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Bochman et al.

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[54] **METHOD AND APPARATUS FOR PRODUCING LARGE DIAMETER MONOCRYSTALS**

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[52] **U.S. Cl.** .... **23/301 SP,** 23/273 SP

[51] **Int. Cl.** **B01j 17/18**

[58] **Field of Search** .... 23/301 SP, 273 SP

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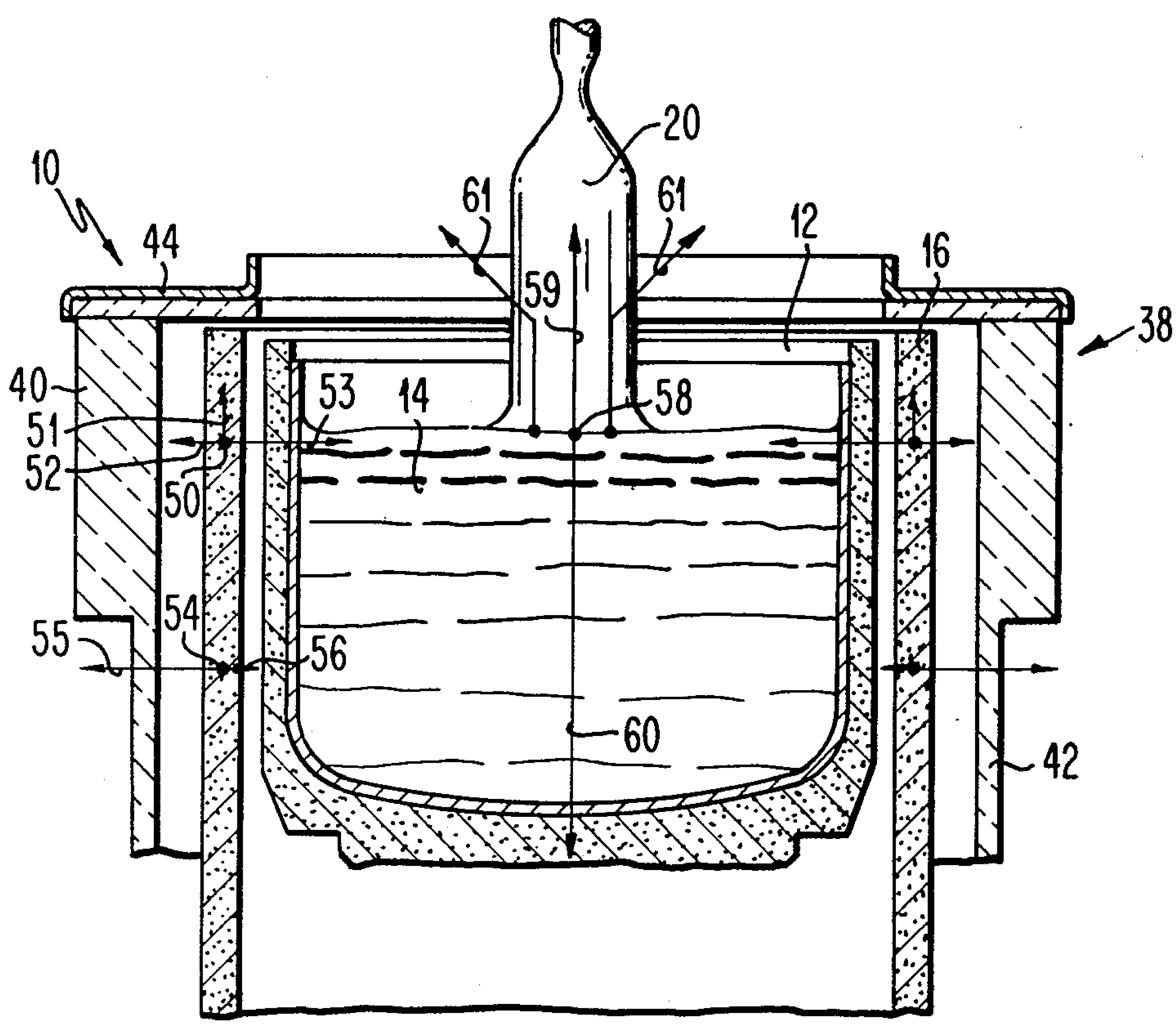
[57] **ABSTRACT**

An improved method and apparatus for producing large diameter semiconductor crystals by the Czochralski process wherein a relatively flat temperature profile is maintained within the melt by adding heat to the sides and top of the melt while simultaneously removing heat from the melt through the crystal being pulled and the lower portion of the melt. In the apparatus, the temperature profile is maintained with a deflector to direct heat energy to the top surface of the melt about the crystal being pulled, a heat exchange element to facilitate removal of heat through the crystal being pulled, and means to remove heat through the lower portion of the crucible containing the melt.

