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3,428,436

METHODS AND APPARATUS FOR ZONE MELTING

Filed Dec. 16, 1963

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FIG. 1

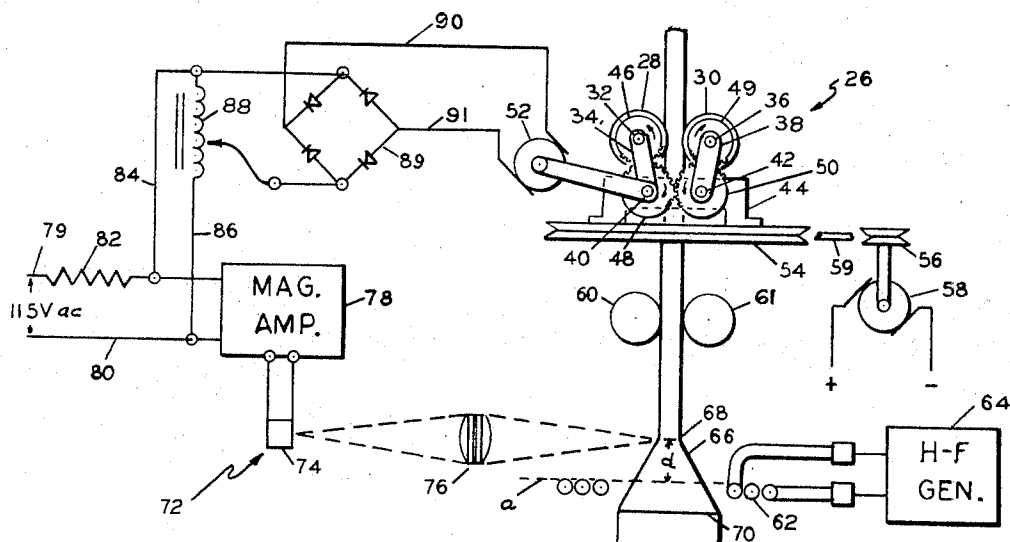
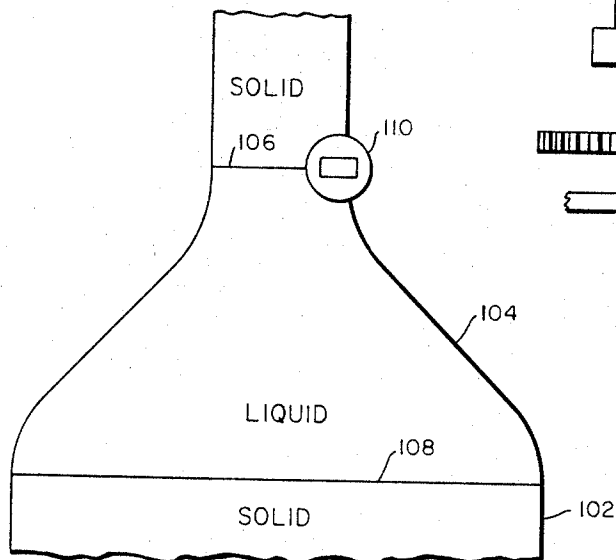


FIG. 4



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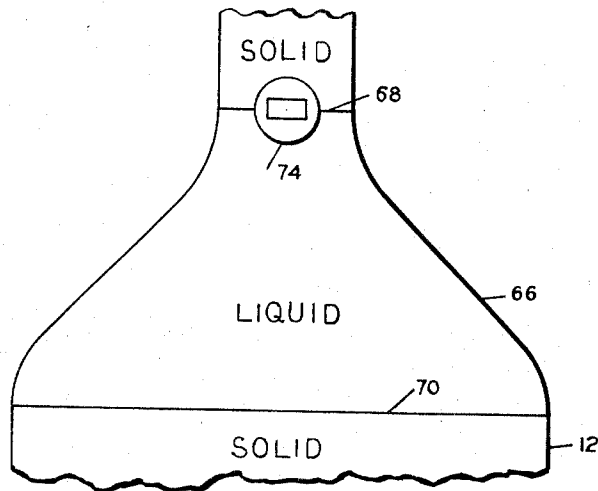


