatile dopant 216 fed to the feed tube 206 flows downward through a channel 228 defined by an annular sidewall 230 of the feed tube 206 and is received by the evaporation capsule 208 which forms a receptacle within the feed tube proximate the second end 212. The evaporation capsule 208 includes a base 232 extending inward from the sidewall 230, and a capsule sidewall 234 joined to the base 232 and extending upwardly from the base 232 along the feed tube axis X_2. In other embodiments, the evaporation capsule 208 may have any other suitable configuration that enables gas doping system 200 to function as described herein. For example, in some embodiments, the capsule 208 may be removably connected to the tube to allow the capsule to be separated from the tube for loading of dopant.

[0042] A portion 236 of the channel 228 through which the gaseous dopant 202 flows is partially defined by the capsule sidewall 234 and the feed tube sidewall 230. The portion 236 of the channel 228 facilitates fluid communication between the evaporation capsule 208 and the open end 212 of the feed tube 206. Thereby, gaseous dopant 202 that is formed by vaporizing volatile dopant 216 received by the evaporation capsule 208 is enabled to flow from the evaporation capsule 208 to the second end 212 and out from the feed tube 206. The cross-sectional area of portion 236 of the channel 228, viewed perpendicular to the feed tube axis X2, may be adjusted in order to increase or decrease the flow rate of gaseous dopant 202 passing therethrough. For example, the cross-sectional area of the portion 236 of the channel 228 may be decreased by extending the length of the base 232 of the evaporation capsule 208. Similarly, the length of the

stated, the radial length of the solid main ingot body of the single crystal silicon ingot 102 is about 75 mm, at least about 75 millimeters, about 100 mm, at least about 100 millimeters, about 150 mm, at least about 150 mm, about 225 mm, or even at least about 225 mm. The main ingot body of the single crystal silicon ingot 102 is eventually grown to an axial length (measured along the pulling axis X_1) at least about 1000 mm, such as at least 1200 mm, such as at least 1250 mm, such as at least 1400 mm, such as at least 1500 mm, or at least 2000 mm, or at least 2200 mm, such as 2200 mm, or at least about 3000 mm, or at least about 4000 mm. In some preferred embodiments, the total axial length of the solid main ingot body of the single crystal silicon ingot 102 is at least about 1100 mm, such as between about 1200 mm and about 1300 mm, such as between about 1200 mm and about 1250 mm.

[0054] In a continuous Czochralski method, during growth of the main ingot body of the single crystal silicon ingot 102, polycrystalline silicon, i.e., granular, chunk, or a combination of granular and chunk, is added to the melt 104 to thereby achieve a constant volume of molten silicon in the melt 104 and constant melt elevation level. Maintenance of a substantially constant melt volume during growth of a substantial portion of the axial length of the main body of the single crystal silicon ingot 102 enables the achievement of high ingot quality over a substantial portion of the axial length of the main body of the single crystal silicon ingot 102 at a constant pull rate. The constant melt volume regardless of the crystal length enables maintaining a constant solid-melt interface 124 and thus uniform crystal quality over a substantial portion of

in FIG. 11). The range defined by the URL and the LRL may be, for example, +/- 15% of a targeted resistivity, +/- 13% of a targeted resistivity, or +/- 10% of a targeted resistivity. The axial resistivity of the main body ingot may be maintained within the range defined by the URL and the LRL over an axial length of at least 300 mm, of at least 500 mm, or even at least 800 mm.

[0081] Referring to FIG. 12, another example ingot puller is indicated generally at 150. The ingot puller 150 includes the same features and elements of ingot puller 100 shown in FIG. 1 and described herein. In addition, the ingot puller 150 includes a second gas doping system 400 for introducing the gaseous dopant 202 into the melt 104. The doping system 400 includes features and elements similar to those included in the gas doping system 200 shown in FIG. 1 and described herein. The ingot puller 150 that includes both the gas doping system 200 and the gas doping system 400 may facilitate improving control of base resistivity of ingots 102 grown by the ingot puller 150.

[0082] As above for the gas doping system 200 (which may be referred to as a "first gas doping system 200"), the gas doping system 400 (which may be referred to as a "second gas doping system 400") includes a dopant feed source 404, a feed tube 406, and an evaporation capsule 408. The feed tube 406 extends along a feed tube axis X_3 between a first end 410 and a second end 412. The first end 410 is located adjacent to the dopant feed source 404, and the second end 412 is located within the inner chamber 110 and oriented toward the surface of the melt 104. The feed tube 406 may extend between the first end 410 and the

CLAIMS:

