SILICON RIBBON GROWTH BY A CAPILLARY ACTION
SHAPING TECHNIQUE

Quarterly Technical Progress Report Number 7

G. H. Schwuttke
T. F. Cizek
A. Kran

April 1, 1977

Work Performed Under Contract No. NAS-7-100-954144

East Fishkill Laboratory
International Business Machines Corporation
Hopewell Junction, New York

MASTER

ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
Division of Solar Energy

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SILICON RIBBON GROWTH BY A CAPILLARY
ACTION SHAPING TECHNIQUE

G. H. Schwuttke, Principal Investigator, 914-897-3140
International Business Machines Corporation
System Products Division, East Fishkill Laboratories
Hopewell Junction, New York 12533

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Under JPL Contract Number: 954144
(Subcontract under NASA Contract NAS7-100)
(Task Order No. RD-152)
Effective Date of Contract: 5/8/75
Contract Expiration Date: 11/8/77

This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, under NASA Contract NAS7-100 for the U. S. Energy Research and Development Administration, Division of Solar Energy.

The JPL Low-Cost Silicon Solar Array Project is funded by ERDA and forms part of the ERDA Photovoltaic Conversion Program to initiate a major effort toward the development of low-cost solar arrays.

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TECHNICAL CONTENT STATEMENT

This report contains information prepared by the International Business Machines Corporation under JPL contract. Its contents are not necessarily endorsed by the Jet Propulsion Laboratory, California Institute of Technology, or by the National Aeronautics and Space Administration.

RESEARCH PROGRAM PLAN

OBJECTIVES

1. Technological assessment of ribbon growth of silicon by a capillary action shaping technique.
2. Economic evaluation of ribbon silicon grown by a capillary action shaping technique as low-cost silicon.

SYNOPSIS OF PROGRAM OF STUDY

1. Crystal growth of silicon ribbons.
2. Characterization of silicon ribbons.
3. Economic evaluations and computer-aided simulation of ribbon growth.

SEVENTH QUARTER HIGHLIGHTS

- Eleven meters of 50-mm-wide silicon ribbon were grown.
- Reuse of quartz crucibles through four meltdown cycles was demonstrated.
- With the use of a High Melt Meniscus (HMM) a 50-mm-wide ribbon of unique crystal perfection was obtained.
- The HMM ribbon crystal had zero SiC particle count over its surface.
- The HMM crystal displayed the largest single-grain structure so far obtained in CAST crystals.
- The HMM crystal showed superior lifetime distribution values compared with regular CAST crystals.
- Development of the comparative silicon sheet material throughput computer model was completed.
- Near-future (conventional) Czochralski technology throughput is rapidly approached by continuously grown 5-cm-wide ribbon.
- Design work for the 100-mm growth system proceeded on schedule.

EIGHTH QUARTER ACTIVITY PLAN

- Finalize design and begin fabrication of 100-mm growth system.
- Evaluate die materials as requested by JPL.
- Obtain quantitative measurements of meniscus height.
- Optimize HMM growth.
- Characterize lifetime-limiting effects in ribbon growth.
- Continue development work on computer model of photovoltaic solar energy conversion system manufacturing.
- Assess feasibility of incorporating JPL-proposed cost-accounting structure into our computer models.
- Ascertain need for updating silicon technology study in view of new development data and specific comments from JPL.
- Define ground rules for tracking price goals via model.

CRYSTAL GROWTH

by

T. F. Ciszek

1.0 INTRODUCTION

The crystal-growth method under investigation is a capillary action shaping technique. Meniscus shaping for the desired ribbon geometry occurs at the vertex of a wettable die. As ribbon growth depletes the melt meniscus, capillary action supplies replacement material. The configuration of the technique used in our initial studies is shown in Fig. 1 and is similar to the edge-defined, film-fed growth (EFG) process described by LaBelle (1). The crystal-growth method has been applied to silicon ribbons for several years (2,3,4). As our work on silicon ribbon growth has progressed, we have found that substantial improvements in ribbon surface quality could be achieved with a higher melt meniscus than that attainable with the EFG technique. Thus, in our later work we have abandoned the EFG technique in favor of the improved capillary action shaping technique which employs the capillary die design shown in Fig. 2.

It represents a departure from the die types used for edge-defined, film-fed growth, in that the bounding edges of the die top are not parallel or concentric with the growing ribbon. The new dies allow a higher central melt meniscus (Fig. 3) with concomitant improvements in surface smoothness and freedom from SiC surface particles, which can degrade perfection.

Fig. 1. A schematic diagram of the capillary action shaping technique for silicon ribbon growth.

Certain problems still await solution before the technique becomes viable for large-scale economical photovoltaic applications. High-density graphite fulfills the durability and wettability requirements of a die (2) and has been used, to date, for most silicon ribbon growth; it is not, however, completely non-reactive. Good crystallographic perfection has been achieved on small ribbon segments (2,3), but the structure of large ribbons is marred by planar, line, and point defects.

Fig. 2. Die for improved capillary action shaping technique ribbon growth.

Fig. 3. Cross section through die and ribbon: (a) central die top before seeding, (b) near edge of die during growth, and (c) near central region of die top during growth.

Our objective in this work is to attain a clear technological assessment of silicon ribbon growth by the capillary action shaping technique and to enhance the applicability of the technique to photovoltaic power device material.

In this report, our progress in 50-mm-wide ribbon growth is detailed. Over 11 meters of uniform 50-mm-wide ribbon have been grown this quarter. We have been able to take fuller advantage of the potential benefits of high melt meniscus (HMM) growth, and have produced 50-mm ribbon less than 0.27 mm in thickness with zero SiC particle density, smooth reflective surfaces, and lifetimes greater than 20 μ sec for electrical charge carriers. It has also been demonstrated that quartz crucibles can be used through at least four melt-down cycles.

2.0 GROWTH OF 50-MM-WIDE RIBBONS

2.1 Introduction

Over 11 meters of 50-mm-wide silicon ribbon were grown during the past quarter (see Appendix I). Thicknesses ranged from 1.02 mm to 0.07 mm. Various die designs were studied, and growth rates were varied in the range 0.9 to 3.0 cm/min. A wide variation in silicon carbide surface particle densities was encountered. These ranged from 0 to 7.6/cm². The main purpose of the growth experiments was to gain experience applicable to the design of a 100-mm-width growth system. The growth experiments are briefly described in Appendix II.

2.2 High Melt Meniscus Growth

Of particular interest was run 70103. In this run, a die with 1.2-mm edge thickness, 1.9-mm central thickness, and a 0.46-mm capillary slot was used. The radius of curvature at the die top was 267 mm. During growth at 19 mm/min, an apparently high melt meniscus was maintained and the resultant ribbon had a number of desirable characteristics: it was thin (less than 0.27 mm except for extreme edges), it had a "zero" SiC particle density over its entire length, it was shiny and highly reflective, and it possessed a larger grain morphology than previous ribbons had exhibited. While meniscus dimensions are not measurable during growth in our apparatus, post-growth examination of the interface striations combined with a knowledge of the curvature of the die top indicates that the meniscus was at least 0.3 mm higher in the central region than at the edges of the growth front. We estimate that the meniscus height was on the order of 0.7 mm in the central region; work is under way to provide a means of recording meniscus height.

In Fig. 4, die-top thickness, capillary slot thickness, and ribbon thickness are plotted versus transverse position. The ribbon is relatively flat, except for several mm near each edge, and has a thickness of 0.15 x die thickness in the central region. It is thinner than the capillary slot dimension by 50%. These relative dimensions are shown schematically in Fig. 5. In cross section the extreme edges of ribbon 70103 appear rounded with a radius of 0.38 mm (Fig. 6). At the cross-sectional position shown in the figure, a

maximum thickness of 0.79 mm is reached at a distance of 0.67 mm from the ribbon edge.

Fig. 4. Thickness of die top, capillary slot, and ribbon as a function of transverse position for run 70103.

The thickness gradually decreases to a uniform value of 0.16 mm at a distance of 4 mm from the edge.

Ribbon 70103 is the first ribbon of significant length (> 0.5 meter) which has been completely free of SiC surface particles. The surface is thus free of longitudinal troughs often associated with such particles. Portions of the ribbon exhibited parallel twinning as shown in the central

Fig. 5. Relative dimensions of ribbon thickness, central die-top thickness, and capillary slot separation for ribbon 70103.

ribbon region of Fig. 7. However, much of the surface exhibited large single grains of the order of 8 mm in width. Frequently these grains were separated by twins with a raised surface morphology at the twin/ribbon surface intersection. Examples can be seen near the edge of the ribbon in Fig. 7. Magnified views of some large crystal grains are shown in Fig. 8. In Fig. 8a, a grain is shown which has a nearly flat

Fig. 6. Cross section of ribbon 70103-42 near an edge. The maximum thickness is 0.79 mm, and the minimum is 0.16 mm.

twin boundary on one edge (left) and a partially raised, partially flat boundary on another edge (upper right).

In Fig. 8b, some twin boundaries are shown which have a prominent, raised-surface morphology. A transverse surface profile scan was recorded (left to right) over the region of the two prominent boundaries at the lower right of Fig. 8b. The most prominent (leftmost) boundary had a peak height of 28 μm , as shown in Fig. 9, and its influence extended a distance of 1.1 mm from the peak. The rightmost boundary had a

Fig. 7. High melt meniscus ribbon section 70103-42.

peak height of $9\text{ }\mu\text{m}$ and influenced the surface height within 0.7 mm of the peak.

The single-crystal nature of one particular grain, $8\text{ mm} \times 27\text{ mm}$ in size, from ribbon 70103 was verified by x-ray topography; the topograph is shown in Fig. 10. This grain is encompassed by a largely nonlinear boundary.

