METHODS FOR PRODUCING A SINGLE CRYSTAL SILICON INGOT USING BORIC ACID AS A DOPANT AND INGOT PULLER APPARATUS THAT USE A SOLID-PHASE DOPANT

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of U.S. Provisional Patent Application No. 62/868,573, filed 28 June 2019, which is incorporated herein by reference in its entirety.

FIELD OF THE DISCLOSURE

[0002] The field of the disclosure relates to methods for producing a single crystal silicon ingot in which the ingot is doped with boron using solid-phase boric acid as the source of boron. The field of the disclosure also relates to ingot puller apparatus that use a solid-phase dopant.

BACKGROUND

[0003] In high resistivity silicon wafer applications, the resistivity of the single crystal silicon ingot from which the wafers are sliced may be controlled by addition of various dopants to the melt. The dopants may be used to compensate for various impurities (e.g., boron or phosphorous) in the source of polycrystalline silicon used to form a melt from which the silicon ingot is withdrawn.

[0004] When one or more dopants are added to achieve a target resistivity in the ingot, certain dopants and/or impurities may accumulate in the melt due to differences in the segregation coefficients of the compounds. For example, boron has a segregation

coefficient of about 0.8 which allows boron to be readily taken up into the growing ingot. Phosphorous has a segregation coefficient of about 0.35 which causes phosphorous to accumulate in the melt relative to boron which is taken up more readily. Accordingly, as the ingot grows and the melt is depleted, phosphorous accumulates in the melt altering the resistivity of the growing ingot. This can cause the resistivity to decrease and fall out of customer specifications and/or for a type-change to occur in the ingot.

[0005] A need exists for methods for counter-doping a silicon melt during ingot growth to increase the length of the ingot that remains within customer specifications. A need exists for doping methods that allow for use of dopant source materials that are readily available and/or relatively inexpensive and that allow the melt to be doped with relative ease. A need exits for ingot puller apparatus that allow a solid-phase dopant to be used as the source of dopant.

[0006] This section is intended to introduce the reader to various aspects of art that may be related to various aspects of the disclosure, which are described and/or claimed below. This discussion is believed to be helpful in providing the reader with background information to facilitate a better understanding of the various aspects of the present disclosure. Accordingly, it should be understood that these statements are to be read in this light, and not as admissions of prior art.

SUMMARY

[0007] One aspect of the present disclosure is directed to a method for producing a single crystal silicon ingot from a silicon melt held within a crucible. Polycrystalline silicon is added to the crucible. The crucible is disposed within an ingot puller inner chamber. The polycrystalline silicon is heated to cause a silicon melt to form in the crucible. A single crystal silicon ingot is pulled from the silicon melt. A source of solid-phase boric acid is provided. A boron-containing gas is produced from the solid-phase boric acid. The boron-containing gas is contacted with a surface of the melt to cause boron to enter the melt as a dopant while pulling the single crystal silicon ingot from the melt.

[0008] Yet another aspect of the present disclosure is directed to an ingot puller apparatus for producing a doped single crystal silicon ingot. The ingot puller apparatus includes an ingot puller outer housing and an ingot puller inner chamber formed within the ingot puller outer housing. A crucible is disposed within the ingot puller inner chamber. An outer feed tube is at least partially disposed exterior to the ingot puller outer housing. The outer feed tube defines an outer feed tube chamber. The outer feed tube has a distal end, a proximal end and an outer feed tube axis that extends through the distal end and the proximal end. An elongate member is moveable within the outer feed tube chamber along the outer feed tube axis. A dopant receptacle is coupled to the elongate member. The dopant receptacle is moveable between a loading position in which the dopant receptacle is disposed exterior to the ingot puller outer housing and a

feed position in which the dopant receptacle is disposed within the ingot puller inner chamber.

[0009] Yet another aspect of the present disclosure is directed to an ingot puller apparatus for producing a doped single crystal silicon ingot. The ingot puller apparatus includes an ingot puller outer housing and an ingot puller inner chamber formed within the ingot puller outer housing. A crucible is disposed within the ingot puller inner chamber. A dopant conduit having a gas inlet is disposed exterior to the ingot puller inner chamber and a gas outlet is disposed in the ingot puller inner chamber. A dopant vaporization unit is disposed exterior to the ingot puller chamber. The dopant vaporization unit includes a dopant chamber for holding solid-phase dopant. The dopant vaporization unit includes a heating device for heating the solid-phase dopant and for producing a dopant gas. The dopant vaporization unit includes an outlet through which the dopant gas passes. The outlet is in fluid communication with the dopant conduit.

