system (not shown) for introducing dopant into the melt 104.

[0025] According to the Czochralski single crystal growth process, a quantity of polycrystalline silicon, or polysilicon, is charged to the crucible 102 (e.g., charge of 250 kg or more). A variety of sources of polycrystalline silicon may be used including, for example, granular polycrystalline silicon produced by thermal decomposition of silane or a halosilane in a fluidized bed reactor or polycrystalline silicon produced in a Siemens reactor. Once polycrystalline silicon is added to the crucible to form a charge, the charge is heated to a temperature above about the melting temperature of silicon (e.g., about 1412°C) to melt the charge. In some embodiments, the charge (i.e., the resulting melt) is heated to a temperature of at least about 1425°C, at least about 1450°C or even at least about 1500°C. The ingot puller apparatus 100 includes bottom insulation 110 and side insulation 124 to retain heat in the puller apparatus 100. In the illustrated embodiment, the ingot puller apparatus 100 includes a bottom heater 126 disposed below the crucible floor 129. The crucible 102 may be moved to be in relatively close proximity to the bottom heater 126 to melt the polycrystalline silicon charged to the crucible 102.

[0026] To form the ingot, the seed crystal 122 is contacted with the surface 111 of the melt 104. The pulling mechanism 114 is operated to pull the seed crystal 122 from the melt 104. The ingot 113 includes a crown portion 142 in which the ingot transitions and tapers outward from the seed crystal 122 to reach a target diameter. The ingot 113 includes a constant diameter

ingot 113 as the ingot is pulled by the pulling mechanism 114.

[0029] The reflector 151 is, in general, a heat shield adapted to retain heat underneath itself and above the melt 104. In this regard, any reflector design and material of construction (e.g., graphite or gray quartz) known in the art may be used without limitation. The reflector 151 has a bottom 138 (Figure 2) and the bottom 138 of the reflector 151 is separated from the surface of the melt by a distance Hr during ingot growth.

[0030] A single crystal silicon ingot 113 produced in accordance with embodiments of the present disclosure and, generally, the Czochralski method is shown in Figure 3. The ingot 113 includes a neck 116, an outwardly flaring portion 142 (synonymously “crown” or “cone”), a shoulder 119 and a constant diameter main body 145. The neck 116 is attached to the seed crystal 122 that was contacted with the melt and withdrawn to form the ingot 113. The main body 145 is suspended from the neck 116. The neck 116 terminates once the cone portion 142 of the ingot 113 begins to form.

[0031] The constant diameter portion 145 of the ingot 113 has a circumferential edge 150, a central axis A that is parallel to the circumferential edge 150 and a radius R that extends from the central axis A to the circumferential edge 150. The central axis A also passes through the cone 142 and neck 116. The diameter of the main ingot body 145 may vary and, in some embodiments, the diameter may be about 150 mm, about 200 mm, about 300 mm,

greater than about 300 mm, about 450 mm or even greater than about 450 mm.

[0032] The single crystal silicon ingot 113 may generally have any resistivity. The single crystal silicon ingot 113 may be doped or undoped.

[0033] In accordance with embodiments of the present disclosure, the ingot main body 145 is grown while applying a horizontal magnetic field to the crucible 102 and melt 104 in accordance with known horizontal magnetic field Czochralski techniques (HMCz). Figures 4-5 show a horizontal magnetic field applied to a crucible 102 and melt 104 during ingot growth. A cylindrical coordinate system for the crucible 102 includes a radial direction R, an angular direction θ, and an axial direction Z. The melt 104 may contain one or more convective flow cells 132, 134 induced by heating of the crucible 102 and rotation of the crucible 102 and/or ingot 113 in the angular direction θ. The structure and interaction of these one or more convective flow cells 132, 134 may be modulated via regulation of one or more process parameters and/or the application of a horizontal magnetic field as described in detail herein below.

[0034] Figure 6 is a diagram illustrating a horizontal magnetic field applied to the crucible 102 and melt 104 in the ingot puller apparatus 100. As shown, the crucible 102 contains the silicon melt 104 from which the ingot 113 is grown. The transition between the melt and the crystal is generally referred to as the crystal-melt interface (alternatively the melt-crystal, solid-melt or melt-solid interface) and is typically non-linear, for

during silicon crystal Cz growth in a horizontal magnetic (HMCZ) field versus growth in a Cusp (or vertical) magnetic field. However, the LZD rate in HMCZ can be lowered with shorter process time by not applying a magnetic field (e.g., a horizontal magnetic field or any type of magnetic field) during neck 116 growth and/or at least a portion of crown 142 growth or by applying a relatively weak horizontal magnetic field (e.g., less than 1500 gauss) during neck 116 growth and/or at least a portion of crown 142 growth.

[0038] In accordance with embodiments of the present disclosure, once the seed crystal 122 contacts the silicon melt 104 and the neck 116 begins grown, a magnetic field is not applied to the melt 104 (i.e., the magnetic poles 157 are not powered) or a relatively weak magnetic field such as 1500 gauss or less is applied. Once the neck 116 is formed, the outwardly flaring crown 142 begins to be pulled from the melt 104. In some embodiments, the entire crown 142 is formed without a magnetic field being applied to the melt or a relatively weak magnetic field such as 1500 gauss or less is applied. In some embodiments, when the crown diameter is less than 120 mm, a magnetic field is not applied to the melt or a magnetic field is applied with the magnetic flux density being less than 1500 gauss. In such embodiments, once a diameter of 120 mm is reached in the crown 142, the magnetic flux density of the horizontal magnetic field may exceed 1500 gauss (e.g., 0 gauss to 4000 gauss). In some embodiments, the magnetic field flux is ramped up (i.e., increase) during crown growth.