Duplication of the experimental conditions used in run 70103 has been attempted with mixed results (see Appendix II). More studies are under way to determine the controlling parameters for HMM ribbon growth. We believe that the re-

a

Fig. 8. Large single-crystal grains in HMM ribbon 70103-42.

moteness of the solid-liquid interface from the die top is responsible for the interesting properties of HMM ribbons.

2.3 Die Design

A problem with thin, two-piece capillary dies has been splaying of the two pieces, at the die bottom, after use.

Fig. 9. Surface profile scan over the two raised-morphology twin boundaries at the lower right of Fig. 8b.

The die is firmly held in a die holder near the die top and maintains reasonably good dimensional constancy there after use. In anticipation of increased splaying problems in the 100-mm growth system, dies (50 mm) have been designed with 2.2-mm-thick ribs at the die edge. This was done to strengthen the dies against warping at growth temperatures. The old dies had a 0.66-mm wall thickness. The reentrant corners, on the outer surface of the die, at the position where the thick ribs ended and the thinner die wall began, were problematic. The corners acted as capillary channels and fed liquid silicon into the space between the die and the

Fig. 10. X-ray topograph of 8 mm x 27 mm
single-crystal grain in ribbon
70103-42.

die holder, causing flooding (run 70205, Appendix II and Fig. 11). By filing a 5-mm-wide slot in the ribs, down to the plane of the exterior die surface, the flooding could be avoided (run 70301, Appendix II). The design has been changed to provide for thicker die walls, but with no ribs.

Fig. 11. Die and die holder. Raised ribs at edges of die caused melt entry into gap between holder and die.

3.0 REUSE OF QUARTZ CRUCIBLES

Experiments were performed to demonstrate the feasibility of reusing quartz crucibles. Crucibles with 51-mm outside diameter, 25-mm-height, and 2-mm wall thickness were used. These are the standard crucibles used in the growth of 12.5, 25, and 38-mm-wide ribbons. They are flat-bottomed, and were typically loaded with 50-60 gram silicon charges. The experiments were conducted in conjunction with 38-mm-wide ribbon growth.

In earlier ribbon growth runs (60917, 60918, 61001, and 61008), it was noticed that all silicon except a small droplet 4 to 10 mm in diameter could be removed from the crucible by continuing ribbon growth until capillary flow starvation occurred. The small droplets did not appear to crack the crucible upon cool-down, and so we decided to attempt reuse of such crucibles. In run 70201, the crucible from run 61001 was reused. In Fig. 12a, the crucible is shown as it appeared after run 61001, in which a 67 x 3.8-cm ribbon was grown. A 5-mm-diameter droplet of silicon was left in the crucible. The crucible was etched in an acid solution of the following composition (by volume)

HNO ₃	(70%)	3 parts
CH ₃ COOH	(Glacial)	2 parts
HF	(49%)	1 part.

Etching was carried out for 24 hours, and the silicon droplet was completely consumed. The etchant also attacked the crucible, decreasing its wall thickness from 1.8 to 1.4 mm. Figure 12b shows the crucible after etching and prior to run 70201. The inner surface of the crucible is seen to be slightly crazed where it had been in contact with the frozen droplet. After etching, the crucible was loaded with 56 grams of silicon and a 76 x 3.8 cm ribbon was grown in run 70201. Again the entire melt was consumed except for a 7.2-mm-diameter droplet near the crucible wall (Fig. 12c).

The crucible was again etched to remove the silicon. The larger droplet left a larger crazed area on the crucible

Fig. 12. Stages in the repeated use and etching of a 51-mm-diameter quartz crucible. See text for details.

(Fig. 12d). The etching further reduced the wall thickness to 1.1 mm.

For the 3rd run with this crucible, another 56-gram charge was loaded and ribbon 70202 was grown (88 x 3.8 cm). The charge was again consumed except for a droplet 13 x 6 mm in size (Fig. 12e). As can be seen, crucible deformation which began to be noticeable in Fig. 12c is quite pronounced after the 3rd run. This is probably because of the thinning effect of the etch.

For the 4th run with this crucible, only a light etch (5 minutes) was used prior to loading another 55-gram charge. This etch did not remove the silicon droplet. A short ribbon (20 cm) was grown in run 70203. It froze to the die. Then, after reseeded, ribbon 70204 was grown from the same melt. It was a 44-cm-long x 3.8-cm-wide ribbon, and again all the silicon was consumed except for the small droplets shown in Fig. 12f. After run 70204, the crucible was badly deformed, but was still intact and conceivably could have been used again. However, a portion of the upper rim was broken during handling.

In summary, the crucible was used in four melt-down cycles and performed satisfactorily. A small amount of crazing occurred in the immediate vicinity of the residual frozen silicon droplets left in the crucible at the onset of capillary starvation, but the crazing was not substantial enough to interfere with the growth process. The crucible deformed with increasing use. This may have been enhanced by the heavy etching which reduced the crucible wall thickness. On the 4th run made with the crucible, it was demonstrated that the etching is not necessary.

Fig. 13. Hot zone for 100-mm ribbon growth furnace.

Material — High Purity
Clear Fused
Quartz

Fig. 14. Crucible for 100-mm ribbon furnace.

4.0 DESIGN OF A 100-MM GROWTH SYSTEM

Detailed design work was begun on the hot-zone for the 100-mm ribbon growth system. A scaled sketch of the basic components is shown in Fig. 13. The crucible design has been finalized (Fig. 14). Crucibles and tubular quartzware have been ordered.

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6.0 ACKNOWLEDGMENT

Technical assistance in ribbon growth was provided by F. Newman.

Appendix I

DIMENSIONAL PROPERTIES OF SILICON RIBBONS GROWN IN THE SEVENTH QUARTER

Ribbon Run No.	Seed		Usable Length (cm)	Width (mm)		Thickness (mm)			
	Orientation					Seed		Tail	
	Axis	Surf		Max	Min	Max	Min	Max	Min
61202	110	100	80	38.0	37.4	.80	.70	.70	.60
61205	110	100	90	49.4	48.6	.98	.72	.90	.72
61206	110	100	95	48.4	47.6	.95	.85	.90	.75
61208	110	100	86	50.0	.0	.70	.50	.80	.53
61210	110	100	120	49.6	48.6	1.02	.57	.96	.39
61211	110	100	44	.0	.0	.00	.00	.00	.00
70101	110	100	120	49.0	47.0	.80	.40	.80	.20
70103	110	100	56	49.6	48.2	.90	.18	.92	.07
70107	110	100	108	49.3	49.1	.90	.33	.90	.23
70109	110	100	96	48.6	48.2	.82	.48	.90	.35
70110	110	100	57	48.6	48.1	.85	.44	.88	.32
70111	110	100	66	48.7	48.2	.87	.42	.88	.30
70201	110	100	76	37.9	36.2	.65	.70	.82	.85
70202	110	100	88	37.5	36.8	.80	.70	.60	.50
70204	110	100	44	37.8	37.2	.80	.70	.70	.60
70205	110	100	121	50.0	49.2	.82	.60	.45	.52
70206	110	100	29	49.7	46.2	.38	.25	.40	.30
70301	110	100	64	50.0	49.7	.70	.55	.55	.40

A 0.0 entry indicates no measurement was made.

Appendix II

RIBBON GROWTH EXPERIMENTS DURING THE SEVENTH QUARTER

Run No.	Die Width (mm)	Die Material	Experimental Variables	Results
61102	50	DFP-3-2	Repeat of 61101 conditions	Ribbon separated from die after 1.5 cm of growth
61103	50	DFP-3-2	All components carefully aligned. Die rotated 90° from run 61102.	Could not grow without freezing to die. Die damaged.
61201	38	DFP-3-2	Gain experience with 38 mm die while waiting for 50 mm dies.	91 cm x 38 mm ribbon grown at 19 mm/min
61202	38	DFP-3-2	Die has 0.75 mm diameter capillary holes and 101 mm radius top (die for run 61201 had 0.38 mm capillary slot and 152 mm radius top).	80 cm x 38 mm ribbon grown at 18 mm/min
61203	38	DFP-3-2	Repeat at faster speed.	Froze at 23 mm/min speed and 24 mm width.
61204	38	DFP-3-2	Repeat	Identical result.
61205	50	DFP-3-2	Die with 1.05 mm edge thickness, 1.93 mm central thickness, and 254 mm top radius.	Heavy residue from vacuum bake-out. Grew 90 cm x 49.4 mm ribbon, 0.72 mm thick. Ribbon has very heavy SiC particle density (7.5/cm ²). Ribbon split while being measured.
61206	50	DFP-3-2	New die. Baked out under argon flow instead of vacuum.	95 cm long ribbon, similar to 61205 (high SiC density). Growth speed 16 mm/min.

Run No.	Die Width (mm)	Die Material	Experimental Variables	Results
61207	50	DFP-3-2	Same die. Checking to see if re-running die and slower growth speed (9 mm/min) affect SiC density.	SiC density was reduced.
61208	50	DFP-3-2	Same die. Checking to see if re-running die and faster growth speed affect SiC density (speed = 24 mm/min).	SiC density lower yet. Ribbon is 86 cm long, 0.8 mm thick at the edge and 0.5 mm thick over large central region.
61209	50	DFP-3-2	New die, 2P502. Baked out in argon.	Froze during seeding.
61210	50	DFP-3-2	Same conditions. 15-18 mm/min growth speed.	120 cm long ribbon, 49.6 mm wide. High SiC density (0.76/cm ²).
61211	50	DFP-3-2	Same die, repeat.	44 cm long ribbon, very smooth (0.03 SiC particles/cm ²).
70101	50	DFP-3-2	4th run with die, to see if SiC particle density changes. Speed = 18 mm/min.	Very smooth (0.014 particles/cm ²) ribbon 1.2 m long x 4.9 cm wide x 0.2 - 0.8 mm thick.
70102	50	DFP-3-2	Repeat.	Die ruined by Si flow into die holder.
70103	50	DFP-3-2	New die, 1.2 mm thick at edges and 1.9 mm thick at midpoint. 0.46 mm capillary slot. 19 mm/min growth speed.	"Zero" SiC particle density on 0.56 m x 4.9 cm x 0.07 - 0.9 mm thick ribbon. Reflective surface, large grains. Thinnest ribbon grown to date (less than 0.27 mm except for extreme edges).
70104	50	DFP-3-2	Repeat.	Froze before reaching full width.

