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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

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MASTER

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Solar Energy

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SUMMARY

We have made substantial progress both in crystal growth and in processing. We have reached a growth rate of 12.5 cm/min with 2 cm wide ribbon. This high growth-rate ribbon has a dendritic structure. We have increased the maximum non-dendritic growth rate to 8 - 9 cm/min by using active cooling (inert gas jets) to steepen the postheater temperature gradient. We have also grown RTR ribbon from 2.5 cm wide CVD polycrystalline feedstock. Doped CVD feedstock can now be grown in widths from 1" to 3", and thicknesses from 125 μm to 250 μm . The poly ribbon thickness is uniform within $\pm 5\%$ along the length of the ribbon.

Our first attempts to grow 5 cm wide ribbon from CVD feedstock were only partially successful, due to buckling in the ribbon prior to crystallization. This buckling creates both longitudinal and lateral curvatures in the ribbon. The curvature is often so great that the sample cannot pass through the 0.1" wide slot of the postheater. The probable cause for this buckling is the non-ideal longitudinal temperature distribution. We will therefore need to control the temperature profile in the feedstock ribbon (as well as in the growing ribbon) in order to overcome this problem.

In our previous reports, it was shown that a degradation in the open circuit voltage of a 50 mv occurs during the metallization step. We have now demonstrated that by using a low-temperature metallization process, this V_{OC} degradation can be reduced to 10 - 15 mv. We have also fabricated solar cells on dendritic ribbon. Preliminary measurements indicate that their performance is at least as high as cells fabricated on non-dendritic substrates.

1.0 APPARATUS

1.1 POSTHEATER DEVELOPMENT

The postheater used in RTR #1 was designed for maximum ribbon widths of ~1". We have constructed a larger postheater which accomodates 2" and 3" wide ribbons. The active heating width is 5", which will allow us to achieve a uniform temperature distribution across the 3"-wide ribbon. The length of the hot zone is ~2". In other respects, design of the new heater is similar to that of the old one, using individual heater elements such that the temperature at each pair (on opposite sides of the ribbon) can be separately controlled. A linear temperature profile can be maintained by adjusting each of the heater element pairs.

However, a number of significant changes are made:

- . The furnace housing was modified to bring the first heater element closer to the molten zone.
- . A highly reflective multifoil primary insulation system was added to the ceramic wool insulation; this is an attempt to use cleaner insulation material.
- . The longer heating elements are supported by slotted alumina plates, since unsupported elements would sag at the expected operating temperatures.

A number of difficulties prevented earlier completion of the new heater. The support plates have cracked or moved during operation allowing some heater elements to sag and short against others. This cracking is probably due to improper mounting procedures, thermal shock caused by increasing the furnace temperature too rapidly, and/or use of a low strength alumina. These problems have been addressed. A manual ramping

controller is used to slow temperature increases. A "floating" support system reduces the forces on the support plates, and these have been fabricated from higher strength materials.

The temperature controller itself has also presented some problems. The first two heater element pairs are driven much harder than the rest. To simplify power supply construction, the first elements are all driven in parallel while the more lightly loaded pairs are driven in series as shown in Figure 1. The high driving requirement of the first elements led to an unstable temperature, i.e., pulsation. This problem was eliminated by using true proportional control and reducing the gain of the feedback system.

1.2 YAG LASER SYSTEM

Although the two YAG laser systems were installed at the end of 1977, they have only recently become operational. We were delayed several weeks by low power output due to difficulties with laser alignment, a defective AR coating on a YAG rod, and low output flash lamps. YAG system 1-2-3 is now working at the expected power output (375 watts with 38 amps/head), but system 4-5-6 is somewhat below par, with a power output of only 330 watts with 40 amps/head. Since the total power loss is only ~6%, we have decided to start using the YAG system for high-speed ribbon growth, instead of incurring further delays.

The YAG laser output is normally divergent (~15 milliradians). Beam expanders are used to collimate the beam so that its diameter at the scanning mirrors is <1". The beam expanders on both systems are absorbing ~25% of the laser power, due to defective AR coatings on their input lenses. These lenses are being replaced. Until we receive the new lenses, we will carry out some preliminary experiments using the defective lenses.

FIGURE 1: FURNACE CONTROL SYSTEM. BECAUSE OF THE HEAVIER LOADING OF THE FIRST TWO HEATER ELEMENT PAIRS THEY ARE PARALLEL DRIVEN (With one controller, for example C1) WHILE MORE LIGHTLY LOADED ELEMENTS ARE SERIES DRIVEN (for example, Pair #n with controller Cn).

Although not a part of this program, we have previously reported successful growth of polycrystalline ribbon using conventional chemical vapor deposition techniques. The initial ribbons were grown $\sim 0.009'' - 0.011''$ thick, while our goal is to match the required RTR ribbon thickness of $100\mu\text{m}$. We have now demonstrated the practicality of this goal; in our most recent run, we produced ribbons $\sim 0.005''$ thick, in 1", 2" and 3" widths. Ribbon thickness is maintained along the ribbon length within $\pm 5\%$.

These poly ribbons are doped throughout the deposition cycle. The dopant is uniformly distributed through the ribbon thickness^{*}, but varies along the 8" length of the ribbon from $0.2\Omega\text{-cm}$ to $1.2\Omega\text{-cm}$. This variation will be eliminated when we go to continuous ribbon production. However, since the current variation may present some problems with solar cell fabrication, we are working on its reduction.

SIMS analysis of the CVD feedstock has shown an estimated molybdenum concentration of 5 ppm at the back surface (the surface in contact with the moly substrate). The concentration of molybdenum drops to less than 0.5 ppm (the instrument detection limit) within $0.5\mu\text{m}$ from the surface. To evaluate the effect (if any) of this back surface moly contamination on the crystal growth and solar cell efficiency of ribbons grown from CVD feedstock, the back surface of a number of CVD samples was etched in HCl vapor at 1100°C to remove ~ 2 mils. We are presently growing ribbons from stock of CVD "back etch" samples for characterization and solar cell processing.

* Resistivity measurements are made using a 4-pt. probe on a p-type epitaxial layer deposited on n-type single crystal wafers simultaneous to ribbon production.

3.0 CRYSTAL GROWTH

3.1 GROWTH USING YAG LASERS

A few preliminary runs were carried out using the YAG lasers. A growth rate of 5"/min., 2:1 ratio mode was reached using 455 watts. The grown ribbon, however, was heavily dendritic. In the lock mode, 0.011" thick ribbon was grown at 3"/min. using 562 watts.

3.2 ACTIVE COOLING

For a given ribbon thickness, the onset of dendritic growth is determined by the postheater profile. The steeper the profile, the greater the growth rate that can be achieved without the onset of dendritic growth. With a linear temperature gradient of $183^{\circ}\text{C}/\text{cm}$, the maximum growth rate for dendrite-free ribbons was 7.6 cm/min. This was the steepest gradient we could achieve with this postheater, due to its large thermal mass. However, by adding inert gas jets to the postheater, the temperature gradient can be further increased. Figure 2 shows the gas jet positions. With a gas flow of 6.5 l/min., the maximum nondendritic growth rate was 8.3 cm/min. When the growth rate was increased to 8.9 cm/min., several large dendrites started to grow. Once the dendritic growth was firmly established, the gas flow rate was increased to 24 l/min., and the dendrites disappeared. With the gas flow rate reduced to 6.5 l/min., the dendrites reappeared.

The temperature profile established in the postheater using a 6.5 l/min. flow rate is shown in Figure 3. However, the silicon ribbon is moving too fast at 8 - cm/min. to actually "see" this temperature profile. For example, the gas flow rate had to be increased to 24 l/min. in order to produce a significant effect.

FIGURE 2: POSITION OF GAS NOZZLES

L

FIGURE 3: POSTHEATER TEMPERATURE PROFILE

In order to accurately measure the temperature distribution of the silicon ribbon itself, a thin platinum resistor will be deposited on an actual ribbon sample. Since the thickness of the platinum resistor ($\sim 10^3 \text{ \AA}$) will be negligible in comparison to the ribbon thickness ($\geq 10^6 \text{ \AA}$), no significant error will be introduced due to sensor inertia. Platinum resistor masks are now being fabricated which should allow temperature measurements to an accuracy of better than $\pm 2\%$. Thus the platinum resistor on a silicon ribbon will function as an accurate temperature sensor which can model the temperature the growing ribbon itself reaches at constant velocity growth.

3.3 GROWTH OF 5 cm WIDE RIBBON

Our first attempt to grow 5 cm wide ribbon was encouraging. The feedstock used was 5 cm wide, 0.006" thick CVD ribbon. However, during the growth a scanning mirror overheated and the run was aborted. We had succeeded in growing ~2.5 cm at a maximum growth of 2.5 cm/min., before shut-down. Subsequent attempts to grow 5 cm-wide ribbon were unsuccessful: the CVD ribbons fractured during the initial laser power increase. We will continue working on the growth of 5 cm-wide ribbon when more feedstock becomes available.

Ribbon buckling is often observed in grown ribbons. Figure 4 shows an example of such ribbon buckling. This type of buckling of grown ribbons has been observed since high velocity ribbon growth has been possible. This problem of ribbon buckling is not unique to the RTR process, ribbons grown by the EFG process also exhibit buckling ⁽¹⁾. The mechanism proposed to account for this buckling has been ascribed to non-linearities in the thermal profile, a hypothesis which we also support. In section 4.3, this mechanism is discussed in more detail.

