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DEVELOPMENT OF A HIGH EFFICIENCY THIN SILICON SOLAR CELL

JPL CONTRACT NO. 954290

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SEVENTH QUARTERLY REPORT

REPORT NO. SX/105/7Q

BY

JOSEPH LINDMAYER, ET AL

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SOLAREX CORPORATION
1335 PICCARD DRIVE □ ROCKVILLE, MD 20850 □ 301 948 0202 □ TWX· 710 828 9709 □ CABLE ADDRESS: SOLAREX

TECHNICAL CONTENT STATEMENT

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I. ABSTRACT

Experimental efforts during this quarter were attenuated by the necessity for concentrating efforts on preparation for the Pilot Line in March and full scale operation of the Pilot Line in April. Experimentation in this quarter concerned reducing the back metallization coverage to reduce the differential thermal expansion of very thin cells, mapping excess injection current at low dark forward voltage, determining the radius of curvature for fracture as a function of silicon thickness and determining absorptance/emittance ratios for thin silicon solar cells.

The Pilot Line efforts during this quarter were reported separately in "Pilot Line Report", JPL Contract 954290, Report No. SX/105/PL, June 1977.

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III SUMMARY

This report deal with efforts during the past quarter devoted to improving the efficiency of the thin silicon solar cells, which were developed at Solarex in the past year. During this quarter a more intensive effort under the same contract was directed to a Pilot Line Production of thin cells in April and caused some disruption of efforts in the experimental area. Despite this, investigations were directed toward cell optimization, including continued experimentation with junction diffusion, back surface alloy, metallization, etc.

Additional areas studied during this quarter concerned the following:

1) Determining the amount of curvature which these new thin cells will survive without breaking. These cells are quite flexible and withstand bending stresses very well, but the strain limit had not been quantified in previous quarters.

2) Very thin solar cells bow slightly due to residual silicon stresses and as a result of the thermal expansion differential between the silicon and the silver. It was found that a relatively modest interruption of the silver layer continuity on the back of the cell can be employed to considerably reduce the expansion-induced curvature, if desired.

3) The absorptance and emittance of thin cells were measured in this quarter and the ratio was found to lie in the range of 1.00 to 1.03 with ceria doped microsheet covers attached.

4) Dark forward I-V characteristics were mapped over orders of magnitude of current density to provide data on expected performance as a function of light intensity.