[0010] Various refinements exist of the features noted in relation to the above-mentioned aspects of the present disclosure. Further features may also be incorporated in the above-mentioned aspects of the present disclosure as well. These refinements and additional features may exist individually or in any combination. For instance, various features discussed below in relation to any of the illustrated embodiments of the present disclosure may be incorporated into any of the above-described aspects of the present disclosure, alone or in any combination.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] Figure 1 is a schematic of an example method for growing a silicon ingot with boric acid as the source of dopant;

[0012] Figure 2 is a partial cross-section side view of an embodiment of an ingot puller apparatus having a dopant receptacle in a dopant loading position;

[0013] Figure 3 is a partial cross-section side view of the ingot puller apparatus with the dopant receptacle in a dopant feed position;

[0014] Figure 4 is a detailed cross-section side view of the ingot puller apparatus with the dopant receptacle in the dopant feed position;

[0015] Figure 5 is a side view of an elongate member that includes a dopant receptacle for holding solid-phase dopant and a translation unit for moving the elongate member;

[0016] Figure 6 is a side view of the translation unit;

[0017] Figure 7 is a cross-section side view of the joint between the elongate member and the translation unit;

[0018] Figure 8 is a perspective cross-section view of the elongate member within an outer tube with the receptacle in the dopant loading position;

[0019] Figure 9 is a cross-section side view of the receptacle;

[0020] Figure 10 is a cross-section side view of another embodiment of an ingot puller apparatus;

[0021] Figure 11 is a cross-section side view of a vaporization unit of the ingot puller apparatus;

[0022] Figure 12 is perspective view of the vaporization unit; and

[0023] Figure 13 is a detailed cross-section side view of the vaporization unit.

[0024] Corresponding reference characters indicate corresponding parts throughout the drawings.

DETAILED DESCRIPTION

[0025] Provisions of the present disclosure relate to methods for doping a silicon melt (e.g., counter-doping) that involve boric acid. Additional provisions relate to ingot puller apparatus configured to dope a silicon melt and, in particular, to dope using a solid-phase dopant such as boric acid.

Methods for Doping using Boric Acid

[0026] An example method of the present disclosure is shown in Figure 1. The method may be carried out by use of an ingot puller apparatus that is configured to produce a boron-containing gas from solid-phase boric acid. Example ingot puller apparatus that may be used in accordance with the methods for doping with boric acid are shown in Figures 2-13. While the method may be described with reference to the ingot puller apparatus 100 shown in Figures 2-9 or the ingot puller apparatus 400 shown in Figures 10-13 to exemplify the method, the method should

not be limited to the ingot puller apparatus 100, 400 unless stated otherwise.

[0027] With reference to Figure 2, in accordance with embodiments of the method for preparing a silicon ingot, a silicon melt is prepared in a crucible 104 disposed within the inner chamber 102 of an ingot puller apparatus 100. The crucible 104 may be supported by a susceptor (not shown). The ingot puller apparatus 100 may be configured to rotate the crucible 104 and/or move the crucible 104 vertically within the ingot puller apparatus 100.

[0028] To prepare the silicon melt, polycrystalline silicon is added to the crucible 104. The polycrystalline silicon is heated to above the melting temperature of silicon (about 1414°C) to cause the polycrystalline silicon to liquefy into a silicon melt 108. A heating system is operated to melt-down the polycrystalline silicon. For example, one or more heaters below or to the side of the crucible 104 are operated to melt-down the silicon.

[0029] Before or after the melt 108 is produced, the melt may be doped with a dopant, typically an n-type dopant, to compensate for p-type impurities (e.g., boron) in the melt. The n-type dopant may be added before growth of the ingot 112 commences. By compensating the melt, the resistivity of the resulting ingot 112 may be increased. For example, the seed end of the ingot (i.e., the portion of the ingot nearest the ingot crown) may have a resistivity of at least about 1,500 Ω-cm or, as in other embodiments, at least about 2,000 Ω-cm, at least about 4,000 Ω-cm, at least about 6,000 Ω-cm, at least about 8,000

Ω-cm, at least about 10,000 Ω-cm or from about 1,500 Ω-cm to about 50,000 ohm-cm or from about 8,000 Ω-cm to about 50,000 Ω-cm. Suitable n-type dopants include phosphorous and arsenic.