Recently, we have encountered considerable difficulty due to the occurrence of severe buckling prior to melt initiation when wide (2") and thin (.005") feedstock is utilized. In this case, substantial longitudinal and lateral curvature are produced by the action of the postheater thermal profile alone. The warping is so severe that the sample could not pass through the post heater which has cross sectional dimensions of .1" X 4". Upon initiation of a melt, and establishment of steady state growth, it is expected that the buckling will not be as severe, partly because the liquid zone separates the upper and lower ribbon portions and partly because steady state temperature profiles at high growth rates tend to be less non-linear.

Because of the importance of these buckling effects, it is worthwhile discussing various observations of ribbon buckling and to consider the nature of the buckling mechanism.

4.1 EXPERIMENTAL OBSERVATIONS

Buckling of RTR ribbons was not observed prior to the implementation of the postheater. The postheater was added to control the post-crystallization

FIGURE 4: BUCKLING IN RTR RIBBONS. THIS SAMPLE IS A CVD FEEDSTOCK RIBBON GROWN IN THE RATIO MODE.

temperature profile in order to reduce frozen-in stresses and to avoid ribbon shattering. These efforts were successful and were instrumental in achieving high growth rates ⁽²⁾. Initially, high peak temperatures and low thermal gradients were utilized. Only recently have steps been taken to reduce peak temperatures and increase thermal gradients in order to achieve even higher growth rates (see section 3.2).

From these numerous growth runs, the following observations have been made:

- . Buckling is much more likely for thin samples as opposed to thick samples. Typically .010" thick samples rarely show buckling whereas ratio mode samples under identical growth conditions can show significant buckling.
- . Buckling is highly dependent on ribbon width. .5" samples show little tendency to buckle, 1" samples have shown moderate buckling and 2" samples show severe buckling.
- . Buckling is dependent on growth velocity. For a given thermal geometry, buckling is absent at low growth velocities but becomes pronounced at higher growth velocities.
- . At very high growth velocities, near the onset of dendritic growth, buckling decreases or vanishes.
- . On most samples, the "wavelength" of the buckling very nearly equals the width of the sample and the lateral and longitudinal curvatures are of the same sign.

The effect of variation of the melt-postheater separation is clearly related to the resulting temperature profile. Figure 5 illustrates the effect of this separation. These curves are composed by a "reasonable" combination of the

FIGURE 5: VARIATION OF RIBBON THERMAL PROFILES WITH VARIOUS MELT-POSTHEATER SEPARATIONS

theoretical "laser only" ribbon profiles and the measured furnace profiles. The resultant profile will of course merge with each of these at the various extremes and will make a smooth transition in the central region. Of interest is the magnitude of the thermal "dip" and its location. The limitation imposed presently on further decrease of the melt-postheater separation is mechanical: it is difficult to construct an active furnace which gets closer to the melt zone without obstructing the laser beam.

From the figure it is apparent that thermal non-linearities will be much greater for large separations. Figure 6 illustrates the effect of a change in post heater peak temperatures and thermal gradients with a given melt-postheater separation. This can also cause an effect in thermal non-linearities. In addition, the high stress region now occurs at a lower temperature.

4.2 STRESS DISTRIBUTIONS ARISING FROM PRESENT THERMAL PROFILES

The effect of these non-linear temperature profiles on the distribution of ribbon stresses is of considerable interest. This problem has been treated theoretically by a number of authors ^(3,4,5,6) with the treatment by Surek ⁽³⁾ being the most directly appropriate. Unfortunately, all these treatments have assumed temperature independent mechanical properties for the materials and have also assumed fully elastic behavior; the latter assumption is particularly bad since considerable plastic deformation does take place. A numerical treatment of the system which allows for elastic-plastic and viscoelastic effects is necessary to achieve a more realistic solution.

The analytic solutions are useful, nevertheless, for obtaining qualitative information relating to stress distributions. Figure 7 illustrates qualitatively the nature of stresses near the molten zone for a case where a substantial (but probably realistic) temperature dip occurs. Positive curvature regions are

FIGURE 6: VARIATION OF RIBBON THERMAL PROFILE
WITH ALTERATIONS IN POSTHEATER PEAK
TEMPERATURES AND THERMAL GRADIENT

FIGURE 7: NATURE OF IN-SITU RIBBON THERMAL STRESSES FOR AN ASSUMED THERMAL PROFILE.

expected to yield edges in compression ($\sigma_{xx} < 0$) and the central portion in tension. Negative curvature regions should give the opposite type of stresses. The fact that the postheater region can induce stresses of the opposite type has been verified experimentally (see section 4.7).

4.3 BUCKLING MECHANISMS

The presence of compressive stresses acting over a substantial area of the ribbon can lead to ribbon buckling. Consider Figure 8. If the compressive stresses are small, then a flat rectangular plate will absorb the energy of compression in the form of elastic strain energy and any tendency of the plate to bend will be opposed because the energy of bending is larger than the work expended in bending the plate; consequently system energy would have to increase. On the other hand, at a critical level of compressive stress, the situation is reversed; under bending, the total energy of the system can decrease and consequently buckling will occur.

The treatment of elastic instabilities is highly developed but again, only simple situations can be analyzed. Nevertheless, some order-of-magnitude estimates can be presented. Analysis of a thin rectangular slab of width W , thickness t and length L acted on by an uniform longitudinal compressive stress σ , simply supported on one side and free on an outer edge, leads ⁽⁷⁾ to the critical stress.

$$\sigma_{CR} = k \frac{\pi^2 D}{t W^2}$$

where

$$D \equiv \frac{E t^3}{12 (1 - \nu^2)}$$

FIGURE 8: THIN PLATE ACTED ON BY COMPRESSIVE STRESSES, σ , IN THE PLANE OF THE PLATE. AT SOME LEVEL OF σ , THE PLATE IS UNSTABLE AND BUCKLING CAN OCCUR.

E and ν are Young's modulus and Poisson's ratio ($\approx .25$) respectively and k is a factor which is a function of ℓ/W .

If $\ell/W < .5$, k tends to W^2/ℓ^2 , i.e. for $\ell/W < .5$,

$$\sigma_{CR} \sim \frac{\pi^2 D}{t \ell^2}$$

Other values of k for various ℓ/W are shown in Table 4.1.

As an example, let us assume the following values:

$$E = 17.10^6 \text{ PSI}$$

$$\nu = .25$$

$$W = .25''$$

$$\ell = .25''$$

$$t = .01''$$

These may be typical for a small compressive region on, say, a 1" wide ribbon.

In this case, $\ell/W = 1$.

$$D = 1.51$$

and

$$\sigma_{CR} = 34,361 \text{ PSI}$$

This is a sizeable stress level -- large in fact compared to estimated yield stresses. The questions which should then be addressed are; a) can such stress levels be generated in the present thermal environment, and b) will stress relaxation due to plastic flow be sufficient to keep the stress below the above critical stress?

Stress levels comparable to the critical stress calculated above can occur. For example, consider the temperature distribution of Figure 7. The temperature dip which occurs away from the molten zone can be seen to have a

TABLE 4.1

l/W	k
.5	4.40
1.0	1.44
2.0	.698
3.0	.564
4.0	.516
5.0	.506

curvature $d_x^2T \sim 10^3 \text{ }^\circ\text{C/cm}^2 \sim 6450 \text{ }^\circ\text{C/in}^2$. Since the "dip" occurs some distance from the molten zone, the analytical solution presented in references (3) and (4) can be used with more confidence. There it is shown that the edge stresses are

$$\sigma_{xx} \sim -1/3 \alpha E C^2 d_x^2T$$

where

α = expansion coefficient

C = half-width of ribbon

Using

$$\alpha = 4 \cdot 10^{-6}$$

$$E = 17 \cdot 10^6$$

$$C = .5''$$

$$d_x^2T = 6450 \text{ }^\circ\text{C/in}^2$$

then

$$|\sigma_{xx}| \sim 36,500 \text{ PSI} > |\sigma_{CR}|$$

This result would indicate that buckling would be possible.

Stress relaxation, however, will probably prevent the above stress levels from being achieved if they occur in too high a temperature region. Stress levels of 10 - 20K PSI lead to rapid stress relaxation for temperatures above 1200°C .⁽⁸⁾ At high growth velocities and correspondingly high strain rates, it is conceivable that such levels might be obtained. Experimentally, we have found that buckling is more likely at high growth velocities as long as dendritic growth is not achieved.

4.4 SIZE EFFECTS

The example treated above indicated a low probability of buckling primarily due to the probability of stress relaxation. Buckling is much more likely for

thinner and wider ribbons, however. Rewriting σ_{CR} (and assuming $l/W < .5$),

$$\sigma_{CR} = \frac{\pi^2 E t^2}{12 l^2 (1 - \nu^2)}$$

σ_{CR} is therefore proportional to t^2 and inversely proportional to l^2 , the stress interaction length. If for example, $t = .005"$, $l = .25"$ then

$$\sigma_{CR} \approx 5965 \text{ PSI}$$

Consequently, thinner samples are much more likely to buckle. This is in complete agreement with experiment. Samples grown in a lock mode with $t \approx .01"$ have rarely shown buckling. Samples grown in a ratio mode ($t \approx .006"$) often show buckling.

