July 11, 1961 W. KELLER 2,992,311

METHOD AND APPARATUS FOR FLOATING-ZONE MELTING OF SEMICONDUCTOR RODS

Filed Sept. 28, 1960 3 Sheets-Sheet 1

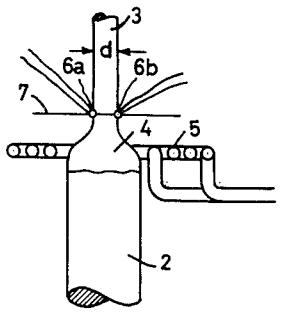


Fig. 1

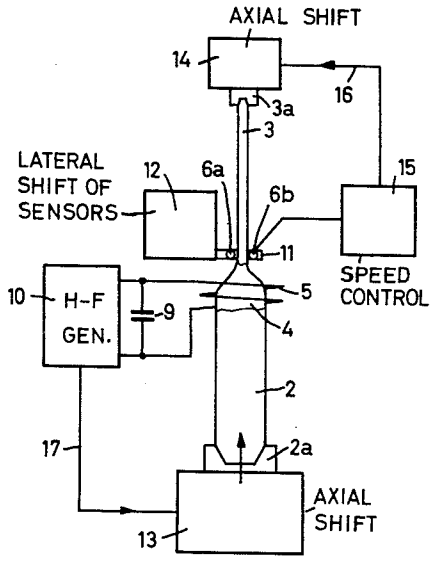


Fig. 3

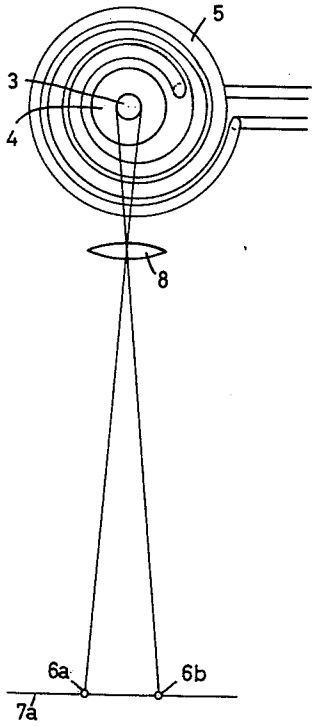


Fig. 2

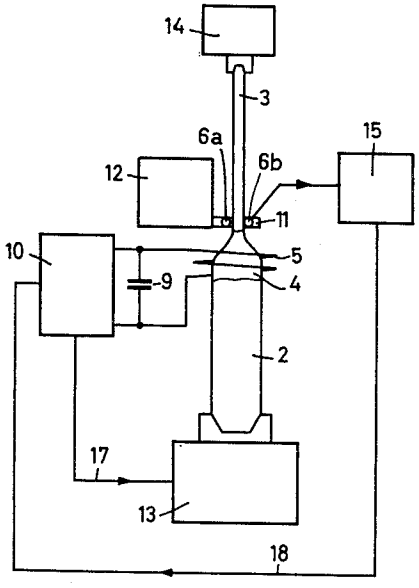


Fig. 5

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METHOD AND APPARATUS FOR FLOATING-ZONE MELTING OF SEMICONDUCTOR RODS

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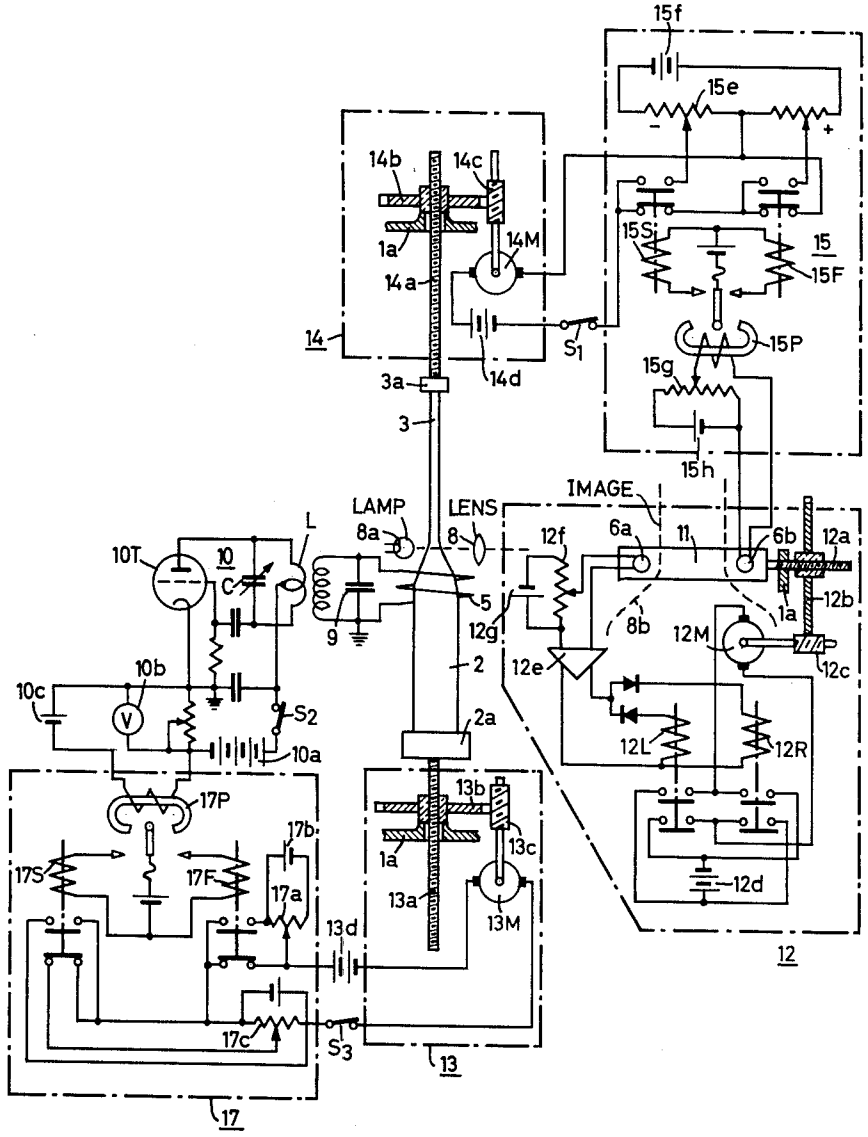


