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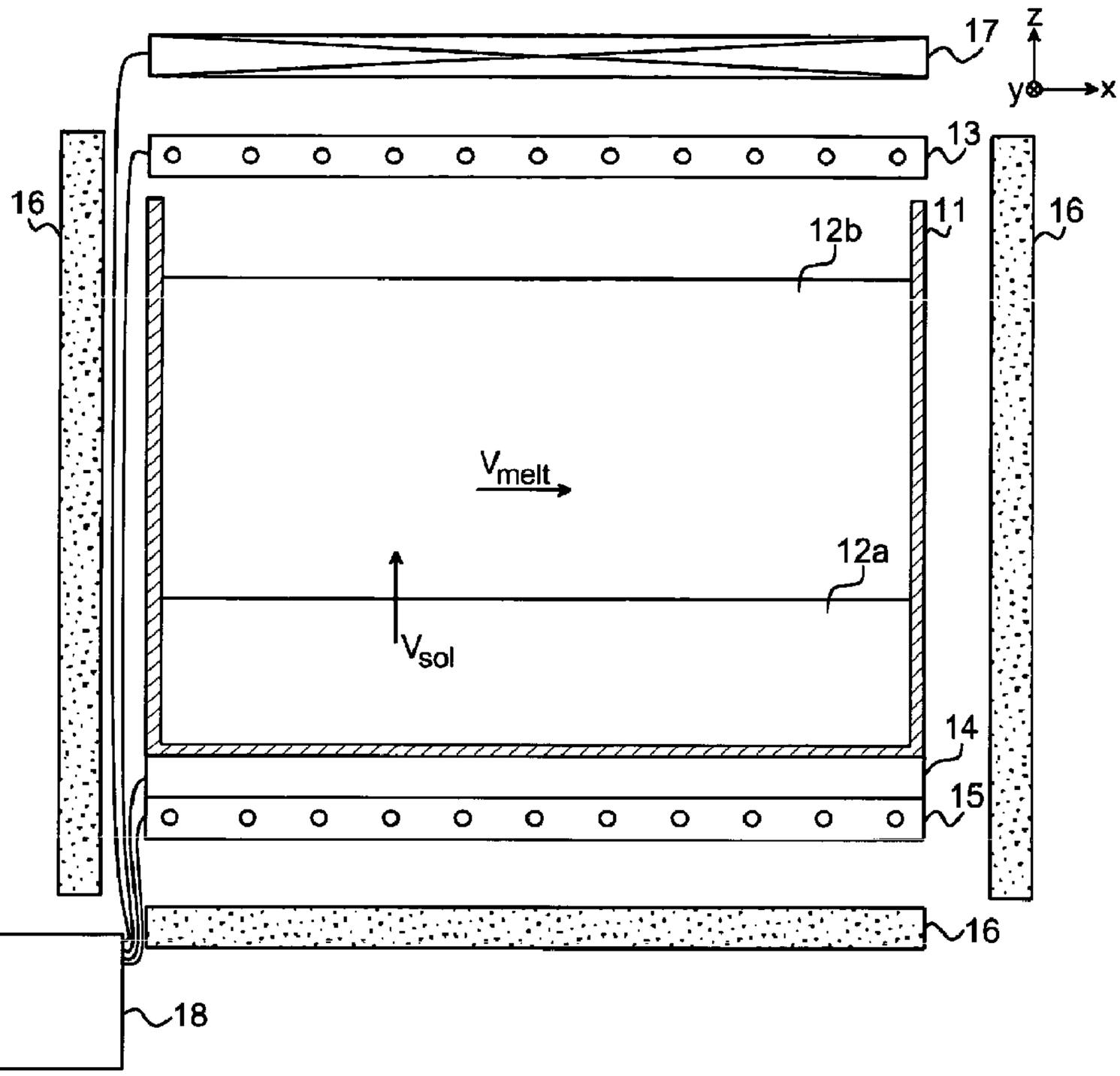

(57) Abrégé/Abstract:
An apparatus for crystallization of silicon comprises a crucible (11) for containing silicon, a heating and heat dissipating arrangement (12) provided for melting the silicon contained in the crucible and for subsequently solidifying the molten silicon, and

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(57) Abrégé(suite)/Abstract(continued):
an electromagnetic stirring device (13) provided for stirring the molten silicon in the crucible during the solidification of the molten silicon. A control arrangement (14) is provided for controlling the heating and heat dissipating arrangement to solidify the molten silicon at a specified solidification rate and for controlling the electromagnetic stirring device to stir the molten silicon in response to the specified solidification rate of the molten silicon such that the ratio of a speed of the molten silicon and the specified solidification rate is above a first threshold value.

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(54) **Title**: APPARATUS AND METHOD FOR CRYSTALLIZATION OF SILICON

