United States Patent

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[54] **SINGLE CRYSTAL GROWTH AND DIAMETER CONTROL BY MAGNETIC MELT AGITATION**
9 Claims, 2 Drawing Figs.

[52] U.S. Cl. ..... 23/301 SP, 23/273 SP, 13/31
[51] Int. Cl. B01j 17/18
[50] Field of Search 23/273, 301

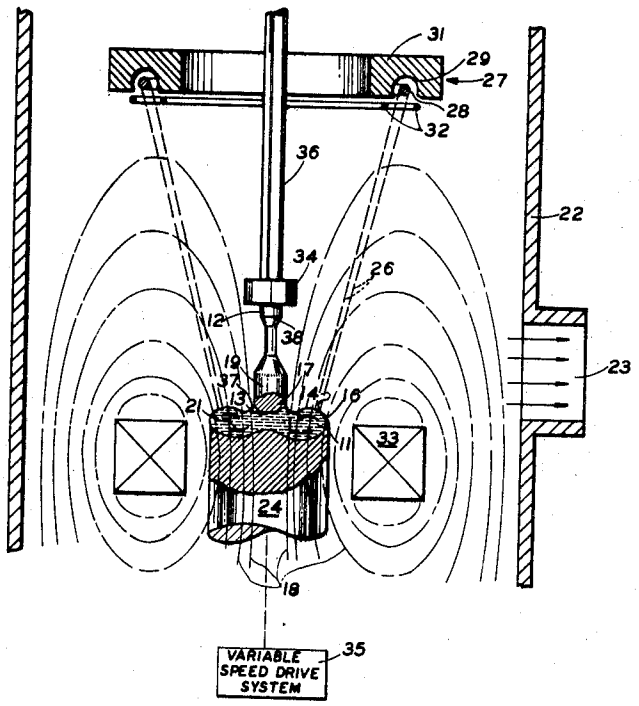
[56] **References Cited**

UNITED STATES PATENTS

3,079,246	2/1963	Smith	75/10
3,258,314	6/1966	Redmond et al.	23/273
3,278,274	10/1966	Liebmann et al.	23/273
3,335,250	8/1967	Purchinsky	23/273

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ABSTRACT: A method and apparatus are described for growing a single crystal from a molten pool formed of crystalline material, such as silicon and super alloy metals. Growth of the single crystal is controlled by controlling the thermal pattern, in the molten pool from which the product is grown, through variation in the relative rotation between the molten pool and a magnetic field.



