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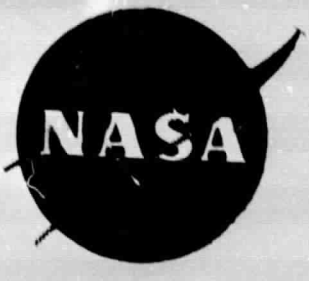

FINAL REPORT

AUTOMATED FABRICATION OF BACK SURFACE FIELD SILICON SOLAR CELLS WITH SCREEN PRINTED WRAPAROUND CONTACTS

by

J. W. Thornhill

Spectrolab, Inc.

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Lewis Research Center

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16. Abstract

The development of a process for fabricating 2 X 4 cm back surface field silicon solar cells having screen printed wraparound contacts is described. This process was specifically designed to be amenable for incorporation into the automated non-vacuum production line developed under Contract NAS3-18566. Techniques were developed to permit the use of screen printing for producing improved back surface field structures, wraparound dielectric layers, and wraparound contacts. The optimized process sequence was then used to produce 1852 finished cells. Tests indicated an average conversion efficiency of 11% at AMO and 28°C, with an average degradation of maximum power output of 1.5% after boiling water immersion or thermal shock cycling. Contact adherence was satisfactory after these tests, as well as long term storage at high temperature and high humidity.

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ABSTRACT

The development of a process for fabricating 2 x 4 cm back surface field silicon solar cells having screen printed wraparound contacts is described. This process was specifically designed to be amenable for incorporation into the automated nonvacuum production line developed under contract NAS3-18566. Techniques were developed to permit the use of screen printing for producing improved back surface field structures, wraparound dielectric layers, and wraparound contacts. The optimized process sequence was then used to produce about 1,850 finished cells. Tests indicated an average conversion efficiency of 11% at AMO and 28^{o}C, with an average degradation of maximum output power of 1.5% after boiling water immersion or thermal shock cycling. Contact adherence was satisfactory after these tests, as well as long term storage at high temperature and high humidity.

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I. SUMMARY

This program is a follow-on investigation to a previous contract (NAS3-18566) which established the feasibility of automating a major portion of silicon solar cell processing. The earlier effort had as a goal a significant reduction in the cost of solar cells by the use of automated processing, especially by employing the more easily automated nonvacuum process (i.e., screen printing techniques) for applying the P+ back surface field layer and the metallization. As a part of that work a laboratory model production line was set up and operated to produce solar cells.

This program extended the capabilities of the laboratory model production line to include the fabrication of screen printed wraparound contact solar cells. Studies were also carried out to improve the back surface field structure using screen printed aluminum. The possibility of using other types of diffusion sources than the phosphine gas previously used was also investigated.

N+ diffusion sources were evaluated using both spin-on and spray-on techniques. During the evaluation of these techniques, it was found that screen printed silver contacts, the standard contact system to be used for this effort, gave excessive shunting effects after the contacts were fired onto the cells, particularly if the cells had diffused layers with sheet resistances greater than 20 ohms per square. The shunting effects appeared to be minimal for diffusions using phosphine gas as the dopant source. Efforts at simultaneous N+ and P+ diffusions, to produce both the collecting junction and the back surface field junction at the same time, yielded cells that exhibited only slight BSF behavior.

An in-house formulated aluminum paste was investigated and found to be satisfactory for producing the back surface field junction by screen printing techniques. This paste contained no glass frit, and could be mixed from readily available materials at a considerable cost saving over purchased pastes.

The production phase of this program consisted of fabricating 2500 2 x 4 cm back surface field silicon solar cells using the wraparound screen printing process. These production cells were made on the modified laboratory model production line in two groups. Because of time and funding limitations not all of the wafers started into the line were completed. A total of 1050 cells were finished from the first group and shipped to NASA Lewis Research Center. An extension in the contract permitted the remaining wafers that had been processed through the back surface field junction formation, to be completed. After the attrition of yield losses, the second group yielded 802 additional cells. Since 1500 cells were started through the production line, the finished cells represent a production yield of 53 percent.

Electrical testing of the completed cells gave an average short circuit current of 275 mA, an open circuit voltage of 590 mV, and an average efficiency of 11.0% when measured at AMO and 28°C for an incident radiation of 135.3 mW per square centimeter. Contact adhesion appeared to be satisfactory; however, as with most screen printed contact systems, sensitivity to humidity was noted.

II. INTRODUCTION

A. Background

The feasibility of automating a major portion of silicon solar cell processing was established by Spectrolab under Contract NAS3-18566 with the NASA Lewis Research Center. As a part of that effort a laboratory model production line was assembled and operated using a process sequence that did not require the use of high vacuum operations. Where possible, processing was chosen that either allowed large batch operations, or that could be readily automated with a minimum of equipment design and development.

The laboratory model was operated to produce a series of demonstration runs of silicon solar cells, and within the time available process steps were optimized as much as possible to give satisfactory cells with acceptable yields. The cells produced were $N^+/P/P^+$ back surface field types having texturized front surfaces, screen printed contacts, and spun-on AR coatings. While the bulk of the demonstration runs were devoted to the production of hexagonal cells (one inch on a straight edge), a few lots of 20 X 40 mm and 20 X 20 mm cells were also made.

The cells produced by the laboratory model production line had an average efficiency of 10.5% and an average curve fill factor of 0.71 when tested at AM0, 25°C, and 135.3 mW/cm^2 incident radiation. Problems were encountered with some lots having less than satisfactory contact adhesion. The back surface field also did not appear to be as effective as had been anticipated. Testing was generally dedicated to measuring the electrical performance of the cells, and environmental testing was minimal, primarily due to a lack of available time.

In general the program under Contract NAS3-18566 was successful in demonstrating the feasibility of automated silicon solar cell production. However additional effort was needed to optimize the back surface field structures, to explore possible improvements in diffusions, and to perform more complete testing under various environmental conditions. It also appeared possible to extend the screen printing technology to include the fabrication of wraparound contact systems, which offered the prospect of increased cell efficiencies.

B. Program Objectives

This program was therefore initiated with the specific objectives of determining, evaluating, and optimizing the processing of back surface field cells, utilizing a process sequence that could be readily incorporated into the laboratory model production line developed under Contract NAS3-18566.

One of the objectives was to determine suitable nongaseous diffusion sources that could be used to produce both the N+/P junction, as well as the back surface field P+/P structure. Sources to be investigated included spin-on emulsions, solid source wafers, and paint-on diffusants, the intention being to identify and select diffusion sources that offered the probability of reducing the cost per cell without sacrificing cell performance.

An additional objective was to extend the screen printing techniques used in the laboratory model production line to fabricate rectangular 20 x 40 mm cells with wraparound screen printed contacts. This effort would necessarily include evaluation and optimization of a variety of conductive and dielectric pastes. In all cases the processes and techniques developed under this contract were to be amenable to incorporation into the laboratory model production line.

Once the above objectives had been attained, the production line was to be operated to produce 2500 back surface field 20 x 40 mm silicon solar cells with screen printed wraparound contacts. Random samples of these cells were then to be tested for electrical performance at AM0 and 28°C, contact adherence, AR coating adherence, and for the effects of thermal shock and high temperature-high humidity environments.

C. Program Organization

In order to attain the objectives stated above, this program was organized into the following specific tasks:

Task I Determine suitable nongaseous diffusion sources which might be used to produce an N+/P junction and a stress-free back surface field in N on P solar cells. Assess the advantages and disadvantages of these sources particularly as to their ability to reduce the cost per cell without any loss in cell performance.

BSF cells produced using these sources were then to be compared to BSF cells produced by the process sequence developed under Contract NAS3-18566.

Task II Determine a process sequence suitable for fabricating rectangular 20 x 40 mm screen printed wraparound contact BSF cells. Consideration had to be given to the possible incorporation of such processing into the automated cell production line. Cells having the wraparound contact configuration were to be compared to similar BSF cells that had screen printed nonwraparound contacts.

Task III The laboratory model production line was to be then modified to accommodate the processing determined under Tasks I and II and then be operated to produce 2500 screen printed wraparound contact BSF solar cells. Random cells were then to be selected from each production line batch for measurement and evaluation of cell performance, contact adherence, AR coating adherence, and the effects of thermal shock and high temperature-high humidity.

III. PROCESS DEVELOPMENT AND EVALUATION

A. Diffusion Processing

General

The baseline diffusion process used during these investigations for comparison utilized phosphine gas in a standard diffusion tube furnace at a temperature of 900°C. Wafers were processed using a standard predeposition/oxidation/and drive-in cycle to give the desired value of sheet resistance. Except for the 900°C temperature, this is the same diffusion process used during Contract NAS3-18566. The 900°C temperature permitted the diffusions to be done in a slightly shorter time than the 850°C used previously. This process is attractive since it allows the diffusion of relatively large batches of wafers at one time; however, a back etch step is required prior to the back surface field formation.

Since the end product solar cells were to be made with a P+ region on the back surface and would have screen printed silver contacts, any N+ diffusion process developed would have to be compatible with these subsequent processes and should not be adversely affected by them. Because of the limited time available, the investigation of nongaseous diffusion dopant sources was limited to spin-on or spray-on emulsion sources which were readily available from commercial suppliers.

It was also required that any process developed be capable of automation, or large batch processing, in order that it would be amenable for incorporation into the laboratory model production line process sequence. It was hoped that by utilizing nongaseous dopant sources a diffusion process could be developed that would permit simultaneous N+ and P+ diffusions to form both the collector junction and the back surface field structure at the same time without requiring either back etching or printing aluminum paste and alloying. For such operations the cross doping around wafer edges had to be minimized, as well as cross doping from wafer to wafer when high density furnace loadings were used.

N+ Diffusions

Initially the capabilities and characteristics of spin-on dopant sources were investigated to make only the illuminated junctions. Of the several types of source materials obtained, the one exhibiting the most promise was Emulsitone N-250. This material was investigated using procedures recommended by the manufacturer. Five to ten drops of N-250 were spun onto 50 mm diameter 10 ohm-cm texturized wafers at 3000 rpm for 10 seconds. The wafers were then dried in air for 15 minutes at 180°C and diffused in a standard diffusion tube furnace at 900°C for an appropriate time in a mixture of 83% nitrogen and 17% oxygen. Wafers processed in this fashion exhibited a uniform diffused layer with sheet resistance values that were in good agreement with the values predicted by the manufacturer, (i.e., a 20 minute diffusion resulted in sheet resistances of 30 ohms/square).

In an effort to reduce the time required to coat each wafer some diffusions were done using N-250 that had been sprayed onto the wafers instead of

spinning on the emulsion. This reduced the time to coat each wafer from about 20 seconds to 10 seconds, but brought about some problems in maintaining a controlled coating thickness. Thin coatings lacked sufficient material and were sometimes incomplete, while thick coatings gave some devitrification and lifting of the glass. It was found that with proper care intermediately thick coatings could be obtained that were uniform and gave results that were comparable to those obtained by spin-on techniques.

