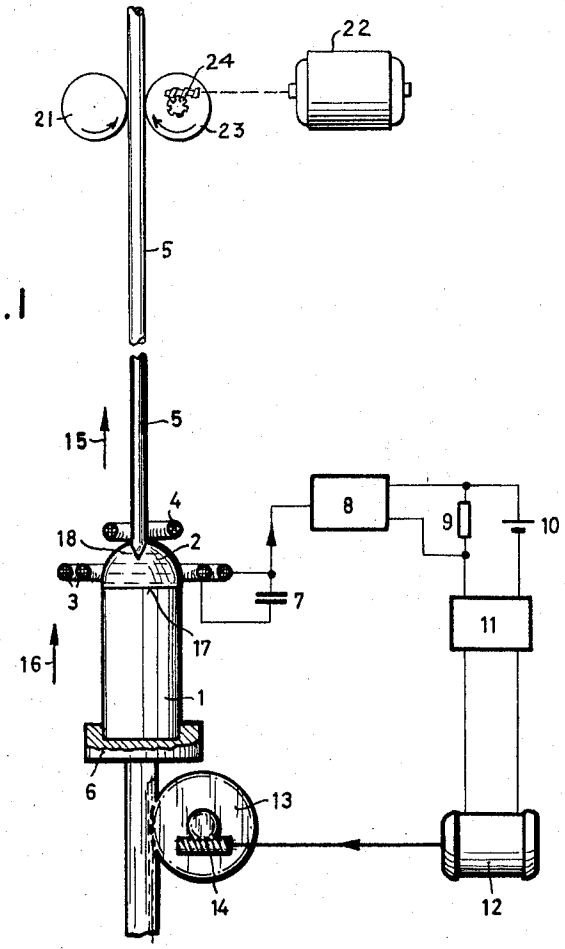
Sept. 27, 1966 W. K. SPIELMANN 3,275,419
METHOD AND APPARATUS FOR PRODUCING ELONGATED STRIP-SHAPED CRYSTALLINE SEMICONDUCTOR BODIES
Filed March 9, 1962 2 Sheets-Sheet 1