Fig. 4

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METHOD AND APPARATUS FOR FLOATING-ZONE MELTING OF SEMICONDUCTOR RODS

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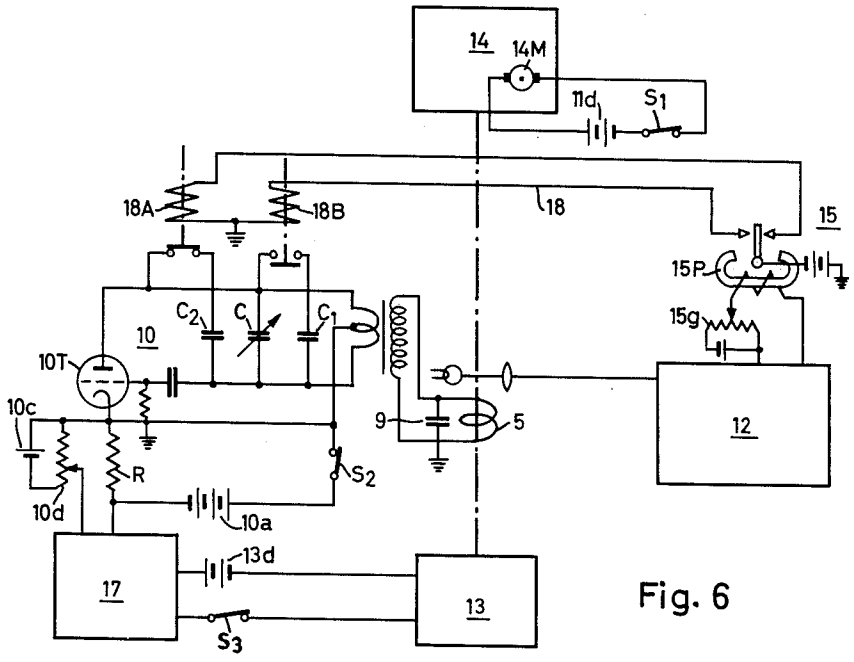


Fig. 6

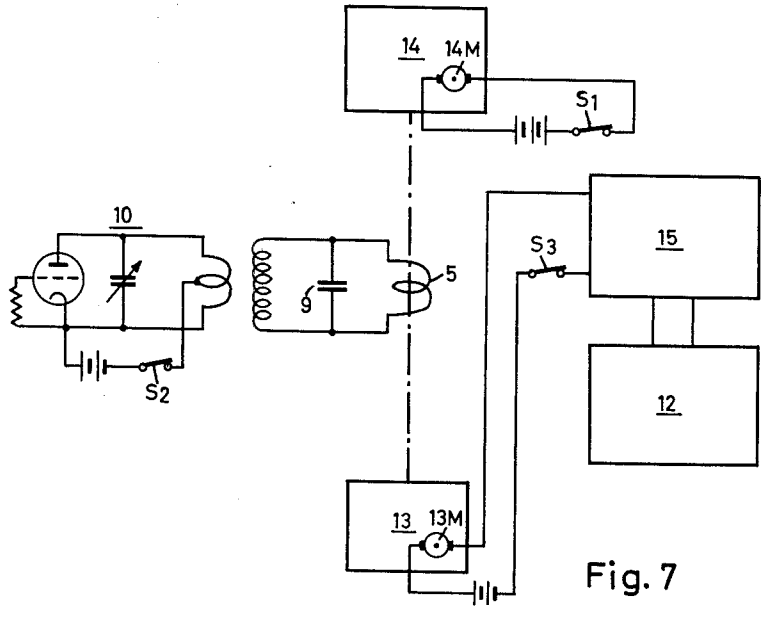


Fig. 7

United States Patent Office 2,992,311 Patented July 11, 1961

2,992,311

METHOD AND APPARATUS FOR FLOATING-ZONE MELTING OF SEMICONDUCTOR RODS

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17 Claims. (Cl. 219—10.77)

My invention relates to a method and apparatus for the crucible-free zone melting of semiconductor material according to which a semiconductor rod is kept vertical between two holders, and a melting zone, produced by an induction coil surrounding the rod is moved longitudinally of the rod.