17 Claims, 8 Drawing Figures



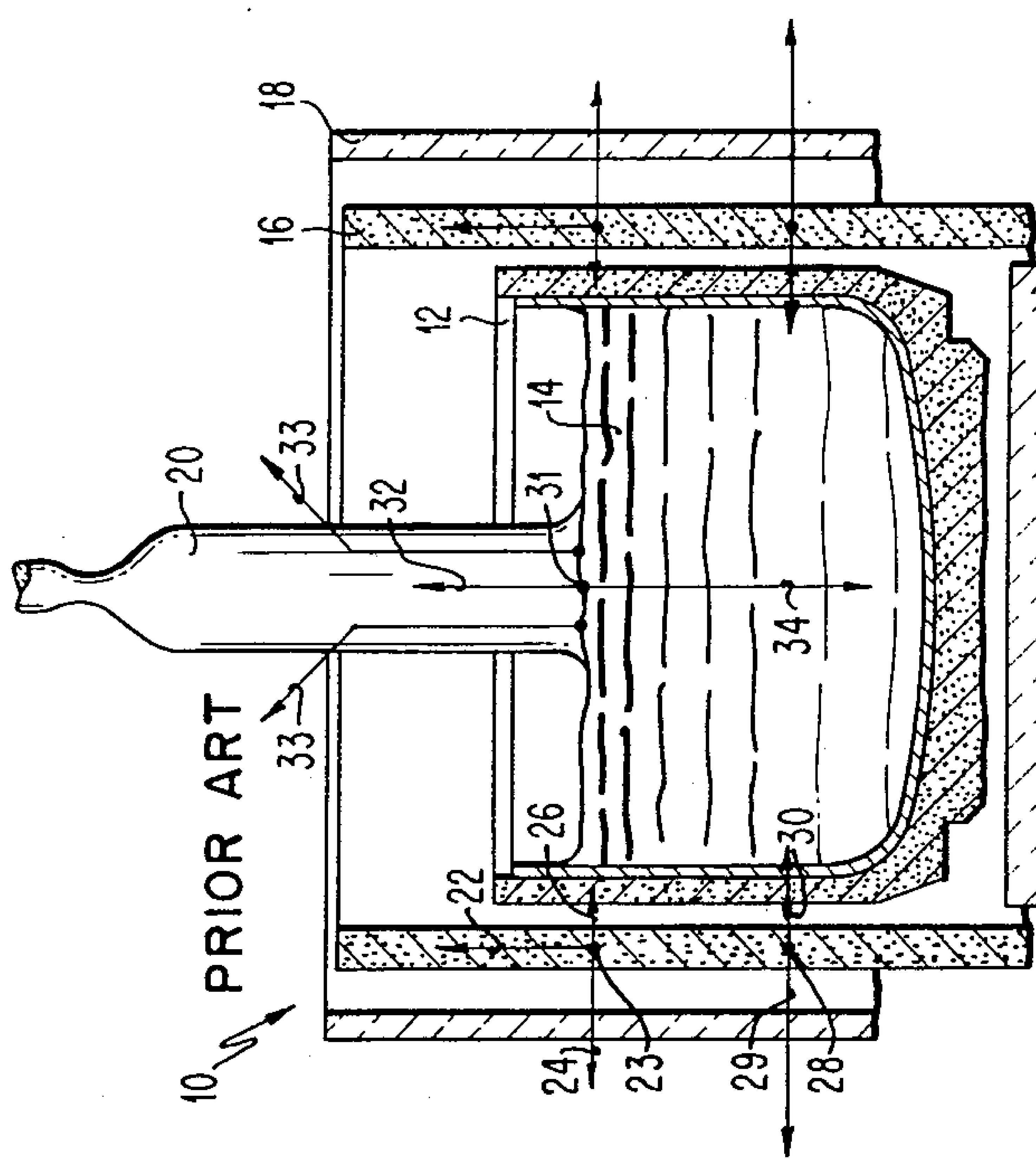


FIG. 2A

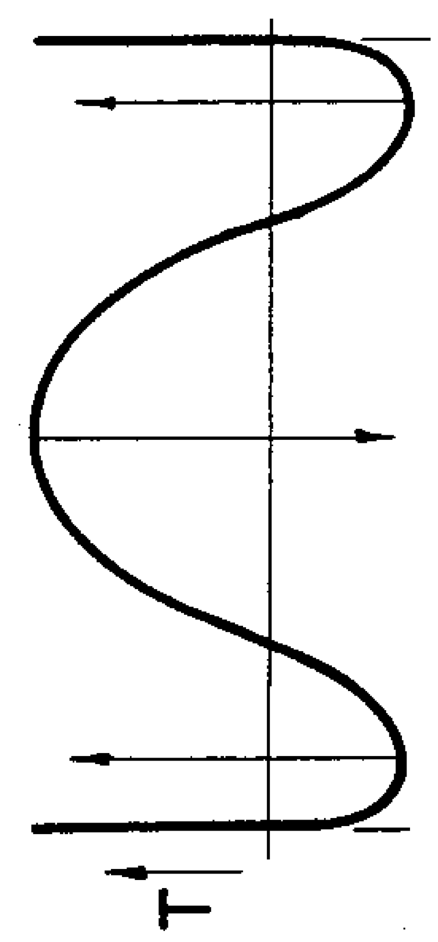


FIG. 2B

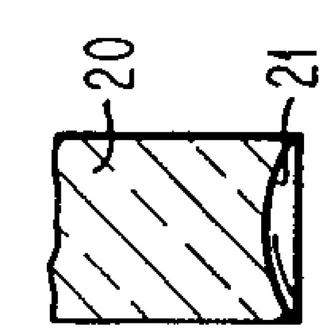


FIG. 2C

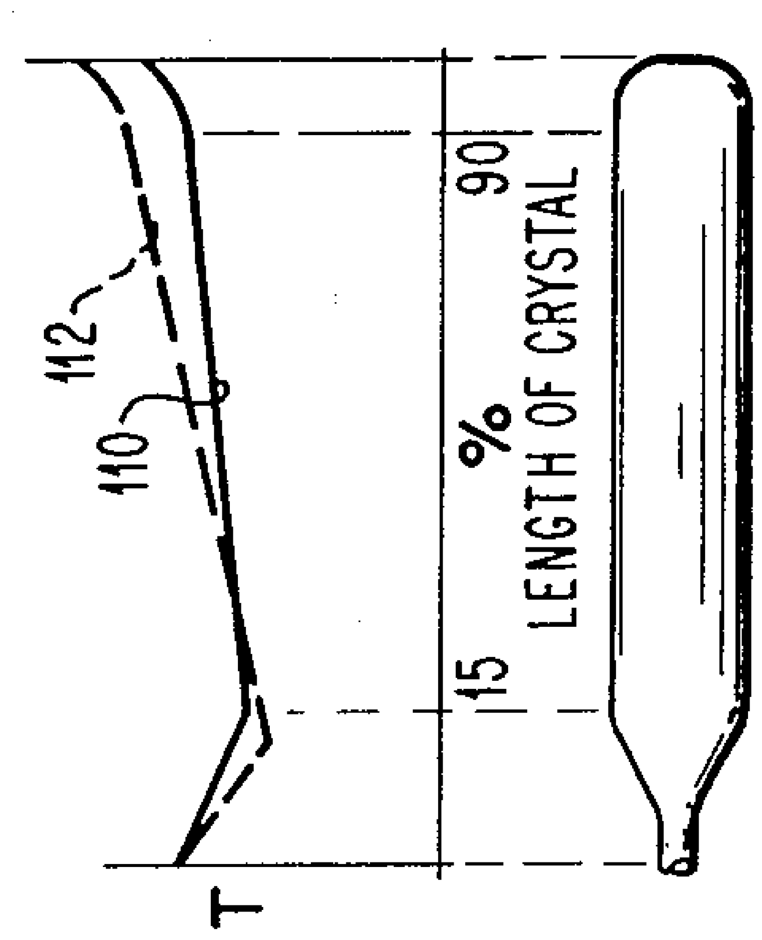


FIG. 4

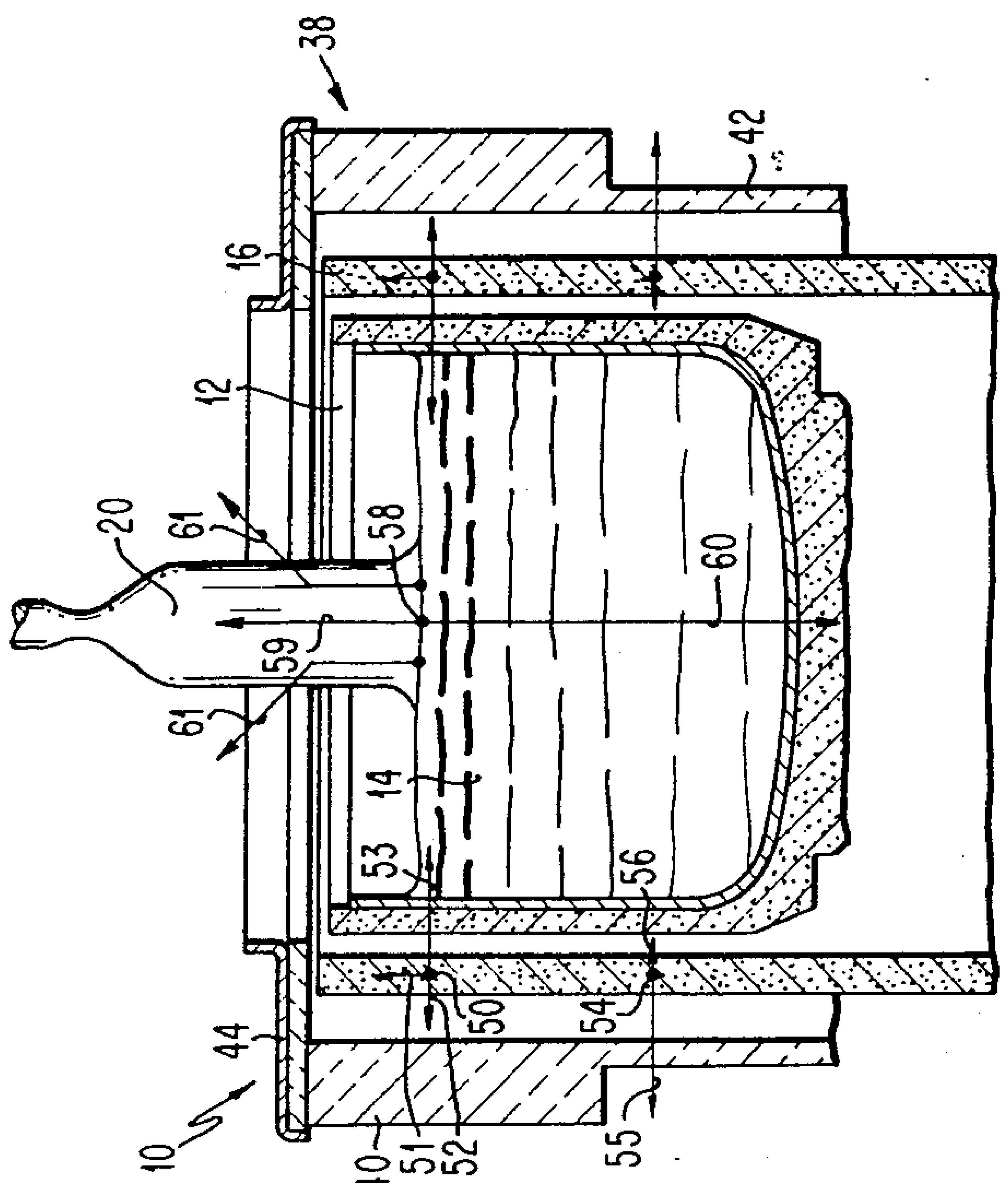


FIG. 1A

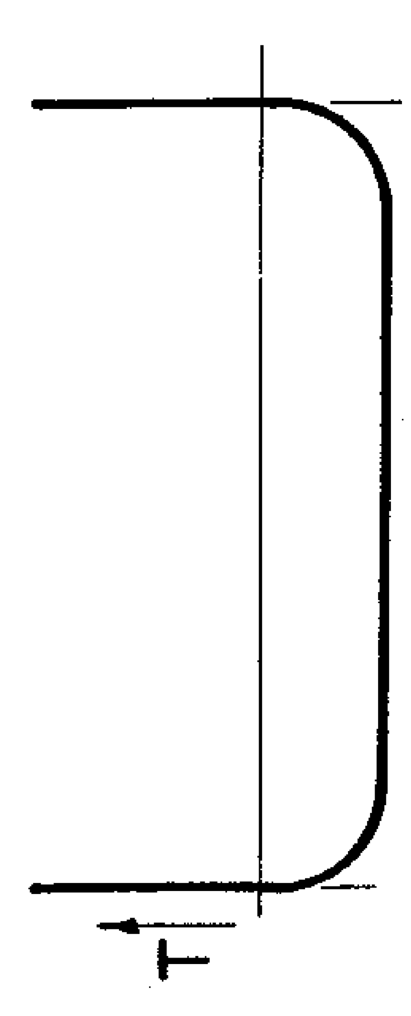


FIG. 1B

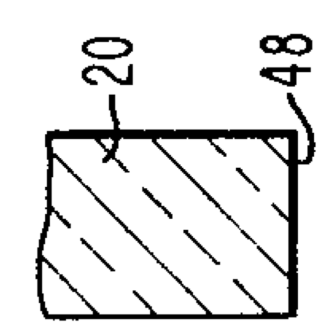


FIG. 1C

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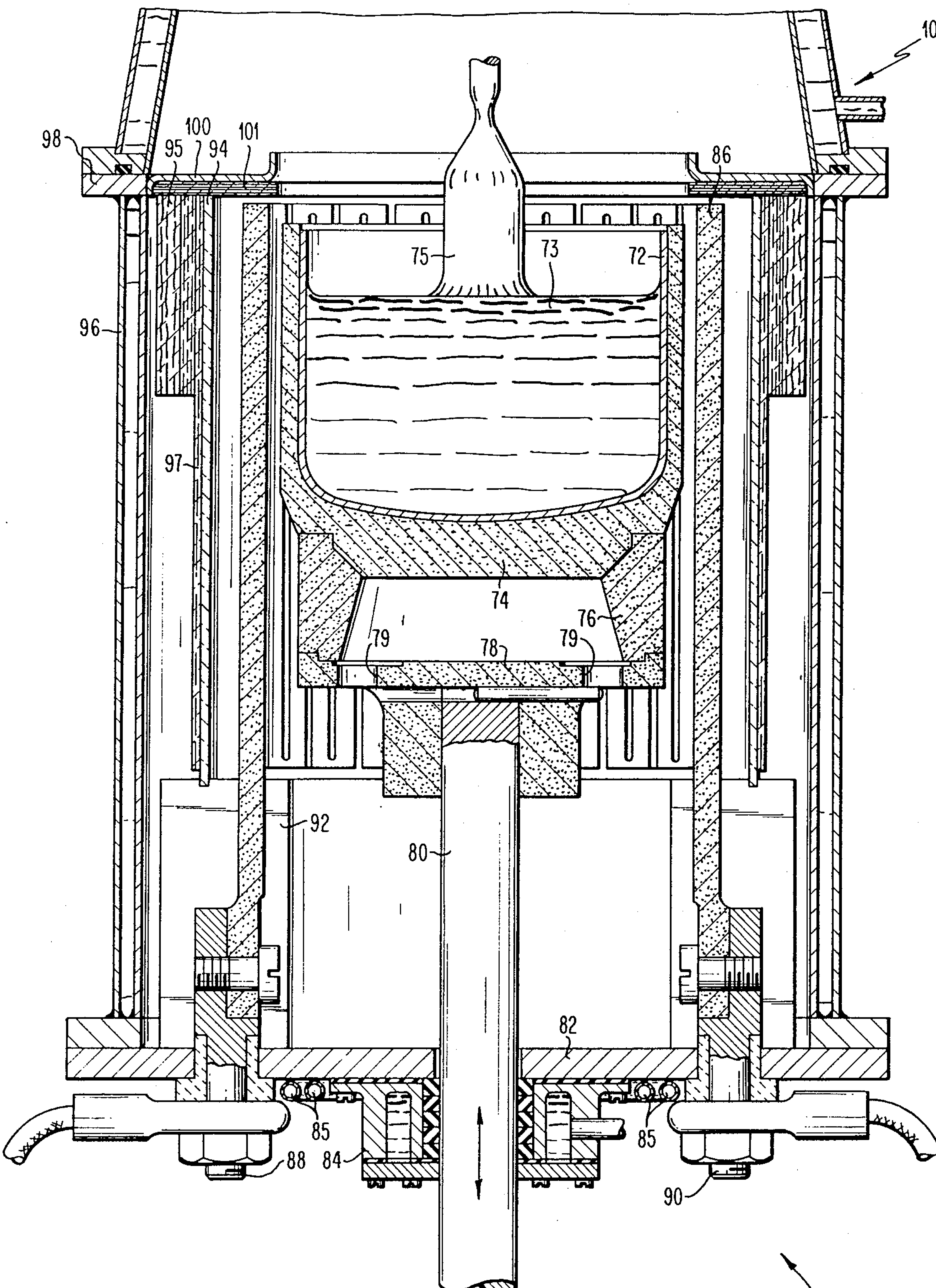
102
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FIG. 3

METHOD AND APPARATUS FOR PRODUCING LARGE DIAMETER MONOCRYSTALS

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates generally to crystal growing method and apparatus, and more particularly to a crystal growing method and apparatus suitable for growing large diameter single crystals of material, such as silicon.

2. Description of the Prior Art

The rapidly expanding semiconductor industry is built around the unique electrical properties and characteristics of monocrystalline semiconductor material. Consequently, a great deal of development has been done to produce in quantity the semiconductor material having the desired quality. This has resulted over the years in a number of techniques to produce monocrystalline semiconductor material. These techniques include the zone recrystallization method, the Czochralski method, and the web growth method. Each method has inherent advantages as well as disadvantages which make it attractive for one use and unattractive for another.

In the zone recrystallization method an elongated bar or rod of polycrystalline material is joined to a relatively short length of monocrystalline material which serves as a "feed" and subsequently a relatively narrow zone is heated and passed through the bar to cause recrystallization and to extend the crystal lattice of the seed throughout the bar. Various techniques have been perfected to suspend the resultant molten zone during the process. In this method there is no significant crucible contamination but it does have the disadvantage that thermal stresses appear in the crystal which can result in a high density of crystalline defects.