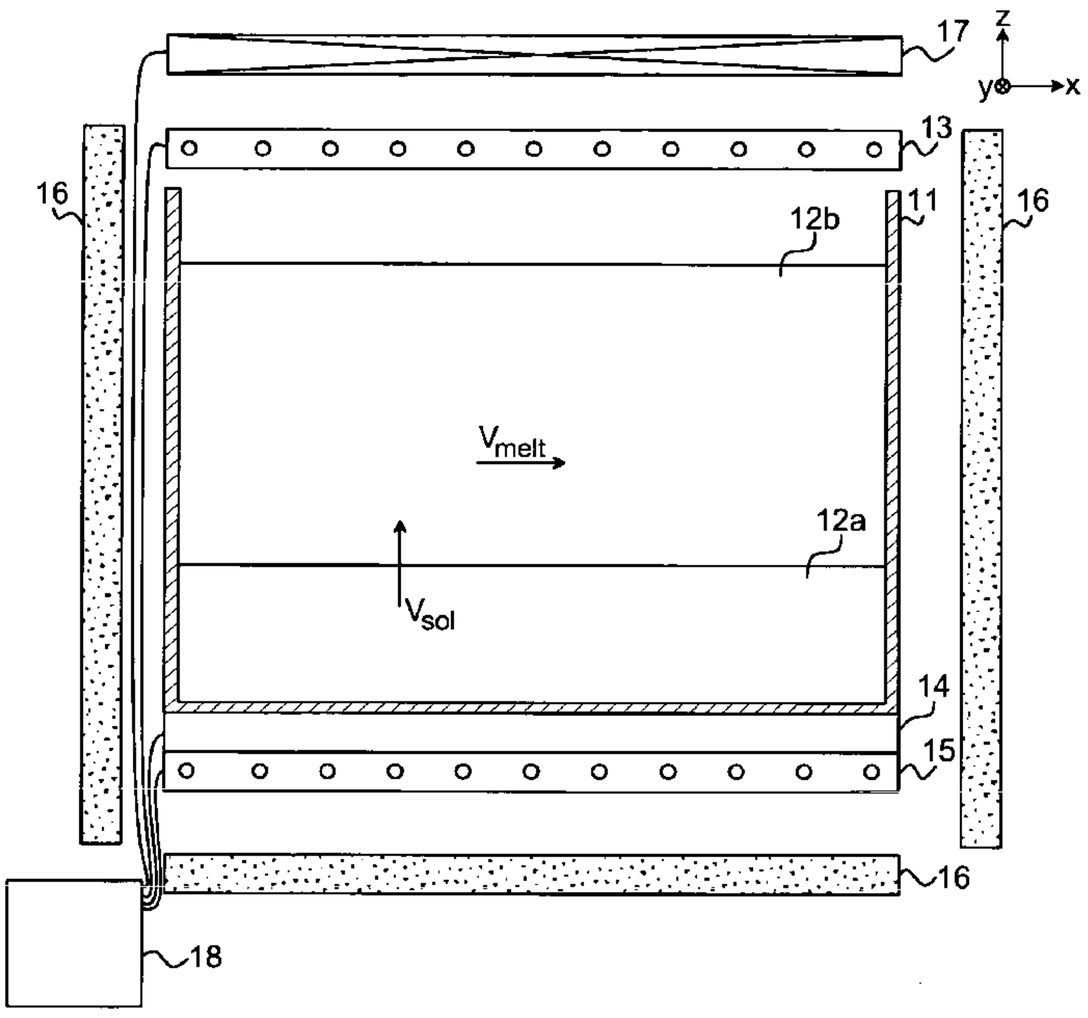

Fig. 1

(57) **Abstract**: An apparatus for crystallization of silicon comprises a crucible (11) for containing silicon, a heating and heat dissipating arrangement (12) provided for melting the silicon contained in the crucible and for subsequently solidifying the molten silicon, and an electromagnetic stirring device (13) provided for stirring the molten silicon in the crucible during the solidification of the molten silicon. A control arrangement (14) is provided for controlling the heating and heat dissipating arrangement to solidify the molten silicon at a specified solidification rate and for controlling the electromagnetic stirring device to stir the molten silicon in response to the specified solidification rate of the molten silicon such that the ratio of a speed of the molten silicon and the specified solidification rate is above a first threshold value.

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APPARATUS AND METHOD FOR CRYSTALLIZATION OF SILICON

TECHNICAL FIELD OF THE INVENTION

The present invention generally relates to crystallization of silicon, particularly silicon used in photovoltaic cells.

DESCRIPTION OF RELATED ART AND BACKGROUND OF THE INVENTION

WO 2007/148988 discloses a method and a furnace for crystallization of silicon for photovoltaic cells. The furnace comprises a crucible or a plurality of crucibles for containing the silicon, a heating device for heating the crucible, a heat discharging device for discharging the heat from the crucible, and a stirring device comprising an electromagnetic device supplied with an alternating current for applying an alternating electromagnetic field to the crucible.

SUMMARY OF THE INVENTION

The stirring of the silicon melt during the crystallization of the silicon is of outermost importance to remove a large amount of impurities while obtaining a unidirectional growth of the silicon. The prior art apparatus does not seem to disclose optimum stirring in order to obtain the purest silicon possible for use in photovoltaic cells.

It is an object of the present invention to provide an apparatus and a method, respectively, for crystallization, which address the above issues.

It is a particular object of the invention to provide such apparatus and method, which provide for an increased purity of the crystallized silicon while a unidirectional solidification front is maintained.

It is a further object of the invention to provide such apparatus and method, by which the stirring can be dynamically controlled during the crystallization.

It is yet a further object of the invention to provide such apparatus and method, which are simple, robust, reliable, and of low cost.

These objects among others are, according to the present invention, attained by apparatuses and methods as described herein.

According to a first aspect of the invention there is provided an apparatus comprising a crucible for containing silicon, a heating and heat dissipating arrangement provided for melting the silicon contained in the crucible and for subsequently solidifying the molten silicon, and an electromagnetic stirring device provided for stirring the molten silicon in the crucible during the solidification of the molten silicon. A control arrangement is provided for controlling the heating and heat dissipating arrangement to solidify the molten silicon at a specified solidification rate and for controlling the electromagnetic stirring device to stir the molten silicon in response to the specified solidification rate of the molten silicon such that the ratio of a speed of the molten silicon and the solidification rate is above a first threshold value. The first threshold value may be 10, 100, 1000 or 10 000 depending on the composition of the raw material silicon and/or on the intended application of the crystallized silicon. Further, the control arrangement may be provided to control the speed of the molten silicon to be below a second threshold value.

In one embodiment the control arrangement is provided for controlling the electromagnetic stirring device to stir the molten silicon in the crucible during two stages such that a

first speed of the molten silicon is obtained in a first one of the stages and a second speed of the molten silicon is obtained in a second one of the stages, wherein the first speed of the molten silicon is higher than the second speed of the molten silicon. The above controlled solidification is performed during the second stage. During the first stage the control arrangement is provided for controlling the heating and heat dissipating arrangement to keep the silicon contained in the crucible molten to allow impurities to be transported in the molten silicon. Alternatively, the control arrangement is, during the first stage, provided for controlling the heating and heat dissipating arrangement to solidify the molten silicon, to cut a way a portion thereof, and to subsequently re-melt the remaining solidified silicon.

In a further embodiment of the invention the electromagnetic stirring device is capable of altering the direction of its stirring and the control arrangement is provided for controlling the electromagnetic stirring device to alter the direction of the stirring of the molten silicon in the crucible during the solidification of the molten silicon.

According to a second aspect of the invention there is provided a method according to which silicon is arranged in a crucible. The silicon in the crucible is molten and subsequently the molten silicon is solidified while the molten silicon in the crucible is stirred by means of an electromagnetic stirring device. The molten silicon is solidified at a specified solidification rate and the stirring by the electromagnetic stirring device is controlled in response to the step of solidifying such that the ratio of a speed of the molten silicon and the solidification rate is above a first threshold value. The stirring of the molten silicon in the crucible by the electromagnetic stirring device may be performed in two stages, wherein the stirring is heavier during the first stage and at least the second stage comprises solidifying molten silicon.

By means of the present invention a clean solidification front can be obtained and remixing of impurities at the silicon melt surface is avoided. Simultaneously, a unidirectional solidification front can be achieved.

According to an aspect of the present invention, there is provided an apparatus for crystallization of silicon comprising:

a crucible for containing silicon;

a heating and heat dissipating arrangement provided for melting the silicon contained in the crucible and for subsequently solidifying the molten silicon; and

an electromagnetic stirring device provided for stirring the molten silicon in the crucible during the solidification of the molten silicon,

wherein a control arrangement is provided for controlling the heating and heat dissipating arrangement to solidify the molten silicon at a specified solidification rate and for controlling the electromagnetic stirring device to stir the molten silicon in response to the specified solidification rate of the molten silicon such that a ratio of a speed of the molten silicon and the specified solidification rate is above a first threshold value.

According to another aspect of the present invention, there is provided a method of crystallization of silicon, the method comprising:

arranging silicon in a crucible;

melting the silicon contained in the crucible; and

solidifying the molten silicon while stirring the molten silicon in the crucible by means of an electromagnetic stirring device, the solidifying comprises the steps of:

solidifying the molten silicon at a specified solidification rate; and

controlling stirring by the electromagnetic stirring device in response to the solidifying such that a ratio of a speed of the molten silicon and the specified solidification rate is above a first threshold value.

