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(54) Title: METHOD FOR PRODUCING A MONOCRYSTALLINE PRODUCT

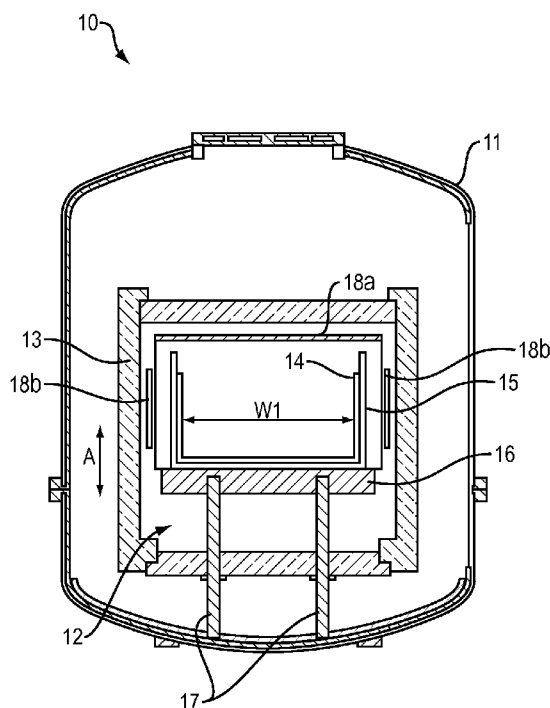


FIG. 1

(57) Abstract: A method of producing a monocrystalline product having a target size is disclosed. The method comprises the step of producing a first crystalline material in the hot zone of a crystal growth apparatus using a first crucible, wherein the first crystalline material has an interior monocrystalline portion that is too small to remove the desired monocrystalline product, and subsequently producing a second crystalline material in the hot zone of the same crystal growth apparatus using a second crucible having defined dimensions. The resulting second crystalline material has a larger interior monocrystalline portion from which the desired monocrystalline product can be removed.



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TITLE

METHOD FOR PRODUCING A MONOCRYSTALLINE PRODUCT

5 CROSS-REFERENCE TO RELATED APPLICATIONS

The present application claims the benefit of U.S. Provisional Patent Application No. 61/515,124, filed August 4, 2011.

10 BACKGROUND OF THE INVENTION

1. Field of the Invention.

15 [0001] The present invention relates to a method for producing a monocrystalline material having a target size.

2. Description of the Related Art.

20 [0002] Crystal growth apparatuses or furnaces, such as directional solidification systems (DSS) and heat exchanger method (HEM) furnaces, involve the melting and controlled resolidification of a feedstock material, such as silicon, in a crucible to produce a crystalline material, often referred to as an ingot. Production of a solidified ingot from molten feedstock occurs in several identifiable steps over many hours. For example, to produce a silicon ingot by the DSS method, solid silicon feedstock is provided in a crucible, often contained in a graphite crucible box, and
25 placed into the hot zone of a DSS furnace. The feedstock is then heated to form a liquid feedstock melt, and the furnace temperature, which is well above the silicon melting temperature of 1412°C, is maintained for several hours to ensure complete melting. Once fully melted, heat is removed from the melted feedstock, often by applying a temperature gradient in the hot zone, in order to directionally solidify the
30 melt and form a silicon ingot. By controlling how the melt solidifies, an ingot having greater purity than the starting feedstock material charged to the crucible can be achieved. This material can then be used in a variety of high end applications, such as in the semiconductor and photovoltaic industries.

[0003] In a typical solidification of silicon feedstock, the resulting solidified silicon ingot is generally multicrystalline, having random small crystal grain sizes and orientations. It has also been shown that a silicon ingot comprising monocrystalline (i.e. single crystal) silicon can also be formed. For example, to produce a monocrystalline silicon ingot using either a DSS or HEM process, one or more solid seeds of monocrystalline silicon can be placed along the bottom of a crucible, along with the silicon feedstock, and then heated to melt. If at least a part of the seeds is maintained after the feedstock has fully melted, directional crystallization of the melt occurs corresponding to the crystal orientation of the monocrystalline seed.

[0004] Typically, as the directional solidification of a monocrystalline silicon ingot occurs, regions of multicrystalline silicon also form, most often along the outside edges of the ingot (sometimes referred to as edge growth), particularly when a seed is placed in the center of the crucible bottom. This results, for example, when crystals nucleate from surfaces other than the seed. In order to form as large a region of monocrystalline material as possible, the entire bottom of the crucible can be covered with a single large seed or a plurality of smaller seeds placed against each other (also called tiling). However, due to conditions used to grow the crystalline material, it has been observed that edge growth may still occur as crystals nucleate from the cooling edges. This reduces the size of the monocrystalline portion of the resulting product, lowering the yield. To obtain a desired size of monocrystalline material, therefore, a larger crucible is needed, in order to compensate for the loss in yield. However, larger crucibles may not fit in the available furnace, forcing the user to obtain larger and more expensive equipment in order to obtain a monocrystalline material having the desired dimensions. Alternatively, changes in the crystal growth conditions can be implemented in order to improve the yield of monocrystalline material. However, this can be time consuming and expensive as well.

[0005] Therefore, there is a need in the industry for a method to produce a monocrystalline material of a desired size without increasing the size of the crystal growth furnace or requiring substantial changes to the conditions used to operate it.