IV TECHNICAL DISCUSSION

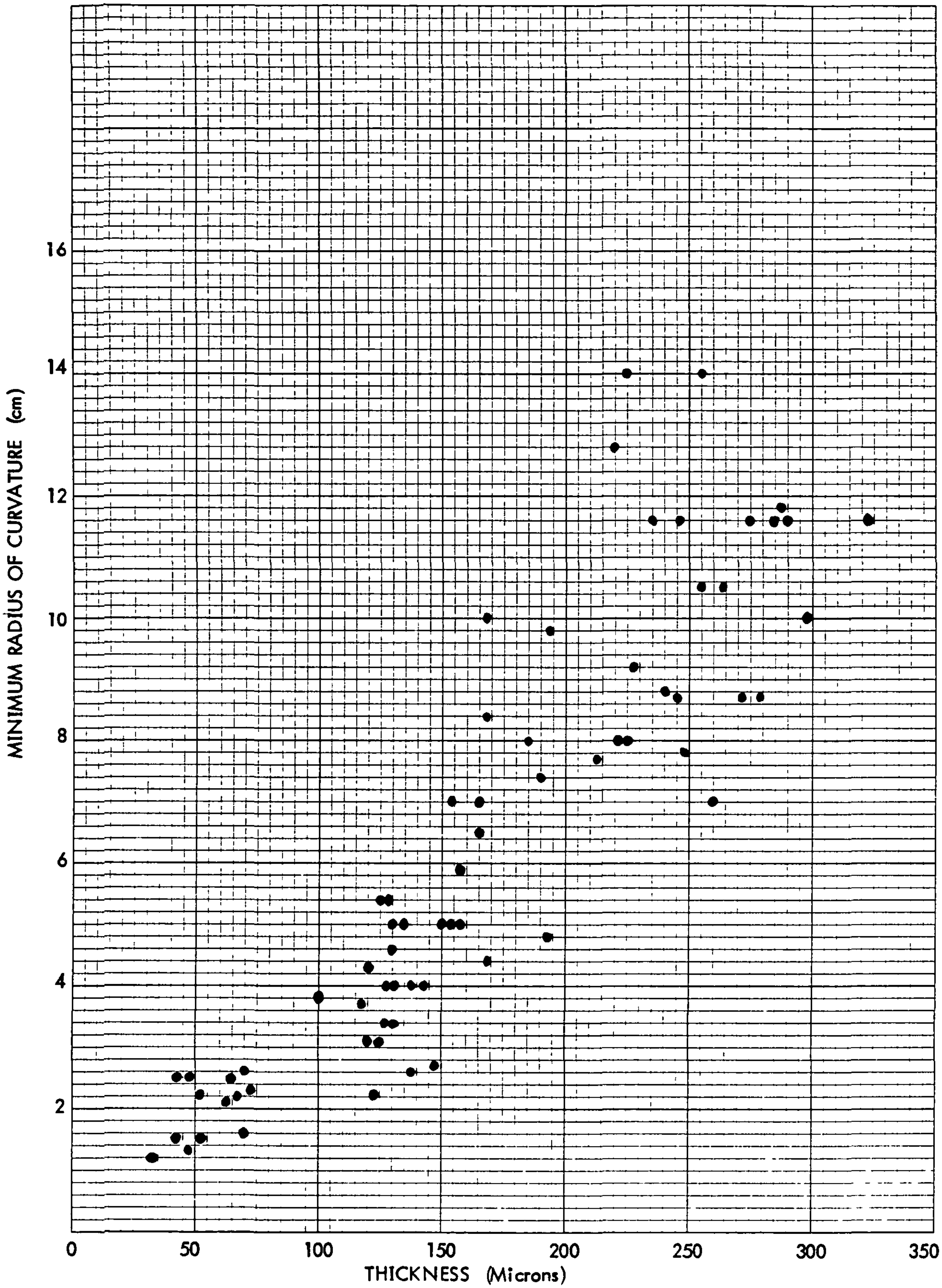
A. Bending Radius of Thin Cells

It has been observed for the past year that very thin silicon slices are considerably more resistant to breakage in handling than was originally expected. This mechanical durability appears to be attributable to two factors, which are the inherent low mass per unit area and the flexibility of the silicon slice. The low mass per unit area reduces forces due to acceleration on the thin cells and thereby lowers the stresses produced by handling. The flexibility of very thin silicon slices and the cells fabricated from then allows them to deflect under mechanical stress without damage.

In order to quantify the flexibility of thin silicon solar cells we devised a static bending apparatus during this quarter. Both silicon slices and completed solar cells were flexed cylidrically until they reached their strain limit and fractured. The radius of curvature was measured down to the point of fracture for each slice or cell. The measurements were repeated for various silicon thicknesses and the resulting radius of curvature attained at fracture was plotted as a function of silicon thickness, as shown in Figure 1, for this case of static displacement. The limiting curvature for the best cases reached a ratio of curvature radius to silicon thickness of 200:1. The great majority of cells under 150 microns (6 mils) attain a 400:1 ratio of radius to thickness. Specifically, this means that the great majority of 50 micron thick cells can be deflected to a 2 centimeter radius of curvature. If there is interest in rolling up cells to this radius, a simple coaxial press with the desired curvature could be employed to sort out those few cells with mechanical defects which would fracture prematurely.

The differences observed in handling durability between very thin cells and, say, cells 150 microns thick are apparently due also to the difference in mass per unit area, which sets the stress under acceleration. The measurements reported

Figure 1. Radius of curvature at fracture vs. cell thickness.



here are strictly for the case of static deflection and do not reflect the differences in the dynamic case.