According to a further aspect of the present invention, there is provided an apparatus for crystallization of silicon comprising:

a crucible for containing silicon;

a heating and heat dissipating arrangement provided for melting the silicon contained in the crucible and for subsequently solidifying the molten silicon; and

an electromagnetic stirring device provided for stirring the molten silicon in the crucible during the solidification of the molten silicon, wherein said electromagnetic stirring device is provided for altering direction of stirring of the molten silicon in the crucible during the solidification of the molten silicon.

According to a further aspect of the present invention, there is provided a method of crystallization of silicon, the method comprising:

arranging silicon in a crucible;

melting the silicon contained in the crucible and subsequently solidifying the molten silicon; and

stirring the molten silicon in the crucible during the solidifying of the molten silicon by means of an electromagnetic stirring device, the stirring comprising the steps of:

altering direction of the stirring of said electromagnetic stirring device during the stirring of the molten silicon in the crucible.

According to a further aspect of the present invention, there is provided an apparatus for crystallization of silicon comprising:

a crucible for containing silicon;

a heating and heat dissipating arrangement provided for melting the silicon contained in the crucible and for subsequently solidifying the molten silicon;

an electromagnetic stirring device provided for stirring the molten silicon in the crucible during the solidification of the molten silicon; and

a control arrangement is provided for controlling the heating and heat dissipating arrangement to solidify the molten silicon at a specified solidification rate and for controlling the electromagnetic stirring device to stir the molten silicon in response to the specified solidification rate of the molten silicon such that a ratio of a speed of the molten silicon and the specified solidification rate is above a first threshold value,

wherein the speed of the molten silicon is a highest speed of the molten silicon, an average speed of the molten silicon, a highest speed of a portion of the molten silicon, or an average speed of a portion of the molten silicon.

According to a further aspect of the present invention, there is provided a method of crystallization of silicon, the method comprising:

arranging silicon in a crucible;

melting the silicon contained in the crucible; and

solidifying the molten silicon while stirring the molten silicon in the crucible by means of an electromagnetic stirring device, the solidifying comprising the steps of:

solidifying the molten silicon at a specified solidification rate; and

controlling stirring by the electromagnetic stirring device in response to the solidifying such that a ratio of a speed of the molten silicon and the

specified solidification rate is above a first threshold value,

wherein the speed of the molten silicon is a highest speed of the molten silicon, an average speed of the molten silicon, a highest speed of a portion of the molten silicon, or an average speed of a portion of the molten silicon.

According to a further aspect of the present invention, there is provided an apparatus for crystallization of silicon comprising:

a crucible for containing silicon;

a heating and heat dissipating arrangement provided for melting the silicon contained in the crucible and for subsequently solidifying the molten silicon;

an electromagnetic stirring device provided for stirring the molten silicon in the crucible during the solidification of the molten silicon, wherein said electromagnetic stirring device is provided for altering direction of stirring of the molten silicon in the crucible during the solidification of the molten silicon; and

a control arrangement is provided for controlling the heating and heat dissipating arrangement to solidify the molten silicon at a specified solidification rate and for controlling the electromagnetic stirring device to stir the molten silicon in response to the specified solidification rate of the molten silicon such that a ratio of a speed of the molten silicon and the specified solidification rate is above a first threshold value,

wherein the speed of the molten silicon is a highest speed of the molten silicon, an average speed of the molten silicon, a highest speed of a portion of the molten silicon, or an average speed of a portion of the molten silicon.

According to a further aspect of the present invention, there is provided a method of crystallization of silicon, the method comprising:

arranging silicon in a crucible;

melting the silicon contained in the crucible;

solidifying the molten silicon while stirring the molten silicon in the crucible by means of an electromagnetic stirring device, the solidifying comprising the steps of:

solidifying the molten silicon at a specified solidification rate; and

controlling stirring by the electromagnetic stirring device in response to the solidifying such that a ratio of a speed of the molten silicon and the specified solidification rate is above a first threshold value; and

stirring the molten silicon in the crucible during the solidifying of the molten silicon by means of an electromagnetic stirring device, the stirring comprising the step of:

altering direction of the stirring of said electromagnetic stirring device during the stirring of the molten silicon in the crucible,

wherein the speed of the molten silicon is a highest speed of the molten silicon, an average speed of the molten silicon, a highest speed of a portion of the molten silicon, or an average speed of a portion of the molten silicon.

Further characteristics of the invention, and advantages thereof, will be evident from the following detailed description of preferred embodiments of the present invention given hereinafter and the accompanying Figs. 1-4, which are given by way of illustration only, and are thus not limitative of the present invention.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 displays schematically in a cross-sectional side elevation view an apparatus for crystallization of silicon according to one embodiment of the invention.

Figs. 2-4 display schematically in side elevation views apparatuses for crystallization of silicon according to alternative embodiments of the invention.

DETAILED DESCRIPTION OF EMBODIMENTS

In Fig. 1 is illustrated an apparatus for crystallization of solar grade silicon to polycrystalline silicon. The apparatus comprises a crucible 11 for containing the solar grade silicon (low purity silicon). The crucible 11 is, during crystallization, arranged in a vacuum furnace (not illustrated) comprising a housing and a top cover which can be removed for loading and unloading. Seals are provided to render the furnace gas tight. Further, fluid inlet (s) and outlet (s) may be provided in order to keep an inert atmosphere in the furnace and optionally to assist in heat dissipation during the crystallization.

The raw material is placed in the crucible before the crystallization process starts. In Fig. 1 is shown a layer of solid crystalline silicon 12a and a layer of molten silicon 12b above the solid crystalline silicon 12a.

The apparatus further comprises a heating devices 13, 15, a cooling or heat dissipating device 14, and heat isolation devices 16 for providing suitable temperatures and temperature gradients in the crucible during the crystallization process. The heating devices 13, 15 are also provided for causing the raw material to melt.

While the heating devices 13, 15 are illustrated as two devices placed above and below the crucible, the present invention is applicable to apparatuses having only one heating device and more than two heating devices and/or wherein the heating device(s) is/are arranged differently.

The heating devices 13, 15 may be based on electric heating elements, for example supplied with a direct current or a single phase or three phase alternating current. The heating devices 13, 15 may be conventional heating elements or induction heating elements or a combination of both.

The cooling or heat dissipating device 14 is arranged directly below the crucible 11 and is arranged to dissipate heat from the crucible 11 for the solidification of the raw material silicon therein. The cooling or heat dissipating device 14 may be realized as a device for circulation of a cooled gas as disclosed in WO 2006/082085 or by circulation of a cooling liquid. Alternatively, the cooling or heat dissipating device 14 is a heat conducting device for conducting heat away from the lower part of the crucible 11. Yet alternatively, the cooling or heat dissipating device 14 is a device with movable parts for convection of heat away from the lower part of the crucible 11.

