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Evaluation of Thick-Film Inks for Solar Cell Grid Metallization

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EVALUATION OF THICK-FILM INKS FOR SOLAR CELL GRID METALLIZATION

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PREFACE

This report documents work performed by the Solar Energy Research Institute, for the U.S. Department of Energy under Task No. 1090.00. It describes efforts of the Thick-Film Technology Group to determine the characteristics of commercially available metallization pastes for contacting solar cells. We would like to thank S. Wagner, T. Coyle, and J. Barrett for many discussions regarding this study.

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Kay Firor

Approved for

SOLAR ENERGY RESEARCH INSTITUTE

11/11/81

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SUMMARY

OBJECTIVE

To present research findings on the performance characteristics of commercially available metallization pastes. Ink manufacturers were asked to recommend inks designed for front (grid) application to solar cells. These inks were then used to determine the typical performance which might be obtained from solar cells processed with the inks.

DISCUSSION

The recommended inks were processed on single-crystal silicon cells according to manufacturer instructions. The processing often was modified to improve the performance of the particular wafers analyzed. Performance characteristics examined included current-voltage (I-V) curves, contact and series resistance values, adhesion properties, and ability to withstand a brief environmental exposure test. Other ink properties, such as afterprint flow and ease of cleaning, also were noted.

Several ink manufacturers recommended base-metal inks in addition to the commonly used silver inks. These inks also were examined for potential applications and were compared with silver inks in performance.

CONCLUSIONS

Twelve silver inks were examined, with most yielding good results. Many inks needed optimized processing. All inks required etching in hydrofluoric acid (HF) to achieve maximum electrical performance. [Infrared (IR) firing was not done.] Both the glass content and amount of dopant materials in the inks were found to be important parameters. None of the base-metal inks gave satisfactory results. The silver-bearing inks, however, are cost-effective and perform acceptably when applied to cells designed for terrestrial use.

TABLE OF CONTENTS

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LIST OF FIGURES

LIST OF TABLES

SECTION 1.0

INTRODUCTION

Thick-film technology has many applications in the photovoltaics field [1]. Specifically, this technology effectively provides electrical contact on solar cells intended for terrestrial applications. Such applications require contacts to be durable yet inexpensive. The thick-film, or screen-printed, technique of applying and sintering a metal-bearing paste provides this electrical contact at a cost of 3¢-5¢/W [2].

A variety of ink manufacturers sell thick-film compositions for general metallization, and many have modified their inks especially for contacting solar cells. We first surveyed the manufacturers to determine what inks were commercially available for applying to the front (grid) surface of single-crystal silicon cells. We then obtained and processed these inks to determine their performance characteristics when fired onto solar cells. For comparison, a conventionally processed (evaporated) Ti-Pd-Ag contacting system also was tested, both before and after an antireflection (AR) coating was applied to the texture-etched crystals.

We expected that the following ink properties would be important in providing good contact on solar cells:

- A fast firing cycle. Conventional thick-film inks are fired at 900°C for 20-60 minutes. A firing time of less than 10 minutes is preferred, however, to avoid the diffusion and degradation of the p-n junction within the cell caused by longer firing.
- A low firing temperature. This also helps minimize the junction degradation.
- A low glass content. The glass particles (frit) contained in an ink facilitate adhesion to the substrate by wetting the surface during the sintering cycle. Upon cooling, the glass hardens to a matrix holding the silver particles to the substrate. This glass, however, creates a contact resistance between the silver conductor and silicon surface. Hence, the glass content must be regulated carefully to attain proper adhesion without excessive contact resistance.
- No specialized steps required to activate the contacts. Etching the finished cell with hydrofluoric acid, for example, reduces the series resistance, which often limits the cell's electrical performance with "as-fired" contacts (i.e., previous to further processing). Several ink manufacturers are developing inks that do not require HF etching.

Ink manufacturers were sent a letter describing the purpose of our study and the characteristics of the wafers (see Appendix A). Several responding manufacturers suggested that we also try selected nonnoble-metal-based inks. The project then grew to include 12 silver-based inks and eight nonnoble-metal inks; of the silver-based inks, 10 had been formulated specifically for silicon cell metallization. Appendix B lists the manufacturers whose inks were analyzed.