SUMMARY OF THE INVENTION

[0006] The present invention relates to a method of producing a monocrystalline product having a target width W and a target length L . The method comprises the steps of placing a first crucible containing at least solid feedstock in a hot zone of a crystal growth apparatus; melting the solid feedstock in the first crucible; and removing heat from the first crucible in the hot zone to form a first crystalline material. The first crucible has an interior width W_1 and an interior length L_1 , wherein $W_1 \geq W$ and $L_1 \geq L$. The first crystalline material comprises an interior monocrystalline portion and an exterior multicrystalline portion, wherein the interior monocrystalline portion has a width W_m and a length L_m , with $W_m < W$ and $L_m < L$. The method further comprises the steps of providing a second crucible having an interior width W_2 and an interior length L_2 , wherein $W_2 \geq W + W_1 - W_m$ and $L_2 \geq L + L_1 - L_m$ and placing the second crucible containing at least solid feedstock in the hot zone of the crystal growth apparatus; melting the solid feedstock in the second crucible; and removing heat from the second crucible in the hot zone to form a second crystalline material, which comprises an interior monocrystalline portion and an exterior multicrystalline portion, wherein the interior monocrystalline portion of the second crystalline material has a width greater than or equal to W and a length greater than or equal to L . The method further comprises the step of removing the monocrystalline product from the interior monocrystalline portion of the second crystalline material.

[0007] It is to be understood that both the foregoing general description and the following detailed description are exemplary and explanatory only and are intended to provide further explanation of the present invention, as claimed.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] FIG 1 and FIG 4 each are a cross-sectional view of a crystal growth apparatus used in different stages of an embodiment of the method of the present invention.

[0009] FIG 2 and FIG 3 each show a crucible containing a crystalline material produced at different stages of an embodiment of the method of the present invention.

FIG 2A and FIG 2B are cross-sectional views the crucible shown in FIG 2, and FIG 3A and FIG 3B are cross-sectional views of the crucible shown in FIG 3.

DETAILED DESCRIPTION OF THE INVENTION

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[0010] The present invention relates to a method for producing a monocrystalline product having a desired width and length.

[0011] The method of the present invention comprises the steps of forming a first crystalline material and a second crystalline material in a crystal growth apparatus, which is a furnace, in particular a high-temperature furnace, capable of heating and melting a solid feedstock, such as silicon, at temperatures generally greater than about 1000°C and subsequently promoting resolidification of the resulting melted feedstock material to form the crystalline materials. For example, the crystal growth apparatus can be a directional solidification system (DSS) crystal growth furnace or a heat exchanger method (HEM) crystal growth furnace, but is preferably a DSS furnace.

[0012] The crystal growth apparatus used in the method of the present invention comprises an outer furnace chamber or shell and an interior hot zone within the furnace shell. The furnace shell can be any known in the art used for high temperature crystallization furnaces, including a stainless steel shell comprising an outer wall and an inner wall defining a cooling channel for circulation of a cooling fluid, such as water. The hot zone of the crystal growth apparatus is an interior region within the furnace in which heat can be provided and controlled to melt and resolidify a feedstock material, described in more detail below. The hot zone is surrounded by and defined by insulation, which can be any material known in the art that possesses low thermal conductivity and is capable of withstanding the temperatures and conditions in a high temperature crystal growth furnace. For example, the hot zone can be surrounded by insulation of graphite. The shape and dimension of the hot zone can be formed by a plurality of insulation panels which can be either stationary or mobile. For example, the hot zone may be formed of top, side, and bottom insulation panels, with the top and side insulation panels configured to move vertically relative to a crucible placed within the hot zone. The bottom insulation panel may also be vertically movable.

[0013] The hot zone also comprise at least one heating system, such as multiple heating elements to provide heat to melt feedstock placed in a crucible. For example, the hot zone can comprise a first heating element, positioned above the crucible, preferably horizontally in the upper region of the hot zone, providing heat from above, and at least one second heating element positioned along the sides of the crucible, preferably vertically along the sides of the hot zone below the first heating element. The temperature in the hot zone may be controlled by regulating the power provided to the various heating element. As such, the first heating element and the second heating element can be controlled together or can be independently controlled.

[0014] In the method of the present invention, a crucible having specified dimensions is placed into the hot zone of the crystal growth apparatus. The crucible can be made of various heat resistant materials known in the art including, for example, quartz (silica), graphite, silicon carbide, silicon nitride, composites of silicon carbon or silicon nitride with silica, pyrolytic boron nitride, alumina, or zirconia and, optionally, may be coated, such as with silicon nitride, to prevent cracking of the ingot after solidification. The crucible can also have a variety of different shapes having at least one side and a bottom, including, for example, cylindrical, cubic or cuboid (having a square cross-section), or tapered. Preferably, when the feedstock is silicon, the crucible is made of silica and has a cube or cuboid shape.

[0015] The crucible in the hot zone can optionally be contained within a crucible box, which provides support and rigidity for the sides and bottom of the crucible and is particularly preferred for crucibles made of materials that are either prone to damage, cracking, or softening, especially when heated. For example, a crucible box is preferred for a silica crucible but may be unnecessary for a crucible made of silicon carbide, silicon nitride, or composites of silicon carbide or silicon nitride with silica. The crucible box can be made of various heat resistant materials, such as graphite, and typically comprises at least one side plate and a bottom plate, optionally further comprising a lid. For example, for a cube or cuboid-shaped crucible, the crucible box is preferably also in the shape of a cube or cuboid, having four walls and a bottom plate, with an optional lid.