FIG. 1



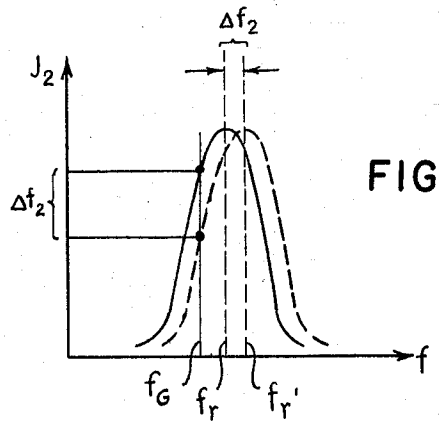


FIG. 2

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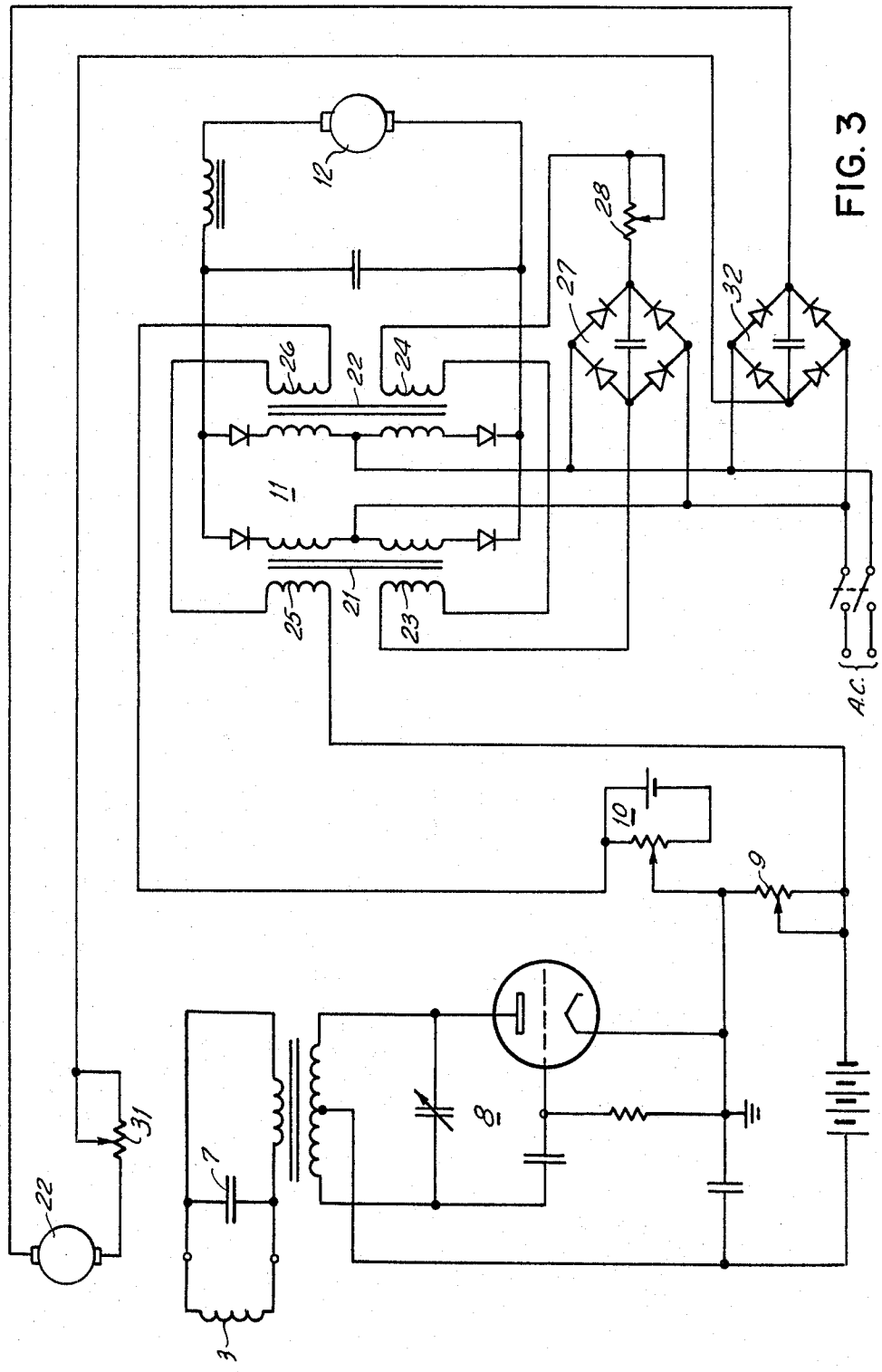


FIG. 3

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3,275,419

METHOD AND APPARATUS FOR PRODUCING ELONGATED STRIP-SHAPED CRYSTALLINE SEMICONDUCTOR BODIES

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4 Claims. (Cl. 23—301)

My invention relates to the production of long crystalline semiconductor strips from a melt of the semiconductor material and more particularly to a method of growing dendritic flat semiconductor strips or tapes by immersing a crystal seed in a partly supercooled melt of the semiconductor material and then pulling the seed with the dentritic growth of material gradually out of the melt.

In a more particular aspect, my invention concerns itself with methods as described in the copending application of W. Spielmann et al., Serial No. 139,400, filed September 20, 1961, and assigned to the assignee of the present invention. According to this method the melt is located on top of a carrier body consisting of the semiconductor material and only the region of the melt immediately adjacent to the still solid carrier is heated by means of an induction coil to a temperature above the melting point of the semiconductor material, whereas the less heated region of the melt is kept slightly below the melting temperature and thus is in supercooled condition, with the result that the crystalline material being grown onto the crystal seed is dendritic, thus forming a relatively thin and flat strip as the seed and the already grown portion of the product are being pulled away from the melt.