The recommendations for processing varied widely among manufacturers; some gave explicit instructions for each step, others offered only broad ranges of processing parameters. We followed closely manufacturer instructions, and if poor performance resulted, we modified the processing steps to improve the performance. We made no attempt to completely optimize the processing parameters.

The electrical output for each cell was recorded in the form of a current-voltage (I-V) curve immediately after firing and again following any further processing steps. Most manufacturers recommended an HF etch, typically prior to a solder dipping step to coat the metallization. One manufacturer, however, recommended an etch following soldering. In addition to the electrical performance measurements, the cells were subjected to adhesion and environmental tests.

Our aim was not to find an optimum process for each ink and then judge the best product; rather, it was to process selected inks according to recommended parameters and then observe the resulting performance of treated solar cells and their sensitivity to processing modifications.

SECTION 2.0

EXPERIMENTAL METHOD

The wafers for this study were processed simultaneously under identical conditions, and they lacked only a front contact. The 1-3 Ω cm, boron-doped, Czochralski-grown, single-crystal silicon wafers were texture-etched in NaOH, and phosphorous, by means of phosphine gas, was diffused in to form a junction at a depth of 0.3 μm. The cells also were etched in a nitric and hydrofluoric acid mixture, and a 2% aluminum, silver-based ink was screen-printed and dried on their backs to form the electrical contact. The ink processing sequence included five major steps: printing, drying, firing, HF etching, and solder dipping.

2.1 PRINTING

A Presco (Model 435) automatic screen printer was used to print the thick-film inks. A grid pattern with lines 250 μm (10 mil) wide, a 2.5-mm square for adhesion testing, and two short 125-μm-wide lines were printed on each cell (Fig. 2-1). The adjustable parameters in the printing step included the screen mesh size, the snapback (distance of the screen above the substrate), and the squeegee pressure. After printing, data were obtained by observing how well the 125-μm line printed and how easily the ink cleaned off the screen after spraying it with trichloroethane solvent.

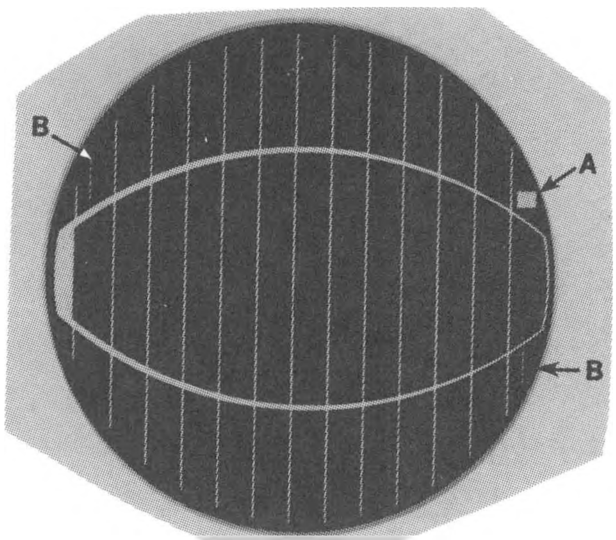


Figure 2-1. Top View of Solar Cell with Screen-Printed Front Contact Showing 250-μm Grid Pattern with (A) Adhesion Test Pad, and (B) 125-μm Line

2.2 DRYING

After printing, the ink was allowed several minutes to settle. Visual inspection after this settling period determined how well the ink flow had smoothed out the screen impressions left on the printed surface of the film. The ink was then air-dried under an infrared (IR) lamp. Adjustable parameters during the drying stage included the time allowed for settling and the exposure time and temperature under the IR lamp.

2.3 FIRING

The cells were placed in a four-temperature-zone, Watkins-Johnson belt furnace for firing immediately after the ink dried. Figure 2-2 shows a typical furnace profile, or plot, of temperature versus time. Firing took place in air, as recommended by all ink manufacturers. On several occasions, however, a nitrogen firing atmosphere was used to test for improved cell performance. Air flow rates, zone temperatures, and firing time were the adjustable parameters in this step. Immediately after the firing process, the first I-V curve was measured for each cell.