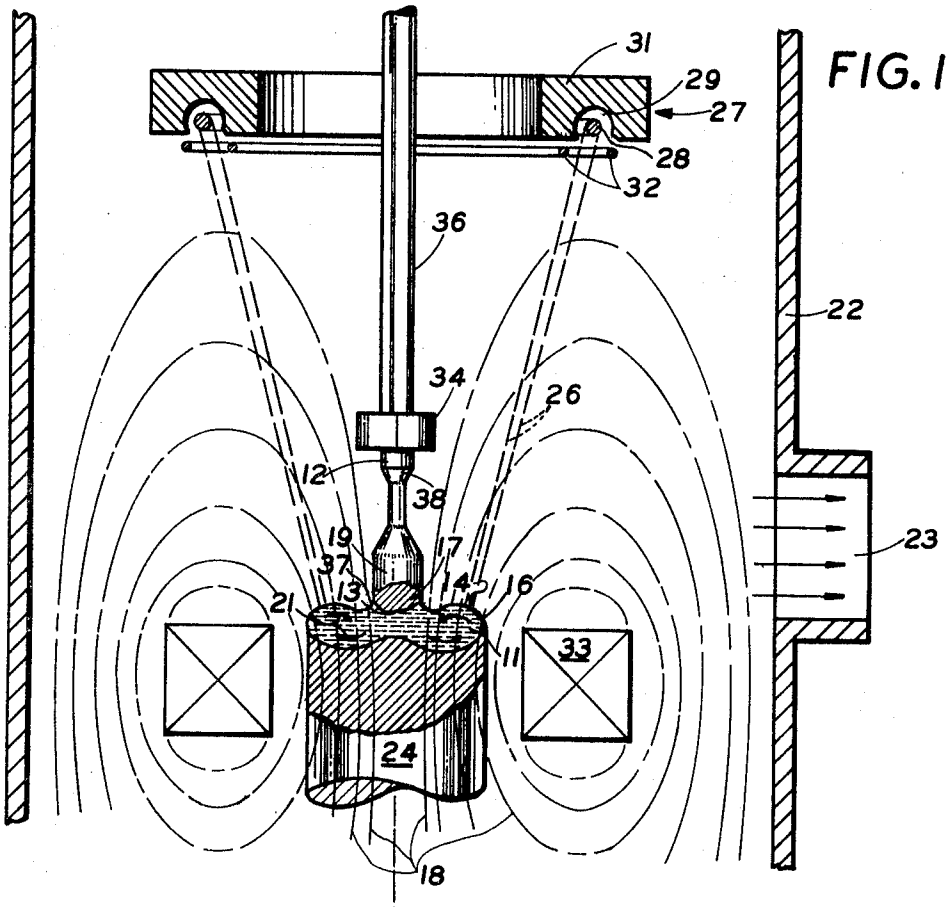


FIG. 1

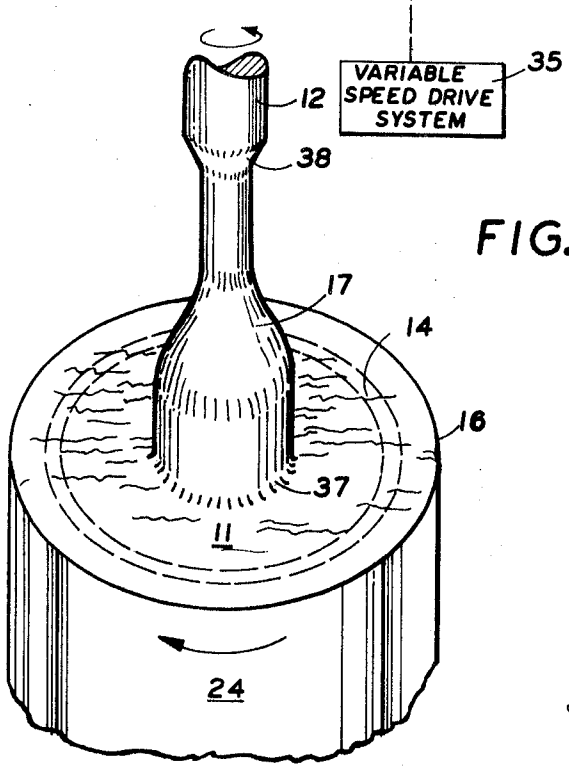


FIG. 2

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SINGLE CRYSTAL GROWTH AND DIAMETER CONTROL BY MAGNETIC MELT AGITATION

This invention relates to single crystals and, more particularly, to an improved method and apparatus for growing such crystals from a molten pool.

Certain articles of manufacture utilize material produced in single crystal form. For example, many types of electronic circuit elements, such as transistors and diodes, are manufactured from thin slices of semiconductor material (e.g., silicon, germanium, aluminum oxide) produced in crystal form. In addition, some items which are subjected to high stresses and high temperatures, such as jet engine turbine blades, may be constructed of certain super alloys (e.g., B–1900 and SM 200) in single crystal form.

One general technique which has heretofore been developed for producing single crystals, from which various items mentioned above may be manufactured, involves the drawing or growing, epitaxially, of the generally cylindrical single crystal from a molten pool. In the growing technique, a single crystal seed is dipped into a molten pool so that an interface is formed between the seed and the molten pool. The seed is then withdrawn from the pool in a manner which causes the molten material at the interface to solidify continuously as the seed is drawn upwardly. The precise way in which this is accomplished may vary considerably, frequently depending on environmental conditions and other factors.

