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Stut

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[54] **METHOD FOR CRUCIBLE FREE ZONE MELTING**

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[51] **Int. Cl.**.. **H05b 5/00**

[58] **Field of Search**...................... 219/10.41, 10.43, 219/10.75, 10.77; 23/273, 301

[56] **References Cited**

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3,198,929 8/1965 Stut............................. 219/10.77 X

3,243,509 3/1966 Stut.................................... 219/6.5

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[57] **ABSTRACT**

Method for crucible free zone melting of a vertically oriented semiconductor rod, wherein the melting zone is monitored by a television camera and the information taken from the electric pulses supplied by the television cameras, not only regarding the cross section of the crystallizing material, but regarding the angle of two tangents of the melting zone profile and are used for the regulation and control of the melted zone. One tangent is applied in the crystallization boundary and the other tangent, beyond the bulge of the melting zone at a distinctive point of the melting zone profile, in particular at an inversion point.

11 Claims, 5 Drawing Figures

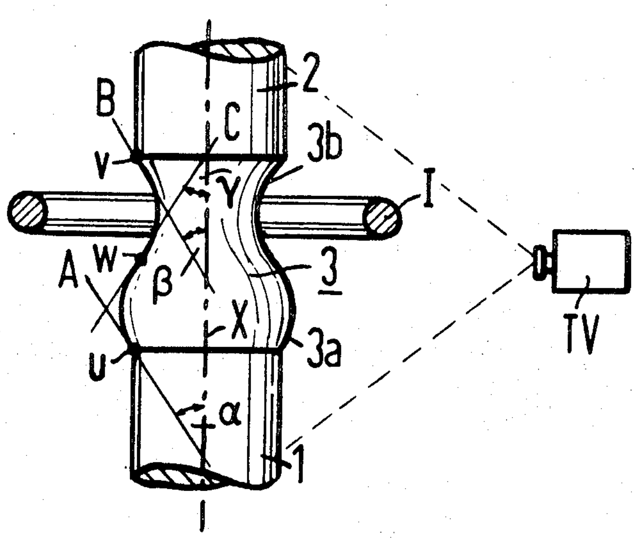


Fig.1

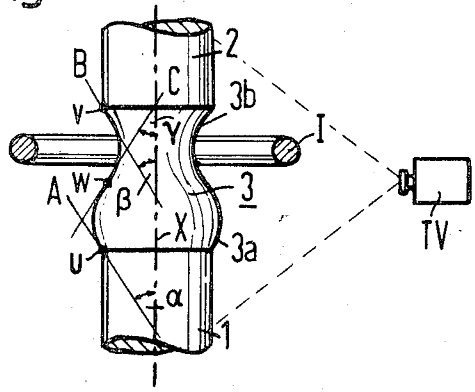


Fig.2

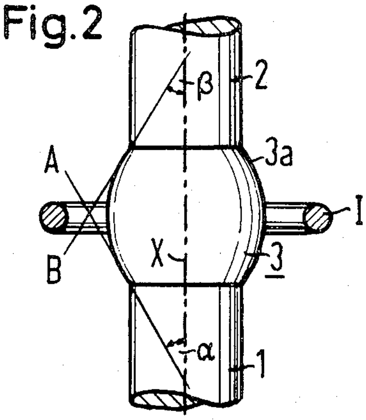


Fig.3

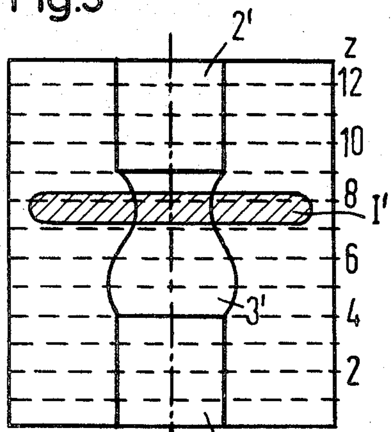


Fig.4

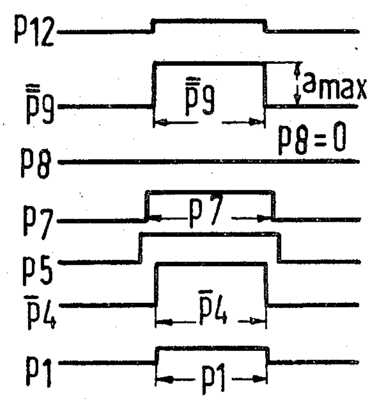
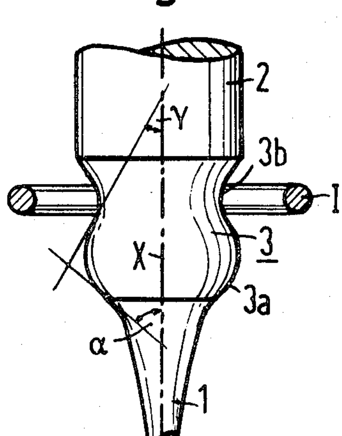


Fig.5



METHOD FOR CRUCIBLE FREE ZONE MELTING

The invention concerns a method for the crucible free zone melting of a vertically oriented rod of semiconductor material, particularly silicon, with a heating device coaxially surrounding the rod and movable parallel to its axis, for the generation of the melting zone, in which pictures of the melting zone successively recorded in its various positions in the rod by a television camera, with the recording conditions kept constant, serve to generate electric pulses with information regarding the cross section area of the section of the rod crystallizing from the melting zone. This information is used for controlling the power supply for the heating device and/or the axial distance of the solid portions of the rod supporting the melting zone and/or of an electromagnetic support field in the sense of controlling the cross section of the material crystallizing at a given instant from the melting zone to a preset desired value.

