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DEVELOPMENT OF ADVANCED METHODS FOR CONTINUOUS
CZOCHELSKI GROWTH

Silicon Sheet Growth Development for the Large Area Silicon Sheet
Task of the Low-Cost Silicon Solar Array Project

Second Quarterly Progress Report, January 1–March 17, 1978

By
R. G. Wolfson
C. B. Sibley
C. P. Chartier

March 17, 1978

Work Performed Under Contract No. NAS-7-100-954884

Varian Associates
Lexington Vacuum Division
Lexington, Massachusetts

MASTER

U.S. Department of Energy

Solar Energy

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DEVELOPMENT OF ADVANCED METHODS
FOR CONTINUOUS CZOCHRALSKI GROWTHSilicon Sheet Growth Development for the
Large Area Silicon Sheet Task of the Low-
Cost Silicon Solar Array Project

SECOND QUARTERLY PROGRESS REPORT

by

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March 17, 1978

Reporting Period January 1, 1978 to March 17, 1978

JPL Contract No. 954884

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The JPL Low-Cost Silicon Solar Array Project is sponsored by the U. S. Department of Energy and forms part of the Solar Photovoltaic Conversion Program to initiate a major effort toward the development of low-cost solar arrays. This work was performed for the Jet Propulsion Laboratory, California Institute of Technology by agreement between NASA and DOE.

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1.0

SUMMARY

The overall purpose of this two-stage program is the demonstration of continuous Czochralski growth. In Stage 1, an existing Varian 2850 Czochralski furnace is to be modified for continuous growth by recharging; in Stage 2, a new puller is to be designed and shown capable of producing 100 kg of crystal from the same crucible with an after-grind yield of at least 70%.

The first stage of the program has progressed to the final assembly of the recharging system on the Czochralski furnace. All components are in place and functional, and the modified furnace is being tested prior to the start of process development. The feasibility of a 100 kg continuous growth process has been demonstrated by a recharge simulation comprising six melt/pull cycles with a single 20 kg charge; the total body length was 249 cm (98 inch) with a calculated mass of 106 kg. Growth conditions were maintained for 67 hours with neither machine malfunction, excessive SiO accumulation, nor crucible failure. Examination of the crucibles revealed that devitrification and deformation are primarily responsible for the decrease in the wall thickness, which reaches ~50% of the minimum starting thickness at the locus of maximum attack - the corner radius. The crucibles also showed no adherence to the residual charge, which may be due to the surface structure produced by the long-term exposure of the silica to molten silicon.

The second stage of the program is about to begin with design layouts of the new puller and general configurational studies.

INTRODUCTION

The overall purpose of this program, which began on October 16, 1977, is the demonstration of continuous Czochralski growth, defined as a throughput of silicon that produces 100 kg of single-crystal material, 10 cm or greater in diameter, from one common container. The two prime constraints on the process to be developed are as follows:

- It is to be amenable to scaling up to large-quantity, minimum-cost processing of silicon consistent with the established cost goals of ~\$2,000 per peak kilowatt for completed arrays by 1982 and ~\$500 per peak kilowatt by 1986.
- It is to be capable of producing silicon with the purity and the degree of structural perfection required for the subsequent fabrication of solar cells with a terrestrial efficiency greater than 14%.

The program is in two coordinated stages, each of which yields a functioning Czochralski puller. In Stage 1, an existing Varian 2850 Czochralski furnace has been modified for continuous growth by recharging, and the feasibility of 100 kg growth cycles has been demonstrated by simulation. Continuous Czochralski growth is now to be accomplished using batch recharging with granular silicon; in addition, continuous recharging with granular silicon is to be attempted, and recharging with molten silicon is to be considered. In Stage 2, a new, prototype Czochralski puller is to be designed and shown capable of producing 100 kg of crystal from the same crucible with an after-grind yield of 70% or greater.

The furnace modification and the 100 kg recharge simulation, both accomplished during the current reporting period, had fallen behind schedule. The concomitant delays had been reported to JPL, and the Program Plan had been adjusted accordingly. The start dates of the several Stage 2 tasks were not affected.

3.0 RESULTS

3.1 Furnace Modification

The recharging system has been assembled on the Varian 2850 Czochralski furnace with all components in place and functional. The principal layout drawings are presented in Appendix I. The most difficult phase was the installation of the lower feeder tube, which required that a port be opened through the water jacket of the furnace chamber. The internal baffle of the water jacket was redirected in the vicinity of the port in order to maintain effective cooling; the lower feeder tube was aligned with reference to both the remainder of the recharging system and the hot zone of the furnace, after which it was welded into position; and, finally, the feeder was wound with copper tubing for additional water cooling.

