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LSSA LARGE AREA SILICON SHEET TASK
CONTINUOUS CZOCHRALSKI PROCESS DEVELOPMENT

Quarterly Report No. 3, April--June 1978

By
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July 1978

Work Performed Under Contract No. NAS-7-100-954887

Texas Instruments Incorporated
Dallas, Texas

U.S. Department of Energy

MASTER

Solar Energy

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ABSTRACT

A Czochralski crystal growing furnace is being set up to permit installation of a continuous molten silicon feed apparatus. Numerous modifications have been designed and constructed to convert a Varian 2898A furnace to a continuous mode of operation. New laboratory facilities to house the continuous furnace were prepared and assembly of the furnace has been completed. Furnace checkout will be carried out early in the next quarter.

Economic modeling of the continuous Czochralski process has continued utilizing the IPEG option of SAMICS. The influence of both crystal size and total furnace run size have been examined. Results of these studies indicate that for 10-cm diameter crystal, 100-kg furnace runs of four or five crystals each are near-optimal. Costs tend to asymptote at the 100-kg level so little additional cost improvement occurs at larger runs. For these conditions, crystal cost in equivalent wafer area of around \$20/m² exclusive of polysilicon and slicing is obtained.

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CONTINUOUS CZOCHRALSKI PROCESS DEVELOPMENT

Texas Instruments Incorporated

Quarterly Report

April - June, 1978

I. INTRODUCTION

This program is to demonstrate feasibility of a continuous Czochralski process employing liquid silicon melt replenishment during growth. An incoming flow of solid granular or nugget polysilicon will be premelted in a small auxiliary crucible from which liquid silicon will be introduced into the main or primary crucible. Liquid melt addition is being pursued since this replenishment technique should cause minimal thermal and mechanical disturbances to the primary melt thereby allowing high crystal productivity.

Figure 1 illustrates the continuous crystal growth machine being developed at Texas Instruments. A Varian 2848A puller was modified extensively to permit continuous silicon feed. Modifications include a new lower chamber addition of a high-temperature vacuum valve, and a modified upper chamber to accept a Hamco cable seed pull mechanism equipped with crystal weight readout. In addition, the polysilicon storage and feed components depicted in Figure 1 were constructed.

Additional economic modeling of this continuous Czochralski process was performed using previous assumptions.¹ Specifically, the effects of furnace run size and crystal size were examined with the interesting result that 100-kg runs consisting of four or five crystals are near-optimal. Crystal cost, expressed in equivalent sheet area, exclusive of polysilicon and slicing costs is around \$20/m².

II. TECHNICAL DISCUSSION

Figure 2 shows the latest program plan which was changed slightly from the previous plan. The major change is in the construction activity

1. S. N. Rea, "Continuous Czochralski Process Development", Quarterly Report, DOE/JPL-954887-78/2, April 1978.

which was stretched out two months to accommodate delays encountered in fabricating the puller components. Overall program duration was held constant at 15 months. All puller components with the exception of the auger feed and auxiliary melter are completed and the puller has been assembled ready for testing. Brief discussions are given below on key furnace elements.

A. Design, Test, and Construction

1. Lower Dome

A new lower chamber was designed and built which will accept the vacuum valve, auger feed, and auxiliary melter. A flat-top chamber was utilized in order to minimize overall puller height. The chamber is double-wall construction with water cooling. A 25-cm (10-inch) diameter side appendage 13 cm (5 inches) long is integral with the lower chamber to provide room for the auger feed and auxiliary melter. Engineering drawings of the chamber are contained in the Appendix.

2. Upper Chamber

The existing upper chamber is being utilized with the addition of transition sections designed and built to mate the vacuum valve and to attach the Hamco cable pull mechanism. Other minor modifications were effected in order to use the existing chamber lift mechanism.

3. Auger Feed

Delivery of the auger, supplied by an outside vendor, slipped badly--approximately 3-1/2 months. When received, the auger required extensive rework both to make it vacuum tight and to meet rather close tolerances required by overall system constraints. This rework is presently in progress.

4. Miscellany

The VAT vacuum valve was received in good working order. It has not been tested yet at high temperature but it will hold a vacuum within the furnace limits at room temperature.