Another factor of considerable importance is the influence of ribbon width. Increases in width substantially increase the probability of buckling for two reasons: 1) the magnitudes of stress components increase with ribbon half-width, C . For example, σ_{xx} as calculated above varied as C^2 . 2) Increasing C also increases the length of stress disturbance which typically vary as x/C , y/C , etc. In otherwords increasing the sample width C , will also increase l and therefore decrease σ_{CR} since $\sigma_{CR} \propto l^{-2}$.

4.5 PREGROWTH BUCKLING OF FEEDSTOCK

It is also of interest to consider semi-quantitatively the buckling we have observed in the wide, thin CVD feedstock. It has occurred prior to melting, i.e., it is due entirely to the postheater profile. Several alternative mechanisms were considered. The CVD samples are separated from a molybdenum substrate and consequently have a "smooth" and "rough" surface. It is conceivable that some material asymmetry exists at the two surfaces, the nature of which is presently unknown. Such an asymmetry in, e.g., expansion coefficient could cause buckling. This possibility was eliminated experimentally. It would give rise to buckling in a uniform temperature field but in fact no buckling is observed under such conditions.

A second possibility is the occurrence of a temperature difference through the thickness of the sample. Such a temperature difference could result if the wall temperatures of the furnace were asymmetrical. To estimate the magnitude of this effect, the radiation heat balance of Figure 9 was calculated. The result was (to a good approximation)

$$\Delta T = T_{S1} - T_{S2} = \frac{t\epsilon\sigma}{2k} (T_1^4 - T_2^4)$$

where ϵ , k and σ are the ribbon emissivity, ribbon thermal conductivity, and Stephan Boltzmans constant respectively.

This temperature difference across a sample with expansion coefficient α will lead to a radius of curvature

$$\rho = \frac{t}{\alpha \Delta T}$$

For a sample of length L , this in turn leads to a deflection of

$$\delta = \frac{L^2}{8\rho} = \frac{L^2 \alpha \Delta T}{8t} = \frac{L^2 \alpha \epsilon \sigma}{16k} (T_1^4 - T_2^4)$$

Note that this is independent of thickness and width. Consequently, the use of wide, thin samples should not have led to a greater effect and this alone rules out this possibility. It is interesting, nevertheless, to evaluate this for an appropriate example. Let $\alpha = 4 \cdot 10^{-6}$, $T_1 = 1500^\circ\text{K}$, $T_2 = 1400^\circ\text{K}$, $t = .1\text{mm}$, $k = .25\text{W/cm}^2\text{K}$, $\sigma = 5.67 \cdot 10^{-12}\text{W/cm}^2\text{K}^4$ then for $L = 10\text{cm}$ we find $\Delta T \sim .083^\circ\text{C}$ and $\delta \sim 4 \mu\text{m}$. Even with an order of magnitude increase in ΔT , this mechanism cannot account for the buckling.

Now let us consider the previously proposed mechanism -- thermal non-linearity induced buckling. From Figure 4, the furnace profile alone gives an estimated curvature of

$$d_x^2 T \sim -266^\circ\text{C/cm}^2 = 1720^\circ\text{C/in}^2$$

FIGURE 9: RADIATION HEAT BALANCE FOR A RIBBON OF THICKNESS $\dagger$ WITH AN EMISSIVITY E AND THERMAL CONDUCTIVITY k IN AN ASYMMETRICAL RADIATION BALANCE. OF INTEREST IS THE RESULTING TEMPERATURE DIFFERENCE $T_{S1} - T_{S2}$ IF $T_1 > T_2$.

In this case, the compressive forces occur near the center of the ribbon and utilizing the same assumptions as previously, the central fiber compression is

$$\sigma_{xx} \sim \frac{\alpha EC^2}{6} d_x^2 T$$

with $\alpha = 4.10^{-6}$, $E = 17.10^6$, $C = 1''$, $d_x^2 T = 1720^\circ\text{C}/\text{in}^2$ we find

$$\sigma_{xx} \sim -19,493 \text{ PSI}$$

The critical stress for buckling can be evaluated as before.. From Figure 7 we estimate $w \sim 1''$, $\lambda \sim .5''$ for a 2" wide sample. Taking $t = .005''$ then leads to

$$\sigma_{cr} \sim -1491 \text{ PSI}$$

Consequently the sample is virtually certain to buckle. On the other hand, a sample of thickness

$$t > \sqrt{\frac{19,493}{1,491}} (.005) = .018''$$

would be stable.

4.6 DISCUSSION OF BUCKLING PROBLEMS

The problems posed by this buckling effect towards RTR growth of wide samples is in some respects unique to the RTR process. This is because we not only have potential buckling problems with regards to the grown ribbon section, but we also have potential buckling to contend with in the feedstock.

Since the buckling is apparently almost entirely due to postheater effects, the post heater temperature peak and the melt postheater temperature dip, it would seem that we should eliminate the postheater. In fact, we have long recognized that simply applying temperature sinks very near to the melt, as in Figure 10, should give us the possibility of maximum growth velocity and minimum thermal non-linearities by forcing a constant heat flux. However, such geometries are difficult to achieve and furthermore, due to variations in thermal

FIGURE 10: POSSIBLE HIGH THERMAL GRADIENT, RTR GROWTH CONFIGURATION.

conductivity and expansion coefficient with temperature, a low stress level will not result and fracture will undoubtedly occur. Some experiments along a similar line are reported in Section 4.7.

The path which we are presently pursuing is to continue use of a post heater but further reducing the size of the postheater and also adding a preheater to achieve a profile as in Figure 11. In this case we shall attempt to control the thermal profile in both the pre- and postcrystallization region to provide a relatively stress-free environment up to $T > 1200^{\circ}\text{C}$. The thermal non-linearities occurring above this temperature for the heaters alone will hopefully not cause buckling since the plasticity is high throughout the stressed region.

Beyond this approach, efforts towards achieving a successful geometry of the sort indicated in Figure 11 will be continued.

4.7 STRIP HEATER EXPERIMENTS

The strip heater shown in Figure 12 was tested as one approach towards establishing steeper thermal profiles and yet achieving relatively low residual stresses. The inner platinum foils are heated by an electrical current passed through them. The outer foils are heat shields to improve the thermal efficiency. A ribbon guide below the foils serves as a heat sink. The total distance from the melt to the heat sink was about 1.5cm. Therefore, assuming at steady state heat sink temperature of 200°C , an average gradient of about $800^{\circ}\text{C}/\text{cm}$ is established. Comparing with Figure 4 we see this represents a higher average gradient than a laser-only heated ribbon radiating to a 0°K ambient, but that it is smaller than the initial thermal gradient.

FIGURE 11: THERMAL PROFILES FOR A PREHEATER AND POSTHEATER COMBINATION WITH LINEAR PROFILE REGIONS BELOW APPROXIMATELY 1200°C.

FIGURE 12: EXPERIMENTAL STRIP HEATER CONFIGURATION

With this apparatus two effects were of interest. First, due to the high reflectivity of platinum ($\sim .9$), ribbon radiation would be reflected back onto itself and therefore the net emissivity of the sample would be reduced. If the effective emissivity could be reduced to zero, the heat transport would become almost entirely due to conduction thereby leading to a more linear thermal profile.

Second, by passing current through the foils, a higher temperature ambient could be simulated which might compensate for radiation losses and have some effect on residual stresses.

A series of simulated 1"/min growth runs were made to determine residual stresses as a function of foil heating current. Stresses were evaluated by the analysis of stress birefringence. A single stress measurement was made near the center of each ribbon. Ribbon samples were 1.25 cm wide, (100) surfaces with [100] growth directions. Partial melting of the sample was utilized so as to maintain a single orientation to facilitate stress analysis.

Figure 13 presents the experimental results. Without any foil current, the central fiber residual stress was compressive at about -5300 PSI while at a current of 40A, the residual stress has become tensional at about 2100 PSI. At 32A of foil current, no residual stresses were detected.

With these results, actual crystal growth was performed. These samples resulted in considerable buckling. The fact that these .5" wide ribbons grown in a lock mode exhibited buckling indicates that very non-linear profiles are occurring. Consequently the zero residual stresses occur not because stresses are being eliminated, but because compensating stresses are being applied due to positive and negative curvature thermal profile regions.

FIGURE 13: MEASURED STRESS AS A FUNCTION OF PREHEATER CURRENT

Experiments with 1"-wide samples were also unsuccessful. It is clear that more control is required over the thermal profile than supplied by this simple approach. However further experimentation at lower current levels where partial stress reduction occurs will be pursued.

5.0 CHARACTERIZATION

5.1 MORPHOLOGY AND DEFECT STRUCTURE

Figures 14 a, b, c are cross-sections of the CVD feedstock ribbon, RTR ribbon grown from CVD feedstock, and of an RTR ribbon grown in the dendritic growth region. Figures 14 a, b show that although the CVD feedstock is rough and bumpy, the grown ribbon is uniformly smooth. The dendritic section (Figure 14 c) however, does show a thickness variation due to a dendrite.