This method, as a rule, is performed by pulling the dendritic product out of the melt at a speed corresponding to the dendritic growth of the semiconductor material so that a corresponding quantity of material is continuously being removed from the melt. In order to maintain growing conditions, it is therefore necessary to provide for a corresponding replenishment of semiconductor material to the melt. This is preferably done by displacing the melt-supporting semiconductor body continuously in the crystal pulling direction at a rate at which corresponding quantities of the rod material are continuously melted into the molten zone.

During performance of the dendritic pulling method, therefore, solid semiconductor material is continuously being melted on the side of the molten zone adjacent to the still solid portion of the carrier body, and it is necessary to take care that the region of the melt surrounding the location of the seed crystal and thereafter the location of the growing dendrit remains properly supercooled.

It has been found difficult to conjointly satisfy these requirements to such an extent as to reliably secure the growth of uniform dendrites over extensive amounts of length, and it is an object of my invention to improve the method in this respect and to reliably obtain uniform products, even under such aggravating temperature conditions as occur with silicon, with the aid of relatively simple and economically applicable means.

According to the invention, I have found it to be essential for uniform dendritic growths to take care that the supercooled region of the molten zone remains situated at the same locality during the entire pulling operation and that also the melting of additional semiconductor material at the liquid-to-solid boundary always occurs at the same place. According to one of the features of my invention, therefore, the above-described method is

performed while gradually advancing the carrier body, such as a semiconductor rod which carries a molten zone inductively heated at one rod end, in the crystal-pulling direction but at a rate which varies in accordance with any variation in consumption of semiconductor material within the molten zone caused by the crystal pulling. The supercooled region as well as the liquid-to-solid boundary thereby remains substantially fixed in space in a fixed spacial relation to the electric inductance coil or other auxiliaries employed for maintaining the molten zone under the proper temperature conditions.

According to a more specific feature of my invention, the electric current flowing through the inductive heater coil around the melt is observed or sensed as to any intensity variation due to changes in the surface shape and volume of the molten zone occurring during crystal pulling, and the departure of the current magnitude from a given datum value is employed, preferably through a control or regulating device, for varying the continuous advancing speed of the carrier body traveling in the pulling direction, thus eliminating any departure until the current in the inductance coil again assumes the datum value.

The replenishment of the semiconductor material to be melted is effected in proportion to the mass of the resulting dendrite strip. Accordingly, the rod and the melting semiconductor material are continuously conveyed into the action range of the inductive heating coil with the result that the semiconductor material of the carrier is always melted at the same locality in space and is always supercooled at the same locality in space, the latter requirement being particularly important for securing the desired uniformity of the dentritic product.

The invention will be further described with reference to the accompanying drawings in which:

FIG. 1 shows by way of example a schematic illustration of processing equipment;

FIG. 2 is an explanatory graph relating to the performance of the equipment; and

FIG. 3 is a schematic circuit diagram relating to the same equipment.

Shown in FIG. 1 is a carrier body in form of a rod of circular cross section having a constant diameter over its entire length. The rod **1** is vertically mounted but is attached only at its lower end, thus leaving the top exposed. Supported on the top of rod **1** is a mound-shaped melt **2** from which a dendritic semiconductor strip **5** is pulled upwardly as indicated by an arrow **15**. The rod with the melt as well as the inductive heating component described below are preferably mounted in a reaction vessel filled with a protective gas of relatively high heat conductance or traversed by such a gas, as is shown and more fully described in the above-mentioned copending application Serial No. 139,400.

The carrier rod **1** consists of the same semiconductor material as the strip-shaped crystalline body to be produced, namely for example of germanium, silicon or a semiconductor binary compound of the $A_{III}B_{V}$ type.