FIG. 2

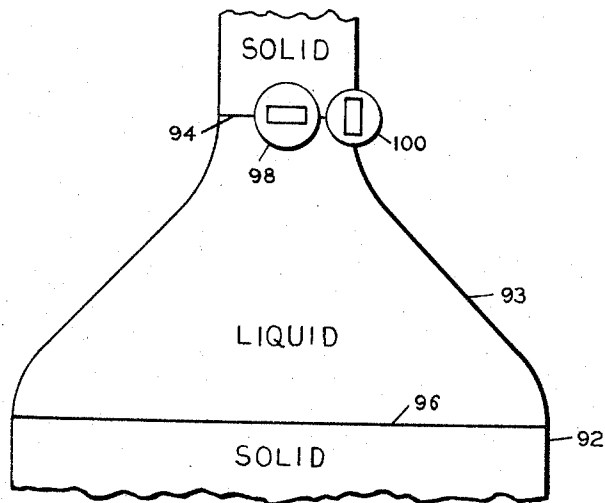


FIG. 3

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METHODS AND APPARATUS FOR ZONE MELTING

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17 Claims

This invention relates to methods and apparatus for zone melting semiconductor materials and more particularly to methods and apparatus for zone melting a vertically positioned rod of semiconductor material such that the rod segment solidified from the molten zone is of relatively constant diameter.

Semiconductor materials are zone melted for a number of purposes. For example, zone melting operations are conducted to effect purification of semiconductor materials, to effect uniform distribution of carrier impurities in semiconductor materials, and to effect the transformation of polycrystalline semiconductor materials into a rod of semiconductor material formed from a single crystal. In other instances the zone melting operation is conducted primarily to effect a change in diameter of a rod of semiconductor material or to remove irregularities in the diameter of a rod material. Instances where it is desirable to effect a change in the diameter of a rod of semiconductor material include the production of slim rods for use in a decomposer and, in many instances, the production of seeds for use in the manufacture of single crystal material.

In all operations of the above type it is normally desirable that the rod of semiconductor material resulting from the zone melting operation be predominantly of an uniform diameter. For example, in the manufacture of slim rods for use in a decomposer if the slim rods are irregular in diameter, the irregularities are amplified during the deposition of polycrystalline material upon the slim rods so that the resulting polycrystalline rod is highly nonuniform in diameter. This results in difficulties if one attempts to employ the polycrystalline rod in a zone melting operation and, because of its nonuniform diameter, one cannot easily subdivide it into chunks of substantially equal weight for use as charges for a crystal puller. As another example, if one is producing rods of extremely small diameter for use in the manufacture of seed crystals, nonuniform diameter seeds result in alignment difficulties when the seeds are used for the manufacture of pulled crystals and the seeds are also less satisfactory for use in the preparation of single crystal rods by zone refining techniques.

The need for means to produce a zone melted rod of uniform diameter has been previously recognized and substantially all zone melting apparatus is provided with either a manual or automatic means for rod diameter control. For the production of small diameter rods diameter control is more difficult and automatic diameter control means are normally embodied into apparatus for producing such rods, the most usual type of automatic diameter control means being as disclosed in U.S. Patent 2,992,311 issued to Wolfgang Keller. In accordance with this U.S. patent, photoelectric means are provided for measuring the diameter of a rod of zone refined material at the point where resolidification of the molten zone is effected. Such a system is satisfactory in the production of rods down to about 5 millimeters in diameter since with rods of this diameter or larger it is possible to maintain diameter fluctuations below about 10 percent; however, in the production of rods of diameters less than about 4 or 5 millimeters, apparatus in accordance with the Keller patent is not entirely satisfactory. For example, in the

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production of slim rods of 3.7 millimeters diameter it is difficult to maintain diameter fluctuations below about 30 percent using apparatus as disclosed in the Keller patent. Uniform semiconductor rods of less than 4 millimeters diameter are advantageous for use in the production of seeds and in the production of slim rods for decomposers and a method and apparatus for producing such rods represents a material advance in the art.