Figure 15 a, b are cross-sections of CVD feedstock (sample 676A) which have been etched (6 minutes in Wright etch) to reveal their grain structure. Figure 15 c, d are cross-sections of the grown RTR ribbon (sample 676A), which has also been etched. For comparison, Figures 16 a, b, c, are cross-sections of RTR silicon grown from single crystal feedstock (sample 697). These micrographs demonstrate that the structure of the ribbon grown from CVD feedstock is, in general, qualitatively similar to the structure of ribbon grown from single crystal feedstock. The grain structure of ribbon grown from CVD feedstock is discussed further in the following section.

Figures 17 a, b are micrographs of a section of an etched sample (676A, ribbon grown from CVD feedstock) taken with an electron microscope. These photos show arrays of dislocations and stacking faults. The dislocation density is $\sim 2.5 \times 10^6/\text{cm}^2$, the stacking fault density $\sim 10^3/\text{cm}$. The shape of the etch pits indicate the grown direction for this ribbon was $\sim [112]$, the face $\sim [111]$.

5.2 X-RAY ANALYSIS -- CVD FEEDSTOCK RIBBON

Figure 18 is a schematic of a sample grown from CVD feedstock. The orientations of various grains on the sample were measured using a Laue camera with a 1 mm aperture. The face of each grain is shown with F ().

FIGURE 14a CROSS SECTION OF CVD FEEDSTOCK

FIGURE 14b CROSS SECTION OF RTR RIBBON GROWN FROM CVD FEEDSTOCK

FIGURE 14c CROSS SECTION OF A DENDRITE RIBBON

FIGURE 15 a,b: CVD FEEDSTOCK GRAIN STRUCTURE -- SAMPLE 676A

FIGURE 15 c,d: RTR STRUCTURE, -- SAMPLE 676A

FIGURE 16a, b, c: CROSS-SECTION OF RTR GROWN FROM SINGLE CRYSTAL FEEDSTOCK

(a)

(b)

FIGURE 17 SEM MICROGRAPHS OF ETCHED SECTION - SAMPLE 676A

FIGURE 18: STRUCTURAL ANALYSIS,
SAMPLE #702

and the growth direction with $G [\quad]$. The direction orthogonal to both the face and the growth direction is actually the direction in which a dominant grain must grow at the expense of the outer grains. This expansion direction is shown as $E [\quad]$.

We have previously⁽⁹⁾ measured the dominant grains in RTR samples grown from polycrystalline silicon. These orientations are listed in Table 5.1, together with the well-defined orientations measured on sample #702. The total number of orientations discussed here is too small to establish a firm pattern. However, some trends can be noted. The most common direction is $E [111]$ with six examples (out of a total 14 grains). None of the faces are (111) . The (110) orientation is most likely to be either a face (4 examples) or a growth direction (4 examples), rather than an expansion direction (1 example).

The most important feature of this sample grown from CVD feedstock is that the crystal structure breaks down about 6 cm from the start of growth. The x-ray photos (# 5, 6, 13, 14) in that area show essentially polycrystalline silicon. Sections taken in this region (see Figure 19) show the material is heavy with dislocations, twin bundles and stacking faults. It is encouraging to note, however, that towards the end of the growth, roughly 8 cm from the polycrystalline region, large grains are again dominating the ribbon structure.

TABLE 5.1

GRAIN ORIENTATIONS ON RTR RIBBON
GROWN FROM POLYCRYSTALLINE FEEDSTOCK

SAMPLE #	FACE	GROWTH DIRECTION	EXPANSION DIRECTION
702 #1	110	$1\bar{1}2$	$\bar{1}11$
#2	100	100	100
#3	110	$1\bar{1}0$	112
#4	102	$21\bar{1}$	$\bar{2}51$
#7	110	$1\bar{1}2$	$1\bar{1}\bar{1}$
#8	001	$1\bar{1}0$	110
#9	115	$3\bar{2}0$	$23\bar{1}$
#10	115	$3\bar{2}0$	$23\bar{1}$
#11	112	$\bar{1}10$	$\bar{1}11$
#12	112	$1\bar{1}0$	$\bar{1}11$
462	211	$0\bar{1}1$	$\bar{1}11$
464	110	$1\bar{1}2$	$\bar{1}11$
466	110	$1\bar{1}1$	$\bar{1}12$
468	123	210	$1\bar{2}1$

FIGURE 19 DISLOCATIONS AND TWIN BUNDLES IN REGIONS OF CVD RTR

6.0 SOLAR CELL PROCESSING

The RTR solar cells that have been fabricated up to now have used a standard fabrication process designed for boron-doped 1 Ω -cm single crystal Czochralski wafers. The main steps in this process are listed in Table 6.1 (cleaning steps have been omitted from Table 6.1). The metallization step has already been identified as a suspect in reducing V_{OC} (see section 6.2), as a result of excessive grain boundary interaction, and a modified (low temperature) metallization process is being developed.

The first (diffusion) step could also be creating a situation responsible for cell efficiencies. Diffusion of boron down grain boundaries may extend (locally) much deeper into the RTR ribbon than in single crystal regions. Thus step #4, etching the front surface to remove the P^+ layer, may not be totally effective, leaving linear regions with P^+ doping. On completed cells, these areas would either be very narrow N^+/P^+ junctions, or P^+ lines on the nominally n-type surface. In either case, solar cell efficiency could be significantly reduced. Table 6.2 lists a modified process sequence that is now being evaluated with the objective of reducing or eliminating these effects.

6.1 GETTERING

We have previously ⁽¹⁰⁾ established that the combination of the phosphorous diffusion and the Si_3N_4 AR coating has a strong gettering effect on RTR silicon grown from single crystal feedstock. We have now observed a similar effect on control cells fabricated on unmelted regions of ribbons grown from single crystal feedstock. Table 6.3 lists the diffusion lengths measured on control

TABLE 6.1

STEP	COMMENT
1. Diffuse both surfaces with BCl_3 .	p^+ doping of back surface for back surface field and ohmic contact.
2. Boron drive-in, grow SiO_2 in steam.	
3. Protect back, strip front	Expose front surface, remove p^+ layer from front surface.
4. Etch front	
5. PH_3 diffusion	Dope front surface with phosphorous to create the p-n junction.
6. Protect back, etch a mesa on the front	Define solar cell area
7. Deposit Si_3N_4	AR coat
8. Pattern front, strip back	Expose pattern for metallization
9. Selective metallization	This metallization process includes a high-temperature sintering step.

TABLE 6.2

STEP	COMMENT
1. Grow a thick oxide layer on both sides of the sample	Protect front surface from the heavy boron doping
2. Protect front, strip back	Expose back for p^+ diffusion
3. BCl_3 diffusion	Dope back surface
4. p^+ drive-in, grow oxide in steam	Drive-in the boron for the BSF, and then protect back
5. Protect back, strip front	Expose front
6. PH_3 diffusion	Dope front surface with phosphorus to create p-n junction
7. Protect back, etch a mesa on the front	Define solar cell area
8. Deposit Si_3N_4	AR coating
9. Pattern front, strip back	Expose pattern for metallization
10. Selective metallization	Use a low-temperature process

TABLE 6.3

CELL #	AVERAGE DISTANCE IN CM FROM INITIAL MELT ZONE	DIFFUSION LENGTH (μm)	
		AFTER P DIFFUSION	AFTER AR COATING
529-C1	+3	43	112
603-C1	+3	17	83
605-C1	+3	47	105
628-C1	+3	56	120
529-C2	+1	4	12.5
603-C2	+1	14	3
605-C2	+1	3	12.5
606-C1	+1	22	5
631-1	-1	25	45
603-1	-1	16	56
605-1	-1	30	30
606-1	-1	12.5	40

cells after the phosphorous diffusion step, and again after the AR coating is applied. On each of the four measurements made on cells ~3 cm from the melt boundary, the diffusion length increases by at least 100%. On the other hand, the measurements made ~1 cm from the melt boundary do not show a definite trend. Table 6.3 also includes diffusion lengths measured on the first cell fabricated on the melted section of the ribbon. Although one cell (#605-1) shows neither improvement nor degradation, the other three improve significantly.

Results on the control cells 3 cm from the initial growth interface show that the total gettering effect may include a relatively low temperature inactivation (or compensation) of an impurity which is already present in the Czochralski feedstock (or introduced during earlier processing steps). The lack of improvement on the control cells 1 cm from the initial melt interface shows that an additional mechanism is responsible for the short diffusion lengths in that area. We have shown ⁽¹⁰⁾ that the dislocation density in that area typically exceeds $10^6/\text{cm}^2$. We have also shown that when the dislocation density exceeds $10^6/\text{cm}^2$, the diffusion length is reduced. Thus the short diffusion lengths in the control area closest to the melt zone boundary are probably due to a high dislocation density. These remain unaffected by the gettering steps. By contrast, the dislocation densities measured in the initial molten zone are typically $\sim 10^5/\text{cm}^2$. Since a high dislocation density is no longer the primary cause for short diffusion lengths, the gettering effect of the AR coating cycle can result in a significant improvement.

