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LASER-ZONE GROWTH IN A RIBBON-TO-RIBBON (RTR) PROCESS, SILICON SHEET GROWTH DEVELOPMENT FOR THE LARGE AREA SILICON SHEET TASK OF THE LOW COST SILICON SOLAR ARRAY PROJECT

Motorola Report No. 2256/1

Technical Quarterly Report No. 1

March 1976

JPL CONTRACT NO. 954376

By

R. W. Gurtler, A. Baghdadi

PREPARED BY

MOTOROLA INC. SEMICONDUCTOR GROUP
5005 E. McDowell Road
Phoenix, Arizona 85005

"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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SILICON SHEET GROWTH DEVELOPMENT FOR THE LARGE AREA
SILICON SHEET TASK OF THE LOW COST SILICON SOLAR
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ABSTRACT

The objective of this research contract is to fully investigate the Ribbon-to-Ribbon (R-T-R) approach to silicon ribbon growth. Initial work has concentrated on modification and characterization of an existing R-T-R apparatus. In addition, equipment for auxiliary heating of the melt is being evaluated and acquired. Modification of the remote viewing system and mechanical staging are nearly complete. Characterization of the laser and other components is in progress and several auxiliary heating techniques are being investigated.
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SUMMARY

Modifications to the RTR growth facility are proceeding on schedule. The two main viewing camera systems have been installed and are operational. A third camera system for edge viewing, not necessary for initial growth experiments, has been designed and is being constructed. Various auxiliary heating techniques are under investigation for utilization in the RTR process; among these, the most promising are direct electrical heating, radiant sources and the "Energy Beam". Evaluation of the laser operating characteristics and performance of optical components has been initiated.

Some mechanical problems have arisen in the ribbon transport fixturing; the ribbon chucks do not move smoothly and consequently could cause sample breakage due to stressing of the ribbon, especially when operating in the independent mode where the feed and uptake chucks operate under separate motor control. Work is continuing to improve the performance of these transport stages.
PROGRESS

Camera System

The camera systems for viewing the ribbon from both sides of the ribbon simultaneously have been installed and are now operational. A third camera installation for edge viewing of the ribbon has been designed (engineering drawings are found in the Appendix) and is now being fabricated.

Since this third camera is not necessary for immediate use in the ribbon growth experimentation phase of the contract, the camera system may be considered operational.

Mechanical Transport System

Previous operation of the RTR apparatus (prior to the present contract) had indicated that our ribbon transport system needed modifications to improve the smoothness of operation and the tracking of the "feed" and "uptake" chucks which are on independent stepping motor drives (Respowsyn HDM150, 2000 steps/rev.). Two precision leadscrews cause the translation of the ribbon chucks and .5" ground rods are used for alignment. Measurements showed separation distance variations (during translation) which were unacceptably large. Since ribbons as thin as 4 mils are to be investigated during the course of the contract, it was deemed desirable to maintain separation variations as small as possible. If the volume of the melt is

\[ V = Wt \ell \]

where

- \( W \) = ribbon width
- \( \ell \) = molten region length
- \( t \) = molten region thickness
then a variation in chuck separation will reflect itself initially as
a variation in \( l, \Delta l \). Maintaining the melt volume constant leads to the
relation

\[
\frac{\Delta l}{l} + \frac{\Delta W}{W} + \frac{\Delta t}{t} = 0
\]

Consequently, a variation in melt length will reflect itself in a variation
in width and thickness. These variations depend on dynamics — a rapid
change in length will probably be taken up initially as almost entirely
a thickness change, because the required material transport needs to occur
over only a short distance in the case of a thickness change, but a relatively
much larger distance in the case of a width change. At worst, we may take

\[
\frac{\Delta t}{t} \ll \frac{-\Delta l}{l}
\]

If a molten region of 10 mils is assumed, a \( \Delta l \) of 1 mil will give a 10%
thickness variation at worst. A goal for the staging was set at a
variation of \( \pm 1 \) mil.