[0016] The crucible and optional crucible box are preferably provided on top of a crucible support block within the hot zone, and, as such, are in thermal communication with each other so that heat can be conducted from one to the other, preferably by direct thermal contact. The crucible support block can be raised on a

plurality of pedestals in order to place the crucible into a central position in the crystal growth apparatus. The crucible support block can be made of any heat resistant material, such as graphite, and is preferably a similar material to the crucible box, if used.

- 5 **[0017]** The crucible within the hot zone contains a charge used to form a crystalline material having both a multicrystalline and a monocrystalline portion (i.e., a region having one consistent crystal orientation throughout). The charge in the crucible comprises at least solid feedstock material, such as alumina or polycrystalline or multicrystalline silicon, which can be in any form known in the art, including
- 10 powder, pellets, or larger chunks or pieces. The charge can further comprise at least one monocrystalline seed, which comprises the same material as the feedstock except having a single crystal orientation throughout. A plurality of monocrystalline seeds can be used arranged along the bottom of the crucible. Any type of seed crystal known in the art can be used. For example, the monocrystalline seeds may be circular
- 15 or polygonal, such as square or rectangular, in cross-sectional shape. Also, each of the seeds can have a flat lower surface to provide good contact with the interior surface of the bottom of the crucible, and, more preferably, further has a flat upper surface as well. The number of monocrystalline seeds can vary depending, for example, on the inner dimensions of the crucible used and on the size of the seeds.
- 20 For example, from 2 to 36 square monocrystalline seeds can be arranged around the interior crucible bottom. As a particular example, 25 square seeds can be arranged in a 5 by 5 pattern on the bottom of the crucible. The monocrystalline seeds can range in size from about 10 cm to about 85 cm along any edge. The seeds can be arranged in a pattern to substantially fully cover the interior surface of the crucible bottom, being
- 25 placed as close to the inside edges and corners of the crucible as is practically possible. Such a placement is sometimes referred to as tiling. Thus, when a plurality of monocrystalline seeds are used, these can be arranged or tiled along the inside bottom surface of the crucible so that each seed is in contact with a neighboring or adjacent seed, forming a close-packed arrangement. The thickness of the seeds can
- 30 also vary, depending on availability and cost. For example, the seeds may have a thickness of about 0.5 cm to about 5 cm, including from about 1 cm to about 4 cm and from about 2 cm to about 3 cm. Preferably, all of the seeds are substantially similar in size, shape, and thickness.

[0018] The crystal growth apparatus used in the method of the present invention further comprises at least one means for removing heat from the hot zone. When the apparatus is a DSS furnace, the means for removing the heat can comprise movable sections of the insulation that surrounds the hot zone and the crucible provided therein. For example, the top and side insulation panels of the hot zone can be configured to move vertically while the bottom insulation panel is configured to remain stationary. Alternatively, as another example, the top and side insulation panels may be configured to remain stationary while the bottom insulation panel is configured to move vertically. Other combinations are also possible. When the apparatus is a HEM furnace, the means for removing heat from the hot zone can be a heat exchanger, such as a helium-cooled heat exchanger, provided to be in thermal communication with the bottom of the crucible placed within the hot zone.

[0019] The method of the present invention is a method of producing a monocrystalline product having one consistent crystal orientation throughout. The monocrystalline product has a desired or target size that is specified or chosen prior to formation and preferably also has a desired cross-sectional shape, including round, oval, or polygonal. For example, the monocrystalline product may have a rectangular cross-sectional shape, having a target width W and target length L , or a square cross-sectional shape, wherein the target width W and length L are substantially the same. The size of the monocrystalline product can vary depending on the desired end use. For example, W and L can each, independently, be from about 60 cm to about 120 cm, including from about 70 cm to about 110 cm and from about 75 cm to about 100 cm, preferably from about 75 cm to about 85 cm or from about 90 cm to about 100 cm. The height of the monocrystalline product can also vary depending, for example, on the desired end use, and can be from about 10 cm to about 80 cm, such as from about 20 cm to about 50 cm. These target dimensions represent values measured anywhere across the monocrystalline product. For example, for a monocrystalline product having a rectangular or square cross-sectional shape, the target width, W , can be the width across the top, the middle, or the bottom of the monocrystalline product. Preferably, these values are averages values. For example, preferably, the target width is an average across the entire width of the monocrystalline product. More preferably, the monocrystalline product has very substantially no variability in the target width, length, and/or height.

[0020] In general, the method of the present invention comprises steps for forming a first crystalline material in the hot zone of a crystal growth apparatus, wherein the first crystalline material comprises an interior monocrystalline portion that is too small to allow removal of a monocrystalline product having the target size, and, in the same hot zone of the same crystal growth apparatus, without substantial modifications, forming a second crystalline material having a larger interior monocrystalline portion from which the desired monocrystalline product can be removed. Preferably this method also does not involve any substantial modification to the crystal growth conditions used to form the first crystalline material – that is, the two crystalline materials are formed using substantially the same crystal growth conditions. Rather, the second crystalline material, having the larger interior monocrystalline portion, is formed in a different, specifically designed crucible compared to the first crystalline material, having the smaller interior monocrystalline portion. The two crystalline material formation steps can occur either immediately after each other or there can be significant time between the two formation steps.