[0039] Once the desired ingot diameter is reached, the shoulder 119 is formed to transition toward

CLAIMS:

1. A method for producing a monocrystalline silicon ingot having a neck and a main body suspended from the neck by the horizontal magnetic field Czochralski method, the monocrystalline silicon ingot being grown in an ingot puller apparatus having a heat shield, the method comprising:

contacting a seed crystal with a silicon melt held within a crucible;

pulling a neck from the silicon melt, wherein:

a horizontal magnetic field is not applied to the melt while the neck is pulled from the melt;

the crucible is rotated at a crucible rotation rate of 8 rpm or more while pulling the neck from the melt; and

a distance between the melt and a bottom of the heat shield is at least 60 mm while pulling the neck from the melt; and

pulling an ingot main body from the melt, the main body being suspended from the neck, wherein a horizontal magnetic field is applied to the melt while the ingot main body is pulled from the melt.

2. The method as set forth in claim 1 comprising pulling an outwardly flaring portion of the ingot, the outwardly flaring portion being disposed between the neck and the ingot main body, wherein a horizontal magnetic field is not applied to the melt while pulling the outwardly flaring portion from the melt.

3. The method as set forth in claim 2 wherein a magnetic field is not applied to the melt while pulling the outwardly flaring portion.

4. The method as set forth in any one of claims 1 to 3 wherein a magnetic field is not applied to the melt while pulling the neck from the melt.

5. The method as set forth in any one of claims 1 to 4, wherein the distance between the melt and the bottom of the heat shield is at least 60 mm while pulling the neck from the melt.

6. The method as set forth in any one of claims 1 to 4 comprising pulling an outwardly flaring portion of the ingot, the outwardly flaring portion being disposed between the neck and the ingot main body, wherein a horizontal magnetic field is not applied to the melt while pulling at least a portion of the outwardly flaring portion from the melt, wherein the distance between the melt and the bottom of the heat shield is at least 40 mm while pulling the outwardly flaring portion from the melt.

7. The method as set forth in any one of claims 1 to 4 comprising pulling an outwardly flaring portion of the ingot, the outwardly flaring portion being disposed between the neck and the ingot main body, wherein a horizontal magnetic field is not applied to the melt while pulling at least a portion of the outwardly flaring portion from the melt, wherein the distance between the melt and the bottom of the heat shield is at least 60 mm while pulling the outwardly flaring portion from the melt.

8. The method as set forth in any one of claims 1 to 7 wherein the neck is grown at a pull rate of at least 1.5 mm/min.

9. The method as set forth in claim 8 wherein the neck is growth at a pull rate of less than 4.5 mm/min.

10. The method as set forth in any one of claims 1 to 9 comprising pulling an outwardly flaring portion of the ingot, the outwardly flaring portion being disposed between the neck and the ingot main body, the outwardly flaring portion having a height that is at least 220 mm.

11. A method for producing a monocrystalline silicon ingot having a neck and a main body suspended from the neck by the horizontal magnetic field Czochralski method, the monocrystalline silicon ingot being grown in an ingot puller apparatus having a heat shield, the method comprising:

contacting a seed crystal with a silicon melt held within a crucible;

pulling a neck from the silicon melt, wherein:

a horizontal magnetic field is applied to the melt while the neck is pulled from the melt, the horizontal magnetic field being generated at a magnetic flux density of 1500 gauss or less;

the crucible is rotated at a crucible rotation rate of 8 rpm or more while pulling the neck from the melt; and

a distance between the melt and a bottom of the heat shield is at least 60 mm while pulling the neck from the melt; and

pulling an ingot main body from the melt, the main body being suspended from the neck, wherein a horizontal magnetic field is applied to the melt while the ingot main body is pulled from the melt.

12. The method as set forth in claim 11 comprising pulling an outwardly flaring portion of the ingot, the outwardly flaring portion being disposed between the neck and the ingot main body, wherein a horizontal magnetic field is not applied to the melt while pulling a portion of the outwardly flaring portion.

13. The method as set forth in claim 11 comprising pulling an outwardly flaring portion of the ingot, the outwardly flaring portion being disposed between the neck and the ingot main body, wherein a horizontal magnetic field is applied to the melt while pulling a portion of the outwardly flaring portion.

14. The method as set forth in claim 13 wherein the horizontal magnetic field is between 0 gauss to 1500 gauss at an outwardly flaring portion diameter of less than 120 mm.

15. The method as set forth in claim 14 wherein the horizontal magnetic field is increased during growth of a portion of the outwardly flaring portion.

16. The method as set forth in any one of claims 11 to 15, wherein the distance between the melt and the bottom of the heat shield is at least 60 mm while pulling the neck from the melt.

17. The method as set forth in any one of claims 11 to 16 wherein the neck is grown at a pull rate of at least 1.5 mm/min.

18. The method as set forth in claim 17 wherein the neck is growth at a pull rate of less than 4.5 mm/min.

19. The method as set forth in any one of claims 11 to 18 comprising pulling an outwardly flaring portion of the ingot, the outwardly flaring portion being disposed between the neck and the ingot main body, the outwardly flaring portion having a height that is at least 220 mm.