The undesired variations in separation were, at least in part, a result of
design of the chucks which held the ribbons; they were cantilevered out
from the main ball bushings which maintained alignment, and the ratio of
the cantilever length to ball bushing support length was relatively large,
i.e., a magnification of small errors would occur. A modification has been
incorporated into the staging which reduced this magnification. This seems
to have improved matters, and indeed, initial tests indicated that variations of
\( \pm 1 \) mil had been attained. Attempts to repeat this performance have been
unsuccessful, however, and presently it is thought that some bearings are
faulty. Efforts will continue to obtain the desired staging accuracies.
Independent staging is not a necessity for initial crystal growth studies since a single "C" shaped fixture which is entirely supported by a single chuck may be used to hold a ribbon. However, reliable independent control will be necessary when attempting seeding operations, and also in studies where thin ribbons are to be pulled from thicker ribbons.

Auxiliary Heating

Auxiliary heating techniques which can serve to relieve the power requirements of the laser, and as a means of reducing strain due to very steep thermal gradients, are being evaluated. It is desirable that the heating technique not interfere with the laser beam nor interfere with the observation of the ribbon. For these reasons, electrical, radiant, and "Energy Beam" heating are attractive.

Electrical Heating

Since silicon is a fairly good electrical conductor at high temperatures, direct electrical heating of the ribbon may be utilized if electrical contacts are provided. A theoretical treatment of an electrically heated ribbon in the presence of radiative and convective cooling, and contacts of a given thermal impedance, has been carried out in a one-dimensional treatment. Referring to Figure 1, the heat equation (steady-state) becomes

\[ -\frac{WtK^2T}{x} = P(x) - 2\tilde{e}W\sigma(T^4 - T_A^4) - 2hW(T - T_A)^n \]

where \( P(x) \) represents the power input per unit length due to electrical heating, the second term represents radiative cooling with an emissivity \( \tilde{e} \) to an ambient at \( T_A \) and the third term represents convective cooling with a heat transfer coefficient \( h \) and a power law of \( n \). \( P(x) \) is given by
FIGURE 1
\[ P(x) = I^2 R(x) = \frac{I^2}{W_t} \rho(x), \]

1 is the current and \( \rho \) is the local resistivity. \( \rho \) is highly temperature dependent unless the sample is heavily doped. Figure 2 gives a plot of \( \rho(T) \) for various doped N type samples. \( \rho(T) \) can be expressed as

\[
\rho(T) = \sigma_{(T)}^{-1} = \left[ q \left\{ (N_D + \eta_i(T)) \mu_e(T) + (N_A + \eta_i(T)) \mu_h(T) \right\} \right]^{-1}
\]

where \( \eta_i(T) \) is the intrinsic carrier concentration, \( N_D \) and \( N_A \) are donor and acceptor concentrations and \( \mu_e \) and \( \mu_h \) are electron and hole mobilities.

From Smith*

\[
\eta_i(T) = 3.873 \cdot 10^{16} T^{-3/2} e^{-7 \cdot 10^3 T}
\]

\[
\mu_e(T) = 4.0 \cdot 10^8 T^{-2.6}
\]

\[
\mu_h(T) = 2.5 \cdot 10^8 T^{-2.3}
\]

The above differential equation was numerically integrated under the boundary conditions

\[
\frac{\partial T}{\partial x} = 0 \text{ at } x=0
\]

and

\[
T(L) = T_A + \theta \omega T \bigg|_{x=L}
\]

where \( \theta \) is a contact thermal impedance. Using the following parameters, the solutions of Figure 3 were obtained.

\[
K = 0.3 \frac{W}{cm^2\circ C} \quad \theta = 10 \circ C/W
\]

\[
h = 0.5 \cdot 10^{-5} \frac{W}{cm^2\circ C \cdot n} \quad T_A = 350\circ K
\]

\[ n = 5/4 \quad 2L = 10 \text{ cm} \]

\[ N_D = 10^{15} \quad W = 2 \text{ cm} \]

\[ t = 0.02 \text{ cm} \]

FIGURE 3
On each curve is noted the voltage and current required to obtain the curve in question. The voltage required for a given temperature is highly dependent on the thermal environment at the contacts since this is the region of high resistivity. On the other hand, the current is dependent only on the physical size of the ribbon and the radiative and convective losses. Note the very flat temperature profile over a substantial portion of the ribbon - conductive losses are unimportant over most of the ribbon.

