

May 3, 1960

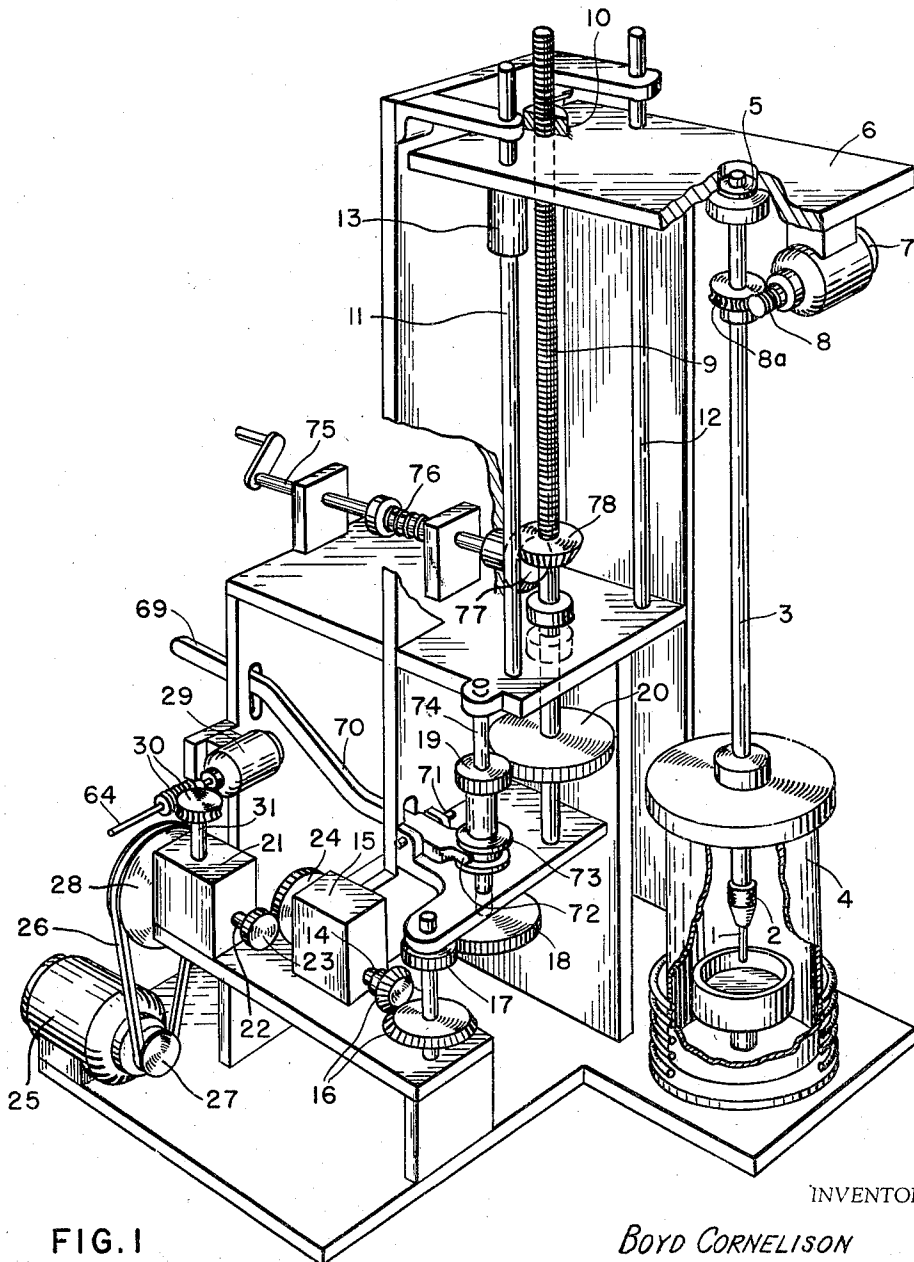
B. CORNELISON

2,935,385

APPARATUS FOR MANUFACTURING SEMICONDUCTOR MATERIALS

Filed March 25, 1955

2 Sheets-Sheet 1



INVENTOR

BOYD CORNELISON

BY *Stevens, Davis, Miller & Mosher*

ATTORNEYS

