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Modification of the mass weighing in A3B5 automated Czochralski crystal growth techniques

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Modification of weight signal of LEC, VCZ crystal growth processes based on the knowledge of the weight signal in the past during the pulling process was considered. This modification is necessary for development and improvement of the direct automated weight control in these techniques of crystal growth.

1 Introduction

Processes of the A3B5 crystal growth by LEC (liquid encapsulated Czochralski crystal growth) and VCZ (vapor pressure controlled Czochralski crystal growth) techniques from the melt with encapsulant above the melt surface using crystal weighing technique for its automatization meet some problems during the automated crystal pulling. The main problem consists of the additional weight signal producing by encapsulant to the weight signal being measured with the weight sensor. It produces incorrect representation of the crystal mass according to its radius. It also produces delays in the changing the weight signal due to the crystal radius change This reasons result in difficulties in the direct automated control of the crystal pulling process according to the direct change of the weight signal.

This paper presents a mathematical technique of modification of the weight signal being measured by the weight sensor taking into account the weight influence of the encapsulant. The main idea of the present paper consists of the estimation of the weight factor of the encapsulant and to make an appropriate approach to produce a weight signal similar to the growth of the crystal without the encapsulant. If it is so, the system “melt – crystal” can be reduced to the automated crystal growth, for example, of silicon or silicon-germanium. For such systems – with anomalous solid and liquid densities relation and non-zero growth angle – direct weight control can be successfully used [1].

2 Results

The process of crystal growth is schematically represented in figure 1. Program mass M_Σ measured by the weight sensor is the sum of mass M which can be without encapsulant and addition M_e which is influence of the encapsulant:

$$M_\Sigma = M + M_e \,. \qquad (1)$$

Real mass $M_{\Sigma,r}$ is also the sum of the same, but real, components:

$$M_{\Sigma,r} = M_r + M_{e,r} \,. \qquad (2)$$

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Deviation ΔM_Σ between real and program masses is equal to the difference between Exs. (2) and (1) and can be written as follows :

$$\Delta M_\Sigma = \Delta M + \Delta M_{en} , \quad (3)$$

here $\Delta M_\Sigma = M_{\Sigma,r} - M_\Sigma$, $\Delta M = M_r - M$, $\Delta M_{en} = M_{e,r} - M_e$.

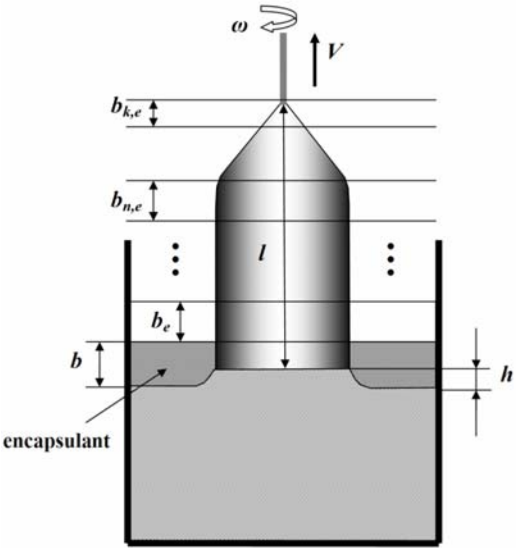

Fig. 1 Scheme of the crystal pulling by LEC and VCZ techniques.

Program influence of the encapsulant due to the Archimed force to the mass, for the planar interface boundary, should be written as follows:

$$M_e = -\int_{l-(b-h)}^{l} \rho_e \pi r^2 dl - \rho_e v_m , \quad (4)$$

here l is a program crystal length, h is a program meniscus height, b is a program height of the encapsulant, v_m is a program meniscus volume, ρ_e is an encapsulant density (Fig. 1).

Real influence of the encapsulant should be written as the next:

$$M_{e,r} = -\int_{l_r-(b_r-h_r)}^{l_r} \rho_e \pi r_r^2 dl - \rho_e v_{m,r} , \quad (5)$$

here l_r is a real crystal length, h_r is a real meniscus height, b_r is a real height of the encapsulant, $v_{m,r}$ is a real meniscus volume.