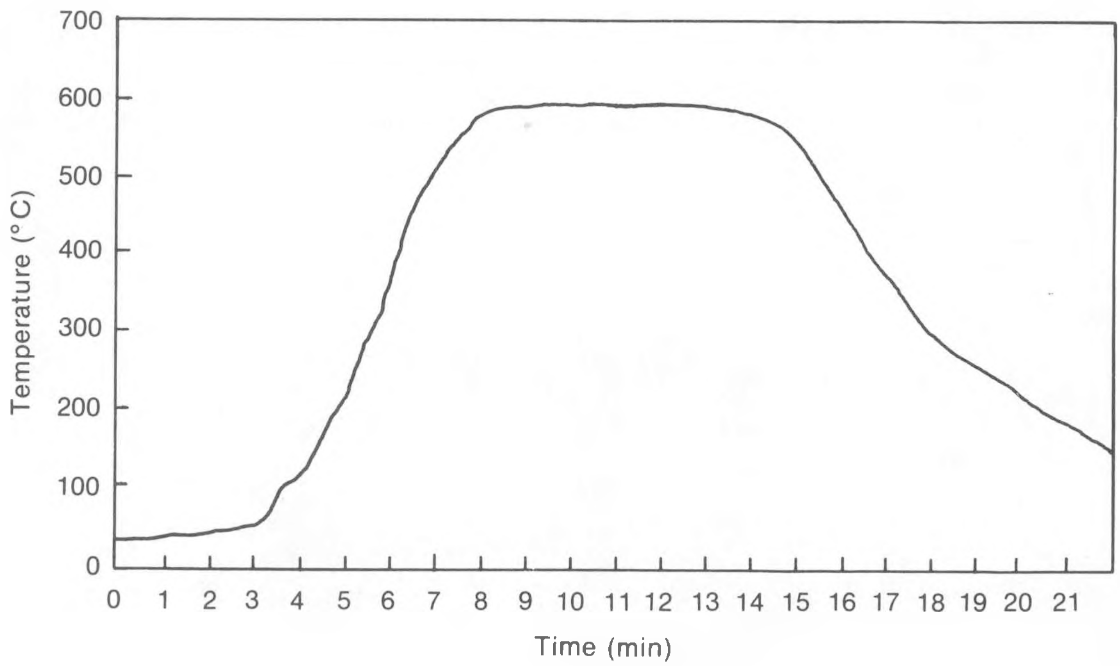


Figure 2-2. Typical Firing Profile

2.4 HF ETCH

The next processing step for most Ag-based inks was an HF etch. The cells were dipped in an aqueous solution of either 2% or 5% (by weight) HF for 5 to 12 seconds. The cells then were rinsed in deionized water for 5 minutes, dried with air, and tested with another I-V curve. HF concentration and the etching time were the parameters adjusted during this step.

2.5 SOLDERING

Each cell was solder-dipped to coat and somewhat protect the cell metallization from air moisture, which causes degradation of film adhesion. The cell metallization was fluxed with either Kester 1544 or Kester 1589 flux. The entire cell then was dipped into a bath of tin-lead solder (with 2% silver), typically heated to 210°C. A visual inspection then determined how well the solder coated the grid. An I-V curve was taken after soldering to determine the effects of this step on cell performance. Dip time, solder bath temperature, and the type of soldering flux were the adjustable parameters.

2.6 RESISTANCE

Many of the inks were tested for cell series and contact resistance. The series resistance was measured by comparing a cell's I-V curves under varying light intensities using a technique described by Wolf and Rauschenbach [3].

The contact resistance (between the ink and the silicon surface) was determined by three methods. The first uses four grid lines and a four-line to three-line measurement technique. The second uses four concentric circles and the same technique. The third involves a multitude of grid lines and a straight-line approximation. The three techniques are described in Appendix C.

2.7 ADHESION

Film adhesion during various processing steps was measured using a Sebastian MARK 1 adhesion tester. The studs pulled by the tester were either soldered or epoxied to the metallization. The tester gave measurements in psi units.

2.8 ENVIRONMENTAL TEST

A limited environmental test was performed on 24 cells. This procedure is described in the test method section of Ref. 4. It consisted of holding cells for one week in a temperature- and humidity-controlled chamber. The temperature varied between 23°C and 45°C each day at a relative humidity maintained at 90% to 95%; the first two days, however, involved preconditioning at a lower humidity. Figure 2-3 shows the test conditions. Current-voltage curves were measured for each cell before the week-long test and immediately after removal from the environmental chamber.