The operation of the recharging system at atmospheric pressure and at reduced pressures is smooth and continuously adjustable from a one-piece-at-a-time mode to a stream. The feed material passes through the charge-isolation valve and the inner guide tube without excessive bunching and then flows evenly down the lower feeder tube into the crucible. The rate of recharging is nicely controlled for granular polycrystalline silicon up to several centimeters long by from one to two centimeters across. Pieces longer than

about five centimeters and very fine chips tend to feed more rapidly than is desirable; if necessary, these very large and very small sizes can be accommodated by the addition of baffles to regulate the flow.

3.2 100 kg Growth Cycle

The feasibility of 100 kg continuous growth was demonstrated by simulation; viz., by pulling and remelting one 15 cm (6 inch) diameter ingot for a sufficient number of cycles, using a 20 kg charge contained in a 12 inch crucible. The first, unsuccessful attempt at recharge simulation was described in the last quarterly progress report. Three more trials were made during the present quarter. The second ended during the growth of the fourth ingot, after 40 hours, and yielded a total body length of 14 cm (55 inch) with a calculated mass of ~60 kg. The third trial continued into the remelt portion of the fifth cycle, lasting 46 hours; it simulated the growth of 177 cm (69½ inches) and 76½ kg. The fourth and last recharge simulation was successful in that six ingots with a total body length of 249 cm (98 inches) and a calculated mass of 106 kg were pulled from the same melt. It also demonstrated that Czochralski growth at reduced pressure can continue for 67 hours with neither machine malfunction, excessive accumulation of silicon monoxide, nor crucible failure. However, not one of the six crystals remained free of dislocations for more than 2½ inches below the crown, and, as seems to be generally true of such large diameter ingots, the loss of dislocation-free growth was eventually followed by the appearance of polycrystalline regions. There were no obvious trends; the last crystal growth did not differ perceptibly from the first. Indeed, since the sixth crystal

was dislocation-free for the first 2 inches, it appears that the problem is one of growth technique rather than impurity build-up. In retrospect, the pull rate, which averaged 6.5 cm per hour (2.5 inches per hour; 2.7 kg solidified per hour), was probably too high.

3.3 Crucible Examination

The recharge simulations provided sufficient used crucible sections to assess the effects of long-term exposure to molten silicon. The most salient observation is that the corrosion due to the reduction of the silica by silicon is negligible in comparison with the effects of devitrification and deformation. The corrosion rate is discussed in Section 4.2 in the context of silicon monoxide evolution.

Devitrification and deformation decrease the wall thickness to a far greater extent than reduction by the melt, but neither of these processes appears to pose an insuperable threat to the integrity of the crucible. Devitrification of the fused silica produces a uniform crust about 3/4-1 mm (0.03 - 0.04 inch) thick over the entire outside surface of the crucible. As is usually true, the devitrification proceeds slowly once steady state is reached, and the thickness of the crust after the 67 hour recharge simulation was not appreciably greater than after a conventional 12 hour crystal growth. Because of the density increase upon crystallization, the crust is friable and easily chipped off at room temperature, leaving a glossy, irregular surface. There is an additional, pronounced thinning of the crucible wall at the corner radius; i.e., at the locus of the minimum radius at curvature. This is also

the location of the highest temperature and of the greatest room-temperature mismatch between the crucible and the graphite cup that supports it. Most likely, the crucible is merely stretched thin to conform to the contour of the cup in this region. Although accelerated reduction of the silica by the molten silicon probably occurs here because of the high temperature, the state of stress, and enhanced fluid flow in the melt, the effect is evidently small. Indeed, the thinning does not appear to proceed rapidly during its later stages, since the wall thickness in the affected area is approximately the same after 40 hours and after 67 hours at temperature.

The combined result of the several processes which act to thin the crucible wall is to reduce the thickness to about 1.5 mm (0.06 inch) at the corner radius, where the minimum starting thickness is 3 mm (0.12 inch). This is clearly the zone of maximum attack, and it is here that the crucible will eventually fail from extended use.

A most interesting and unexpected phenomenon was observed after each of the four recharge simulations: there was essentially no bonding between the crucible and the residual melt which had been allowed to freeze in situ at the end of growth. In no case did the crucible adhere to the silicon. Examination of the inner surface of the crucible revealed that it was comprised of an array of ridges and valleys parallel to successive positions of the melt surface. It may be that this surface structure precludes appreciable wetting by the melt; another possibility is that the ridged interface provides a low-strength path for parting. One obvious application for such a non-adherent quartz crucible is the horizontal zoning of silicon, which would permit the use of current germanium technology, with a potentially large reduction in the add-on cost for solidification.

4.0 DISCUSSION

4.1 Remelting of Silicon Ingots

The most difficult aspect of the recharge simulations proved to be the remelting of the ingots. Indeed, two of the four simulations were terminated prematurely when the ingot was advanced too rapidly into the melt and touched the bottom of the crucible, snapping off at the seed. The occurrence of two such accidents requires explanation. Also, since the lowering of a one-piece polycrystalline rod has potential for both batch and continuous recharging, our limited experience on this mode of melt replenishment may be useful.