Such a method is described in the German Patent 1,231,761 which corresponds to U.S. Pat. No. 3,243,509. The method described there is suitable if the cross section of the material crystallizing from the melting zone is to remain constant. However, if it is desired that the cross section of the crystallizing material changes, it was recognized in accordance with the invention, that the monitoring of at least one additional parameter serving as criterion for the mechanical stability of the melting zone is necessary.

The present invention provides information serving for controlling the melting zone regarding the angles between two lines tangent to the profile of the melting zone and the vertical axis of the rod be taken from the pulses supplied by the television camera. One tangent is placed in the point of origin of the melting zone profile at the crystallization boundary, while the other tangent is at a distinctive point of the melting zone profile beyond its bulge.

The invention will be described hereinbelow with reference to the drawings, wherein:

FIG. 1 depicts a melting zone being monitored by a television camera;

FIG. 2 depicts a semiconductor rod with the molten zone shifted toward the upper solid rod end;

FIG. 3 shows a television image from the television camera;

FIG. 4 shows the qualitative shape of some pulses occurring during the scanning of the television image; and

FIG. 5 shows another semiconductor rod with molten zone.

In crucible free zone melting described, the profile of the melting zone, shown in FIG. 1, normally adjusts itself, provided the diameters of the two solid parts of the rod 1 and 2, supporting the melt 3, as well as the diameter of the melting zone 3, have mutually identical or approximately identical magnitudes. Illustratory external forces acting upon the melting zone are the surface adhesion of the liquid material at the two solid parts of the rod 1 and 2 and the force of gravity. Further external forces such as electromagnetic support fields or a force effect due to the heating device, respectively,may have to be taken into consideration. These external forces are counteracted by the cohesion in the melt and thus by the surface tension resulting from it. The force of gravity causes a downward direction gradient of the hydrostatic pressure in the melting zone 3. If then, the adhesion forces at the upper and lower end of the melting zones are comparable with each other, this distribution or pressures causes a bulging *3a* at the lower part and the constriction *3b* in the upper part of the melting zone 3. This applies for the case wherein the electromagnetic effect on the melting zone of a support field or of an inductively operated heating device I, respectively, is appreciably smaller than the effect of the force of gravity.

In FIG. 1, three tangents A, B and C are laid to the profile of the melting zone. The tangent A touches the melting zone profile at its lower point of origin μ and forms the acute angle α with the vertical axis X of the rod. The tangent B touches the profile of the melting zone at the upper point of origin *b* and forms the actuve angle β with the vertical axis X of the rod. The tangent C touches the melting zone profile at the inversion of deflection point W between the bulge *3a* and the constriction *3b*. It forms the acute angle γ with the rod axis X. The acute angles α and β open toward the top, while the angle γ opens toward the bottom.

The melting zone profile shown in FIG. 1 is normally present if the melted zone is passed from the bottom to the top through the rod to be zone melted and the diameter of the rod crystallizing from the melting zone and if the part 1 of the rod supporting the melting zone 3, differs by not more than 40 percent from the diameter of the part of the rod 2, which is to be remelted, and borders the top of the melting zone, then the magnitude of the angle α determines whether the diameter of the rod 1 to be crystallized from the melting zone increases, remains constant or even decreases. For silicon, a critical value of this angle is at about 8°. If the angle α is larger than 8°, the diameter of the material crystallizing from the melt increases to an extent, depending on the difference of the actual value of α from the value of 8°, while for an angle α less than 8°, the diameter of the crystallizing material becomes continuously smaller in a similar manner.

If, however, the diameter of the rod 1 growing from the melting zone 3 is to remain constant, the angle α must be 8°. As the melting zone 3, seen from FIG. 1, has a bulge *3a* in its lower part, the acute angle α is open toward the top. If furthermore, silicon is the semiconductor material used, the angle α has approximately the correct value of 8° under customary conditions, (the melting zone height H is 10 – 40 mm and inductive heating of the melting zone) so that it is possible to cause a cylindrical rod grow from the bottom to the top through the rod to be zone-melted without using further auxiliary means, for instance, of an electromagnetic support field generated by a special support coil. The situation is different, if the melting zone is led through the rod from the top to the bottom. To this end, if is necessary that the tangent angle β has the value 8° and is open toward the bottom in order to crystallize the silicon from the melting zone with constant cross section. This is achieved by shifting the bulge of the melting zone *3a* toward the upper boundary, as is seen in FIG. 2. Such a shifting can be obtained by the application of suitable electromagnetic support fields and/or by compressing the melting zone, i.e., by suitably bringing the rod portions 1 and 2 closer to each other. In this case, there is no constriction of the melting zone.

The melted zone 3 can be destroyed by pulling away and/or by dripping. More obtuse the tangent angle α at the lower boundary of the melting zone 3 becomes the greater the danger of dripping becomes. Thus, there exists a critical value for this angle α, which must not be exceeded and which depends on the cross section of the support area and the cross section of the upper rod portion **2**. On the other hand, the depth of the constriction *3b* and therefore the magnitude of the acute angle γ of the inversion tangent with the X axis is a criterion for the stability of the melting zone against pulling away, which occurs naturally at the narrowest point, i.e., at the constriction *3b*. It will be recognized from FIG. **1** that the danger of pulling away becomes greater the more obtuse the angle γ becomes, which is open towards the bottom. In the case of silicon, a value of $\gamma = 50°$ can be assumed as the critical value. One could also use the diameter at the narrowest point of the constriction of the melting zone as the criterion instead of the angle γ. However, this point is usually covered by the heating source I.