The most commonly and most widely used method of producing single crystals for use in a semiconductor device at the present time is the Czochralski method. Basically the growing technique consists of dipping a "seed" crystal in a melt of semiconductor material at a precise temperature at or below the melting point and then withdrawing the seed under controlled conditions. The semiconductor material will freeze on the end of the seed in the same basic crystalline formation resulting in a single crystal. Normally a suitable dopant material is incorporated in the molten mass in the crucible and is subsequently recrystallized along with the semiconductor into the rod.

In the web growth technique the crystal is grown in the form of a thin web. Basically two dendrites are formed beneath the surface of the liquid melt which grow in long continuous lengths. The liquid film, which is drawn up by surface tension between the dendrites, solidifies to form the web. This is a relatively new development which has not been fully perfected at present.

The usual method in the industry in fabricating integrated circuit devices is to grow a monocrystalline silicon ingot by the Czochralski process, slice the ingot into thin wafers, and produce diffused regions, deposit passivating layers and metallurgy on the surface to produce the desired integrated circuit device configuration. In order to make the fabrication process more efficient, it would be desirable to increase the diameter of the semiconductor wafers in order to increase the

number of devices per wafer. The work involved in processing the wafer is not significantly different in the case of small and large wafers. The usual standard diameter of the wafer in industry is an inch and one-quarter although efforts have been made to increase this diameter. While crystals having a larger diameter can be grown by the Czochralski process, it has been found that the resultant wafers grown in accordance with known techniques have a very high density of crystallographic imperfections. As the size of the active devices in integrated circuit devices is decreased, which is the trend in modern semiconductor fabrication, the disruptive effect of crystallographic defects becomes more serious. A crystallographic defect such as a dislocation can render a device inoperative, or cause a leak which will destroy the utility of the entire integrated circuit device, which may include up to several hundred active devices. This very significantly reduces the yield of a production line.

There is a great present need for a process and an apparatus which will produce significantly larger diameter monocrystalline wafers having a zero or very low crystallographic defect density. The present interest in forming of devices on the **<100>** crystalline orientation plane accentuates the problems with growing large diameter crystals since growth in this general direction is more difficult than grown in the **<111>** plane which was previously universally utilized.

SUMMARY OF THE INVENTION

An object of this invention is to provide a method whereby large diameter monocrystalline semiconductor boules can be grown by the Czochralski process.

Another object of this invention is to provide an apparatus which will maintain desirable thermal conditions in the melt whereby large diameter crystals can be produced, which crystals have a zero or low crystallographic defect density.

Another object of this invention is to provide a method and an apparatus for growing monocrystalline semiconductor material in which the thermal conditions in the melt is conducive to the formation of large diameter crystals having a zero or low crystallographic defect density.

Another object of this invention is to provide a method and apparatus adapted to produce large diameter monocrystalline semiconductor wafers of high quality suitable for use in fabricating microminiaturized integrated circuit devices.

In the method of the invention for producing large diameter substantially defect-free single semiconductor crystals by the Czochralski process wherein a monocrystal is pulled from a molten melt of semiconductor material the improvement resides in maintaining a relatively flat temperature profile within the melt by adding heat to the sides and top of the melt while simultaneously removing heat from the melt through the crystal being pulled and the bottom of the melt.

In the apparatus of the invention for producing large diameter substantially defect-free semiconductor crystals by the Czochralski process, which includes a heater or RF coil disposed about the side of the container, a mechanism for supporting and lifting the crystal formed in the melt, the improvement is providing a means to direct more intense heat energy to the top region of the melt about the crystal being pulled, a means to effectively remove heat from the upper central portion of the melt through the crystal being pulled, and a means to remove heat from the lower portion of the container. The objective is to avoid a heat build-up under the crystal being pulled and thereby cause crystallization to occur in substantially a planar front. Further, by proper control of heating the crystallization front can be placed very near the top of hot zone, i.e. keeping only a small portion of the grown crystal in the hot zone during growth, while the major portion is being pulled through the cold zone, i.e. the region above the heater. This provides a greater surface area for heat dissipation the space enclosed by the heater, thereby promoting more effective heat transfer and a more rapid rate of crystallization.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other objects, features and advantages of the invention will be apparent from the following more particular description of a preferred embodiment of the invention as illustrated in the accompanying drawing.

FIG. 1A is a schematic elevational view in cross-section of the apparatus of the invention illustrating the general structure and heat flow.

FIG. 1B is an idealized temperature profile which exists in the melt of the apparatus and process of the invention.

FIG. 1C is an elevational view in broken section of a crystal produced by the invention illustrating the planar surface shape of the interface between the crystal and the melt.

FIG. 2A is a schematic elevational view in cross-section of a crystal puller apparatus typical of the prior art illustrating the heat flow into and out of the crucible.

FIG. 2B is a typical temperature profile which exists in a melt of the type apparatus illustrated in FIG. 2A.

FIG. 2C is an elevational view in cross-section of a representative crystal produced in the apparatus illustrated in FIG. 2A which illustrates the surface shape of the interface between the crystal and the melt.

FIG. 3 is an elevational view in cross-section of a preferred specific embodiment of the crystal pulling apparatus of the invention.

FIG. 4 is a graph of heater temperature vs percent of crystal length from seed dip to withdrawal to be followed when practicing the method of the invention.

DESCRIPTION OF THE PREFERRED EMBODIMENT

The Czochralski process as practiced by the prior art is capable of growing usable silicon crystals of up to two inches in diameter up to generally a length of 5 to 6 inches. When crystals are longer in length, the diameter must be significantly less than 2 inches. When silicon crystals having a diameter significantly greater than two inches are grown, the crystallographic defect density is so high that use of the wafers for producing integrated circuit devices and obtaining respectable yields are not economically feasible. FIG. 2A illustrates a typical prior art apparatus for growing semiconductor crystals by the Czochralski process. Apparatus **10** has a crucible **12** containing a melt **14** of silicon. Heater **16** is provided to maintain the temperature of melt **14** near the freezing-point. A uniform layer of insulation **18** surrounds heater **16** to improve the efficiency of the apparatus. The semiconductor crystal **20** is pulled from melt **14** by a suitable lift mechanism (not shown) controlled by a suitable sensor (not shown) which is responsive to the diameter of the crystal. A suitable mechanism (not shown) may be provided for raising or lowering the crucible **12** to maintain the level of the melt **14** in the same position relative to heater **16.** The crystal growing process is performed in an atmosphere of inert gas typically argon, which is contained in a suitable chamber associated with apparatus **10.** Element **19** is shown as closing the chamber below crucible **12** thus indicating schematically that structure exists which impedes heat transfer.