6.2 METALLIZATION

We have now demonstrated that the generally observed degradation in open circuit voltage due to metallization can be reduced by using low temperature processes exclusively. Four solar cells were metallized eliminating

all sinter and bake steps. Since the solder step was also omitted, the nickel step was repeated twice for cells 3 and 4, so that the short-circuit current could be measured. The results are shown in Table 6.4. The overall voltage reduction is only ~10 - 15 mv. This is a major improvement over the ~50 mv degradation consistently obtained with the full high-temperature metallization process.

In addition to developing a low temperature metallization sequence which can withstand soldering without a degradation in V_{OC} , an alternate scheme was tried. This process used the same plating steps up to the nickel. Then, instead of using solder to reduce series resistance, an electroplated layer of silver was applied. A sufficient thickness of silver can be put down on the nickel to yield efficiencies (9%) comparable to our soldered cells, with no voltage degradation. Since this was our first attempt, the thickness of the silver was not optimum for achieving a good fill factor. Excessive plating results in peeling of the silver, but a moderate increase in thickness (and thus decreased series resistance) is probably feasible.

6.3 DENDRITIC SOLAR CELLS

Solar cells have been fabricated on dendritic ribbon grown from single crystal feedstock. Most of these cells are awaiting metallization, but probing the open circuit voltage prior to metallization indicates values at least as high as those obtained with nondendritic cells ($V_{OC} = 0.50 - 0.52$ volts). One moderately dendritic cell was metallized using the low temperature sequence described in Section 3.3. No V_{OC} degradation was observed. The open-circuit voltage was $V_{OC} = 0.515$, and the short circuit current was $I_{SC} = 29 \text{ ma/cm}^2$ on a 1.4 cm^2 cell. Since we could not successfully solder to the low temperature nickel plating, we could not accurately measure the

TABLE 6.4
EFFECT OF METALLIZATION ON V_{OC}

STEP	V_{OC} #1 (mv)	V_{OC} #2 (mv)	V_{OC} #3 (mv)	V_{OC} #4 (mv)	I_{SC}^* #3 (ma)	I_{SC}^* #4 (ma)
Before Metallization	512	503	512	515	--	--
After Pd-Ni Plating	496	504	508	505	--	--
Ni Plating	--	--	516	512	31.9	30.7
Additional Ni Plating	--	--	505	500	40	36.4

* The cell area was 1.4 cm^2

cell's conversion efficiency. However, if a typical fill factor of 0.70 is assumed, the cell efficiency would be about 10.5%.

6.4 CVD FEEDSTOCK RIBBON

The first lot of ribbons grown from CVD feedstock has been entered into our processing sequence. Unfortunately, we had a very poor yield, primarily due to breakage in the cleaning steps preceding the first high-temperature process. We are now growing a second lot of ribbons for processing and solar cell evaluation.

The next lot of CVD ribbons will contain some ribbons which have been exposed to 1200°C and given an HCl etch, followed by a steam oxidation. It is hoped that the high temperature will reduce residual stress and improve yield. Also, the oxide will be used to protect the front against the Boron diffusion. No gettering effect due to the HCl/oxide step was observed on this lot.

7.0 PROBLEMS

We have uncovered a problem with the buckling on the wide ribbons.

8.0 NEW TECHNOLOGY

No new technology.

9.0 PROGRAM PLAN/MILESTONES

Activities associated with the total program are shown in the Program Plan/Milestone charts contained in Appendix II.

REFERENCES

1. A. D. Morrison, et. al., "Large Area Silicon Growth by EFG," Annual Progress Report, ERDA/JPL Subcontract #954355, pp 12 - 14 (Sept. 1976).
2. R. W. Gurtler, et. al., "Laser-Zone Growth in a Ribbon-to-Ribbon (RTR) Process," Technical Quarterly Report #954376, pp 1 - 5 (Mar. 1977).
3. A. D. Morrison, et. al., "Large Area Silicon Sheet by EFG," Fourth Quarterly Report ERDA/JPL Subcontract #954355, pp 27 - 54 (Sept. 1976).
4. B. A. Boley, "The Determination of Temperature Stresses and Deflections in Two-Dimensional Thermoelastic Problems," J. of Aero. Sci. Vol. 22, #1, pp 67 - 75 (Jan. 1956).
5. J. N. Goodier, Phys., Vol. 7, p 156 (1936).
6. J. S. Born and G. Horvay, "Thermal Stresses in Rectangular Strips," J. of Appl. Mech., Trans A.S.M.R., Vol. 77, pp 401 - 406, (1955).
7. S. Timosheuko, "Theory of Elastic Stability," McGraw-Hill Book Co., Inc., N. Y. 1936 pp 338 - 340.
8. C. D. Graham, et. al., "Hot Forming of Silicon Sheet," Quarterly Report #2, ERDA/JPL Contract #954506 (Sept. 1976).
9. R. W. Gurtler, et. al., "Laser-Zone Growth in a Ribbon-to-Ribbon (RTR) Process," Technical Annual Report ERDA/JPL #954376, (Sept. 1976)
10. R.W. Gurtler, et. al., "Laser-Zone Growth in a Ribbon-to-Ribbon (RTR) Process," Technical Quarterly Report ERDA/JPL #954376-78/1, (Dec. 1977).

APPENDIX 1

Reprint of "Silicon Ribbon Growth Via the Ribbon-to-Ribbon (RTR) Technique: Process Update and Material Characterization", R. W. Gurtler, A. Baghdadi, R. J. Ellis, I. A. Lesk, accepted for publication in The Journal of Electronic Materials.

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SILICON RIBBON GROWTH VIA THE RIBBON-TO-RIBBON
(RTR) TECHNIQUE: PROCESS UPDATE
AND MATERIAL CHARACTERIZATION

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The current state of development of the RTR process for silicon ribbon growth is reviewed. Present growth capabilities, material characterization, and device performance are summarized. Specific process problems, such as poor laser coupling efficiencies, are discussed and approaches to their solution are described. Problems related to thermal stresses are discussed in some detail. Stress induced birefringence measurements are used to evaluate residual stresses. A linear temperature profile post-heater is effective for reduction of residual stresses. A correlation may be obtained between minority carrier diffusion lengths, dislocation densities, and thermal stress levels.

Key words: Crystal growth, silicon, silicon ribbon, laser melting, solar energy, stress-birefringence, thermal stresses, SPV, OCPV, dislocation densities.

Introduction

In efforts to achieve the goal of large scale economical utilization of photovoltaic cells for generation of electricity, very impressive advances in crystal growth

and slicing have been reported (1,2). Nevertheless, it remains clear that a technique which can alleviate the necessity for the expense and severe waste of material due to slicing and damage removal, and yet produce high quality solar cells of an optimum thickness, would ultimately replace the highly developed conventional processes. Ribbon growth of silicon would seem to offer such a process and at least four distinct methods have been developed to some advanced state; the Web-Dendritic (3) process, the shaping die techniques typified by the EFG (4) and Stepanov (5) processes, the RTR (6) process, and the Toyo (7) process.

The purpose of this paper is to review the status of developmental efforts by the authors on the RTR process, and to discuss some effects, common to most of the other ribbon growth technologies as well, which presently limit performance of RTR ribbons.

RTR Process

Figure 1 relates the original concept of the RTR process previously described in more detail (6,8). Preformed polysilicon ribbon is scanned with a focussed laser beam which forms a narrow melt zone. As the polysilicon ribbon is fed into the melt region and allowed to resolidify, self seeding occurs to such an extent that large crystalline regions form. Auxiliary heating techniques can also be used to supplement the laser power and also serve to reduce thermal stresses.

The RTR process has some features which are significant departures from other ribbon techniques. First, no crucible, which can cause contamination of the melt and which must also be replaced periodically, is required. Second, no materials other than ambient gases are in contact with the melt, and these can be adequately controlled. Third, the melt geometry and thermal conditions are flexible and easily controlled since the thermal time constant is on the order of 0.1 seconds.

These advantages should be significant in the long run. The resulting ribbon will be as pure as the starting material and will not exhibit variations in properties as would be the case for a crucible configuration if a non-unity segregation coefficient is in effect (actually, the

Fig. 1. Ribbon-to-Ribbon (RTR) growth of single crystal or macrocrystalline ribbon from polysilicon.

high growth velocities anticipated may result in no significant segregation effects in crucible grown ribbon either).

The flexibility of the RTR process can be illustrated by an example. The melt is created by a scanned and focussed laser beam; by performing both x and y scanning (or by using appropriate mirror geometries) a curved melt can be achieved. By choice of the proper curvature, grain propagation towards the edges of the ribbon may be hastened. Figure 2 illustrates a ribbon grown under these conditions. The regrown region was only a few inches long, started growth as polycrystalline material, but rapidly converted into one single orientation. Extensive experimentation with this technique over longer growth lengths has not yet been possible but we consider single crystal growth a definite possibility.

D8741

Fig. 2. Ribbon growth from polysilicon feedstock with a curved melt zone. After a few inches of growth, one orientation (designated D*) remained.

While at present no continuous source of doped polysilicon ribbon exists, and this has been a major limitation on the length of ribbons grown so far, several promising techniques are under development which promise to provide such a source quite economically. Our efforts so far have concentrated more on what we felt was the more difficult task -- conversion of polysilicon ribbon into macrocrystalline ribbon of the proper geometry, at high throughput, and also of sufficient quality so as to allow processing of these ribbons into efficient (e.g., 12 - 15%) solar cells.