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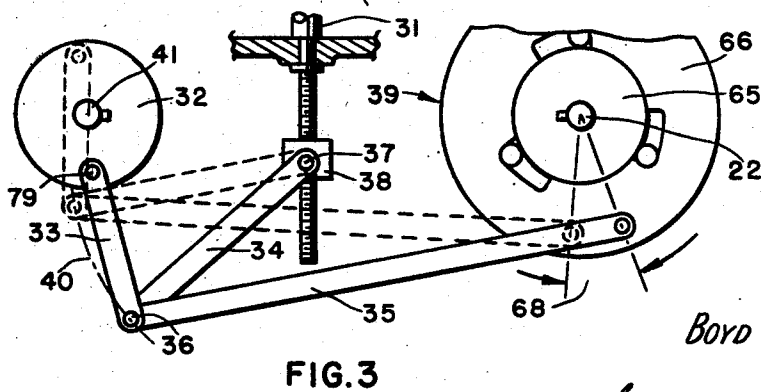
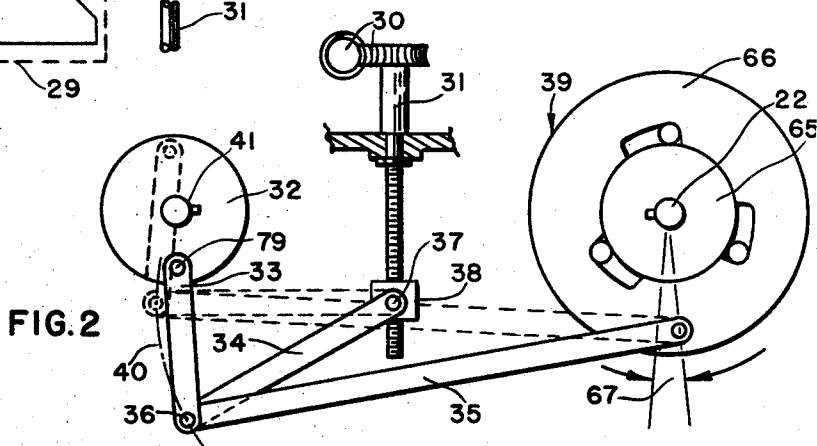
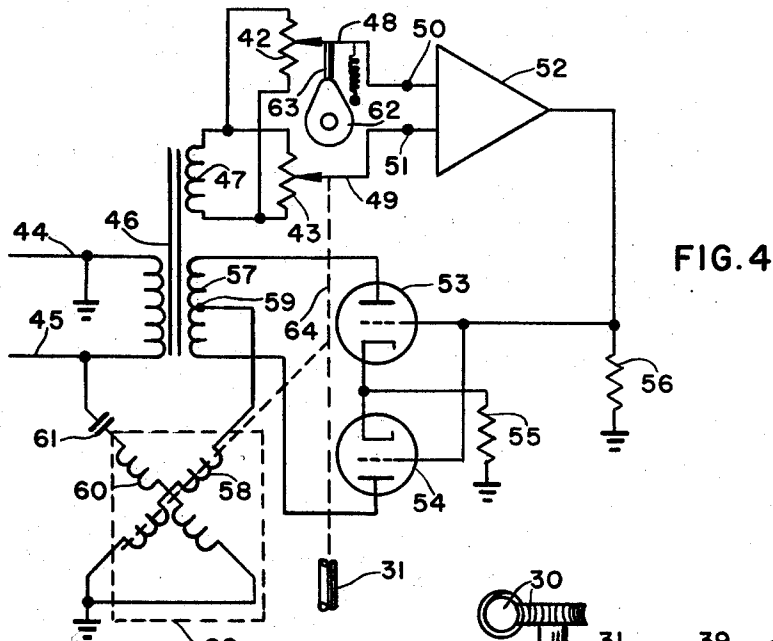
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BY *Stevenson, Davis, Miller & Mosher*
ATTORNEYS