The invention can be carried out with a melting zone traveling through the rod from the bottom to the top (FIG. **1**) as well as with a melting zone (FIG. **2**) traveling from the top to the bottom. In the former case, the tangent angles α and β (and/or γ) are used to control and/or regulate parameters, in addition to the diameter *d* of the material crystallizing in each case. In the second case, the tangent angles β and α are used. In the former case, a and γ or β, while in the second case, α serves as stability parameters. Furthermore, α in the first case and β in the case, is used as the control parameter for the behavior of the cross section of the material crystallizing from the melting zone.

The method of the invention is preferably carried out with a melting zone traveling from the bottom to the top. For the further discussion, which will serve for the better understanding of the invention, conditions of rotational symmetry with the axis of the rod X as the symmetry axis will be assumed. Then the melting zone has the shape described in FIG. **1**. It generates in the television camera an image of the melting zone and its environment on an image screen, which has known special electrical properties, for instance, a vidicon target. The image is then systematically scanned by a fine electron beam, which closes at least one electric circuit. As the image screen offers locally different electric resistance depending on the exposure, the electric current caused by the electron beam will have different intensities, depending on whether it impinges on a brighter or darker point of the image of the melting zone on the image screen of the television camera.

Let us assume, for instance, that the current flowing in the electron beam, which is controlled by the image of the melting zone **3**, becomes the larger, the brighter, the corresponding point of the image becomes in the television camera and therefore in the imaged system also. It should be noted here that the brightness of the melting zone **3** is approximately constant and is appreciably less than the brightness at the end of the rod parts **1** and **2** supporting it. If, as is usual, the heating source is a perponderantly flat horizontal induction coil I, a horizontal partial zone of the melting zone **3** is shielded off and appears in the image of the television camera as a dark area. A similar situtation applies for the further surroundings of the melted zone as care is taken by suitable filters in the pick-up optics of the television camera that the image of the melting zone stands out with as much contrast as possible against the image of its surrounding.

It is further advisable to ensure that the imaging of the melting zone **3** projected in the television camera occurs under constant conditions. This will be achieved practically by arranging the heating device and the melting zone stationery in space and by pushing the rod through the annular shaped heating device in the axial direction, according to the intended speed of the melting zone. The optical system of the camera is advantageously aligned so that its optical axis is perpendicular to the axis of the rod X and is directed approximately toward the center of the melting zone. Finally, the electron beam should scan the image on the image screen of the television camera in unilaterally directed mutually parallel lines. The lines are perpendicular to the image X' of the axis X by suitable orientation of the camera. The spacing of two adjacent lines should have (as usual) a constant value *h*, for instance, h = total image height $= 625$.

Under these assumptions an image of the melting zone and its surroundings is generated in the television camera as is shown in FIG. **3**. The shape of the melting zone corresponds here to the conditions according to FIG. **1**. The image of the melting zone is designated **3'**, that of the lower part of the rod **1'**, that of the upper part of the rod **2'**, and the image of the heat source (induction coil) I'. This image is now scanned line by line by the electron beam in the television camera. The spacing between two scanning lines is *h*. In FIG. **3, 13** lines are shown although in practice the number of lines is, of course, many times larger. The lines will be designated with $z_1, z_2 \ldots z_\nu$. It will be seen that the line indexes **1, 2,** . . . ν can be considered and treated as independent coordinates, for instance as integral *x* values.

As the electron beam is led along the individual lines $z_1, z_2, \ldots z_\nu$, it passes both bright and dark points of the image of the melting zone **3'**. This results, as indicated above, in different electric resistances for the current carried by the scanning electron beam. As this current is closed via an external circuit through the electrical terminals of the television camera, these fluctuations can be evaluated technically. The operating current leaving the television camera therefore contains pulse-like fluctuations P_ν, the individual pulses $P_1, P_2 \ldots P_\nu$ being correlated to the lines $z_1, z_2, \ldots z_\nu$ as well as to certain values of the axia coordinate of the melting zone **3** which follow successively at certain constant spacing. Each scanning cycle, therefore, leads tosuch a sequence of pulses P.

FIG. **4** shows qualitative shape of some of these pulses P_ν as they occur during the scanning of the image of the melting zone according to FIG. **3**. The pulse P_4 corresponds to the lower boundary and the pulse P_9 to the upper boundary of the melting zone. These pulses P_4 and P_9 have correspondingly high amplitudes α_γ, because of the particularly brightly radiating solid rod ends **1** and **2**. The width of the pulse P_ν will be designated with P_ν. The width P_ν can now be considered as a measure not only for the diameter of the melting zone image **3'**, or respectively the image **1'** and **2'** of the incancescent rod parts **1** and **2** at the point of the corresponding line z_ν, but also as a measure for the respective diameter *D* of the melting zone **3**, or respectively, of the solid rods parts at the line *z* of the solid rod parts at the coordinate z_ν corresponding to the line x_ν. The diameter D_μ at the crystallization boundary, which is recorded per scanning cycle is of interest. The correspondingly desired value is to be differentiated from the determined desired value D^μ (μ = number of the scanning cycle). D_μ corresponds to a pulse P^μ_ν of the μth scanning cycle, namely $\bar{P}^\mu_\nu$. It will also be seen that the scanning of the appreciably darker melting zone image 3', in comparison to the images 1', 2' of the bright rod ends 1 and 2, must lead to a correspondingly smaller amplitude α_ν of the corresponding pulses P^μ_ν (pulses P_6, P_7).