The molten zone **2** is heated by means of an induction coil **3**. The coil is rather flat in comparison with the height of the molten zone and its fixed position in space is such that it heats the lower region of the molten zone above the melting point of the semiconductor material. For supercooling the upper region of the melt, the device is provided with a short circuiting ring **4** of electrically good conducting material such as copper or aluminum, whose field effect results in weakening the induction current generated by the coil **3** in the upper region of the melt, thus securing the required supercooling. The temperature in the supercooled region need be only a few degrees, for example 10° C. below the melting point of the semiconductor material. The supercooling of the

upper region in the melt can also be produced by other means, for example the heat dissipation on the surface of the upper region can be increased by heat dissipation from the peripheral surface of the lower region. This can be done, for example, by directing a current of gas against the top region of the melt. In this and other respects the melting and dendrite pulling process can be performed as more fully described in the above-mentioned copending application Serial No. 139,400.

During pulling of the dendritic crystal **5**, the carrier body **1** is advanced upwardly as indicated by an arrow **16**. For securing an undistributed dendritic growth of the strip-shaped semiconductor body, it is essential according to the invention that during the course of the process, new semiconductor material is melted and thereby added to the molten zone always at the same locality so that the liquid-to-solid boundary **17** always maintains the same height and particularly that the supercooled region **18** of the molten zone is always located at the same spot with respect to the fixed inductance coil **3** and the supercooling means **4**.

The location of the boundary **17** and of the supercooled region **18** depends upon the volume and surface shape of the molten zone **2**. The given volume and a given surface shape of the molten zone always correspond to a definite value of the current flowing in the induction coil **3**. This will be further explained with reference to FIG. 2. The current J_2 flowing in the high-frequency coil **3**, which in the illustrated embodiment simultaneously serves as inductive heater coil, induces in the molten zone **2** a voltage which produces a current whose magnetic field acts in opposition to that produced by the coil **3**. Consequently, the system coil-zone can be looked upon as constituting two mutually coupled inductance coils. The current J_2 flowing in coil **3** is therefore dependent upon the shape and volume (conjointly called "zone-filling degree") of the molten zone which both tend to vary as a result of the continuous depletion caused by the withdrawal of the dendrite **5**. Any such change is tantamount to a change in effective inductance of the coil **3** in the tank circuit formed by that coil together with the capacitor **7**. Consequently a change in the filling degree of the molten zone is accompanied by a change in the resonance frequency f_r of the parallel tank circuit formed by coil **3** and capacitor **7**.

In FIG. 2 a typical current-frequency characteristic is shown, indicating the values of coil current J_2 on the ordinate and the frequency value f on the abscissa. A normal operating frequency is denoted in FIG. 2 by f_r on the solid-line curve. The above-mentioned changed resonance frequency is denoted by f_r' on the dashed curves. Since this tank circuit is loosely coupled to the internal oscillatory circuit of the high frequency generator **8** feeding the coil, the change in natural frequency Δf_2 (FIG. 2) of the oscillatory heating circuit (tank circuit **3**, **7**) causes only the negligible change in frequency of the current delivered by the generator **8**, and the resonance curve of the tank circuit becomes displaced relative to the approximately fixed generator frequency f_G which in turn causes a change of the current J_2 in the induction coil **3** by the amount ΔJ_2. In this respect it is essential that the operating point is located on a flank of the normal operation resonance curve shown by a solid line in FIG. 2, preferably on the flank that ascends with increasing frequency. The change in coil current J_2 causes a change of the direct-current load or plate circuit of the HF generator **8**. This plate current is applied to a comparator or mixer network where it is compared with a datum value, and the departure of the generator current and hence of the current in the inductive heater coil **3** from the given datum value is then applied for controlling the advancing speed of the rod **1** so as to regulate the inductive heating current to a constant value. As a result, the molten zone is also regulated to retain its filling degree with the effect that the liquid-to-solid boundary **17** and the supercooled region **18** remain substantially fixed in space.