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APPARATUS FOR MANUFACTURING SEMICONDUCTOR MATERIALS

Boyd Cornelison, Dallas, Tex., assignor to Texas Instruments Incorporated, Dallas, Tex., a corporation of Delaware

Application March 25, 1955, Serial No. 496,896

2 Claims. (Cl. 23—273)

This invention relates to improvements in apparatus for the production of the semiconductor materials used in manufacturing semiconductor devices such as rectifiers and transistors. More particularly, this invention relates to improvements in the machines used to produce large single crystals of semiconductor material.

In the manufacture of semiconductor devices such as rectifiers and transistors, one of the early steps is the production of large single crystals of semiconductor material from which are cut the crystal segments for the finished semiconductor devices. The electrical characteristics and general quality of each individual device depends almost entirely on the crystal structure of the semiconductor segment which in turn depends on the crystal lattice structure of the monocrystalline mass from which it has been cut. In order to produce large single crystals of the desired specific structure wherein the lattice defects and impurity concentrations are controlled as to location and area, intricate machines have been developed. Most of these machines produce semiconductor crystals by the method known as the "pulling" method.

In the pulling method of growing semiconductor crystals, a quantity of extremely pure semiconductor material, such as germanium or silicon, is melted in an atmosphere of inert gas or in a vacuum. Next, a small piece of a like type of semiconductor material with a single crystal lattice structure, called a seed, is brought into rotating contact with the molten material. The rotating seed is then withdrawn from the melt at a rate substantially equal to the rate of solidification of the molten material adhering to the seed. While the seed is being withdrawn, a single crystal of semiconductor material of the same lattice structure as the seed forms as the material of the melt solidifies or "grows" at the bottom of the seed. Through careful and precise control of temperature, withdrawal rate, and the introduction into the melt of exact quantities of impurities at specific times, the size, shape and electrical characteristics of the growing crystal can be controlled. To illustrate the precise control required, the machines used in this "pulling" method of manufacturing semiconductor crystals must be capable of controlling the temperature of the semiconductor material to within $\pm 0.2^\circ$ C. of any desired temperature over a range of from less than 900° C. to more than 1800° C. Also, these machines must be capable of controlling the withdrawal rate of the seed to within ± 0.005 mil/second at a high rate of pull such as 5.0 mils/second and to within ± 0.001 mil/second at a low rate of pull such as 0.005 mil/second.

Crystal pulling machines in use at the present time usually employ a radio-frequency induction furnace with a thermocouple controlled servo-system to regulate the radio-frequency generator power output and thus the temperature of the furnace.

In order to control the withdrawal rate, the pulling mechanisms of present crystal pulling machines usually consist of a D.-C. motor driving a lead screw through a reduction gear train arrangement. As the lead screw

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is turned, a guided platform threaded to the lead screw is caused to move up or down. Rotatably attached to this platform is a rod with the seed crystal affixed to its lower end portion. The withdrawal rate of the seed crystal from the melt is controlled through a servo-mechanism which operates to govern the speed of the D.-C. motor by means of a thyatron-rectifier motor speed control of the type described by H. H. Leigh in "Simplified Thyatron Motor Control," General Electric Review, September 1946.