A series of experiments were then performed to compare N+ dopant sources and to investigate different N+/P junction depths on cells having P+ back surfaces and silver paste front contact grids. Four groups of 12 wafers each were etched to a thickness of 0.25 mm and texturized in sodium hydroxide. Two groups were then diffused using the phosphine gas baseline process to sheet resistances of 40 ohms/square and to 20 ohms/square respectively. The remaining two groups were diffused to the same sheet resistance values using the Emulsitone N-250 spin-on dopant source. All wafers were then back etched, printed with aluminum paste, alloyed, printed with silver paste front contact grids, fired, cut into 20 x 40 mm rectangles, and finally dipped in a proprietary solution formulated to improve the curve shape of the finished cells. No AR coatings were applied.

The electrical characteristics were then measured at AMO and 28°C. The resulting data are summarized below:

Group No.	Diffusion Source	Sheet Resistance (ohms/sq)	V_{oc} (mV)	I_{sc} (mA)	$I_{.49V}$ (mA)
1	PH_3 Gas	40	574	244	203
2	PH_3 Gas	20	594	234	220
3	N-250	40	∿ 200	--	--
4	N-250	20	∿ 300	--	--

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Both groups having the N-250 phosphorous spin-on source were excessively shunted, as indicated by the very low open circuit voltages obtained. The short circuit currents and the currents at 0.49 volts were not recorded.

These results indicated that a relatively deep N+ junction with a sheet resistance of about 20 ohms/square would be required to obtain satisfactory BSF cells with screen printed silver contact grids. It was not clear whether the shunting observed was due to the effects of the screen printed contacts on the more shallow junctions or because of impurity diffusion occurring during the aluminum paste alloying step. Four groups of cells were then prepared using the baseline phosphine gas diffusion process. Two groups were diffused to a sheet resistance of 30 ohms/square and two were diffused to a sheet resistance of 20 ohms/square. The two 30 ohms/square groups were screen printed with DuPont silver paste and with Thick Film Systems 3303 silver paste respectively, as were the two 20 ohm/square groups.

Figure 1 illustrates the type of I-V characteristic curves obtained with the two different groups of cells having different junction depths and using DuPont silver paste contacts. The deeper junction cells (20 ohm/square) have the expected curve shape and voltage for this type of cell, while the shallower junction cells (30 ohm/square) have the poor curve shape and voltage normally attributed to shunting. The deeper junction group has a lower short circuit current, but is superior at the maximum power point. The groups fabricated using the 3303 silver paste exhibited the same effect.

These results are somewhat surprising since a sheet resistance of 30 ohms/square is normally considered to be more than adequate for use with silver paste contact systems. It is possible that the particular sodium hydroxide etch technique used to prepare the test samples also created an increased sensitivity to shunting. The tetrahedral structures obtained on the test specimens is somewhat different from that obtained using the standard production processing, with the tetrahedrons being much smaller and more densely packed.

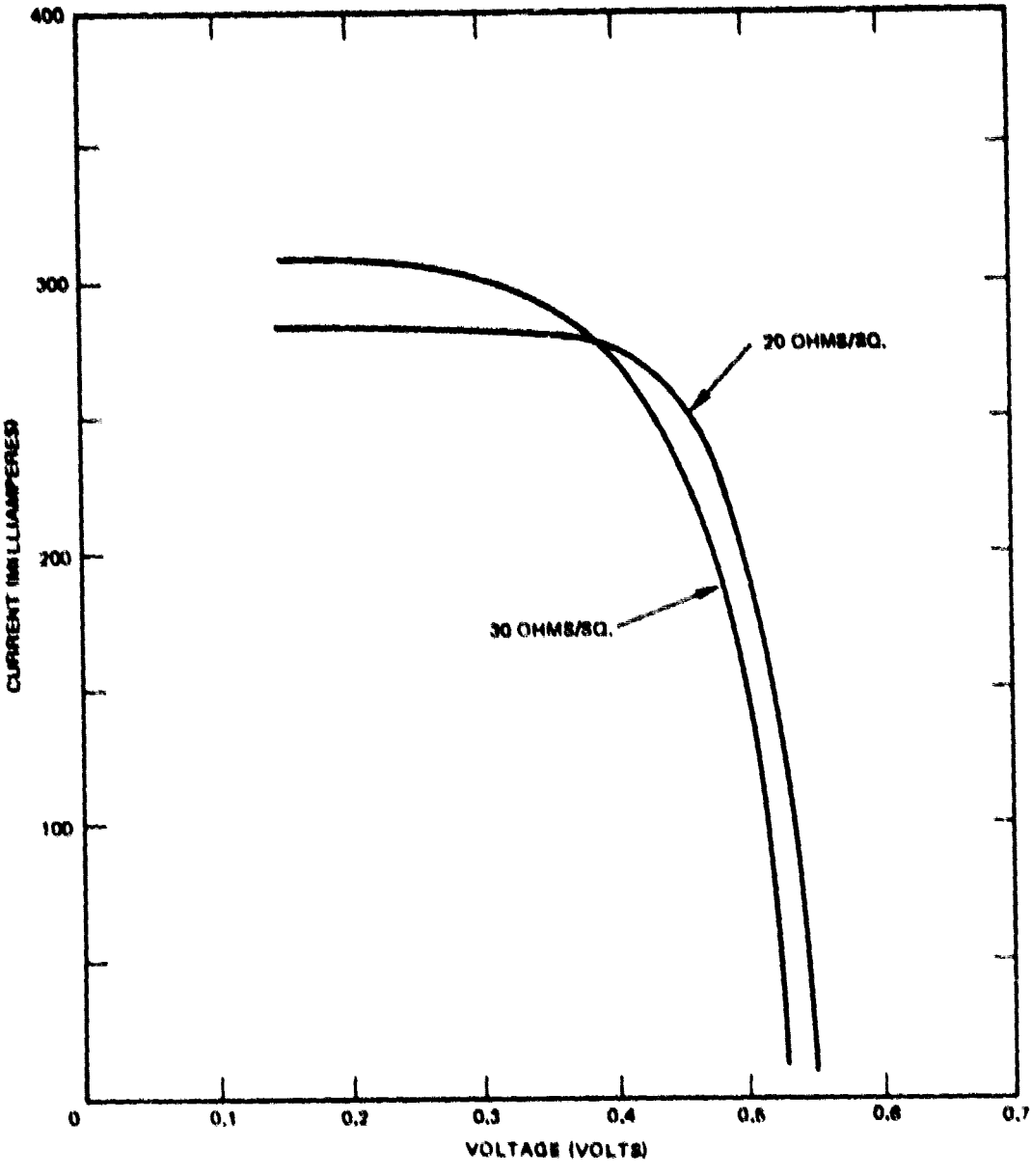

Figure 1. Influence of Junction Depth on Curve Shape for Silver Screen Printed Contacts (10 ohm-cm texturized cells with no BSF or AR coating)

Additional efforts to use the Emulsitone N-250 spin-on diffusion source were made, both using spin-on techniques and spray-on procedures. In either case the finished cells with silver paste contacts were invariably badly shunted, even for junctions having sheet resistances of 20 ohms/square. It was therefore decided that this type of diffusion source does not provide adequate junction formation for use on texturized cells with silver paste contacts and was thus not useful in making the type cells required for this contract.

Simultaneous N+/P and P+/P Junction Formation

Concurrently with the N+ junction studies described above, attempts were made to perform simultaneous diffusions of the illuminated front surface junction and the back surface field structure. Test groups of wafers were prepared by spinning on the N-250 coating, drying it, and then printing the aluminum paste on the back surface. The reverse sequence of first printing on the aluminum paste and then spinning on the N-250 was also tried. In either case the same problems were encountered in maintaining the surface cleanliness required for prediffusion processing.

Coated wafers were fired at a temperature of 900°C in a diffusion tube furnace using an atmosphere of nitrogen and oxygen for varying lengths of time to obtain sheet resistances of 40-50 ohms/square. Silver paste contacts were then printed on, dried, and fired and 20 x 40 mm cells were then cut from the wafers using a Tempress dicing saw. In no case were open circuit voltages found that were greater than 200 mV, although in some instances satisfactory open circuit voltages were found prior to firing on the printed contacts. Again, shunting through the illuminated junction appears to be the most likely cause, as was the case for the sequentially processed groups described above. Further efforts to perform simultaneous junction formation were therefore abandoned in favor of optimizing a sequential process, particularly in view of the time available for development.

B. Back Surface Field Processing

Aluminum Paste Considerations

A commercial aluminum paste, Engelhard 3113, was used during the previous contract as a P+ dopant source and a back contact. Two major problems encountered at that time were inconsistent back surface field formation and excessive bowing of the silicon wafers. The latter problem appeared to be especially significant in view of the thin cell requirements for the present program.

The 3113 paste consists of aluminum powder and a low melting glass frit, both suspended in an organic vehicle. Much of the thermal coefficient of expansion mismatch between the paste and the silicon wafers is attributed to the glass frit and is responsible for the bowing. Another paste obtained from the same company, E-227-A, does not contain any glass, and was used to obtain equally good back surface field effects with negligible bowing, even on 0.20 mm wafers.

In an effort to gain some insight into the mechanisms involved, and hoping to reduce the cost of the paste, an in-house paste was prepared using a formula derived from chemical analysis of commercial products. This paste consisted of 28% Terpineol, 2% Ethyl Cellulose, and 70% Aluminum power. The Terpineol and ethyl cellulose are mixed by stirring at a low temperature (about 60^{o}C) and then the aluminum powder is stirred into the mixture. The resulting paste is quite thick and must be thinned to the desired viscosity, suitable for screen printing, by adding small amounts of butyl carbitol.

From the onset, good back surface field effects were obtained with this in-house formula, as indicated by high open circuit voltages (greater than 600 mV) on 10 ohm-cm test samples. After alloying it was found that an outer layer of aluminum powder, heavily oxidized, could be removed to reveal a shiny layer of fused aluminum that could serve as a mechanically and environmentally stable back contact.

The aluminum powder used to prepare this paste was obtained from Alcoa and was designated 1401. Specifications obtained from the manufacturer

indicated that its average particle size was 6-9 microns typically with 98% smaller than 325 mesh. Its major impurities, besides Al_2O_3, are typically 0.18% iron and 0.12% silicon. Alcoa is phasing this powder out of its production line, but a similar powder is available from Reynolds Aluminum and was used with equally satisfactory results in one series of experiments. The other required components of the paste are available from any number of suppliers.

The cost of the in-house aluminum paste, even based on small volume procurement of the necessary materials, is less than $0.50 per ounce, including the labor of mixing it. This is at least an order of magnitude lower than the cost of commercial pastes and represents a considerable cost savings for cell production.

Optimization of the aluminum paste P+ process involved a continuous readjustment of many interdependent variables, and lasted well into the production phase of this program. These variables include the actual screen printing operation, prebaking, and the high temperature alloying. Each is discussed separately below.