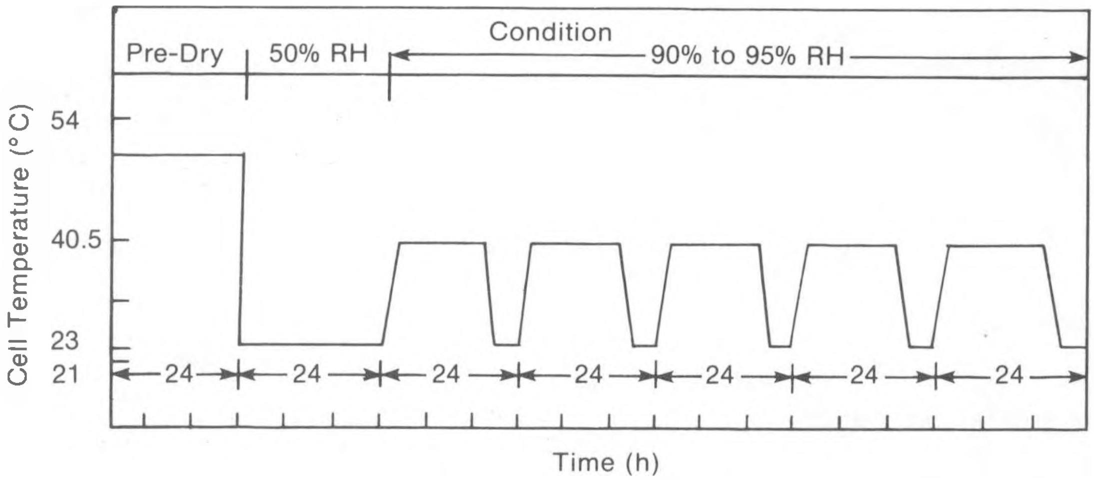


Figure 2-3. Environmental Test Temperature and Humidity Cycle Conditions

SECTION 3.0

RESULTS

The conclusions of this study are based primarily on the I-V curves of the test cells. The I-V curves provide a good means of comparing different inks, original and revised processing parameters, the effect of ink glass content, and the behavior of a cell before and after environmental stress. The I-V curves were obtained using a two-point probe system, which introduced a uniform current loss when compared to four-point (separate current and voltage leads) or Kelvin probe measurements. The two-point probe technique greatly decreased the apparent cell output, and hence the values for cell efficiencies and fill factors are valid only in comparison with each other; they are not absolute. Later analyses with Kelvin probes determined accurate series resistance values, and they indicated that a 20% increase in final efficiency values was typical. Discussion of the results of the experimental methods is divided into two sections: one for the silver inks and one for the base-metal inks.

3.1 SILVER-BASED INKS

3.1.1 Printing/Firing

Researchers have previously shown the effects of the printing parameters on the films obtained [5]. In this study, these parameters were adjusted to yield good print characteristics, and few modifications were necessary for all the inks studied. The results of visual inspections of the printing of the inks are presented in Table 3-1. Initially we fired the cells according to ink manufacturer recommendations. If poor results were obtained, we modified the firing schedule. We found that the firing profile was the most critical parameter during the processing of the cells.

3.1.2 HF Etch

HF etching is the least understood step in cell processing. The power output of a solar cell with screen-printed metallization is not very high after firing. Figure 3-1 shows the improvement in the I-V curve and cell output after the HF etching of an as-fired cell. Without exception, the output of a cell with screen-printed and conventionally fired silver contacts always improved after HF etching. The ranges of cell efficiencies obtained with each ink before and after HF etching are shown in Fig. 3-2.

Experiments show that increased cell output following etching is associated with a reduction in contact resistance between the silver grid and the silicon surface. Hydrofluoric acid attacks the glass in the silver film and the oxide layer on the silicon. Work presently underway to determine the conduction mechanism within this thick-film silver and silicon system will explain the change in conductivity caused by the removal of glass in the film.