It is an object of this invention to provide improved methods and apparatus for producing zone melted rods of semiconducted material of relatively uniform diameters.

It is another object of this invention to provide methods and apparatus for producing very small diameter semiconductor rods which vary less than about 10 percent from a mean diameter.

The above as well as other objects of the invention are accomplished by apparatus including means to support at either end of a rod of semiconductor material, means to form a molten zone in the rod intermediate to its ends, and means to control the relative movement of the two ends in response to variations in the displacement of the interface of resolidification, which forms one longitudinal boundary of the molten zone, from the mean plane of the heating means or any arbitrarily selected reference plane extending transversely through the rod of semiconductor material. It has been found that fluctuations in rod diameter which occur with apparatus embodying a conventional automatic diameter control system are partially or largely the result of changes in the degree of heater coupling with perceptible diameter changes. It has further been found that the interface of resolidification makes a discernible move relative to the heater prior to the time that a readily discernible change in diameter of the rod being solidified from the molten zone has occurred and that if the control system is responsible partially or totally to this movement of the interface of resolidification, rather than solely to changes in rod diameter, that changes in rod diameter can be maintained at a very low level.

Several specific embodiments of the invention will now be described with reference to the accompanying drawings in which FIGURE 1 is a schematic drawing of a slim rod pulling apparatus designed to produce a rod of small diameter from a larger diameter rod as a result of a zone melting operation and which embodies rod diameter control means in accordance with this invention.

FIGURE 2 is an enlarged view of the molten zone with adjacent portions of each of the solid ends of a rod of semiconductor material being zone melted in the apparatus of FIGURE 1.

FIGURE 3 is an enlarged view of the molten zone and adjacent portions of a rod of semiconductor material showing an alternative arrangement in which not only the position of the interface of resolidification is detected but in which the diameter of the rod at the interface of resolidification is also detected using a separate photoelectric cell.

FIGURE 4 is an enlarged view of a molten zone as in FIGURE 3 wherein a single photoelectric cell is used to detect both the position of the interface of resolidification and the diameter of the rod at the interface of resolidification.

With particular reference to FIGURE 1 of the drawings there is illustrated a lower rod holding means 10 designed to secure the lower end of a rod of semiconductor material 12 in a vertical position. The rod holder 10 is supported upon a threaded vertically disposed shaft 14 which engages an internally threaded collar 16 carrying a horizontally disposed gear 18, the collar 16 being rotatably supported upon a support frame member 20 board to receive the vertical shaft 14. Horizontally disposed gear 18 is in operative engagement with a second

gear 22 which is driven through a conventional reduction gear train, not illustrated, by a suitable electric motor 24. Shaft 14 is free to move vertically but is keyed against rotation so that by rotation of gear 18, the shaft 14 and rod holder 10 can be moved vertically as desired.

The reference numeral 26 generally indicates a second rod holding means which in this instance is shown to comprise a pair of grooved rollers 28 and 30. The roller 28 is mounted upon a shaft 32 which is journaled through a pair of support arms, one of which is shown at 34, on either side of the roller 28. Roller 30 is similarly mounted upon a shaft 36 which is journaled at either end through a pair of support arms one of which is shown at 38. Support arms 34 and 38 are respectively carried by a pair of shafts 40 and 42 which are journaled through a support member 44. The support arms 34 and 38 are rotatable about shafts 40 and 42 respectively but relative movement between the arms and shafts 40 and 42 is preferably not friction free for reasons which will subsequently be made apparent.

Secured to one end of roller 28 is a gear 46 which meshes with a gear 48 secured to shaft 40. Similarly, secured to one end of roller 30 is a gear 49 which meshes with a gear 50 secured to shaft 42 and which in turn meshes with gear 48 so that gear 48 drives both rollers 28 and 30 but in opposite directions. A suitable electric motor schematically illustrated at 52 is provided for driving shaft 40, to which gear 48 is secured, through a suitable conventional gear reduction train, not illustrated.