Paste Deposition

Several methods of paste deposition were considered, including brushing on, rolling, and screen printing. While good results were obtained in each case, the screen printing produced the most consistent results. Uniform paste layer thickness is obtained over large surface areas by screen printing and the thickness can be controlled by the screen mesh size used. Screen printing is also well suited to automated processing and is a well established technology. For these reasons printing was chosen as the most suitable method of paste deposition.

The most critical parameters associated with screen printing Al paste as a P+ dopant source were found to be screen mesh size and aluminum powder particle size, which together determines the resulting paste layer thickness and its density. Initially the best results were obtained using a 200 mesh screen.

However, when a new batch of Alcoa 1401 aluminum powder was introduced into the process a 15-20 mV reduction in open circuit voltage occurred. Subtle changes in paste texture and printing characteristics suggested that the new batch of powder had a slightly higher value of average particle size. Fortunately this problem was eliminated by simply changing to a coarser screen mesh, 165. A fine mesh screen, 325, was tried with both new and old batches of powder. In both cases prohibitive voltage reduction was incurred.

A number of secondary variables associated with the printing process were identified, including platen height, squeegee hardness, squeegee pressure, screen tension, stroke speed. Convenient values were established for each of these variables and no further investigation was undertaken.

Immediately after printing, coated wafers are baked in air to burn off most of the organic vehicle. An optimum temperature range for baking was found to be between 200°C and 250°C. Below this range violent outgassing during alloying results in a separation of the paste from the silicon surface, thus preventing alloying. During production, 100 cell lots were baked in a 250°C oven for 10-15 minutes. In the context of automated cell fabrication, it is expected that a conveyor belt furnace could be utilized most effectively to perform this process step, with wafers transferred directly from the printer to a conveyor belt.

Alloying Operations

A series of test samples were coated with the aluminum paste which did not contain any glass frit. These samples had been previously diffused using the baseline phosphine gas diffusion process and back etched. The samples were then alloyed at 850°C in air for progressively shorter periods of time. The samples were then checked for open circuit voltage values. Maximum voltages of 603 mV were obtained for alloying periods between 30 seconds and 10 minutes. Shorter and longer times yielded lower voltages. The shorter times appeared to not provide sufficient time for complete alloying, while the longer times gave shunting effects, which also resulted in lowered open circuit voltages.

The alloying time was then kept at 5 minutes and the furnace temperature was varied in increments of 50°C. Satisfactorily high open circuit voltages were obtained in the temperature range of 750°C to 900°C. Below 750°C voltages similar to non-P^+ cells were found, probably due to insufficient or spotty alloying.

Other parameters were also found to affect the open circuit voltages obtained. These include paste thickness, alloy temperature program, and the furnace atmosphere used, but efforts were made during these experiments to keep these factors constant, although not necessarily optimum.

The alloy operation ultimately evolved into a batch process where 12 wafers at a time were loaded vertically on a ladder boat. The boat was then pushed at a relatively slow speed into a 900°C tube furnace in air, held in the hot zone of the furnace for 30 seconds, and then rapidly withdrawn. Because of the short time cycle no attempts were made to fire more than twelve wafers at a time, since this process was capable of keeping pace with other processing steps. For automated operations a properly profiled conveyor belt furnace would be able to perform this step.

Powder Layer Removal

After alloying the aluminum paste layer onto the back surface of the wafers the surface has a coating of spongy or powdery material. This material, heavily oxidized aluminum, offers a poor surface for making good electrical contact or obtaining good adhesion. Various mechanical removal techniques were tried including sanding, vapor honing, wire brushing, and ultrasonic cleaning. Most of these methods were objectionable because of the additional wafer handling and the mechanical damage that could result. Experiments showed that a short chemical treatment in warm 1% NaOH followed by ultrasonic agitation removed the powder completely, leaving an exposed aluminum surface, to which both screen printed dielectric and silver contact layers adhered satisfactorily.

Flame Spraying

An alternate method of depositing an aluminum layer on the back surface of diffused wafers was investigated briefly. Working with a vendor who had the

necessary equipment, a number of 0.38 mm thick silicon wafers were flame spray coated with a layer of aluminum to a thickness of 0.1 mm. After alloying and boiling in hydrochloric acid to remove excess aluminum, a uniformly doped region was obtained on the back surface of the wafers which gave strong P+ indications with a hot point probe. Little wafer bowing was found and the aluminum did not flow when the wafers were heated to 850°C upright in a ladder boat. This is probably due to the fact that the flame sprayed layer is granular in nature, thus providing considerable stress relief. Individual grains of aluminum are kept in place by the substructure of the aluminum oxide.

Additional samples, this time 0.25 mm thick previously diffused and back etched silicon wafers, were flame spray coated with aluminum and then alloyed. Little P+ back surface field effect was obtained with this group of samples, probably because efforts to reduce the aluminum layer thickness resulted in a less than continuous coating.

Further test samples which had been phosphine diffused and back etched were flame sprayed with 75-125 microns of aluminum yielding what appeared to be continuous coverage of the back surfaces. After alloying, some at 850°C and some at 900°C, only a minor P+ effect was produced and the wafers became excessively bowed. It appeared that much of the aluminum layer was tied up by a matrix of aluminum oxide thus preventing aluminum from alloying with the silicon. There was no evidence of aluminum flow on the wafers which were positioned upright during the heating cycle, even though they were heated to temperatures well above the melting point of aluminum. This effort was therefore discontinued in view of the success that was being obtained with screen printed aluminum layers, the lack of an in-house facility to perform flame spraying, and the lack of success with this technique.

C. Wraparound Screen Printing Processes

Dielectric Layers

Three commercially supplied dielectric glass pastes were investigated, namely,

Transene 1000, Thick Film Systems 1141, and Thick Film Systems 1126RCB. Twenty-five micron layers of each of these materials were screen printed on silicon substrates and then fired in a tube furnace using an atmosphere of 83% nitrogen/17% oxygen at 650°C, 550°C, and 575°C respectively, the firing temperatures recommended by the manufacturers. Visual inspection revealed dense layers that appeared to be relatively pinhole-free. Silver paste overlayers about one square centimeter in size were then applied over the dielectric layers and fired at 500°C. Using a VTVM the resistance between the silver and the silicon substrate was then measured with the following results:

Paste	Typical Resistance
Transene 1000	0.10 Megohm
TFS 1141	6.00 Megohms
TFS 1126RCB	0.03 Megohm

Since it was important that the dielectric glass layer be compatible with the silver paste process developed under Contract NAS3-18566, a process that required firing in a conveyor belt furnace, additional tests were undertaken. The belt furnace to be used in firing the silver paste contacts had the time-temperature profile shown in Figure 2. The belt speed was approximately 1 mm. per second. Test samples of each type of glass were fired in this furnace and then inspected. The Transene 1000 and the TFS 1141 both appeared to be slightly over-fired, having some evidence of devitrification. The TFS 1126RCB appeared to be satisfactory. Silver paste overlays were then printed on the glass layers and the samples were then refired in the same belt furnace. Typical resistance measurements were:

Paste	Typical Resistance
Transene 1000	60,000 ohms
TFS 1141	5,000 ohms
TFS 1126RCB	6,000 ohms

The TFS 1126RCB glass appeared to be the most attractive material, based on its lack of devitrification during the subsequent firing cycles and minimal

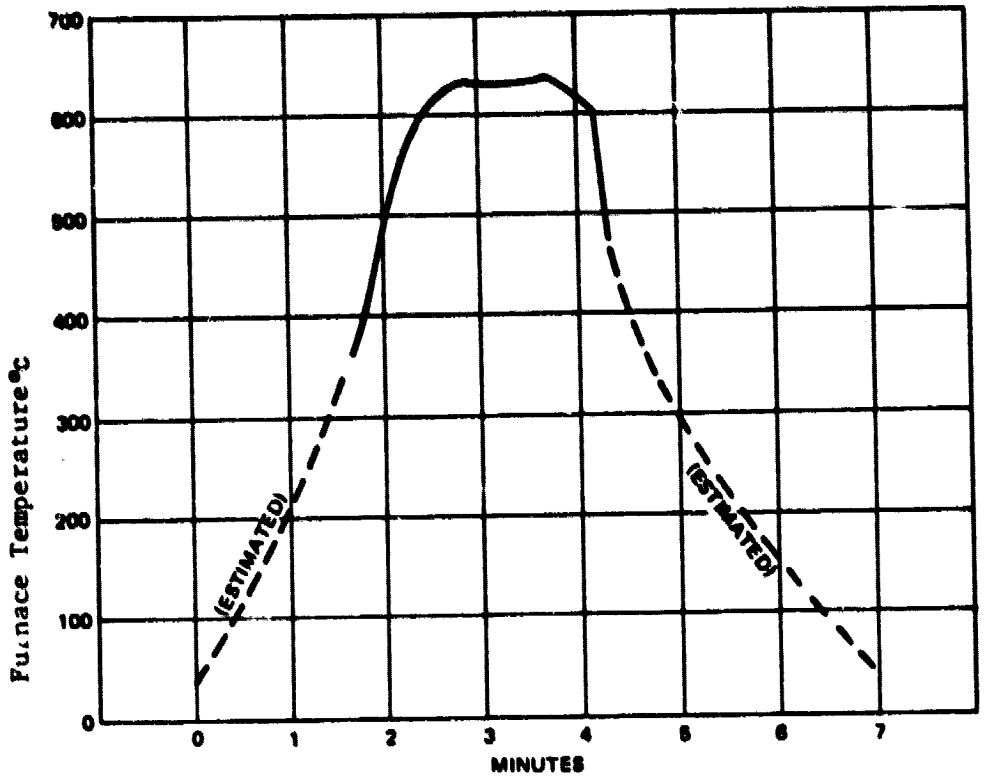

Figure 2. Conveyor Belt Furnace Time–Temperature Profile

reflow during contact firing. Double printed layers of TFS 1126RCB were prepared by printing the dielectric, drying, and then reprinting and drying another layer. These samples were then fired in the belt furnace, over-printed with silver paste, and then fired again. In all cases it was found that this process yielded essentially open circuit isolation.

The double printed layer of dielectric is a technique recommended by the manufacturer for minimizing pinholes, and appears to be effective; however, it does add another printing step to the process sequence. This is not a major difficulty, since the first dielectric layer need not be fired prior to over-printing the second layer. It was decided to continue use of the TFS 1126RCB paste, since it gave satisfactory isolation and was compatible with the silver paste and the firing cycle that was to be used.

Wraparound Screen Printing

Screens were then designed and obtained for printing the dielectric isolation layer, the front silver contact grid lines, and the back contact pads. Since the front contact fingers and the dielectric glass had to wraparound one long edge of the 20 x 40 mm cells, the design provided for appropriate over-printing of the edge of the cell. If the platen height and the squeegee pressure are properly adjusted, the motion of the squeegee on the printing stroke not only coats the edge of the cell, but forces some of the paste under the cell putting about 0.25 mm along the edge of the under side. Careful control of the printer settings will minimize the formation of a thick "bead" along the edge, which, in the case of the dielectric layers, makes it more difficult to subsequently wrap around the contacts, and may also give rise to large thermal stresses.