Significant progress has been made in most aspects of the process to date. Nominal simultaneous parameters obtained on recent ribbons are:

Length	25cm
Growth Rate	7.5cm/min
Ribbon Width	2.0cm
Ribbon Thickness	150 μ m

Ribbons as thin as 90 μ m have been grown, and 10cm/min growth rates have been achieved. Solar cells fabricated on RTR substrates have exhibited AM1 efficiencies >11%.

Figure 3 is a photo of one of our thin ribbon samples. The sample width is 1.3cm. the regrown length is about 25cm and the thickness is about 100 μ m. Figure 4 shows the flexibility of a sample which has been grown from conventional polysilicon stock. Samples grown from poly ribbons cut from large ingots are undoped and would not be processed further. For solar cell processing experiments, single crystal starting material is normally used since this allows direct comparison between ribbons and equivalently doped Czochralski single crystal material under identical processing conditions.

Process Evolution

The conceptually simple process depicted in Figure 1 has evolved into a somewhat more complex process as system requirements have become better understood. A few of these process requirements should be briefly mentioned.

Fig. 3. Sample ribbon grown via the RTR process.

Fig. 4. Flexural capabilities of thin (125 μ m) RTR ribbons.

Post Heater for Stress Relief

The simple process described by Figure 1 has actually been used for growth of good ribbons, but because of the severe thermal profile, large stresses are generated. Figure 5 illustrates the calculated temperature profiles, as a function of velocity, for a 0.127mm thick ribbon. As indicated here, velocities of 12cm/min should be feasible before melt width increases might cause growth instabilities. Experimentally, the thermal stresses generated by the temperature profiles of Figure 5 cause shattering of the ribbons if growth velocities exceed something like 1cm/min

Fig. 5. Calculated thermal profiles for RTR growth at various velocities. L_M represents an excess semi-molten region length due to an inability to remove latent heat rapidly enough, and non-zero values of L_M indicate possible growth instabilities and therefore are indicative of growth speed limitations.

for a 1.25cm wide ribbon. Consequently, to achieve higher growth velocities it was necessary to add a post heater to the process to allow stress relief. More will be said about this aspect in later sections.

Laser Coupling Inefficiencies

Another area of difficulty has been the efficiency of laser coupling to the ribbon. Theoretical estimates of the laser power required for even advanced stages of development (7.5cm wide, 7.5cm/min) indicated modest power requirements ($\approx 400 - 500W$ for a 0.127cm thick ribbon). However, for these

analyses, a liquid silicon absorption coefficient was assumed to be about 55% of that of solid silicon near the melting point. This estimate was made from measurements of emissivity differences between solid and liquid silicon as observed in the visible spectrum. Experimentally, this assumption has proven to be greatly in error -- especially at the $10.6\mu\text{m}$ wavelength of a CO_2 laser. The reflectivity of liquid silicon is evidently much higher than solid silicon and this results in a spatial absorption dependence as indicated in Figure 6. Figure 7 indicates the effective absorption coefficient as a function of melt width and liquid - solid absorption ratios. At high velocities, the

Fig. 6. Influence of melt-solid emissivity (or absorptance) differences on laser beam absorption. A gaussian energy distribution is assumed and various melt-solid emissivity ratios are shown. w_S is the spot width at the e^{-2} power points of the beam. For a CO_2 laser α_M/α_S appears to be near 0.1.

Fig. 7. Effective absorption coefficient (α_E) as compared to solid silicon absorption coefficient (α_S) for various melt-solid emissivity ratios (α_M/α_S) as a function of melt width-spot width ratios. A linear irradiation pattern with gaussian cross section was assumed.

surface melt width must be a significant fraction of the beam width in order that the central region of the ribbon can be completely melted. These effects resulted in a growth velocity limitation of about 7.5cm/min for a 1.25cm wide, 0.01cm thick ribbon with our first laser (CO₂, 375W) even with the aid of a post heater.

In order to achieve the goals of our program, higher power lasers have been obtained. This is a brute force method at the present stage of development. However, we are also investigating the use of Nd:YAG lasers. Nd:YAG lasers are the only alternatives to CO₂ lasers at the present time in terms of power, and they have a significantly shorter wavelength (1.06μm). The shorter wavelength is better on both theoretical and experimental grounds. Silicon evidently becomes metallic (9) in the liquid state and reflection properties are due to free electrons. As such, the reflectivity is expected to be reduced at shorter wavelengths. Experimentally we have observed an absorption improvement of perhaps a factor of five when using a Nd:YAG laser.

Nd:YAG lasers, albeit more efficient in coupling to ribbon, are less efficient overall than CO₂ lasers and in addition are probably significantly more costly to operate due to maintenance and lamp replacement costs. It is very probable though, that alternative short wavelength lasers will become available in the near future (especially due to the impetus of laser-fusion research).

Hemispherical Reflectors

One technique is available which promises to provide significant improvement in the effective absorption coefficient of liquid silicon. This is the use of hemispherical reflectors to capture and reimage reflected (and radiated) energy back onto the melt. This concept is schematically presented in Figure 8. A linear melt will reimage secondary beams upon itself. If a perfectly specular reflecting liquid surface is assumed, the primary energy will be lost out the entrance port for normal incidence; for angles larger than that subtended by the entrance port, multiple reflections back to the melt region can occur. A diffusely scattering surface could result in even greater

Fig. 8. Hemispherical reflectors for enhanced coupling of laser beam and reduced radiation losses.

enhancement due to multiple reflections. Experiments have been performed which verify that this technique substantially reduces required laser power. In one set of experiments, we have verified that the effective absorption coefficient nearly doubles. The use of hemispherical reflectors in a production unit would therefore seem very promising.

Material/Device Performance

Before proceeding into more detailed discussion of current areas of study, it is useful to indicate the present character and performance of RTR ribbons.

Material Evaluation

As-grown ribbons to date show large crystallite sizes but exhibit high dislocation densities and short diffusion lengths. Figure 9 illustrates properties on one typical ribbon grown with a flat melt zone at 5cm/min with a grown thickness of ≈ 0.11 mm. Each grain exhibits a variety of dislocation densities or linear (non-intersecting twin bundle) defect densities. SPV diffusion length measurements (10) are indicated for the same regions.

Solar Cell Evaluation

Solar cells have been fabricated from this same material; a photo of such a ribbon cell is shown in Figure 10. The active area of this device (excluding the large "bar" contact, which is included for convenience, but including the small fingers) is about 1.3cm^2 . Figure 11 shows the measured load curve for a good ribbon cell. An efficiency of 11.1% is exhibited by this device and represents one of the better cells to date; "typical" values are around 8 - 9%. For comparison, Figure 12 shows the measured load curve of a control cell fabricated on a non-regrown portion of a ribbon. These control cells exhibited efficiencies of $\approx 14 - 16\%$.

An indication of the reason for poorer performance by ribbon solar cells can be gleaned from the spectral curves

Fig. 9. Linear (N_{LD}) and point dislocation (N_D) densities, and SPV $_{LD}$ diffusion lengths on ribbon sample grown with a flat molten zone. Photos indicate dislocation structure as emphasized by Wright etching.

Fig. 10. Photo of ribbon solar cell.

Fig. 11. Load curve for good ribbon solar cell.

Fig. 12. Load curve for "Control" solar cell.

of Figure 13. These data show that the ribbon solar cells exhibit degraded performance at long wavelengths; this is indicative of short diffusion lengths. (The apparent better short wavelength response of the ribbon solar cells is a result of normalizing the curves.)

Diffusion Length Measurements via Solar Cell Open Circuit Voltages

For the measurement of diffusion lengths, the surface photovoltage (SPV) technique is utilized. This technique can be applied to either as-grown substrates, or completely processed solar cells (11). In the latter case, we use the open circuit photovoltage of the cell rather than the surface potential normally used for an unprocessed substrate. Use of the open circuit configuration allows utilization of high impedance preamplifiers, and also insures that the depletion region is minimized. When used on a solar cell, the open-circuit photovoltage (OCPV) technique allows high

Fig. 13. Spectral response curves for control and ribbon solar cells.

ambient light levels present during the measurement -- a feature not possible with the SPV technique.

OCPV measurements on the sample of Figure 10 are shown in Figure 14. For these measurements, a relatively small spot size of about 2mm diameter was used to allow mapping of diffusion lengths. Large variations occur and we notice that significantly higher diffusion lengths are observed on the finished cell as compared to those of the starting material (see Figure 9) -- this indicates that some sort of gettering (or redistribution) effects are occurring during processing.

Fig. 14. Open circuit photovoltage (OCPV) diffusion lengths as a function of position for the solar cell of Figure 10.

Material/Process Studies

Residual Stresses

Of considerable importance for further improvements in material performance, and continued increases in the throughput (width, velocity, etc.) of the RTR process, are efforts towards reduction of thermal stresses.

The process as depicted in Figure 1 can actually be used to grow reasonable crystals if the growth rate is low, e.g., up to 1cm/min. However, for growth rates greater than 1cm/min, and often at even lower rates, the residual stresses incorporated into the material are so severe that the ribbons shatter. As can be seen from Figure 5, the thermal gradient is initially very high. However, it is not necessarily the thermal gradient, but any non-linearities in the thermal profile which causes stress -- in principle a very steep, but linear profile will produce no stresses if the coefficient of thermal expansion is constant. For silicon, the thermal expansion coefficient is relatively constant for temperatures between 800°C and 1400°C.