[0021] Thus, the method of the present invention is a method of producing a monocrystalline product having a target width W and a target length L . The method comprises the step of placing a first crucible containing a charge, which comprises at least solid feedstock, in a hot zone of a crystal growth apparatus. The crystal growth apparatus, crucible, and charge can be any of those described above. For example, the crystal growth apparatus can be a DSS furnace, and the crucible can be a silica or quartz crucible containing a charge comprising silicon feedstock and at least one silicon seed. Thus, for this example, the first crystalline material is a silicon ingot. The first crucible has inner dimensions that would be expected to be sufficient to form a crystalline material from which a monocrystalline product having the desired dimensions can be removed. Thus, the first crucible has an interior width W_1 , wherein $W_1 \geq W$, and an interior length L_1 , wherein $L_1 \geq L$. The amount of solid feedstock can vary depending on the size of the crucible and the size of the hot zone of the crystal growth apparatus, but, typically, a sufficient amount of solid feedstock is used to substantially completely fill the crucible.

[0022] After the first crucible is charged and placed within the hot zone of a crystal growth apparatus, the method of the present invention further comprises the steps of heating and melting the feedstock material in the first crucible. Any of the heating systems described above can be used in this method to heat and melt the

charge comprising at least feedstock material. When the charge further comprises at least one monocrystalline seed, preferably melting of the seeds is substantially avoided when the feedstock is heated and melted. As such, in a preferred embodiment, the method of the present invention does not comprise the step of fully melting any of the seeds and, in a more preferred embodiment, the method does not comprise partially melting the seeds. The extent of melt can be determined using any method known in the art, including using a dip rod lowered from above the crucible into the forming melt.

[0023] After heating and melting, the method of the present invention further comprises the step of removing heat from the first crucible in the hot zone to form a first crystalline material. Any of the methods described above for removing the heat can be used to form the first crystalline material. These crystal growth conditions are sufficient to form a crystalline material comprising an interior monocrystalline portion and an exterior multicrystalline portion, but preferably are insufficient to form a crystalline material that is substantially fully monocrystalline. Thus, the interior monocrystalline portion of the first crystalline material has a width W_1 and a length L_1 , wherein $W_1 < W$ and $L_1 < L$. Therefore, the interior monocrystalline portion of the first crystalline material is too small to permit removal a monocrystalline product having the target width W and length L , even though the first crucible has inner dimensions greater than or equal to W and L respectively. Thus, the interior monocrystalline portion comprises from about 40-95%, such as from about 50-85% or from about 60-80%, of the resulting first crystalline material.

[0024] In order to form a crystalline material having a monocrystalline portion large enough to remove a monocrystalline product having the target size, the method of the present invention further comprises the step of providing a second crucible having interior dimensions that are larger than those of the first crucible but having exterior dimensions small enough to still fit within the restrictive confines of the hot zone of the crystal growth apparatus that was used to form the first crystalline material. Thus, the second crucible has an interior width W_2 , wherein $W_2 \geq W + W_1 - W_m$, and an interior length L_2 , wherein $L_2 \geq L + L_1 - L_m$. The second crucible is charged with at least feedstock material, which is the same material as was used in the first crucible, although, due to its larger size, additional material, particularly solid feedstock, may be used.

[0025] Once charged, the second crucible containing at least solid feedstock is placed in the hot zone of the crystal growth apparatus used in the previous step, without substantial modifications, and the solid feedstock is then heated and melted. As with the heating and melting of the feedstock in the first crucible, any heating system described above can be used. Preferably, the conditions used to heat and melt the solid feedstock in the second crucible are substantially the same as the conditions used to heat and melt the solid feedstock in the first crucible, although additional time may be needed if additional solid feedstock is used.

[0026] After heating and melting the solid feedstock in the second crucible, the method of the present invention further comprises the step of removing heat from the second crucible in the hot zone to form a second crystalline material. As with the step of removing heat from the first crucible, any of the methods described above can be used to form the second crystalline material. Preferably, substantially the same crystal growth conditions used for the forming the first crystalline material are used for forming the second crystalline material, although some additional time may be needed if additional material is used. The resulting second crystalline material comprises an interior monocrystalline portion and an exterior multicrystalline portion, similar to the first crystalline material. Thus, the interior monocrystalline portion comprises from about 40-95%, such as from about 50-85% or from about 60-80%, of the resulting first crystalline material. However, the interior monocrystalline portion of the second crystalline material has a width greater than or equal to W and a length greater than or equal to L . Thus, the second crystalline material comprises a monocrystalline portion that is large enough to remove a monocrystalline product having the desired or targeted dimensions.

[0027] The method of the present invention further comprises the step of removing the monocrystalline product from the interior monocrystalline portion of the second crystalline material. This can be done using any method known in the art, including using a wire saw. The resulting monocrystalline product has a width W and a length L and can be further processed, such as by cutting into bricks to be used in wafering. For example, if the monocrystalline product is silicon having a square cross-sectional shape with a width of 78 cm, 25 square monocrystalline silicon bricks of equal size can be cut from this product, which are of the appropriate size for preparing wafers to be used in solar applications.

[0028] A specific embodiment of the method of the present invention for producing a monocrystalline product having a target width W and a target length L is shown in the figures and will be discussed in more detail below. It should be apparent to those skilled in the art that these are merely illustrative in nature and not limiting, being presented by way of example only. Numerous modifications and other embodiments are within the scope of one of ordinary skill in the art and are contemplated as falling within the scope of the present invention. In addition, those skilled in the art should appreciate that the specific configurations are exemplary and that actual configurations will depend on the specific system. Those skilled in the art will also be able to recognize and identify equivalents to the specific elements shown, using no more than routine experimentation.