The reference numeral 54 designates a rotary support platform upon which the rod holding means 26 is positioned. While it is not necessary that platform 54 rotate it has been found and is well known in the art that rotation of one or both rod holding means securing the ends of a rod of semiconductor material being zone refined is normally desirable and gives improved results. A small pulley 56 driven by an electric motor schematically illustrated at 58 is provided for rotating platform 54 by means of a belt 59 running in a suitable groove in the periphery of the platform. To reduce vibration and assist in maintaining the upper solid portion of rod 12 in proper alignment, a pair of freely rotatable idler rollers 60 and 61 are disposed below platform 54 and are yieldably biased toward each other to form a nip through which rod 12 passes.

The reference numeral 62 designates a convention RF (high frequency) heater coil operatively disposed around the rod of semiconductor material 12. The heater coil 62 is electrically connected to a suitable source of high frequency current such as a conventional high frequency generator schematically illustrated at 64 so that by passing a high frequency current through the coil 62 a molten zone 66 can be created in the upstanding rod of semiconductor material 12. As will subsequently be made clear, the molten zone 66 is bounded at its upper extremity by a transverse interface of resolidification 68 and at its lower extremity by a transverse interface of melting 70.

The reference numeral 72 generally indicates means for sensing variations in the distance between the transverse interface of resolidification 68 and an arbitrarily selected reference plane passing transversely through the rod of semiconductor material and moving relative to the longitudinal axis of rod 12 at a rate equal to the mean rate of movement of molten zone 66. For purposes of illustration a reference plane has arbitrarily been selected to correspond to the upper surface of the heater coil 62 and is shown by dotted lines in FIGURE 1 of the drawings and indicated by the reference letter *a*, and the distance between the selected reference plane and the interface of resolidification is indicated by the reference letter *d*. In actual practice the desired result can readily be obtained by mounting the sensing

means 72 on the bracket or platform which supports heating coil 62 so that the sensing means is in fixed positional relationship to the heater coil.

The distance measuring means 72 is illustrated as comprising a photoelectric cell 74, which in this instance can suitably be a variable resistance cadmium selenide cell, and a lens system schematically illustrated at 76. As best shown in FIGURE 2 of the drawings, lens 76 produces an image upon the surface of photoelectric cell 74 of a portion of the surface of rod 12 including adjacent surface areas of the solid portion of rod 12 above interface 68 and of the molten zone 66. With this arrangement vertical movement of the interface of resolidification 68 relative to plane *a* results in a change in the radiation received by the surface of cell 74 due to a difference in the intensity of radiation being emitted from the solid and molten areas of rod 12.

The photoelectric cell 74 is connected through suitable electrical leads to a magnetic amplifier, indicated by the reference numeral 78, which in turn is connected through suitable leads 79 and 80 to a source of alternating current electricity. Suitable magnetic amplifiers for use in accordance with this invention are commercially available and may be obtained from a number of different manufacturers. The photoelectric cell 74 is connected to the magnetic amplifier 78 such that a decrease in the radiation being received upon the surface of the photoelectric cell through lens 76 results in an increase in the resistance of the photoelectric cell which in turn results in an amplified effective resistance or impedance to the flow of AC current in leads 79 and 80 through the magnetic amplifier. A resistor, indicated by the reference numeral 82, is disposed in lead 79 between the source of electric power and the magnetic amplifier, and a lead 84 is connected to lead 79 intermediate resistor 82 and magnetic amplifier 78. It will be seen that with this arrangement the voltage across leads 84 and 80 varies with changes in radiation received by photoelectric cell 74. A lead 86, connected to lead 79, together with lead 84 supplies power to an adjustable auto-transformer 88 which in turn is connected to a full wave rectifier indicated by the reference numeral 89. Rectifier 89 supplies a controlled rectified voltage to motor 52 through commutator rings, not illustrated, and leads 90 and 91. The voltage supplied to motor 52 with this arrangement can be manually controlled by means of variable transformer 88 and is automatically varied in response to variations in the light energy projected upon the surface of photoelectric cell 74.