The remelting of the silicon ingots was accomplished in the following manner. With a residual melt of 2-3 kg, on the order of 2 cm deep, the crucible was brought to its lowest position within the hot zone, the power input was increased to 79 kVA, and the crystal was lowered to a position just above the melt surface. After preheating, the remelt was begun by touching the crystal to the melt. When the molten silicon pulled away from the ingot, signalling the melting off of the tip, the crystal was advanced about 3 mm (1/8 inch), and the procedure was repeated.

It was subsequently realized, however, that this incremental advance could be safely maintained for only a few inches. As the mass of molten silicon increased, the crystal began to melt more rapidly at the periphery, and the originally flat interface gradually developed a protrusion at its center. This change was not apparent to the operator; the meniscus at the central spike was hidden by the ingot itself, and the liquid column still appeared to fall away abruptly with melt-back. The spike slowly elongated, and,

by the time that remelting was half completed, it was long enough to preclude any acceleration of the procedure. This was the cause of the two accidents. After about one hour of incremental 3 mm advances, with a deep melt and an apparently short length of ingot remaining, the operator increased the rate of advance -- with disastrous results.

4.2 Silicon Monoxide Evaporation and Crucible Corrosion

Silicon monoxide is evolved by the melt as the product of its reduction of the silica crucible, and its rate of evaporation limits the rate of crucible corrosion. The discussion presented below shows that there is good agreement between theory and experience on the rates of both evaporation and reduction; it supports our contention that crucible corrosion per se is not a likely failure mechanism.

The mass evaporation rate Γ of a pure substance is given by the Hertz-Knudsen equation:*

$$\Gamma = m(dN/dt) = \alpha_v (m/2\pi kT)^{+1/2} (p^\bullet - p)$$

where dN/dt = the number of molecules evaporating from unit surface area during time dt ;

m = the mass of the evaporant molecule;

α_v = the evaporation coefficient, defined as the ratio of the observed rate in vacuo to the theoretical maximum rate;

* See, for example, R. Glang In "Handbook of Thin Film Technology" (L.I. Maissel and R. Glang, eds.), p 1-26 ff. McGraw-Hill, New York (1970).

k = Boltzmann's constant;
 T = the absolute temperature in $^{\circ}\text{K}$;
 $p^{\bullet}$ = the equilibrium vapor pressure of the
 evaporant in the pure state;
 p = the hydrostatic pressure of the evaporant
 in the gas phase.

Under the conditions that obtain during the Czochralski growth of silicon at reduced pressure, it can be assumed that the evaporation surface is uncontaminated and that the evaporant is swept away before appreciable recondensation occurs. Thus, α_v goes to unity, p vanishes, and the rate equation assumes its maximum theoretical value:

$$\Gamma = (m/2\pi kT)^{+1/2} p^{\bullet}$$

When the evaporant is a component of a solution, its vapor pressure is decreased below that of the pure substance. This is expressed by Raoult's law, which states that the vapor pressure p_i' of the i th component in the solution is proportional to the product of its mole fraction x_i and its equilibrium vapor pressure $p_i^{\bullet}$ in the pure state.

$$p_i' = f_i x_i p_i^{\bullet}$$

The constant of proportionality, the activity coefficient f_i , is defined by this relationship. (It reaches its maximum value of unity for an ideal solution.) The mass evaporation rate of component i is, thus,

$$\Gamma_i = (m_i/2\pi kT)^{+1/2} (f_i x_i p_i^{\bullet})$$

Evaluation of the constants and introduction of the gram molecular mass M_i yields

$$r_i = 5.83 (10^{-2}) (M_i/T)^{+1/2} (f_i \times_i p_i^{\bullet})$$

where the rate is in g per cm^2 -sec for pressure in Torr. Applying this last expression to the evolution of silicon monoxide from molten silicon contained in quartz,

$$\begin{aligned} r_{\text{SiO}} &= 9.39 (10^{-3}) p_{\text{SiO}}' \\ &= 9.39 (10^{-3}) f_{\text{SiO}} \times_{\text{SiO}} p_{\text{SiO}}^{\bullet} \end{aligned}$$

for $M_{\text{SiO}} = 44.1$ g and $T = 1700^{\circ}\text{K}$. The identification of the evaporant as silicon monoxide is supported by the recent mass spectrometric investigation of Wills and Niesz;* the results show that the vapor-phase concentration of oxygen and all other oxygen-bearing species above the melt are negligibly small compared with that of the monoxide. The vapor pressure p_{SiO} can be evaluated from data in the general literature by means of Raoult's law. Using the commonly accepted values for the equilibrium vapor pressure of pure silicon monoxide** and for the solubility of oxygen

* R.R. Wills and D.E. Niesz, "Development and Evaluation of Die and Container Materials" (Silicon Sheet Task of the Low Cost Silicon Solar Array Project). JPL Contract No. 954876, First Quarterly Progress Report (January 18, 1978), Tables 5 and 6.