The curvature in the thermal profile is highest near the molten zone, but this is also the region in which the ribbon is most plastic. At high temperatures, depending on the time allowed, plastic flow will occur quite readily in response to the thermal stresses. As the ribbon is translated, each region successively encounters a lower temperature and a lower thermal stress environment, and progressively becomes less plastic.

As the sample recedes from the melt region, thermal stresses begin to vanish, but plastic flow which previously occurred to relieve stresses now forms residual stresses in an isothermal condition -- these stresses will be opposite in sign and proportional in magnitude to the relieved stresses at the higher temperatures. However, at lower temperatures, the plasticity of the material has all but vanished and if the residual stresses are high enough, fracture can occur. The reason that crystals may be grown at low velocities is that plastic flow can occur at lower temperatures over a longer period of time, resulting in lower ultimate residual stresses.

The thermal stresses induced into a perfectly elastic silicon ribbon with a thermal profile similar to that of Figure 5 have been discussed by T. Surek (12). However, such a treatment cannot indicate the amount of residual stresses since the magnitude of stress relief due to plastic flow must be accounted for and this is a complex function of stress levels, temperature, and time. The resulting residual stress levels can be measured, however.

Residual Stress Measurements

We have used the phenomenon of stress-induced birefringence to study residual stresses in RTR ribbons. Silicon is normally an optically isotropic material, i.e., it exhibits no polarization effects on light. In a stressed condition it becomes birefringent and thereby allows areas of stress to be observed if viewed between crossed polarizers. Previously, (13) this technique has been applied to the observation of stresses in silicon to good advantage. Figure 15 is a photo of the apparatus used to observe (or photograph) residual stresses in ribbons. Required are a pair of infrared polarizers, a source of infrared ($>1\mu\text{m}$

Fig. 15. Photo of stress birefringence apparatus used for observation and photography.

wavelength), a rotatable sample holder, and an infrared viewer. We have used a silicon wafer AR coated with Si_3N_4 as an efficient filter for a quartz-halogen lamp to obtain a convenient IR source. Figure 15 illustrates the system as it is used for observation; photos may be taken by removing the eyepiece from the viewer and using a low power microscope with a camera.

Figure 16 is a photo of the typical pattern observed for RTR ribbons if the crossed polarizers are aligned at 45° to the axis of the ribbon. (If the axes of the polarizers coincide with the ribbon axes, no birefringence is observed.) Also shown is the same sample after a short (15 second) anneal at $T \approx 1100^\circ\text{C}$. These distributions are typical of the "steady state" region of growth; if observations are made near the start or finish region of growth, quite complex patterns, as shown in Figure 17, are observed.

(a)

(b)

Fig. 16. (a) Typical "steady state" stress distribution in RTR growth without post heaters. (b) The effect of a short (15 sec.) anneal at $\approx 1100^{\circ}\text{C}$.

(a)

(b)

Fig. 17. Typical (complex) stress distributions near melt initiation and termination regions; (a) polarizers at 45° to ribbon axes (b) polarizers parallel to ribbon axes.

Quantitative evaluation of stresses by observation of stress-induced birefringence can be quite complex in general. This is because the birefringence is described by an index ellipsoid which is related to the internal stresses by a fourth order elasto-optic tensor. Because of symmetry, silicon requires only three distinct coefficients for the total description of the elasto-optic effects, but still,

the crystal orientation and stress orientations can give quite complex birefringence behavior -- sometimes being uniaxial, sometimes being biaxial. Nevertheless, the geometry and symmetry of the ribbon, together with knowledge of the crystal orientation, can allow a complete analysis of ribbon residual stresses. A more detailed account of the analysis is given elsewhere (14), but briefly, because of a small thickness relative to the width and length, a situation of plane stress is a close approximation (actually some thickness dependence does have to be accounted for). Figure 18A illustrates a ribbon coordinate system and a general principal stress coordinate system for a particular point in the ribbon. From the symmetry of the ribbon and of the thermal profile, we can see that one principal axis of stress must be normal to the ribbon, i.e., at any particular point in the ribbon we can deduce that Figure 18B will be appropriate. (The assumption of nearly plane stress will allow us to assume σ_3 is zero, or negligible.) From the observation of Figure 16, it is deduced further that the optical axes are aligned with the ribbon length and width. If we assume uniaxial behavior (or if we choose the proper crystallographic orientation) then we can deduce that the principal axes of the internal stresses also coincide with the ribbon coordinate system. This leads to Figure 18C, which now is correct for any point in the ribbon. Finally, by symmetry again, we can deduce that $\partial_y \sigma_{xx} = \partial_y \sigma_{yy} = 0$ with σ_{zz} assumed zero. These considerations, and the fact that σ_{xx} vanishes at the edges of the ribbon, can be shown to require that $\sigma_{xx} \equiv 0$ everywhere. Consequently, only σ_{yy} is non-zero to the plane stress approximation (and also, it may be shown, to the next level of approximation.)

These considerations greatly simplify the analysis of residual stresses since birefringence really results from shear stress which is actually the difference between principal stress components; but if all components of stress vanish except one, σ_{yy} in our case, then an absolute determination of stresses may be obtained.

It should be emphasized here that these considerations concerning the residual stress field can be argued only for a homogeneous material. An actual ribbon is usually

Fig. 18. Ribbon coordinates and principal stress coordinates; (a) in general, (b) for thin sample and (c) for a thin sample with symmetry about the ribbon axes (x, y) .

multiply-connected due to the presence of grain boundaries. Discontinuous displacements and orientations occur at these boundaries; this places new boundary conditions on each homogeneous domain and makes a general treatment of the

nature of the residual stress field impossible. However, experiments can be performed to produce entirely single crystal material and yet experience virtually identical thermal stresses as routine RTR growth samples. These experiments utilize single crystal ribbon feedstock which is melted only partially through the thickness. Such samples are utilized for detailed investigations of the thermal environment.

Quantitative Measurements

For quantitative analysis of stresses, the actual birefringence of the sample, on a point by point basis, must be determined. To accomplish this, a Soleil-Babinet compensator, properly oriented with respect to the sample and polarizers, is used as indicated schematically in Figure 19 to measure the retardation at a given point. An aperture is used to isolate a region ($\approx 1\text{mm}$ in diameter) of the sample. To optimally determine the compensation, an optical chopper is introduced into the beam path and a photodetector is placed by the viewer image. A lock-in amplifier is used to detect the (weak) signal; this procedure is necessary because the efficiency of infrared film polarizers is very poor and even in a crossed position, extinction is not complete. Consequently, the retarder is adjusted for a minimum reading. Figure 20 is a photo of the system used for quantitative analysis.

Once the retardation of a point is determined, knowledge of the sample thickness and stress-optic coefficients allows calculation of the residual stress through the relation (14, 15)

$$T = \frac{t n_o^3}{2\ell \lambda_o} q$$

where T is the stress, ℓ is the retardation in wavelengths, λ_o is the wavelength of observation in air, t is the thickness, n_o is the unstressed index of refraction, and q is the stress-optic coefficient. Translation of the sample allows an entire distribution to be obtained.

Fig. 19. Schematic illustration of apparatus used for quantitative analysis of ribbon stresses.

Fig. 20. Photo of stress analysis system.

Residual Stress Reduction

In order to totally eliminate residual stresses, thermal stress levels would have to be eliminated throughout the entire plastic temperature regime ($\approx > 700^{\circ}\text{C}$) of the cool-down region.

A linear temperature profile would theoretically provide no thermal stresses and can be approximated by altering the thermal environment of the cool down region through use of active heating or cooling devices. We have attempted stress reduction through use of a post-heater with a linear temperature profile. This choice was made for several reasons: as can be seen from Figure 5, the thermal gradient at the melt is about $200^{\circ}\text{C}/\text{mm}$; to attempt to linearize the temperature by heat sinking or active cooling would require sinking the ribbon 2 or 3mm from the melt with a temperature of 600°C . This may be possible but it would

also increase the laser power requirements. At that time, we were already finding that reflection losses were much greater than anticipated; use of a post heater would supplement the laser and allow the achievement of higher growth rates at less laser power.

Figure 21 is a schematic illustration of the furnace and laser growth configuration presently in use. The furnace has an active heating length of 5cm and incorporates 9 heater element pairs which can be individually controlled in temperature. Figure 22 illustrates one of the heater elements (which has provision for a thermocouple for temperature control). Since it is the heater element temperature which is sensed, a calibration profile must be measured to allow set points for each heater element to be determined.

Performance of Profile Furnace

Use of the linear profile furnace immediately allowed routine growth rates of 5cm/min to be achieved and over 7.5 cm/min to be demonstrated. Recently, with the incorporation of more powerful lasers, 2cm wide ribbons have been grown at 10cm/min. Measurements by the stress-birefringence technique have indicated negligible residual stresses on occasion.