In operation, a large rod of semiconductor material is inserted in rod holder 10 and properly aligned in a vertical position. Vertical alignment can be checked by rotating rod holder 10 and noticing the amount of lateral movement at the upper end of the rod of semiconductor material. In most instances it is desirable to insert a piece of molybdenum or other electrically conductive material in rod holder 10 along with the rod of semiconductor material 12 to act as a preheater since hyper-pure semiconductor materials are normally such poor conductors at low temperatures that an effective coupling cannot be accomplished with a high frequency heater coil and a segment of the semiconductor material must be heated to a relatively high temperature at which it becomes conducting before an effective couple can be established.

With the rod of semiconductor material 12 in proper position a seed rod of small diameter is inserted between rollers 28 and 30 and lowered until it is slightly above the upper end of the rod of material held by rod holder 10. The apparatus is then sealed so that the zone refining operation can be conducted in an inert atmosphere or in a vacuum as desired.

To begin the zone refining operation, heater coil 62 is lowered or rod holder 10 is raised until the heater coil is even with a piece of molybdenum or the like

held by the rod holder 10 so that the piece of molybdenum is, when a high frequency current is passed through coil 62, heated to a high temperature and in turn heats the lower extremity of rod 12 to a temperature such that it becomes electrically conductive. In the case of silicon this is usually a red heat. While continuing the flow of a high frequency current through coil 62 it is then moved upwardly relative to holder 10 at a very slow rate so that the couple established between the heater coil and the rod of semiconductor material is not broken. By this means the hot area of rod 12 can be moved from its lower extremity to its upper extremity. When the heater coil is approximately even with the upper extremity of the rod of semiconductor material held by holder 10, the current being passed through coil 62 is increased so that the upper extremity of the rod of semiconductor material held by holder 10 becomes molten. At this time the seed rod of semiconductor material held by rollers 28 and 30 is lowered to contact the upper molten extremity of the rod of semiconductor material held by holder 10. The apparatus is now ready for automatic operation and for the production of a small diameter rod from the large diameter rod inserted in holder 10.

With the seed rod held by rollers 28 and 30 in contact with the molten upper extremity of the rod held by holder 10, motors 58, 24 and 52 are placed in operation and the rate of operation of motors 24 and 52 are correlated so that the upward movement of the lower solid extremity of rod 12 relative to the rate of upward movement of the upper solid extremity of rod 12 (it being understood that the upper solid extremity of rod 12 was initially provided by the seed rod inserted between rollers 28 and 30) is such that a small diameter rod of the desired mean diameter is withdrawn from the molten zone 66. As the lower extremity of rod 12 is pushed upwardly into the molten zone by means of motor 24, the upper solid extremity of rod 12 is withdrawn from the molten zone by motor 52 at a rate such that the two solid portions of the rod are continuously receding from each other, and the large diameter feed stock is transformed into a small diameter product by means of the zone refining operation. It will thus be seen that since the lower solid extremity of rod 12 is being continually fed into molten zone 66 and the upper solid portion of rod 12 is being continually withdrawn from molten zone 66, the molten zone is bounded at the bottom by an interface of melting and at the top by an interface of resolidification.

It was previously mentioned that movement of arms 34 and 38 relative to shafts 40 and 42 is preferably not friction free. It will now be seen that the reason for this is that, in normal operation, friction between shaft 40 and arm 34 and between shaft 42 and arm 38 results in rollers 28 and 30 being urged toward each other so that the upper solid portion of rod 12 is gripped more forcefully. This reduces the possibility of slippage between rod 12 and rollers 28 and 30 and reduces the extent to which rollers 28 and 30 need be spring biased toward each other.