A fixture has been constructed (diagram contained in Appendix) which allows electrical heating of a ribbon within the RTR apparatus. Boron nitride blocks provide the electrical isolation from the fixture and graphite blocks serve as the electrical contacts. Gold plated stainless steel contacts hold the graphite and ribbon under moderate tension and serve as the high conductivity connections to the graphite blocks.

The electrical heating fixture has been successfully tested. Detailed comparison with theory has not yet been performed, but general observations are in agreement with the presented model. In particular, very flat temperature profiles are obtained. Uniform heating to 1250°C has so far been attained, but some improvement in contacting uniformity is still desirable.

Electrical heating of ribbon promises to be a very useful research tool since one can very easily adjust the ribbon temperature and study the effects on laser input power requirements to melt. Also, by adjusting the ribbon temperature, the thermal gradient at the freezing point may be continuously varied. In addition, this will provide an effective way to measure optical and thermal properties of thin ribbon pieces.
Energy Beam

The Energy Beam is a trade name for an interesting Rf heating device manufactured by Energystics*. Figure 4 represents our conception of the Energy Beam operation. A gas stream is passed through a conducting tube which is in contact with an RF oscillator output coil (it actually serves to cool the coil also). A second, cylindrically concentric gas stream passes over this tube and serves to collimate the inner jet, i.e. buffer it from the atmosphere and maintain laminar flow; initially it is also electrically isolated from the inner stream. RF energy ionizes the gas within the inner jet which then, because of its macroscopic motion in the gas stream, effectively provides a conducting path (plasma) along the inner jet stream. The inner plasma jet thus serves as a conductive extension of the output coil and if an object is allowed to intercept this stream, dielectric and conductive heating will occur at the sample, little energy being expended in the plasma jet. The return path of the circulating RF current is through leakage to the atmosphere. Alternatively one can electrically ground the sample.

The device has very good overall efficiency (≈60%) and can locally heat a spot of the order of 3/16" at 4"-5" working distances. A trip was made to the Energystics facility to evaluate the Energy Beam as a means of auxiliary heating. A linear array of Energy Beams is evidently feasible and they are attempting to demonstrate relatively uniform heating in this mode. If this can be demonstrated, a 2KW unit will be obtained.

* Energystics Inc., Toledo, Ohio
Radiant Heating

One vendor (Fusion Systems) has shown considerable interest in supplying radiant heat sources for our requirements. We have sent them some ribbon samples for experimentation and if they are successful in reaching temperatures near the melting point, at reasonable angles and working distances, then a system will probably be obtained. The lamps are arc lamps and they have expressed some willingness to adjust gas compositions in order to better match the spectral output to the absorption of silicon.

RF Heating

Investigation is continuing into the use of RF heating (KHZ to MHZ) for pre-heating and post-heating of silicon ribbon. Eight vendors have been contacted, and our initial inquiries are now being followed up with appropriate vendor discussions. The most probable approach for implementing RF heating for these applications is via the use of a shaped susceptor which is encapsulated in a quartz envelope; the RF coils are placed externally around the susceptor with a coil-to-coil spacing which varies to allow the desired temperature profiling along the length of the susceptor. The application to auxiliary heating by this method is questionable because of the difficulty of allowing for the entrance of the laser beam. If this proves to be too much of a problem, RF heating may still find use in stress relief at a location somewhat removed from the actual growth area.

Laser Characterization

The laser employed for the RTR growth apparatus is a Photon Sources, model 300, CO₂ laser with a conservatively rated 375W CW output. In operation, various gas mixtures need to be adjusted to optimize the
operation of the laser. The gas mixtures (He, CO₂ and N₂) affect the output mode as well as total output power. Several experiments have been performed to evaluate the laser characteristics as well as a few of the optical components.

Utilized for these evaluations were a galvanometer mirror scanner (General Scanning G-300 PDT), a 1% ZnSe beam splitter (to reduce power to the detector), a moderate bandwidth (20Hz - 100kHz) pyroelectric detector (Laser Precision KT-2010S 1mm detector and KTH-201(7) preamplifier), a pyroelectric radiometer (Laser Precision RK 3440) and a high speed optical chopper (Laser Precision CTX-534).

Beam Profile

The apparatus used to measure the beam profile is shown schematically in Figure 5. The beam splitter used for this measurement transmits 1% of the incoming beam. Figure 6 is a transmission spectrum of the beam splitter showing 1% transmission at the CO₂ laser wavelength, 10.6 microns.