Stress-Dislocation-Diffusion Length Studies

Ability to grow at high velocities is only a portion of the problem of thermal stresses. As mentioned before, the presence of thermal stresses at high temperatures results in plastic flow. Plastic flow implies the generation of dislocations since the predominant mechanism of plastic flow in silicon is via generation and motion of dislocations. High dislocation densities can be instrumental in reducing lifetime, and high dislocation densities are observed in RTR grown samples. In fact, dislocation densities measured on samples grown with the post heater have shown virtually no improvement over those grown without the post heater. This must mean that the linear profile furnace is allowing stress annealing (and therefore generation of dislocations) but thermal stress reduction, per se, is not being accomplished (and, in fact, thermal stresses

Fig. 21. Furnace-laser configuration used for reduction of residual stresses. The furnace has individually controlled heater elements to achieve a linear temperature profile.

may be worse). This possibility is indicated in Figure 23 where the measured furnace temperature profile and the theoretical laser-induced thermal profile along a 0.4mm thick ribbon are shown. Also indicated are the ideal and probable composite temperature profiles. In the latter case, the non-linearity (or curvature) of the thermal profile could be worse than that of a "laser only" situation.

Experiment Description

To ascertain the performance of the linear profile furnace for thermal stress reduction, experiments with single crystal, ribbon-like samples were performed. In these experiments, 20mm wide and 0.4mm thick single crystal

Fig. 22. Heater elements used in linear profile furnace. The active heating length is about 5cm. The furnace is capable of temperatures in excess of 1300°C.

samples were subjected either to a laser-only, a laser-plus-furnace, or a furnace-only thermal environment. In those cases where the laser was used, a melt was achieved at one location, held for one minute, and then allowed to freeze -- no melt translation was used. In using the furnace, the sample was inserted at a velocity of 2.5cm/min from the "cool" end until a portion of the sample projected completely through the "hot" end. It was then held in this position for one minute (and melted if the laser was used) and then withdrawn again at 2.5cm/min.

In order that stresses could most simply be analyzed, (100) samples were cut along the <100> direction. Czochralski p-type 3 - 5Ωcm samples, which had measured diffusion lengths of the order of 100μm, were used.

Fig. 23. Laser-furnace temperature profile. The furnace temperature profile is measured, the laser temperature profile is calculated for a 0.4mm thick ribbon. Also indicated are the ideal and (probable) composite temperature profiles.

Results

Figures 24 and 25 indicate dislocation densities and diffusion lengths measured as a function of position for laser-only and laser-plus-furnace samples respectively. Dislocation densities are high in both cases. Also indicated is some correlation between dislocation densities and SPV-measured diffusion lengths. In particular, we note that regions adjacent to the melt, but which were not melted, exhibit dislocation densities and diffusion lengths typical of RTR samples. However, we also note that even when the dislocation densities have all but vanished, significantly reduced diffusion lengths still persist. This indicates that purely thermal effects are involved. A glance at Figures 23 and 25 for the case of a laser-plus-furnace environment indicates that temperatures as low as 700°C are detrimental to diffusion lengths. These effects are probably due to precipitation (or activation) of point defects.

Another interesting feature of the two Figures (24 and 25) is the presence of a pronounced peak in dislocation density approximately 0.5cm from the melt for the laser-plus-furnace experiment. This implies that the maximum stress is occurring between the melt and the furnace, and in this region conditions are worse than for the laser only condition. The dislocation density at the melt is lower than for the laser-only sample indicating a reduced stress level there.

In an actual growth situation, these results would imply a higher than normal level of dislocations because of the presence of the peak. But dislocation generation is a time-dependent process and if high velocities were used (e.g., 7.5cm/min) the resulting dislocation density could be less than these results at lower velocity.

Stress-Dislocation Correlation

For the laser-plus-furnace sample of Figure 25, it was observed that stress relief was not complete, and, in fact, stresses were exhibited throughout a large portion of the sample. Figure 26 illustrates a stress analysis performed in the region of the peak dislocation density of Figure 25. Also indicated is the lateral distribution of dislocation

Fig. 24. Dislocation densities and diffusion lengths for "laser-only" experiment.

Fig. 25. Dislocation densities and diffusion lengths for "laser-plus-furnace" experiment.

densities. The effect of stress is apparent -- maximum dislocation densities occur in regions exhibiting the maximum (absolute) values of residual stress.

Conclusion

The RTR process has evolved considerably with demonstration of high growth rates, high crystallinity, a capability for growth of thin ribbons, and respectable solar cell efficiencies. Further evolution of the process promises straightforward achievement of the goal of 100μm thick, 7.5cm wide ribbons grown at high rates. Improvements in cell efficiencies will require further efforts at elimination of thermal stresses (and therefore reduction of dislocations) and further elucidation of lifetime degradation effects due to point defects. No fundamental limitations to the ribbon quality are evident for this process, and increased cell efficiencies are expected via improved material quality as promising optimization occurs.

Fig. 26. Residual stresses and dislocation densities measured across sample of Figure 25 at maximum dislocation density position.

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References

1. S. N. Rea, P. S. Gleim, Third Quarterly Report, ERDA/JPL-76/3 (1976).
2. S. C. Holden, R. R. Fleming, Fifth Quarterly Report, ERDA/JPL 954374-77/2 (1977).
3. R. G. Seidensticker, Proc. 12th IEEE Photovoltaic Specialists Conference, pp 299 - 302, May 6 - 8, (1976).
4. K. V. Ravi, H. B. Serreze, H. E. Bates, A. D. Morrison, D. N. Jewett and J. C. T. Ho, *ibid.*, pp 280 - 289.
5. A. V. Stepanov, Zh Tekhn Fiziki, 29, 381 (1959) (Trans. Soviet Physics - Technical Physics).
6. I. A. Lesk, A. Baghdadi, R. W. Gurtler, R. J. Ellis, J. A. Wise, M. G. Coleman, Proc. 12th IEEE Photovoltaic Specialists Conference, pp 173 - 181, May 6 - 8, (1976).
7. Kinzoki Jihyo, No. 770, 3 (407), (1975).
8. R. W. Gurtler, A. Baghdadi, Technical Quarterly Report #2, ERDA/JPL 954376-76/2, (1976).
9. Yu, G. Poltavtsev, Sov. Phys.-Semiconductors 8, #10, 1315 (1975).
10. Goodman, A. M., Journal Applied Physics, 32, pp 2550 - 2552 (1961).
11. Ed Stokes and T. L. Chu, Appl. Phys. Lett. 30, 8, (1977).
12. A. D. Morrison, K. V. Ravi, C. V. Hari Rao, T. Surek, D. F. Bliss, L. C. Garone and R. W. Hogencamp, Annual Progress Report, ERDA/JPL 954355/76-11, (1976).
13. S. R. Lederhandler, J. Appl. Phys., 30 #11, pp 1631 - 1638, (1959). J. Hornstra, P. Penning, Philips Res. Repts., 14, 237 (1959).
14. R. W. Gurtler, to be published.
15. W. R. Runyan, "Silicon Semiconductor Technology", McGraw-Hill, p 203 (1955).

Appendix II

Activities associated with the Total Program - Program
Plan/Milestones.

WORK BREAKDOWN SCHEDULE NO.1

Model 1 RTR Apparatus

MOTOROLA PROJECT NO. 2319

06

FIGURE 1 PROGRAM PLAN/MILESTONE CHART

EGEND SCHEDULED COMPLETED DELIVERY SCHEDULE DEL RED

FIGURE 2

PROGRAM PLAN/MILESTONE CHART

LEGEND □

SCHEDULED

■

COMPLETED

*

Done on RTR #1

△ DELIVERY SCHEDULE

▲ DELIVERED

WORK BREAKDOWN SCHEDULE NO. 2 (CONT.)

Model 2 RTR Apparatus

MOTOROLA PROJECT NO. 2320

96

FIGURE 2 (Cont.) PROGRAM PLAN/MILESTONE CHART
 SEND [] SCHEDULED [] COMPLETED * Done on RTR #1
 △ DELIVERY SCHEDULE ▲ DELIVERED

Thermal Stress Analysis

MOTOROLA PROJECT NO. 2321

93

FIGURE 3

PROGRAM PLAN/MILESTONE CHART

LEGEND

SCHEDULED

COMPLETED

DELIVERY SCHEDULE

DELIVERED

WORK BREAKDOWN SCHEDULE NO. 4

Ribbon Characterization

MOTOROLA PROJECT NO. 2322

94

FIGURE 4 PROGRAM PLAN/MILESTONE CHART
 SEND SCHEDULED COMPLETED
 △ DELIVERY SCHEDULE ▲ DELIVERED

95

FIGURE 5

PROGRAM PLAN/MILESTONE CHART

LEGEND ◻

SCHEDULED ■

COMPLETED

◻ DELIVERY SCHEDULE

▲ DELIVERED

WORK BREAKDOWN SCHEDULE NO. 6

Economic Analysis

MOTOROLA PROJECT NO. 2324

DESCRIPTION	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR
Economic Analysis of RTR Growth														

96

WORK BREAKDOWN SCHEDULE NO. 7

Program Management and Documentation

MOTOROLA PROJECT NO. 2325

FIGURE 7 PROGRAM PLAN/MILESTONE CHART

LEGEND SCHEDULED COMPLETED DELIVERY SCHEDULE DELIVERED