Run No.	Die Width (mm)	Die Material	Experimental Variables	Results
70106	50	DFP-3-2	Repeat.	Same. Having problems with alignment of furnace components.
70107	50	DFP-3-2	Repeat. Die had shifted and froze uneven in holder. Lower heat shield was shimmed to make it even with die top.	1.08 m long by 4.93 cm wide ribbon, 0.23 to 0.90 mm thick. Surface looks good.
70108	50	DFP-3-2	Repeat.	Ribbon shattered while growing. Apparently seed holder caught on pull port.
70109	50	DFP-3-2	Repeat, improved alignment.	0.96 m x 4.9 cm x .35-.90 mm thick ribbon, at 18 mm/min speed.
70110	50	DFP-3-2	Repeat with higher pulling speed (27 mm/min).	.57 m x 4.9 cm x .32-.88 mm thick ribbon. Ran out of melt. Die holder and susceptor cracked.
70111	50	DFP-3-2	6 mm taller susceptor support used. New die.	Ribbon froze at 0.66 m length. Much higher operating temperature required. Ribbon 4.9 cm wide x .30-.88 mm thick.
70201	38	DFP-3-2	Crucible from run 61001 etched to remove residual Si, and reused.	Crucible worked O.K. Grew 76 cm ribbon, again nearly emptying crucible.
70202	38	DFP-3-2	Crucible from last run etched again and reused.	Crucible again worked O.K. Grew 88 cm ribbon, nearly emptying crucible.

Run No.	Die Width (mm)	Die Material	Experimental Variables	Results
70203	38	DFP-3-2	Crucible etched only lightly (not enough to remove Si) and reused.	Froze after 16 cm of growth.
70204	38	DFP-3-2	Repeat (same melt)	44 cm ribbon. Crucible worked O.K., but deformed during run.
70205	50	DFP-2	New die, 2PA501, with thicker walls and reinforced edges. Growth speed 19 mm/min.	Grew 121 cm long ribbon, but melt flooded into space between die and holder because of reentrant corners on die. Ribbon thickness 0.5-0.6 mm in central region.
70206	50	DFP-2	Repeat at 30 mm/min speed.	29 cm long ribbon, 0.25-0.3 mm thick in central region. Die split after run.
70301	50	DFP-2	New die. Reentrant corners filed away in critical areas to avoid flooding.	No flooding of melt. Grew 64 cm x 50 mm ribbon, 0.4 to 0.55 mm thick in central region.

CHARACTERIZATION

by

K. H. Yang and G. H. Schwuttke

1.0 INTRODUCTION

The high melt meniscus (HMM) crystal of run 70103 was characterized through MOS C-t measurements. As discussed before, this crystal possessed some interesting features. Its surface was exceptionally clean and free of SiC particles. In addition, it contained very large grains several mm in size. Such a grain structure is unconventional for CAST crystals.

This crystal was characterized using a high-density map of MOS capacitors, as shown in Fig. 1. Seven crystal sections 5 cm wide and 6 cm long were MOS-processed, and their lifetime was measured. In this experiment approximately 3000 capacitors were evaluated. The results are summarized as follows.

2.0 LIFETIME DISTRIBUTION

The lifetime distributions of these crystal sections are shown in Figs. 2 through 8. The majority of the capacitors have a lifetime around 1 μ sec. The averaged lifetime for these sections ranges from 0.9 to 17.5 μ sec. For a relatively "bad" section such as 70103-14, a large population of the capacitors has a lifetime below 0.1 μ sec. For a relatively "good" section such as 70103-48, a large population has a

lifetime of more than 20 μ sec. Lifetime of this order is almost equal to that of Czochralski wafers. The crystal section of 70103-48 has the best lifetime distribution obtained in any CAST crystal section so far. The average lifetime of 345 capacitors in this section is 17.5 μ sec.

Fig. 1. High-density MOS capacitor mask (420 devices) as used for the evaluation of lifetime high meniscus melt crystal (crystal 70103).

WAFER ID: 315 600 315 601 315 602 315 603 315 604 315 605 315 606 315 607 315 608 315 609 315 610 315 611
 315 612 315 613 315 614 315 615 315 616 315 617

15M WAFER OR LOT DESCRIPTION: RIBBON 701103-60 DENSE MASK 60 MIL DOTS

NUMBER OF CAPACITORS : 306
 MAX LIFETIME(MICROSECS): 71.000
 MIN LIFETIME(MICROSECS): 0.001
 MEAN LIFETIME : 5.859
 STANDARD DEVIATION : 11.633
 MEDIAN : 0.921
 MODE : 0.19
 TOTAL NO OF CAPACITORS : 306

Fig. 2. Generation lifetime analysis of ribbon samples: ribbon 701103-60.

WAFER ID: 315 400 315 401 315 402 315 403 315 404 315 405 315 406 315 407 315 408 315 409 315 490 315 491
 315 492 315 493 315 494 315 495 315 496 315 497 315 498 315 499

IBM WAFER OR LOT DESCRIPTION: RIBSON 701103-48 DENSE MASK 60 MIL DOTS

NUMBER OF CAPACITORS : 345
 MAX LIFETIME(MICROSECS): 280.000
 MIN LIFETIME(MICROSECS): 0.025
 MEAN LIFETIME : 17.507
 STANDARD DEVIATION : 39.314
 MEDIAN : 2.580
 MODE : 0.43
 TOTAL NO OF CAPACITORS : 345

Fig. 3. Generation lifetime analysis of ribbon samples: ribbon 701103 48.

WAFER ID: 315 360 315 361 315 362 315 363 315 364 315 365 315 366 315 367 315 368 315 369 315 370 315 371
 315 372 315 373 315 374 315 375 315 376 315 377 315 378 315 379 315 380 315 381 315 382 315 383 315
 384

IBM WAFER OR LOT DESCRIPTION: RIBBON 701103-36 DENSE MASK 60 MIL DOTS

NUMBER OF CAPACITORS : 425
 MAX LIFETIME(MICROSECS): 87.500
 MIN LIFETIME(MICROSECS): 0.010
 MEAN LIFETIME : 5.075
 STANDARD DEVIATION : 9.895
 MEDIAN : 0.854
 MODE : 0.30 0.47 0.47 0.62 1.05
 TOTAL NO OF CAPACITORS : 425

Fig. 4. Generation lifetime analysis of ribbon samples: ribbon 701103-36.

WAFER ID: 316 300 316 301 316 302 316 303 316 304 316 305 316 306 316 307 316 308 316 309 316 310 316 311
 316 312 316 313 316 314 316 315 316 316 316 317 316 318 316 319 316 320 316 321

ITEM WAFER OR LOT DESCRIPTION: RIBBON 701103-30 DENSE MASK 60 MIL DOTS

NUMBER OF CAPACITORS : 328
 MAX LIFETIME(MICROSECS): 133.000
 MIN LIFETIME(MICROSECS): 0.000
 MEAN LIFETIME : 2.335
 STANDARD DEVIATION : 9.767
 MEDIAN : 0.395
 MODE : 0.04 0.04
 TOTAL NO OF CAPACITORS : 328

Fig. 5. Generation lifetime analysis of ribbon samples: ribbon 701103-30.

WAFER ID: 315 200 315 201 315 202 315 203 315 204 315 205 315 206 315 207 315 208 315 209 315 210 315 211
 315 212 315 213 315 214 315 215 315 216 315 217 315 218 315 219 315 220 315 221 315 222 315 223 315
 224 315 225 315 226 315 227 315 228

15M WAFER OR LOT DESCRIPTION: RIBBON 70103-20 DENSE MASK 60 MIL DOTS

NUMBER OF CAPACITORS : 487
 MAX LIFETIME(MICROSECS): 53.900
 MIN LIFETIME(MICROSECS): 0.001
 MEAN LIFETIME : 2.926
 STANDARD DEVIATION : 5.254
 MEDIAN : 1.280
 MODE : 1.20
 TOTAL NO OF CAPACITORS : 487

Fig. 6. Generation lifetime analysis of ribbon samples: ribbon 701103-20.

WAFER ID: 316 140 316 141 316 142 316 143 316 144 316 145 316 146 316 147 316 148 316 149 316 150 316 151
 316 152 316 153 316 154 316 155 316 156 316 157 316 158 316 159 316 160 316 161 316 162 316 163 31
 164 316 165 316 165

IBM WAFER OR LOT DESCRIPTION: RIBBON 701103-14 DENSE MASK 60 MIL DOTS

NUMBER OF CAPACITORS : 428
 MAX LIFETIME(MICROSECS): 31.200
 MIN LIFETIME(MICROSECS): 0.000
 MEAN LIFETIME : 0.896
 STANDARD DEVIATION : 1.871
 MEDIAN : 0.435
 MODE : 0.04
 TOTAL NO OF CAPACITORS : 428

Fig. 7. Generation lifetime analysis of ribbon samples: ribbon 701103-14.