The image of the melting zone 3 is continuously recorded during the entire process by the optical pick-up system of the television camera. However, the evalutation, that is the generation of the pulses P^μ_ν will be confined to scanning cycles separated in time from each other, for instance, one cycle per second to one cycle per minute because according to the invention, the melting zone changes correspondingly slowly within the range of stability.

Depending on the chosen line density for the scanning electron beam, as many pulses P^μ_ν as desired can be derived per scanning cycle. The pulses P^μ_ν appear also in the current at the output of the television camera and are evaluated according to the teachings of the invention.

The pulses P^μ_ν supplied by the television camera can be evaluated in different ways as a control process. Here, it is the goal to extract from these pulses P^μ_ν information regarding the tangent angle ϕ^μ_ν belonging to each line z_ν and determine in this connection particularly the values of the tangent angles at the boundary of the melting zone, i.e., at the points u, v as these are to be particularly monitored and controlled. If present, the inversion point w of the melting zone profile and the value of the tangent angle ϕ^μ, for this point, must be determined. Finally, information is also extracted, as is known, regarding the cross section or diameter D^μ respectively, of the material crystallizing out any any moment of the process. The values obtained then cause the melting zone profile to be controlled to programmed, preset values, within the limits of stability of the melting zone.

For this purpose it will be advantageous to evaluate the pulses P^μ_ν as to both their amplitude a_ν and width P^μ_ν. As will be seen from FIG. 4, two groups must be distinguished regarding the amplitude a^μ_ν of the pulses P^μ_ν

a. The pulses of particularly high amplitude, which correspond to the especially brightly radiating rod ends 1 and 2 at the transition to the melting zone 3, and which become successively smaller with increasing distance from the pulses associated with the melting zone.

b. The pulses corresponding to the appreciably darker melting zone with correspondingly lower amplitude which, however, is constant over the entire melting zone.

c. The scanning lines Z_ν corresponding to the dark points of the image to be scanned, particularly at the place of the image I', of the induction coil I which produces the melting zone. These lines, however, do not lead to pulses with appreciable amplitude.

In each of the pulse trains corresponding to the individual scanning cycles P^μ_ν the two pulse pairs which correspond to the two transitions from the solid material to the melting zone and possible vice versa, are to be determined and filtered out first. If, as already noted, the image of the melting zone and its surroundings is scanned by horizontal lines z_ν, which are mutually displaced from the bottom to the top one obtains, corresponding to the brightness increase with increasingly close approach to the image proper 3' of the melting zone 3, pulses P^μ_ν are obtained with successively increasing amplitude and of a duration (width $= P_\nu$) corresponding to the diameter d' at each instance of the image 1' of the lower rod portion 1. The largest amplitude a_{max} is given to the last pulse associated with the image 1', i.e., the pulse $\bar{P}^\mu_\nu$ with the width $\bar{P}^\mu_\nu$ (FIG. 4, pulse P^μ_1).

The following of the pulses P_ν are associated with the image proper 3' of the melting zone 3. The first of these pulses, namely the pulse $P_\nu = \mu$ should be noted particularly. The amplitude a_ν is distinctly smaller as compared to the amplitude a_{max} of the last pulse $\bar{P}^\mu_\nu$ associated with the rod portion 1. Experience has shown, however, that the amplitudes have practically the same value for all of these pulses P_ν (pulses P_6, P_7 in FIG. 4). When the electron beam reaches the scanning lines z which are associated to the image I' of the induction coil I, the pulses P^μ_ν practically disappear (pulse P_9 in FIG. 4) and reappear again as soon as the electron beam reaches those scanning lines z_ν which correspond to the portion of the melting zone image 3' proper which is located above the image I' and is not shielded.

Thereafter, the pulses P^μ_ν regain their former amplitude, which corresponds to the brightness of the melting zone image. The last of these pulses, namely the pulse $P^{**\mu}_\nu$ corresponding to the point ν of the melting zone profile, should be noted particularly. Finally, the scanning electron beam reaches the image 2' of the upper portion of the rod 2 which delineates and supports the melting zone. Pulses P^μ_ν then show immediately again a high amplitude corresponding to the more brightly glowing solid material at the end of the rod (pulse P^μ_9 in FIG. 4). However, with increasing distance from the image 3' proper of the melting zone 3, the amplitude of the pulses P^μ_ν decreases rapidly to zero. The first of the pulses P^μ corresponding to the solid rod portion 2 is designated by $\bar{\bar{P}}^\mu_\nu$. Its amplitude $\bar{\bar{a}} = a_{max}$ is also a maximum. One now needs:

1. the pulses $\bar{P}^\mu_\nu$ and $\bar{\bar{P}}^\mu_\nu$ which just still or already, respectively, correspond to the solid material at the boundary of the melting zone 3. Their widths $\bar{P}_\nu$ and $\bar{\bar{P}}_\nu$, respectively, are proportional to the diameter d_ν of the solid material at the points in question of the solid portions of the rod 1 and 2, respectively.
2. the first and the last of the pulses associated with the melting zone, and particularly the pulses, $p^{*\mu}_\nu$. and $P^{**\mu}_\nu$. Finaly, if the melting zone has a construction 3b, one must derive above the bulge 3a of the melting zone further pulses P^μ_ν 24 for the determination of the value of the angle γ^μ.