** C.E. Drumheller In "Seventh National Symposium on Vacuum Technology Transactions" (C.R. Meissner, ed.), p 306. Pergamon, New York (1961).

in silicon[†] near the melting temperature,

$$p_{\text{SiO}}^{\bullet} = 9.1 \text{ Torr}$$

$$x_{\text{SiO}} = 1.8 (10^{-4}) / 1.25$$

$$= 1.4 (10^{-4})$$

and assuming that this very dilute solution behaves ideally with unit activity coefficient,

$$p_{\text{SiO}}' = 1.3 (10^{-3}) \text{ Torr}$$

which yields, upon substitution into the rate equation,

$$r_{\text{SiO}} = 1.2 (10^{-5}) \text{ g per cm}^2\text{-sec}$$

This value is 3 times larger than the rate determined by Schmid and Khattak* from crucible wall recession measurements:

$$4.2 (10^{-6}) \text{ g per cm}^2\text{-sec}$$

It is 11 times larger than the minimum rate determined in our

[†] W. Kaiser, P. M. Keck, and C.F. Lange, J. Appl. Phys. 28, 882 (1957); Y. Yatsurugi, N. Akiyama, E. Nozaki, and T. Nozaki, J. Electrochem. Soc. 120, 975 (1973).

* F. Schmid and C.P. Khattak, "Heat Exchanger - Ingot Casting/Slicing Process" (Silicon Sheet Task of the Low Cost Silicon Solar Array Project). JPL Contract No. 954373, Eighth Quarterly Progress Report (October 1, 1977), pp 35-36.

laboratory* by collecting and weighing the silicon monoxide deposited within the furnace during Czochralski growth:

$$1.1 (10^{-6}) \text{ g per cm}^2\text{-sec}$$

(The above rate is termed a minimum since some silicon monoxide is known to have been carried away in the argon stream.) Clearly, there is sufficiently good agreement between theory and experience to recommend confidence in the results.

The mass evaporation rate can be used to estimate the crucible corrosion, provided that the reduction of the quartz by the molten silicon is limited by the loss of the product silicon monoxide. Since the value calculated from the maximum theoretical expression for Γ is the larger, it will be employed in what follows. The pertinent dimensions of the crucible are given below.

The standard 12 x 9 inch fused quartz crucible used in the present study has the following nominal dimensions: 29.6 cm inside diameter, 22.4 cm inside height, 5.08 cm corner radius, and 40.0 cm bottom radius. For ease of calculation, it can be divided into a lower part approximating half an ellipsoid of revolution with volume $2,380 \text{ cm}^3$ and surface area 840 cm^2 , and an upper, cylindrical part of length 17.8 cm with volume 688 cm^3 per cm of length and surface area 93 cm^2 per cm of length. With a 20 kg charge of silicon, the melt fills the crucible to a depth of 12.6 cm and covers 1580 cm^2 of inner surface; the free surface of the melt has an area of 688 cm^2 .

* Research Journal No. 100, p 24. Varian Associates, Lexington Vacuum Division, Lexington, MA.

The total mass evaporation rate of silicon monoxide from the free surface of the melt is

$$0.0083 \text{ g SiO per sec}$$

neglecting both the loss of evaporation surface to the crystal-melt interface and the reduction in area when the melt level falls into the rounded bottom of the crucible (depth less than 4.6 cm; mass less than 6.1 kg). Since one formula weight of silica is converted to two of silicon monoxide, the mass and volume removal rates of material from the crucible are, respectively,

$$0.0056 \text{ g SiO}_2 \text{ per sec}$$

$$0.0021 \text{ cm}^3 \text{ SiO}_2 \text{ per sec}$$

with the density set equal to 2.65 g per cm^3 as was done by Schmid and Khattak (loc.cit.). The volume removal rate can be divided by the effective surface area of the crucible in contact with the melt to yield a depth removal rate; using the full area covered by a 20 kg charge gives

$$0.0048 \text{ cm per hr}$$

$$0.0019 \text{ inch per hr}$$

This rate of wall recession is approximately three times larger than that reported by Schmid and Khattak, as would be expected from the difference between the theoretical and observed mass evaporation rates. It is also twice the empirical "one mil per hour" rule-of-thumb which has general

currency in the silicon industry. Thus, the reduction of silicon dioxide by the molten silicon is sufficiently slow to obviate concern that the crucible will be breached by this process alone during a 100 kg growth cycle.