[0029] In this exemplary embodiment of the method of the present invention, a first crucible **14** is provided in a crystal growth apparatus **10**, which is shown in a cross-sectional view in FIG 1. The first crucible **14** contains solid silicon feedstock and a plurality of silicon seeds tiled along its bottom (not shown) and has an interior width W_1 and an interior length L_1 (perpendicular to this cross-sectional view). Crystal growth apparatus **10** comprises a furnace shell **11** and hot zone **12**, surrounded and defined by insulation **13**, within furnace shell **11**. Crucible **14**, contained within crucible box **15**, is provided in hot zone **12** atop crucible support block **16** raised on pedestals **17**. Hot zone **12** further includes a heating system comprising top heater **18a** above first crucible **14** and side heaters **18b** surrounding all sides of first crucible **14**. The top and side heaters may be controlled together or independently controlled by a controller system (not shown). Insulation cage **13** is movable vertically, as shown by arrow **A**, and this is the primary means for removing heat from hot zone **12** and first crucible **14** which exposes these components to furnace shell **11** cooled using a cooling medium such as water. As shown in FIG 1, crucible **14** fits within the restrictive confines of hot zone **12** surrounded by heaters **18a** and **18b** and insulation **13**.

[0030] For this exemplary embodiment, the method further comprises the step of forming a first crystalline material in first crucible **14** by heating and melting the solid silicon feedstock without substantially melting the plurality of silicon seeds, followed by removal of heat from first crucible **14** in hot zone **12**. The resulting first crystalline material is shown in FIG 2. First crystalline material, **20**, in first crucible **14**, comprises an interior monocrystalline portion, **21**, surrounded by an exterior

multicrystalline portion, **22**, which may represent edge growth of non-monocrystalline material. This is also shown in FIG 2A and FIG 2B, which are cross-sectional views of first crucible **14** containing first crystalline material **20** along lines **A** and **B**, respectively, shown in FIG 2. Thus, as shown, first crystalline material **20** comprises interior monocrystalline portion **21** having a width W_m and a length L_m . Both of these are smaller than the target width W and length L due to the presence of exterior multicrystalline portion **22**. Thus, first crystalline material **20** is too small to remove the desired monocrystalline product having the targeted dimensions, even though first crucible **14** has a width W_1 and a length L_1 which are greater than W and L respectively.

[0031] In order to produce a monocrystalline product having the target dimensions, the exemplary method further comprises the step of providing a second crucible that is larger than first crucible **14**, having width $W_2 > W_1$ and length $L_2 > L_1$, and placing this second crucible containing at least silicon feedstock in crystal growth apparatus **10**. This is shown in FIG 4, which is the same crystal growth apparatus shown in FIG 1, with the exception that a larger second crucible **40** is placed in hot zone **12**. Necessarily, for this embodiment, a larger crucible box **41** is also used. However, no other significant modifications are necessary. Thus, while second crucible **40** is larger than first crucible **14**, it fits within the restrictive confines of hot zone **12**, which is shown in FIG 4. Thus, the size of second crucible **40** is limited by the available space in hot zone **12**. The interior width and length of second crucible **40** are chosen based on the target dimensions of the desired monocrystalline product and the results observed for producing the first crystalline product. For this specific embodiment of the method of the present invention, the size of second crucible **40** is chosen based on the equations $W_2 = W + W_1 - W_m$ and $L_2 = L + L_1 - L_m$, and the height is unchanged.

[0032] Thus, in this exemplary embodiment, second crucible **40** is placed in hot zone **12** of crystal growth apparatus **10**. The crucible contains a charge (not shown in FIG 4) that is essentially the same as that used in first crucible **14**, with the exception that, due to the larger crucible dimensions, more solid silicon feedstock can be used. Once placed in hot zone **12**, a second crystalline material is formed in second crucible **40** by heating and melting the solid silicon feedstock without substantially melting the plurality of silicon seeds, using substantially the same conditions used to heat and melt the solid feedstock in first crucible **14**.

Subsequently, heat is removed from second crucible **40** in hot zone **12**, using substantially the same crystal growth conditions as was used for forming first crystalline material **20**, to form a second crystalline material, **30**, shown in FIG 3. Second crystalline material **30** comprises an interior monocrystalline portion, **31**,
5 surrounded by an exterior multicrystalline portion, **32**, shown in FIG 3A and FIG 3B, which are cross-sectional views of second crucible **40** containing second crystalline material **30** along lines **A** and **B**, respectively, shown in FIG 3. As shown, second crystalline material **30** comprises interior monocrystalline portion **21** having a width W and a length L , from which the desired monocrystalline product may be removed.

10 **[0033]** As a specific example for this embodiment, for a square monocrystalline product having a target size of 79.2 cm (which is just large enough, including a saw kerf of 0.3 cm, to remove 25 monocrystalline bricks that are 15.6 cm square, from which standard wafers may be sliced), if a first crystalline material is grown in a square first crucible having a width W_1 and length L_1 of 84 cm and found
15 to have a square interior monocrystalline portion having a width W_m and length L_m of 75.2 cm, in order to produce the desired monocrystalline product, a second square crucible would be provided having a width W_2 and a length L_2 of at least 88 cm. While larger than the first crucible, this size second crucible would fit into the same hot zone of the same crystal growth apparatus used to grow the first crystalline
20 material (a maximum size would be expected to be about 92 cm). A second crystalline material grown in this second crucible using the same crystal growth conditions as was used to grow the first crystalline material would therefore be large enough to remove the target monocrystalline product.