1. A method of growing a doped single crystal silicon ingot using an ingot pulling apparatus including an inner chamber, a crucible disposed within the inner chamber, a heat source, and a feed tube having an open end, the feed tube comprising a capsule proximate the open end, the method comprising:

adding polycrystalline silicon to the crucible;

heating, by the heat source, the crucible to form a silicon melt from the polycrystalline silicon in the crucible;

growing a single crystal silicon ingot from the melt by contacting the melt with a seed crystal and pulling the seed crystal away from the melt to grow the single crystal silicon ingot, the single crystal silicon ingot having a neck region, a shoulder region, and a body region;

adding a charge of a volatile dopant into the feed tube, the charge of the volatile dopant being received by the capsule;

positioning the feed tube within the inner chamber such that the open end of the feed tube has a first height relative to a surface of the melt;

adjusting the feed tube within the inner chamber to move the open end of the feed tube from the first height to a second height relative to the surface of the melt, the second height being smaller than the first height, the open end of the feed tube being moved from the first height to the second height at a speed rate;

heating, by the heat source and radiant heat from the surface of the melt, the capsule containing the volatile dopant to form a gaseous dopant as the open end is moved

from the first height to the second height at the speed rate, each of the second height and the speed rate being selected to control a vaporization rate of the volatile dopant; and

introducing dopant species into the melt while growing the body region of the single crystal silicon ingot by contacting the surface of the melt with the gaseous dopant, wherein the vaporization rate is controlled such that the dopant species are introduced at a rate sufficient to maintain a resistivity of the body region over an axial length of the body region,

wherein multiple charges of the volatile dopant are added into the feed tube, each of the multiple charges being added after dopant species from a previous volatile dopant charge have been introduced into the melt.

2. The method of claim 1, wherein the vaporization rate is controlled such that the dopant species are introduced at a rate sufficient to maintain a resistivity of the body region within a predetermined range and to control variations in the resistivity of the body region to within +/- 15% over an axial length of at least 300 mm.

3. The method of claim 1, wherein the vaporization rate is controlled such that the dopant species are introduced at a rate sufficient to maintain a resistivity of the body region within a predetermined range and to control variations in the resistivity of the body region to within +/- 15% over an axial length of at least 500 mm.

4. The method of claim 1, wherein the vaporization rate is controlled such that the dopant species are introduced at a rate sufficient to maintain a resistivity

of the body region within a predetermined range and to control variations in the resistivity of the body region to within +/- 15% over an axial length of at least 800 mm.

5. The method of claim 1, wherein the vaporization rate is controlled such that the dopant species are introduced at a rate sufficient to maintain a resistivity of the body region within a predetermined range and to control variations in the resistivity of the body region to within +/- 10% over an axial length of at least 300 mm.

6. The method of claim 1, wherein the vaporization rate is controlled such that the dopant species are introduced at a rate sufficient to maintain a resistivity of the body region within a predetermined range and to control variations in the resistivity of the body region to within +/- 10% over an axial length of at least 500 mm.

7. The method of claim 1, wherein the vaporization rate is controlled such that the dopant species are introduced at a rate sufficient to maintain a resistivity of the body region within a predetermined range and to control variations in the resistivity of the body region to within +/- 10% over an axial length of at least 800 mm.

8. A method of growing a doped single crystal silicon ingot using an ingot pulling apparatus including an inner chamber, a crucible disposed within the inner chamber, a heat source, and a feed tube having an open end, the feed tube comprising a capsule proximate the open end, the method comprising:

adding polycrystalline silicon to the crucible;

heating, by the heat source, the crucible to form a silicon melt from the polycrystalline silicon in the crucible;

growing a single crystal silicon ingot from the melt by contacting the melt with a seed crystal and pulling the seed crystal away from the melt to grow the single crystal silicon ingot, the single crystal silicon ingot having a neck region, a shoulder region, and a body region;

adding a charge of a volatile dopant into the feed tube, the charge of the volatile dopant being received by the capsule;

positioning the feed tube within the inner chamber such that the open end of the feed tube has a first height relative to a surface of the melt;

adjusting the feed tube within the inner chamber to move the open end of the feed tube from the first height to a second height relative to the surface of the melt, the second height being smaller than the first height, the open end of the feed tube being moved from the first height to the second height at a speed rate;

heating, by the heat source and radiant heat from the surface of the melt, the capsule containing the volatile dopant to form a gaseous dopant as the open end is moved from the first height to the second height at the speed rate, each of the second height and the speed rate being selected to control a vaporization rate of the volatile dopant; and

introducing dopant species into the melt while growing the body region of the single crystal silicon ingot by contacting the surface of the melt with the gaseous dopant,

wherein the vaporization rate is controlled such that the dopant species are introduced at a rate sufficient to maintain a resistivity of the body region over an axial length of the body region, wherein the vaporization rate is controlled such that introducing the dopant species includes increasing an amount of the dopant species to a maximum dopant concentration at a constant rate and subsequently decreasing the amount of the dopant species at a constant rate.

