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Energy consumption of silicon crystal growth

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Abstract. We calculate the energy consumption of several methods of silicon crystal growth. The results indicate that the methods designed to produce cylindrical crystals are the methods which require the minimum amount of energy. They also indicate that in the majority of the methods studied the energy employed in the growth of the crystals is very small in comparison with the total amount of energy consumed in the complete manufacturing process of Si solar cells. This information indicates that in the design of new equipments we do not have to strive trying to reduce the energy consumption of the system, but instead focus our attention on other aspects, such as the quality of the crystals or the price of the equipment.

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1. Introduction

The life of mankind in its present form heavily depends on an adequate supply of energy. At present, nearly 50% of the energy requirements of the industrialized countries still depends on petroleoum. This dependence obviously conceals a threat to the future of mankind, and we are forced to hasten our study of alternataive sources of energy in order to be ready when petroleoum begins to scarce.

Solar energy is one of the alternatives which will be helpful in the coming future. At present, photovoltaic solar energy does already exist, but its applications are limited to small systems and space-related technology, because the manufacturing of solar cells is more expensive in comparison with other sources of electrical energy.

In the technology of photovoltaic cells it is important to know the amount of energy employed in the manufacturing of the cells. This amount of energy determines the payback time of the cell, i.e., the time that the cell must operate in order to generate an amount of energy equal to the energy employed in its own production.

The production process of Si solar cells involves, in general, three stages: (i) purification of the silicon, (ii) growth of the silicon crystals and (iii) slicing of the crystals and assembling of the cells. There are calculations concerning the first and third stages of this process [1]. This article deals basically with the second stage.

There are many procedures to obtain Si crystals, and a comparative study of the energy consumption of these processes has not been done. The purpose of the present paper is to evaluate the energy consumption of thirteen processes designed to grow Si crystals which have been reported in the Journal of Crystal Growth [2-14].

2. Evaluation methods

The procedures of silicon growth considered in this article can be divided in three groups:

1) Procedures designed to produce cylindrical crystals (Czochralski, floating zone and pedestal techniques).
2) Procedures designed to obtain silicon sheets starting from a melt (Dendritic web, Stepanov, horizontal growth and supported growth techniques).
3) Procedures based on vapor deposition (CVD method).

To evaluate the energy consumed in each of the processes that will be studied in this article it is necessary to calculate:

a) the energy required to melt the silicon (for processes of groups 1 and 2 only),
b) the energy leaving the system due to thermal conduction, convection and radiation,
c) the energy consumed in the decomposition of the silicon-containing vapor used (only in processes of group 3).

To explain how to calculate these three contributions the following symbols will be used:

G energy consumed in the growth process considered,
Q energy required per unit mass to melt the silicon,
A area of the growing surface
v growth speed
ρ density of silicon
q_k heat flow due to conduction through the walls of the growing system
q_c heat flow due to convection
q_r heat flow due to radiation
q_{kr} heat flow through the crystal, involving conduction and radiation
q_d energy consumed in the decomposition of the silicon-containing vapor ($SiHCl_3$ or SiH_4).

Then, to calculate the energy consumed in the processes of the first two groups, we can use the following equation:

$$G = Q + \frac{q_k + q_c + q_r + q_{kr}}{\rho v A}, \tag{1}$$

and for the processes of the third group, the equation

$$G = \frac{q_k + q_c + q_r + q_d}{\rho v A}. \tag{2}$$

The methodology to calculate the values of the parameters q_k, q_c, q_r, q_{kr} and q_d is explained below.

The heat flow due to conduction, q_k, was calculated by means of the well-known

Fourier law [16]

$$q_k = -Sk\frac{dT}{dx}, \tag{3}$$

where k is the thermal conductivity and S the area of the surface considered.

The heat flow due to convection, q_c, was estimated according to the Newton's law of cooling [16], which states that the heat flow q_c between a gas at temperature T_g and a surface at temperature T_s is equal to

$$q_c = Sh(T_s - T_g), \tag{4}$$

where S is the area of the surface in contact with the gas, and h is the heat transfer coefficient. In general, the calculation of h is difficult because it depends on the shape of the surface and the physical properties of the gas. Moreover, h depends on the type of convection, which can be free or forced. For free convection we used an empirical equation given in Ref. [16]. For forced convection another empirical equation was used [17].

To calculate the heat flow due to radiation, denoted q_r, we employed the Stefan-Boltzmann's law [15]. According to this law, if we have a surface of emisivity, e, area S and temperature T_1, enclosed by a second surface at a different temperature T_2, the radiated power from the inner to the outer surface in given by

$$q_r = S\sigma e\left(T_1^4 - T_2^4\right), \tag{5}$$

where $\sigma = 5.669 \times 10^{-12}$w cm^{-2}K^{-4}.

The heat flow q_{kr} passing through the crystal is a combination of conduction and radiation. The value of this parameter must be equal to the power required to mantain one of the ends of the crystal at the melting temperature T_m. For a cylindrical crystal of radius r we have [20]

$$q_{kr} = (6.67 \times 10^{-6})(ek)^{1/2} r^{3/2} T_m^{5/2}, \tag{6}$$

where e and k are the emisivity and thermal conductivity of the crystal at the temperature T_m. For ribbon-shaped crystals a similar reasoning leads to the equation

$$q_{kr} = \left(\frac{4e\sigma kS}{5}\right)^{1/2} uT_m^{5/2}, \tag{7}$$

where u and S are the width and thickness of the ribbon, respectively.