Although the accuracy of this type of pull-rate control has generally been found to be satisfactory for use in the manufacture of production quantities of single crystals of semiconductor materials, it has certain disadvantages. For example, the thyatron motor speed control device with the accuracy of control which is required for this particular application uses from five to eight electron tubes with their associated components, each a potential point of failure and, in addition, making such a control is somewhat expensive. Another undesirable feature is that voltage regulator equipment must be used in series with the power lines if the speed of the D.-C. motor is to be unaffected by voltage fluctuations in the primary electrical power. Still another undesirable feature is size since a thyatron control unit suitable for use in semiconductor crystal pulling machines occupies a volume of approximately nine and one-half cubic feet. A still further disadvantage is that D.-C. motors will not run below a certain minimum speed and no control can be provided between this speed and zero output nor can the lower speeds at which the motor will run be accurately controlled. Also, there is a limited range of speed variation in such controls, the maximum ratio being approximately 50:1.

Accordingly, it is an object of the present invention to provide a pull-rate control system for semiconductor crystal pulling machines which is less susceptible to operational failures than the type of controls presently used.

It is another object of the present invention to provide a pull-rate control for semiconductor crystal pulling machines which is much less expensive than controls presently used.

It is another object of the present invention to provide a pull-rate control mechanism for semiconductor crystal pulling machines which will be unaffected by voltage fluctuations in the primary electrical power lines.

It is a further object of the present invention to provide a pull-rate control mechanism for semiconductor crystal pulling machines which may be varied continuously and accurately from a zero speed to its maximum speed to provide pulling rates from zero to approximately 15 mils/second.

It is still another object of the present invention to provide a pull-rate control system for semiconductor crystal pulling machines which is much smaller than control systems now in use.

The above objects together with further objects and details of the pull-rate control system of the present invention will become apparent from the following description when taken in conjunction with the accompanying drawings in which:

Figure 1 is a diagrammatic representation of the pull-rate mechanism and control system of the present invention;

Figure 2 is a diagrammatic illustration of the linkage of a variable speed reduction unit suitable for use in the pull-rate control system of the present invention;

Figure 3 is a further diagrammatic representation of the linkage of Figure 2 illustrating the manner in which linkage is adjusted to vary the system pull-rate; and

Figure 4 is a schematic diagram of a control servo-system suitable for use with the present invention.

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Referring now to Figure 1, the seed crystal 1 to be used in the production of a single, large semiconductor crystal is held in the chuck 2 of the pull rod 3 which extends into the sealed container 4 of the induction furnace where the crystal is to be grown. The pull rod 3 is rotatably suspended by the thrust bearing 5 from the movable platform 6. Also mounted on the platform 6 is a small variable speed motor 7 which, through the worm gear 8, drives the gear 8a keyed to the pull rod 3 to impart a spinning motion to the seed crystal 1 and thus provide the necessary stirring action in the molten semiconductor material in the furnace. Vertical motion of the platform 6 is supplied by rotation of the lead screw 9 which is in threaded engagement with the platform 6 at 10. The platform 6 is guided in a true vertical plane of motion by the two vertical guide rods 11 and 12 slidably journaled in the platform sleeve 13 and another such sleeve not shown. A close fit of the guide rods 11 and 12 in the long sleeves of the platform prevents wobble of the platform and the consequent binding of the lead screw 9 which could conceivably produce malformations in the growing crystal due to uneven or jerky pulling motion. The lead screw 9 is turned by the output shaft 14 of the constant-ratio reduction gear box 15 through the bevel gears 16 and the reduction gear train comprised of the gears 17, 18, 19, and driving gear 20 keyed to the lead screw 9. The input shaft (not shown) of the constant-ratio reduction gear box 15 is driven from the variable-ratio speed reduction unit 21 by means of the output shaft 22 and the gears 23 and 24 affixed to the shafts of the two units 21 and 15 respectively. The primary drive of the entire pull system is supplied by the synchronous motor 25 through a chain or timing belt 26 connecting the pulley 27 of the motor 25 to the pulley 28 fixed to the input shaft (not shown) of the variable-ratio speed reduction unit 21. Although various types of motors other than synchronous motors may be used, this type motor is most desirable because its speed is affected only by line frequency changes and not by line voltage changes.