These measurements do relate to one consequence of flexibility as a function of thickness. Large ultra-lightweight arrays made from thin cells can be rolled up onto quite small drums for launch configuration without damaging the cells.

B. Minimization of Bowing

Thin silicon slices of only some 50 microns thickness have some residual bowing after etching to thickness, as do the solar cells after processing. This curvature is a result of the cells' flexibility, residual stress in the silicon, having full coverage of 8 microns of silver on the backs of the solar cells and silver ony in the gridwork on the fronts. Upon cooling after the contact sintering treatment the silver (which has the larger coefficient of thermal expansion) shrinks more than the silicon, adding slightly to the curvature. This does not occur to any significant degree for thick cells where the silver is a small fraction of the silicon thickness and the slices are too stiff to bow themselves.

Although the residual bowing of finished 50 microns 2cm x 2cm cells is only in the neighborhood of a millimeter at room temperature it does increase significantly upon dropping some 200^{o}C to liquid nitrogen temperature. Since we have not observed fracturing of cells even with the latter degree of bowing, it is not necessarily deleterious to cell life in space environments. However, in this quarter we have experimented with interrupting the continuity of the silver layer on the cell back to observe its effect on bowing from differential expansion. It was found that interrupting the silver on the back by shadowing with a screen grid which eliminated some 10% to 20% of the silver area reduced the bowing by approximately a factor of five. After cooling in liquid nitrogen the usual five millimeter bowing of uncovered 2cm x 2cm cells was reduced to approximately one millimeter. Very similar results were obtained with a dot pattern which eliminated approximately 50% of the silver coverage on the backs. Sample cells from this experiment were forwarded to JPL for evaluation.

Although gaps were introduced in the back silver layer's current path, no significant increase in series resistance was observed. This was not surprising, considering the full coverage of the cell back by the p+ aluminum alloyed layer under the interrupted Ti-Pd-Ag.

C. Absorbtance and Emittance Measurements

The absorptance and emittance of representative 50 micron thick solar cells were measured with ceria doped microsheet covers attached. The absorptance was obtained by measuring reflectance from 240nm to 2500nm on our Beckman DK-2A spectrophotometer with its Gier - Dunkle integrating sphere, weighting with AM0 spectral irradiance in 100nm intervals and subtracting the result from unity. The emittance was obtained by measuring wide-band long wave infra-red reflectance with our Gier - Dunkle infra-red reflectometer and subracting the reflectance from unity. The values obtained for absorptance for the 50 micron cells were found to lie in the range of 0.85 to 0.87 with the differences due mainly to the silicon-aluminum interface. The emittance with the ceria doped covers was 0.85, which results in alpha to epsilon ratios of 1.00 to 1.03.

Earlier efforts under this contract were concerned with the reflectance at the back silicon interface, which was not a consideration in selecting these samples. They were not optimized for internal reflectance, but just picked from current representative samples. Changing the internal reflectance would alter the absorptance.

D. Excess Forward Current

The application of very thin silicon solar cells to interplanetory missons which can experience multiples of 1AU provokes interest in how the junction forward voltage varies as a function of injected current density. An ideal forward characteristic has the form:

$$I = I_0 \exp \left(\frac{qV}{kT} - 1\right)$$

Crystal damage, resulting electronically active defect centers, mid-gap states from undesirable impurities and imperfect edge finishing modify the ideal characteristic to:

$$I = I_1 + I_2 = I_{01} \exp \left(\frac{qV}{n_1 kT} - 1\right) + I_{02} \exp \left(\frac{qV}{n_2 kT} - 1\right)$$