Table 3-1. Results of Visual Inspection Tests for Each Ink

Ink ID No.	Test			
	5-mil Line Print	Ease of Cleaning	Ink Flow	Solder Wetting
2	Good	Poor	Good	Fair
3	Good	Good	Excellent	Fair
4	Fair	Good	Poor	Fair
5	Good	Fair	Good	Good
6	Good	Fair	Fair	Good
7	Good	Fair	Good	Excellent
8	Good	Fair	Good	Fair
9	Good	Fair	Poor	Good
10	Fair	Excellent	Excellent	Good
11	Good	Good	Excellent	Poor
12	Good	Good	Excellent	Did not wet
13	Good	Fair	Good	Good

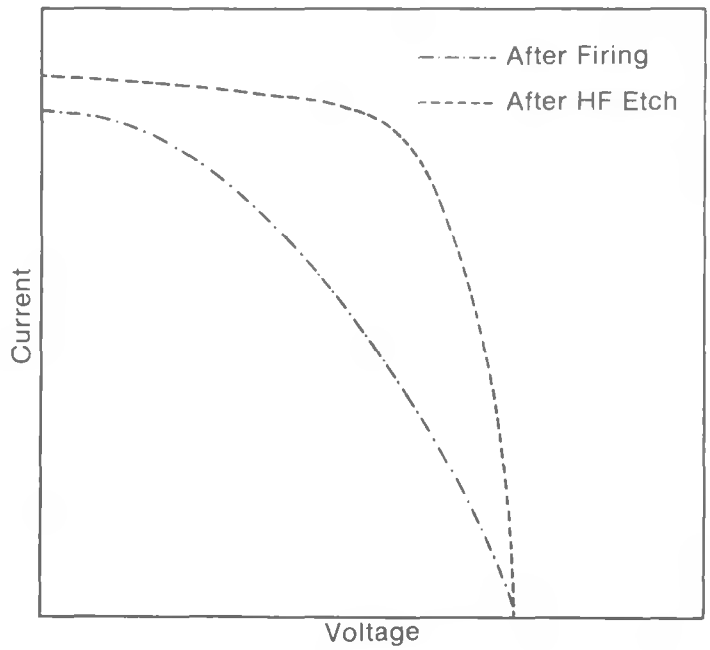


Figure 3-1. I-V Curves for a Typical Cell Showing the Difference in Cell Output After Firing and HF Etch