It is by means of the variable-ratio speed reduction unit 21 that the pull rate is governed. A servo-mechanism is used to control the rotation of the rotor shaft 64 of the balance motor 29 which, through the worm gear coupling 30 to the control shaft 31 of the variable speed reduction unit 21, controls the speed of the output shaft 22 of the variable speed reduction unit 21. A variable speed reduction unit of the type suitable for use in the present invention is manufactured by Revco Incorporated of Minneapolis, Minnesota, under the trade-name "Zero-Max." Figures 2 and 3 illustrate the mechanism of such a device.

In Figure 2, the input shaft of the variable speed reduction unit 21 is designated by the numeral 41. Attached to the input shaft 41 is a crank disk 32 with a bar or link 33 pivoted on the crank pin 79 near its outer edge. The other end of the link 33 is connected to two other links 34 and 35 by the pin 36 in such a way that all three links are free to pivot about the pin 36. The control link 34 is pivoted at its other end on the pin 37 of the adjustable pivot block 38. Movement of the pivot pin 37 and block 38 is restrained by the threaded engagement of the block 38 to the control shaft 31. The drive link 35 is connected to the outer plate 66 of some overrunning clutch mechanism such as an internal cone friction clutch 39, which is well known in the art, while the inner plate 65 of clutch 39 is attached to the output shaft 22 of the speed reduction unit 21.

This linkage constitutes, in essence, two four-bar linkages with a common link 34 adjustably connected to the control shaft 31 of the variable speed mechanism. As illustrated by the dashed lines of Figure 2, when the input shaft 41 and crank disk 32 rotate, motion is transmitted through the link 33 to the junction point 36 of the three links. Because the pivot point 37 is restrained, the common point of connection 36 of the three links is

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restricted to an oscillating motion along the arc 40 centered at the pivot point 37. This motion causes the drive link 35 to oscillate which, in turn, oscillates the outer plate 66 of the overrunning clutch 39 through part of a revolution as indicated at 67. The clutch 39 engages and turns the inner clutch plate 65 together with the output shaft 22 keyed thereto in one direction of rotation but disengages on the return motion and, consequently, does not turn inner clutch plate 65 and output shaft 22 in the other direction of rotation. Thus, each revolution of the input shaft 41 turns the output shaft 22 through part of a revolution. By placing a number of such mechanisms on the input and output shafts and arranging them so that the links are at equally spaced points about the input shaft, a relatively smooth, continuous rotation is transmitted to the output shaft.

Figure 3 illustrates the method of changing the speed reduction ratio of the unit 21 by changing the position of the pivot point 37 through rotation of the control shaft 31. As the control shaft 31 is rotated, the pivot block 38 is caused to move up or down by its threaded engagement with the control shaft 31. In Figure 3, the pivot point 37 has been moved up from the position illustrated in Figure 2 so that the movement imparted to the overriding clutch by the oscillating motion of link 35 is of a greater amplitude as indicated at 68. Thus, the rotational speed of the output shaft 22 has been increased although the rotational speed of the input shaft 41 remains the same. The described linkage provides a very satisfactory means for varying the speed of output shaft 22 but this invention is not to be construed as limited to the use of the four-bar linkage arrangement since other mechanisms such as a hydraulic coupling can be used for this purpose.

As stated above, the pull rate of the system of the present invention is selected and varied by a servo-mechanism operating the motor 29 to turn the control shaft 31 of the variable-ratio speed reduction unit 21. A servo-system well suited for use with the present invention is illustrated in Figure 4.