It has become known to vary during zone melting the axial spacing between the holders to which the rod ends are attached, so as to maintain a constant diameter of the rod being processed. It has also been proposed to control such change in axial spacing in dependence upon the magnitude of the alternating current passing through the inductance heater coil, this current being dependent upon the degree of inductive coupling between coil and melting zone and hence also upon the diameter of the zone. This method affords producing a zone-melted rod of strictly defined cross section which is constant over the processed length of the rod.

Such current-responsive regulation, however, is dependent, for satisfactory performance, upon certain conditions and limitations. For example, when the diameter of the rod is very small, such as only a few millimeters, the changes in heating current due to diameter variations of the melting zone are too slight for accurate regulating performance. Difficulties are also encountered when the zone melting is to be performed in such a manner as to thereby change, particularly reduce, the diameter of the original rod.

It is an object of my invention, therefore, to devise an improved method and apparatus capable of performing or facilitating the crucible-free zone-melting operation with reliable accuracy regardless of the magnitude of the rod diameter or for the purpose of changing the diameter.

To this end, and in accordance with a feature of my invention, I produce a preferably magnified image or shadow picture of a rod portion which comprises the transition of the melting zone to the newly frozen semiconductor material, such image being produced by means of optical or other radiation. I further provide radiation sensing means at the location of the image for providing a variable voltage in response to dimensional changes of the image and hence of the zone diameter, and I control the axial spacing between the ends of the semiconductor rod in dependence upon the sensor voltage thus obtained.

According to another, more specific feature of the invention I provide two radiation sensors horizontally spaced from each other a normally fixed distance corresponding to the desired diameter of the resolidified semiconductor material, the horizontal line of mutual spacing intersecting the image of the resolidifying semiconductor material in the immediate vicinity of the melting zone. I further jointly displace both sensors along this line, preferably by an automatic regulating device, so as to keep one sensor located on the image edge of the recrystallizing semiconductor material; and whereas I use the other sensor for regulating, preferably by another automatic device, the diameter of the recrystallizing semiconductor material so as to maintain the second sensor located on the other image edge of the recrystallizing semiconductor material.

The invention is particularly advantageous for changing the cross section of a semiconductor rod by zone melting to a desired, different value. This advantage is particularly conspicuous when reducing the cross section of the semiconductor rod because it may happen in such cases that the reduced rod portion has too slight a reaction upon the heating current supplied to the inductance coil, so that this effect can no longer be employed for regulating purposes as is the case in the known method mentioned above.

In the following, therefore, the invention will be particularly described with reference to the performance of the novel method or the reduction in cross section of the semiconductor rod, although the method is equally well applicable for other purposes, such as simply processing a semiconductor rod without change in cross section, particularly the processing of very thin rods.

For various purposes the semiconductor rods to be zone melted must have a very small diameter, although, as a rule, the material originally produced has much greater thickness. For example, according to a known process, semiconductor material, such as silicon, is produced by chemical decomposition of a gaseous compound which is precipitated upon a filament or core rod for example of 2 to 5 mm. diameter, of the same material until the original core with the precipitated material has grown to a semiconductor rod of the usual thickness, such as 10 to 20 mm., which can readily be subjected to the known zone-melting methods. The production of the filaments or cores involves various difficulties whose elimination constitutes another object of the present invention. It is particularly difficult to secure a uniform diameter of these thin products, and it is therefore a more specific object of the invention to reliably secure such uniformity. Among other purposes of relatively thin semiconductor rods is the production of seed crystals to be employed for growing monocrystalline products from polycrystalline materials.

The foregoing and other objects, advantages and features of my invention, said features being set forth with particularity in the claims annexed hereto, will be apparent from, and will be described in, the following with reference to the embodiments of apparatus according to the invention illustrated by way of example on the accompanying drawings in which:

FIG. 1 illustrates, on enlarged scale, the portion of a semiconductor rod in which a reduction in cross section is to be produced by zone melting.

FIG. 2 shows a top view of a portion of apparatus according to the invention corresponding substantially to a horizontal section through the upper portion of FIG. 1 along the line 7 and supplemented by a magnifying lens.

FIG. 3 is a block diagram of apparatus for performing the method according to the invention.

FIG. 4 illustrates details and an electric circuit diagram of the apparatus according to FIG. 3.

FIG. 5 is a schematic diagram of a modified apparatus according to the invention.

FIG. 6 illustrates an electric circuit diagram of apparatus according to FIG. 5, and a schematic representation in block fashion of those components that are identical with those shown more in detail in FIG. 4.

FIG. 7 illustrates another modification of apparatus according to the invention with a block-fashion illustration of the components more fully shown in FIG. 4.

Shown in FIG. 1 is a portion 2 of a rod consisting, for example, of silicon, germanium, indium arsenide, indium antimonide or other semiconductor substance. The originally thick rod is to be reduced to a portion 3 of a given smaller diameter *d*. Located between the two rod portions is a melting zone 4 which is produced by

means of an inductance coil 5 consisting preferably of a flat spiral made of copper tubing which is traversed by cooling water when in operation. Further shown in FIG. 1 are two radiation sensors 6*a* and 6*b*, such as photoelectric cells or thermocouples. These are shown mounted along a horizontal line 7 extending at a right angle to the rod axis. The spacing between the two cells 6*a* and 6*b* is shown to be equal to the diameter *d* of the thin rod portion 3. Actually however, the cells 6*a* and 6*b* are not located directly at the semiconductor rod, but are horizontally spaced therefrom so as to respond to an image of the rod. The horizontal line 7 intersects the semiconductor rod or its image at a right angle to the travelling motion of the two rod holders to which the respective rod ends are attached. The line 7 is located in the direct vicinity of the melting zone or its image at the location where the liquid material resolidifies and forms the thinner rod diameter.