An example beam profile in both the X and Y directions is shown in Figure 7. The two dimensions were obtained by directly measuring the profile as indicated in Figure 5 for the X direction and then incrementing the detector in the Y direction to obtain the Y variation. Although the beam profile is not an ideal Gaussian, it serves our purposes well: it is sharply peaked, and has no "ringing" or "doughnut" modes. The 1/e² points are about 9mm apart in both the Y and X directions.

Beam Stability

The apparatus used to measure the beam stability is shown in Figure 8. A single-sweep oscilloscope trace of the measured output is shown in Figure 9.
FIGURE 5

FIGURE 6
FIGURE 7

X-X  X-direction
0-0  Y-direction

(the beam is sweeping in the X-direction)
Power: 200 Watts
Current Setting: 138
He Flow: 12.0
CO₂ Flow: 4.5
N₂ Flow: 2.5
Vertical Scale*: Relative Power
Horizontal Scale: 50 ms/cm
*Power Indication is Difference Between Upper and Lower Heavy Traces
Note that the total sweep time is 0.5 seconds. The power output of the laser thus has random fluctuations on the order of 5% - 10%. The fluctuations are also random in their time intervals, ranging from 5 msecs to hours.

"Far-field" Power

A significant portion of the radiation produced by the CO$_2$ laser does not go into the coherent, collimated laser beam. Due to aperture diffractions and imperfections in the laser cavity, some of the radiation is uncollimated, and thus does not reach the silicon ribbon. The power meter we have been using for these experiments was mounted by Photon Sources inside the laser apparatus, at the end of the laser cavity opposite to the output mirror. It therefore measures the "near-field" power, including some energy that is not delivered in the "far-field". We measured the far-field power using the apparatus shown in Figure 10. The results of this measurement are straightforward: once steady-state operation is reached, the far-field power meter reads about 6% lower than the Photon Sources near-field meter. Since the ZnSe lens absorbs 1% of the power it transmits, we conclude that about 5% of the laser power may be lost in a strongly diverging beam, although the calibration accuracies of the power meters are no better than 5% themselves. Under certain conditions, during initial warm-up, large discrepancies (~30%) between the two measurements can occur; this however, should not be a problem during operation.

Operating Parameters

Four parameters are used to control the output power of the laser: plasma current, Helium flow, CO$_2$ flow and N$_2$ flow. The same output power can be achieved using many different values of the operating parameters. The apparatus used for these measurements was shown in Figure 5. Figure 11a
FIGURE 10
Power: 300 Watts
Laser Current: 490
Vertical Scale: Relative Power
Horizontal Scale: ≈ 4mm/Div
He Flow: 8.0*
CO₂ Flow: 4.5
N₂ Flow: 2.2

* Flow rates are dial settings only

Power: 300 Watts
Laser Current: 364
Vertical Scale: Relative Power
Horizontal Scale: ≈ 4mm/Div
He Flow: 12.0
CO₂ Flow: 4.5
N₂ Flow: 2.5

FIGURE 11
shows the beam profile obtained at 300 watts using the operating parameters suggested by Photon Sources, Inc. Figure 11b shows the optimal beam profile so far obtained. By using higher He and N₂ flow rates, with a lower plasma current, a narrower, more efficient beam profile was obtained. Similar results were obtained at all power levels.

Problems
As mentioned previously, some problems have arisen in the mechanical staging. These problems will receive more attention in an attempt to resolve them, but it should be realized that little impact is expected on the program initially, because of the ability to utilize a single stage for most of our investigations. In addition, the instabilities in laser output power need to be reduced to a minimum, and measures will be taken to accomplish this.

Plans
During the next quarter we will have proceeded from the sheet growth facility modification task (Task I) into the actual sheet growth (Task II) and ribbon characterization stages (Tasks III & IV).

Yet to be accomplished under Task I are the full characterization of the laser and other optical components, evaluation and implementation of some auxiliary heating techniques, and fabrication of a growth velocity "Programmer". Some optical and thermal analysis of various electrically heated ribbon samples will be performed to obtain some useful physical data relevant to the ribbon samples used in RTR growth. The thermal measurement instrumentation will be tested and calibrated, and the environmental control of the enclosure will be evaluated.
ENGINEERING DRAWINGS

Drawings of the side-looking camera system and an electrical heating fixture are found in the Appendix.