Although satisfactory in many respects, some previously known ways of accomplishing crystal growing tend to be expensive and difficult to carry out. Coating flakes, condensate and dirt on the seed surface, etc., can cause nucleation and growth of other crystals, destroying the single crystal nature of the final product. Disturbing conditions at the original surface of the seed may result in poor surface quality in the crystal being grown. Surface imperfections, and surface nucleation agents can be caused to "grow out" of the surface by reducing the diameter of the crystal at an angle of fresh surface which is greater than about 30° from the crystal axis. To do this may be difficult, however, for the reason that it is usually necessary to precisely vary the temperature at the interface and, in most known systems, temperature has a very slow response.

Other difficulties may be encountered during crystal growing. Variation in environmental conditions may have a deleterious affect on quality of the single crystal by producing nonsymmetrical intracrystalline growth and consequent dislocations. Difficulties in achieving a desired crystal length and diameter may also present problems in previously known ways of crystal growing.

Accordingly, it is an object of this invention to provide an improved method and apparatus for producing a single crystal.

Another object of the invention is to provide a method and apparatus for producing a single crystal by which a high degree of consistency and quality in results may be obtained.

It is another object of the invention to provide a method and apparatus for growing a single crystal from a seed, which minimizes the effect of crystal nucleation agents that may be residing on the surface of the seed, and which allows the reproduction of the subsurface quality of the seed.

A further object of the invention is to provide a method and apparatus for growing a single crystal wherein the cross-sectional size of the single crystal during growth may be readily varied.

Other objects of the invention will become apparent from the following description taken in connection with the accompanying drawings wherein:

FIG. 1 is a schematic sectional view of apparatus constructed according to the invention for practicing the method of the invention; and

FIG. 2 is a schematic perspective view of apparatus of FIG. 1, illustrating the movements of the single crystal and the molten pool in accordance with a preferred way of practicing the invention.

Very generally, the apparatus of the invention operates in practicing the method of the invention by contacting the surface of the molten pool **11** of material which is capable of epitaxial growth with a single crystal seed **12** to establish an interface **13** between the seed and the molten pool. The material in the molten pool is heated at a region **14** of the pool between the interface and the periphery **16** of the pool. The seed is withdrawn from the molten pool at a rate such that a single crystal **17** is grown. A magnetic field having lines of force **18** is established, such lines of force extending through the molten pool generally parallel with the axis **19** of the single crystal. A relative rotation is effected between the molten pool and the magnetic field to produce a flow of molten material, indicated by the arrows **21**, from the heated region toward the interface. The rate of such flow is controlled to control the diameter of the single crystal by controlling the rate of relative rotation between the molten pool and the magnetic field.

Referring now more particularly to FIGS. **1** and **2**, a preferred form of the apparatus of the invention used in practicing the method of the invention will be described in detail. The apparatus illustrated in FIGS. **1** and **2** is for growing a single silicon crystal **17** of generally circular cross section, such as is used in the manufacture of certain types of transistors and diodes. The single silicon crystal is produced in an electron beam furnace having a vacuumtight enclosure **22**. The region inside the enclosure is evacuated, through a duct **23** in a wall of the enclosure, by a suitable vacuum pump, not illustrated. Pressure inside the enclosure **22** is preferably reduced to less than 1 torr.

The polycrystalline silicon feed material from which the single crystal **17** is grown is provided by means of a vertical cylindrical pedestal **24**. The pedestal **24** is preferably substantially greater in diameter than the ultimate diameter of the single crystal, and the single crystal is grown from the molten pool **11** formed at the top of the pedestal. The pedestal is moved upwardly at a rate selected to replenish material removed from the pool as the crystal is pulled. As will be explained in greater detail subsequently, the thermal pattern in the molten pool is regulated so that the pool is contained, at its periphery **16**, by surface tension, the periphery thereby being about the same diameter as the pedestal **24**. As an alternative to the pedestal type growth described herein, the molten pool may be contained in a cooled crucible wherein a skull of solidified silicon or other material being used is formed between the crucible and the molten pool.

The molten pool **11** is heated in the region **14** by bombarding its surface with an electron beam **26** of annular cross section. Accordingly, the heated region is correspondingly annular in shape, extending around the vertical crystal axis **19**. The electron beam **26** is produced by an electron gun **27**, positioned above the pedestal **24**. The electron gun **27** includes an annular emitter **28** comprised of a suitable electron emissive material, such as tungsten. The emitter is disposed in an annular recess **29** in an annular backing electrode **31**. A pair of spaced annular accelerating anodes **32** of different diameters are disposed adjacent the open side of the recess **29**.