The final design of the dielectric layer and contact geometry for the front and back faces of the cells is shown in Figure 3. In this design approximately 8% of the illuminated front surface of the cell is occupied by contact fingers. This is an improvement over the nonwraparound contact geometry used for the 20 x 40 mm cells made under Contract NAS3-18566 where about 15%

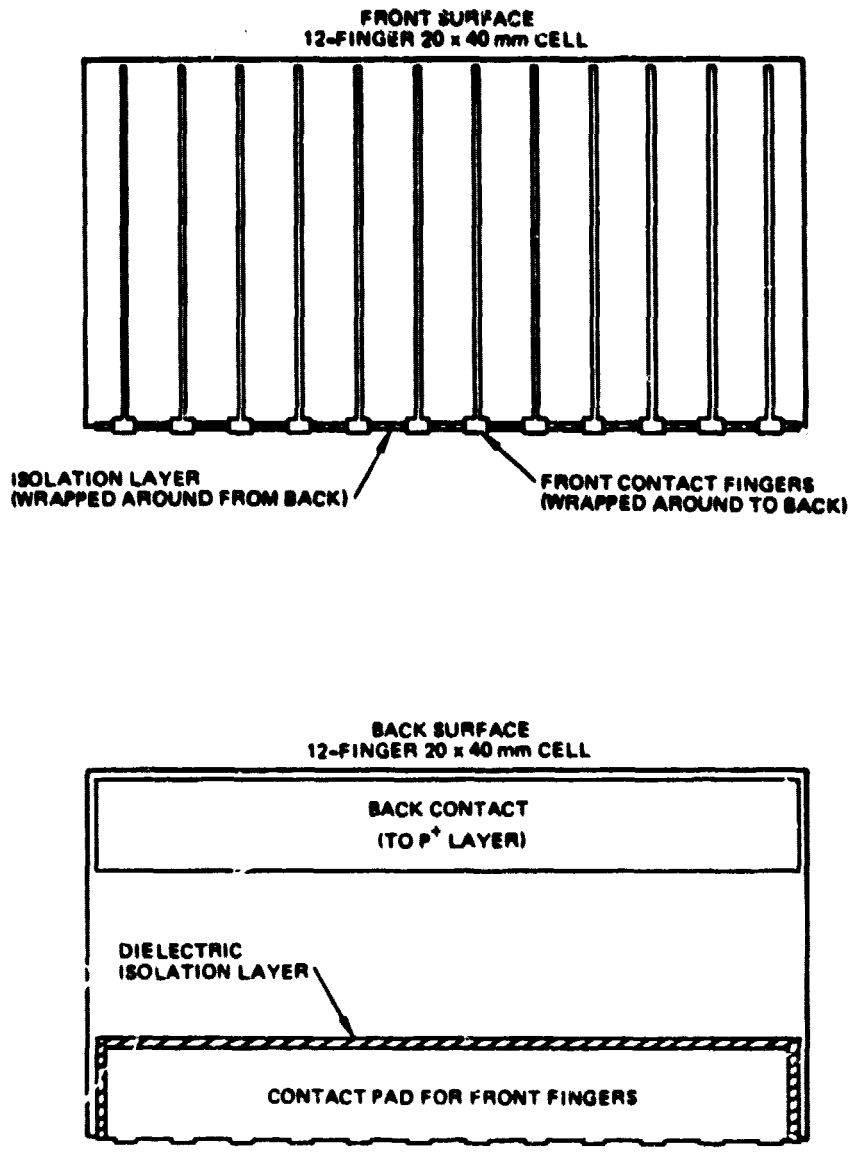

Figure 3. Design for 12-Finger 20 x 40 mm Cell With Wraparound Contacts

of the front surface of the cell was covered by the bus and the contact fingers. While screen printing is capable of producing somewhat finer contact fingers (i.e., widths of 0.15 mm), the present design was held at 0.25 mm primarily because there was a possibility that different silver pastes might be used and there was some uncertainty as to the particle sizes that might be encountered.

Figure 4 is a photomicrograph of a portion of a wraparound contact cell showing the contact fingers wrapping around the edge. A higher magnification photomicrograph in Figure 5(a) shows a single connection viewed normal to the front surface of the cell. Figure 5(b) shows the same wraparound connection viewed nearly edge-on to the cell. Figure 6 is a photomicrograph of a corner of the cell from the back side showing the geometry of the silicon the dielectric insulating layers, and the silver bus making contact to the front contact fingers. In all of the photographs the bead-like buildup of the dielectric glass along the edge of the cell is evident.

D. AR Coating Processes

A brief investigation was made of several types of AR coatings that could be applied by various nonevaporative techniques. The spin-on process used on the previous contract, while satisfactory for round cell geometries, offered some problems when used for rectangular cells. If relatively high spin speeds (10,000 rpm) are used, a major portion of the cell is uniformly coated, but there is a buildup of excess material at the corners of the cells. The AR coating material was a mixture of silicon-titanium organometallic compounds in an alcohol based vehicle. This was a commercial mixture produced by Emulsitone, and had an index of refraction of 1.96, as stated by the manufacturer. This material, when spun on and baked, gave an enhancement of the short circuit current of about 5%, although after the cell was mounted under a silicone resin and glass covering it gave an enhancement of about 14.5%, compared to about 16% for evaporative coatings of silicon monoxide.

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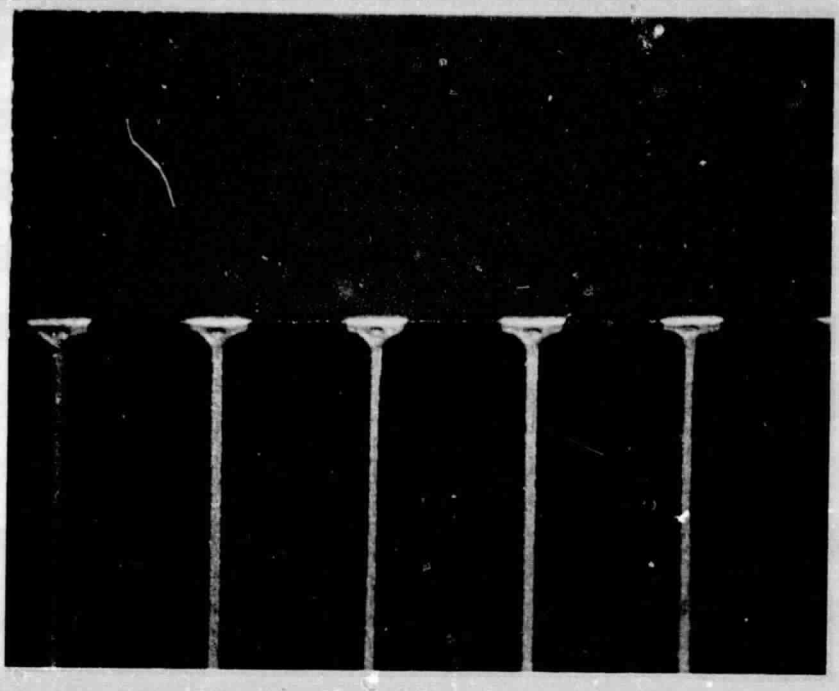

Figure 4 Photomicrograph Showing Detail of Edge of Wraparound Contact Cell

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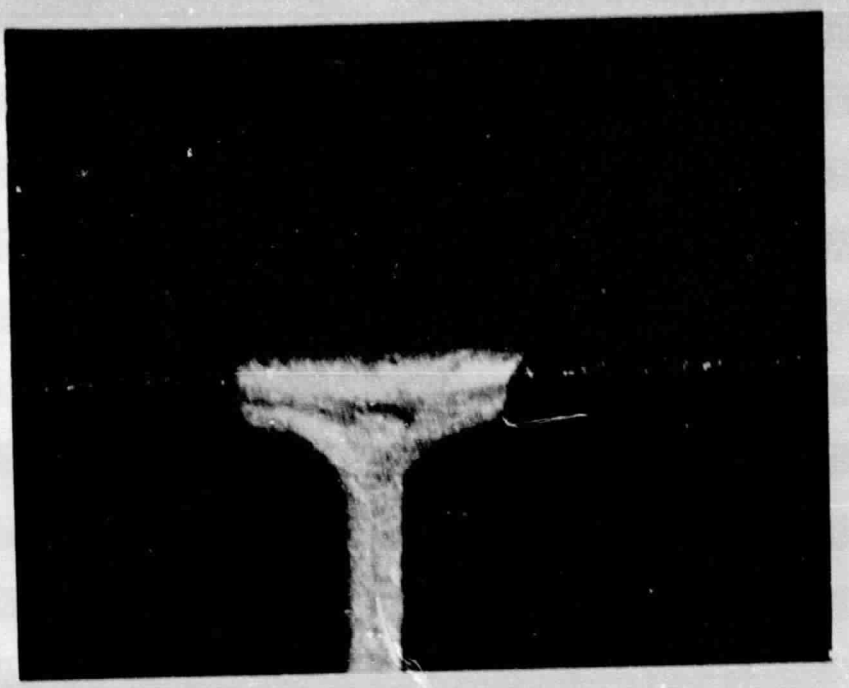
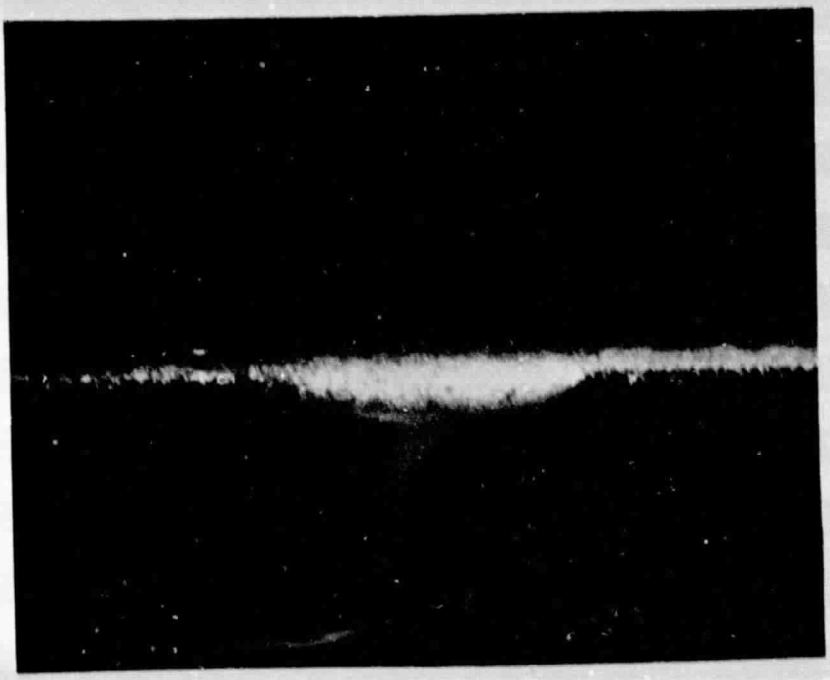