Finally, the decomposition energy q_d was calculated from the known values of the dissociation energies of the compounds $SiHCl_3$ and SiH_4 [18,19].

The details of all the calculations can be found in Ref. [21].

3. Results

For each of the thirteen processes examined, four factors were calculated: G, PC, E and T. The meanings of these numbers are explained below.

The parameter G is the energy consumed in the processes considered, as mentioned in the previous section.

The parameter PC is the percentage which G represents of the total energy consumed in the manufacturing of a solar cell. If we call a and b the amounts of energy consumed in the first (purification) and third (slicing and assembling) steps of the production process of a Si solar cell, the value of PC is given by the equation

$$PC = \frac{G/\xi}{(a+G)/\xi + b} \times 100, \tag{8}$$

where ξ is the fraction of the grown Si crystals which is actually transformed into solar cells. The remaining fraction $(1-\xi)$ becomes useless during the process of slicing and assembling, or is rejected in quality control tests. According to L.P. Hunt [1], the values of a and b are 621 kwh/kg and 138 kwh/kg, respectively. The value of ξ is 0.18 for processes of groups 1 and 3, and 0.36 for processes of group 2.

The parameter E is the total energy consumption of each cell. The value of this parameter can be calculated with the equation

$$E = \left[\frac{(a+G)}{\xi} + b\right] m, \tag{9}$$

where $m = 2.84 \times 10^{-4}$ kg is the mass of a Si wafer of 4 cm^2 of area and 300 μm of thickness.

Finaily, T is the payback time of the cell. The value in hours of T can be calculataed from

$$T = \frac{E}{p}, \tag{10}$$

where p is the power generataed by a single Si cell. To transform this number of hours into years we assumed that a solar cell works five hours daily, and therefore

$$T = \frac{E}{p} \times (5 \times 365)^{-1} \qquad (T \text{ in years}). \tag{11}$$

Assuming an approximate value of $I = 10^{-4}$ kw/cm^2 for the flux of solar energy reaching the Earth, and considering that a solar cell has an approximate area of $S = 4$ cm^2, the power p is given by

$$p = SI\eta, \tag{12}$$

Ref.	Method	G(kwh/Kg) calculated	experimental	ξ	PC	E(kwh)	η	T(years)
2	Czochralski	8.3	15	0.18	2.3%	1.04	0.18	7.9
3	Floating zone	13.4	15.2	0.18	2.3%	1.04	0.18	7.9
4	Pedestal	9.5	8.0	0.18	1.2%	1.03	0.18	7.8
5	Pedestal	9.0		0.18	1.4%	1.03	0.18	7.8
6,7	Dendritic web	103		0.36	13.3%	0.61	0.125	6.7
8	Edge-supported	16		0.36	2.3%	0.54	0.13	5.7
9	Stepanov	349		0.36	34.2%	0.80	0.118	9.3
10	Stepanov	12.6		0.36	1.8%	0.54	0.118	6.3
11	Horizontal ribbon	47		0.36	6.5%	0.57	0.1	7.8
12	Supported growth	844		0.36	55.7%	1.19	0.1	16.3
13	Vapour deposition	1590	467	0.18	42.0%	1.02	0.12	11.6
14	Vapour deposition	74-146	100	0.18	13.4%	0.44	0.06	10.0

TABLE I.

where η is the efficiency of the cell.

The values that we obtained for the parameters G, PC, E and T, corresponding to each of the thirteen processes examined, are shown in Table 1.

4. Discussion and conclusions

The results presented in Table 1 show that the methods of the first group (methods designed to obtain cylindrical crystals) are the methods which require the minimum amount of energy. This fact is clearly shown by the extremely small values of the parameter PC.

The methods of the second group (methods which produce Si sheets) require considerably more energy. However, the method with the shortest payback time can be found in this group.

Finally, the methods of the third group (methods based on vapor deposition) are, in the mean, the methods which require the greatest amounts of energy and have the longest payback times.

In general, the values presented in Table 1 reveal that the energy spent in most of the crystal growth processes represent a very small fraction of the total amount of energy consumed during the complete manufacturing process of the cells. This information is specially useful in the design of new equipment for growing Si crystals. It shows that we do not have to strive trying to reduce the energy consumption of

the system, but instead focus our attention on the improvement of the crystals quality and the reduction of the equipment's price.

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Resumen. En este trabajo se calculan los consumos de energía que se requieren en diferentes métodos de crecimiento de silicio. Los resultados indican que los métodos que utilizan menor energía son aquéllos diseñados para producir cristales cilíndricos. También se observa que en la mayoría de los métodos analizados la energía empleada en el crecimiento del cristal es muy pequeña comparada con la energía total consumida en el proceso completo de manufactura de una celda solar. Esto indica que en el diseño de nuevos equipos de crecimiento el esfuerzo no debe enfocarse en minimizar el consumo de energía, sino en mejorar la calidad de los cristales o bien en reducir el costo del equipo.