A suitable heating current, preferably a direct current, is passed through the emitter **28** to cause electrons to be emitted from the surface thereof. The shaping electrode **31** and the emitter **28** are maintained at a high negative potential with respect to the anode rings **32**. Accordingly, electrons are accelerated out of the recess **29** to pass between the anode rings **32** in a beam having an annular cross-sectional shape. Although a single electron gun with an annular emitter is shown, a plurality of separate electron guns may also be utilized distributed circumferentially about the crystal axis **19**. Such individual guns may be arranged to project beams which combine to approximate a beam of annular cross section.

In order to produce an electron-optical image of the emitter **28** on the surface of the molten pool **11**, a magnetic field is established having generally elliptical lines of force with their major axes generally parallel with the axis of the crystal. The lines of force converge slightly from the emitter to the pool

surface to reduce the mean diameter of the beam, but in the region of the pool the lines of force are substantially parallel with the crystal axis. The intensity of the magnetic field is adjusted in accordance with well-known principles of electron optics to achieve a sharp emitter image.

The mean diameter of the annular impact pattern of the beam on the surface of the molten pool **11** is selected to be of such a size, and the heat input (electron beam power) is selected to be of such an amount, that the center of the molten pool **11** acquires the correct temperature for growing crystals of the desired size. The impact pattern mean diameter must not be so large, or the heat input so high, that the pool becomes too deep or hot at the periphery **16** thereof for surface tension to maintain the integrity of the pool. On the other hand, the preferred operation of the method of the invention is that the beam impact pattern diameter not be so small, or the power input not be so low, that the outer edge of the melt stock or pedestal **24** solidifies to contain the molten pool. By preventing this latter occurrence, a thermal steady state may be achieved during operation in which the pedestal **24** is moved upwardly to melt continuously into the molten pool **11** at a uniform rate across the entire upper surface of the pedestal. It thus becomes unnecessary to effect a significant change in the diameter of the beam impact pattern or the power level of the beam.

The magnetic field for focusing and directing the electron beam **26** onto the surface of the molten pool **11** is produced by an electromagnetic coil **33**. The coil **33** may be constructed in accordance with known techniques and is supplied with energizing current from a suitable source, not illustrated. The axis of the coil is aligned with the axis **19** of the single crystal **17**, and the coil is positioned at approximately the level of the molten pool **11**. With this coil position, the lines of force or flux lines **18** of the magnetic field, as noted above, extend generally linearly and with a slight convergence from the accelerating anodes **32** to the surface of the molten pool **11**. The molten pool is, therefore, immersed in the magnetic field, and the lines of force, as previously mentioned, extend generally parallel with the axis **19** of the single crystal **17** in the region of the pool.

The single crystal **17** is formed by drawing it upwardly out of the molten pool **11**. The growth of the crystal is initiated by immersing a suitable single crystal seed **12** in the pool and beginning a slow upward withdrawal. The seed is held in a suitable clamp **34**, and an actuating rod **36** is secured to the clamp **34**. The rod **36** extends upwardly through the gun **27** and is coupled to a motor driving mechanism, not illustrated. The motor-driving mechanism is used to rotate the rod **36** and hence the single crystal **17**, relative to the molten pool **11**, while the crystal is being drawn upwardly. As is known in the art, such rotation provides a substantially cylindrical crystal with few irregularities on its surface, since any irregularities in the thermal pattern of the molten pool are integrated due to the rotation of the crystal relative thereto.

The pedestal **24** is also rotated, in a direction opposite to the direction of rotation of the crystal **17**. Such pedestal rotation is effected by a suitable variable speed drive system **35**. Accordingly, a relative rotation between the pedestal **24** and the magnetic field **18** is effected. In accordance with the invention, such relative rotation is utilized in a unique manner for purposes explained below. In the event the molten pool is contained in a cooled crucible, the crucible may be rotated to effect the desired relative rotation between the molten pool and the magnetic field.

