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Process for producing a silicon single crystal, and heater for carrying out the process

The invention relates to a process for producing a silicon single crystal by the Czochralski method. The invention also relates to a heater which is intended for heating a silicon-filled crucible and is arranged below the crucible.

For the production of silicon single crystals by the Czochralski method, solid silicon is melted in a quartz-glass crucible, also referred to hereafter as just "crucible". A seed crystal is then dipped into the melt and a single crystal is pulled from the melt. Since its incipience, the method has continued to be developed, and it is currently possible to pull single crystals having diameters in excess of 200 mm. However, producing large single crystals raises a number of problems. One of these problems relates to the thermal and rheological conditions when the silicon is melted and when the single crystal is pulled. It is desirable to melt the silicon as quickly as possible and to obtain thermal and rheological conditions in the melt that are necessary for dislocation-free pulling of the single crystal. In order to produce large single crystals, correspondingly large volumes of silicon need to be melted in the crucible. As a rule, use is made of polycrystalline fragments or single crystals which contain dislocations and need to be remelted. The heating energy required for the melting is usually provided by resistive heating elements which are arranged around the sides of the crucible and below the crucible. A device having heating elements of this type is, for example, disclosed in US-5,360,599. A factor against melting the silicon quickly by heating the heating elements to temperatures which are much higher than the melting point of silicon is the fact that liquid silicon attacks the crucible if the wall of the crucible is overheated. There is a risk of particles being detached from the material of the crucible, reaching the crystallization front during the pulling of the single



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crystal, and causing dislocations. An excessive temperature gradient between the wall of the crucible and the crystallization front furthermore produces uncontrolled convection currents which in turn lead to undesired local
5 fluctuations in the temperature of the melt and the concentration of dopant and impurities in the melt.

The invention achieves the object of reducing the time taken to melt silicon in a quartz-glass crucible, protecting the crucible from overheating and stabilizing
10 the melt.

The invention relates to a process for producing a silicon single crystal by melting silicon in a quartz-glass crucible and pulling the single crystal from a silicon melt, which is characterized in that energy is
15 delivered to the melt at least some of the time inductively using a coiled heater arranged under the crucible.

The invention also relates to a heater, intended for heating a silicon-filled quartz-glass crucible and arranged below the crucible, the heater being designed in
20 the form of a wound coil and having electrical connections which are configured for alternating-current and direct-current operation.

A particular distinguishing feature of the invention is that heat energy is not only transferred directly to the silicon melt, but is also distributed quickly and uniformly in the melt by the field-induced melt convection. Because of the substantially higher electrical resistance of the other furnace components
25 (graphite), the energy is delivered predominantly to the melt. The manner in which the heat energy is transferred, and the described consequences, significantly reduce the time required to melt the silicon. Furthermore, the crucible is protected by the thermal transport directed
30 into the interior of the crucible from overheating by the resistive heater arranged around its sides. During the pulling of the single crystal, the convection forced in the melt by inductive heating can be used to reduce uncontrolled local fluctuations in the temperature and
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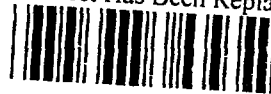
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the concentration of dopants and impurities, and to stabilize the melt. This in turn promotes the pulling of a dislocation-free and uniformly doped single crystal.

5 Since it is only in the liquid state that silicon has the desired interaction with the induced electromagnetic field, at the start of the process solid silicon is melted with the aid of a resistive heater. As well as a conventional heater arranged around the crucible, it is also possible for a heater according to the invention,
10 referred to hereafter as bottom heater, to be used for this. The bottom heater is connected to a DC current source and is operated for resistive heating. However, to melt most of the silicon, the bottom heater is switched to alternating-current operation, so that the energy
15 transferred to the silicon takes place inductively. A sinusoidal AC voltage, and AC voltage modulated with DC voltage components or an AC voltage produced by repeated switching is preferably applied. The frequency of the AC voltage is preferably from 20 Hz to 10 kHz. For higher
20 frequencies of the AC voltage, the melt undergoes stronger local heating than at lower frequencies. However, at lower frequencies the energy delivery reaches further into the interior of the crucible. It is therefore recommended, when melting the silicon, to work
25 initially at higher frequencies in order to melt silicon as fast as possible, and later to change to operation at lower frequencies in order to stabilize the melt. During the pulling of the single crystal, the bottom heater can be operated either with direct current, with a customary
30 resistive heating function, or, to stabilize the melt further, with alternating current or with modulated direct current.