where the values of n are greater than unity (n_2 is nearly unity) and the values of I_0 are larger than in the ideal case. The most common effect on a solar cell is to reduce the junction forward voltage at low injection current densities (where I_1 is dominant) from the ideal case and consequently the output voltage of the cell at low light levels. One of the physical factors affecting the junction forward characteristic is residual work damage from sawing slices out of ingots. In general, very thin cells are etched more than thicker cells and thereby have their junctions at a position in the slice which is further from the original sawed surface. Consequently, they tend to have more ideal forward characteristics than thick cells simply because there is less chance of residual work damage in the resulting slice. In addition, of course, there are a myriad of other factors which require a sophisticated approach to their control. These include such topics as impurity solubilities, interfacial segregation, crystal stresses, slice flexure during high temperature furnance treatment, etc., which are a topic of continuing study.

The present status of typical thin solar cell junction characteristics in this quarter is demonstrated in Figure 2. The two samples in the plot are from different experimental groups and the lot-to-lot variation in the I_1 component is apparent. We are working on this area and think I_1 will be brought under control in the near future.

Figure 3 is a plot which shows the low temperature behavior of the cell having the lower I_1 component in Figure 2. Here the importance of controlling the I_1 component of the junction injection current becomes obvious. On missons reaching multiples of of 1AU both the incident light intensity and the cell temperature will drop. In order to fully realize the benefit of higher voltages expected at lower temperatures the cell's I_1 component must not intersect the I_2 component at current densities greater than a fraction of the short circuit current produced at the decreased incident intensity. The cell characteristics shown in Figure 3 have an intercept of the I_1 and I_2 components at approximately 1.3% af the 1AU AM0 short circuit current even at -100°C. The rise in the intercept current level occurs because I_2 is controlled by the silicon bandgap energy, while I_1 has a considerably smaller activation energy and therefore changes less as the temperature is decreased. The lower I_1 is the better maintenance of the fill factor and the better the improvement of operating voltage to help compensate for decreasing Isc at multiples of 1AU.

Figure 4 shows the illuminated I-V characteristics at 25°C and -100°C for 5% of AM0 1AU incident intensity of a thin cell from the same group as in Figure 3. It can be seen that these cells have an I_1 component of injection current low enough to maintain their fill factors at low intensities. The efficiency at 25°C for 5% sun is only 8.3%, but that is an artificial laboratory condition. In space, the cell temperature drop at low light levels improves the voltage and recovers the efficiency. This cell's efficiency at 5% sun and -100°C is 13%. The low-temperature, low-current efficiencies can be kept quite high with these cells and probably can be improved further.

Figure 2. Dark forward characteristics of two current representative thin solar cells.