After immersion of the seed **12** in the molten pool **11**, the seed partially melts at its immersed end and forms a generally hemispherical interface **13** between the solid portion of the seed and the molten pool. Crystal growth by solidification of silicon takes place at this interface. Such epitaxial growth will occur in the direction of the intracrystalline structure of the seed, as is known in the art. As the single crystal **17** is grown, a meniscus forms between the crystal and the surface of the molten pool **11**.

The temperature distribution in the molten pool **11**, and particularly the temperature of the molten pool near the interface **13**, is a significant factor in controlling the manner in which the silicon solidifies. Various techniques are known in the art for regulating the temperature distribution of a molten silicon pool. For example, in practicing one well-known method, the temperature near the interface is controlled by changing the power or heat input to the molten pool. Such a technique is in prevalent use in connection with induction heated or radiant heated crystal growing equipment. This particular technique has a relatively long thermal response time, that is, the time it takes for a change in heat impact to manifest itself by a change in the diameter of the crystal being grown. A significantly shorter response time greatly enhances the likelihood of success in crystal growing because of the closer temperature regulation possible.

One manner in which successful crystal growing with fast thermal response may be achieved, in apparatus utilizing electron beam heating, is to change the diameter of the annular beam impact pattern. The impingement of an electron beam on the surface of molten material produces a region of turbulence adjacent the impact area because of the localized introduction of energy at the surface. This turbulence is characterized by an outward flow of superheated molten material at and near the pool surface from the region of highest heat toward the regions of lower heat. A return flow of cooler material inwardly and then upwardly occurs at a lower depth in the molten pool. By changing the diameter of the impact area, the turbulence region may be brought closer to or farther from the interface of the growing crystal, as desired. An increased washing effect by the region of turbulence will cause a reduction in crystal diameter, and a decreased washing effect will cause a corresponding increase in diameter. Although the foregoing technique may provide significant advantages in many instances, the required deflecting fields and associated control circuits for closely controlling the mean diameter of the beam impact area may make it desirable, in some circumstances, to use alternatives. Moreover, where pedestal type feed is utilized, variations in impact area mean diameter may make it difficult to maintain the temperature at the pool periphery sufficiently constant for uniform melting.

In accordance with the invention, a substantial flow of material from the heated region **14** toward the interface **13**, indicated by the upper ones of the arrows **21**, is produced and regulated by means which supplement and alter the thermal action above described. Regulation of this flow does not require corresponding changes in the mean diameter of the beam impact pattern. The flow produced in accordance with the invention is greater than that produced by thermal action alone and, without changes in beam position, provides a high level of sensitivity to enable very precise control over the crystal growing process.

The flow produced in accordance with the invention utilizes the effect on the molten pool **11** of the axial magnetic field, represented by the lines of force **18**, as the pedestal **24** is rotated. By energizing the coil **33** with a current direction to provide a polarity of north magnetic pole up and south magnetic pole down, the magnetic field lines are directed down through the molten pool. By rotating the pedestal and hence the molten pool clockwise, looking in the direction of the magnetic lines of force (i.e., down), the hotter molten material near the surface of the pool which moves inwardly toward the center due to thermal action is aided in its flow by forces produced as the material crosses the magnetic lines of force of the field. With the polarity reversed, a similar aiding of inward flow may be achieved by rotation of the pedestal in the opposite direction. Increased inward flow increases the washing action at the interface and deepens the liquid pool in the center. Reduction of inward flow has the opposite effect. The mean diameter of the beam impact area is selected to maintain thermal balance throughout the molten pool for the full range of flow variation desired. The pool in the area of the crystal being pulled is maintained sufficiently deep by adequate in-

ward flow that "freezing out" in the center of the pool is avoided. Such freezing out occurs when a bridge of solid material forms between the pedestal **24** and the crystal **17** and prevents proper crystal growth. Although the magnetic field would theoretically oppose return flow of cooler material at lower levels in the pool, this appears, in actual practice, to not have a significant effect on response time.