[0030] Once the melt 108 is prepared, a single crystal silicon ingot 112 is pulled from the melt 108. A seed crystal 118 is secured to a seed chuck 114. The seed chuck 114 and crystal 118 are lowered until the seed crystal 118 contacts the surface of the silicon melt 108. Once the seed crystal 118 begins to melt, a pulling mechanism slowly raises the seed crystal 118 up to grow the monocrystalline ingot 112.

[0031] A process gas (e.g., argon) is caused to circulate through the inner chamber 102 of the ingot puller apparatus 100. The process gas creates an atmosphere within the chamber 102.

[0032] As shown in Figure 1, embodiments of methods of the present disclosure include providing a source of solid-phase boric acid (H_3BO_3). The boric acid may be relatively pure such as about 99% pure or more, 99.9% pure or more, or 99.99% pure or more. In some embodiments, the boric acid may be relatively isotopically pure (i.e., boron-11). For example, boric acid may be provided within the inner chamber 102 of the ingot puller apparatus 100 (i.e., within the housing 116) such as in the receptacle 156 (Fig. 4) of the ingot puller apparatus 100 of Figures 2-9. Alternatively, the solid-phase boric acid may be disposed exterior to the ingot puller outer housing 416 such as within the dopant chamber 424 of the vaporization unit 414 of the ingot puller apparatus 400 of Figures 10-13.

[0033] A boron-containing gas is produced from the solid-phase boric acid. The gas that is produced is generally in the form of boric acid (H_3BO_3) or derivatives thereof ($B_xO_yH_z^+$ complexes) and not other compounds (e.g., diborane (B_2H_6) or boron dihydride (BH_2)). However, it should be understood that other boron compounds may be added to the boron-containing gas.

[0034] The solid-phase boric acid may be heated to above its melting temperature (about 171°C) to liquefy the solid-phase boric acid and to produce a boric acid liquid. The boric acid liquid is then heated above its vaporization temperature (about 300°C) to produce a boron-containing gas. For example, the solid-phase boric acid may be heated by heat radiated from the silicon melt 108 in the ingot puller apparatus of Figures 2-9 or by a heating device 428 (Fig. 12) of the vaporization unit 414 of the ingot puller apparatus of Figures 10-13.

[0035] Once the boron-containing gas is produced, the boron-containing gas contacts the surface of the melt 108 to allow boron to diffuse into the melt. For example, the flow path of the boron-containing gas in the exit tube 168 (Fig. 4) may be restricted such that the boron-containing gas may only move through the tube outlet 170 as in the ingot puller apparatus 100 of Figures 2-9 or the boron-containing gas may be carried by a process gas as in the ingot puller apparatus 400 of Figures 10-13.

[0036] Once boron enters the melt, boron compensates for phosphorous which has concentrated in the melt due to the relatively low segregation coefficient of phosphorous, thereby increasing the resistivity of the

remaining portion of the ingot 112 that forms in the ingot puller apparatus.

Ingot Puller Apparatus for Doping by use of Solid Dopants

[0037] An example ingot puller apparatus 100 is generally shown in Figures 2-9 and another example ingot puller apparatus 400 is shown in Figures 10-13. The apparatus 100 of Figures 2-9 and the apparatus 400 of Figures 10-13 may be used to dope the ingot with boron using solid-phase boric acid as in the method described above or may be used with other solid-phase dopants that may be vaporized below the melting point of silicon (about 1414°C) in either the native form, or a hydrated form, or in a compound that is non-contaminating to the crystal growth process (e.g., doped glass with a relatively high concentration of B_2O_3 intermixed with SiO_2 or a heavily doped Si-B alloy).

[0038] Referring now to Figure 2, the ingot puller apparatus 100 includes an ingot puller outer housing 116 that defines an ingot puller inner chamber 102 within the housing 116. A crucible 104 is disposed within the ingot puller inner chamber 102. The crucible 104 contains the silicon melt 108 from which the silicon ingot 112 is pulled. The ingot 112 is shrouded by a heat shield 120.