It is preferable to produce a magnified image of the rod particularly when the diameter *d* is very small. For this purpose, according to FIG. 2, a magnifying lens 8 or lens system is provided. The sensors 6*a* and 6*b* are located on a line 7*a* which corresponds to line 7 in FIG. 1 but is located in the plane of the magnified image. The vertical spacing of line 7 or 7*a* from the plane of the flat heater coil 5 may either be adjusted to a fixed value or may be made variable. In the first case, a certain safety distance between the upper boundary of the melt and the reference line 7 or 7*a* must be preserved so that minute variations in shape and size of the melting zone as may occur by the regulating operation and other minor effects, will not have the result that the radiation sensors become located in front of the melting zone 4 instead of in front of the tin rod portion 3. When operating with variable vertical spacing between melting zone and reference line, a further radiation sensor may be provided for controlling a device which regulates the vertical spacing between reference line and heater coil by maintaining the line 7 or 7*a* always coincident with the upper boundary of the melting zone 4 or its image. In the following explanations, it is assumed that the reference line 7 or 7*a* has a fixed vertical spacing from the plane of the heater coil 5.

FIG. 3 shows the same semiconductor rod vertically held between holders 2*a* and 3*a*. A capacitor 9 is connected parallel to the induction coil 5 for compensating the reactive (wattless) current. The oscillatory circuit (heating circuit) thus formed is energized from a high-frequency generator 10. The frequency of the generator is preferably so adjusted that it is almost, but not quite, identical with the natural frequency of the heating circuit 5, 9 so that the generator operates on a flank of the resonance peak in the current-versus-frequency characteristic of the heating circuit. This permits adjusting or regulating the current in coil 5 by correspondingly changing the frequency tuning of the generator.

The radiation sensors 6*a* and 6*b*, consisting for example of photoelectric cells or thermocouples, are firmly mounted on a carrier 11 at a normally fixed but ad justable horizontal distance from each other. The carrier 11 is displaceable horizontally along the line 7*a* (FIG. 2) by means of a shifting device 12. Such horizontal shifting of carrier 11 is controlled by the sensor 6*a* in such a manner that this sensor is always located at the left margin of the image formed by the thin rod portion 3. Such automatic displacement regulation of carrier 11 can be carried out, for example, by having the thin rod portion 3 form a bright image on a dark background and having the radiation sensor 6*a* control the shifting device 12 so as to move the carrier 11 to the right when the sensor 6*a* is located on a dark area, and to move the carrier 11 to the left when the sensor 6*a* is located on a bright area and hence within the image of the thin rod portion 3. The circuitry used for this purpose is preferably such that the shifting device 12, with the carrier 11 and the two sensors 6*a* and 6*b*, is at standstill when the sensor 6*a* is located on such a gray value as will obtain at the edge of the image formed by the thin rod portion.

For simplicity of illustration it is disregarded in FIG. 3 (also in FIG. 5) that the transition from the thicker to the thinner rod portion is actually represented by an enlarged image and hence that the axial spacing between the sensors 6*a* and 6*b* is larger than apparent from FIG. 3 (or FIG. 5). This is more accurately illustrated in FIGS. 2 (and 4). Due to the magnified image, the regulating accuracy of the devices described is increased accordingly.

The radiation sensor 6*a*, here shown to consist of a single cell, may actually comprise two photocells closely beside each other of which one is normally located on the image of the semiconductor rod (bright), whereas the other component cell must be located on the background (dark) in order to keep the shifting device 12 with carrier 11 and sensors 6*a*, 6*b* at standstill. The radiation sensor 6*b* can be given a corresponding design. In this case, the image edge of the thin rod portion must always be located accurately between the two photocells.

During zone-melting operation, the lower, thick rod portion 2 is kept in slow upward motion by means of an axial shifting device 13. Simultaneously the thin rod portion 3 is likewise shifted upwardly by an axial shifting device 14 but at greater speed in accordance with the reduced cross section of the rod.

The sensor 6*b* furnishes its measuring quantity to a speed control device 15 by means of which, through a connection 16, the speed of the upper axial shifting device 14 can be varied. When the sensor 6*b* is located on a dark area, the travelling speed of the thin rod portion 3 is reduced so that thickening of the melting zone and hence of this rod portion will result. When the sensor 6*b* is located on the bright image of the thin rod portion 3, the speed of the axial shifting device 14 is increased so that the upward travel of the thin rod portion is correspondingly accelerated in order to reduce the cross section of the melting zone and hence of the thin rod portion 3. As described above with reference to the sensor 6*a* for control of the lateral joint shifting motion of both sensors, the circuitry of sensor 6*b* is preferably such that this sensor will not issue any speed-change commands when it is located in the gray region corresponding to the edge of the image representing the thin rod portion 3.

As will be more fully explained below, the increase and reduction in travelling speed of the holder 3*a* to which the thin rod portion 3 is attached can be effected, for example, by switching an auxiliary voltage, variable in magnitude and direction, upon the drive motor of the upper axial shifting device 14.