The auxiliary melter power supply has been received and an additional control panel for the melter, hopper, auger, and crystal weight readout has been constructed.

B. Economic Analysis

The IPEG option of SAMICS was used to estimate costs of the continuous Czochralski process as a function of run size and crystal size. Basically, the same assumptions used previously¹ were employed with the key ones listed below.

1. Basic Assumptions

- a. 10-cm diameter crystal pulled at 10 cm/h
- b. Equipment cost is \$121,000
- c. 83% equipment utilization
- d. Furnace floor space is 150 ft²
- e. Two pullers per operator
- f. Direct labor costs \$5.00/h
- g. 100% yield/run results in 20 slices/cm crystal

In addition, operating supplies were assumed \$248/run exclusive of argon and crystal seeds up to 100 kg runs. For runs larger than 100 kg, supplies were increased 1% per kilogram per run. Thus, a 120 kg run would consume $(\$248)(1.2) = \297.60 in operating supplies. Argon costs are proportional to cycle time and were computed at \$1/h. This argon cost represents a decrease from past analyses and is based on measured argon flow through the puller at operating pressure of around 25 mm Hg.

2. Furnace Run Size

The sensitivity of crystal cost to run size was examined assuming a crystal weight of 20 kg exclusive of bottom taper. This crystal weight is convenient from a handling and length standpoint and is compatible with current practice. Table I gives pertinent data for this case along with the yearly costs used in IPEG.

A graph of the resulting crystal costs is shown in Figure 3. It is very interesting that the cost curves approach a minimum asymptote at about 100 kg/run. The reason for this is apparent from Table I. Yearly labor cost per furnace is independent of the number of runs and materials, utilities, and wafer output are essentially constant from 100 kg up. Thus, crystal costs flatten out and become independent of run size. As mentioned, material costs were increased proportional to run size above 100 kg. However, removing this restriction does not alter the fundamental result presented here. If materials were held constant at \$248/run, crystal costs at the 200 kg/run level would be only 8% lower than those shown in Figure 3.

TABLE I

COST PARAMETERS FOR VARIOUS RUN SIZES

<u>Run Size</u>	<u>Poly Charged</u>	<u>Cycle Time</u>	<u>Power</u>	<u>Runs/yr</u>	<u>Labor/yr</u>	<u>Mat'l's/yr</u>	<u>Utilities/yr</u>	<u>Wafers/yr</u>
20 kg	20.6 kg	16.9 h	740 kW-h	429.0	\$18,127	\$116,115	\$ 9,524	7345 m ² /yr
40	41.3	30.8	1420	235.4	18,127	68,327	10,028	8061
60	61.9	44.7	2100	162.2	18,127	50,258	10,219	8331
80	82.5	58.6	2800	123.7	18,127	40,753	10,391	8472
100	103.2	72.5	3530	100.0	18,127	34,905	10,590	8561
120	122.6	86.4	4180	83.9	18,127	35,089	10,521	8619
140	144.4	100.3	4870	72.3	18,127	35,239	10,563	8665
160	165.1	114.2	5550	63.5	18,127	35,343	10,573	8698
200	206.3	142.0	6930	51.1	18,127	35,511	10,624	8749

TABLE II

COST PARAMETERS FOR VARIOUS CRYSTAL SIZES

NOMINAL 100 kg RUNS

<u>No. Crystals</u>	<u>Crystal Weight</u>	<u>Cycle Time</u>	<u>Runs/yr</u>	<u>Labor/yr</u>	<u>Mat'l's/yr</u>	<u>Utilities/yr</u>	<u>Wafers/yr</u>
4	25 kg	69.4 h	104.4	\$18,127	\$35,600	\$10,600	8921 m ² /yr
5	20	72.5	100.0	18,127	34,900	10,600	8561
6	16.7	75.6	95.9	18,127	34,300	10,500	8225
7	14.3	78.6	92.6	18,127	33,800	10,500	7942
8	12.5	81.4	89.0	18,127	33,200	10,500	7605
10	9.9	87.0	83.3	18,127	32,400	10,400	7066

3. Crystal Size

The effect of crystal size on add-on costs was examined for a nominal 100 kg run size. Table II presents pertinent parameters for this analysis and Figure 4 shows the results using IPEG. Crystal costs vary almost linearly with the number of crystals/run (crystal size) having a slope of about \$0.60/m² per crystal. Obviously, productivity is increased the fewer the number of crystals/run so that the yearly wafer output increases the larger the crystal. The ultimate limit would be growing a single 100 kg crystal which would be approximately 16% cheaper than the 4-crystal case in Figure 4. It is desirable to minimize the crystals per run (maximize size) since in addition to cost/productivity improvements accompanying larger crystals there will be fewer furnace operation interruptions with their attendant dangers.