During recharging, as contrasted with recharge simulation, the reduction of the silica crucible would be hastened by the repeated addition of charge material unsaturated with oxygen. According to the continuous growth cycle proposed in the First Quarterly Report*, the production of 100 kg of usable crystal would require a throughput of 106 kg. Assuming that the charge is oxygen-free, saturation of the ingots and the residual melt would require approximately 12 g of oxygen. Making the conversions presented above, this corresponds to 22 g of silica, 8.3 cm³ of silica, and 0.13 mm (0.0052 inch) of wall recession. In other terms, the maximum quantity of crucible material required to saturate the silicon with oxygen is about as much as would be consumed by evaporation (at the maximum theoretical rate) during 2-3/4 hours. This is an insignificant amount.

4.3 Conclusions and Recommendations

It may be concluded, on the basis of the 100 kg recharge simulation, that such extended growth cycles are within the capabilities of a suitably modified Czochralski furnace using standard quartz crucibles. (The minimum wall thickness specified for the corner radius may be increased, as a precaution.) Unfortunately, the failure to maintain dislocation-

* R. G. Wolfson and C. B. Sibley, "Development of Advanced Methods for Continuous Czochralski Growth" (Silicon Sheet Task of the Low Cost Silicon Solar Array Project). JPL Contract No. 954884, First Quarterly Progress Report (January 11, 1978), Table II.

free growth beyond the first 2 inches of body length precludes drawing any conclusions about attainable crystal quality, although the problem seems to have been one of growth technique.

It is recommended that the absence of bonding between the crucibles used in the recharge simulations and the residual silicon charges be investigated further. In particular, it should be determined whether the ridged morphology produced on the crucible surface is responsible for the potentially useful non-adherent behavior.

5.0 PLANS

Plans for the immediate future are as follows:

- Completion of testing of the recharging system.
- Start of batch melt-replenishment experimentation.

Plans for the next quarter comprise both the development of batch-recharge process and the start of the design of all components of the prototype puller.

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APPENDIX I

New Technology

Engineering Drawings and Sketches

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NEW TECHNOLOGY

No new technology was generated during the reporting period.

ENGINEERING DRAWINGS AND SKETCHES

The principal layout drawings of the several components of the recharging system are presented:

- K6991 Chamber Weldment
- K7018 Feeder Assembly
- K7164 Retractable Chute Assembly

The detail and assembly drawings will be included in the next quarterly report, after the completion of testing.

Also presented here is the drawing of the port opened through the water jacket of the Varian 2850 Czochralski furnace:

- K7171 Transition Machining

1	K6991-001	FLANGE	K6991	1
2	K6992-001	FLANGE	K6992	2
3	K6993-001	FLANGE	K6993	3
4	K6994-001	FLANGE	K6994	4
5	K6995-001	BOTTOM FLANGE	K6995	5
6	K6996-001	BOTTOM FLANGE	K6996	6
7	K6997-001	BOTTOM FLANGE	K6997	7
8	K6998-001	BOTTOM FLANGE	K6998	8
9	K6999-001	TOP FLANGE	K6999	9
10	K7000-001	TOP FLANGE	K7000	10

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APPENDIX II

Man Hours and Costs

Program Plans, Updated

- Milestone Chart
- Direct Labor Summary
- Incurred Cost Summary

MAN-HOURS AND COSTS

During the reporting period January 1, 1978 to March 17, 1978, total man-hours were 1,227 and total costs were \$58,197. The previous totals were 1,466 man-hours and \$56,378. As of March 17, 1978, the cumulative totals were thus 2,693 man-hours and \$114,575.

DEVELOPMENT OF ADVANCED METHODS FOR CONTINUOUS CZOCHRALSKI GROWTH

Varian Associates/Lexington Vacuum Division
JPL Contract 954884

SC-2 Program Plan
Page 1 of 3 pages

Recharging

1. Furnace Modification
2. 100 kg Growth Cycle
3. Batch Recharging with Solid
4. Continuous Recharging with Solid
5. Continuous Recharging with Liquid

Prototype Puller

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6. Lower Assembly: Design
Manufacture
7. Hot Zone and Power Supply
8. Crystal Lift Mechanism: Design
Manufacture
9. Upper Assembly: Design
Manufacture
10. Transducers and Control
11. Process Demonstration

Design Analysis Cost Study

12. Economic Model

MILESTONE CHART

RGW 10/22/77
Updated 3/17/78

DEVELOPMENT OF ADVANCED METHODS FOR CONTINUOUS CZOCHRALSKI GROWTH

Varian Associates/Lexington Vacuum Division
JPL Contract 954884

SC-2 Program Plan
Page 2 of 3 pages

RGW 10/20/77
Updated 3/17/78

Total Hours: 10,440
Hours to Date: 2,693

Planned - - - -
Incurred _____

DIRECT LABOR SUMMARY

DEVELOPMENT OF ADVANCED METHODS FOR CONTINUOUS CZOCHRALSKI GROWTH

Varian Associates/Lexington Vacuum Division
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SC-2 Program Plan
Page 3 of 3 pages