Deviation of the influence of the encapsulant as a difference between real $M_{e,r}$ and program M_e influences according to the expressions (4) and (5) can be written as the next :

$$\Delta M_{en} = -\int_{l_r-(b_r-h_r)}^{l_r} \rho_e \pi r_r^2 dl + \int_{l-(b-h)}^{l} \rho_e \pi r^2 dl - \rho_e (v_{m,r} - v_m) \quad (6)$$

Multiplying and dividing the parts of the Ex. (6) by corresponding densities it should be produced:

$$\Delta M_{en} = -\frac{\rho_e}{\rho_s} \int_{l_r-(b_r-h_r)}^{l_r} \rho_s \pi r_r^2 dl + \frac{\rho_e}{\rho_s} \int_{l-(b-h)}^{l} \rho_s \pi r^2 dl - \frac{\rho_e}{\rho_l} \rho_l (v_{m,r} - v_m) , \quad (7)$$

here ρ_s is a crystal density, ρ_l is a melt density.

We can write Eq. (7) in the next form :

$$\Delta M_{en} = -\frac{\rho_e}{\rho_s} (M_{k,r} - M_{k,e,r}) + \frac{\rho_e}{\rho_s} (M_k - M_{k,e}) - \frac{\rho_e}{\rho_l} (M_{m,r} - M_m) , \quad (8)$$

here M_k and $M_{k,r}$ are the program and real masses of the crystal without meniscus, relatively; $M_{k,e}$ and $M_{k,e,r}$ are the program and real masses of the crystal part above the level of encapsulant, respectively; M_m and $M_{m,r}$ are the program and real masses of the meniscus, respectively.

Adding and subtracting the part $\frac{\rho_e}{\rho_s}(M_{m,r} - M_m)$ in Eq. (8) we can modify Eq. (8):

$$\Delta M_{en} = -\frac{\rho_e}{\rho_s}\left((M_{k,r} + M_{m,r}) - (M_k + M_m) - (M_{k,e,r} - M_{k,e})\right) + \rho_e\left(\frac{1}{\rho_s} - \frac{1}{\rho_l}\right)(M_{m,r} - M_m)\ , \quad (9)$$

here $M_{k,r} + M_{m,r} = M_r$ is a real mass without influence of encapsulant; $M_k + M_m = M$ is a program mass without influence of encapsulant; $M_{m,r} - M_m = \Delta M_m$ is a deviation of the real meniscus mass from its program value without influence of encapsulant. And $M_r - M = \Delta M$ is a deviation of the real whole mass from its program value without influence of encapsulant. So, Eq. (9) can be written as follows:

$$\Delta M_{en} = -\frac{\rho_e}{\rho_s}\left(\Delta M - (M_{k,e,r} - M_{k,e})\right) + \rho_e\left(\frac{1}{\rho_s} - \frac{1}{\rho_l}\right)\Delta M_m\ . \quad (10)$$

In Eq. (10) we add and subtract the part $M_{m,e,r} - M_{m,e}$ with corresponding densities and obtain :

$$\Delta M_{en} = -\frac{\rho_e}{\rho_s}\left(\Delta M - \Delta M_e - \left(1 - \frac{\rho_s}{\rho_l}\right)\Delta M_m + \Delta M_{m,e}\right)\ . \quad (11)$$

Using Exs. (3) and (11) we can find expression for ΔM :

$$\Delta M = \frac{\rho_s}{\rho_s - \rho_e}\Delta M_\Sigma - \frac{\rho_e}{\rho_s - \rho_e}\Delta M_e - \frac{\rho_e(\rho_l - \rho_s)}{\rho_l(\rho_s - \rho_e)}\Delta M_m + \frac{\rho_e}{\rho_s - \rho_e}\Delta M_{m,e}\ . \quad (12)$$

In the Ex. (12) mass deviation ΔM without influence of encapsulant is expressed through the measured deviation signal ΔM_Σ (with influence of encapsulant), meniscus mass deviation ΔM_m and meniscus mass deviation $\Delta M_{m,e}$ which was in the past corresponding to the level of encapsulant. We can represent a signal ΔM_e according to the Eq. (12) using data in the more far past and write as follows:

$$\Delta M = \frac{\rho_s}{\rho_s - \rho_e}\Delta M_\Sigma - \frac{\rho_e\rho_s}{(\rho_s - \rho_e)^2}\Delta M_{\Sigma,e} + \frac{\rho_e^2}{(\rho_s - \rho_e)^2}\Delta M_{2e} - \frac{\rho_e(\rho_l - \rho_s)}{\rho_l(\rho_s - \rho_e)}\Delta M_m +$$
$$\frac{\rho_e}{\rho_s - \rho_e}\left(1 + \frac{\rho_e(\rho_l - \rho_s)}{\rho_l(\rho_s - \rho_e)}\right)\Delta M_{m,e} - \frac{\rho_e^2}{(\rho_s - \rho_e)^2}\Delta M_{m,2e} \quad (13)$$