Heat energy is added to melt **14** from two sources, namely from heater **16** and from the crystallization process occurring at the interface between the bottom of the crystal **20** and melt **14.** The heat energy rate added by crystallization process can be calculated from the rate of growth of the crystal, the diameter of the crystal, and the heat of crystallization of the silicon, or other semiconductor material being grown. FIG. **2B** indicates temperatures in the melt in a plane slightly below the surface of the melt along a diameter line of the crucible. As the profile depicted in FIG. **2B** indicates the temperature of the melt **14** is relatively high about the outside wall of the crucible and in the center directly under the semiconductor crystal **20.** There is a temperature drop in the melt in the area between the crystal and the exterior wall of the crucible. When a crystal is pulled abruptly from the melt **14** thus halting the crystallization process the bottom surface **21** as indicated in **2C** has a concave configuration. Surface **21** represents the shape of the growing interface between the melt and the crystal as it is being produced in the apparatus as it is known to the prior art. It is theorized that the concave surface is caused by the build-up of heat due to the heat of crystallization and non-uniform heat loss across the crystal diameter. This results in a nonplanar crystallization growth front which results in built-in stresses in the crystal. Dislocations and other crystallographic defects thus occur during the actual growth of the crystal, and also result later due to the stresses being equalized when the crystal **20** is cooled.

During operation a significant amount of heat is radiated from the surface of the melt. Consequently, heat must be added by the heater to maintain this portion of the melt near the melting point or the surface will freeze and completely disrupt the operation. The crystallization in an orderly operation occurs because heat energy is removed from the melt through the crystal as it is being pulled. It has been observed that in known apparatus the crystallization actually occurs at or slightly below the surface of the melt. To prevent excessive heat loss and resulting freezing, the crystallization front must be kept well within the heat zone. This significantly impedes heat transfer through the crystal and consequently reduces the growth rate. The heat in this environment must pass through the immersed portion of crystal, which is slow because there is a small temperature differential, and subsequently longitudinally through the crystal to a region of the crystal where it can be dissipated by conduction or convection.

The arrows in FIG. **2A** attempt to explain the thermal conditions within the melt which result in the temperature profile depicted in FIG. **2B.** Arrow **22** represents the vector component of the heat transferred from point **23** in the heater **16** in the general plane of the melt surface that is lost from the heat emission from the top of the heater. Arrow **24** depicts the amount of heat which emanates outwardly from heater **16** and which is lost through insulation **18.** Arrow **26** represents the vector component of heat energy which is transferred inwardly to the crucible **12** which in turn is transferred to the melt **14.** In the set of arrows below point **23** at second point **28,** arrow **29** depicts the amount of heat loss outwardly from the heater **16** through insulation **18.** Arrow **30** depicts the amount of heat energy directed inwardly toward crucible **12** from point **28.** Note that the length of arrow **30** is somewhat longer than corresponding arrow **26.** However, the proportion of heat directed inwardly and outwardly is generally similar to that at point **23.** The magnitude of the heat is different. This condition exists because at point **28** there is a minimal amount of heat directed upwardly or downwardly unlike point **23** where there is an upward loss as indicated by arrow **22.** This has the effect of increasing the temperature of the melt in the lower portion of the crucible.

Vector arrow **32** represents the amount of heat conducted upwardly from point **31** located in the center of crystal **20** at the crystallization front. Arrows **33** indicate the heat energy conducted upwardly from the outside perimeter of the crystal front. This heat is subsequently dissipated radially in the cold zone. As arrows **32** and **33** indicate, heat is conducted away from the crystallization front faster at the periphery of the crystal than at the center. This results in a concave crystallization front of the type shown in FIG. 2C. Vector arrow **34** represents the heat lost through the bottom of the crucible. Heat is radiated from the top surface of the melt resulting in a lower surface temperature. The temperature gradient of the melt produced by the conditions described results in a relatively hot spot beneath the crystal downward wherein dissipation of the heat of crystallization cannot proceed efficiently because a greater heat is being applied to the bottom portion of the crucible and no means is provided to promote conduction of the heat away from the bottom of the crucible.

FIG. 1A is a schematic drawing of an apparatus which embodies the inventive concept of the invention. As in FIG. 2A crucible **12** contains melt **14** from which crystal **20** is pulled therefrom. Heating element **16** surrounds crucible **12** which is in turn enclosed in an insulating member **38** having a relatively thick upper portion **40** and a relatively thinner lower portion **42.** The reason for the insulation configuration will become apparent in the following description of the process. Disposed above heater **16** resting on insulation member **38** is a cover element **44** which minimizes upward radiation of heat from heater **16** and directs the heat inwardly. The space below crucible **12** is shown open to indicate generally that the structure is such to promote efficient transfer of heat from the bottom portion of the crucible.