During zone-melting the amount of power supplied to the heating circuit 5, 9 and hence to the melting zone 4 is kept constant by having the high-frequency generator 10 operate at a constant frequency and maintaining the output or plate current of the generator at a constant value. This can be effected, for example, by causing the load circuit of the generator to produce a corresponding voltage drop in a resistor serially connected in the load circuit, and comparing this voltage drop with an adjusted datum voltage so as to obtain a difference voltage whose polarity and magnitude depend upon the departure of the generator load current from the desired datum value. This difference voltage can be used for controlling a polarized relaying device to add an additional positive or negative voltage to the one normally supplied to the drive motor of the lower axial shifting device 13. An action line 17 is shown in FIG. 3 to symbolize such control of the lower shifting device 13 by the load current of the generator 10. With such a feedback control, an increase or decrease in the degree of coupling between melting zone 4 and heating coil 5 produced by the faster or slower travel of the thick rod portion 2,

has the effect of increasing or decreasing the generator output current in the sense required to maintain this current constant at the datum value.

Details of the above-described apparatus of FIG. 3 will be explained presently with reference to FIG. 4, the reference characters being identical with those used for corresponding elements in all other illustrations.

As shown in FIG. 4, a lamp **8***a* and a lens **8** produce a magnified image of the melting-zone region as identified above with reference to FIG. 1, the contour line of the image in FIG. 4 being denoted by **8***b*. The two sensor cells **6***a* and **6***b* are mounted on the carrier **11** so that one cell is horizontally adjustable relative to the other, for example by a micrometer screw (not illustrated). The carrier **11** is shown attached to a screw spindle **11***a* which is horizontally displaceable but not revolvable with respect to a fixed supporting or frame structure **1***a* of the apparatus. Horizontal displacement of spindle **12***a* is effected by means of its threaded engagement with the hub of a worm gear **12***b* which meshes with a worm **12***c* driven from a motor **12M**. This motor is reversible and is energized from a direct-current source **12***d* under control by two contactors **12L** and **12R**. The two contactors are polarized by means of diodes so that contactor **12L** will pick up and cause the motor **12M** to shift the carrier **11** to the left when an amplifier **12***e* supplies negative output voltage, whereas the contactor **12R** picks up to make motor **12M** shift the carrier **11** to the right when the amplifier **12***e* supplies positive output voltage. The amplifier output voltage is controlled by the above-mentioned sensor cell **6***a* whose voltage is compared with an adjusted datum voltage taken from a potentiometer **12***f* energized from a constant direct-voltage source **12***g*. Thus, the input voltage and hence also the output voltage of amplifier **12***e* is either positive or negative depending upon whether the sensor **6***a* is subjected to bright or dark areas of radiation or illumination as explained above. As long as the sensor **6***a* is in the marginal gray area, neither contactor is energized so that the motor **12M** is at rest. In this manner the lateral shifting device **12** controls the horizontal position of carrier **11** so as to keep the sensor **6***a* properly located at one edge of the image.

The axial shifting device **13** for the lower rod-end holder **2***a* comprises a reversible motor **13M**. The holder **2***a* is rigidly connected with a vertical screw spindle **13***a* which is longitudinally displaceable but not revolvable in the rigid supporting or frame structure **1***a* and is in threaded engagement with a worm gear **13***b* meshing with a worm **13***c* driven from motor **13M**.

The upper holder **3***a* is similarly connected with a vertical screw spindle **14***a* which is axially displaceable but not revolvable in supporting structure **1***a* and is operated from a reversible motor **14M** by means of a worm gear **14***b* in mesh with a worm **14***c*.

The circuits of motors **14M**, **13M** and of the generator **10** comprise ganged switch contacts **S1**, **S2**, **S3** which are to be closed when the apparatus is to be put into operation.

The motor **14M** of the upper axial shifting device **14** is energized from a direct-current source **14***d* under control by two contactors **15S** and **15F** whose respective contacts connect to the motor circuit an auxiliary voltage of negative or positive polarity relative to the voltage of main source **14***d*. The auxiliary voltage is taken from a potentiometer **15***e* energized from a source **15***f* of constant direct voltage. When contactor **15S** is energized, it causes the motor **14M** to reduce its speed to a value adjusted at potentiometer **15***e*. When contactor **15F** picks up it correspondingly increases the speed of motor **14M** in accordance with a value adjusted at potentiometer **15***e*. Energization of the contactors **15S** and **15F** is controlled by polarized relay means here shown as an electromagnetic relay **15P**. This relay is controlled by the output voltage of the second radiation sensor **6***b* in differential relation to a reference voltage tapped off a potentiometer **15***g* energized from a direct-voltage source **15***h*. It may be mentioned at this point that while, for simplicity of illustration, separate current sources are illustrated, they can all be supplied from a single power supply or a suitable group of supplies, preferably energized from an available alternating-current or direct-current utility line.

When the voltage from sensor **6***b* is above the datum value set at potentiometer **15***g* one of contactors **15S**, **15F** will respond, and when the sensor voltage is below the datum value, the other contactor will operate. As a result, the motor **14** is speed controlled in dependence upon whether the sensor **6***b* is in front of a bright or dark area, as expalined above. As long as the sensor **6***b* is located in the marginal gray zone of the image, the polarized relay **15P** is inactive and the motor **14M** then runs at the normal speed. This speed is properly related to that of the motor **13M**, and any suitable electrical or mechanical transmission means for securing a proper speed ratio between devices **13** and **14** can be used if desired. For example, only one of motors **13M**, **14M** can be used and the other motor be substituted by a step-down transmission gearing between devices **13** and **14**, having an adjustable transmission ratio controlled by device **15** to clamp the speed ratio under control by sensor **6***b* in the sense explained above.