RGW 10/20/77
Updated 3/17/78

Total Cost: \$460,155
Cost to Date: 114,575

Planned - - - -
Incurred _____

INCURRED COST SUMMARY

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APPENDIX III

SUMMARY OF ECONOMIC ANALYSIS DATA

TABLE I

1978

ONE CRYSTAL GROWN FROM A 12 INCH DIAMETER CRUCIBLE
AT 55% AFTER-GRIND YIELD

Description of Czochralski Growth Process

A. Facilities and Operation

- Cost of Czochralski furnace: \$115,000
- Floor space per Czochralski furnace: 80 ft²
- Utilization of Czochralski furnace: 85%
- Operators per 13 Czochralski furnaces: 3 @ \$12,247/PRSN*YR [†]
- Foreman per 13 Czochralski furnaces: 1 @ \$16,330/PRSN*YR ^{††}
- Operating days per year: 345
- Shifts per day for round-the-clock operation: 4
- After-grind yield: 55%

B. Process

- Average solidification rate: 2 kg/hr
- Argon flow: 40 ft³ (standard)/hr
- Power for melting: 80 kw
- Power for steady-state growth: 60 kw
- Mass of taper: 1 kg
- Mass left in crucible: 1 kg

C. Cycle time

-- Clean furnace	0.5 hr
-- Load and melt charge (20 kg)	2.5 hr
-- Seed; grow neck, crown, and shoulder	1.0 hr
-- Grow body of crystal (18 kg)	9.0 hr
-- Grow taper (1 kg)	0.5 hr
-- Cool and remove crystal	1.5 hr
-- Maintain and repair furnace	2.5 hr
	17.5 hr.

[†]. Pay rate assumed equal to that of occupational classification 812884 (welder).

^{††} Pay rate assumed equal to that of occupational classification 726130 (assembly foreman).

1978 (continued)

Input Data

1.	Direct Equipment Initial Capital Cost		
	-- Czochralski furnace		<u>\$115,000</u>
		EQPT	\$115,000
2.	Direct Manufacturing Floor Space		
	-- Czochralski furnace		<u>80 ft²</u>
		SQFT	80 ft ²
3.	Annual Direct Labor Salaries		
	-- Operator/furnace-year		
	(3/13 operators/furnace-shift)(4 shifts/day)		
	(\$12,247/PRSN*YR)		\$ 11,305
	-- Foreman/furnace-year		
	(1/13 foreman/furnace-shift)(4 shifts/day)		
	(\$16,330/PRSN*YR)		<u>\$ 5,025</u>
		DLAB	\$ 16,330
4.	Directly Used Materials and Supplies [†]		
	-- Poly charge/furnace-year @ \$54.50/kg ^{††}		
	(20 kg/cycle) (473 cycle/year)		
	(\$54.50/kg)		\$515,570
	-- Crucible/furnace-year @ \$210 ea.		
	(1 crucible/cycle) (473 cycle/year)		
	(\$210 ea)		\$ 99,330

[†] The cost of the boron dopant required to produce a resistivity of 3 ohm-cm at the top of the crystal is on the order of \$0.01 per kg of poly; it has been omitted from these calculations.

^{††} This is the current price for grade 1 (semiconductor) poly in nugget form in lots of 1500 kg.

1978 (continued)

-- Argon/furnace-year @ \$0.0494/ft ³ [†]		
(13.5 hr/cycle) (473 cycle/year)		
(40 ft ³ /hr)(\$0.0494/ft ³)		\$ 12,618
-- Single-crystal seed/furnace-year @ \$150 ea.		
(1/15 seed/cycle)(473 cycle/year)		
(\$150 ea)		\$ 4,730
-- Miscellaneous/furnace-year, including		
graphite-component usage		
(473 cycle/year)(\$15/cycle)		<u>\$ 7,095</u>
	MATS	\$639,343
5. Direct Process Utilities Usage ^{††}		
-- Electricity/furnace-year @ \$0.03187/kw-hr		
[(1.5 hr/cycle)(80 kw) + (10.5 hr/cycle)(60 kw)]		
(473 cycle/year)(\$0.03187/kw-hr)		<u>\$ 11,306</u>
	UTIL	\$ 11,306
6. Annual Production		
-- (20 kg/cycle)(473 cycle/year)		
(0.55)		<u>5,203 kg</u>
	QUAN	5,203 kg

[†] This is the current price for ultrahigh purity argon, from liquid.

^{††} It is assumed that the cooling water is recirculated, with the total cost appearing in the appropriate overhead constant.