(a) Detail of Wraparound Contact Finger (Normal View)



(b) Detail of Wraparound Contact Finger (Oblique View)

Figure 5

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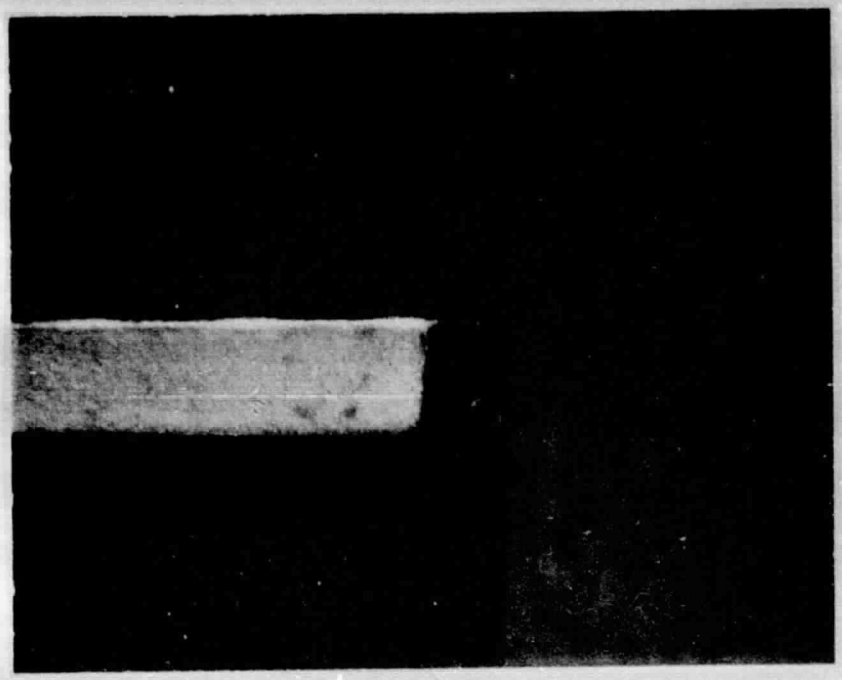


Figure 6 Detail of Corner of Back Side of Wraparound Contact Cell Showing Geometry of Screen Printed Layers

Some samples were coated with the Emulsitone AR mixture by spraying with an air brush, but it was found that there was a lack of uniformity in the resulting thickness. Other spray-on materials were tried, such as butyl acetate, which gave enhancements up to 11.5%, but these were found to be incapable of withstanding boiling water immersions without peeling. Therefore it was decided to use the Emulsitone material and the spin-on process in view of the limited time available for developing an improved process. Figure 7 shows the I-V characteristic curve for a 20 x 40 mm cell after spinning on the Emulsitone coating. Also shown is a curve for the same cell after an additional glass forming emulsion (Emulsitone 306) had been spun on and baked.

IV CELL FABRICATION

A. Production Processing

Once the various process steps had been established and optimized, they were then incorporated into the laboratory model production line which had been set up under Contract NAS3-18566. Because of time limitations some process steps were not completely investigated or optimized, and some development efforts were being expended on the later steps in the process sequence even as the production phase of the program was getting under way.

The production phase of the program consisted of operating the laboratory model production line to fabricate 2500 finished 20 x 40 mm solar cells with back surface field structures and screen printed wraparound contacts. A block flow diagram of the process sequence used is shown in Figure 8. In keeping with the work done under the previous contract, all process steps were chosen and developed such that they could be easily automated, using equipment that was readily available from commercial suppliers.

The first four steps of the process sequence, namely damage removal etch, texturizing etch, diffusion, and back etch, were performed in the Spectrolab

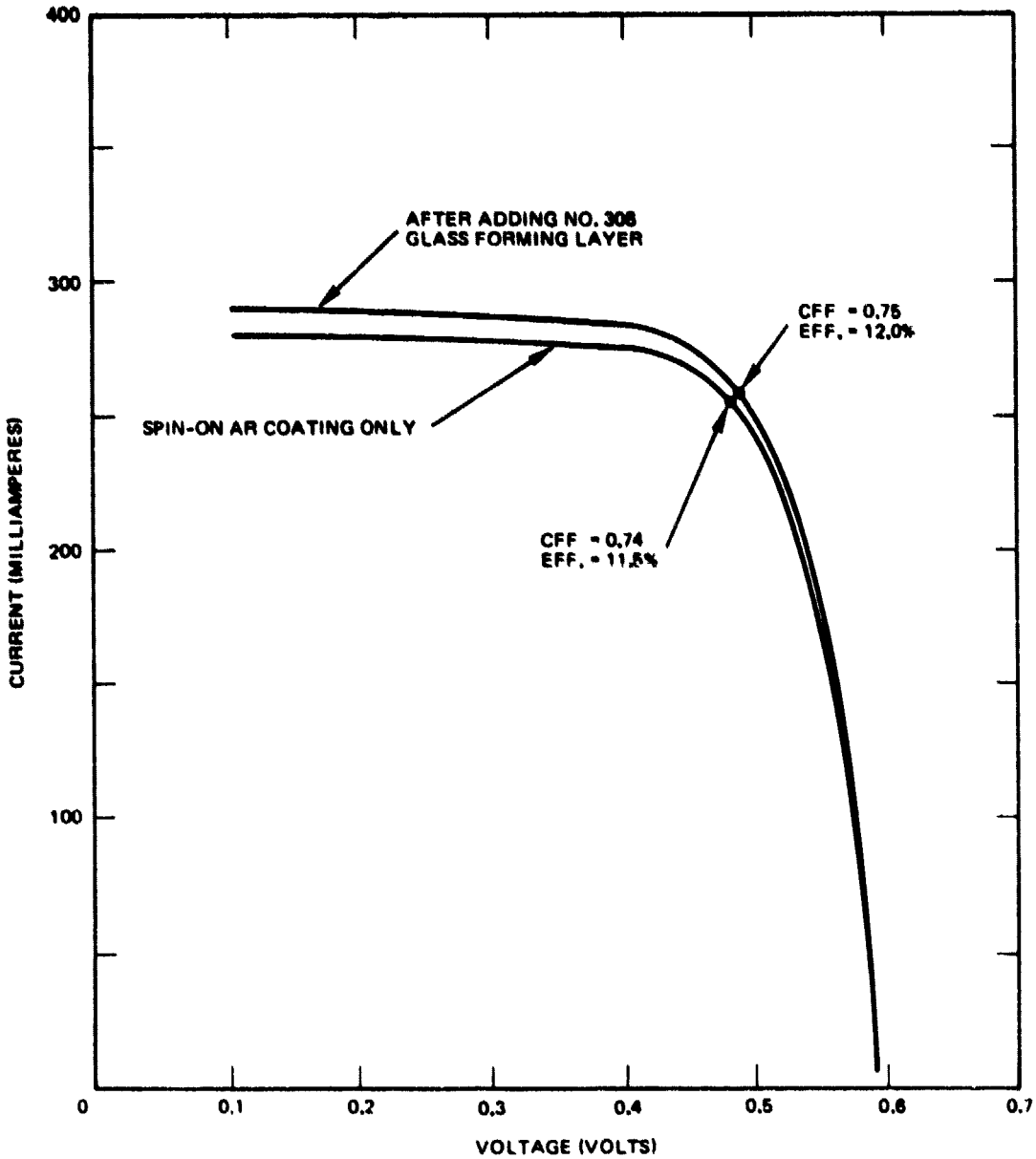
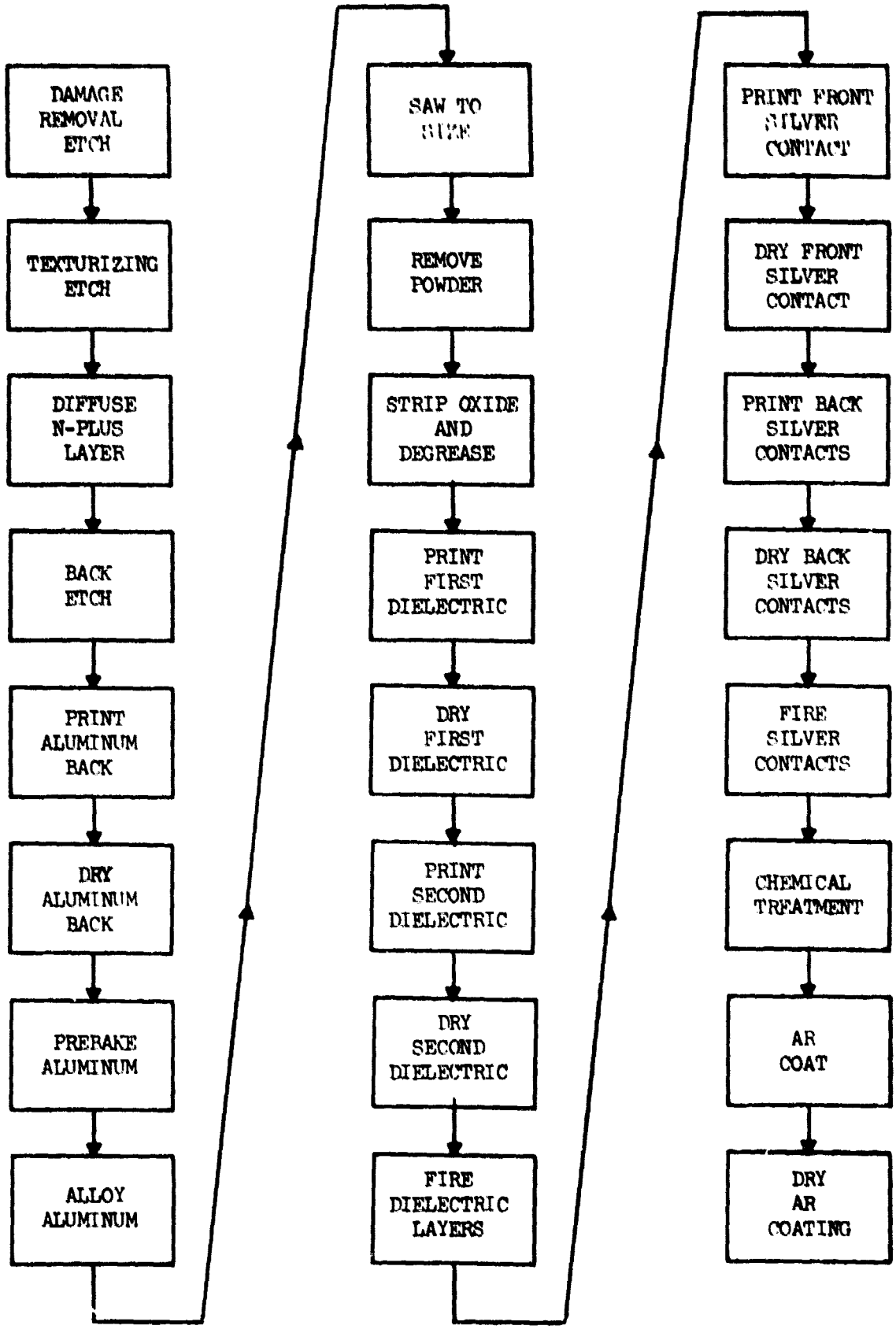


Figure 7. Spin-on AR Coated Cell Before and After Spinning on Additional No. 306 Glass Forming Solution
(Measured at AMO - 28°C - 135.3 mW/cm^2.)