In the embodiment shown in FIG. 1, the current from generator **8** passes through a resistor **9** and the voltage drop along the resistor, being proportional to the current intensity, is compared with a datum voltage from the source **10**, the difference voltage being applied to an amplifier **11** which controls the speed of a direct-current motor **12**. The unidirectional speed of the motor **12** is thus varied as required for the above-described purpose. The motor shaft is connected by a transmission with the support **6** of the carrier rod **1**. The transmission is shown to comprise a worm gearing joined with a spur gear in meshing engagement with a rack **13'** for raising the rod **1**.

During the operation just described, the dendrite **5** is pulled upwardly at constant speed by means of pinch rollers **21** and **23** which are driven from another direct current motor **22** through a worm gearing **24**.

It is particularly advantageous for the purposes of the invention to employ a regulating amplifier **11** of the magnetic type, particularly a network of two magnetic amplifiers in push-pull connection as exemplified by the circuit diagram shown in FIG. 3. A departure of the induction-coil current from the datum value then results in a corresponding variation in output voltage of the magnetic amplifier network which correspondingly varies the rotating speed of the drive motor **12**. Such a regulation by means of magnetic amplifiers has the advantage that a rapid departure of the inductive heater current from the datum value causes a correspondingly rapid follow-up regulation, whereas an only slight departure of the current from the datum value results in a slower follow-up regulation. Consequently, the current supplied to the input stage of the magnetic amplifier network from the comparator or compensating network of the system is continuously amplified and thereby a continuous advance of the semiconductor material into the active range of the heater coil is secured.

In the circuit diagram of FIG. 3, the two magnetic amplifiers of the push-pull network are denoted by (network **11**) **21** and **22** respectively, and the alternating-current windings of the amplifiers are energized from an alternating-current supply A.C. The magnetizable and saturable cores of the respective amplifiers are further provided with direct-current bias windings **23**, **24** and with direct-current control windings **25**, **26** respectively. The bias windings **23** and **24** are energized by adjustable direct voltage, namely through a rectifier **27** energized from the alternating-current supply, a control rheostat **28** being provided for adjusting the normal premagnetization of the magnetic amplifiers and thereby the normal rectified output voltage supplied to the drive motor **12** for advancing the semiconductor rod, thus determining the base speed of this motor. The control windings **25** and **26** are connected into the above-mentioned comparator or compensating network which includes the voltage-drop resistor **9** and the auxiliary source of datum voltage **10** in series-opposed relation to each other as long as the current of the HF generator **8**, passing through resistor **9**, has the proper value and therefore the current in the heater coil **3** has also the correct value, the voltage drop of resistor **9** is compensated by the voltage impressed upon the control circuit from source **10** so that the control windings **25** and **26** are inactive. However, when the generator current departs upwardly or downwardly from the datum value, the difference voltage in the control circuit of windings **25** and **26** assumes a finite value of one or the other polarity so that the control windings **25**, **26** increase or decrease the resultant premagnetization of the magnetic amplifiers depending upon whether the inductive heater current departed upwardly or downwardly from the correct value. As a result, the output voltage of the magnetic push-pull amplifier impressed upon the motor **12** is varied as explained above. The motor **22** for performing the dendrite pulling operation is energized through a control rheostat **31** from a rectifier **32** connected to the alternating current supply A.C.

The rheostat **31** serves to adjust the proper constant speed of the pulling operation in relation to the base speed of the rod-advancing motor **12** set by means of the rheostat **28**.

While independent voltage sources are schematically shown in the HF generator portion of the diagram, it will be understood that in practice the required direct voltage may be derived through rectifiers from the alternating current supply A.C. For simplicity the field windings of motors **12** and **22** are not shown, it being understood that both motors may be supplied with normally constant armature current and that the speed setting or regulation need be imposed only upon the respective field windings of these motors. Also for simplicity, conventional disconnect or starting switches as well as protective devices and calibrating bias windings on the magnetic amplifier are omitted.