[0039] The ingot puller apparatus 100 includes a dopant feed system 126. The dopant feed system 126 includes an outer feed tube 130 that is at least partially disposed exterior to the ingot puller housing 116. The outer feed tube 130 defines an outer feed tube chamber 136 therein. The outer tube 130 has a distal end 140 furthest from the outer housing 116 and a proximal end 144 nearest the housing 116. An outer feed tube axis A_{130} extends

through the distal end 140 and the proximal end 144 of the outer feed tube 130. The outer feed tube 130 may be made of stainless steel or other suitable materials.

[0040] An elongate member 150 is moveable within the outer feed tube 130 along the outer feed tube axis A_{130}. The elongate member 150 may be lowered into the ingot puller inner chamber 102 as shown in Figure 4. In the illustrated embodiment, the elongate member 150 is a tube. In other embodiments, a rod or shaft may be used. The elongate member 150 may be made of any material that withstands the environment within the ingot puller chamber 102 such as quartz.

[0041] A dopant receptacle 156 is coupled to the elongate member 150 (Fig. 4) (e.g., nested within it). As shown in Figure 8, the receptacle 156 may abut a ledge 160 of the elongate member 150. The receptacle 156 may include a shoulder 162 (Fig. 9) that is seated on the ledge 160. By moving the elongate member 150, the dopant receptacle 156 moves between a raised position (Fig. 2, which may also be referred to as a "dopant loading position") in which the dopant receptacle 156 is disposed exterior to the ingot puller outer housing 116 and a lowered position (FIGS. 3 and 4, which may also be referred to as a "dopant feed position") in which the receptacle 156 is disposed within the ingot puller inner chamber 102 near the surface of the melt 108. The heat shield 120 may include a channel 124 (Fig. 2) formed therein to provide a pathway for the elongate member 150 and dopant receptacle 156 coupled thereto to approach the melt 108.

[0042] The receptacle 156 may be separable from the elongate member 150. The elongate member 150

includes a notch 164 (Fig. 5) that enables access to the receptacle 156. In the loading position (Fig. 2), the receptacle 156 may be removed from the elongate member 150 to charge it with dopant. The notch 164 is aligned with an access port 166 when the receptacle 156 is in the loading position to allow access to the receptacle 156. The receptacle 156 may be grasped by a connecting loop 172 of the receptacle 156 to pull the receptacle 156 through the notch 164 and access port 166. In other configurations, dopant may be added to the receptacle 156 when the receptacle 156 is disposed in the elongate member 150.

[0043] In the feed position of the receptacle (FIGS. 3 and 4), a dopant gas is produced from the solid-phase dopant. The dopant gas travels down an exit tube 168 and through an outlet 170 where it is directed to the surface of the melt 108.

[0044] In the illustrated embodiment, the receptacle 156 is a capsule 158 (Fig. 9) that holds the solid-phase dopant. The capsule 158 includes an outer capsule housing 180. A weir 182 is disposed within the outer capsule housing 180. The weir 182 forms a channel 184 therein. The weir 182 has an upper end 188 and a lower end 190 that are each open such that gas may pass through the channel 184. An annular chamber 194 is disposed between the weir 182 and the outer capsule housing 180. Solid dopant 174 (e.g., boric acid) is disposed within the annular chamber 194 and rests on the capsule floor. When the receptacle 156 is in its lowered position (Figs. 3 and 4), the solid-phase dopant 174 heats which causes the dopant to either sublime or to melt and evaporate. The dopant gas rises in the annular chamber 194 and enters the weir channel 184 through the upper end 188 of the weir 182.

The gas continues to pass down through the channel 184 and exits through the open lower end 190 of the weir 182. The dopant gas proceeds through the exit tube 168 (Fig. 4), through the tube outlet 170 and toward the surface of the melt.

[0045] The elongate member 150 includes a gas barrier wall 240 (Fig. 8) which prevents gas from back-flowing up the elongate member 150. Alternatively, the elongate member may be a rod or shaft which does not include a pathway for gas to back-flow.

[0046] Referring now to Figure 4, the ingot puller apparatus 100 includes an isolation valve 200 within the outer feed tube 130. The isolation valve 200 seals the ingot puller inner chamber 102 when the elongate member 150 is withdrawn from the ingot puller inner chamber 102. This allows the dopant receptacle 156 to be accessed through the access port 166 while the port 156 is isolated from the inner chamber 102. When the elongate member 150 is lowered, the access port 166 may be closed or connected to a source of process gas (e.g., argon). The isolation valve 200 is connected to a valve controller 202 which actuates the valve 200.