Figure 8

FLOW DIAGRAM - SCREEN PRINTED WRAPAROUND CONTACT SOLAR CELLS



terrestrial solar cell production facility. These steps were essentially the same as those used in standard production, with only minor modifications. Lots were defined as being 500 wafer starts, and for convenience were grouped into sublots of 100 wafers.

The remainder of the processing was carried out in the Advanced Development Department, since most of these process steps were not common to standard production operations. The exception to this was the firing of the screen printed pastes, which required the use of the same conveyor belt furnace used by the terrestrial cell production facility.

Printing operations were carried out using a manual screen printer manufactured by Aremco (Accu-Coat, Model 3130). A photograph of this machine is shown in Figure 9. The printer was fitted with a rotatable X-Y table which was necessary because of the accurate registration required between the silicon cell, the dielectric layers, and the contact patterns. A teflon topped post was designed for printing the aluminum layers on the round 2 inch wafers and is shown in Figure 10. Provision was made for vacuum hold-down and pop-up positioning pins to accurately locate the wafers. A second printing post, shown in Figure 11, was designed for the wraparound printing operations. Again retracting pop-up pins were used to accurately locate the 20 x 40 mm cells. Excess paste from overprinting the edge of the cells during the wraparound printing operation was deposited on a paper tape under the cell. After each printing the tape was pulled along a few inches to provide a fresh, clean surface for the next cell to be printed. The tape used was standard one inch paper tape which was dispensed by a reel assembly. Both of the printing posts were bolted securely to the X-Y table when in use.

Prebaking the aluminum paste and drying the silver contact pastes was carried out in a standard mechanical convection oven Model OV-490A-2 manufactured by the Blue-M Electric Company. The ultrasonic cleaning for removing the aluminum powder residue after alloying and chemical treatment was done in an ultrasonic tank Model UT-1.5-6 powered by an ultrasonic generator Model DS-600, both manufactured by Delta Sonics Inc.

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Figure 9 Screen Printer Used for Cell Production
(Aremco Model 3130 Accu-Coat Printer)

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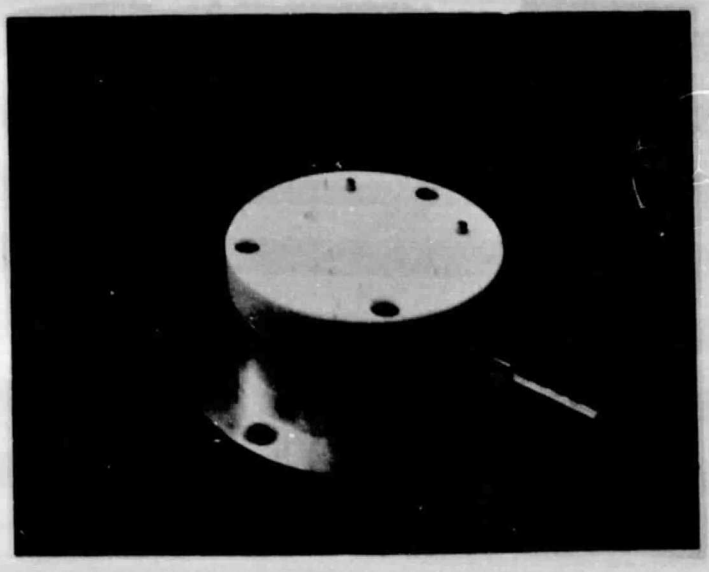

Figure 10 Printing Post Used for Applying Aluminum Layers

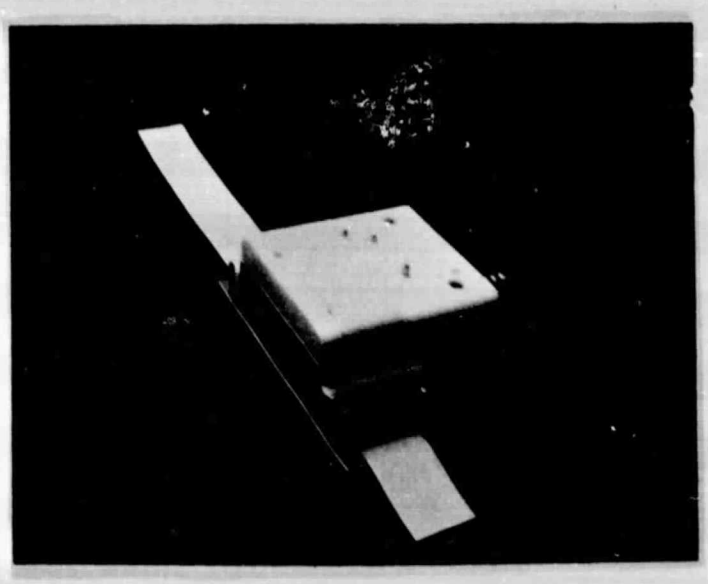

Figure 11 Printing Post Used for Applying Dielectric Layers, Wraparound Contact Grid Lines, and Contact Pads

No serious problems developed during the production phase of the program and yields were essentially the same as those found in the previous contract. Losses due to mechanical breakage were slightly higher due to the additional printing operations required, the fact that these cells were somewhat thinner, and since higher squeegee pressures were needed to print the wraparound configurations. Generally, however, yields remained satisfactorily high.

Since the firing steps required the use of the conveyor belt furnace, which was shared with the on-going production of commercial cells, these steps had to be scheduled. This resulted in some intermittent processing so that the lots often moved in "bubble" fashion through the processing sequence. Continuous flow was also difficult because only one screen printer was used, requiring several changes of screen patterns and setups each day.

While all of the wafers started into the laboratory model production line were processed through the aluminum alloying step, insufficient time and funding remained to complete 2500 cells. As a result only four lots, consisting of 500 "starts" each, were processed completely through the line. The remaining unfinished wafers were placed on "hold" until a decision could be made as to whether they could be completed or not. Permission to complete the remaining three lots was requested and granted along with the necessary additional funding to cover labor costs. These later lots were completed through electrical testing to bring the total of finished cells with satisfactory electrical characteristics delivered to 1852. The overall line yield for the laboratory model production line was thus 53%.

V. TESTING AND EVALUATION

A. Cell Performance

The electrical performance of the finished screen printed wraparound contact cells was evaluated using a Spectrolab Solar Simulator, Model X-25, Mark III at air mass zero and 28°C. The simulator was adjusted to an incident illumination level of 135.3 mW per square centimeter using a NASA calibrated Standard

cell. The cells under test were held at $28^{\circ}C \pm 1^{\circ}C$ by placing them in a test fixture having provision for vacuum hold-down and rear surface contacting.

The testing indicated that, while there were many cells in each lot having satisfactory I-V characteristics, approximately 50% of the completed cells gave some indication of shunting with less than optimum curve shape. The following data for the completed cells is divided into two groups, "A" and "B", where group A consists of the cells initially completed within the time limits of the program, and Group B consists of cells from the three lots finished at a later time. The data for Group A intentionally omitted cells exhibiting low open circuit voltages and excessive shunting, while the data for Group B included both "good" cells and those with relatively poor characteristics. The data from these tests are shown in Tables 1 (Group A) and 2 (Group B). Indicated are the measured values for I_{sc}, V_{oc}, and P_{max}, as well as the calculated values for CFF and efficiency. The calculated average values for the two groups are shown below, and should be considered keeping in mind that the Group A data was from "better" cells only, while the Group B data is from somewhat larger groups of randomly selected cells.

	Group A	Group B
Average Open Circuit Voltage	594 mV	589 mV
Average Short Circuit Current	278 mA	275 mA
Average Maximum Power (per sq. cm.)	15.5 mW	14.8 mW
Average Efficiency (calculated)	11.4%	10.9%
Average Curve Fill Factor	.750	.730

It was found during the early electrical tests that cells which initially exhibited satisfactory characteristics often during later tests exhibited shorts or severe shunting. This appears to be caused by switching transients in the test equipment, particularly when shifting from fixed point testing to the I-V curve tracing equipment. The dielectric isolation apparently can be damaged by such transients. During later tests it was found that this could be avoided by removing the cell from the test fixture whenever it was necessary to switch from one test set to another.

Table 1

Group A Cell Electrical Performance Characteristics
(Ten Better Cells from each Production Lot)

Lot No.	V_{oc} (mV)	I_{sc} (mA)	Max. Pwr. (mW/cm^2)	Calc. Eff.	Calc. CFF
1	594	291	16.4	12.1	.759
1	593	296	16.3	12.0	.743
1	590	286	15.6	11.6	.740
1	598	287	16.0	11.8	.746
1	596	280	15.8	11.6	.757
1	595	284	15.6	11.5	.739
1	591	276	15.3	11.3	.750
1	595	275	15.4	11.4	.753
1	598	289	16.3	12.0	.755
1	590	292	16.1	11.9	.748
2	594	283	15.6	11.5	.742
2	600	260	15.1	11.1	.774
2	600	275	15.6	11.5	.756
2	598	273	15.4	11.4	.755
2	594	275	15.3	11.3	.749
2	600	272	15.6	11.5	.765
2	598	276	15.6	11.5	.756
2	600	288	15.8	11.6	.731
2	601	285	16.3	12.0	.761
2	601	279	16.0	11.8	.763
3	588	275	15.3	11.3	.757
3	598	270	15.0	11.1	.743
3	599	275	15.6	11.5	.758
3	590	272	15.5	11.5	.773
3	598	276	15.5	11.5	.751
3	591	270	15.4	11.4	.772
3	584	280	15.3	11.3	.749
3	590	278	15.0	11.1	.732
3	595	275	15.3	11.3	.748
3	592	281	15.5	11.5	.745
4	596	277	15.5	11.5	.751
4	590	265	14.8	10.9	.757
4	590	275	15.0	11.0	.740
4	588	275	15.3	11.3	.757
4	588	275	15.1	11.1	.747
4	591	287	15.4	11.4	.726
4	590	282	15.4	11.4	.740
4	591	270	14.8	10.9	.742
4	589	280	15.4	11.4	.747
4	586	276	14.5	10.7	.717

Table 2

Group B Cell Electrical Performance Characteristics
(Twenty Random Cells from each Production Lot)