WAFER ID: 316 800 316 801 316 802 316 803 316 804 316 805 316 806 316 807 316 808 316 809 316 810 316 811
 316 812 316 813 316 814 316 815 316 816 316 817 316 818 316 819 316 820 316 821 316 822 316 823 316
 824 316 825 316 826 316 827 316 828 316 829 316 830

124 WAFER OR LOT DESCRIPTION: WAFER 701103-8 DENSE MASK 60 MIL DOTS

NUMBER OF CAPACITORS : 463
 MAX LIFETIME(MICROSECS): 22.000
 MIN LIFETIME(MICROSECS): 0.001
 MEAN LIFETIME : 2.013
 STANDARD DEVIATION : 2.741
 MEDIAN : 1.200
 MODE : 1.46
 TOTAL NO OF CAPACITORS : 463

Fig. 8. Generation lifetime analysis of ribbon samples: ribbon 701103-8.

2.1 Position Dependency of Lifetime

As shown in Quarterly Technical Progress Report Number 5, the lifetime of minority carriers in ribbon depends strongly on the position of the MOS dot relative to the edges of the ribbon. The better lifetimes were found for dots located in the center of the ribbon. The same dependency was observed in this HMM, 5-cm-wide crystal. This is illustrated in Fig. 9. In this figure, the generation lifetime is plotted against the position of the MOS dot relative to the ribbon edge. Rows A and U are close to the left and right edges of the ribbon. Each data point is the averaged lifetime of the same row in the seven crystal sections shown in Figs. 2 through 8. One row in a crystal section has 21 dots. Therefore, each data point represents the averaged lifetime of 14.7 dots approximately at the same position relative to the ribbon edge. It is apparent from this figure that the dots located in the center of the ribbon have better lifetime than those near the ribbon edge. Figure 9 further shows that the large part of the HMM crystal, i.e., 18 out of 21 rows, has a lifetime value of more than 1 μ sec. The lifetime for this HMM, 5-cm-wide crystal is even higher than the one found in the 2.5-cm-wide ribbons shown in Quarterly Progress Report Number 5. This suggests that the growth of wider ribbons may not necessarily cause any degradation in ribbon quality.

Fig. 9. Position dependency of lifetime values in ribbon surfaces:
ribbon 70103.

It should be noted that, in a crystal section, the lifetime value for the dots in the same row is almost equal. The

change of lifetime from one row to the next is, in most cases, gradual. When an abrupt change in lifetime occurs, one row of the two is always found to be associated with electrically active defects such as grain boundaries. The ratio of average lifetime for rows located in the middle of a crystal section and for those located close to the edge can be as large as 200. This arises because the density of active crystal defects is much higher at the ribbon edges compared with the middle of a ribbon crystal.

2.2 Influence of Crystal Defects on Lifetime

As shown in Quarterly Technical Progress Report Number 5, the lifetime of silicon ribbons is controlled by various kinds of crystal defects present in the ribbons. Ribbon quality was classified as shown in Table I.

Table I. Influence of Crystal Defects on Lifetime

Class	Crystal Defects	Lifetime range (μ sec)
I	Parallel twinning and single crystal	> 1
II	Parallel twinning and dislocation bands	0.01 to 1
III	Grain boundaries and dislocation bands	≤ 0.01
IV	Silicon carbide dendrites and inclusions	Not measurable

An examination of the HMM crystal indicates that the lifetime value of this ribbon can also be classified according to Table I. This is shown in Figs. 10 and 11. In these figures the circular outline corresponds to the etched silicon surface of a 60-mil MOS dot. Lifetime was correlated with

Fig. 10. Ribbon quality of class 1:

- (a) Dislocation-free single crystal, lifetime: 14.1 μsec
- (b) Dislocation-free parallel twins, lifetime: 18.6 μsec .
- (c) Single crystal with dispersed dislocations, lifetime: 1.52 μsec .
- (d) Parallel twins with dispersed dislocations: 2.43 μsec

a

b

Fig. 11. (a) Ribbon quality of class II,
parallel twins and dislocation
bands, lifetime: $0.11 \mu\text{sec.}$
(b) Ribbon quality of class III,
grain boundaries and dislocation
bands, lifetime: $0.009 \mu\text{sec.}$

crystal defects present in a particular dot. Figure 10 shows that the lifetime values are typically larger than 10 μ sec for dislocation-free single crystals and parallel twins. Parallel twins are essentially electrically inactive and do not cause any significant degradation in lifetime. Quite often, the single crystals and parallel twins were found to have a dislocation density of 10^4 to 10^5 per cm^2 . The presence of dislocations reduces the lifetime to a value between 1 and 10 μ sec. The influence of dislocations on lifetime can be seen by comparison of Fig. 10a and c and Fig. 10b and d. The density of dislocation etch pits in Fig. 10c and d is about 5×10^4 per cm^2 . These figures represent ribbon quality of Class I, which has a lifetime value of more than 1 μ sec. The good lifetime distribution of this HMM crystal, as shown in Figs. 2 through 8, results from the fact that the larger part of this crystal contains single grains and parallel twins.

Ribbon quality degrades with the presence of dislocation bands (Class II) and grain boundaries (Class III). The dislocation bands and grain boundaries are shown in Fig. 11a and b, respectively. No degradation resulting from SiC particles was observed. This was expected because the surface of this HMM crystal is free of SiC particles.

3.0 SUMMARY

The main results of this investigation are summarized as follows:

- (a) The HMM ribbon showed superior lifetime distribution values over areas as large as 5 cm in width and 6 cm in length as compared with regular CAST crystals.
- (b) The superior lifetime results from the fact that this HMM crystal contains large single grains and mainly parallel twins.
- (c) The growth of wider ribbon does not cause any degradation in ribbon quality.
- (d) Ranked according to the severity of their impact on lifetime, lifetime-degrading defects are grain boundaries, dislocation bands, and dispersed dislocations.

4.0 ACKNOWLEDGMENTS

The MOS processing and measurements were done by C. P. Schneider, H. F. Ilker, and S. A. Focht.

COMPUTER ANALYSIS MODEL OF COMPETING SHEET GROWTH TECHNIQUES

by

A. Kran

1.0 INTRODUCTION

It is becoming increasingly apparent that an analysis of manufacturing operations, where more than one operation is involved (e.g., Czochralski sheet growth), must, in order to be considered representative of the actual world, reflect the simultaneous operation and interaction of all production equipment. A comparative analysis between competing fabrication methods (e.g., Czochralski vs CAST), or a projection in time and/or technology, complicates this task even further.

Accordingly, as the first step towards this type of detailed study, or, for that matter, in the design and layout of an actual factory, a good deal of judgment and preliminary analysis is required to select, in accordance with available resources, the right type and combination of equipment and manpower in order to achieve a reasonably balanced, and thus maximum, product output.

To aid in the tasks of analyzing the economics of silicon sheet growth and of comparing the capabilities of competing technologies, a silicon area throughput computer model has been defined, which uses equipment and materials processing

parameters as input and provides as output a pictorial representation of materials area versus time.

A throughput comparison based upon current and projected Czochralski and CAST ribbon technology parameters, listed in Table I, has been performed. Optimization of the throughput cycle, in order to achieve a more balanced output, will be discussed in conjunction with current technology.

2.0 DESCRIPTION OF COMPUTER MODEL FORMAT

This computer model is another tool developed for analyzing the future potential of silicon sheet. It is coded in APL, which is a high-level, interactive programming language, readily accessed by means of a vector graphics computer terminal, and rapidly iterated. (The APL code is provided in the Appendix.) After execution of START, stored parameters and their assigned values are displayed on the CRT screen in the form of a menu. Parameter values may be changed by pointing a hairline cursor to the particular item, depressing the spacebar, and then typing in the desired new value. After review of output, this procedure is readily iterated until satisfactory results are achieved.

An example of the input values ("Present") for the model is shown in Figs. 1 and 2. Figure 1 depicts Czochralski technology parameters to be analyzed, and Fig. 2 the corresponding CAST ribbon values.

Table I. Sheet Material Processing Technology Matrix

Czochralski					Cast Ribbon				
	Present	Near Future	Future	Limit		Present	Near Future	Future	Limit
Crystal Pulling					Crystal Pulling				
Diameter (cm)	7.62	10.0	12.0	15.0	Width (cm)	2.5	5.0	10.0	25.0
Growth rate (% of max)	22.2	25.0	40.0	40.0	Growth rate (% of max)	30.0	40.0	50.0	60.0
(cm/hr)	10.0	9.83	14.3	12.8	(cm/hr)	152	203	253	304
Max length (cm)	60	80	100	120	Thickness (cm)	0.03	0.03	0.03	0.03
Equipment available (%)	65	65	65	65	Equipment available (%)	70	80	90	95
Yield (%)	80	80	80	80	Yield* (%)	56	68	81	90
Crystal Slicing					*Dimensional yield x acceptable quality				
Slices/hr	35	14	100	100					
Slice thickness (cm)	0.04	0.05	0.025	0.025					
Kerf (%)	50	50	50	50					
Equipment available (%)	80	80	80	80					
Yield (%)	90	90	90	90					
Wafer Polish/Etch									
Wafers/hr	72	72	1000	1000					
Equipment available (%)	80	80	80	80					
Yield (%)	90	90	90	90					

CZOCHEWSKI TECHNOLOGY:

EQUIP AVAIL,PCT: 65 80 80

YIELD, PCT: 80 90 90

CRYSTAL PULLING

10 CM/HR OR...AS PCT OF MAX: 22.2

7.62 CM DIA

60 CM MAX LENGTH

CRYSTAL SLICING

100 SECS/CYCLE

0.5 KERF LOSS

0.04 CM THICK SLICES

WAFER POLISHING/ETCHING

72 WAFERS/HR

END

Fig. 1. Menu depicting present Czochralski parameters
and their assigned values.