[0047] The ingot puller apparatus 100 includes a translation device 208 (Fig. 2) for moving the dopant receptacle 156 between the dopant loading position (Fig. 2) and the dopant feed position (Figs. 3 and 4). The translation device 208 moves the elongate member 150 and dopant receptacle 156 in and out of the inner chamber 102 of the ingot puller apparatus 100 and within the outer feed tube chamber 136 (i.e., along outer feed tube axis A_{130}). Generally, any translation device 208 that allows the

receptacle 156 to be moved between the dopant loading and dopant feed positions of the receptacle 156 may be used unless stated otherwise.

[0048] In the illustrated embodiment, the translation device 208 is a magnetically coupled through-wall translation unit. The translation device 208 includes an outer tube 212 and an inner member 214 that moves within the outer tube 212. The inner member 214 is magnetically coupled to a translation device handle 216. The outer tube 212 may be made of stainless steel (non-magnetic) or other suitable materials. The translation device handle 216 and inner member 214 may have magnets embedded therein to enable magnetic coupling between the handle 216 and inner member 214.

[0049] The inner member 214 is also connected to the elongate member 150 at a joint 220 (Fig. 7). The example joint 220 includes a threaded member 224 that engages threads on a sleeve 218 that surrounds and is pinned to a lower portion of the inner member 214. The joint 220 includes first and second o-rings 228, 232 and a bushing 236 disposed between the o-rings 228, 232. The threaded member 224 compresses the o-rings 228, 232 causing them to move radially outward to facilitate a frictional connection between the translation device inner member 214 and the elongate member 150.

[0050] The handle 216 of the translation device 208 may be moved up and down along axis A_{130} (Fig. 2). As the handle 216 moves, the inner member 214 moves within the outer tube 212. Because the inner member 214 is coupled to the elongate member 150, the elongate member 150 and receptacle 256 are caused to move in and out of the

inner chamber 102 of the ingot puller apparatus 100. In some embodiments, when the receptacle 156 is in a lowered position for feeding dopant, the distance between the receptacle 156 and the melt 108 may be changed (e.g., by an operator) to vary the heat applied to the receptacle 156 and solid-phase dopant therein to control the rate at which dopant gas is produced. In other embodiments, the receptacle 156 may be moved between its loading position (Fig. 2) and the dopant feed position (Figs. 3 and 4) by an actuator rather than manually.

[0051] As noted above, the translation device 208 may have other configurations. Other example translation devices may include a bellows system or an externally operated linear translation device (e.g., a rod attached to either an externally isolated linear rail or pneumatic cylinder). Any external actuator should be isolated from the heat and vacuum inside the inner chamber 102.

[0052] Another example ingot puller apparatus 400 is shown in Figures 10-11. The ingot puller apparatus 400 may operate similar to the ingot puller apparatus 100 described above and the operation of the apparatus 100 should be considered to be applicable to apparatus 400 (i.e., in aspects not related to use of the solid-phase dopant). For example, the ingot puller apparatus 400 includes an outer housing 416 that forms an inner chamber 402 within the housing 416. A crucible 404 for holding a silicon melt 408 therein is disposed in the chamber 402. The apparatus 400 includes a heat shield (not shown) that shrouds the ingot that is pulled from the melt.

[0053] The ingot puller apparatus 400 includes a dopant vaporization unit 414 that feeds doped gas to a dopant conduit 430. The doped gas passes through the dopant conduit 430 to contact the melt 408 to cause the melt 408 to be doped. The dopant conduit 430 includes a gas inlet 422 (Fig. 11) disposed exterior to the ingot puller chamber 402 and a gas outlet 426 disposed in the ingot puller inner chamber 402 and positioned relatively near the surface of the melt 408.

[0054] The dopant vaporization unit 414 is disposed exterior to the ingot puller inner chamber 402. The dopant vaporization unit 414 includes a dopant chamber 424 (Fig. 13) for holding the solid-phase dopant (e.g., boric acid as discussed in the method above). A process gas (e.g., argon) may be circulated through the vaporization unit 414 through first and second process gas inlets 436, 440. A doped gas outlet 452 of the vaporization unit 414 is in fluid communication with the dopant conduit 430 (Fig. 11) to move doped gas to the surface of the melt 408.