The heat isolation devices 16 are provided for reducing the heat required for melting the raw material silicon and for allowing the temperature field to be accurately and precisely controlled. In one embodiment the heat isolation devices 16 are movable or capable of altering their heat isolation properties in order to assist in the dissipation of heat from the crucible 11 during the solidification process.

The heating devices 13, 15, the cooling or heat dissipating device 14, and optionally the heat isolation devices 16 are in the following referred to as a heat and heat dissipating arrangement.

Further, the inventive apparatus comprises an electromagnetic stirring device 17 provided for stirring the molten silicon 12b in the crucible during the solidification of the molten silicon 12b in order to affect the distribution of doping atoms as well and avoid impurities to crystallize into the ingot of solidified silicon. The largest amount of impurities is collected at the top of the ingot and is removed before the ingot is sliced into silicon wafers to be used in photovoltaic cells.

The electromagnetic stirring device 17 comprises one or several electromagnetic devices supplied with an alternating current for applying an alternating electromagnetic field to the molten silicon 12b in the crucible 11. The electromagnetic device can for example comprise coils or other types of electrically conducting rails suitable to provide a sufficient alternating electromagnetic field when supplied with an alternating current.

Any material or parts located between the electromagnetic stirring device 17 and the silicon melt should be made of a non-magnetic material such as austenitic steel, a ceramic, or a polymer in order to not increase the magnetic resistance for the electromagnetic stirring device 17.

The heat and heat dissipating arrangement and the electromagnetic stirring device 17 are connected to a suitable power supply arrangement.

A control arrangement 18 is operatively connected to the heat and heat dissipating arrangement and to the electromagnetic stirring device 17 for control thereof during the crystallization process. The control arrangement 18 is suitably realized as one or more microcomputers provided with suitable software and input data regarding the structure of the apparatus, the composition of the raw material silicon, and specified solidification rate and amount of stirring. In Fig. 1 the solidification rate v_{sol} is indicated as a vertical arrow and the amount of stirring expressed as a velocity v_{mel} of the molten silicon 12b is indicated as a horizontal arrow. Typically, the solidification is performed from below and upwards. The stirring forces are typically applied in a horizontal direction. The speed v_{mel} of the molten silicon 12b may be expressed as a highest speed of the molten silicon, an average speed of the molten silicon, a highest speed of a portion of the molten silicon, or an average speed of a portion of the molten silicon. The portion may be a portion located at or above but close to the solidification front of the crystallized silicon 12a.

The speed v_{mel} of the molten silicon 12b can easily be controlled since it is proportional to the current in the electromagnetic stirring device 17 for a given height of the molten silicon and the solidification rate can easily be controlled since it is proportional to the difference of the heat supplied to, and the heat removed from, the solidification front.

According to one embodiment the control arrangement 18 is provided for controlling the heating and heat dissipating arrangement to melt the raw material silicon and to subsequently solidify the molten silicon at a specified solidification rate v_{sol} and for controlling the electromagnetic stirring device 17

to stir the molten silicon 12b in response to the solidification rate v_{sol} of the molten silicon such that the ratio of a speed v_{mel} of the molten silicon and the solidification rate v_{sol} is above a first threshold value TV1, that is:

$$v_{mel}/v_{sol} > TV1$$

The first threshold value TV1 may be 10, 100, 1000 or 10 000 depending on the composition of the raw material silicon and/or on the intended application of the crystallized silicon. By means of relating the stirring to the solidification rate according to the above expression a clean and unidirectional solidification front can be achieved.

Optionally, the ratio v_{mel}/v_{sol} should be below a second threshold value TV2, that is:

$$v_{mel}/v_{sol} < TV2$$

The second threshold value TV2 may be 100 000, 50 000 or 30 000 depending on the composition of the raw material silicon and/or on the intended application of the crystallized silicon.

The control arrangement 18 is preferably provided to control the speed of the molten silicon to be below a third threshold value TV3, that is a maximum speed. This speed is preferably in the range of 1 cm/s to 30 cm/s.

By means of keeping the stirring below a maximum allowed level (related or not related to the solidification rate) a unidirectional solidification front can be achieved.

In another embodiment the control arrangement 18 is provided for controlling the electromagnetic stirring device 17 to stir the molten silicon 12b in the crucible 11 during two stages such that a first speed v_1 of the molten silicon is obtained in a first one of the stages and a second speed v_2 of the molten silicon is obtained in a second one of the stages, wherein the

first speed of the molten silicon is higher than the second speed of the molten silicon, that is:

$v_1 > v_2$

During the second stage the control arrangement is preferably provided for controlling the heating and heat dissipating arrangement to obtain a specified solidification rate of the molten silicon and for controlling the electromagnetic stirring device to obtain a speed of the molten silicon in response to the solidification rate such that the ratio of the speed of the molten silicon and the solidification rate is fulfilling any of the above expressions containing the first and second threshold values.

During the second stage the control arrangement 18 is preferably provided to control the speed of the molten silicon to be below the third threshold value TV3.

Typical operation data during the second stage are: speed of the molten silicon v_{mel} of 0.05 m/s and a solidification rate v_{sol} of 10 mm/h. This gives a ratio v_{mel}/v_{sol} of 18 000.

During the first stage the control arrangement 18 is provided for controlling the heating and heat dissipating arrangement to keep the silicon contained in the crucible molten to allow impurities to be transported in the molten silicon. Inclusions in the melt such as oxygen, carbon, oxides, and carbides can be transported from the interior of the melt up to the melt surface.

Alternatively, the control arrangement 18 is, during the first stage, provided for controlling the heating and heat dissipating arrangement to solidify the molten silicon, to cut away a top portion thereof, and to subsequently re-melt the remaining solidified silicon. Hereby a double casting process is achieved. In the first solidification (during the first stage) the crystal

quality and the unidirectional growth of the silicon are not critical and therefore an increased stirring and possibly also a higher solidification rate can be used.

In a further embodiment, the control arrangement 18 is provided for controlling the electromagnetic stirring device 17 to obtain an altered speed of the molten silicon and for controlling the heating and heat dissipating arrangement to alter its heating and heat dissipating in response to the altered speed of the molten silicon, preferably while maintaining the solidification rate. Preferably, the speed is increased while the heat supplied to, and the heat removed, from the solidification front are reduced while the difference of the heat supplied to, and the heat removed, from the solidification front is kept substantially unchanged. Hereby, a more homogenous temperature at the solidification front is obtained at increased stirring.

In still a further embodiment the control arrangement 18 is provided for controlling the electromagnetic stirring device 17 to obtain an altered, preferably increased, speed of the molten silicon and for controlling the heating and heat dissipating arrangement to alter its heating and heat dissipating in response to the altered speed of the molten silicon such that the ratio of a speed of the molten silicon and the specified solidification rate is kept substantially unchanged.

An increased stirring during solidification in a latter part of the crystallization process is advantageous to avoid high concentration of doping atoms in the molten silicon. Reduced stirring in the beginning of the crystallization process increases the amount of doping atoms in the lower portion of the solidified silicon (ingot).