As the pulses $\bar{P}^\mu_\nu$ and P^μ_ν are distinguished from the pulses P_ν, which are situated between them in time and belong to the melting zone 3, by their particularly high amplitude a_{max} one will first filter out from the individual sequences of pulses P^μ_ν obtained per scanning cycle, those, the amplitude of which has the value a_{max}. One will therefore provide a suitable separator, which makes the desired choice. (It subdivides each pulse sequence into three partial groups, of which the first and the last is related to the solid incandescent rod ends **1** and **2**, and the middle one, which may be separated by an interval without pulses, to the melted zone). In any event, the pulses $\bar{P}^{\mu}_{\nu}$ and P^{μ}_{ν} can easily be filtered out from the train of the ordinary pulses, due to their particularly large amplitude. Their duration in time (pulse width $\bar{P}^{\mu}_{\nu}$ and P^{μ}_{ν}) can be evaluated as a measure for the magnitude of the diameters of the solid rod portions **1** and **2** at the phase boundary or of the images **1'** amd **2'**, respectively, corresponding to them. As in the present example, the width $\bar{p}_{\nu}$ of the pulse P is considered as the measure for the diameter of the crystallizing material and $\bar{\bar{p}}_{\nu}$ is used as the control quantity for the following.

The difference between the two pulses $\bar{P}_{\nu}$ and $\bar{\bar{P}}_{\nu}$ are particularly monitored as they are used for the monitoring and control of the melted zone. Nevertheless, the computing processes to be described in the following, can be performed successively for all pulses P_{ν} of each scanning cycle.

According to the invention, the sequence of first order differences

$$\Delta^{\mu}_{\nu} = P^{\mu}_{\nu+1} - P^{\mu}_{\nu}$$

are now formed between the widths P_{ν} of successive pulses P_{ν} of each pulse sequence. If the adjacent pulses P_{ν} in each case differ with respect to their width P_{ν}, the difference has an finite value; in the event these widths are equal the difference Δ_{ν}^{1}, becomes zero. The index ν, which is initially provided only for counting the individual lines z_{ν} and the pulses P_{ν} derived from them, runs through the sequence of the integers 1, 2, 3 . . . n, the first line and therefore the index "1" being assigned to the lower edge of the image on the image target of the television pick-up tube and "n" being assigned to the upper edge of that image. As, however, the same distance h always exists between two adjacent lines z_{ν} and $z_{\nu+1}$, the width P_{ν}, just as the pulses P_{ν} themselves can be correlated to the values

$\xi = h, 2h, 3h, \ldots nh$ of the axial image coordinate ξ.

On the other hand, these ξ are nothing but a similar image of the axial coordinates x for the different points of the melting zone **3** and its surroundings. One is, therefore, justified to consider the pulse widths p_{ν} as different values of a function

$$p = p\,(\xi)$$

wherein the function p can be assumed to be continuously differentiable. Its first derivative with respect to ξ is defined by

$$dp/d\xi = p'(\xi).$$

For the values $\xi_{\nu} = h, 2h \ldots nh$ it assumes the values $p_{\nu} = p_1, p_2 \ldots p_n$. According to the averaging theorem of differential calculus, the value of the first derivative is related to the associated first order difference according to the equation

$(dp/d\,\xi) = h^{-1}\ \Delta_{\nu} = h^{-1}\{p\,((\nu+1)h) - p(\nu h)\}$ at the point $\nu h < \xi < (\nu+1)\cdot h$. However, due to the geometric similarity of the image contained in the television camera with respect to reality, the identity

$$dD/dx = dp/d\xi$$

exists, where D corresponds to the diameter of the melting zone at the point corresponding to the line z_{ν}. Consequently, one obtains for the angle ϕ of the tangent to the melting zone profile with the x-axis (rod axis) the relation

$$2\tan\phi_{\nu} = h^{-1}\{p\,(\nu+1)\,h) - p\,(\nu\,h)\}\,;\nu=1,2,\ldots n$$

which is valid in good approximation. From the difference of the widths of the first two pulses after the pulse P^{μ}_{ν}, i.e., the pulse P^{μ}_{ν} and the immediately following pulse $P^{\mu}_{\nu+1}$, one obtains the value of the tangent of the angle α^{μ}.

From the difference of the last two pulses preceding the pulse $\bar{P}^{\mu}_{\nu}$, i.e., the pulse $P^{**\mu}_{\nu}$ and the pulse $P^{**\mu}_{\nu-1}$ immediately preceding it, one obtains the tangent of the angle β^{μ}. Therefore we have

$$\tan\alpha^{\mu} = (h/2)^{-1}\cdot[P^{*\mu}_{\nu+1} - P^{*\mu}_{\nu}]$$

$$\tan\beta^{\mu} = (h/2)^{-1}\cdot[P^{**\mu}_{\nu} - P^{**\mu}_{\nu-1}].$$

Corresponding to the shape of the profile of a meltling zone **3** as per FIG. **1**, the value of Tan ϕ^{μ} decreases gradually, starting with the value tan α^{μ}, reaches the value 0 (bulge **3a**), changes its sign, goes through a minimum (corresponding to the inversion point w), then increases again gradually, passes through the value 0 (corresponding to the constriction **3b**) and finally reaches the value tan β^{μ} (corresponding to the upper boundary of the melting zone **2**). For this reason, it is possible to determine from the first order differences and specifically from their minimum, the value of tan γ^{μ} and we obtain