[0034] Prior to the development of the method of the present invention, in
25 order to overcome the problem of having a crystalline material with an interior monocrystalline portion that is too small to remove a monocrystalline product having a desired size, it would have been expected that either a larger crystal growth apparatus would be needed in order to produce a larger crystalline material (i.e., increase the total quantity of material formed), or, alternatively, the crystal growth
30 conditions would need to be substantially changed to increase the amount of the interior monocrystalline portion in the crystalline material (i.e., increase the monocrystalline yield). Both of these approaches would require significant investment in time and expense. However, with the method of the present invention, without any significant modifications to the furnace, and, more preferably, without

any significant modifications to the crystal growth conditions, the desired monocrystalline product can now be produced in the same crystal growth apparatus using a specifically chosen and designed crucible in which to grow it. Surprisingly, it has been found that the larger sized crucible can not only be used to grow a crystalline material having an interior portion that is large enough to provide a monocrystalline product having the targeted size, but, further, such a crucible can fit within the tight tolerances and confines of the hot zone of the crystal growth apparatus in which such a material originally could not be produced.

[0035] The foregoing description of preferred embodiments of the present invention has been presented for the purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise form disclosed. Modifications and variations are possible in light of the above teachings, or may be acquired from practice of the invention. For example, while it is preferred that the crystal growth conditions used for forming the first crystalline material and the second crystalline material as substantially the same, it is possible to use different conditions for forming the second crystalline material, which may result in higher or lower monocrystalline yields (i.e., the percentage of the crystalline material that is the interior monocrystalline portion). The embodiments were chosen and described in order to explain the principles of the invention and its practical application to enable one skilled in the art to utilize the invention in various embodiments and with various modifications as are suited to the particular use contemplated. It is intended that the scope of the invention be defined by the claims appended hereto, and their equivalents.

[0036] What is claimed is:

CLAIMS

1. A method of producing a monocrystalline product having a target width W
5 and a target length L, the method comprising the steps of:

- i) placing a first crucible containing at least solid feedstock in a hot zone
of a crystal growth apparatus, wherein the first crucible has an interior
width $W_1 \geq W$ and an interior length $L_1 \geq L$;
- ii) melting the solid feedstock in the first crucible;
- 10 iii) removing heat from the first crucible in the hot zone to form a first
crystalline material comprising an interior monocrystalline portion and
an exterior multicrystalline portion, wherein the interior
monocrystalline portion has a width $W_m < W$ and a length $L_m < L$;
- iv) providing a second crucible having an interior width W_2 and an
15 interior length L_2 , wherein $W_2 \geq W + W_1 - W_m$ and $L_2 \geq L + L_1 -$
 L_m ;
- v) placing the second crucible containing at least solid feedstock in the
hot zone of the crystal growth apparatus;
- vi) melting the solid feedstock in the second crucible;
- 20 vii) removing heat from the second crucible in the hot zone to form a
second crystalline material comprising an interior monocrystalline
portion and an exterior multicrystalline portion, wherein the interior
monocrystalline portion of the second crystalline material has a width
greater than or equal to W and a length greater than or equal to L; and
- 25 viii) removing the monocrystalline product from the interior
monocrystalline portion of the second crystalline material.

2. The method of claim 1, wherein, in steps iii) and vii), heat is removed from the
hot zone under substantially similar crystal growth conditions.

30

3. The method of claim 1, wherein the second crucible contains more solid
feedstock than the first crucible.

4. The method of claim 1, wherein $W = L$.

5. The method of claim 1, wherein the first crucible, the second crucible, or both have a square cross-sectional shape.

5

6. The method of claim 1, wherein W and L are from about 75 cm to about 85 cm.

7. The method of claim 1, wherein W and L are from about 90 cm to about 100 cm.

10

8. The method of claim 1, wherein the interior monocrystalline portion of the first crystalline material comprises from about 40-95% of the first crystalline material.

15 9. The method of claim 1, wherein the interior monocrystalline portion of the first crystalline material comprises from about 50-85% of the first crystalline material.

10. The method of claim 1, wherein the interior monocrystalline portion of the first crystalline material comprises from about 60-80% of the first crystalline material.

20

11. The method of claim 1, wherein the interior monocrystalline portion of the second crystalline material comprises from about 40-95% of the second crystalline material.

25 12. The method of claim 1, wherein the interior monocrystalline portion of the second crystalline material comprises from about 50-85% of the second crystalline material.

13. The method of claim 1, wherein the interior monocrystalline portion of the second crystalline material comprises from about 60-80% of the second crystalline material.