Once a proper pull rate, i.e., the rate at which the upper solid extremity of rod 12 is withdrawn from the molten zone 66, is established, lens 76 is focused upon the interface of resolidification 68 so that an image of a surface area of rod 12 is projected upon the surface of photoelectric cell 74. With experience, proper positioning of the lens 76 can be accomplished prior to the initiation of the zone refining operation since with a selected diameter of feed stock and product, the position of the interface of resolidification can be accurately estimated. If for any reason, such as fluctuations in the diameter of the lower section of rod 12 being fed into molten zone 66 or fluctuations in the current being passed through coil 62, there is movement of the interface 68 relative to heater coil 62 so that there is a change in d ,

the radiation being received by the surface of cell 74 changes so that the resistance of photocell 74 changes and the speed of pull motor 52 is increased or decreased as the case may be. If the illumination on photocell 74 is increased due to a downward movement of interface 68 (radiation from the surface of the molten zone 66 is lower per unit area than from the surface of adjacent solid portions of rod 12), the speed of motor 52 is increased due to a decrease in the resistance of the photocell and an increase in voltage across leads 84 and 80, and if the illumination on photocell 74 is decreased due to a relative upward movement of interface 68, the rate of operation of motor 52 is decreased to thereby reduce the pull rate. As previously mentioned, it has been found that if factors which result in a relative downward movement of interface 68 are allowed to persist, an increase in the diameter of the segment of rod 12 being withdrawn from molten zone 66 results, but a readily discernible movement of interface 68 occurs prior to any substantial change in the diameter of the rod segment above the molten zone. Thus, factors which normally would result in an increase in rod diameter can be corrected, under favorable conditions, before any substantial increase occurs. In a similar manner undesirable decreases in the diameter of the rod segment above molten zone 68 are also controlled so that there is produced by solidification of the molten zone a rod segment varying only within narrow limits from a selected diameter.

With particular reference to FIGURE 3 of the drawings there is illustrated an arrangement in which two photoelectric cells are employed in series to control the rate of operation of a motor corresponding to motor 52 in FIGURE 1 of the drawings so that the pull rate is determined both by the position of the interface of resolidification and by the diameter of the rod of semiconductor material. With particular reference to this figure of the drawings there is illustrated a rod of semiconductor material 92 in which there is formed a molten zone 93 which is bounded at its upper extremity by an interface of resolidification 94 and at its lower extremity by an interface of melting 96. A first photoelectric cell 98, which corresponds generally to photoelectric cell 74 in FIGURE 1 of the drawings, receives radiation from a surface area of rod 92 including a portion of molten zone 93 and a portion of the rod 92 above interface 94. A second photoelectric cell 100 is positioned such that it receives, over approximately 50 percent of its surface, radiation from rod 92 and over the remainder of its surface receives only background radiation. The photoelectric cells 98 and 100 are electrically connected in series so that the resistance across the two cells decreases in response to a downward movement of interface 94 and/or in response to a decrease in diameter of the rod 92. With this arrangement the pull rate is less sensitive to movement of the interface of resolidification 94 but changes in diameter which result from large fluctuations in the diameter of rod 92 at the interface of melting 96 are also controlled. This arrangement, therefore, is of particular value when working with feed stock of irregular diameter.

With specific reference to FIGURE 4 of the drawings there is illustrated an arrangement similar to that shown in FIGURE 3 except that only a single photoelectric cell is employed. In this figure of the drawings the reference numeral 102 indicates a rod or semiconductor material in which a molten zone 104 is formed by a suitable heater, not illustrated, the molten zone being bounded at its upper extremity by an interface of resolidification 106 and at its lower extremity by an interface of melting 108. A photoelectric cell 110 is so arranged that it normally receives light over about $\frac{2}{3}$ of its surface from a surface area of rod 102 selected to include adjacent portions of the solid rod above interface 106 and of the molten zone below interface 106, and such that over the remaining $\frac{1}{3}$ of its surface it normally receives only background radiation. With this arrangement the photoelectric cell 110

receives an increasing amount of radiation as interface 106 is lowered relative to the photoelectric cell or as rod 102 increases in diameter so that the pull rate is dependent upon both rod diameter and the position of interface 106.