Figs. 2-4 display schematically in side elevation views apparatuses for crystallization of silicon according to alternative embodiments of the invention. Each of the

apparatuses comprises a plurality of crucibles 11 and heat and heat dissipating arrangements for melting and solidifying silicon in the crucibles 11. The crucibles 11 and the heat and heat dissipating arrangements are housed in a vacuum furnace (not illustrated).

The embodiment of Fig. 2 comprises an electromagnetic stirring device 21 which is movable horizontally according to double arrow 22 along the crucibles 11 with respect to one another such that the electromagnetic stirring device 21 can stir the molten silicon in the crucibles 11, one after the other, during the solidification of the molten silicon. The electromagnetic stirring device 21 may be movable along rails mounted in the ceiling of the vacuum furnace by means of an electric motor.

The embodiment of Fig. 3 comprises an electromagnetic stirrer device 31 which is adapted in shape and sized to the number of the crucibles 11 such that the electromagnetic stirrer device 31 can stir the molten silicon in all the crucibles 11 concurrently during the solidification of the molten silicon.

The embodiment of Fig. 4 comprises a power source 42 and a plurality of electromagnetic stirrer units 41, the number of which corresponds to the number of the crucibles 11. Each of the electromagnetic stirrer units 41 is powered by the common power source 42 and is adapted to stir the molten silicon in a respective one of the crucibles 11 during the solidification of the molten silicon. Typically, each of the electromagnetic stirrer units 41 is controlled by a single controller.

A method for crystallization of silicon is provided according to a yet further embodiment of the invention. According to the method silicon is, in a first step, arranged in a crucible. The silicon contained in the crucible is, in a second step, molten. Subsequently, the molten silicon is, in a third step, solidified while the molten silicon in the crucible is stirred by means of

an electromagnetic stirring device. In the third step, solidification of the molten silicon is controlled at a specified solidification rate and the stirring by the electromagnetic stirring device is controlled in response to the solidification rate such that the ratio of a speed of the molten silicon and the solidification rate is above a first threshold value. The control may be performed automatically by a control device, semi-automatically, or manually. This embodiment of the invention may be modified according to any other of the embodiments of the present invention.

A problem of a typical prior art apparatus for crystallization of silicon is that the solidification of the silicon is uneven along the solidification front leading to deteriorated performance of the photovoltaic cells manufactured from the crystallized silicon.

To solve the above problem and to promote a unidirectional growth of the silicon an apparatus for crystallization of silicon is provided, which is identical with the apparatus illustrated in Fig. 1 but in which the control arrangement 18 is provided for controlling the electromagnetic stirring device 17 in a novel manner. During the solidification of the molten silicon the control arrangement 18 is arranged to control the electromagnetic stirring device 16 to alter the direction of its stirring, preferably repeatedly or continuously.

In one embodiment the direction of the stirring of the electromagnetic stirring device 17 is reversed, preferably by means of reversing the current in the electromagnetic stirring device 17.

In another embodiment, the electromagnetic stirring device 17 comprises electric circuitry and a rotating device provided for rotating the electric circuitry under control of the control arrangement 18, thereby rotating the direction of the stirring

of the molten silicon in the crucible during the solidification of the molten silicon.

The altering of direction of the stirring during the solidification of the molten silicon provides a more homogenous temperature profile at the solidification front, which promotes the unidirectional growth of the silicon.

The embodiments of the invention in which an exclusive property or privilege is claimed are defined as follows:

1. An apparatus for crystallization of silicon comprising:

a crucible for containing silicon;

a heating and heat dissipating arrangement provided for melting the silicon contained in the crucible and for subsequently solidifying the molten silicon;

an electromagnetic stirring device provided for stirring the molten silicon in the crucible during the solidification of the molten silicon; and

a control arrangement is provided for controlling the heating and heat dissipating arrangement to solidify the molten silicon at a specified solidification rate and for controlling the electromagnetic stirring device to stir the molten silicon in response to the specified solidification rate of the molten silicon such that a ratio of a speed of the molten silicon and the specified solidification rate is above a first threshold value,

wherein the speed of the molten silicon is a highest speed of the molten silicon, an average speed of the molten silicon, a highest speed of a portion of the molten silicon, or an average speed of a portion of the molten silicon.

2. The apparatus of claim 1, wherein said first threshold value is 10.

3. The apparatus of claim 1, wherein said first threshold value is 100.

4. The apparatus of claim 1, wherein said first threshold value is 1000.

5. The apparatus of claim 1, wherein said first threshold value is 10 000.

6. The apparatus of claim 1, wherein said control arrangement is provided to stir the molten silicon in response to the specified solidification rate of the molten silicon such that the ratio of the speed of the molten silicon and the specified solidification rate is below a second threshold value which is higher than said first threshold value.

7. The apparatus of claim 2, wherein said second threshold value is 100 000.

8. The apparatus of claim 2, wherein said second threshold value is 50 000.

9. The apparatus of claim 2, wherein said second threshold value is 30 000.

10. The apparatus of any one of claims 1 to 9, wherein the speed of the molten silicon is a highest speed of a portion of the molten silicon or an average speed of a portion of the molten silicon, and wherein the portion of the molten silicon is located at or close to a solidification front of the solidifying molten silicon.

11. The apparatus of any one of claims 1 to 10, wherein the control arrangement is provided for controlling the electromagnetic stirring device to stir the molten silicon in the crucible during two stages such that a first speed of the molten silicon is obtained in a first one of the stages and a second speed of the molten silicon is obtained in a second one of the stages, and wherein the first speed of the molten silicon is higher than the second speed of the molten silicon.

12. The apparatus of claim 11, wherein said control arrangement is, during the second stage, provided for controlling the heating and heat dissipating arrangement to obtain the specified solidification rate of the molten silicon and for controlling the

electromagnetic stirring device to obtain the speed of the molten silicon in response to the specified solidification rate such that the ratio of the speed of the molten silicon and the specified solidification rate is within a specified range.

13. The apparatus of claim 11 or 12, wherein said control arrangement is, during the second stage, provided to control the speed of the molten silicon to be below a third threshold value.

14. The apparatus of any one of claims 11 to 13, wherein said control arrangement is, during the first stage, provided for controlling the heating and heat dissipating arrangement to keep the silicon contained in the crucible molten to allow impurities to be transported in the molten silicon.

15. The apparatus of any one of claims 11 to 13, wherein the control arrangement is, during the first stage, provided for controlling the heating and heat dissipating arrangement to solidify the molten silicon, to cut away a portion thereof, and to subsequently melt the remaining solidified silicon.

16. The apparatus of any one of claims 1 to 15, wherein said electromagnetic stirring device is capable of altering direction of stirring of the molten silicon in the crucible and said control arrangement is provided for controlling the electromagnetic stirring device to alter the direction of the stirring of the molten silicon in the crucible during the solidification of the molten silicon.

17. The apparatus of any one of claims 1 to 16, wherein said control arrangement is provided for controlling the electromagnetic stirring device to obtain an altered speed of the molten silicon and for controlling the heating and heat dissipating arrangement to alter heating and heat dissipating in response to said altered speed of the molten silicon.