C. Molten Silicon Viscosity

The physical properties of molten silicon are of considerable interest in designing equipment to contain and transport this substance. A bibliographic search of molten silicon references was purchased from CINDAS at Purdue University. Most of the references supplied are in the Russian literature and efforts are underway to obtain the few English papers reported. To date, silicon viscosity is the only property obtained.

Figure 5 presents viscosity as a function of temperature derived from the indicated reference. The data were least squares curve fit using third, fourth, and fifth order polynomials, all of which would correlate the data within $\pm 4\%$ up to 1800°C. The third order polynomial is shown in Figure 5. In the vicinity of the melting point the kinematic viscosity is 3×10^{-3} cm²/s. Using a molten silicon density of 2.49 g/cm³, the absolute viscosity is 0.75 centipoise or 7.5×10^{-4} N-s/m².

III. CONCLUSIONS AND RECOMMENDATIONS

The continuous crystal growth furnace is built, assembled, and ready for checkout. A few items remain before full scale growth experiments can begin. These include completing the auger assembly and installing the auxiliary crucible/heater. The revised schedule is very tight but feasible assuming no major catastrophe.

Continuing economic modeling indicates that the 100 kg run size goal for continuous growth is an excellent choice. Run sizes larger than this contribute only a very slight improvement in costs. However, as few crystals as practical should comprise the 100 kg runs. Larger crystals

improve furnace productivity since less dead time is involved in crystal removal, seed-in, and taper. It appears that four, 25 kg crystals is probably ideal at the present for current furnace designs and sizes.

Fewer crystals per run imply longer, heavier crystals and will require some innovations in puller design--particularly in regard to crystal removal and handling. For instance, a 50 kg, 10-cm crystal is about 2.75 meters long and would require several people exercising great care to unload it from the puller. It is likely that continuous Czochralski machines of the future will require permanent scaffolding built around their superstructure to facilitate assembly, maintenance, and crystal handling.

IV. NEW TECHNOLOGY

The continuous Czochralski furnace concept under development in this program in which a flow of solid silicon is premelted in-situ prior to entering the primary crucible was submitted as a new technology item. Appropriate documentation was submitted June 21, 1978, to JPL Patent Attorney Norman L. Chalfin regarding this technology.

V. PLANS FOR NEXT QUARTER

The revised program plan in Figure 2 will be followed with no significant deviation anticipated. Specific plans include:

1. Conduct trial crystal growth runs without liquid feed to checkout and debug the modified puller.
2. Complete modifications on the auger feed and calibrate feed rates.
3. Install and begin trial runs using the auxiliary melter.
4. Perform additional thermal modeling of the furnace hot zone.
5. Conduct program reviews as appropriate with JPL.

VI. PROGRAM COST

During the latest quarter 1047 man hours were expended and a total cost of \$55,931 was incurred. To date, through June 30, 1978, cumulative labor is 3377 man hours and total costs including fee are \$173,916. Figures 6 and 7 depict labor and cost performance versus original baseline plans.

FIGURE I. CONTINUOUS CZOCHRALSKI SILICON FURNACE

Figure 2. Program Plan

Figure 3. Effect of Furnace Run Size on Continuous Czochralski Add-On Cost

Figure 4. Effect of Crystal Size on Continuous Czochralski Add-On Cost

Figure 5. Silicon Viscosity (From Baum, Gel'd, and Kocherov, Russian Metallurgy, 1, 27, 1967)

Figure 6. Program Labor Hours

Figure 7. Total Program Cost

APPENDIX

ENGINEERING DRAWINGS