It will be understood that rod diameter control apparatus in accordance with this invention can be utilized with any zone refining apparatus, whether of the gas or vacuum type. As previously mentioned, however, it is particularly advantageous for use with zone refining apparatus designed to produce small diameter rods having a mean diameter of less than about 4 or 5 millimeters. It will likewise be understood that various modifications may be made in the electrical, mechanical or optical systems of the embodiments illustrated without departing from the spirit of the invention.

Having thus described my invention and several specific embodiments thereof, what I desire to claim and secure by Letters Patent is:

1. In a method of zone melting a rod of semiconductor material in which the rod is vertically supported at both ends and a transverse molten zone is formed in said rod intermediate the two ends thereof, said molten zone being caused to move relative to said rod along the longitudinal axis thereof so that it is bounded at one extremity by a transverse interface of melting and at the other extremity by a transverse interface of resolidification, and in which the diameter of the rod being solidified from said molten zone is controlled by movement relative to each other of the solid portions of said rod on either side of said molten zone, the improvement which comprises continually detecting variations in the distance between at least one point on said interface of resolidification and an arbitrarily selected reference plane passing transversely through the longitudinal axis of said rod and moving relative to said rod along said longitudinal axis at a uniform rate equal to the mean rate of movement of said molten zone relative to said rod, and moving the solid portions of said rod on either side of said molten zone relative to each other in response to changes in said distance to thereby produce by solidification of said molten zone a rod segment varying only within narrow limits from a selected diameter.

2. In a method of zone melting a rod of semiconductor material in which the rod is vertically supported at both ends and a transverse molten zone is formed in said rod intermediate the two ends thereof, said molten zone being caused to move relative to said rod along the longitudinal axis thereof so that it is bounded at one extremity by a transverse interface of melting and at the other extremity by a transverse interface of resolidification, and in which the diameter of the rod being solidified from said molten zone is controlled by movement relative to each other of the solid portions of said rod on either side of said molten zone, the improvement which comprises sensing the radiation emitted from a surface area of said rod selected to include a portion of the surface of said molten zone and an adjacent portion of the surface of said rod resolidified from said molten zone, said selected surface area being a constant mean distance from an arbitrarily selected reference plane passing transversely through the longitudinal axis of said rod and moving relative to said rod along said longitudinal axis at a uniform rate equal to the mean rate of movement of said molten zone relative to said rod, whereby movement of said interface of resolidification relative to said reference plane results in a corresponding change in the amount of energy being radiated from said selected surface area, and moving the solid portions of said rod on either side of said molten zone relative to each other in response to radiation sensed from said selected area to thereby produce by solidification of said molten zone a rod segment varying only within narrow limits from a selected diameter.

3. A method as in claim 2 wherein relative movement is effected between the upper solid portion of said rod

and the lower solid portion of said rod such that during at least a selected portion of the zone refining operation the two solid portions of the rod are continuously receding from each other, whereby the diameter of said rod at said interface of resolidification is less than the diameter of said rod at said interface of melting.

4. A method according to claim 3 wherein the diameter of said rod at said interface of resolidification is less than about 4 millimeters.

5. A method according to claim 4 wherein the rate of movement of the lower solid portion of said rod relative to said molten zone is relatively uniform and wherein the rate of movement of the upper solid portion of said rod relative to said molten zone is varied to maintain the diameter of said rod at said interface of resolidification substantially constant.