9. The method of claim 1, further comprising introducing an inert gas flow into at least one of the inner chamber and the feed tube to produce an inert atmosphere and guiding the gaseous dopant to the surface of the melt using the inert gas flow.

10. The method of claim 1, wherein adding the charge of the volatile dopant into the feed tube includes adding a charge of a solid dopant into the feed tube.

11. The method of claim 10, wherein the solid dopant is a solid n-type dopant.

12. The method of claim 10, wherein the solid dopant is a solid p-type dopant.

13. The method of claim 12, wherein the solid dopant is boric acid.

14. A method of growing a doped single crystal silicon ingot using an ingot pulling apparatus including an inner chamber, a crucible disposed within the inner chamber, a heat source, and at least two feed tubes, each feed tube having an open end and comprising a capsule proximate the open end, the method further comprising:

adding polycrystalline silicon to the crucible;

heating, by the heat source, the crucible to form a silicon melt from the polycrystalline silicon in the crucible;

growing a single crystal silicon ingot from the melt by contacting the melt with a seed crystal and pulling the seed crystal away from the melt to grow the single crystal silicon ingot, the single crystal silicon ingot having a neck region, a shoulder region, and a body region;

adding a charge of a volatile dopant into each feed tube, the charge of the volatile dopant being received by the capsule of the respective feed tube;

positioning each feed tube within the inner chamber such that the open end of the respective feed tube has a first height relative to a surface of the melt;

adjusting each feed tube within the inner chamber to move the open end of the feed tube from the first height to a second height relative to the surface of the melt at a speed rate, the second height being smaller than the first height;

heating, by the heat source and radiant heat from the surface of the melt, the capsule of each feed tube containing the volatile dopant to form a gaseous dopant as the open end of each feed tube is moved from the first height to the second height at the speed rate, each of the second height and the speed rate being selected to control a vaporization rate of the volatile dopant in each capsule; and

introducing dopant species into the melt while growing the body region of the single crystal silicon ingot by contacting the surface of the melt with the gaseous dopant

from each capsule, wherein the vaporization rate is controlled such that the dopant species are introduced at a rate sufficient to maintain a resistivity of the body region over an axial length of the body region.

15. The method of claim 1, wherein the ingot pulling system includes a heat shield surrounding the single crystal silicon ingot being grown, and positioning the feed tube within the inner chamber includes positioning the open end of the feed tube in a channel defined between the heat shield and the body region of the single crystal silicon ingot.

16. The method of claim 1, wherein the ingot pulling system includes a heat shield surrounding the single crystal silicon ingot being grown, the heat shield defining a gap above the surface of the melt, and positioning the feed tube within the inner chamber includes positioning the open end of the feed tube in the gap.

17. The method of claim 1, wherein adjusting the feed tube is performed after a predetermined axial length of the body region of the single crystal silicon ingot has been grown.

18. The method of claim 1, wherein the second height and the speed rate selected to control the vaporization rate are determined, at least in part, on a simulated temperature profile of the open end of the feed tube as a function of a height of the open end relative to the surface of the melt.

19. The method of claim 1, wherein the second height and the speed rate selected to control the vaporization rate are determined, at least in part, on a doping

efficiency profile of the volatile dopant as a function of a height of the open end relative to the surface of the melt.

20. The method of claim 14, wherein the vaporization rate is controlled such that the dopant species are introduced at a rate sufficient to maintain a resistivity of the body region within a predetermined range and to control variations in the resistivity of the body region to within +/- 15% over an axial length of at least 300 mm.

21. An ingot pulling apparatus for growing a doped single crystal silicon ingot, the apparatus comprising:

an outer housing defining an inner chamber;

a crucible disposed within the inner chamber for holding a silicon melt; and

a gas doping system for introducing dopant species into the melt, the gas doping system comprising:

a feed tube extending between a first end and a second end, the second end located in the inner chamber, the feed tube including a capsule disposed proximate the second end;

a dopant feed source coupled in flow communication with the first end of the feed tube, the dopant feed source being configured to add volatile dopant to the feed tube;

a positioning system configured to adjust the position of the feed tube between a first position, in which the second end of the feed tube is at a first height above a surface of the melt, and a second position, in which the second end of the feed tube is

at a second height above the surface of the melt that is smaller than the first height; and

a controller communicatively coupled to the dopant feed source and the positioning system, the controller being configured to cause the dopant feed source to add a targeted amount of volatile dopant to the feed tube and to cause the positioning system to move the feed tube to the second position at a speed rate, each of the second height and the speed rate being selected to control a vaporization rate of the volatile dopant in the feed tube during an ingot pulling process.