The Fig. 1 (Present) menu depicts the same parameter values summarized in Table I. The equipment availability values in the third line apply to the crystal pulling, slicing, and polishing/etching sectors respectively. In other words, the equipment is growing crystal 65% of the time, with the remainder allocated to such tasks as setup, crucible heatup, and maintenance. The corresponding menu for CAST ribbon (Fig. 2) is similar, but, in addition to continuous ribbon growth, it makes provision for a situation where ribbon growth is not continuous and must be interrupted after a number of ribbons of a given length have been grown.

RIBBON TECHNOLOGY:

1 SIMULTANEOUS RIBBON(S)

0.03 CM THICK

152 CM/HR OR...AS PCT OF MAX:30

2.5 CM WIDE

CONT GROWTH OR... SPECIFY

EQUIP AVAIL(INCL SU*HU),PCT: 70
YIELD FACTORS, PCT: 70 80

END

Fig. 2. Menu depicting present CAST ribbon parameters
and their assigned values.

The model output results in two curves, such as shown in Fig. 3 (for data listed in Figs. 1 and 2). The materials area (m^2) is plotted against processing time (hours). The solid curve, representing Czochralski wafer fabrication, will be discussed first. Line segment AB depicts the crystal pulling process, where volume is converted into (hypothetical) area without kerf loss. Segment BC is the crystal cropping and shaping yield loss. Segment CD represents the slicing operation, where area is lost because of kerf. Segment DE is the slicing yield loss, and, finally, EF the etching/polishing operation and segment FG the yield loss due to this sector. The second curve (dashed) depicts the amount of ribbon material that can be grown in the time required to complete the Czochralski processing cycle from polysilicon material to polished/etched wafers ready for cell fabrication.

Fig. 3. Area throughput comparison: Present.

3.0 RATIONALE FOR Si SHEET THROUGHPUT MODEL

A difficulty commonly encountered in relating differing processing methods is how to ensure an equal comparison, in other words, the old "apples to apples" problem. This problem is overcome, assuming that the following simplification applies: If competing technologies are implemented using equal resources, then their product outputs (per unit time) are directly related. In other words, if a total of \$150,000 is spent to purchase a Czochralski puller, slicer, and pol-

isher, and another \$150,000 to buy several CAST ribbon machines, and each production line requires one technician, then the outputs of both lines may be directly compared. For instance, if line A produces 2 m² of sheet material per hour and line B 1 m², then line A is twice as cost-effective as line B. For the purposes of this "first-order effects" analysis, this axiom is further simplified as follows: Assume sufficient funding is available to purchase one ribbon puller, and an equal amount of funding to "lease," on a part-time basis, a reasonably balanced Czochralski production capacity. The resultant output of these two lines is directly comparable, thus justifying the sequential representation shown in Fig. 3. In actuality, this situation is not uncommon in manufacturing concerns where many similar (slicing) machines are grouped into operational sectors, and only the actual time used on the equipment is charged to the product as a direct cost item.

It is recognized that in a small factory dependent upon serial (Czochralski) processing operations, the throughput is gated by the slowest production equipment component. Unless multiple machines of the same type (e.g., slicers) or a balanced production line is assumed, the question of underutilized machine capacity and its effect on product cost cannot be ignored.

4.0 Si AREA THROUGHPUT COMPARISON:

4.1 Present

Present Czochralski technology, as defined in Fig. 2, yields about 3 m² of silicon-sheet materials area per throughput

cycle (38 hours), or less than one m² every ten hours. Closer inspection of Fig. 3 reveals that only one quarter of the cycle is needed to convert silicon into single-crystal material, and the last three quarters to process it into sheet form suitable for solar-cell fabrication.

Ribbon technology, on the other hand, produces only one-half m² during the same time period, or one-fifth the area of Czochralski.

The silicon sheet materials throughput cycle has been further analyzed for "Present" technology, as summarized in Table II. Here the effect of adding slicers/polishers, in order to achieve a more balanced (thus higher) output per unit time, is investigated.

Table II. Analysis of Silicon Sheet Material Throughput Cycle: Present

Czochralski													CAST				Equip. Cost/ Cycle (k\$)		Ratios Czoch./CAST	
Crystal Puller				Slicer				Polisher/Etch												
No.	EU	Cost (k\$)	ERTC (k\$)	No.	EU	Cost (k\$)	ERTC (k\$)	No.	EU	Cost (k\$)	ERTC (k\$)	TP	No.	Cost (k\$)	ERTC (k\$)	TP	Czoch.	CAST	Equip.	TP
1	0.24	125	30	1	0.45	30	13	1	0.31	33	10	740	1	50	50	160	53	50	1.1	4.6
1	0.31	125	39	2	0.31	60	19	1	0.38	33	13	930	1	50	50	160	71	50	1.4	6.6
1	0.28	125	35	1	0.53	30	16	2	0.19	66	13	810	1	50	50	160	64	50	1.3	5.1
1	0.39	125	49	2	0.39	60	23	2	0.22	66	15	1210	2	100	100	320	87	100	0.9	3.8

LEGEND:

- No. - Number of machines
- EU - Equipment utilization as fraction of throughput cycle
- Cost - Equipment cost in k\$
- ERTC - Equipment cost as required by throughput cycle
(EU x Cost)
- TP - Material throughput (cm²/hr)

The data on line 1 of Table II apply to Fig. 3, where it takes 38 hours to complete the cycle of processing polycrystalline silicon into single-crystal material: 9 hours, or 24% of the cycle, for crystal growth, 17 hours (45%) for slicing, and 12 hours (31%) for polishing/etching. Accordingly, this particular processing cycle requires a crystal puller 24% of the time, worth \$30k ($\$125k \times 0.24$), a slicer's time worth \$13k, and polishing/etching equipment at a rate of \$10k. This totals to \$53k, and is more expensive than the CAST equipment by a factor of 1.1. The last column of row 1 shows that, by utilizing this particular set of capital equipment, processing technology, and materials throughput cycle, about five times more area is generated by Czochralski than by CAST processing.

In the subsequent rows, the addition of equipment and the effect upon equipment ratio and materials area throughput are shown. As might be expected, the highest Czochralski/CAST throughput ratio (6.6) occurs where the Czochralski line is best balanced and the equipment ratio is also highest (1.4).

A graphical representation of these four cases is shown in Fig. 4a through d, with the corresponding parameter listings to the left. It should be noted that, since a specific parameter for representing more than one piece of equipment is not defined in the model, this condition is simulated in Czochralski processing by reducing the slicing cycle by a factor of 2 (100 to 50 secs/cycle), and doubling the polishing throughput (72 to 144 wafer/hours). In the CAST process, this is simulated by specifying multiple ribbon growth.

TECHNOLOGY PROJECTION: PRESENT
 CROCKFORDS TECHNOLOGY:
 EQUIP AVAIL, PCT: 65 80 80
 YIELD, PCT: 80 90 90
 CRYSTAL PULLING
 10 CM/HR OR...AS PCT OF MAX: 22.2
 7.62 CM DIA
 60 CM MAX LENGTH
 CRYSTAL SLICING
 100 SECS/CYCLE
 0.5 KERF LOSS
 0.34 CM THICK SLICES
 WAFER POLISHING/ETCHING
 72 WAFERS/HR
 RIBBON TECHNOLOGY:
 1 SIMULTANEOUS RIBBON(S)
 0.03 CM THICK
 152 CM/HR OR...AS PCT OF MAX: 30
 2.5 CM WIDE
 EQUIP AVAIL (INCL SU*HU), PCT: 70
 YIELD FACTORS, PCT: 70 80

a

TECHNOLOGY PROJECTION: PRESENT
 CROCKFORDS TECHNOLOGY:
 EQUIP AVAIL, PCT: 65 80 80
 YIELD, PCT: 80 90 90
 CRYSTAL PULLING
 10 CM/HR OR...AS PCT OF MAX: 22.2
 7.62 CM DIA
 60 CM MAX LENGTH
 CRYSTAL SLICING
 50 SECS/CYCLE
 0.5 KERF LOSS
 0.34 CM THICK SLICES
 WAFER POLISHING/ETCHING
 72 WAFERS/HR
 RIBBON TECHNOLOGY:
 1 SIMULTANEOUS RIBBON(S)
 0.03 CM THICK
 152 CM/HR OR...AS PCT OF MAX: 30
 2.5 CM WIDE
 EQUIP AVAIL (INCL SU*HU), PCT: 70
 YIELD FACTORS, PCT: 70 80

b

Fig. 4. Graphical comparison of silicon sheet material throughput (sheet 1 of 2) .

TECHNOLOGY PROJECTION: PRESENT
 CZOCHRALEWSKI TECHNOLOGY:
 EQUIP AVAIL. PCT: 85 80 80
 YIELD, PCT: 80 90 90
 CRYSTAL PULLING
 10 CM/HR OR...AS PCT OF MAX: 22.2
 7.62 CM DIA
 60 CM MAX LENGTH
 CRYSTAL SLICING
 100 SECS/CYCLE
 0.5 KERF LOSS
 0.04 CM THICK SLICES
 WAFER POLISHING/ETCHING
 144 WAFERS/HR
 RIBBON TECHNOLOGY:
 1 SIMULTANEOUS RIBBON(S)
 0.03 CM THICK
 152 CM/HR OR...AS PCT OF MAX: 30
 2.5 CM WIDE
 EQUIP AVAIL (INCL SU+HU), PCT: 70
 YIELD FACTORS, PCT: 70 80

C

TECHNOLOGY PROJECTION: PRESENT
 CZOCHRALEWSKI TECHNOLOGY:
 EQUIP AVAIL. PCT: 85 80 80
 YIELD, PCT: 80 90 90
 CRYSTAL PULLING
 10 CM/HR OR...AS PCT OF MAX: 22.2
 7.62 CM DIA
 60 CM MAX LENGTH
 CRYSTAL SLICING
 50 SECS/CYCLE
 0.5 KERF LOSS
 0.04 CM THICK SLICES
 WAFER POLISHING/ETCHING
 144 WAFERS/HR
 RIBBON TECHNOLOGY:
 2 SIMULTANEOUS RIBBON(S)
 0.03 CM THICK
 152 CM/HR OR...AS PCT OF MAX: 30
 2.5 CM WIDE
 EQUIP AVAIL (INCL SU+HU), PCT: 70
 YIELD FACTORS, PCT: 70 80

d

Fig. 4. Graphical comparison of silicon sheet material throughput (sheet 2 of 2).