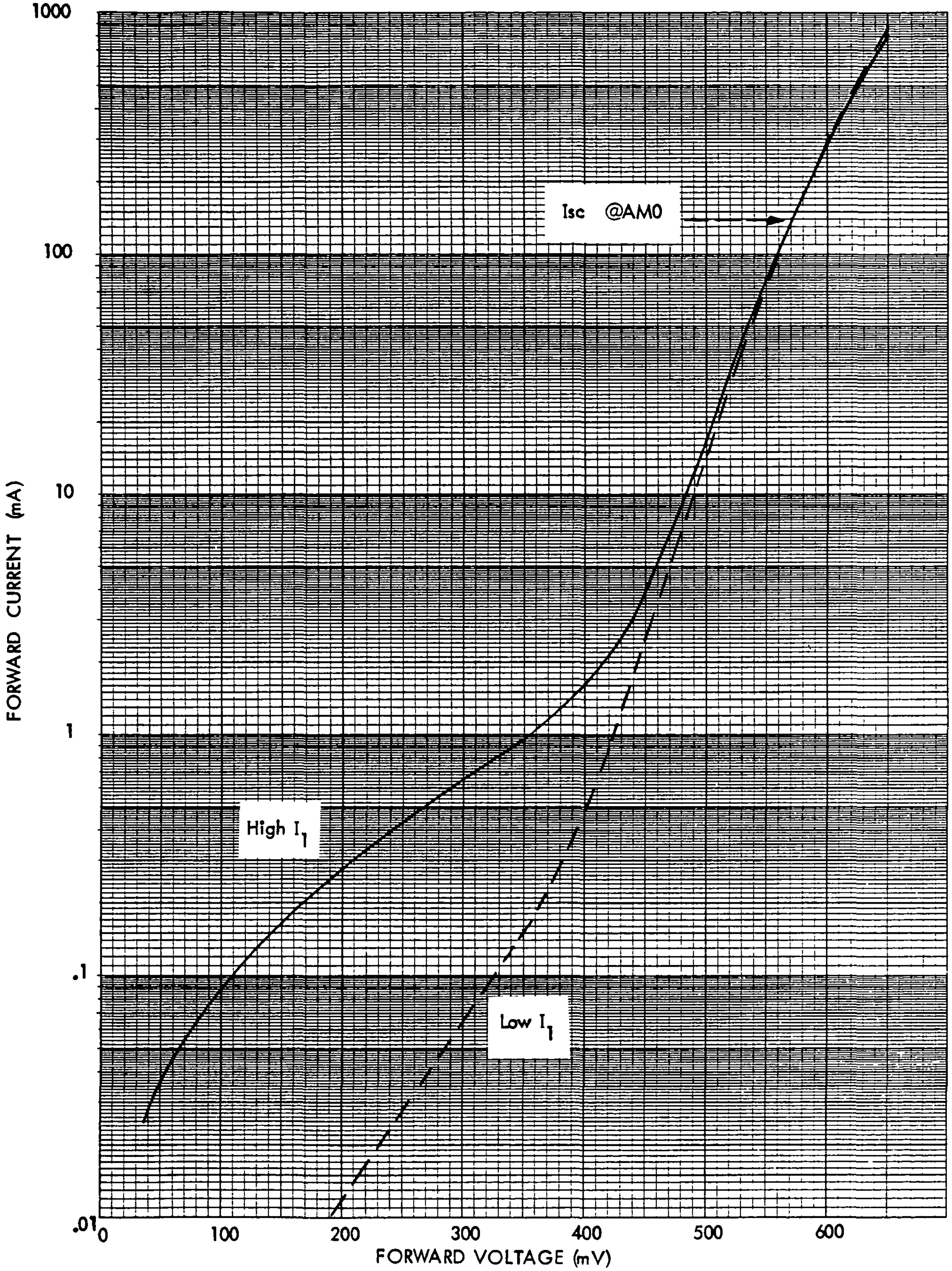


Figure 3. Effect of low temperature on the junction forward I-V characteristic for the thin cell of the lower curve in Figure 2.