As mentioned, the lower axial shifting device **13** is controlled in dependence upon the load current of the high-frequency generator **10**. This generator is shown to comprise an electronic triode **10T** connected with a tank circuit which comprises a capacitor C and an inductance coil L. The coil forms the primary winding of a transformer which couples the generator **10** with the heating circuit **5**, **9**. The load current of triode **10T**, coming from a current source **10***a*, passes serially through a resistor R which develops a voltage drop proportional to the load current. This load current is dependent upon the thickness of the melting zone as mentioned above.

The voltage drop of resistor R, and hence the amount of load current, is indicated by a measuring instrument **10***b* and is compared with a datum voltage from a source **10***c* of constant reference voltage. The resulting difference voltage is applied to suitable polarized relay means, again shown as a polarized electromagnetical relay **17P**. Dependent upon whether the generator load current is above or below the datum value corresponding to the voltage of source **10***c*, the polarized relay **17P** energizes one or the other of two contactors **17S** and **17F**.

The motor **13M** of the lower axial shifting device **13** is energized from a current source **13***d* which is normally alone effective to determine the motor voltage and hence the travelling speed of the lower rod holder **2***a*. However, when the current in the heating circuit increases due to the diameter of the melting zone becoming too large, this is sensed by the polarized relay **17B** which then energizes the contactor **17F** with the effect of connecting into the motor circuit an auxiliary voltage taken from a potentiometer **17***a* which is energized from a current source **17***b* and so poled as to increase the terminal voltage of the motor thus increasing the travelling speed of the holder **2***a* which then pulls the two rod portions **2**, **3** farther apart and thereby reduces the cross section of the melting zone and returns the current to the proper value.

Conversely, when the load current of the generator decreases because the diameter of the melting zone drops below the correct value, the departure of the load current from the datum value is sensed by the polarized relay **17P** which then energizes the contactor **17S**. Contactor **17S** then connects into the circuit of motor **13M** a voltage taken from a potentiometer **17***c* which is energized from a current source **17***d* and so poled as to reduce the resultant voltage impressed upon the motor **13M**, thus causing a reduction in travelling speed of the rod holder **2***a*.

As a consequence, the heating current supplied to the coil 5 is regulated to remain substantially constant at the datum value determined by the voltage of reference source 10*c*.

The apparatus illustrated in FIG. 5 is fundamentally similar to the one described above with reference to FIGS. 3 and 4, with the exception of the following modifications. The variation in diameter of the thin rod portion 3 is effected, not by changing the speed of the upper axial shifting device 14 but by varying the frequency of the generator 10. The load current of the high-frequency generator 10, as in the embodiment of FIGS. 3 and 4, is kept constant by correspondingly varying the travelling speed of the thick rod portion 2, whereas the frequency of the generator 10 is controlled by the sensor-responsive device 15 in the desired sense through a controlling connection 18. In this case, the thin rod portion 3 is moved upwardly at constant speed. The frequency variation of generator 10 causes a corresponding variation in power supply to the heater coil 5 and hence a corresponding change in generator load current. By change in upward travel speed of the thick rod portion 2, such a change in frequency is immediately eliminated. The ultimate effect, therefore, is that the diameter of the thin rod portion, travelling at constant speed relative to the heater coil which receives a constant power supply, is maintained at the desired value by correspondingly varying the travelling speed of the thick rod portion 2.

An example of details of the just-mentioned modification will be described with reference to FIG. 6, it being understood that the components 12, 13, 14 and 17 in FIG. 6 may be identical with those described above with reference to FIG. 4.

According to FIG. 6, the motor 14M of the upper axial shifting device 14 is energized by constant voltage from source 11*d* in order to move the upper rod holder at constant speed. The high-frequency generator 10 has its tank circuit provided not only with the main capacitance C but also with auxiliary capacitors C1 and C2 of which the capacitor C1 is normally connected parallel to main capacitance C through the contact of a relay 18A, whereas the auxiliary capacitor C2 is normally disconnected from the tank circuit under control by another relay 18B. When the polarized relay 15P is in the normal position, namely when the sensor 6*b* according to FIG. 4 is properly located on the gray margin of the image, the frequency of the generator 10 is determined only by the two thin active capacitors C and C1. When relay 15P moves its contact from the inactive to one of its two active positions, depending upon whether the sensor 6*b* enters into the dark or bright range of the background or image, one of the two relays 18A, 18B is selectively energized and thereby increases or decreases the total capacitance of the tank circuit in the generator, thus shifting the frequency above or below the datum value with the effect of varying the current of heater coil 5 accordingly. This operation requires that the generator operate at a frequency on a flank portion of the current-versus-frequency characteristic of the heating circuit so that a change in generator frequency causes an increase or decrease of the generator load current.