18. The apparatus of claim 17, wherein said control arrangement is provided for controlling the electromagnetic stirring device to obtain the altered speed of the molten silicon and for controlling the heating and heat dissipating arrangement to alter the heating and heat dissipating in response to said altered speed of the molten silicon while maintaining said specified solidification rate.

19. The apparatus of any one of claims 1 to 18, wherein said control arrangement is provided for controlling the electromagnetic stirring device to obtain an increased speed of the molten silicon during the solidification of the molten silicon.

20. The apparatus of any one of claims 1 to 19, further comprising a plurality of crucibles for containing silicon, wherein the heating and heat dissipating arrangement is provided for melting the silicon contained in the crucibles and for subsequently solidifying the molten silicon, and wherein the electromagnetic stirring device is provided for stirring the molten silicon in the crucibles during the solidification of the molten silicon.

21. The apparatus of claim 20, further comprising moving means for moving the electromagnetic stirring device and the crucibles with respect to one another such that the electromagnetic stirring device can stir the molten silicon in the crucibles one after another during the solidification of the molten silicon.

22. The apparatus of claim 20, wherein the size of the electromagnetic stirring device is adapted to the number of said crucibles such that the electromagnetic stirring device can stir the molten silicon in the crucibles concurrently during the solidification of the molten silicon.

23. The apparatus of claim 20, wherein the electromagnetic stirring device comprises a power source and a plurality of electromagnetic stirrer units, wherein the number of said electromagnetic stirrer units corresponds to the number of said crucibles, and wherein each of the electromagnetic stirrer units is powered by the power source and is adapted to stir the molten silicon in a respective one of the crucibles during the solidification of the molten silicon.

24. A method of crystallization of silicon, the method comprising:

arranging silicon in a crucible;

melting the silicon contained in the crucible; and

solidifying the molten silicon while stirring the molten silicon in the crucible by means of an electromagnetic stirring device, the solidifying comprising the steps of:

solidifying the molten silicon at a specified solidification rate; and

controlling stirring by the electromagnetic stirring device in response to the solidifying such that a ratio of a speed of the molten silicon and the specified solidification rate is above a first threshold value,

wherein the speed of the molten silicon is a highest speed of the molten silicon, an average speed of the molten silicon, a highest speed of a portion of the molten silicon, or an average speed of a portion of the molten silicon.

25. The method of claim 24, wherein stirring of the molten silicon in the crucible by the electromagnetic stirring device is performed in two stages such that a first speed of the molten silicon is obtained in a first one of the stages and a second speed of the molten silicon is obtained in a second one of the stages, and wherein the first speed of the molten silicon is higher than the second speed of the molten silicon.

26. The method of claim 25, wherein the steps of solidifying the molten silicon and controlling the stirring are performed during the second stage.

27. The method of claim 25 or 26, wherein the step of controlling the stirring is performed during the second stage such that the speed of the molten silicon is kept below a second threshold value.

28. The method of any one of claims 25 to 27, wherein the silicon contained in the crucible is kept molten during the first stage to allow impurities to be transported in the molten silicon.

29. The method of any one of claims 25 to 27, wherein the molten silicon is solidified, a portion thereof is cut away, and the remaining solidified silicon is subsequently re-molten during the first stage.

30. An apparatus for crystallization of silicon comprising:

a crucible for containing silicon;

a heating and heat dissipating arrangement provided for melting the silicon contained in the crucible and for subsequently solidifying the molten silicon;

an electromagnetic stirring device provided for stirring the molten silicon in the crucible during the solidification of the molten silicon, wherein said electromagnetic stirring device is provided for altering direction of stirring of the molten silicon in the crucible during the solidification of the molten silicon; and

a control arrangement is provided for controlling the heating and heat dissipating arrangement to solidify the molten silicon at a specified solidification rate and for controlling the electromagnetic stirring device to stir the molten silicon in response to the specified solidification rate of the molten silicon such that a ratio of a speed of the molten silicon and

the specified solidification rate is above a first threshold value,

wherein the speed of the molten silicon is a highest speed of the molten silicon, an average speed of the molten silicon, a highest speed of a portion of the molten silicon, or an average speed of a portion of the molten silicon.

31. The apparatus of claim 30, wherein said electromagnetic stirring device is provided for reversing the direction of stirring of the molten silicon in the crucible during the solidification of the molten silicon.

32. The apparatus of claim 31, wherein said electromagnetic stirring device is provided for reversing the direction of stirring of the molten silicon in the crucible during the solidification of the molten silicon by means of reversing a current in the electromagnetic stirring device.

33. The apparatus of claim 30, wherein said electromagnetic stirring device comprises electric circuitry and a rotating device provided for rotating said electric circuitry, thereby rotating the direction of stirring of the molten silicon in the crucible during the solidification of the molten silicon.

34. The apparatus of any one of claims 30 to 33, wherein said electromagnetic stirring device is provided for altering the direction of stirring of the molten silicon in the crucible during the solidification of the molten silicon repeatedly or continuously.

35. A method of crystallization of silicon, the method comprising:

arranging silicon in a crucible;

melting the silicon contained in the crucible;

solidifying the molten silicon while stirring the molten silicon in the crucible by means of an electromagnetic stirring device, the solidifying comprising the steps of:

solidifying the molten silicon at a specified solidification rate; and

controlling stirring by the electromagnetic stirring device in response to the solidifying such that a ratio of a speed of the molten silicon and the specified solidification rate is above a first threshold value; and

stirring the molten silicon in the crucible during the solidifying of the molten silicon by means of an electromagnetic stirring device, the stirring comprising the step of:

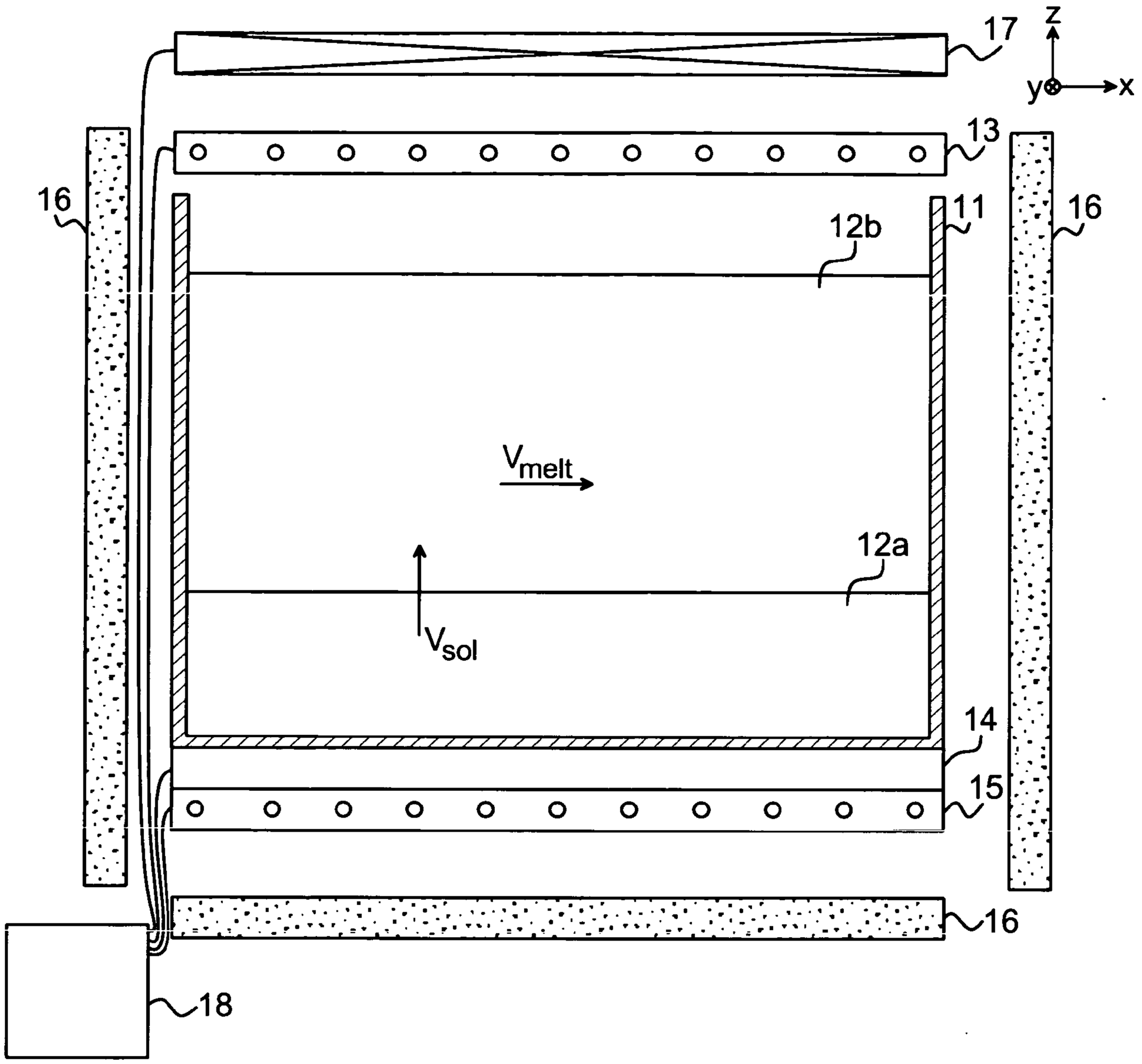
altering direction of the stirring of said electromagnetic stirring device during the stirring of the molten silicon in the crucible,

wherein the speed of the molten silicon is a highest speed of the molten silicon, an average speed of the molten silicon, a highest speed of a portion of the molten silicon, or an average speed of a portion of the molten silicon.

36. The method of claim 35, wherein the direction of the stirring of said electromagnetic stirring device is reversed during the stirring of the molten silicon in the crucible.

37. The method of claim 35, wherein the direction of the stirring of said electromagnetic stirring device is rotated during the stirring of the molten silicon in the crucible.

38. The method of claim 35, wherein the direction of the stirring of said electromagnetic stirring device is altered repeatedly or continuously during the stirring of the molten silicon in the crucible.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y
x
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13
16
11
12b
16
V_{melt}
12a
V_{sol}
14
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16
18

Fig. 1

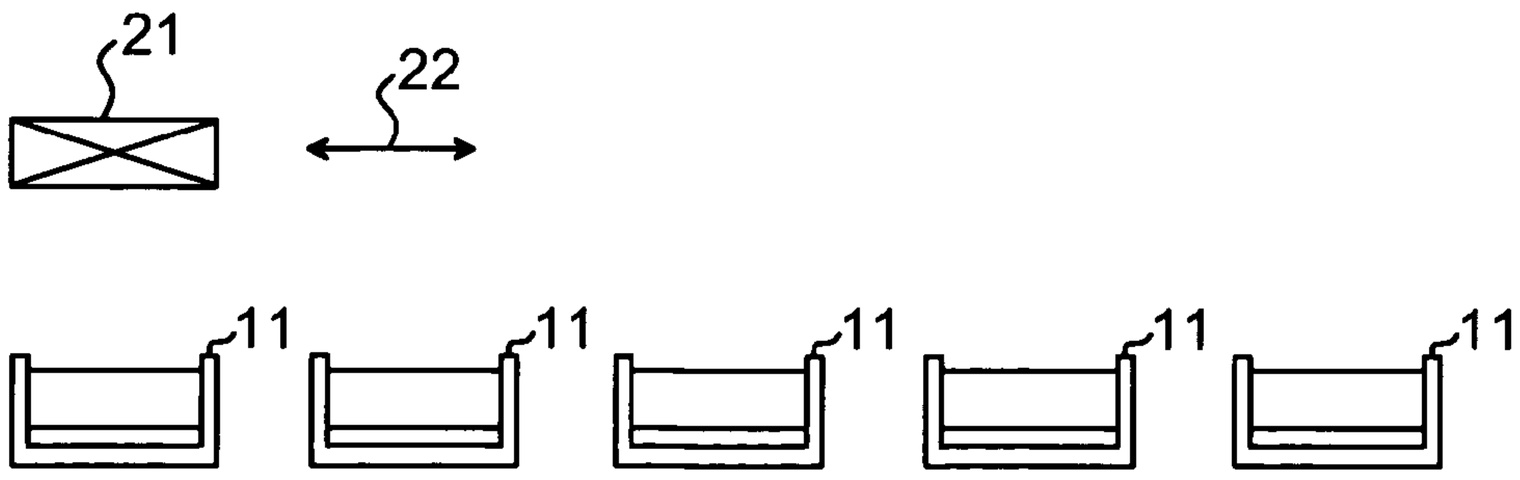
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Fig. 2