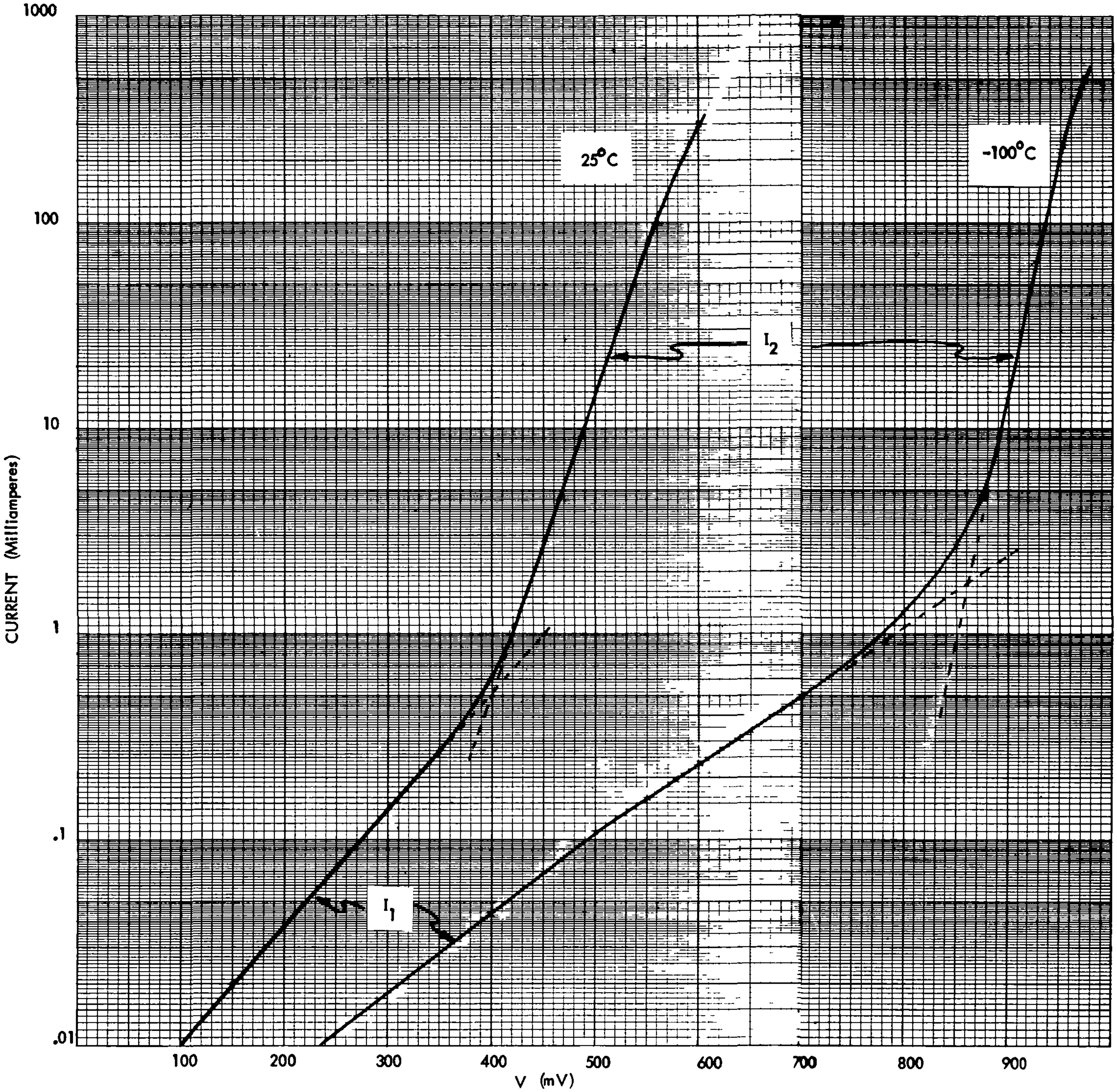
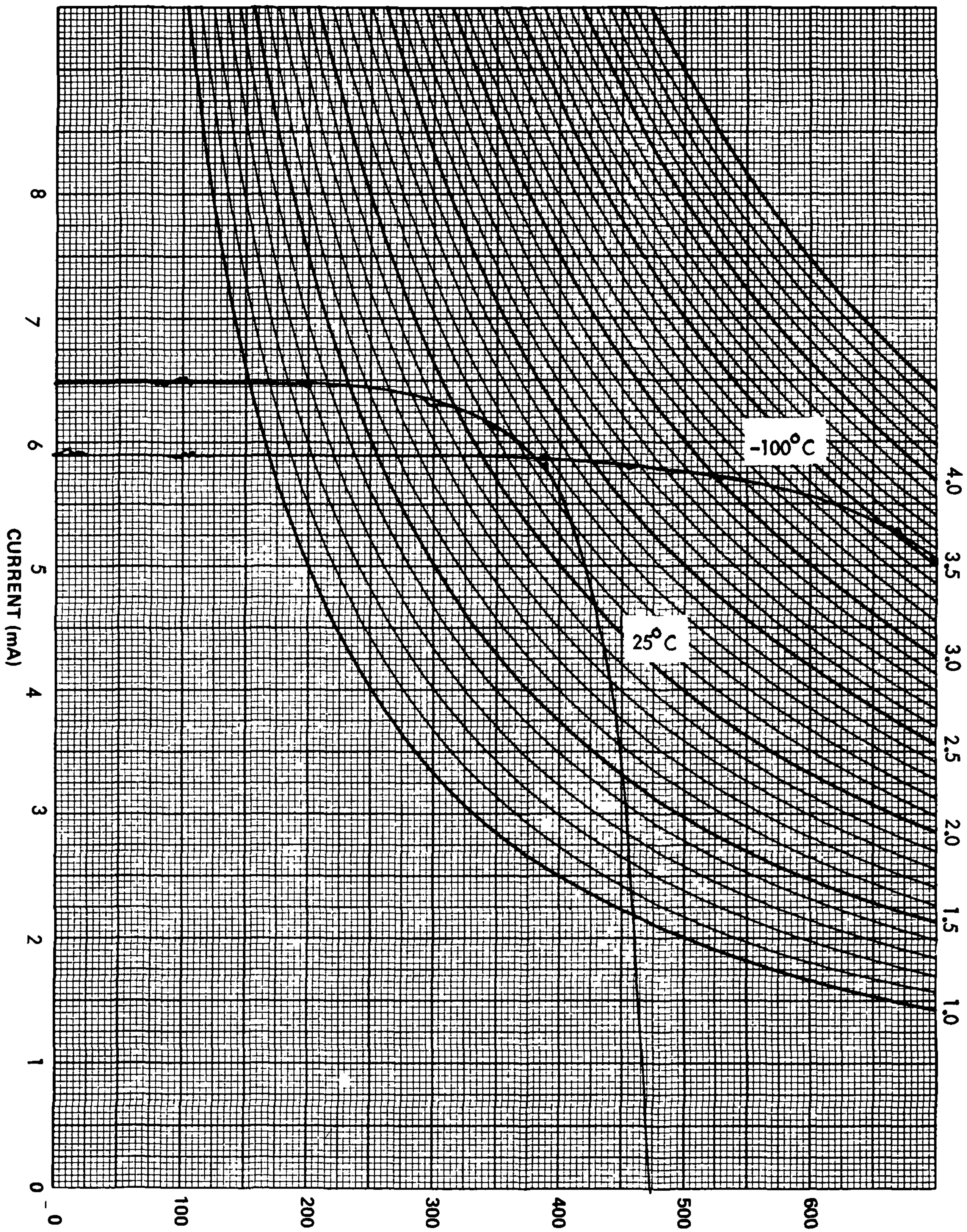