1978 (concluded)

IPEG Price

$$\text{Price} = [(C_1 * \text{EQPT}) + (C_2 * \text{SQFT}) + (C_3 * \text{DLAB}) + (C_4 * \text{MATS}) + (C_5 * \text{UTIL})] / \text{QUAN}$$

$$\text{where } C_1 = \$0.49/\text{year per dollar}$$

$$C_2 = \$97/\text{year per ft}^2$$

$$C_3 = \$2.1/\text{year per dollar}$$

$$C_4 = \$1.3/\text{year per dollar}$$

$$C_5 = \$1.3/\text{year per dollar}$$

In 1978 dollars,

$$\text{price} = \$944,247 / 5,203 \text{ kg}$$

$$= \$182 \text{ per kg}$$

In 1975 dollars,

$$\text{price} = \$151 \text{ per kg}$$

This price is comprised of two major components: the direct poly cost and the Czochralski add-on cost, the latter including the overhead applied to the poly cost. Further, if the crystal mass is converted to sheet area, this price can be combined with the 1978 wafer price goal allocation to yield the margin available for the wafering add-on cost.

Using the 1978 slicing yield of 0.6689 m^2 per kg, and expressing all costs in 1975 dollars,

1978 standardized price, PWAVERS	\$381 per m^2
direct poly cost	\$123 per m^2
Czochralski add-on cost	\$103 per m^2
margin available for wafering add-on cost	\$155 per m^2

TABLE II

1980

FIVE CRYSTALS (100 kg) GROWN FROM ONE 12 INCH DIAMETER CRUCIBLE [†] AT 55% AFTER-GRIND YIELD

Description of Czochralski Growth Process

A. Facilities and Operation

Same as 1978 with the following two exceptions:

- Cost of Czochralski furnace: \$147,600
- Floor space per Czochralski furnace: 100 ft²

B. Process

Same as 1978 with the following two exceptions:

- Argon flow: 60 ft³ (standard)/hr
- Mass left in crucible: 4 kg (crystals 1-4); 1 kg (crystal 5)

C. Cycle Time

Crystal 1:

-- Clean furnace	0.50 hr
-- Load and melt charge (20 kg)	2.50 hr
-- Seed; grow neck, crown, and shoulder	1.00 hr
-- Grow body of crystal (15 kg)	7.50 hr
-- Grow taper (1 kg)	0.50 hr
-- Cool and remove crystal during recharge	- -

Crystal 2:

-- Recharge (21½ kg)	1.50 hr
-- Seed; grow neck, crown, and shoulder	1.00 hr
-- Grow body of crystal (20½ kg)	10.25 hr
-- Cool and remove crystal during recharge	- -

[†] All costs are in 1980 dollars, except where a conversion to 1975 dollars is specified.

1980 (continued)

Crystal 3:

Same as Crystal 2 13.25 hr

Crystal 4:

Same as Crystal 3 13.25 hr

Crystal 5:

-- Recharge ($21\frac{1}{2}$ kg) 1.50 hr

-- Seed; grow neck, crown, and shoulder 1.00 hr

-- Grow body of crystal ($23\frac{1}{2}$ kg) 11.75 hr

-- Grow taper (1 kg) 0.50 hr

Maintain and repair furnace 12.00 hr

80.00 hr

Input Data

1. Direct Equipment Initial Capital Cost

-- Czochralski furnace \$147,600

EQPT \$147,600

2. Direct Manufacturing Floor Space

-- Czochralski furnace 100 ft²

SQFT 100 ft²

3. Annual Direct Labor Salaries [†]

-- Operator/furnace-year

(3/13 operators/furnace-shift)(4 shifts/day)

(\$14,285/PRSN*YR) \$ 13,186

-- Foreman/furnace-year

(1/13 foreman/furnace-shift) (4 shifts/day)

(\$19,047/PRSN*YR) \$ 5,861

DLAB \$ 19,047

[†] These are the 1978 salaries inflated at R = 0.08.

1980 (continued)

4.	Directly Used Materials and Supplies [†]	
	-- Poly charge/furnace-year @ \$61/kg ^{††}	
	(106 kg/cycle)(103.5 cycle/year)	
	(\$61/kg)	\$669,231
	-- Crucible/furnace-year @ \$245 ea	
	(1 crucible/cycle)(103.5 cycle/year)	
	(\$245 ea)	\$ 25,358
	-- Argon/furnace-year @ \$0.0576/ft ³	
	(66.5 hr/cycle)(103.5 cycle/year)	
	(60 ft ³ /hr)(\$0.0576/ft ³)	\$ 23,787
	-- Single-crystal seed/furnace-year @ \$175 ea	
	(1/3 seed/cycle)(103.5 cycle/year)	
	(\$175 ea)	\$ 6,038
	-- Miscellaneous/furnace-year, including	
	graphite-component usage	
	(103.5 cycle/year)(\$87/cycle)	<u>\$ 9,005</u>
		MATS \$733,419
5.	Direct Process Utilities Usage	
	-- Electricity/furnace-year, @ \$0.0400/kw-hr	
	[(7.5 hr/cycle)(80 kw) + (57.5 hr/cycle)(60 kw)]	
	(103.5 cycle/year)(\$0.0400/kw-hr)	<u>\$ 16,767</u>
		UTIL \$ 16,767
6.	Annual Production	
	-- (106 kg/cycle)(103.5 cycle/year)	
	(0.55)	<u>6,034 kg</u>
		QUAN 6,034 kg

[†] The 1978 costs were inflated at R = 0.08 for commodities and at R = 0.12 for energy.