$$\tan\gamma^{\mu} = (\tan\phi^{\mu}_{\nu})_{min}$$

The values of tan ϕ^{μ} can therefore be determined easily for each picture line, and therefore also for the corresponding x values of the acutal metling zones and its surrounding by a suitable computing apparatus. To this end, the pulses P^{μ}_{ν}, delivered by the television camera, are first fed to a measured value converter. Here each of the pulses P^{μ}_{ν} initiates the generation of a sequence of equally spaced switching pulses and identical shape, the number of which in each case is a measure for the corresponding width P^{μ}_{ν} of the respective pulse P^{μ}_{ν}. Thus a binary code, corresponding to the individual pulses P^{μ}_{ν}, is generated. This code, in turn, is fed to a digital computer in which the described computations for determining the diameter D^{μ} of the material crystallizing out from the melting zone and of tan ϕ^{μ} are carried out with emphasis of tan α^{μ}, tan γ^{μ} and/or tan β^{μ}. Furthermore, a comparison is carried out with the programmed desired values by determining the deviation of the acutal values determined by means of the television camera for the quantities mentioned. Finally, control of the melting zone is effected through these deviations according to the teachings of the invention.

Of the two pulses with maximum amplitude a_{max} i.e. the pulses $\bar{P}^{\mu}_{\nu}$ and $\bar{\bar{P}}^{\mu}_{\nu}$ only the pulse belonging to the crystallization front needs to be retained. If the the material to be remelted, the pulse $\bar{P}_{\nu}$ is accord- the material to be remelted, the pulse $\bar{P}_{\nu}$ is accordingly to be emphasized particularly. This is possible, for instance, by means of an amplitude peak detecting circuit.

Furthermore, all coded pulses corresponding to the P_{ν} are fed into the computer and are used for the determination of the tan ϕ_{γ} values. This computer is, on the other hand, subordinated to a reference value setter, i.e., to a control mechanism with preset program.

In order to establish the program for the reference values of D, tanα, tanβ, tanγ, respectively, again either a sequence of discrete values D_μ, tan α_μ, tan γ_μ and/or tan β_μ ($\mu = 1, 2, 3, \ldots m$) or a continuous function for these parameters must be given. In this connection, it should be taken into consideration that the coordinate values ξ associated with the scanning lines z_ν of the image in the television camera, or of the axial coordinates x_ν corresponding to them, of the actual melting zone are not suitable for programming. Here, one needs a new axial coordinate, which corresponds to the different positions of the melting zone in the rod to be zone-melted.

As already mentioned, it is sufficient if the image of the melting zone and its surroundings, projected by the optical system of the television camera, is not scanned continuously but, for instance, at regular time intervals, for instance, only once per second or per minute or even less frequently. One then obtains a number of successively following scanning cycles, to which one can assign, according to their order, the numbers $\mu = 1, 2, 3, \ldots m$. For each of these scanning cycles $\mu = 1,2,3, \ldots m$, the corresponding reference values D_μ, tanα_μ, tanγ_μ and/or tanβ_μ are preprogrammed, where of course, these values must be in accordance with the mechanical stability of the melting zone. If these pulses P^μ_ν of the μ^{th} scanning cycle then arrive at the computer, the corresponding reference values D_μ, tan α_μ, tan γ_μ and/or tan β_μ are made available, to the computer, by the stores program values and compared there with the actual value supplied by the pulses P^μ_ν ($\mu = 1, 2, 3, \ldots m$ = the number of the scanning cycle; $\nu = 1, 2, 3, \ldots n$ = number of the scanning line z_ν and the pulse P^μ_ν corresponding to this scanning line in the μ^{th} scanning cycle).

It is clear that the index μ can also be assigned the meaning of a longitudinal coordinate via the travel velocity of the crystallization front of the melting zone or via the length increase of the material crystallized from the course of the individual desired values D_μ, tan α_μ, tan γ_μ, tan β_μ via the distance from the heat source of the holder for the portion of the rod growing from the melting zone.

If in the μ^{th} scanning cycle, with the melting zone traveling from the bottom to the top, P^μ_ν is the last pulse which still clearly corresponds to the rod part **1**, and if $P^\mu_{\nu+1}$, $P^\mu_{\nu+2}$ are the immediately succeeding pulses (now associated with the melted surface), we have, according to the proceeding:

$$\tan \alpha^\mu = (h/2)^{-1} [P^\mu_{\nu+2} - P^\mu_{\nu+1}]$$

This value is to be compared with the reference value tan α_μ. The pulse $\overline{P}^\mu_\nu$ with the amplitude a_{max} (which considered as constant), filtered for each pulse sequence by means of the amplitude peak measuring circuit, then serves at the same time as the signal to determine the two immediately following pulses and at the value of tan α_μ derived from it, and to emphasize it particularly and compare it with the corresponding programmed reference value of tan α_μ.

The next value to be singled out particularly for tan ϕ^μ_ν exists if a melting zone with a constriction is used. In this case, tan γ_μ must be kept constant and compared with the corresponding reference value tan γ_μ. The actual value tan γ^μ is obtained as the minimum value of all tan ϕ^μ_ν values of the μ^{th} scanning cycle. This value can be determined without difficulty by means of a digital computer.

Finally, for processes in which the angle β is used as a criterion, the pulses $\overline{\overline{P}}^\mu_\nu$ and the tangent of β must be kept constant and controlled. The value of tan β_μ is obtained, as described above, from the pulses P^μ_ν and $P^\mu_{\nu-2}$ immediately preceding in time the pulse $\overline{\overline{P}}^\mu_\gamma$, or their associated widths $P^\mu_{\nu-1}$, $P^\mu_{\nu-2}$.