Figure 4. Low light level I-V characteristic of a 50 micron 2cm x 2cm cell for 5% of AM0 1AU illumination.



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Cell Type 2 mil No 2009-3 By C.W. Date 4/12/77

D. Deliverable Samples

A sample quantity of twenty one hundred (2100) 2cm x 2cm thin solar cells from this quarter's efforts, approximately 50 microns in average thickness, was sent to JPL for evaluation. These included some cells with interrupted Ti-Pd-Ag coverage on the back side. All of the solar cells delivered had tantalum oxide antireflective coatings. Two thousand of the delivered cells were from the Pilot Line effort and one hundred were experimental samples. The great majority of cell fabrication efforts in this quarter were in the Pilot Line.

V CONCLUSIONS

Thin silicon solar cells do not reach their fracture limit until bent to a radius of curvature of approximately 1 centimeter per 25 microns of silicon thickness.

The very slight inherent bowing of thin cells and increases due to differential thermal expansion can be further reduced by decreasing the silver coverage on the back of the cells.

The absorptance/emittance ratios for thin cells covered with ceria doped microsheet ranges between 1.00 and 1.03 without optimized internal reflectance.

Excess forward injection currents tend to be lower in thin cells than thick cells.

Twenty one hundred (2100) sample thin 2cm x 2cm solar cells were delivered to JPL for evaluation, 2000 of which were from the Pilot Line effort and the remainder from experimental samples.