The amount of load current causes a corresponding voltage drop in the resistor R, and this voltage drop is compared with an adjusted and normally constant datum voltage taken from a potentiometer 10*d* energized from a source 10*c* of constant reference voltage. As a result, the control components of device 17 act upon the lower axial shifting device 13 in the same manner and by the same means as explained above with reference to FIG. 4. The system therefore tends to maintain the diameter of the thin rod portion at the desired constant value by regulating the power supply to the heater coil 5 to a constant value while varying the travelling speed of the lower rod portion.

The just-mentioned apparatus may be further modified by eliminating the connecting devices 17 and thus the control of the lower axial shifting device 13 by the load current of the generator 10. In this case, the only change effected for regulating purposes is the change in generator frequency by means of the connecting devices 18, whereas the diameter regulation of the thin rod portion 3 is effected, at constant travelling speed of both rod portions, exclusively by changing the power supplied from the generator to the heater coil 5.

Still another possibility of regulation for the purposes of the invention is to have the device 15 directly control the lower axial shifting device 13 and hence the travelling speed of the thick rod portion 2. Such a modification is illustrated in FIG. 7, it being understood that the components 12, 13, 14 and 15 may be identical with those described above with reference to FIG. 4.

As shown in FIG. 7, the speed control device 15 acts upon the motor 13M so as to increase or decrease its speed in dependence upon the sensing operation of sensor 6*b*. The motor 14M is driven at constant speed, and the frequency of the generator 10 is normally kept at a constant value. When thus operating with a constant travelling speed of the thin rod portion 3 and with a constant frequency of the generator 10, the regulating effect imposed upon the diameter of the thin portion is ultimately again due to the fact that the power supply to the heater coil 5 is controlled by correspondingly increasing or decreasing the size of the melting zone with the aid of a corresponding change in speed of displacement imparted to the lower rod portion.

It will be understood by those skilled in the art that in other respects the method and apparatus according to the invention may be carried out in conventional manner. For example, the semiconductor rod as well as the components of the heating circuit and the carrier 11, as well as other parts of the equipment, can be located within a bell or other recipient which is evacuated during the zone-melting operation, and this recipient as well as the extraneous components of the apparatus may be mounted together on a common carrier to form a single transportable unit. Such and other modifications, particularly with respect to structural details or circuitry, are readily available to those skilled in the art upon a study of this disclosure, without departure from the essential features of my invention and within the scope of the claims annexed hereto.

I claim:

1. In a method of zone melting a semiconductor rod, in which the rod is vertically supported at both ends and a molten zone is formed in the rod by a surrounding inductive heater coil energized by current from an alternating-current generator and the zone is caused to move relative to and lengthwise of the rod, the improvement comprising the steps of forming an enlarged image of a rod portion containing the transition from the molten zone to the resolidifying rod material, sensing the edges of the enlarged image at two locations horizontally spaced from each other a fixed distance along a line intersecting the image of the resolidifying area at a right angle to the rod axis, jointly shifting both sensing locations horizontally so as to maintain one of said sensing locations on the corresponding one edge of the image, and controlling the cross-sectional width of the molten zone in the resolidifying rod area so as to thereby maintain the second sensing location on the second edge of the image.

2. In a method of zone melting a semiconductor rod, in which the rod is vertically supported at both ends and a molten zone is formed in the rod by a surrounding inductive heater coil energized by current from an alternating-current generator and the zone is caused to move relative to and lengthwise of the rod, the improvement comprising the steps of progressively increasing the axial spacing between the two rod ends so as to reduce the cross section of the rod axially along the molten zone, forming an enlarged radiation image of the transition

from the thick to the thin rod portion, said image representing the molten zone and the adjacent resolidifying boundary region of the rod, sensing the edges of the enlarged image at two locations horizontally spaced from each other a fixed distance along a line intersecting the resolidifying region at a right angle to the rod axis, jointly shifting both sensing locations horizontally so as to maintain one of said sensing locations on the corresponding one edge of the image, and controlling the cross-sectional width of the molten zone in the resolidifying rod area so as to thereby maintain the second sensing location on the second edge of the image.

3. In a method of zone melting a semiconductor rod, in which the rod is vertically supported at both ends and a molten zone is formed in the rod by a surrounding inductive heater coil energized by current from an alternating-current generator and the zone is caused to move relative to and lengthwise of the rod, the improvement comprising the steps of progressively increasing the axial spacing between the two rod ends so as to reduce the cross section of the rod axially along the molten zone, forming an enlarged radiation image of the transition from the thick to the thin rod portion, said image representing the molten zone and the adjacent resolidifying boundary region of the rod, sensing the edges of the enlarged image at two locations horizontally spaced from each other a fixed distance along a line intersecting the resolidifying area of the thin rod portion at a right angle to the rod axis, jointly shifting both sensing locations horizontally so as to maintain one of said sensing locations on the corresponding one edge of the image, and varying the axial spacing between the rod ends to thereby control the cross section of the resolidifying thin rod portion as required to maintain the second sensing location on the second image edge of the thin rod portion.