To those skilled in the art, it will be obvious upon a study of this disclosure, that with respect to materials, equipment and circuitry, my invention permits of various modifications and may be given embodiments other than particularly illustrated and described herein, without departing from the essential features of the invention and within the scope of the claims annexed hereto.

I claim:

1. The method of pulling an elongated dendritic crystal strip of semiconductor material out of a melt electrically heated by an inductance coil surrounding the melt, which comprises supporting a rod of the semiconductor material in vertical position and leaving an end portion thereof exposed at the location of the heating coil, energizing the coil by electric current and maintaining thereby a molten zone above the melting temperature in a region adjacent to the still solid portion of the rod simultaneously supercooling to promote dendritic growth, a region of the molten zone farthest removed from the solid portion of the rod, immersing the end of a seed crystal of the same material into the supercooled region of the melt and thereafter pulling the seed with the growing crystalline product away from the molten zone at substantially the rate of crystalline growth, sensing the variations of the coil current due to changes in shape and volume of the molten zone occurring during crystal pulling, and advancing the rod in the pulling direction in dependence upon the departure of the sensed current variation from a given datum value to regulate the coil current for constancy, whereby the liquid-to-solid boundary of the rod and the supercooled region are maintained in a fixed relation to said coil location.

2. The method of pulling an elongated dendritic crystal strip of semiconductor material out of a melt electrically heated by an inductance coil surrounding the melt, which comprises supporting a rod of the semiconductor material in vertical position and leaving an end portion thereof exposed at the location of the heating coil, energizing the coil by electric current and maintaining thereby a molten zone above the melting temperature in a region adjacent to the still solid portion of the rod simultaneously supercooling to promote dendritic growth, a region of the molten zone farthest removed from the solid portion of the rod, immersing the end of a seed crystal of the same material into the supercooled region of the melt and thereafter pulling the seed with the growing crystalline product away from the molten zone at a constant speed, said pulling speed being substantially the rate of crystalline growth, sensing the variations of the coil current due to changes in shape and volume of the molten zone occurring during crystal pulling, and continuously advancing the rod at a variable rate dependent upon the departure of the coil current from a given datum value to regulate the coil current for constancy, whereby the liquid-to-solid boundary of the rod and the supercooled region are maintained in a fixed relation to said coil location.

3. The method of pulling an elongated dendritic crystal strip of semiconductor material out of a melt electrically heated by an inductance coil surrounding the melt, which comprises supporting a rod of the semiconductor material in vertical position and leaving an end portion thereof exposed at the location of the heating coil, energizing the coil by electric current and maintaining thereby a molten zone above the melting temperature in a region adjacent to the still solid portion of the rod simultaneously supercooling to promote dendritic growth, a region of the molten zone farthest removed from the solid portion of the rod, immersing the end of a seed crystal of the same material into the supercooled region of the melt and thereafter pulling the seed with the growing crystalline product away from the molten zone at substantially the rate of crystalline growth, sensing the variations of the coil current due to changes in shape and volume of the molten zone occurring during crystal pulling, forming a difference magnitude from the comparison of current departure with the datum value, amplifying the difference magnitude, and varying the rate of rod advance in dependence upon polarity and magnitude of the amplified magnitude, whereby the liquid-to-solid boundary of the rod and the supercooled region are maintained in a fixed relation to said coil location.

4. Apparatus for producing a dendritic semiconductor body, which comprises a semiconductor carrier, heating means for heating an end of said carrier to form a melt thereof, inserting and withdrawing means for inserting and withdrawing a seed crystal and growth thereon, cooling means for supercooling the melt in the immediate vicinity of said seed crystal, tank circuit means inductively coupled with the melt and having a variable frequency responsive to the zone filling degree of said melt, comprising means connected to said tank circuit means for comparing said frequency with a datum value thereby forming a departure magnitude, amplifier means for amplifying said departure magnitude, and means for gradually varying the rate of carrier advance in dependence upon the polarity and magnitude of the amplified departure magnitude.

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