4.2 Near-Future

Near-future Czochralski technology (Fig. 5) is characterized by 10-cm-diameter crystals, grown at about 25% of maximum growth rate (9.83 cm/hr), sliced with conventional ID saws, and followed by the traditional polishing operation. It is interesting to note that, under those conditions, 5-cm-wide, continuously pulled ribbon becomes a close competitor (Fig. 6).

Also, even though twice as much (12.5 vs 6.8 m²) material was grown during the crystal-pulling phase, total throughput per fabrication cycle remains unchanged at 0.074 m²/hr, because of the time-consuming aspects of ID slicing of larger-diameter crystals. This confirms our view that, for crystals larger than 10 cm in diameter, ID slicing is becoming less cost-effective.

Inspection of Fig. 6 reveals that 44 out of 69 hours, or 64% of the processing cycle, is spent in the slicing sector. Utilization of either 2 or 3 slices would enhance throughput considerably.

4.3 Future

Future Czochralski technology (Fig. 7) is envisioned as producing 12-cm-diameter crystals grown at about 40% maximum growth rate (14.3 cm/hr) and multiple-blade-sliced or multiple-wire-sliced into thin (0.025-cm) wafers, at a rate of at least 100/hr. The expensive polishing operation is expected to be replaced by a large-batch (1000) etching step, yielding wafers with surfaces suitable for solar-cell fabrication.

CZOCHEWSKI TECHNOLOGY:

EQUIP AVAIL,PCT: 65 80 80

YIELD, PCT: 80 90 90

CRYSTAL PULLING

9.83 CM/HR OR...AS PCT OF MAX: 25.0

10 CM DIA

80 CM MAX LENGTH

CRYSTAL SLICING

250 SECS/CYCLE

0.5 KERF LOSS

0.05 CM THICK SLICES

WAFER POLISHING/ETCHING

72 WAFERS/HR

END

RIBBON TECHNOLOGY:

1 SIMULTANEOUS RIBBON(S)

0.03 CM THICK

203 CM/HR OR...AS PCT OF MAX:40

5 CM WIDE

CONT GROWTH OR... SPECIFY

EQUIP AVAIL(INCL SU+HU),PCT: 80
YIELD FACTORS, PCT: 80 85

END

Fig. 5. Technology projection: Near-Future.

Fig. 6. Area throughput comparison: Near-Future utilization of either 2 or 3 slicers would enhance throughput considerably. .

Processing silicon under these conditions yields about 0.62 m²/hr of Czochralski material, almost a factor of four more than the projected ribbon-material throughput (Fig. 9). The expensive (crystal growing and slicing) operations are reasonably well-balanced, contributing to the high throughput rate.

CZOCHEWALSKI TECHNOLOGY:

EQUIP AVAIL,PCT: 65 80 80

YIELD, PCT: 80 90 90

CRYSTAL PULLING

14.3 CM/HR OR...AS PCT OF MAX: 40

12 CM DIA

100 CM MAX LENGTH

CRYSTAL SLICING

36 SECS/CYCLE

0.5 KERF LOSS

0.025 CM THICK SLICES

WAFER POLISHING/ETCHING

1000 WAFERS/HR

END

RIBBON TECHNOLOGY:

1 SIMULTANEOUS RIBBON(S)

0.03 CM THICK

253 CM/HR OR...AS PCT OF MAX:50

10 CM WIDE

CONT GROWTH OR... SPECIFY

EQUIP AVAIL(INCL SU*HU),PCT: 90
YIELD FACTORS, PCT: 90 90

END

Fig. 7. Technology projection: Future.

Fig. 8. Area throughput comparison: Future larger-diameter crystals.

4.4 Limit

Finally, if we compare the Limit of both technologies (Fig. 9) from where we stand today, the result (as shown in Fig. 10) is still inconclusive, but somewhat favoring Czochralski, which yields a potential throughput of $\sim 1 \text{ m}^2/\text{hr}$.

The result is still considered inconclusive, since achieving these long-range Czochralski slicing and elimination-of-polishing objectives appears as difficult as reaching future ribbon milestones.

5.0 CONCLUSIONS

The throughput analysis model represents an additional tool for comparing the potential of competing sheet-growth techniques. It is useful for rapid analysis of sheet-material throughput capability, based upon the conventional Czochralski process, and for comparison of output with silicon area produced by means of ribbon-growth techniques.

Also, the model may be used as an aid in equipment or processing technology evaluation, as it applies to achieving a balanced production line for maximum product volume.

Generally speaking, any comparison technique, once applied and analyzed, should be supplemented by other, more sophisticated, approaches, in order to "fine-tune" the results. For instance, a discrete event system simulation study might be appropriate.

Two specific observations are of interest:

1. Near-future (conventional) Czochralski technology throughput is rapidly approached by continuously grown, 5-cm-wide ribbon.
2. An aggressive Czochralski technology projection (e.g., 15 cm in diameter, 40% of maximum growth rate, 0.025-cm-thick slices) is very difficult to match, in terms of throughput, even with 25-cm-wide ribbon. However, achieving these Czochralski and ribbon-growth objectives is considered equally difficult.

CZOCHEWSKI TECHNOLOGY:

EQUIP AVAIL,PCT: 65 80 80

YIELD, PCT: 80 90 90

CRYSTAL PULLING

12.8 CM/HR OR...AS PCT OF MAX: 40

15 CM DIA

120 CM MAX LENGTH

CRYSTAL SLICING

36 SECS/CYCLE

0.5 KERF LOSS

0.025 CM THICK SLICES

WAFER POLISHING/ETCHING

1000 WAFERS/HR

END

RIBBON TECHNOLOGY:

1 SIMULTANEOUS RIBBON(S)

0.03 CM THICK

304 CM/HR OR...AS PCT OF MAX:60

25 CM WIDE

CONT GROWTH OR... SPECIFY

EQUIP AVAIL(INCL SU&HU),PCT: 95
YIELD FACTORS, PCT: 95 95

END

Fig. 9. Technology projection: Limit.

Fig. 10. Area throughput comparison: Limit.

6.0 ACKNOWLEDGMENT

Terminal system output support was provided by Mrs. S. A. Focht.

Appendix

LISTING OF COMPUTER MODEL APL FUNCTIONS

This computer model for graphical analysis of the throughput of competing single-crystal silicon-sheet growth techniques utilizes the IBM licensed GRAPHICAL ANALYSIS PROGRAM, Number 5796-PFK, a highly interactive system for presenting data in pictorial form. The functions listed here have been written as an applications package to GAP as part of this contract, and, when entered into the APL GAP workspace, constitute the model used as part of this report.

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    ▽ CALC;BU;BU;SL;SL;SR;AR;AR;AR;X;X;Y;Y1;X1;T;CT;X2;Z;Z;Q
    ;PR
[1]  BU←(÷100)×YC[1]×BU←(÷10000)×(ML÷TH)×O((DIA÷2)*2)
[2]  SL←(÷100)×YC[2]×SL←ML÷(TH+(2×TH×KL))
[3]  AR←(÷100)×YC[3]×AR←(÷100)×YC[2]×AR←(÷10000)×O SL×(DIA÷2
    )*2
[4]  YY1←0,BU,BU,AR,AR,AR,AR
[5]  X←ML÷(GR×MC[1]÷100)
[6]  SR←SR
[7]  →(SR≠0)↑G1
[8]  SR←10*10
[9]  G1:Z←SL×(SR×MC[2]÷100)÷3600
[10] PR←PR
[11] →(PR≠0)↑G0
[12] PR←10*10
[13] G0:XX2←XX1←0,X,X,(Z+2ρX),((Z+X)+2ρ(SL÷(PR×MC[3]÷100)))
[14] YY2←(XX1[16]×X),XX1[7]×(×/YR)×(10*-4)×X+W×RG×SI×MR÷(10
    0×10000)
[15] →((SU=0)^(HU=0))/0
[16] T←⌈/XX1
[17] CT←XX2+YY2←0
[18] G2:→(CT>T)/0
[19] T←T-CT+SU+HU+Q←(NO×LM)÷(RG×MR÷100)
[20] X1←(⌈/XX2)+Q
[21] X2←X1+SU+HU
[22] XX2←XX2,X1,X2
[23] Y←(⌈/YY2)+(W×RG×SI×Q×(×/YR)×10*-4)÷10000
[24] YY2←YY2,Y,Y
[25] →G2

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▽

```

    ▽ HIT1;B;E
[1]  B←IN[2]
[2]  E←IN[1]
[3]  R←0
[4]  →((B≥90)^(B≤110))/0
[5]  →(((B≥1)^(B≤30))^(E≥817)^(E≤1020))/G1
[6]  □←8↑ 995 15 CHAR ' '
[7]  CN←8+□
[8]  CN←2CN
[9]  R←7
[10] →0
[11] G1:→((B≥440)^(B≤480))/G2
[12] R←1
[13] →0
[14] G2:→((B≥340)^(B≤380))/G3
[15] R←2
[16] →0
[17] G3:R←3