FIG. 1C depicts the end portion of a crystal **20** which has been abruptly pulled from the melt as it is being grown by the process of this invention. The lower surface portion **48** is relatively planar indicating that the interface between the melt and the crystal during crystallization is planar. This results in the formation of fewer crystallographic defects and stresses set up within the crystal. FIG. 1B indicates the general shape of the temperature profile of melt **14** along a center line slightly below the surface of the melt during the crystallization process. As indicated the temperature across the melt is relatively uniform which is consistent with the formation of a flat surface **48** on crystal **20.** The arrows in FIG. 1A again depict the vector quantities of heat radiating from various points in the apparatus. Considering point **50,** arrow **51** represents the upwardly directed heat loss. Arrow **51** is smaller than corresponding arrow **22** in FIG. 2A since this component is minimized by shield **44.** Arrow **52** represents the amount of heat radiated outwardly through insulation **40.** This arrow is smaller in magnitude than corresponding arrow **24** in FIG. 2A since the insulation layer **40** is more effective to reduce heat losses. Arrow **53** depicts the heat transferred inwardly toward the crucible at the general region of the melt surface. Note that this is larger than corresponding arrow **26** in FIG. 2A. There is less heat loss upwardly and outwardly and thus the major portion is directed inwardly toward the crucible. Considering point **54,** arrow **55** indicates a greater heat loss outwardly through the portion of insulation **42.** This is larger than corresponding vector arrow **52** in FIG. 1A since the insulation **42** is substantially less effective than insulation **40.** Arrow **56** indicates the amount of heat directed inwardly towards the crucible. The arrow **56** is smaller than arrow **53.** A greater proportion of the heat is directed outwardly leaving a smaller portion to be directed inwardly. The end result considering the heat distribution from points **50** and **54** is that a greater amount of heat is directed inwardly toward the crucible in the region of the melt surface and less at the bottom portion of the melt. Considering now point **58** located in the center of crystal **20** at the crystal front, arrow **59** indicates in vector form the amount of heat transferred upwardly through the central portion of the crystal **20.** Arrows **61** indicate the upward and outward heat transferred from the peripheral region of the crystal front. This heat is dissipated transversely from the surface of crystal **20** at a region above the hot zone as indicated by the broken arrows **61.** Note that the magnitude of arrows **59** and **61** is generally similar. This would promote a flat crystallization front on crystal **20** which will minimize crystallographic defects. A cooling coil (not illustrated) can be disposed about the upper portion of the crystal to provide a more effective conduction of heat. Further shield **44** maintains a cooler temperature in the region above the crystal, i.e. the cold zone, thus providing a greater temperature differential and more efficient cooling. Further, the chamber about the crystal can be water cooled. Arrow **60** indicates the quantity of heat removed downwardly through the bottom of the crucible **12.** This quantity is relatively large when compared to **34** because the bottom portion of the apparatus is designed to more effectively conduct heat away from the bottom of the crucible. This can be done by water cooling the support for the crucible or otherwise providing means to more effectively conduct heat away from the crucible bottom. The objective of the apparatus is to inject heat near the top of the melt from the outside, and confine the vertical distances or thickness of the hot zone, and to more effectively conduct heat from the center of the melt which would reduce the temperature difference illustrated in the profile shown in FIG. 2B.

The crystallization front can be placed very near the top of the hot zone by the action of the shield **44** and the insulation configuration **40** which direct radiant heat to the surface of the melt to compensate at least in part for the heat normally radiated upwardly from the melt. Heating the surface reduces the amount of heat that must be directed to the melt through the crucible. Ordinarily the temperature of the surface must be maintained near the freezing point to prevent freeze-up over the surface. The heat in prior art apparatus comes from within the melt which must be at a higher temperature. The surface temperature of the melt of the subject invention is maintained more nearly at the temperature of the lower melt. In operation, because the length of the crystal that the heat of crystallization must pass through is shorter, a more uniform heat transfer gradient across crystal front is obtained, and also the crystallization rate can be significantly increased.

In FIG. 3 is depicted a specific embodiment of the apparatus of the invention adapted to carry out the method of the invention. The apparatus illustrated has structure for controlling the thermal conditions in the melt to promote crystal growth on the bottom of the crystal being grown in a generally planar face. This objective is accomplished by adding a proportionately greater amount of heat to the top region of the melt than to the bottom from the outside, and reducing the heat build-up at the center of the melt due to the heat of crystallization.

Apparatus **70** has a crucible **72** supported by crucible support **74**, resting on support ring **76**, in turn supported on support plate **78**. Plate **78** is mounted on the upper end of support rod **80** which extends through base plate **82** and a water cooled seal assembly **84**. Base plate **82** may also be provided with a fluid cooling coil **85**. Support rod **80** is actuated by a suitable lift mechanism adapted to maintain the upper surface of melt **73** in the same position relative to the heating element **86** and which also rotates the crucible. Heating element **86** is the "picket type" made of graphite having electrodes **88** and **90** which are water cooled. Annular support ring **92** rests on base plate **82** and supports the cylindrical carbon insulator support **94**. The upper portion of **94** is provided with a relatively thick insulation, typically graphite felt **95** and pyrolytic graphite tape **97**. At a point below the top surface of melt **73**, the thickness of the insulation is materially decreased. Positioned about the entire assembly mounted on base **82** is a water cooled jacket **96** provided with a top flat ledge **98**. Within **98** resting on cylindrical support **94** is an annular molybdenum shield **100** disposed over an annular pyrolytic graphite ring **101**. Pyrolytic graphite is an anisotropic material which conducts heat quite efficiently in one direction but is an effective insulation which restricts heat transfer in the transverse direction. Ring **101** is formed so that heat from the heating element is reflected and directed inwardly toward the melt **73** and lower end of the crystal **75**. This provides localized heating of the top surface of the melt and maintains the region above the melt at a relatively cooler temperature. This permits more efficient cooling of the crystal, and growing of the crystal higher in the hot zone as discussed previously. Frusto-conical, water cooled chamber **102** is mounted on ledge **98**. This chamber supports a mechanism to lift and rotate the crystal **75** as it is grown from melt **73**. The water cooled chamber **102** in combination with shield **100** and ring **101** serve to control the temperature above the crucible and about the crystal. It is normal practice to grow the crystal **75** in an atmosphere of inert gas such as argon.