In conjunction with a measuring circuit serving for the detection of the amplitude peak value, known per se, a device can be combined without difficulty which permits determining in the tan ϕ^μ_ν value immediately preceding, i.e., tan β^μ, and to evaluate it.

In the manufacture of silicon rods free of dislocations, it is customary, as is well known, to generate a melted zone at the end of a silicon rod of suitable purity. The letter is then brought in contact with a seed, with the aid of which a so-called "bottleneck" is then drawn from the melted zone. From this "bottleneck" begins a conical part of the material crystallizing from the melting zone until finally the diameter of the material crystallizing from the melting zone and the middle part of the melting zoe are equivalent to the diameter of the rod portion to be remelted. This process can be carried out with the melting zone traveling from the top to the bottom (pedestal method) as well as with a melting zone traveling from the bottom to the top, in which case the melting zone has a shape corresponding to FIG. **1**, (see also FIG. **5**) in the preparation of the conical part.

In such a process, four operating phases can be distinguished, which must be under control for trouble free programming:

1. Production of the cylindrical part of the material crystallized from the melted zone;
2. Production of the conical part as the transition between the seed body and the cylindrical portion of the rod of the material crystallizing from the melted zone;
3. Production of the bottleneck for the manufacture of dislocation free rods; and
4. Matching of the initial conditions after the fusing of the seed with the melted zone.

For the establishment of a program, the following is firmly given or can be set:

1.The rod diameter as a function of the axial coordinate x;
2. The velocity of the melting zone as a function of the coaxialqcoordinate x;
3. The rotation of the rod about its vertical axis X;
4. The horizontal position of the heat source, in particular the induction coil; and
5. Excentricity of the rod relative to the coil.

Some quantities are operational parameters which must be preset or known, respectively, for instance:

1. ll he coil or secondary circuit geometry (in the case of inductive coupling, the induction coil producing the melted zone);
2. coupling of the current generator supplying the power for the induction coil.

During the operation of the zone melting process an therefore of the program execution, corrections must then be made with respet to the following quantities:

1. axial distance of the portions of the rod supporting the melted zone;
2. frequency of the AC current heating the melted zone (generator frequency);
3. melting energy; and
4. poisition of the heating coil relative to the rod to be zone melted or of the melting zone produced.

These four quantities are not independent of each other. A correction according to item 4 is probably necessary only to establish unequivocal initial conditions.

Problems may be expected if bumps appear in the semiconductor rods growing from the melting zone, as well as if annular bulges occur, especially during the generation of the conically shaped transition when fusing a small seed crystal to a thick rod to be zone melted.

For the cylindrical portion of the rod one can say: for a change of the diameter, a change of the volume of the melting zone is necessary. In this connection, the power supplied to the melting zone and therefore the heating of the melting zone can remain constant unless excessively large changes are involved. A change of the volume of the melted zone is also possible by changing the frequency of the electric current causing the heating of th melting one. Iftthe possibility of an absolute measurement of the diameter exists, it is recommended to correct the volume of the meltingzone via a subrodinated control circuit until the diameter of th1 melting zone is correct.

As already discussed in detail the information necessary for regulation or program control, respectively, of the process can in all cases be derived only from the profile of the melted zone itself. In the case of non rotation symmetrical conditions, it may here be necessary to provide two television cameras with optical systems oriented perpendicularly to each other. The angles α^μ and γ^μ, or α^μ and β^μ, respectively, which are to be monitored and controlled, respectively, according to the invention, are entirely usuable as the information sources, as discussed above. From experience, at least with respect to zone melting of silicon rods, the following can be stated with regard to the control of their values

1. According to experience, the angles α and β depend, in the case of inductive heating of the melting zone (FIGS. AND %), to a particular degree of the axial distance of the solid portions of the rod supporting the melted zone, and the angle γ depends on the heating of the melting zone. A similar statement applies for the distances of the lower edge of the melted zone from the induction coil. However, these considerations are valid only as long as no special support fields are used. It is therefore recommended to control, for the purpose of controlling γ and β, the distance of the two rod parts 1 and 2, and for the purpos of controlling α and β, heating of the melting zone.

The problems with the occurrence of unround rods, which exist particularly in the manufacture of dislocation free rods can be circumvented, for instance, by arranging the scanning after the position of the "bump" is determined, synchronous with the rotation of the rod to be zone melted, especially the part of the rod crystallizing from the melted zone, in such a manner that always the smallest diameter is considered as the measured and controlled quanity. Likewise, if can be expected that the occurrence of bulge-like rings can largely be avoided by suitable programming of the horizontal position of the coil.

As already mentioned, it appear advisable to structure the data processing digitially, especially since the television camera supplies the diameter by counting the width of the melting zone an therefore in digital form. Similarly, the generator frequency can most practically be determined by counting. Finally also the power supplied to the melting zone or to the heating device, respectively can simply be displayed in this form by a digital voltmeter.

With regard to the design of control circuits for single parameter control and regulation, particularly with respect to the diameter of the material crystallized from the melting zone, reference can be made to German Pat. Nos. 1,209,551 an 1,231,671 which correspond respectively to U. S. Pat. No. 3,198,929 and 3,243,509. As in the method according to the invention, control and regulation with respect to at least three parameters is involved, the arrangement must be expanded accordingly.