```

▽

```

      ▽ HIT3;X;B;E
[1]  X←8
[2]  E←IN[1]
[3]  B←IN[2]
[4]  R←0
[5]  →((B≥90)^(B≤110))/0
[6]  →((B≥600)^(B≤640))/G100
[7]  CSZ 2
[8]  ▯←8↑ 0 600 CHAR ' '
[9]  ▯←'CRYST PLG EQUIP AVAIL,PCT: '
[10] MC[1]←▯
[11] ▯←'SLICING EQUIP AVAIL ,PCT : '
[12] MC[2]←▯
[13] ▯←'POLISHING EQUIP AVAIL,PCT: '
[14] MC[3]←▯
[15] CSZ 4
[16] →0×R←1
[17] G100:→((B≥550)^(B≤590))/G10
[18] CSZ 2
[19] ▯←8↑ 0 800 CHAR ' '
[20] ▯←'POLY YLD TO SLICING,PCT : '
[21] YC[1]←▯
[22] ▯←'SLICING YLD W/O KERF,PCT: '
[23] YC[2]←▯
[24] ▯←'POLISHING YLD, PERCENT : '
[25] YC[3]←▯
[26] CSZ 4
[27] →0×R←1
[28] G10:→(((B≥410)^(B≤430))^(E≥465)^(E≤590))/G11
[29] ▯←(8↑ 440 420 CHAR ' '),BS,BS
[30] GR←▯(X+▯)
[31] →0×R←1
[32] G11:→(((B≥410)^(B≤430))^(E≥630)^(E≤950))/G1
[33] ▯←8↑ 915 392 CHAR ' '
[34] P1←▯(X+▯)
[35] →0×R←1
[36] G1:→((B≥380)^(B≤400))/G2
[37] ▯←8↑ 440 390 CHAR ' '),BS,BS
[38] DJA←▯(X+▯)
[39] →0×R←1
[40] G2:→((B≥350)^(B≤370))/G3
[41] ▯←(8↑ 440 360 CHAR ' '),BS,BS
[42] ML←▯(X+▯)
[43] →0×R←1
[44] G3:→((B≥280)^(B≤300))/G4
[45] ▯←(8↑ 440 290 CHAR ' '),BS,BS
[46] SR←▯(X+▯)
[47] →0×R←1
[48] G4:→((B≥250)^(B≤270))/G51
[49] ▯←(8↑ 440 260 CHAR ' '),BS
[50] KL←▯(X+▯)
[51] →0×R←1
[52] G51:→((B≥220)^(B≤240))/G5
[53] ▯←(8↑ 440 230 CHAR ' '),BS,BS

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[54] TH← $\frac{1}{2}$ (X+ $\bar{U}$ )
[55] →0×R←1
[56] G5:→((B≥140)∧(B≤160))/G6
[57]  $\bar{U}$ ←8↑ 440 150 CHAR ' '
[58] PR← $\frac{1}{2}$ (X+ $\bar{U}$ )
[59] →0×R←1
[60] G6:R←2
  ▽

```

```

  ▽ HIT4;X
[1] E←IN[1]
[2] X←8
[3] B←IN[2]
[4] R←0
[5] →((B≥90)∧(B≤110))/0
[6] →((B≥580)∧(B≤620))/G111
[7]  $\bar{U}$ ←(8↑ 435 600 CHAR ' '), (7ρBS)
[8] TR← $\frac{1}{2}$ (X+ $\bar{U}$ )
[9] →0×R←1
[10] G111:→((B≥630)∧(B≤670))/G11
[11]  $\bar{U}$ ←8↑ 435 650 CHAR ' '
[12] SI← $\frac{1}{2}$ (X+ $\bar{U}$ )
[13] →0×R←1
[14] G11:→(((B≥530)∧(B≤570))∧((E≥452)∧(E≤580)))/G1
[15]  $\bar{U}$ ←8↑ 410 550 CHAR ' '
[16] RG← $\frac{1}{2}$ (X+ $\bar{U}$ )
[17] →0×R←1
[18] G1:→(((E≥670)∧(E≤940))∧((B≥530)∧(B≤570)))/G12
[19]  $\bar{U}$ ←X↑ 875 528 CHAR ' '
[20] P2← $\frac{1}{2}$ (X+ $\bar{U}$ )
[21] →0×R←1
[22] G12:→((B≥480)∧(B≤520))/G2
[23]  $\bar{U}$ ←(8↑ 450 500 CHAR ' '), (6ρBS)
[24] W← $\frac{1}{2}$ (X+ $\bar{U}$ )
[25] →0×R←1
[26] G2:→(((B≥430)∧(B≤470))∧((E≥688)∧(E≤806)))/G31
[27] ERASE
[28] CSZ 2
[29] LM← $\square$ , 0ρ $\bar{U}$ ←'MAX RIBBON LENGTH, CM'
[30] NO← $\square$ , 0ρ $\bar{U}$ ←'NUMBER OF RIBBONS PER RUN'
[31] SU← $\square$ , 0ρ $\bar{U}$ ←'SET UP TIME, HRS'
[32] HU← $\square$ , 0ρ $\bar{U}$ ←'CRUCIBLE HEAT UP TIME, HRS'
[33] CSZ 4
[34] C←R←4
[35] →0
[36] G31:→((B≥150)∧(B≤170))/G32
[37] CSZ 2
[38]  $\bar{U}$ ←8↑ 0 800 CHAR ' '
[39]  $\bar{U}$ ←'YLD TO RIBBON DIMENSION,PCT: '
[40] YR[1]← $\frac{1}{2}$  $\bar{U}$ 
[41]  $\bar{U}$ ←'YLD OF' 'CELL QTY' 'RIBBON ,PCT: '
[42] YR[2]← $\frac{1}{2}$  $\bar{U}$ 
[43] CSZ 4

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[44]  →0×R←1
[45]  G32:→((B>170)^(B≤190))/G3
[46]  ▯←8↑ 900 180 CHAR ' '
[47]  MR←2(X+▯)
[48]  →0×R←1
[49]  G3:→((B>110)^(B<140))/G4
[50]  SU←HU←NO←LM←0
[51]  R←2
[52]  VMAX
[53]  →0×R←5+C←0
[54]  G4:R←3
```

▽

▽ MENU1;B

```
[1]  B←R
[2]  →(B≠3)/G1
[3]  20 20 CHAR 'POINT TO MENU'
[4]  →0
[5]  G1:ERASE
[6]  300 750 CHAR T,Q[KL;]
[7]  430 670 CHAR 'PROCESS PARAMETERS:'
[8]  450 460 CHAR 'DEFINE'
[9]  450 360 CHAR 'DISPLAY'
[10] 430 100 CHAR 'NEXT'
```

▽

▽ MENU2;B

```
[1]  B←R
[2]  →(B≠3)/G1
[3]  20 20 CHAR 'POINT TO MENU'
[4]  →0
[5]  G1:ERASE
[6]  300 750 CHAR T,Q[KL;]
[7]  430 670 CHAR 'DEFINE:'
[8]  450 460 CHAR 'CZOCHRALSKI PARAMETERS'
[9]  450 360 CHAR 'RIBBON PARAMETERS'
[10] 430 100 CHAR 'END'
```

▽

▽ MENU3;B

```
[1]  B←R
[2]  →((B=1)∨(B=6))/G1
[3]  20 20 CHAR 'POINT TO PARAMETER YOU WANT TO CHANGE'
[4]  →0
[5]  G1:ERASE
[6]  300 770 CHAR T,Q[KL;]
[7]  430 670 CHAR 'CZOCHRALSKI TECHNOLOGY:'
[8]  450 620 CHAR 'EQUIP AVAIL,PCT: ',MC
[9]  450 570 CHAR 'YIELD, PCT: ',YC
[10] 450 460 CHAR 'CRYSTAL PULLING'
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[11] 480 420 CHAR,(4+PGR),' CM/HR OR...AS PCT OF MAX: ',(4+
PCC)
[12] 480 390 CHAR,(DIA),' CM DIA'
[13] 480 360 CHAR,(ML),' CM MAX LENGTH'
[14] 450 330 CHAR 'CRYSTAL SLICING'
[15] 480 290 CHAR,(SR),' SECS/CYCLE'
[16] 480 260 CHAR,(KL),' KERF LOSS'
[17] 480 230 CHAR,(TH),' CM THICK SLICES'
[18] 450 190 CHAR 'WAFER POLISHING/ETCHING'
[19] 480 150 CHAR,(PR),' WAFERS/HR'
[20] 430 100 CHAR 'END'

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▽

▽ MENU4;B

```

[1] B←R
[2] →(B≠3)/G1
[3] 20 20 CHAR 'POINT TO PARAMETER YOU ARE CHANGING'
[4] →0
[5] G1:ERASE
[6] 300 770 CHAR T,Q[KL;]
[7] 430 720 CHAR 'RIBBON TECHNOLOGY:'
[8] 470 650 CHAR,(SI),' SIMULTANEOUS RIBBON(S)'
[9] 470 600 CHAR,(TR),' CM THICK'
[10] 470 550 CHAR,(3+PRG),' CM/HR OR...AS PCT OF MAX: ',(4+
PCR)
[11] 470 500 CHAR,(W),' CM WIDE'
[12] 470 450 CHAR 'CONT GROWTH OR... SPECIFY'
[13] →(R=3)+G3
[14] →((B≠4)^(C≠4))/G2
[15] G3:
[16] 720 450 CHAR 7p'_'
[17] 505 390 CHAR,'MAXL',[2](4,2)ρBSLF
[18] 555 390 CHAR,'NUMBER',[2](6,2)ρBSLF
[19] 600 390 CHAR,'SU TIME',[2](7,2)ρBSLF
[20] 650 390 CHAR,'HU TIME',[2](7,2)ρBSLF
[21] 475 420 CHAR ' '
[22] 4 0 3 0 4 1 4 1 PLM,NO,SU,HU
[23] 430 140 CHAR,'RESET TO CONTINUOUS GROWTH'
[24] G2: 430 180 CHAR,'EQUIP AVAIL(INCL SUαHU),PCT: ',PMR
[25] 430 160 CHAR,'YIELD FACTORS, PCT: ',PZR
[26] 430 100 CHAR 'END'

```

▽

▽ PLG;I;K;IN;A