In the servo-system illustrated in Figure 4, an A.C. voltage from power lines 44 and 45 through the transformer 46 is impressed across the end terminals of two precision potentiometers 42 and 43. Because these two potentiometers are connected in parallel across the secondary coil 47 of the transformer 46, their voltages are of exactly the same phase. Therefore, if the sliders 48 and 49 of the potentiometers 42 and 43 contact their respective potentiometers at the same relative point, no voltage will be supplied to the input terminals 50 and 51 of the amplifier 52 since the sliders to which these terminals are connected will be at the same potential. However, if one of these sliders 48 is displaced, a voltage is developed between the terminals 50 and 51. The phase of this voltage will be determined by the direction of displacement of the slider 48 and its amplitude will be determined by the amount of displacement. For example, if the slider 48 is displaced toward the top of the drawing, the signal across the terminals 50 and 51 will be in phase with the signal across the secondary coil 47 of the transformer 46. However, if slider 48 is displaced toward the bottom of the drawing, the phase of the voltage to the terminals 50 and 51 will be reversed and it will be 180° out of phase with the voltage of coil 47.

Any signal voltage at terminals 50 and 51 is amplified by the amplifier 52 and fed to the grids of two triode tubes 53 and 54. The tubes 53 and 54 have their cathodes connected together and to ground through the common cathode resistor 55. The grids likewise are connected together and to ground through a common grid resistor 56. The plates of the two tubes are connected to opposite ends of another secondary coil 57 of the same transformer 46 which supplies voltage to the two precision potentiometers 42 and 43. The center tap 59 of the secondary coil 57 is connected to ground through the rotor coil 58 of

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the balance motor 29 so that the plate voltages of the two tubes 53 and 54 are 180° out of phase. Since the grid signal voltage is derived from the same transformer 46 as the plate voltage, the grid voltage on the tubes 53 and 54 will always be in phase with the plate voltage of one of the tubes and 180° out of phase with the other and only the tube in which the grid voltage and plate voltage are in phase will conduct currents. The direction of displacement of the slider 48 determines the phase of the grid voltage to the tubes 53 and 54 and, therefore, the direction of displacement of the slider 48 determines which of the tubes, 53 or 54, conducts.

By referring to the diagram of Figure 4, it can easily be seen that any current which flows in the rotor coil 58 of the balance motor 29 must also flow through either the upper or lower half of the transformer secondary coil 57. Thus, the current of the rotor coil 58 must be of one of two phases, each 180° different from the other, and the phase of this current depends on the part of coil 57 in which current is flowing or which tube, 53 or 54, is conducting. In other words, the phase of the current in the rotor coil 58 of the balance motor 29 is determined by the direction of displacement of the slider 48. As shown in Figure 4, slider 48 is displaced by means of the cam 62 and follower mechanism 63 but any of several means may be used for this purpose.

The voltage of the stator coil 60 of the balance motor 29 is produced from the power supply lines 44 and 45 and, were it not for the condenser 61 inserted in the line to the stator coil 60, the voltage would be either in phase or 180° out of phase with the rotor coil 58 voltage. However, the condenser 61 shifts the stator coil 60 voltage in phase by 90°. Since any currents which flow in the rotor and stator coils 58 and 60 of the balance motor 29 will always be 90° out of phase with each other, the rotor of the balance motor 29 will turn when current flows in the rotor coil 58 and its direction of rotation will be determined by whether the current in the rotor coil 58 is lagging or leading the current of the stator coil 60.

Coupled to the rotor shaft 64 of the balance motor 29 are the control shaft 31 of the variable speed reduction unit 21 and the slider 49 of the "follow-up" potentiometer 43. The coupling of slider 49 to shaft 64 may be either direct or by means such as gearing depending upon the number of turns on shaft 31 and the construction of potentiometer 43. When current flows in the rotor coil 58 as a result of displacement of the slider 48, the rotor shaft 64 turns and there is produced a change in the pull-rate of the system through rotation of the control shaft 31 of the variable speed reduction unit 21. The rotor shaft 64 will continue to turn and the pull-rate of the system will continue to change until the slider 49 coupled to the rotor shaft 64 is displaced from its original contact point on the potentiometer 43 to a contact point at which its potential is exactly the same as the potential of the slider 48. At this point, no further signal is developed between terminals 50 and 51 and thus no grid voltage signal is fed to the tubes 53 and 54. Without a grid voltage, no current will pass through either of the tubes and, consequently, no current will flow in the rotor coil 58. Of course, when current no longer flows in the rotor coil 58, the control shaft 31 no longer turns and the pull-rate of the system ceases to change.