The objective of the aforedescribed preferred embodiment of the invention is to achieve a flat temperature profile in crucible **72** by directing a proportionately greater amount of heat from the heater **86** to the top portion of the crucible in the vicinity of the melt surface, while decreasing the amount of heat directed to the lower portion of the crucible. This objective is achieved by providing more insulation near the top of the crucible, and providing of shield **100** and ring **101** which direct the heat downwardly into the melt maintaining a lower temperature in the cold zone above the crucible. A portion of the heat in the center of the crucible generated by the heat of crystallization is removed through the lower portion of the crucible. Apertures **79** in support plate **78**, the water cooled jacket surrounding the support rod **80** and cooling coils **85** on base **82** all serve to aid in the transfer of heat away from the melt. Thus, heat is removed from the lower portion of the crucible by radiation and by conduction. Heat is also removed from the center portion of the crucible through crystal **75**. Heat is generally radiated from the crystal **75** outwardly particularly above shield **100** and dissipated through the upper water cooled jacket **102**. Shield **100** and ring **101** by directing the heat from the heating element **86** downwardly and inwardly maintains essentially a relatively shallow hot zone immediately over the melt and a cool zone above the hot zone. The resulting temperature differential through which the crystal extends increases the heat transfer. This arrangement makes possible a crystal growth rate of 5 – 8 inches per hour for a crystal diameter of 2 ½ inches and greater. Prior art techniques permit generally a rate of 2 to 3 inches per hour for a crystal less than 2 inches in diameter.

The heat distribution to the crucible form the heating element can also be achieved by designing the heat element to generate more heat at the top portion than at the bottom in lieu of shaping the insulation, such as an R.F. coil with many turns at top and fewer below. Further, the objective might also be achieved by the combination of heater and insulation design. Heat dissipation through the crystal could be enhanced by providing a heat exchanger to remove heat directly from the crystal. Heat removal through the lower portion of the crucible could be enhanced by cooling the crucible support by any suitable heat exchanger.

FIG. 4 depicts a heater temperature program for growing a crystal by the method of the invention. Curve **110** depicts a program for growing a large diameter crystal, while curve **112** is for growing a smaller diameter crystal. In the initial growth portion both curves indicate a sharp temperature drop of the heater temperature. This is done to expand the diameter of the original seed crystal to the desired crystal diameter. The heater temperature is subsequently slowly increased to compensate for a larger amount of heat conducted away from the melt through the crystal, as the length of the crystal is increased. The increased length generates more surface area for heat transfer within the cool zone above the melt. The slope of curve **112** is steeper than the slope of curve **110**.

While the invention has been particularly shown and described with reference to a preferred embodiment thereof, it will be understood by those skilled in the art of various changes and form and detail may be made therein without departing from the spirit and scope of the invention.

We claim:

1. A method for producing a large diameter single semiconductor crystal having a low crystallographic defect density by the Czochralski process, comprising;

pulling a monocrystal from a molten metal of the semiconductor material, and

controlling the thermal conditions within the melt to establish and maintain a relatively flat temperature profile, said profile attained and maintained by directing with an annular baffle element radiant heat energy emanating from the heater surrounding the melt to the surface of the melt and away from the upper surface of the crystal being grown,

simultaneously removing heat from the bottom of the melt,

the profile thereby maintained by proportionally increasing the input of heat energy at the surface of the melt, removing heat energy from the crystallization zone of the melt through the crystal being grown, and through the bottom of the melt,

the total heat removed from the melt being equal to the heat added plus the heat of formation of the crystal.

2. The method of claim 1 wherein heat is removed from the bottom of the melt through a heat exchange means.

3. The method of claim 1 wherein a proportionately larger amount of heat is directed to the top of the melt by providing a more efficient insulation about the heating element in the region of the top surface of the melt.

4. The method of claim 3 wherein relative rotation is provided between the melt and the crystal being grown.

5. The method of claim 3 wherein heat is removed from the center portion of the melt through the crystal.

6. The method of claim 5 wherein a heat exchange means is provided to conduct heat away from the crystal being grown.

7. The method of claim 5 wherein a lower hot zone over the melt, and an upper overlying cooler zone is maintained, and the crystal is withdrawn upwardly through said zones.

8. The method of claim 7 wherein said hot zone is formed at least in part by directing heat from a heating element inwardly and downwardly toward the melt, and shielding the cooler zone from the heating element.

9. The method of claim 8 wherein the heater temperature is gradually increased as the length of the crystal increases to compensate for increasing heat transfer through the crystal.

10. In an apparatus for producing a large diameter substantially defect-free single semiconductor crystal by the Czochralski process having a container for the melt, a heater disposed about the side of said container, and a mechanism for supporting and lifting the crystal formed in the melt, the improvement comprising;

a means to direct a greater porportion of heat energy to the top region of the melt than to the bottom, including an annular shield positioned above the heater to direct radiant heat energy from said heater downwardly and inwardly toward the top surface of the melt, and preventing at least in part radiant heat energy from impinging on the upper portion of the crystal,

a heat exchange means to remove heat from the lower portion of the melt,

said annular shield and heat exchange means adapted to establish and maintain a relatively flat temperature profile in the melt in the region slightly below the top surface of the melt.

11. The apparatus of claim 10 wherein said means to remove heat from the lower portion of the container includes a support shaft and a heat exchange means to cool said shaft.

12. The apparatus of claim 10 wherein said means to remove heat from the upper portion of the melt includes a heat exchange means adapted to effectively cool the crystal as it is withdrawn from the melt.

13. The apparatus of claim 10 wherein said annular shield a ring of anisotropic material which directs heat inwardly and restricts upward heat transfer.

14. The apparatus of claim 13 wherein said annular shield is formed of pyrolytic graphite.

15. The apparatus of claim 10 wherein said means to direct heat energy to the top region of the melt includes insulation means surrounding the upper portion of the crucible and shaped to deflect a proportionately greater amount of heat toward the upper portion of the crucible than the bottom portion.

16. The apparatus of claim 15 wherein said insulation means includes a layer of pyrolytic graphite tape surrounding substantially the entire outside area of the heater, and a layer of insulation covering the upper portion of the heater, in the region of the melt surface.

17. The apparatus of claim 16 wherein said layer of insulation is a layer of graphite felt.

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