30

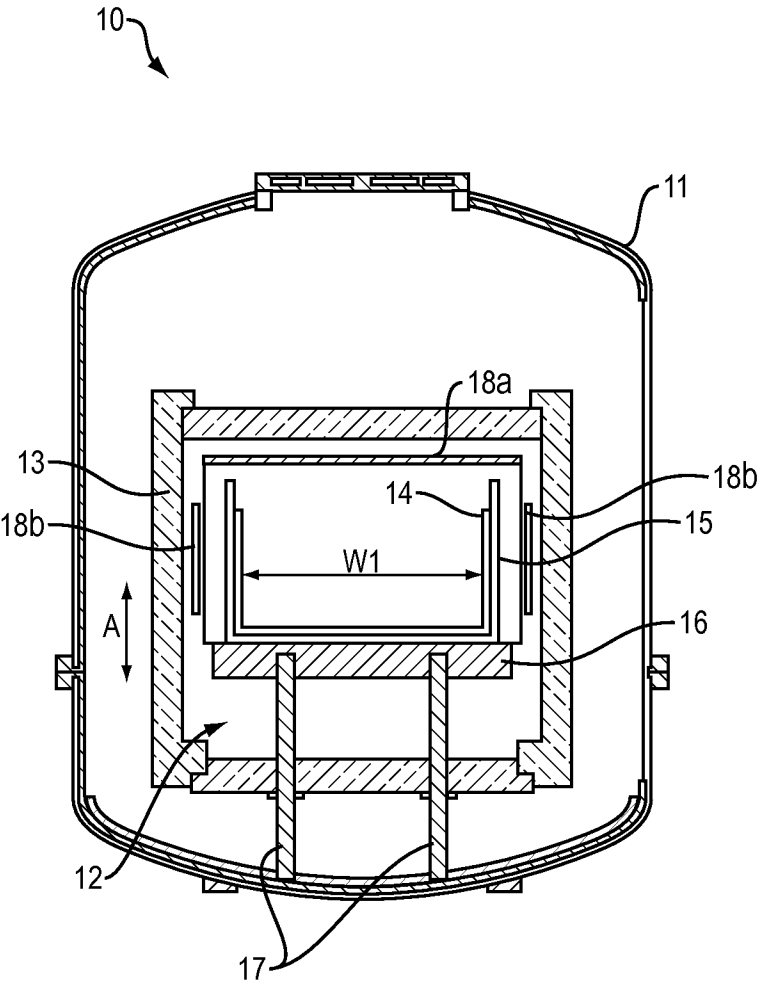


FIG. 1

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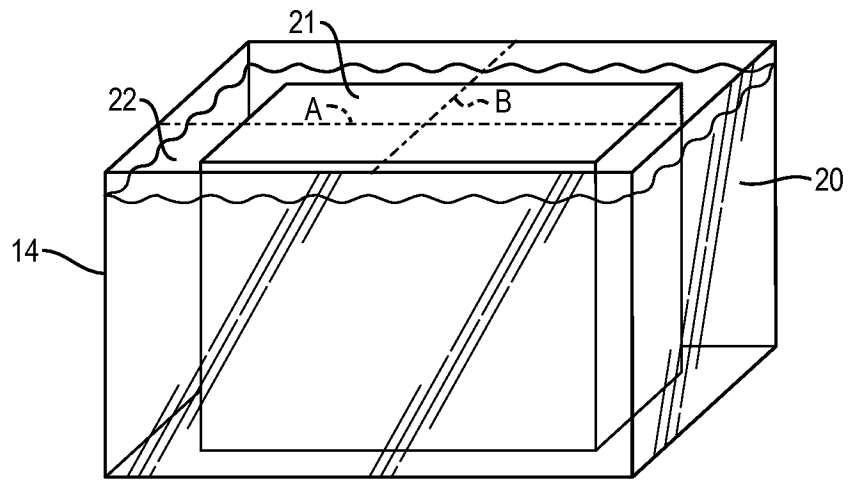