What is claimed is:

1. The method for crucible free zone melting of a vertically oriented rod of semiconductor material with a heating device coaxially surrounding the rod and movable parallel to its axis for the generation of the melting zone, in which pictures of the melting zone successively recorded in its various position in the rod by a television camera, with the recording conditions kept constant, except for the generation of electric pulses with information regarding the cross section area of the section of the rod crystallizing from the melting zone, and this information is used for controlling the power supply for the heating device, the axial distance of the solid portions of the rod supporting the melting zone and an electromagnetic support field in the sense of controlling the cross section of the material instantaneously crystallizing from the melting zone to a preset desired value, the improvement which comprises controlling the melting zone, from the electric pulses supplied by the television camera via the angles of two tangents to the profile of the melting zone with respect to the vertical axis of the rod, one of said tangents being placed at the point of origin of the melting zone profile at the boundary of the crystallization and the other of said tangents being at a distinctive point of the profile of the melting zone beyond its bulge, by changing the power supply for th heating device, the axial distance of the solid portions of the rod supporting the melting zone and an electromagnetic support field thereby controlling the cross section of the material instantaneously crystallizing from the melting zone to a preset desired value.

2. The method of claim 1, which further comprises, when a melting zone travels through the rod to be zone melted from the top to the bottom constanty monitoring the diameter of the material crystallizing from the melting zone the angle β of the tangent to the profile of the melting zone at the crystallization front with the vertical axis of th rod, and the angle α of the tangent to the profile of the melting zone at the melting front with the vertical axis of the rod.

3. The method of claim 1, which further comprises, when melting zone travels through the rod to be zone melted from the bottom to the top, monitoring the angle α of the tangent to the profile of the melting zone at the crystallization front, with the vertical axis of the

rod and at least one of the angle γ of the tangent at the inversion point of the profile of the melting zone, with the vertical axis of the rod and the angle β of the tangent to the profile of the melting zone at the melting front with the vertical axis of the rod.

4. The method according to claim **1**, which further comprises orienting the televison camera with respect to the melted zone and its surroundings in such a manner that the direction of the lines of the electron beam scanning the image picked up by the television camera is perpendicular to the image of the axis of the rod.

5. The method of claim **4**, which further comprises scanning the image picked up by the television camera by the electron beam in scanning cycles, said cycles following each other at regular time intervals generating pulses corresponding to the number of scanning lines.

6. The method of claim **5**, successive pulses $P_\nu{}^\mu$ of the μ^{th} scanning cycle for the determination of the values of the tangent function for angles ϕ_ν^μ of the tangent to the respective point of the profile of the melting zone related to the respective pulse P^μ with the vertical axis of the rod.

7. The method of claim **1**, which further comprises prescribing, for each of all the scanning cycles provided, a reference value regarding the rod diameter D, or the tangent junctions of the angle α and at least one of angles β and γ, comprising during the emitting zone process and during a μ^{th} scanning cycle, the reference values assigned to the μ^{th} scanning cycle with acutal values of F^μ, tan α^μ, tan β^μ, tan γ^μ derived from the pulses P_ν^μ supplied by the television camera, and depending upon the difference determined in each case, forcing the actual value to approach the desired value of these parameters.

8. The method of claim **7**, which further comprises, when an inductively heated melting zone traveling through the rod to be zone melted from the bottom to the top, particularly if a flat disc shaped coil, is used as the induction coil, regulating and controlling the angles α or β, respectively of the tangents at the boundaries of the melting zone profile with the solid material with the vertical axis of the rod by varying the distance between the two solid parts of the rod supporting the melted zone and regulating and controlling the angles of the inversion tangent to the profile of the melting zone with the vertical axis of the rod by varying the supply of power to the induction coil.

9. The method for crucible free zone melting of a vertically held semiconductor rod wherein a melting zone, which passes through the semiconductor rod, is produced by a heating device coaxially surrounding the rod and movable parallel to its axis, which comprises monitoring the semiconduclor rod with the melting zone by a television camera under constant recording conditions; adjusting the television camera in relation to the semiconductor rod so that the image of the axis of the semiconductor rod upon the target of the television camera is perpendicular to equidistant scanning lines on the target of the television camera; modulating the electron beam, which scans the image of the semiconductor rod and of the melting zone along the indicated scanning line in the form of electrical pulses; said modulating being effected by the image of the semiconductor rod and the emitting zone; said electrical pulse correspond directly to the bright image of the glowing melting zone and to the glowing portions of the solid semiconductor rod; during the individual scanning cycles the electron beam selecting two retained pulse groups which consist of at least two immediately adjacent pulses and through limiting to the respective pulse group determining half the difference between the lengths of respectively adjacent pulses of the concerning pulse group; the pulses of a first pulse group of the scanning line, which coincides with the image of the crystallization front of the melting zone and of the scanning line, which is adjacent to said scanning line, and already lies inside the actual melting zone image, correspond on one hand, and the pulses of a second pulse group of at least two adjacent scanning lines and the scanning lines wich li beyond a point of convexity but still belong to the actual image of the melting zone correspond to the other hand; finally, compairing the half difference from the pulse lengths of the first pulse group, and the half differences of the pulse lengths of the second pulse group, with datum values assigned to them, and controlling the shape of the melting zone utilizing any deviations from the respective datum values for.

10. The method of claim **9**, wherein the melting zone is guided from above downward through the semiconducor rod, the second pulse group is selected so that the pulses belonging thereto belong to the scanning line which coincides with the image of the melting side of the emlting zone an to the scanning lineqadjacent to said first scanning line which falls in the image proper of the interior of the melting zone.

11. The method as claimed in claim **9**, wherein the melting zone is guided frmm above downward through the semiconductor rod, the second group of pulses is selected so that it consists of three adjacent pulses and that the middle of said pulses corresponds to the scanning line which passes through a turning point of the image of the melting zone profile.

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