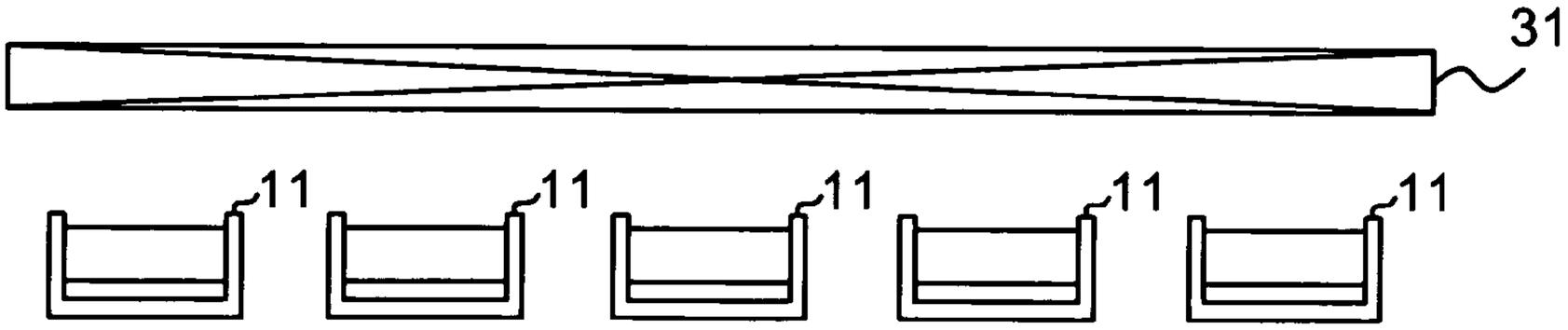


Fig. 3

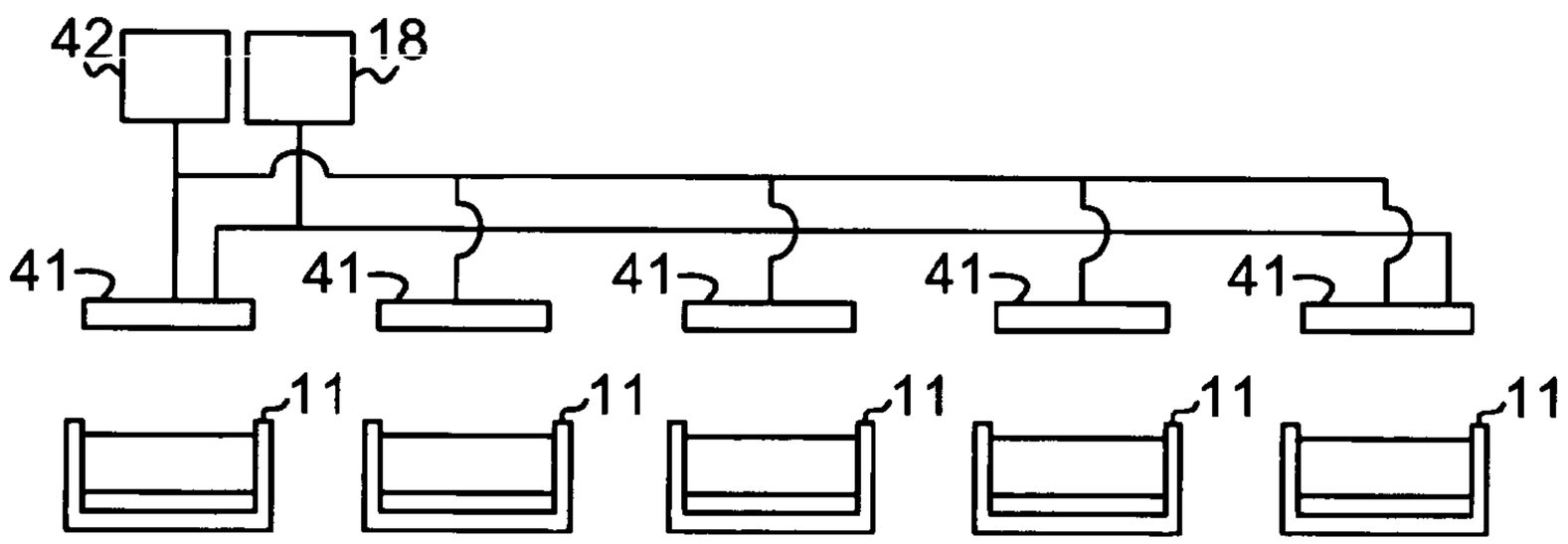
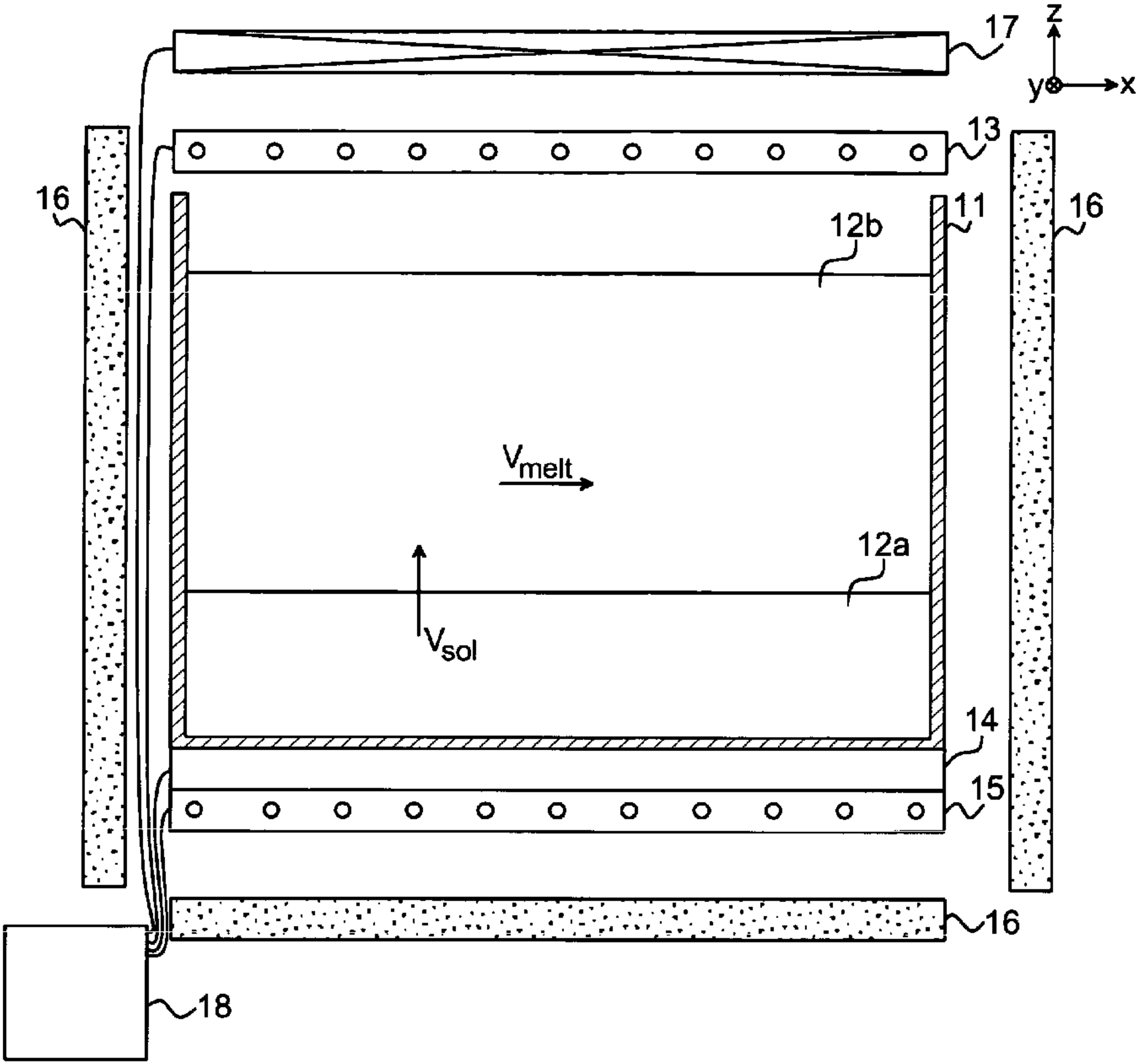


Fig. 4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12b
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V_{melt}
12a
V_{sol}
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