Lot No.	V_{oc} (millivolts)	I_{sc} (milliamps.)	P_{max} (milliwatts/cm^2.)	Calculated Efficiency	CFF
5	595	259	14.46	10.7	.750
5	577	284	14.07	10.4	.687
5	581	285	15.10	11.2	.729
5	588	289	15.26	11.3	.718
5	581	282	14.63	10.8	.714
5	594	277	15.31	11.3	.745
5	586	276	14.75	10.9	.729
5	582	272	14.52	10.7	.734
5	592	275	14.67	10.8	.721
5	592	279	14.82	11.0	.718
5	596	281	15.50	11.5	.740
5	587	274	14.16	10.5	.704
5	595	280	15.62	11.5	.750
5	582	277	14.16	10.5	.703
5	589	281	14.73	10.9	.712
5	591	282	14.34	10.6	.688
5	587	278	14.28	10.6	.700
5	585	273	14.82	11.0	.742
5	591	277	14.43	10.7	.705
5	593	279	15.37	11.4	.743
6	595	283	15.70	11.6	.746
6	597	274	15.22	11.2	.744
6	596	277	15.52	11.5	.752
6	597	279	15.64	11.6	.751
6	594	280	15.28	11.3	.735
6	583	264	13.70	10.1	.712
6	595	287	15.76	11.7	.738
6	591	288	15.52	11.5	.729
6	595	291	15.76	11.7	.728
6	590	287	15.28	11.3	.722
6	595	282	15.28	11.3	.728
6	596	280	15.40	11.4	.738
6	591	270	14.55	10.8	.729
6	595	274	15.04	11.1	.738
6	587	281	14.37	10.6	.697
6	589	277	14.85	11.0	.728
6	592	260	14.07	10.4	.731
6	591	269	14.37	10.6	.723
6	593	284	15.34	11.3	.729
6	593	283	15.52	11.5	.740

(continued)

Table 2
(continued)

Lot No.	V_{oc} (mV)	I_{sc} (mA)	Max. Power (mW/cm^2.)	Calc. Eff.	Calc. CFF
7	588	276	15.16	11.2	.747
7	591	265	14.61	10.8	.746
7	584	265	14.13	10.4	.730
7	561	267	13.74	10.2	.734
7	589	269	14.25	10.5	.719
7	585	263	14.25	10.5	.741
7	585	269	14.40	10.6	.732
7	585	266	14.36	10.6	.739
7	589	268	14.79	10.9	.750
7	588	276	14.7[illegible]	10.9	.726
7	590	264	14.1[illegible]	10.4	.726
7	592	270	15.04	11.1	.753
7	593	272	14.97	11.1	.743
7	591	270	14.73	10.9	.739
7	587	267	14.37	10.6	.733
7	594	268	14.70	10.9	.740
7	591	277	15.10	11.2	.738
7	589	267	14.67	10.8	.746
7	585	266	13.80	10.2	.708
7	582	257	13.64	10.1	.730

B. Contact Adherence

The contact pad adherence was measured for five randomly selected cells from each of the Group A production lots. In these tests a 26 gauge wire was soldered to each of the contact pads on the reverse side of the cells using liberal amounts of solder and flux. These soldered wires were then subjected to pull tests using a Chatillon DPP-1kg dial push-pull gauge. The results of these tests are shown in Table 3.

C. Coating Adherence

Five random cells were selected from each completed production lot. Each of these cells was then rubbed with a Pink Pearl eraser for 20 strokes with a force of 20 ounces. No damage or peeling of the AR coating was visible on any of the samples.

The effect of immersion in boiling water was also investigated for sample cells from each production lot. Five cells were selected from each production lot and tested electrically. The maximum power was calculated for each cell at AMO and 28°C with the incident radiation adjusted to 135.3 mW/cm^2. These cells were then suspended in boiling deionized water for a period of thirty minutes. The cells were then blotted dry and baked for a few seconds at 225°C. (Cells from Lots 5, 6, and 7 were baked for three minutes at 110°C.) All cells were then subjected to a tape pull test using Scotch brand 810 tape. No peeling of the front contacts or the dielectric layers was observed. In a few cases a slight peeling of the edges of the back contact pads was found. However, in each case where this occured, the bulk of the pad was unaffected. The cells were then tested again electrically and the maximum power again determined and compared with the original values. The percent power change was calculated in each case and this data is presented in Table 4. The I-V and maximum power curves for a typical cell taken before and after the boiling water immersion are shown in Figure 12.

Table 3

Contact Adherence Pull Tests

Lot No.	N-Contact	P-Contact
1	Pass	Pass
1	Pass	Pass
1	Cell Broke	Pass
1	Pass	Pass
1	Pass	Pass
2	Pass	Pass
2	Pass	Pass
2	Pass	Pass
2	Pass	Pass
2	Pass	Pass
3	Pass	Pass
3	Pass	Pass
3	Pass	Pass
3	Pass	Pass
3	Pass	Pass
4	Pass	Pass
4	Pass	Pass
4	Pass	Fail
4	Cell Broke	Pass
4	Pass	Pass
5	Pass	Pass
5	Pass	Pass
5	Pass	Pass
5	Pass	Pass
5	Pass	Pass
6	Pass	Fail
6	Pass	Pass
6	Pass	Pass
6	Pass	Pass
6	Pass	Pass
7	Pass	Pass
7	Pass	Pass
7	Pass	Pass
7	Pass	Pass
7	Cell Broke	Pass

Note: Pass indicates a pull strength greater than 500 grams.
Fail indicates a pull strength less than 500 grams.
All tests were made with the #26 wire pulled normal to the surface.

Table 4

Power Change After 30 Minute Boiling Water Immersion

Lot No.	Change in P_{max} (%)
1	- 1.2
1	- 3.1
1	- 0.8
1	0.0
1	- 2.4
2	N/A (cell broke)
2	- 3.5
2	N/A (cell broke)
2	- 1.2
2	- 1.6
3	N/A (cell broke)
3	- 1.5
3	- 0.8
3	0.0
3	0.0
4	- 3.8
4	N/A (cell broke)
4	- 0.8
4	- 2.6
4	- 6.4
5	+ 0.4
5	- 2.9
5	- 0.8
5	+ 0.8
5	- 2.9
6	0.0
6	- 1.2
6	- 0.4
6	- 0.5
6	+ 2.5
7	- 1.3
7	+ 0.8
7	0.0
7	- 0.4
7	- 0.8

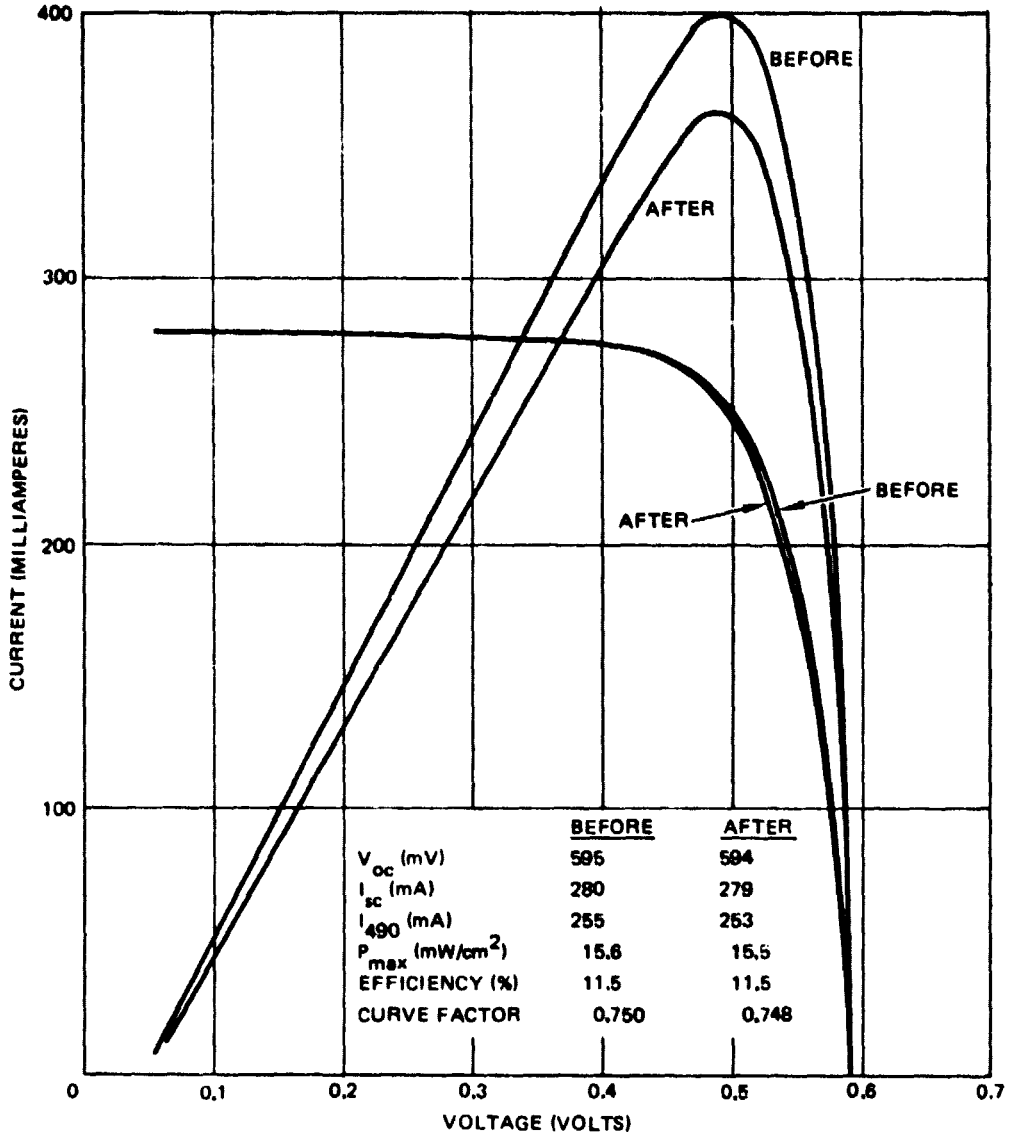

Figure 12. I-V and Maximum Power Curves for a Typical Cell Before and After Boiling Water Immersion (AMO/28°C/135.3 mW/cm^2)

D. Thermal Shock Tests

Five cells from each production lot were subjected to ten temperature cycles between -196°C and +100°C. The cells were suspended in boiling deionized water for two minutes, removed from the water and cooled for two minutes, and then dipped in liquid nitrogen for two minutes. Two minutes were allowed at room temperature again for the cells to warm up before immersing them again in the boiling water. After the thermal cycling was completed the cells were tested electrically.

Cells from Group A were tested only after the thermal shock cycles, while cells from Group B were tested both before and after the cycles. The data from these measurements is presented in Tables 5(a) and 5(b), and a typical before and after set of I-V characteristics are shown in Figure 13. In the cases where before and after measurements were made it was found that there usually was a slight loss in P_{max} and degradation of curve factor. It was also noted that in several cases there was a slight increase in open circuit voltage along with a slight loss in short circuit current and curve factor. Since these changes are nearly always in the same direction, the effect appears to be real, and is probably due to slight changes in the dielectric layer.