NEW TECHNOLOGY

There have been no reportable "New Technology" items uncovered during this reporting period.
CONCLUSIONS AND RECOMMENDATIONS

Progress is proceeding essentially on schedule and problems which have surfaced are not expected to have any impact on our ability to meet the objectives of the contract. No recommendations are, therefore, offered at this time.
APPENDIX

ENGINEERING DRAWINGS
PELCO LENS BRACKET

B.D. Bass 2-10-76  SCALE: 1-1
R-021076-2
T.V. MOUNT BRACKET

By D. Dunn  2-11-76  SCALE: FULL

R-021076-3
MATERIAL: 6061-T6
TOL:
    .XX  = ± 0.02
    .XXX  = ± 0.005

MIRROR BASE

By R.D. 2-11-76  SCALE: FULL
R-021076-4A
MATERIAL: AL 6061-T6
TOL:
LX = ± .02
WXX = ± .005
ANGLES ± 1°

MIRROR HOLDER
B. R. 2-12-76 SCALE FULL
R-021076-7
K

.219 DIA THRU 2 PLS

.43

.75

.25

.1.00

.1.50

MIN BEND 12

.062 STKC

.12

.193 DIA THRU 2 PLS

.25

.25

.1.50

.1.00

#8-32 TAP THRU 2 PLS

.1.00

.2.5

.021O76-8

STC® JF

12S

STK.. 25

-32 TAP

TIAPL

-2 PAS

1.00

1.50

LOGb

-4po mmp--

ALL', ANC^L.ES'^ i/ZC

2

-o21o7ca-

F

MATL: AL 6061-T6

TOL:

.xxx = ± .02

.xxx = ± .005

ANGLES = ± 1/2°

GLASS HOLDER

By D. Dell 2-12-76 SCALE=FULL

R-021076-8
F #B =3Z - , C.S X .37L4

.75

.21

(9

\^ I D A T4?-Q

x-r)L.-:

7aOfol

T Co

.93DM ThED

.150

.75

.187

.25

.000

.000

.75

.219 DIA THRU

2 PLS

.193 DM THRU

2REQD

.8-32 S.H.C.S X .37L6

2REQD

MATERIAL: AL 6061-T6

TOL:

.2X ± .02

.3XX ± .005

ANGLES ± 1°

MIRROR HOLDER (FOR SCALE)

B. D. Co. 5-76. SCALE = FULL

R-021076-9
MATL: 6061-T6 AL ANGLE  
TOL:  
\[ XX = \pm 0.02 \]  
\[ XXY = \pm 0.005 \]  
ANGLES \( \pm 10^\circ \)  

IRCON HEAD MOUNT  
B. D. - 2.13.76  
SCALE - FULL  
R-021076-10
SCREW TO SUIT

.187 DIA THRU

.001 DIA THRU, 2 PL'S

.20

.50

1.00

1.37

1.88

4.50

1.87 REF

4.00

.87

.090

.187 STK

.125

.50

2 REQ'D

.140 DIA THRU

.250

.37

.87 STK

.001

.005

ANGLES ± 1°
PIVOT MOUNT (IRCON)

B: D. Does 2-13-76 SCALE=FULL
R-021076-12
MIRROR HOLDER

MATERIAL: 6061-T6

TOLERANCES:
XXK = ± .02
XXKK = ± .005

SCALE: FULL

DRAWN: 3-5-76

R021076-28
RIBBON FIXTURE
FOR ELECTRICAL HEATING
CLEARANCE FOR 4-40 APERTURE 2 PLACES

CLEARANCE COUNTERBORE FOR 4-40 SCREWホール 2 PLACES

1" 25"

INSULATING BLOCK
MATÉ: BORON NITRIDE
4 REQ'D

4-40 CLEARANCE ¼"

1.5" × .35"

BOTTOM CONTACT TYPE A
MATÉ: STAINLESS
2 REQ'D

1.5" × .35"

BOTTOM CONTACT TYPE B
2 REQ'D

# R-022876-1
Mounting Block

Material: 3/8" SS

2 Required