The rotational speed of the molten pool **11** relative to the magnetic field thereby has a marked thermal effect at the interface where the crystal is growing. In practicing the method of the invention, the particular rotational speeds utilized depend upon a number of factors. Among these factors is the average pool temperature, the power of the electron beam or beams, the rate at which the crystal is pulled, the mean diameter of the impact area of the electron beam or beams, and the heat losses due to radiation of heat from the pool to the surrounding environment and due to conduction of heat from the pool through the crystal and the pedestal. The precise conditions required for successful operation are established empirically and may usually be determined after a few test runs. Some examples of satisfactory operating conditions are described below.

Operation of the illustrated apparatus in accordance with the method of the invention, as above described, enables variation and control over the diameter of the crystal being grown by means which provide a very fast and sensitive response. Such a fast and sensitive temperature response is of significance in crystal growing. For example, variation in diameter of the crystal being pulled or grown may be accomplished almost immediately after a change in the rotational speed of the pool in the described manner. This facilitates the "growing out" of the crystal nucleation agents and surface imperfections, and is described subsequently. Moreover, variation in environmental conditions may be very quickly compensated for by appropriate adjustment of the rotational speed of the pool.

By regulation of the rotational speed (and, if desired, by regulation of the beam power, providing a relatively slow supplemental response) the size and average temperature of the molten pool may be kept relatively constant. The constant conditions of purity, temperature, pool size, etc., result in production of a crystal which is symmetrical in its intracrystalline structure, being substantially free of dislocations, providing the subsurface structure of the seed crystal is also substantially free of dislocations.

A specific manner of practicing the invention will now be described, although the method of the invention is not limited to being practiced in this manner. The seed crystal **12** is immersed in the rotating molten pool, and held therein until the interface **13** forms and the proper temperature at the interface **13** forms and the proper temperature at the interface has been achieved, this temperature being approximately 1,425° C. During this period, the meniscus **37** will form at the surface of the molten pool **11** and, once the meniscus is established between the seed and the rotating pool, the seed is drawn upwardly by the rod **36** at a slow rate, for example, about 2 inches per hour. At about the same time, the rotational speed of the molten pool is adjusted so that the surface of the crystal growing from the seed tapers inwardly at the region indicated **38**, at an angle which is greater than 30° from the vertical axis of the crystal due to the washing action of the hot molten material as it flows inwardly. With the growing crystal getting smaller in diameter than the seed at an angle of fresh surface greater than 30° from the vertical, crystal nucleation agents that may be residing on the surface of the seed grow out of the crystal because the maximum angle at which they can grow is about 30°. Such crystal nucleation agents may consist of coating flakes, condensate on the seed surface (which are all amorphous atoms), and dirt from faulty seed-handling procedures. In addition to minimizing the effect of crystal nucleation agents residing on the surface of the seed, the growth conditions maintained in the region **38** wipes out any influence of disturbing conditions at the original surface of the seed. Thus the surface of the single crystal **17** being grown is of the subsurface quality of the seed **12**.

When examination of the crystal "lines" on the surface shows that the grown material has the correct orientation, as is known in the art, the rotation of the molten pool **11** relative to the magnetic field is adjusted to make the crystal grow larger in diameter, at a desirable rate, until the desired ultimate size is reached. The speed of rotation is then once again adjusted to cause the crystal to grow at a constant diameter.

In growing single silicon crystals, successful results may be achieved in utilizing the method of the invention for the following examples:

EXAMPLE 1

Seed crystal diameter: 3/16 inch
Ultimate Silicon Crystal diameter: 7/8 inch
Furnace Vacuum: 3×10^{15} torr
Average electron beam power: 6 kw.
Magnetic field strength: 120 gausses
Mean diameter of beam impact area: 2¼inch
Pedestal diameter: 3½inch

Procedure: The seed is immersed in the pool to a depth of about ⅛ inch and is rotated at 15 r.p.m. The pedestal is rotated at 10 r.p.m. Once a good meniscus forms, the seed is drawn upwardly at 2 inches per hour to begin crystal growth. At the same time, pedestal rotation is increased to 35 r.p.m. to increase the inward flow of molten material and undercut the crystal at greater than 30° from the axis. When the crystal surface appears satisfactory, the pedestal rotation is reduced to 25 r.p.m. and the rate of crystal withdrawal is increased to 6 inches per hour, causing a constant diameter growth. After about 1 minute, the pedestal rotation is reduced to 20 r.p.m., causing the crystal to begin increasing in diameter. With the increasing crystal diameter, the periphery of the crystal gets closer to the hot region of beam impact and thus growth will automatically terminate at an equilibrium diameter. This point may be extended outwardly as desired by appropriately and gradually reducing the pedestal rotation. An ultimate crystal diameter of ⅞ inch may be reached with a reduction in pedestal rotation to about 10 r.p.m.