By means such as the cam 62 and follower 63 mechanism, wherein the variations in radius along the circumference of cam 62 are proportional to the pull-rate changes to be produced, the signals for a predetermined program of pull-rate changes can be introduced into the system. Using a similar cam and follower to produce signals for temperature changes in a temperature control servosystem of the crystal pulling machine and a small motor to drive both cams at the same speed, the crystal pulling procedure can be made into an almost completely automatic process.

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Returning now to Figure 1, provision has been made so that the seed may be raised or lowered manually at a greater speed. The gears 18 and 19 are first disengaged from the gears 17 and 20 respectively by a downward motion of the handle 69 of the lever 70 pivoted on the pin 71 to raise the yolk 72 and collar 73 attached to the shaft 74. As the shaft 74 is lifted, the gears 18 and 19 also connected thereto are lifted out of mesh with the gears 17 and 20. The crank 75 is then moved in an axial direction against spring 76 to engage the bevel gear 77 with the bevel gear 78 attached to the lead screw 9. By rotating the crank 75, the lead screw 9 is turned and the platform 6 and pull rod 3 may be raised or lowered to the desired position. When the crank 75 is released, spring 76, which was compressed by the axial movement of the crank 75, returns the crank 75 to its original axial position thus disengaging the bevel gears 77 and 78. The handle 69 may then be raised engaging the gears 19 and 20 and 17 and 18 to begin, as described above, the controlled movement of the pull rod and its attached crystal.

Thus, there has been described a pull-rate mechanism for semiconductor crystal pulling machines which, compared with other such mechanisms presently in use, has the advantages of being smaller and more compact, less expensive, less susceptible to failures, unaffected by voltage fluctuations of the primary power and capable of producing continuous control from a zero pull rate to its maximum pull rate with an accuracy of ± 0.001 mil/second at pull rates above zero.

It is recognized that many changes, substitutions, and alterations in the illustrated embodiment, still within the scope and spirit of the present invention, will suggest themselves to those skilled in the art. Therefore, it is to be understood that the scope of the present invention is not to be limited to the embodiment illustrated herein but is to be limited only as set forth in the appended claims.

What is claimed is:

1. In an apparatus for producing single crystals of semiconductor material, a mechanism for driving the crystal seed support and withdrawal means at a continuously variable controllable speed comprising in combination a synchronous motor, a continuously variable ratio transmission means driven by said motor and driving the crystal seed support and withdrawal means, and a servomechanism controlling the transmission ratio of said transmission means, said transmission means comprising an input shaft, a plurality of discs keyed to said input shaft, a plurality of unidirectional clutches each with an inner and an outer plate, said inner plate fixed to an output shaft, a plurality of linkages each interconnecting one of said discs and one of said outer plates, and a control shaft coupled both to said interconnecting linkages and to said servomechanism.

2. In an apparatus for producing single crystals of semiconductor material, a mechanism for driving the crystal seed support and withdrawal means at a continuously variable controllable speed comprising in combination a synchronous motor, a continuously variable ratio transmission means driven by said motor and driving the crystal seed support and withdrawal means, and a servomechanism controlling the transmission ratio of said transmission means, said transmission means comprising an input shaft, a plurality of discs keyed to said input shaft, a plurality of unidirectional clutches each with an inner and an outer plate, said inner plate fixed to an output shaft, a plurality of linkages each interconnecting one of said discs and one of said outer plates, and a control shaft coupled both to said interconnecting linkages and to said servomechanism, each of said plurality of linkages being comprised of two 4-bar linkages with a link common to both of said 4-bar linkages and each of said common links adjustably coupled to said control shaft.

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