4. In a method of zone melting a semiconductor rod, in which the rod is vertically supported at both ends and a molten zone is formed in the rod by a surrounding inductive heater coil energized by current from an alternating-current generator and the zone is caused to move relative to and lengthwise of the rod, the improvement comprising the steps of simultaneously displacing the two rod ends axially in the same direction relative to the heater coil at respectively different rates for reducing during zone melting the cross section of the rod axially along the molten zone, forming an enlarged radiation image of the transition from the thick to the thin rod portion, said image representing the molten zone and the adjacent resolidifying boundary region of the rod, sensing the edges of the enlarged image at two locations horizontally spaced from each other a fixed distance along a line intersecting the resolidifying area at a right angle to the rod axis, jointly shifting both sensing locations horizontally so as to maintain one of said sensing locations on the corresponding one edge of the image, and varying the displacing speed of one of said rod ends to thereby control the cross section of the resolidifying thin rod portion as required to maintain the second sensing location on the second image edge of the thin rod portion.

5. The zone melting method of claim 4, wherein constant current is supplied from the generator to the heater coil, and the variation in displacing speed is applied to the end of the thin rod portion.

6. In the zone melting method of claim 4, wherein said heater coil forms part of a high-frequency tank circuit and said generator supplies high-frequency current of constant frequency to the coil, the steps of applying the variation in displacement speed to the thick rod portion so as to thereby maintain said current at a constant value.

7. In a method of zone melting a semiconductor rod, in which the rod is vertically supported at both ends and a molten zone is formed in the rod by a surrounding inductive heater coil energized by current from an alternating-current generator and the zone is caused to move relative to and lengthwise of the rod, the improvement comprising the steps of progressively increasing the axial spacing between the two rod ends so as to reduce the cross section of the rod axially along the molten zone, forming an enlarged radiation image of the transition from the thick to the thin rod portion, said image representing the molten zone and the adjacent resolidifying boundary region of the rod, sensing the edges of the enlarged image at two locations horizontally spaced from each other a fixed distance along a line intersecting the resolidifying region of the thin rod portion at a right angle to the rod axis, jointly shifting both sensing locations horizontally so as to maintain one of said sensing locations on the corresponding one edge of the image, maintaining the displacement speed of one of the rod ends constant, and varying the current passing through the heater coil in dependence upon the departure of the second sensing location from the second image edge to thereby control the cross section of the resolidifying thin rod portion as required to maintain the second sensing location on the second image edge of the thin rod portion.

8. In the zone-melting method of claim 2, wherein the heater coil forms part of a tank circuit, the steps of maintaining the end of the thin rod portion at constant axial travelling speed relative to the heater coil, and controlling the diameter of the thin rod portion by varying the frequency of the generator along a flank of the resonance characteristic of the tank circuit.

9. The zone-melting method of claim 8, the step of maintaining the end of the thick rod at a constant axial travelling speed relative to the heater coil.

10. In the zone-melting method of claim 2, wherein the heater coil forms part of a tank circuit and the current source has a frequency on the flank of the resonance characteristic of the tank circuit, the steps of controlling said cross-section of the thin rod portion by varying the axial travel speed of the thick rod end relative to the heater coil so as to maintain the current intensity in the heater coil at a constant value.

11. Apparatus for zone melting of a semiconductor rod, comprising two rod-end holders vertically spaced from each other and defining a vertical processing axis, an axially flat inductance heater coil surrounding said axis, an alternating-current source connected to said coil for energizing said coil, drive means for providing relative travel between said coil and said holders whereby said coil is caused to produce in said rod a melting zone travelling lengthwise of the processing axis, radiation means disposed in fixed relation to said coil for producing an enlarged image of a rod portion containing the transition from the molten zone to the resolidifying rod material, two radiation sensors responsive to opposite edges respectively of the image and having a carrier in common, said two sensors being horizontally spaced from each other a normally fixed distance along a line intersecting the resolidifying area of the image at a right angle to the processing axis, said carrier with said sensors being displaceable along said line, first control means connected with said carrier for horizontally displacing said carrier, one of said sensors being connected to said control means for causing it to horizontally displace said carrier so as to maintain said one sensor in fixed space relation to one of said image edges, means for regulating the cross-sectional width of said zone, said second sensor being connected to said regulating means for controlling it in dependence upon departure of said second sensor from the second image edge so as to maintain said second sensor on said second edge.

12. In zone-melting apparatus according to claim 11, said heater coil and said image-producing means being fixed, and said two rod-end holders being jointly displaceable axially in the same direction for causing travel of the melting zone relative to the processing axis.

13. In zone-melting apparatus according to claim 12,

said drive means having two component drives of respectively different speeds connected with said respective two holders for progressively lengthening said vertical spacing, whereby the rod being processed is reduced in diameter within the melting zone.

14. In zone-melting apparatus according to claim 13, said regulating means comprising one of said component drives for varying the axial speed of the appertaining one holder under control by said second sensor.

15. Zone-melting apparatus according to claim 14, comprising current sensing means responsive to the magnitude of current supplied to said heater coil, and further control means connecting said current sensing means with said other component drive for varying the axial travel speed of the other holder under control by said current sensing means so as to maintain said current magnitude constant.

16. In zone-melting apparatus according to claim 15, said one component drive being connected with the lower one of said holders and said lower holder being adapted for attachment of the thick rod portion, said other component drive being connected with the upper holder for the thin rod portion and having greater normal speed than said one component drive.

17. In zone-melting apparatus according to claim 11, said current source comprising a high-frequency generator, a tank circuit of which said heater coil forms part, said regulating means comprising frequency adjusting means in said generator for varying the generator frequency within a range corresponding to a flank portion of the resonance characteristic of said tank circuit, whereby the cross-sectional width of the zone is controlled by variation of the generator frequency under control by said second sensor.

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