```

[1] A← 100 900 100 700
[2] →(0=ρGI)/0
[3] ERASE
[4] I←,KL
[5] K←0
[6] S3:→((ρI)<K+K+1)/0
[7] ERASE
[8] 'GRAPH ';I[K]

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[9]  IN←GDES
[10] IN←(4↑IN),AXES X Y L M I[K]
[11] (I[K],A) GRAPH IN
[12] GLVAL I[K]
[13] IN←□
[14] →S3

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▽

▽ RESET

```

[1]  →((R=1),(R=2),(R=3))/G1,G0,0
[2]  MA←(4ρ1),(4ρ80),(8ρ90),(4ρ65),(8ρ80)
[3]  MA←MA, 60 80 100 120 0.04 0.05 0.06 0.070000000000000000
    1 ,(4ρ0.5), 8 10 12 15
[4]  MA←MA,(8ρ 10.11 9.83 9.69 9.31), 59 46 39 31 ,(4ρ72)
[5]  MA←MA, 2.5 5 10 25 0.03 0.02 0.015 0.01 ,(8ρ 150 248 3
    58 527)
[6]  MA←MA,(24ρ0), 70 80 90 95 80 85 90 95 70 80 90 95
[7]  MA← 34 4 ρMA,24ρ0
[8]  →0
[9]  G0:
[10] SI←MA[1;KL]
[11] YC←MA[2 3 4 ;KL]
[12] MC←MA[5 6 7 ;KL]
[13] ML←MA[8;KL]
[14] TH←MA[9;KL]
[15] KL←MA[10;KL]
[16] DIA←MA[11;KL]
[17] GR←MA[12;KL]
[18] GR←MA[13;KL]
[19] SR←MA[14;KL]
[20] PR←MA[15;KL]
[21] W←MA[16;KL]
[22] TR←MA[17;KL]
[23] RG←MA[18;KL]
[24] RG←MA[19;KL]
[25] SU←MA[20;KL]
[26] HU←MA[21;KL]
[27] LM←MA[22;KL]
[28] NO←MA[23;KL]
[29] P1←MA[24;KL]
[30] P2←MA[25;KL]
[31] YR←MA[26 27 ;KL]
[32] MR←MA[28;KL]
[33] PCR←MA[29;KL]
[34] PCC←MA[30;KL]
[35] LM←MA[31;KL]
[36] NO←MA[32;KL]
[37] SU←MA[33;KL]
[38] HU←MA[34;KL]
[39] →0
[40] G1:
[41] MA[1;KL]←SI
[42] MA[2 3 4 ;KL]←YC

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[43] MA[5 6 7 ;KL]+MC
[44] MA[8;KL]+ML
[45] MA[9;KL]+TH
[46] MA[10;KL]+KL
[47] MA[11;KL]+DIA
[48] MA[12;KL]+GR
[49] MA[13;KL]+GR
[50] MA[14;KL]+SR
[51] MA[15;KL]+PR
[52] MA[16;KL]+W
[53] MA[17;KL]+TR
[54] MA[18;KL]+RG
[55] MA[19;KL]+RG
[56] MA[24;KL]+P1
[57] MA[25;KL]+P2
[58] MA[26 27 ;KL]+YR
[59] MA[28;KL]+MR
[60] MA[29;KL]+PCR
[61] MA[30;KL]+PCC
[62] MA[31;KL]+LM
[63] MA[32;KL]+NO
[64] MA[33;KL]+SU
[65] MA[34;KL]+HU

```

▽

▽ START;I;K;KL;M;IN;A;B;T;Q;R

```

[1] T←'TECHNOLOGY PROJECTION: '
[2] Q← 4 11 ρ'PRESENT NEAR-FUTUREFUTURE LIMIT
[3] R←R+C←0
[4] G2:
[5] KL←0
[6] 'RESET? (Y OR N)'
[7] →('N'=1↑□)↑G1
[8] R←0
[9] RESET
[10] G1:
[11] R←2
[12] →(5=KL←KL+1+R←0)/G3
[13] G4:
[14] START1
[15] (M←1+(KL-1)×4) ACUR XX1
[16] (M+1) ACUR XX2
[17] (M+2) ACUR YY1
[18] (M+3) ACUR YY2
[19] KL AGRAP 4↑(4×KL-1)↑116
[20] KL ATYPE(2×KL)ρ1
[21] R←1
[22] RESET
[23] →(R=10)↑G1
[24] PLG
[25] ERASE
[26] 'REPEAT (Y OR N)'

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[27]  →('Y'≠1↑□)↑G6
[28]  →((R≠4)^(C≠4))/G7
[29]  R←3
[30]  →G4
[31]  G7:
[32]  R←2
[33]  →G4
[34]  G6:
[35]  →(KL<4)↑G1
[36]  G3:'SUMMARY? (Y OR N)'
[37]  →('Y'≠1↑□)↑G5
[38]  R←2
[39]  SUM
[40]  □
[41]  ERASE
[42]  G5:
[43]  'PICTURE? (Y OR N)'
[44]  →('Y'≠1↑□)↑S4
[45]  DEFP
[46]  PLP
[47]  S4:ERASE

```

▽

▽ START1

```

[1]  RESET
[2]  G1:MENU1
[3]  IN←LTPEN
[4]  HIT1
[5]  ERASE
[6]  →(R= 0 1 2 3)/G8,G2,G3,G1
[7]  G2:VMAX
[8]  →((R=6),(R=5))/G4,G5
[9]  MENU2
[10] IN←LTPEN
[11] HIT1
[12] →(R= 0 1 2 3 7)/G3,G4,G5,G2,G2
[13] G4:MENU3
[14] G6:IN←LTPEN
[15] HIT3
[16] →(R= 0 1 2)/G2,G6,G4
[17] G5:MENU4
[18] G7:IN←LTPEN
[19] HIT4
[20] →(R= 0 1 3 4 5)/G2,G7,G5,G5,G5
[21] G3:CALC
[22] VMAX
[23] ERASE
[24] →((R=2),(R≠2))/0,G1
[25] G8:R←10
[26] CALC
[27] VMAX

```

▽

```

▽ SUM;A;AP;C;D;E;F;G;H;K;O;P
[1] ERASE
[2] CSZ 4
[3] 300 780 CHAR 'SUMMARY OF INPUT PARAMETERS'
[4] O← 3 6 p 1 290 760 0 690 760 1 400 720 0 400 10 1 50 4
    00 0 800 400
[5] BLINE 0
[6] CSZ 1
[7] 850 10 CHAR TIME
[8] D← 21 2 p0
[9] KL←0
[10] G1:
[11] →(4<KL←KL+1)/G2
[12] RESET
[13] A←□CR 'MENU3'
[14] A←(14,((-1↑pA)-8))pA[6+114;8+1-1↑pA]
[15] H←□CR 'MENU4'
[16] H←(7,((-1↑pH)-8))pH[(7+15), 25 26 ;8+1-1↑pH]
[17] H[6;]←(4+H[6;]),4p' '
[18] A←A,[1](H,' ')
[19] E←4p 550 50
[20] A P CHANGES SEQUENCE OF SUMMARY LOCATIONS TO QUADRANTS
[21] A 1 2 3 4 AS IN PIC. 11/2/76
[22] P← 1 2 4 3
[23] D[;1]←21pE[P[KL]]
[24] F← 720 720 350 350
[25] D[;2]←F[P[KL]]-13×121
[26] A←(▽D),A
[27] C←59p('AP',57p' ')
[28] A←C,[1] A
[29] G←□FX A
[30] AP
[31] →G1
[32] G2:
[33] CSZ 4

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▽

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▽ VX←V X
[1] VX←100×0.87911×((2÷X)*0.5)
[2] →(X>1)/0
[3] VX←100×0.87911×((1÷X)*0.5)

```

V

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      ▽ VMAX;A;B
[1]  B←R
[2]  V1←V DIA
[3]  →(GR>V1)/E1
[4]  V2←V TR
[5]  →(RG>V2)/E2
[6]  PCC←(GR÷V1)×100
[7]  PCR←(RG÷V2)×100
[8]  →((P1>100)∨(P2>100))/E3
[9]  →((PCC>100),(PCR>100))/E1,E2
[10] →((B=1),(P1=0))/0,G1
[11] PCC←P1
[12] GR←(V1×P1)÷100
[13] P1←0
[14] G1:→(GR=GR)/G2
[15] PCC←(GR÷V1)×100
[16] GR←GR
[17] G2:→(P2=0)/G3
[18] PCR←P2
[19] RG←(V2×P2)÷100
[20] P2←0
[21] G3:→(RG=RG)/0
[22] PCR←(RG÷V2)×100
[23] RG←RG
[24] →0
[25] E1:ERASE
[26] 'FOR ';DIA;' CM DIA CZO CRSTL MAX G.R. IS ';V1;' CM/HR
[27] 'YOU SPECIFIED ';GR;' CM/HR'
[28] PCC←P1←100
[29] GR←V DIA
[30] R←6
[31] A←LTPEN
[32] →0
[33] E2:ERASE
[34] 'FOR ';TR;' CM THICK RIBBON MAX G.R. IS ';V2;' CM/HR'
[35] 'YOU SPECIFIED ';RG;' CM/HR'
[36] PCR←P2←100
[37] RG←V TR
[38] A←LTPEN
[39] R←5
[40] →0
[41] E3:'PERCENT CANNOT EXCEED 100; RESET TO ORIGINAL VALUE'

[42] P1←P2←0
[43] A←LTPEN
[44] →R+1
      ▽

```