6. In an apparatus for zone melting a rod of semiconductor material comprising upper and lower holding means for supporting the ends of a rod of semiconductor material such that the longitudinal axis of said rod extends vertically, heating means for providing a transverse molten zone in said vertically extending rod of semiconductor material, transverse means for effecting relative movement of said heating means longitudinally of said vertically extending rod of semiconductor material so that said molten zone is bounded at one extremity by a transverse interface of melting and at the other extremity by a transverse interface of resolidification, and means for effecting at controlled rates relative movement between the upper and lower solidified portions of said rod of semiconductor material to thereby determine the diameter of said rod at said interface of resolidification, the improvement which comprises means for sensing variations in the distance of said transverse interface of resolidification from a reference plane passing transversely through said rod of semiconductor material in fixed positional relationship to said heating means, and means responsive to said sensing means to control the rate of movement of said upper and lower solidified portions relative to each other to thereby produce by solidification of said molten zone a rod segment varying only within narrow limits from a selected diameter.

7. Apparatus according to claim 6 wherein said sensing means comprises means for measuring the radiation emitted from a selected surface area of said rod, said area being a fixed mean distance from said reference plane and including a portion of the surface of said molten zone and an adjacent portion of the surface of the portion of said rod resolidified from said molten zone.

8. Apparatus according to claim 7 wherein said radiation measuring means comprises a photoelectric cell.

9. Apparatus according to claim 7 including means for moving the solid portion of said rod resolidified from said molten zone relative to said heating means at a rate in excess of that at which the yet to be melted portion of said rod and said heating means approach each other, whereby a zone melting operation conducted with said apparatus results in a reduction in the diameter of a rod of semiconductor material.

10. Apparatus according to claim 9 wherein said radiation measuring means comprises a photoelectric cell.

11. Apparatus according to claim 10 wherein said radiation measuring means additionally comprises a lens system for producing an image upon said photoelectric cell of said selected surface area of said rod of semiconductor material.

12. Apparatus according to claim 11 including support means for said heating means and wherein said lens system and said photoelectric cell are carried by said support means.

13. In an apparatus for zone melting a rod of semiconductor material comprising upper and lower holding means for supporting a rod of semiconductor material such that the longitudinal axis of said rod extends vertically, heating means for providing a transverse molten

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zone in said vertically extending rod of semiconductor material, traverse means for effecting relative movement of said heating means longitudinally of said vertically extending rod of semiconductor material so that said molten zone is bounded at one extremity by a transverse interface of melting and at the other extremity by a transverse interface of resolidification, and such that said rod comprises a solid portion resolidified from said molten zone and a second solid portion which is yet to be melted, and means for moving said first named solid portion and said heating means relatively away from each other at a rate in excess of that at which said second named solid portion and said heating means approach each other so that the diameter of said rod is reduced as a result of its being zone melted, the improvement which comprises means for measuring the radiation emitted from a selected surface area of said rod, said area being a fixed mean distance from a reference plane passing transversely through said rod of semiconductor material and centrally through said heating means, said reference plane being stationary relative to said heating means, and said selected surface area including a portion of the surface of said molten zone and an adjacent portion of the surface of said first named solid portion of said rod, and control means responsive to said radiation measuring means to decrease the rate of movement of said two solid portions of said rod relative to each other when the radiation emitted from said selected area decreases below a predetermined level and to increase the rate of movement of said solid portions of said rod relative to each other when the radiation emitted from said selected area, increases above another predetermined level.

14. Apparatus according to claim 13 wherein said radiation measuring means comprises a photoelectric cell and a lens system for producing an image upon said photoelectric cell of said selected surface area of said rod.

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15. Apparatus according to claim 13 including diameter measuring means for sensing changes in the diameter of said rod at said interface of resolidification and wherein said control means is responsive both to said radiation measuring means and said diameter measuring means.

16. Apparatus according to claim 15 wherein said radiation measuring means and said diameter measuring means in each instance comprises a photoelectric cell and a lens system for producing an image upon said photoelectric cell of a selected portion of the surface of said rod.

17. Apparatus according to claim 15 wherein said radiation measuring means and said diameter measuring means comprise a single photoelectric cell and a lens system for projecting an image upon said photoelectric cell of a portion of the surface of said rod, said portion increasing as the diameter of said rod at said interface of resolidification increases and decreases as the diameter of said rod at said interface of resolidification decreases.

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U.S. Cl. X.R.

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