FIG. 2

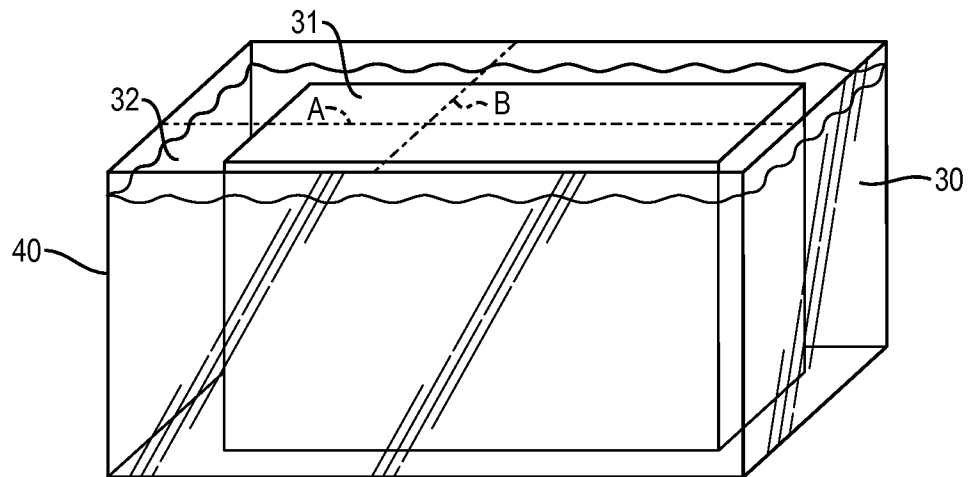


FIG. 3

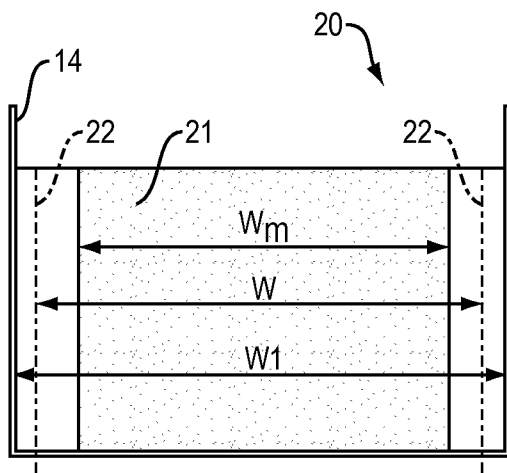


FIG. 2A

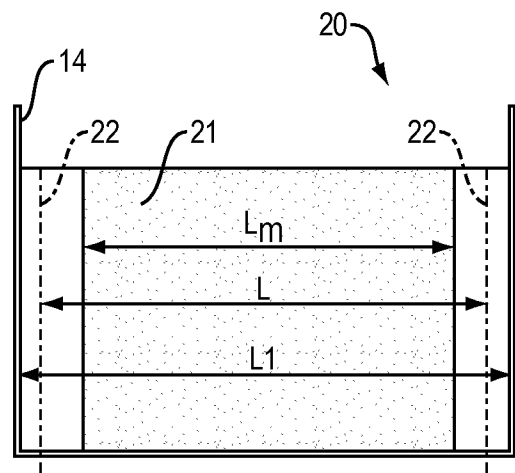


FIG. 2B

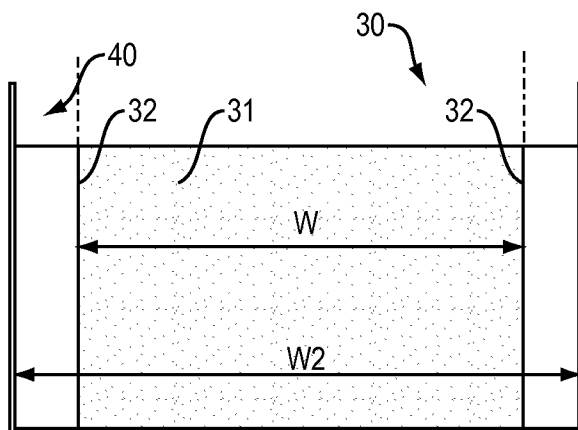


FIG. 3A

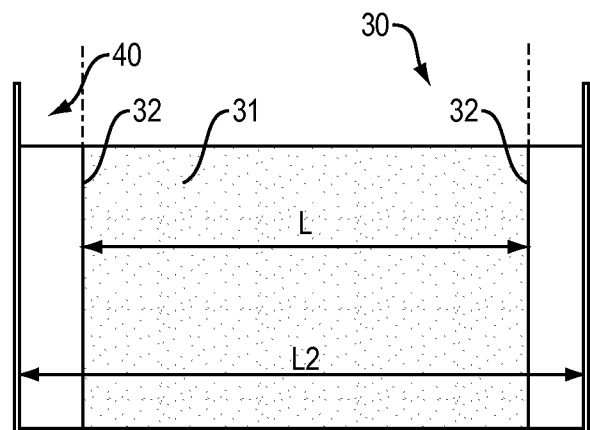


FIG. 3B

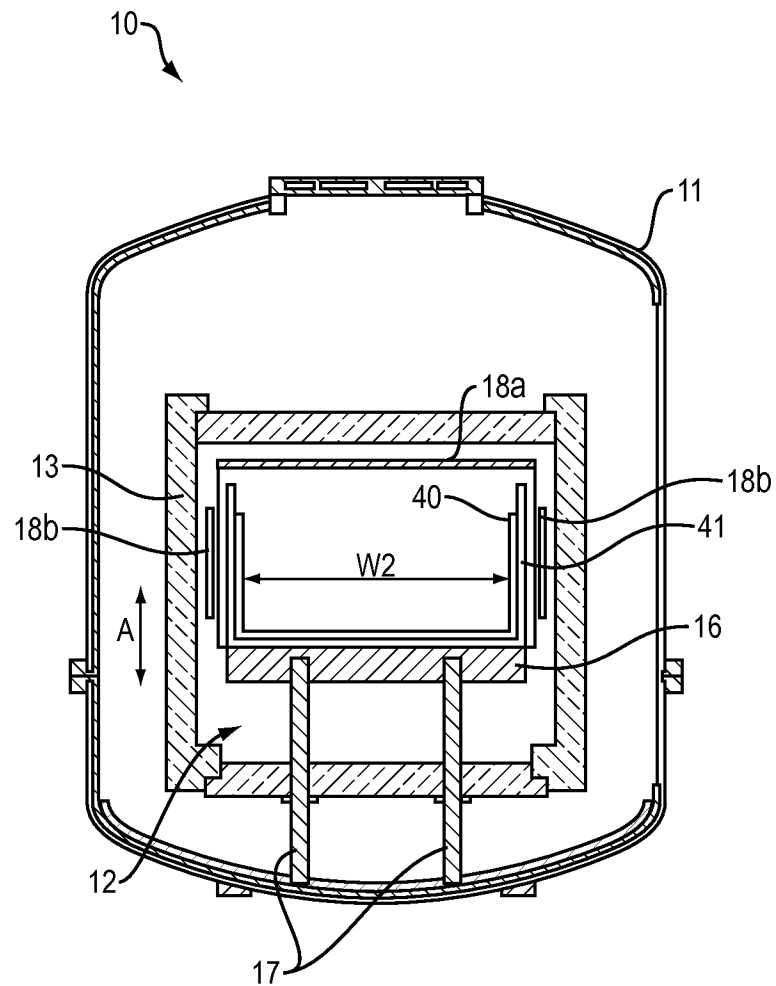


FIG. 4