EXAMPLE 2

Seed crystal diameter: 5 mm.
Ultimate Silicon Crystal diameter: 30 mm.
Furnace Vacuum: 1×10^{15} torr
Average electron beam power: 8 kw.
Magnetic field strength: 100 gausses
Mean diameter of beam impact area: 75 mm.
Pedestal diameter: 110 mm.

Procedure: The seed is immersed in the pool to a depth of about 3 mm. and is rotated at 15 r.p.m. The pedestal is rotated at 20 r.p.m. Once a good meniscus forms, the seed is drawn upwardly at 2 inches per hour to begin crystal growth. At the same time, pedestal rotation is increased to 30 r.p.m. to increase the inward flow of molten material and undercut the crystal at greater than 30° from the axis. When the crystal surface appears satisfactory, the pedestal rotation is reduced to 20 r.p.m. and the rate of crystal withdrawal is increased to 6 inches per hour, causing a constant diameter growth. After minutes, the pedestal rotation is reduced to 18 r.p.m., causing the crystal to begin increasing in diameter. With the increasing crystal diameter, the periphery of the crystal gets closer to the hot region of beam impact and thus growth will automatically terminate at an equilibrium diameter. This point may be extended outwardly as desired by appropriately and gradually reducing the pedestal rotation. An ultimate crystal diameter of 1¼ inches may be reached with a reduction in pedestal rotation to about 15 r.p.m.

By way of further illustration, the method of the invention may be practiced for materials other than silicon, such as with super alloys as follows.

EXAMPLE 3

Material: B–1900 High Strength Low Creep Nickel Base Alloy

Seed crystal diameter: ½ inch

Furnace vacuum: 2×10^{15} torr

Average electron beam power: 10 kw.

Magnetic field strength: 100 gausses

Mean diameter of beam impact area: 4 inch

Pedestal diameter: 6 inch

Procedure: The seed is immersed in the pool to a depth of about ¼ inch and is rotated at 10 r.p.m. The pedestal is rotated at 20 r.p.m. Once a good meniscus forms, the seed is drawn upwardly at inches per hour to begin crystal growth. Super alloy crystals or grains are usually of satisfactory quality when grown in the naturally preferred direction of crystal growth (as opposed to silicon crystals for semiconductors). Crystal diameter may, therefore, usually be increased directly to its ultimate value by reducing the rotational speed of the molten pool appropriately once growth is begun. After 2 minutes, the pedestal rotation is reduced to 15 r.p.m., causing the crystal to begin increasing in diameter. With the increasing crystal diameter, the periphery of the crystal gets closer to the hot region of beam impact and thus growth will automatically terminate at an equilibrium diameter. This point may be extended outwardly as desired by appropriately and gradually reducing the pedestal rotation. An ultimate crystal diameter of inches may be reached with a reduction of pedestal rotation to about 12 r.p.m.

Where DC heating is used for the emitter **28**, the electrons will come off of the emitter at approximately a 10° angle to the vertical in the surface of a right cylinder extending through the emitter. When an electron enters a magnetic field at an angle with respect to the field lines, the electron acquires a helical path along the field line. This is described by K. T. Spangenberg in "Vacuum Tubes," McGraw-Hill, 1948, pp. 114–115. These helical excursions may be sufficient to cause electrons to strike the crystal **17** above the molten pool and produce undesired heating thereof or melting. The emitter **28** is therefore positioned a distance above the surface of the molten pool equal to the pitch of the helix described by the electrons. Such calculations may be made in accordance with the information given in the foregoing cited publication. The direction of the heating current in the filament is adjusted so that the final movement of the electrons in the helices which they describe is from the outside in, thereby avoiding any interference with the crystal being grown when the beam passes close to the crystal due to convergence of the magnetic field.