[0055] Surrounding the dopant chamber 424 is a heating chamber 472 (Fig. 13). A heating device 428 (e.g., resistive heating element) heats gases circulating in the vaporization unit 414. The heated gases contact the solid-phase dopant in the dopant chamber 242 causing a dopant gas to be produced (e.g., through sublimation or by liquefaction and vaporization of the solid-phase dopant). The dopant gas is picked up the process gas to produce a doped process gas that is discharged through the doped gas outlet 452 and into the dopant conduit 430 (Fig. 11). The vaporization unit 414 includes a thermal shield 476 to reduce heat lost through the walls of the heating chamber

472. The heating chamber 472 may be made of quartz to reduce contamination.

[0056] An isolation valve 460 is within the process gas pathway downstream of the heating chamber 472 and dopant chamber 424. The isolation valve 460 isolates the vaporization unit 414 from the inner chamber 402 of the ingot puller apparatus 400 to seal the chamber 402 when dopant is not being added to the melt 408. A valve controller 464 may be used to actuate the valve 460.

[0057] The vaporization unit 414 includes a temperature sensor 448 (Fig. 12) to measure the temperature of the heating chamber 472 (Fig. 13). The temperature sensor 448 may send a signal to a control unit to vary the output of the heating device 428 based on the sensed temperature. The vaporization unit 414 includes a vacuum port 456 for pump-down, leak testing and to equalize the pressure with the ingot puller apparatus inner chamber 402 prior to opening isolation valve 460 for doping.

[0058] Compared to conventional methods for producing a single crystal silicon ingot from a silicon melt, the methods of embodiments of the present disclosure have several advantages. In embodiments in which the melt is counter-doped by using boric acid, a larger portion of the ingot may be within customer specifications (e.g., high resistivity) and/or a type-change in the ingot may be prevented. Solid-phase boric acid has a relatively low melting and vaporization temperatures which allows a dopant gas to be produced with relative ease.

[0059] Compared to conventional ingot puller apparatus, the ingot puller apparatus of embodiments of the present disclosure have several advantages. In embodiments

in which a dopant receptacle is used to hold solid dopant, the receptacle may be placed in relative proximity to the melt surface which allows the heat of the melt to melt and vaporize the dopant. Positioning the receptacle near the melt also reduces or prevents the formation of precipitation or condensation of elemental boron or boron compounds that result in loss of crystal structure or integrity. Use of a dopant receptacle that includes a weir allows dopant particles to move within the receptacle without being propelled out of the receptacle and into the melt. Entry of dopant particles directly into the melt may cause loss of zero dislocation in the ingot. Use of an isolation valve allows the inner chamber of the ingot puller to be isolated from the solid-phase dopant system which prevents contamination of the melt and enables reloading of solid-phase dopant. Use of a magnetically coupled through-wall translation unit simplifies sealing and allows the system to be more robust (e.g., no separate seals) to maintain a gas-tight environment.

[0060] In embodiments in which the solid-phase dopant is converted to a gas by a vaporization unit exterior to the ingot puller housing, a heating device may be used to heat the dopant which allows for improved control of the rate at which dopant is added to the melt. The rate at which process gas is circulated through the vaporization unit may also be used to control the rate at which the melt is doped. In embodiments in which a feed tube or conduit is moveable within the ingot puller apparatus, the distance from the melt may be controlled which allows the rate of dopant addition to the melt to be controlled.

[0061] As used herein, the terms “about,” “substantially,” “essentially” and “approximately” when used in conjunction with ranges of dimensions, concentrations, temperatures or other physical or chemical properties or characteristics is meant to cover variations that may exist in the upper and/or lower limits of the ranges of the properties or characteristics, including, for example, variations resulting from rounding, measurement methodology or other statistical variation.

[0062] When introducing elements of the present disclosure or the embodiment(s) thereof, the articles "a", "an", "the" and "said" are intended to mean that there are one or more of the elements. The terms "comprising," "including," “containing” and "having" are intended to be inclusive and mean that there may be additional elements other than the listed elements. The use of terms indicating a particular orientation (e.g., "top", "bottom", "side", etc.) is for convenience of description and does not require any particular orientation of the item described.

[0063] As various changes could be made in the above constructions and methods without departing from the scope of the disclosure, it is intended that all matter contained in the above description and shown in the accompanying drawing[s] shall be interpreted as illustrative and not in a limiting sense.