^{††} This value is the 1980 price goal allocation.

1980 (concluded)

IPEG Price

Applying the IPEG price equation and overhead constants reproduced above, in 1980 dollars,

$$\begin{aligned}\text{Price} &= \$1,097,265/6,034 \text{ kg} \\ &= \$182 \text{ per kg}\end{aligned}$$

In 1975 dollars,

$$\text{Price} = \$135 \text{ per kg}$$

Using the 1980 slicing yield goal of 0.803 m^2 per kg, and expressing all costs in 1975 dollars,

1980 standardized price, PWAVERS	\$245 per m^2
direct poly cost	\$102 per m^2
Czochralski add-on cost	\$65.5 per m^2
margin available for wafering add-on cost	\$77.5 per m^2

TABLE III

1982

FIVE CRYSTALS (100 kg) GROWN FROM ONE 12 INCH DIAMETER CRUCIBLE [†]
AT 70% AFTER-GRIND YIELD

Description of Czochralski Growth Process

A. Facilities and Operation

Same as 1980 with the following two exceptions:

- Cost of Czochralski furnace: \$229,000
- After-grind yield: 70%

B. Process

Same as 1980.

C. Cycle time

Same as 1980.

Input Data ^{††}

1. Direct Equipment Initial Capital Cost

- Czochralski furnace \$229,000
- EQPT \$229,000

2. Direct Manufacturing Floor Space

- Czochralski furnace 100 ft²
- SQFT 100 ft²

3. Annual Direct Labor Salaries

- Operator/furnace-year
- (3/13 operators/furnace-shift)(4 shifts/day)
- (\$16,662/PRSN*YR \$ 15,380)
- Foreman/furnace-year
- (1/13 foreman/furnace-shift)(4 shifts/day)
- (\$22,217/PRSN*YR \$ 6,836)
- DLAB \$ 22,216

[†] All costs are in 1982 dollars, except where a conversion to 1975 dollars is specified.

^{††} These are the 1978 costs inflated at R = 0.07 for equipment, at R=0.08 for labor and commodities, and at R=0.12 for energy.

1982 (continued)

4.	Directly Used Materials and Supplies		
	-- Poly charge/furnace-year @ \$38/kg [†]		
	(106 kg/cycle)(103.5 cycle/year)		
	(\$38/kg)		\$416,898
	-- Crucible/furnace-year @ \$286 ea		
	(1 crucible/cycle)(103.5 cycle/year)		
	(\$286 ea)		\$ 29,601
	-- Argon/furnace-year, @ \$0.0672/ft ³		
	(66.5 hr/cycle)(103.5 cycle/year)		
	(60 ft ³ /hr)(\$0.0672/ft ³)		\$ 27,751
	-- Single-crystal seed/furnace-year @ \$204 ea		
	(1/3 seed/cycle)(103.5 cycle/year)		
	(\$204 ea)		\$ 7,038
	-- Miscellaneous/furnace-year, including		
	graphite-component usage		
	(103.5 cycle/year)(\$102/cycle)		<u>\$ 10,557</u>
		MATS	\$491,845
5.	Direct Process Utilities Usage		
	-- Electricity/furnace-year, @ \$0.0501/kw-hr		
	[(7.5 hr/cycle)(80 kw) + (57.5 hr/cycle)(60 kw)]		
	(103.5 cycle/year)(\$0.0501/kw-hr)		<u>\$ 21,001</u>
		UTIL	\$ 21,001
6.	Annual Production		
	-- (106 kg/cycle)(103.5 cycle/year)		
	(0.70)		<u>7,680 kg</u>
		QUAN	7,680 kg

[†] This value is the 1982 price goal allocation.

1982 (concluded)

IPEG Price

Applying the IPEG price equation and overhead constants reproduced above,
in 1982 dollars,

$$\begin{aligned}\text{Price} &= \$835,264/7,680 \text{ kg} \\ &= \$109 \text{ per kg}\end{aligned}$$

In 1975 dollars,

$$\text{Price} = \$71.6 \text{ per kg}$$

Using the 1982 slicing yield goal of 0.892 m^2 per kg, and expressing all
costs in 1975 dollars,

1982 standardized price, PWAVERS	\$128 per m^2
direct poly cost	\$40.0 per m^2
Czochralski add-on cost	\$40.3 per m^2
margin available for wafering add-on cost	\$47.7 per m^2