In Eq. (13) data with index $2e$ are related to the data being on the second level of encapsulant in the past. Representing a signal ΔM_{2e} and other the same signals with use of Eq. (12) we can obtain next sum of the row:

$$\Delta M = \frac{\rho_s}{\rho_s - \rho_e}\sum_{n=0}^{k}(-1)^n\frac{\rho_e^n}{(\rho_s - \rho_e)^n}\Delta M_{\Sigma,ne} - \left(1 + \frac{\rho_e(\rho_l - \rho_s)}{\rho_l(\rho_s - \rho_e)}\right)\sum_{n=0}^{k}(-1)^n\frac{\rho_e^n}{(\rho_s - \rho_e)^n}\Delta M_{m,ne} +$$
$$+ \Delta M_m + (-1)^{k+1}\frac{\rho_e^{k+1}}{(\rho_s - \rho_e)^{k+1}}\left(\Delta M_{(k+1)e} - \Delta M_{m,(k+1)e}\right)\ , \quad (14)$$

here index n designates the number of height of the encapsulant at the crystal length (with the meniscus height) relating to the current "crystal-meniscus" state, index k+1 corresponds to the maximal quantity of the encapsulant heights at the crystal length (with the meniscus height) relating to the current "crystal-meniscus" state.

Thus, in Eq. (14) mass deviation ΔM without influence of encapsulant is expressed through the measured deviation signal $\Delta M_{\Sigma,ne}$ (with influence of encapsulant) at the previous levels of the encapsulant, meniscus mass deviation ΔM_m and meniscus mass deviation $\Delta M_{m,n,e}$ which was in the past corresponding to the (n) level of encapsulant.

Taking into account the densities of A3B5 material and encapsulant (for GaAs and B_2O_3 as encapsulant: ρ_s = 5.32 g/cm^3, ρ_l = 5.71 g/cm^3, ρ_e = 1.67 g/cm^3) it is possible to neglect with part $\frac{\rho_e(\rho_l - \rho_s)}{\rho_l(\rho_s - \rho_e)}$) of Eq. (14)

because it is equal to approximately 0.031. Then Eq. (14) should be written as the next:

$$\Delta M = \frac{\rho_s}{\rho_s - \rho_e} \sum_{n=0}^{k} (-1)^n \frac{\rho_e^n}{(\rho_s - \rho_e)^n} \Delta M_{\Sigma,ne} - \sum_{n=1}^{k+1} (-1)^n \frac{\rho_e^n}{(\rho_s - \rho_e)^n} \Delta M_{m,ne} + (-1)^{k+1} \frac{\rho_e^{k+1}}{(\rho_s - \rho_e)^{k+1}} \Delta M_{(k+1)e} \quad (15)$$

Designating $a_n = (-1)^n \frac{\rho_s}{\rho_s - \rho_e} \cdot \frac{\rho_e^n}{(\rho_s - \rho_e)^n}$ and $c_n = (-1)^n \cdot \frac{\rho_e^n}{(\rho_s - \rho_e)^n}$ Eq. (15) can be written as follows:

$$\Delta M = \sum_{n=0}^{k} a_n \Delta M_{\Sigma,ne} - \sum_{n=1}^{k+1} c_n \Delta M_{m,ne} + (-1)^{k+1} \frac{\rho_e^{k+1}}{(\rho_s - \rho_e)^{k+1}} \Delta M_{(k+1)e} \quad (16)$$

Estimations of the factors a_n and c_n depending on the number n of the encapsulant heights are presented in table 1.

Table 1 Factors a_n and c_n of the Ex. (16) depending on the number n of the encapsulant heights.

n	0	1	2	3	4
a_n	1.4575	-0.667	0.305	-0.14	0.064
c_n	–	0.4575	-0.209	0.096	-0.044

As it is shown in the table 1 the sequences a_n and c_n are fading. Therefore, there is no sense to consider data from the 5-th number of the encapsulant height and further in the past. Practical use of the Eqs. (14) – (16) meets some difficulties connected with necessity to know, at each period of control, the deviation of the meniscus mass $\Delta M_{m,ne}$ and real height of the encapsulant. But this deviation of the meniscus mass and real height of the encapsulant can be estimated with a special "observer" developed (see for example [2]).

3 Conclusions

Modification of weight signal of LEC, VCZ crystal growth processes was produced based on the knowledge of the weight signal in the past during the pulling process. Modified weight signal added with "observer" of the real meniscus mass and real encapsulant height can be used for the direct weight control in LEC, VCZ crystal growth processes. The influence of the weight signal in the past during the pulling process decreases with increase of the crystal length.

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