It may therefore be seen that the invention provides an improved method and apparatus for producing a single crystal. Crystal growth conditions are readily controlled without varying the mean diameter of the beam impact pattern. In accordance with the invention, a smooth surface single crystal of high quality is produced, the cross-sectional size of which may be selected as desired. Replenishment of the molten pool from which the single crystal is grown is readily accomplished without deleterious effect on growth conditions.

Various modifications of the invention in addition to those shown and described herein will be apparent to those skilled in the art from the foregoing description and accompanying drawings. Such other modifications are intended to fall within the scope of the appended claims.

1. A method of growing a single crystal from a molten pool of a material capable of epitaxial growth, comprising:

a. contacting the upper surface of the molten pool with a single crystal seed to establish an interface between the seed and the molten pool;

b. heating the material in the molten pool at a region at the upper surface of the pool between the interface and the periphery of the pool;

c. withdrawing the seed from the molten pool at a rate such that a single crystal of material is grown;

d. establishing a magnetic field having lines of force extending through the molten pool upper surface generally parallel with the axis of the single crystal;

e. rotating the molten pool at a speed and in a direction relative to the magnetic field to produce a flow of molten material from the heated region toward the interface; and

f. controlling the rate of relative rotation between the magnetic field and the molten pool to control the rate of such flow and thereby control the diameter of the single crystal being grown.

2. A method according to claim **1** wherein the heated region of the pool is heated by means of electron beam bombardment.

3. A method according to claim **1** wherein the relative rotation between the single crystal and the molten pool is controlled to cause a necking down of the single crystal at a surface angle greater than 30° from the axis of the single crystal.

4. A method according to claim **3** wherein, after necking down, the relative rotational speed is reduced to produce an enlargement of the single crystal cross section

5. Apparatus for growing a single crystal from a molten pool of material capable of epitaxial growth, comprising, means for supporting the molten pool, means for supporting a single crystal seed and for contacting the surface of the molten pool with the seed to establish an interface between the seed and the molten pool and for withdrawing the seed from the molten pool at a rate such that a single crystal of material is grown, means for heating the material in the molten pool at a region of the pool between the interface and the periphery of the pool, means for establishing a magnetic field having lines of force extending through the molten pool generally parallel with the axis of the single crystal, means for rotating said pool-supporting means to effect a relative rotation between the molten pool and the magnetic field to produce a flow of molten material from the heated region toward the interface, and means for controlling the rate of rotation of said pool-supporting means to control the rate of such a flow, thereby controlling the diameter of the single crystal being grown.

6. Apparatus according to claim **5** wherein said pool supporting means comprise a solid pedestal composed of the epitaxial growth material.

7. Apparatus according to claim **5** wherein said heating means comprise an electron beam gun having an annular emitter so that the impact pattern is annular, surrounding the single crystal.

8. Apparatus according to claim **5** wherein the lines of force of the magnetic field are directed to produce an initial inward excursion of electrons, and wherein the emitter is positioned above the molten pool a distance substantially equal to the pitch of the helical electron paths.

9. Apparatus according to claim **5** wherein said field producing means comprises an annular electromagnetic coil positioned surrounding said pool at the level of the surface thereof.

UNITED STATES PATENT OFFICE

CERTIFICATE OF CORRECTION

Patent No. 3,607,139 Dated September 21, 1971

Inventor(s) Charles W. Hanks

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

Column 1, line 11, insert "single" before crystal.
Column 5, line 33, delete "the" before crystal.
Column 5, lines 51-52, sentence appears twice:
"13 forms and the proper temperature at the"

Column 6, lines 18 and 48, Column 7, line 6,
change "15" to $--^{-5}--$.

Signed and sealed this 18th day of April 1972.

(SEAL)
Attest:

EDWARD M.FLETCHER, JR.
Attesting Officer

ROBERT GOTTSCHALK
Commissioner of Patents

FORM PO-1050 (10-69)

USCOMM-DC 60376-P69
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