E. High Temperature - High Humidity Tests

A total of ten cells were randomly selected from the production runs from several different lots. These cells were stored at 40°C and 90% relative humidity for one week. The cells were then tested electrically and subjected to a tape pull test using Scotch brand 600 tape. There were no adhesion failures in the tape pull tests for the contact grid lines, the contact pads, or the dielectric layers. The average values for the measured electrical parameters of the ten cells are shown below:

Table 5(a)

Post Thermal Shock Electrical Performance
(Cells from Group A)

Lot No.	V_{oc} (mV)	I_{sc} (mA)	Max. Power (mW/cm^2.)	Calc. Eff.	Calc. CFF
1	589	289	15.29	11.3	.719
1	591	292	15.19	11.2	.704
1	588	283	15.24	11.3	.710
1	588	292	15.24	11.3	.733
1	591	278	15.19	11.2	.739
2	595	288	15.82	11.7	.739
2	598	275	15.35	11.3	.746
2	600	281	16.16	11.9	.767
2	600	276	15.78	11.7	.762
2	580	275	14.09	10.4	.707
2	594	265	14.52	10.7	.738
3	589	265	14.64	10.8	.750
3	586	269	14.55	10.8	.738
3	580	288	14.72	10.9	.705
3	580	284	14.96	11.1	.726
3	590	276	15.12	11.2	.743
3	596	275	15.31	11.3	.747
4	585	278	14.69	10.9	.722
4	585	275	14.75	10.9	.733
4	582	273	14.51	10.7	.731
4	590	270	15.04	11.1	.755
4	580	270	14.73	10.9	.752
4	590	276	15.34	11.3	.753

Table 5(b)

Electrical Performance Before and After Thermal Shock
(Cells from Group B)

Lot No.	V_{oc} (mV)	I_{sc} (mA)	Max. Power (mW/cm^2.)	Calc. Eff.	Calc. CFF	% Change (Max. Power)
5	591	282	14.34	10.6	.688	
5	592	280	13.98	10.3	.675	- 2.5
5	587	278	14.28	10.6	.700	
5	----------	----------	Shorted	----------	----------	
5	588	273	14.82	11.0	.739	
5	587	270	14.34	10.6	.724	- 3.2
5	591	277	14.43	10.7	.705	
5	593	275	14.19	10.5	.696	- 1.7
5	593	279	15.37	11.4	.742	
5	594	276	14.88	11.0	.725	- 3.2
6	589	277	14.85	11.0	.728	
6	589	277	14.61	10.8	.716	- 1.8
6	592	260	14.07	10.4	.731	
6	594	261	14.07	10.4	.726	0.0
6	591	269	14.37	10.6	.723	
6	595	269	14.38	10.6	.719	0.0
6	593	284	15.34	11.3	.729	
6	594	284	15.34	11.3	.727	0.0
6	593	283	15.52	11.5	.740	
6	596	284	15.31	11.3	.724	- 1.7
7	594	268	14.70	10.9	.740	
7	595	267	14.37	10.6	.724	- 2.8
7	591	277	15.10	11.2	.738	
7	593	278	14.97	11.1	.727	- 0.8
7	589	267	14.67	10.8	.746	
7	591	266	14.55	10.8	.740	- 0.8
7	585	266	13.80	10.2	.708	
7	585	266	13.40	9.9	.689	- 2.8
7	582	257	13.64	10.1	.730	
7	586	255	13.58	10.0	.727	- 0.4

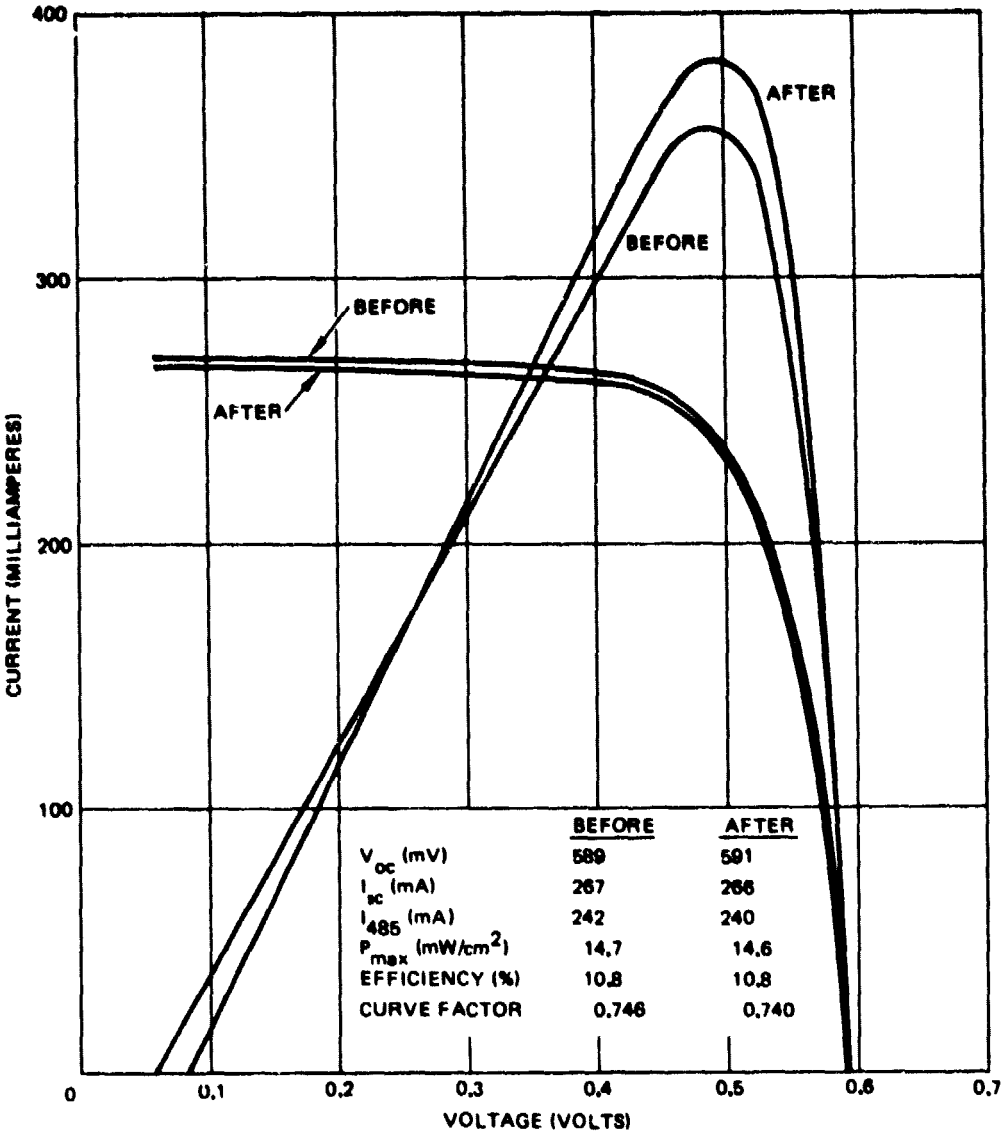

Figure 13. I-V and Maximum Power Curves for a Typical Cell Before and After Thermal Shock Cycles (AMO/28°C/135.3 mW/cm^2)

Average V_{oc}	591 mV
Average I_{sc}	277 mA
Average Max Power	15.17 mW/cm^2
Average Calculated Effic.	11.2%
Average Calculated CFF	.743

VI CONCLUSIONS

During the course of this program spin-on and spray-on diffusion sources were investigated and compared with the baseline phosphine gaseous diffusion process. This effort included both sequential and simultaneous processing to form the P+ back surface field structure. It was found that the screen printed silver contacts gave serious shunting effects with shallow junctions, regardless of the diffusion techniques used. With sheet resistance values of 20 ohms/square some shunting was found with the spin-on source diffusions, but results were generally satisfactory for phosphine gas diffusions.

Simultaneous formation of both the collector junction and the P+ back surface field structure was not successful. It was found that cross-doping effects could be avoided with proper care but shunting again was a problem with the higher sheet resistance junctions. BSF effects were not found to be as satisfactory as for sequentially processed structures. Therefore, due to time limitations, a sequential process was adopted, using phosphine gas diffusions and the screen printed aluminum paste BSF structure. It was found possible to use aluminum paste, made in-house, that did not include any glass frit, to make completely adequate BSF cells.

Satisfactory wraparound dielectric layers and contacts were made by an overprinting of the cell edge. Tests indicated that two dielectric layers are required to give proper insulation. Electrical testing, along with adherence tests, indicate that the wraparound structures would not significantly degrade after boiling water immersions, thermal shock tests, and humidity tests.

It would therefore appear that wraparound contact screen printed cells having useful electrical characteristics can be made by a processing sequence that is completely compatible with the processes used in Contract NAS3-18566 and the laboratory model production line developed for that program.

VII RECOMMENDATIONS

A. Printed Contacts on Diffusion Junctions

A part of the initial effort of this program was devoted to establishing the limits of the junction depth for compatability with the screen printed silver contact pastes that were available for the grid structures. Because of time and funding limitations no effort was expended to modify any of the commercial pastes used. Instead, it was merely established what was the highest sheet resistance value that gave adequate and reproducible results without undesirable shunting effects, and that was the diffusion program adopted for the production processing.

It would be advantageous to use somewhat higher sheet resistances (shallower junctions) to improve the efficiency of the finished cells. It would also be desirable to reduce the width of the printed contact fingers in the contact grid, as this too would tend towards increased efficiencies. A study of various contact pastes seems worthwhile for this particular application in order to take proper advantage of the progress made to date in developing screen printed contact space type solar cells along with the potential cost reductions they offer.

B. Back Surface Field Structures and Processes

This program developed a viable process for producing P+ back surface field structures using screen printed aluminum paste. The resulting back surface of the cell was essentially a bright aluminum layer covering the entire back surface of the cell. The open circuit voltage enhancement obtained with this

process appears to certainly equal that obtained with evaporated aluminum layers, and offers a nonvacuum process that offers marked cost reductions.

While the process gave quite reproducible results, now and then cells are found with open circuit voltages in the neighborhood of 610 mV for AMO at 28°C and an incident energy level of 135.3 mW/cm^2. This was not the average case, however, which gave values usually in the 595-600 mV range. It would therefore appear that additional effort should be capable of optimizing this process to produce cells with an average open circuit voltage of at least 605 mV, and therefore an improved maximum power output.

C. Wraparound Printing Techniques

The success in obtaining satisfactory screen printed wraparound dielectric and contact layers using a technique of overprinting the edge of the cells, brought about a decision not to investigate other possible techniques. This was partially because of time limitations. It is possible that other methods might also be useful, and also that the present process might be optimized still further by additional investigations.

D. AR Coatings

The cells produced under this program were AR coated by spinning on a commercial material, and then baking the cells. The enhancement of short circuit current was only about 5% for the average cell. Spinning is not an optimum technique for rectangular cells, as there is a tendency for the material to build up at the corners of the cell. Further development might be useful in the area of AR coating techniques to develop more uniform coatings and higher current enhancements with nonvacuum processes.