If the heater is operated with modulated direct current, it is also possible for the oxygen content of
35 the melt to be controlled. The oxygen content is, in particular, influenced by the speed of the convection movement in the melt. The AC component of the modulated current determines the power delivered to the melt and therefore the convection drive, while the required



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overall heating power of the heater is controlled with the DC component. The convection speed can therefore be controlled independently of the total heat budget by varying the modulation amplitude.

5 A further possibility of controlling the oxygen content in the melt consists in selecting a relatively strong modulation amplitude and thereby setting up a high convection speed, and braking the latter deliberately by a external static magnetic field which penetrates the
10 melt.

 A further possibility of influencing the oxygen content of the melt is afforded by varying the frequency of the AC component, since the change in frequency varies the skin depth of the electromagnetic field and therefore
15 the convection.

 Details of the device will now be described in further detail with the aid of figures. Only those features are represented which are necessary for clearer understanding of the invention. Figure 1 schematically
20 shows a longitudinal section through a device for pulling a single crystal by the Czochralski method, with a heater according to the invention. Figures 2 to 4 are detail representations of preferred design features of the heater. Figure 5 represents a particularly preferred
25 embodiment of the heater. In the figures, the same features are given identical reference numbers.

 Reference will firstly be made to Figure 1, which represents a quartz-glass crucible 1 which is embedded in a support crucible 2 and, together with the latter, is
30 supported on a support plate 3 of a rotatable and axially displaceable shaft. The crucible 1 is surrounded at its sides by a cylindrical resistive heater. A bottom heater 4 according to the invention is arranged below the crucible. Radial slots (not represented in the figure)
35 reduce undesired inductive coupling to the support crucible 2. Correspondingly, other device parts next to the bottom heater are preferably also radially slotted. The bottom heater 4 consists essentially of a coil which is preferably made of graphite, CFC (carbon fiber



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composite) or metals such as molybdenum or tantalum. The turns 6 of the coil lead in widening paths from an inner electrical connection 7 to an outer electrical connection 8. The number of turns is dictated by the coil material, coils made of carbon having, because of the higher electrical resistivity of this material, fewer turns than metal coils of the same diameter. The turns of the coil may be arranged in a single layer or in a plurality of layers, one above the other. Below the bottom heater there is a thermally insulating base plate 9. It is preferable for each of the turns of the coil to be fixed mechanically to the base plate at at least three support points, for example using support elements which are fitted to the turns and are electrically insulating or are made of electrically insulating material. The support elements at the same time hold the turns of the coil at a constant distance from one another and damp possible vibrations of the turns. The base plate is preferably made of graphite and expediently serves at the same time as an electrical connection for the inner electrode of the bottom heater.

The support element used may, for example, be the bridging element 10 which is represented in Figure 2, is connected to a turn 6 and protrudes from the latter in the manner of a foot. In the embodiment which is represented, the base plate 9 consists of a composite formed by a graphite plate and underlying graphite-felt plates. The bridging element 10 fits into a socket 11 which is preferably made of quartz glass. The socket is embedded in a corresponding bore in the base plate.

Figure 3 shows a further example of how the turns of the coil can be supported on a base plate. In this case, a comb-shaped electrically insulating spacer 12, preferably made of boron nitride and resting on a base plate (not represented), here functions as the support element. On one side, the spacer has prongs 13 which are fitted into the gaps between the turns 6.

