as in counter-doping embodiments). For example, the first dopant may be P-type with the second dopant being N-type. Alternatively, the first dopant may be N-type with the second dopant being P-type.

Referring now to FIG. 2, there is a distance D that extends along the surface of the melt 104 between the main body of the single crystal silicon ingot 113 and the sidewall 131 of the crucible 102. The doped silicon particulate drops into the melt 104 in an impact region 140 in which the particulate silicon impacts the surface of the melt 104. The position of the impact region 140 may be selected based on the particle size of the doped particulate silicon. Once the particle size and/or weight of the doped particulate silicon that will be added during ingot growth is determined, the flow and melt speed of the doped particulate silicon in the melt may be modeled (see Example 4 below). For example, the flow and melt speed of the particulate silicon in the melt may include modeling the likelihood of loss of zero dislocation in the single crystal silicon ingot (e.g., correlating a size or weight of the particulate silicon to an impact region at which loss of zero dislocation is least likely to occur).

[0037] The impact region of the melt surface at which doped particulate silicon is added to the melt is selected based on the modeled melt flow and melt speed of the particulate silicon in the melt. The position of the tube 130 between the ingot 113 and crucible sidewall 131 may be pre-set in the ingot puller apparatus (i.e., during set-up of the hotzone) or may be adjusted by a dopant tube translation device (not shown). In some embodiments, the hotzone limits the position of the dopant tube (e.g., because of the heat shield design) such as to 0.08*D to 1.0*D.

[0038] In accordance with some embodiments of the present disclosure, the weight of the doped silicon particles is less than 10 milligrams (mg) (e.g., at least 50%, at least 75%, at least 90%, at least 95%, at least 99% or substantially all of the particles have a weight less than 10 mg). The weight and/or size of the doped silicon particles may be controlled to be less than 10 mg by screening the doped particulate silicon prior to addition to the melt. In other embodiments, the weight of the silicon particles is less than 9 mg, less than 7 mg, less than 5 mg, or from 1 mg to 10 mg or from 1 mg to 5 mg. The particulate dopant may have a thickness typical for single crystal silicon wafers (e.g. 0.5 mm to 1 mm).

[0039] In some embodiments, the amount of doped particulate silicon added to the melt is based on a measured resistivity of a single crystal silicon wafer that is crushed or cut to produce the doped particulate silicon.

[0040] In some embodiments of the present disclosure, the impact region extends from 0.08*D to 0.1*D from the silicon ingot (e.g., with the weight of silicon particles being less than 10 mg to reduce or eliminate LZD). In impact regions from about 0.1*D to 0.6*D, the weight of the silicon particles may be less than 400 mg (e.g., 25 to 400 mg). In impact regions greater than 0.6*D, the weight of the silicon particles may be less than 800 mg.

[0041] Compared to conventional methods for doping a silicon melt, the methods of the present

CLAIMS:

1. A method for forming a single crystal silicon ingot comprising:

adding an initial charge of polycrystalline silicon to a crucible, the crucible having a floor and a sidewall that extends from the floor;

heating the initial charge of polycrystalline silicon to cause a silicon melt to form in the crucible, the silicon melt having a surface;

contacting a seed crystal with the surface of the silicon melt;

withdrawing the seed crystal from the melt to grow a single crystal silicon ingot, there being a distance, D, that extends along the surface of the melt between the single crystal silicon ingot and the sidewall of the crucible;

determining an impact region of the melt surface at which doped particulate silicon is added to the melt;

modeling the flow and melt speed of the doped particulate silicon in the melt;

selecting a particle size or weight of doped particulate silicon to be added to the melt during growth of the single crystal silicon ingot based on the modeled flow and melt speed of the doped particulate silicon in the melt; and

adding doped particulate silicon having the selected particle size to the melt in the impact region during growth of the single crystal silicon ingot.

2. The method as set forth in claim 1 comprising cutting or crushing one or more single crystal silicon wafers to produce the doped particulate silicon.

3. The method as set forth in claim 1 or claim 2 wherein modeling the flow and melt speed of the doped particulate silicon in the melt includes modeling the likelihood of loss of zero dislocation in the single crystal silicon ingot.

4. The method as set forth in any one of claims 1 to 3 wherein modeling the flow and melt speed of the doped particulate silicon in the melt includes correlating a size or weight of the doped particulate silicon to an impact region at which loss of zero dislocation is least likely to occur.

5. A method for forming a single crystal silicon ingot comprising:

adding an initial charge of polycrystalline silicon to a crucible, the crucible having a floor and a sidewall that extends from the floor;

heating the initial charge of polycrystalline silicon to cause a silicon melt to form in the crucible, the silicon melt having a surface;

contacting a seed crystal with the silicon melt;

withdrawing the seed crystal from the melt to grow a single crystal silicon ingot, there being a distance, D, that extends along the surface of the melt between the single crystal silicon ingot and the sidewall of the crucible; and

adding doped particulate silicon to the melt during growth of the single crystal silicon ingot, the

concentration of dopant in the doped particulate silicon being at least 1 x 10^{14} atoms/cm^3, the doped particulate silicon impacting the surface of the melt in an impact region that extends from 0.08*D from the silicon ingot and toward the crucible sidewall, the doped particulate silicon having a weight of less than 10 milligram (mg).

6. The method as set forth in claim 5 wherein the impact region extends from 0.08*D from the silicon ingot to 0.1*D from the silicon ingot.

7. The method as set forth in claim 5 or claim 6 wherein the doped particulate silicon is crushed or cut from one or more single crystal silicon wafers.

8. The method as set forth in any one of claims 5 to 7 comprising cutting a single crystal silicon wafer to produce the doped particulate silicon.

9. The method as set forth in any one of claims 5 to 8 comprising:

determining the resistivity of the single crystal silicon wafer; and

determining the amount of doped particulate silicon added to the melt based, at least in part, on the resistivity of the single crystal silicon wafer.

10. The method as set forth in any one of claims 5 to 9 wherein the dopant is a second dopant, the method comprising doping the melt with a first dopant before the single crystal silicon ingot is grown, the first dopant being of a type different than a type of the second dopant.

11. The method as set forth in claim 10 wherein the first dopant is p-type and the second dopant is n-type.

12. The method as set forth in claim 10 wherein the first dopant is n-type and the second dopant is p-type.

13. The method as set forth in any one of claims 5 to 12 wherein the dopant is boron.

14. The method as set forth in claim 13 wherein the concentration of boron in the doped particulate silicon is from 1×10^{14} atoms/cm^3 to 1×10^{20} atoms/cm^3.

15. The method as set forth in any one of claims 5 to 14 comprising pre-loading doped particulate silicon into one or more dopant storage vessels before ingot growth, the vessel being disposed within a dopant feeder housing to seal the vessel from an ambient atmosphere, the vessel being external to an ingot puller housing.

16. The method as set forth in claim 15 comprising dispensing preloaded doped particulate silicon from the vessel during ingot growth, the preloaded doped particulate silicon passing through a dopant tube that extends through an ingot puller housing.

17. The method as set forth in any one of claims 5 to 16 wherein the doped particulate silicon has a weight of less than 9 mg.

18. The method as set forth in claim 5 wherein the doped particulate silicon has a weight from 1 mg to 5 mg.