22. The apparatus of claim 21, further comprising a second gas doping system for introducing dopant species into the melt, the second gas doping system comprising:

a second feed tube extending between a first end and a second end, the second end of the second feed tube located in the inner chamber, the second feed tube including a second capsule disposed proximate the second end;

a second dopant feed source coupled in flow communication with the first end of the second feed tube, the dopant feed source being configured to add a volatile dopant to the second feed tube; and

a second positioning system configured to adjust the position of the second feed tube between a first position, in which the second end of the second feed tube is at a first height above a surface of the melt, and a second position, in which the second end of the second feed tube is at a second height above the surface of the melt that is smaller than the first height;

wherein the controller is communicatively coupled to the second dopant feed source and the second positioning system and configured to cause the second dopant feed source to add a targeted amount of the volatile dopant to the second feed tube and to cause the second positioning system to move the second feed tube to the second position at a speed rate, each of the second height and the speed rate of the second feed tube being selected to control a vaporization rate of the volatile dopant in the second feed tube during the ingot pulling process.

23. The apparatus of claim 22, wherein the second height of the second feed tube is different from the second height of the feed tube.

24. The apparatus of claim 22, wherein the speed rate of the second feed tube is different from the speed rate of the feed tube.

25. The apparatus of claim 21, further comprising a heat shield surrounding a growth chamber within the inner chamber through which a single crystal silicon ingot is grown, wherein the second end of the feed tube in the second position is located in a channel within the growth chamber defined by the heat shield.

26. The apparatus of claim 21, further comprising a heat shield surrounding a growth chamber within the inner chamber through which a single crystal silicon ingot is grown, the heat shield defining a gap above the surface of the melt, wherein the second end of the feed tube in the second position is located in the gap.

27. The apparatus of claim 21, wherein the controller is configured to determine the second height and the speed

rate based on a simulated temperature profile of the second end of the feed tube as a function of a height of the second end relative to the surface of the melt.

28. The apparatus of claim 21, wherein the controller is configured to determine the second height and the speed rate based on a doping efficiency profile of the volatile dopant as a function of a height of the second end relative to the surface of the melt.

29. The apparatus of claim 21, wherein the dopant feed source is configured to add a charge of a solid dopant into the feed tube.

30. The apparatus of claim 29, wherein the solid dopant is a solid n-type dopant.

31. The apparatus of claim 29, wherein the solid dopant is a solid p-type dopant.

32. The apparatus of claim 31, wherein the solid dopant is boric acid.

33. An ingot pulling apparatus for growing a doped single crystal silicon ingot, the apparatus comprising:

an outer housing defining an inner chamber;

a crucible disposed within the inner chamber for holding a silicon melt; and

a first gas doping system and a second gas doping system for introducing dopant species into the melt, the first and second gas doping systems each comprising:

a feed tube extending between a first end and a second end, the second end located in the inner

chamber, the feed tube including a capsule disposed proximate the second end;

a dopant feed source coupled in flow communication with the first end of the feed tube, the dopant feed source being configured to add a volatile dopant to the feed tube;

a positioning system configured to adjust the position of the feed tube between a first position, in which the second end of the feed tube is at a first height above a surface of the melt, and a second position, in which the second end of the feed tube is at a second height above the surface of the melt that is smaller than the first height; and

a controller communicatively coupled to the dopant feed source and the positioning system, the controller being configured to cause the dopant feed source to add a targeted amount of the volatile dopant to the feed tube and to cause the positioning system to move the feed tube to the second position, the second height being selected to control a vaporization rate of the volatile dopant in the feed tube during an ingot pulling process.

34. The apparatus of claim 33, wherein the second height of the feed tube of the second gas doping system is different from the second height of the feed tube of the first gas doping system.

35. The apparatus of claim 33, wherein the controller of each of the first and second gas doping systems is configured to cause the respective positioning system to move the respective feed tube at a speed rate that is

selected to control a vaporization rate of the volatile dopant in the respective feed tube.

36. The apparatus of claim 35, wherein the speed rate of the feed tube of the second gas doping system is different from the speed rate of the feed tube of the first gas doping system.

37. The apparatus of claim 33, further comprising a heat shield surrounding a growth chamber within the inner chamber through which a single crystal silicon ingot is grown, wherein the second end of each feed tube in the second position is located in a channel within the growth chamber defined by the heat shield.

38. The apparatus of claim 33, further comprising a heat shield surrounding a growth chamber within the inner chamber through which a single crystal silicon ingot is grown, the heat shield defining a gap above the surface of the melt, wherein the second end of each feed tube in the second position is located in the gap.

39. The apparatus of claim 33, wherein the controller of each of the first and second gas doping systems is configured to determine the second height of the second end of the respective feed tube based on a simulated temperature profile of the second end of the respective feed tube as a function of a height of the second end relative to the surface of the melt.

40. The apparatus of claim 33, wherein the dopant feed source of each of the first and second gas doping systems is configured to add a charge of a solid.