A further example for constructing the support of the turns is represented in Figure 4. The proposed



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support element is an annular, electrically insulating spacer 14 which supports two adjoining turns 6 and is screwed to a base plate 9 using a screw 15. The head 16 of the screw fixes the turns to the spacer via an insulating washer 17. The screw is preferably made of CFC. The spacer and the washer preferably consist of boron nitride. Another similar possibility (not represented) of supporting a turn consists in the turn being supported on the base plate by an annular, electrically insulating spacer. In this case, it is expedient to connect the turn to the base plate, for example by a screw, which is electrically insulating or is made of electrically insulating material, being screwed into the turn through the base plate and the spacer. If the base plate is made of electrically insulating material, for example boron nitride, the turns can be fastened directly to the base plate by CFC screws.

During the pulling of a single crystal, it is usual to raise the crucible using the shaft, in order to keep the surface of the melt at constant level in spite of the decreasing volume of the melt. Since the amount of energy delivered depends on the distance between the bottom heater and the crucible, it is preferable to slave the bottom heater to the axial movement of the crucible, and likewise keep its distance from the crucible constant. In principle, a separate mechanism may be provided for this, which moves the bottom heater synchronously with the crucible. In a preferred embodiment, axial movements of the crucible and of the bottom heater are brought about by a specially designed shaft 18 (Figure 5). The shaft 18 is divided into two coaxial parts 18a and 18b, the inner part being designed as an inner electrical connection of the bottom heater 4. Together with a base plate 9 and a tube 19, the outer part serves as an outer electrical connection for the bottom heater and at the same time supports the base plate 9. Together with the tube 19 and a support crucible 2, the base plate forms a cavity 20 which contains the bottom heater 4. The bottom heater is substantially enclosed in the cavity, so



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that impurities originating from it cannot reach the melt via the gas phase. The electrical connections are joined to a current source via slip rings 21a and 21b.

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Patent claims

1. Process for producing a silicon single crystal by melting silicon in a quartz-glass crucible and pulling the single crystal from a silicon melt, characterized in that energy is delivered to the melt at least some of the time inductively using a coiled heater arranged under the crucible.
2. Process according to claim 1, characterized in that the heater is operated at least some of the time with alternating current during the melting of the silicon.
3. Process according to claim 2, characterized in that the frequency of the alternating current is varied.
4. Process according to claim 1, characterized in that the heater is operated at least some of the time with modulated direct current during the melting of the silicon.
5. Process according to claim 1, characterized in that the heater is operated with direct current during the pulling of the single crystal.
6. Process according to claim 1, characterized in that the heater is operated with alternating current during the pulling of the single crystal.
7. Process according to claim 1, characterized in that the heater is operated with modulated direct current during the pulling of the single crystal, and the ratio between the AC component and the DC component is varied.
8. Process according to claim 1, characterized in that the heater is operated with modulated direct current during the pulling of the single crystal, and a static magnetic field which penetrates the melt is produced.
9. Process according to claim 1, characterized in that the heater is operated with modulated direct current during the pulling of the single crystal, and the frequency of the AC component is varied.
10. Heater, intended for heating a silicon-filled crucible and arranged below the crucible, characterized in that the heater is designed in the form of a wound



coil.

11. Heater according to claim 10, characterized in that the turns of the coil are mechanically fixed to a base plate via bridging elements.

5 12. Heater according to claim 10, characterized in that turns of the coil are mechanically fixed to a base plate via a spacer which is made of electrically insulating material and engages between them in comb fashion.

10 13. Heater according to claim 10, characterized in that the turns of the coil are mechanically fixed to a base plate via annular spacers made of insulating material.

14. Heater according to claim 10, characterized in that the turns of the coil are fastened directly to a base plate made of electrically insulating material.

15 15. Heater according to one of claims 12 to 14, characterized in that the electrically insulating material is boron nitride.

16. Heater according to one of claims 10 to 15, characterized in that the coil can be displaced vertically.

20 17. Heater according to one of claims 10 to 16, characterized in that the coil is placed in a cavity.