WHAT IS CLAIMED IS:

1. A method for producing a single crystal silicon ingot from a silicon melt held within a crucible, the method comprising:

adding polycrystalline silicon to the crucible, the crucible being disposed within an ingot puller inner chamber;

heating the polycrystalline silicon to cause a silicon melt to form in the crucible;

pulling a single crystal silicon ingot from the silicon melt;

providing a source of solid-phase boric acid;

producing a boron-containing gas from the solid-phase boric acid; and

contacting the boron-containing gas with a surface of the melt to cause boron to enter the melt as a dopant while pulling the single crystal silicon ingot from the melt.

2. The method as set forth in claim 1 comprising adding an n-type dopant to the crucible prior to pulling the single crystal silicon ingot from the melt.

3. The method as set forth in claim 2 wherein the n-type dopant is phosphorous.

4. The method as set forth in any one of claims 1 to 3 wherein the boron-containing gas is produced by:

liquefying the solid-phase boric acid to produce a boric acid liquid; and

evaporating the boric acid liquid to produce the boron-containing gas.

5. The method as set forth in any one of claims 1 to 4 wherein the solid-phase boric acid is disposed within the ingot puller inner chamber.

6. The method as set forth in claim 5 wherein the solid-phase boric acid is disposed within a capsule.

7. The method as set forth in any one of claims 1 to 4 wherein the solid-phase boric acid is disposed exterior to the ingot puller housing.

8. The method as set forth in claim 7 wherein the solid-phase boric acid is within a chamber of a vaporization unit.

9. An ingot puller apparatus for producing a doped single crystal silicon ingot, the ingot puller apparatus comprising:

an ingot puller outer housing;

an ingot puller inner chamber formed within the ingot puller outer housing;

a crucible disposed within the ingot puller inner chamber;

an outer feed tube that is at least partially disposed exterior to the ingot puller outer housing, the outer feed tube defining an outer feed tube chamber and having a distal end, proximal end and an outer feed tube axis that extends through the distal end and the proximal end;

an elongate member that is moveable within the outer feed tube chamber along the outer feed tube axis; and

a dopant receptacle coupled to the elongate member that is moveable between a loading position in which the dopant receptacle is disposed exterior to the ingot puller outer housing and a feed position in which the dopant receptacle is disposed within the ingot puller inner chamber.

10. The ingot puller apparatus as set forth in claim 9 wherein the dopant receptacle is a capsule that is separable from the elongate member.

11. The ingot puller apparatus as set forth in claim 10 wherein the capsule comprises:

an outer capsule housing; and

a weir disposed within the outer capsule housing, the weir forming a channel for dopant gas to pass through, the weir having an upper end and a lower end, the upper end and lower ends being open, an annular chamber disposed between the weir and the ingot puller outer housing for holding solid-phase dopant.

12. The ingot puller apparatus as set forth in any one of claims 9 to 11 comprising a tube disposed below the dopant receptacle to direct dopant gas to a surface of a melt.

13. The ingot puller apparatus as set forth in any one of claims 9 to 12 wherein the elongate member is a tube.

14. The ingot puller apparatus as set forth in any one of claims 9 to 13 further comprising a valve for sealing the ingot puller inner chamber when the elongate member is withdrawn from the ingot puller inner chamber.

15. The ingot puller apparatus as set forth in any one of claims 9 to 14 comprising a translation device for moving the dopant receptacle between the loading position and the feed position.

16. The ingot puller apparatus as set forth in claim 15 wherein the translation device is a magnetically coupled through-wall translation unit.

17. The ingot puller apparatus as set forth in claim 15 wherein the translation device is a bellows system.

18. An ingot puller apparatus for producing a doped single crystal silicon ingot, the ingot puller apparatus comprising:

an ingot puller outer housing;

an ingot puller inner chamber formed within the ingot puller outer housing;

a crucible disposed within the ingot puller inner chamber;

a dopant conduit having a gas inlet disposed exterior to the ingot puller inner chamber and a gas outlet disposed in the ingot puller inner chamber; and

a dopant vaporization unit disposed exterior to the ingot puller chamber and comprising:

a dopant chamber for holding solid-phase dopant;

a heating device for heating the solid-phase dopant and producing a dopant gas; and

an outlet through which the dopant gas passes, the outlet being in fluid communication with the dopant conduit.

19. The ingot puller apparatus as set forth in claim 18 further comprising an inlet for introducing a process gas, the inlet being in fluid communication with the dopant chamber, the process gas passing through the dopant chamber and through the outlet.