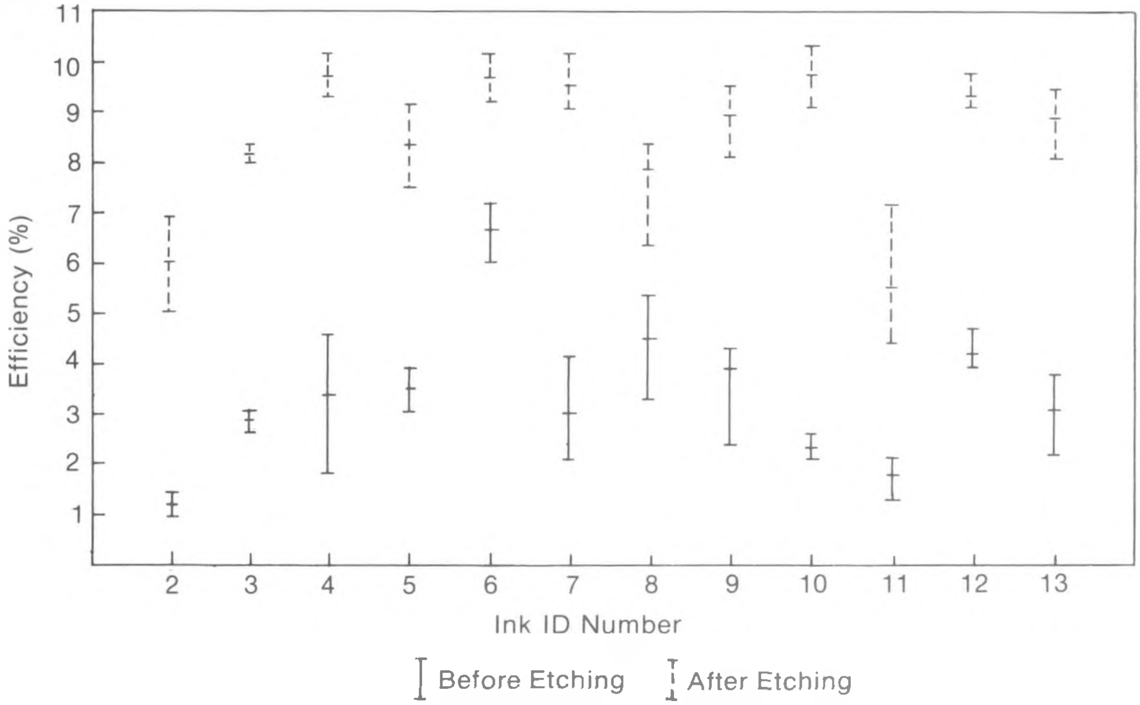


Figure 3-2. Ranges of Cell Efficiencies Before and After HF Etching

Because the glass in the ink allows the film to adhere to the silicon, the HF etch can destroy this adhesion. The duration of the HF etch is critical; for each ink an optimum etch time must be found--long enough to improve the cell output without destroying the grid's adhesion. An 8-second etch (± 2 s) in 5% HF met this requirement for most inks. Figure 3-3 shows the results of etching a cell too long: the grid has peeled off the silicon. The ability of the metallization to withstand environmental stress following HF etching is also a critical factor.

Future cell processing methods may eliminate the need for HF etching. A number of research groups, including several thick-film manufacturers and solar cell manufacturers [6], are exploring ways to obtain adhesion without forming an insulating glass layer. The most successful method involves firing the films in an infrared (IR) furnace. The parameters used in this technique are critical; the technique appears to be most effective with a very short firing time (under 90 s) and temperatures above 700°C. Such a firing cycle presumably prevents glass in the ink from covering the silicon surface to the extent found in a normal firing cycle, thereby reducing the contact resistance. An IR furnace was not available for this study; details about these proposed mechanisms will be provided in a future report.

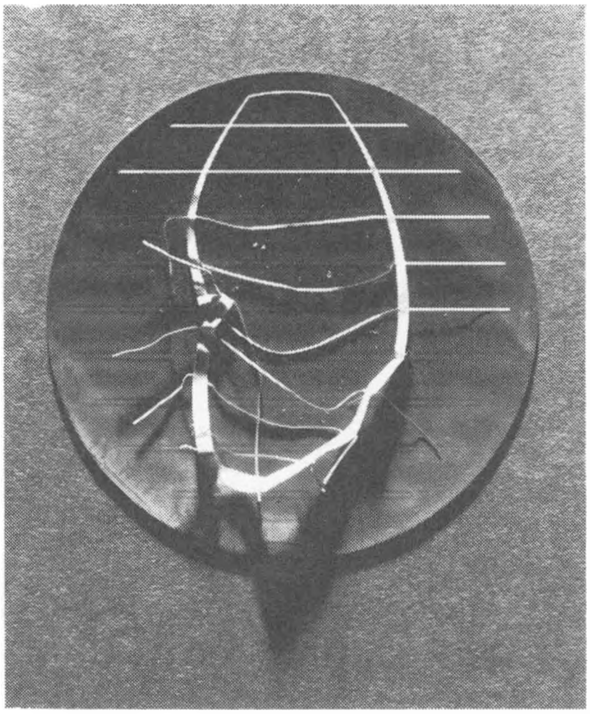


Figure 3-3. Loss of Adhesion Caused by Prolonged HF Etching

3.1.3 Soldering

Conclusions from the visual inspections on the ability of the solder to wet the metal are summarized in Table 3-1. Soldering also improved the cell power output; Fig. 3-4 illustrates the improvement in the I-V curve following solder dipping after an HF etch. Dipping increases the grid conductivity (i.e., the solder conductivity is greater than that of the film) and possibly extends the glass etching process. A solder dip period of 3 s was adequate for almost all inks, while dipping beyond 5 s created adhesion problems due to silver leaching.

One ink manufacturer recommended soldering before HF etching. We discovered that this procedure also worked quite well with several other manufacturers' inks. Because the solder protects the fired silver film, an HF etching after soldering must last much longer than an etching before soldering. To improve the output of soldered cells at least 45-60 seconds in the 5% HF solution was required.

3.1.4 Process Revisions

Each ink manufacturer offered suggestions for processing the inks. In some cases recommended procedures resulted in good solar cells. In other cases, totally unacceptable results were obtained, requiring revisions in the processing until fairly good cells were produced. Figure 3-5 shows the ranges of efficiencies obtained with each ink following recommended and revised processing. Revisions usually involved adjustments in the firing schedule.

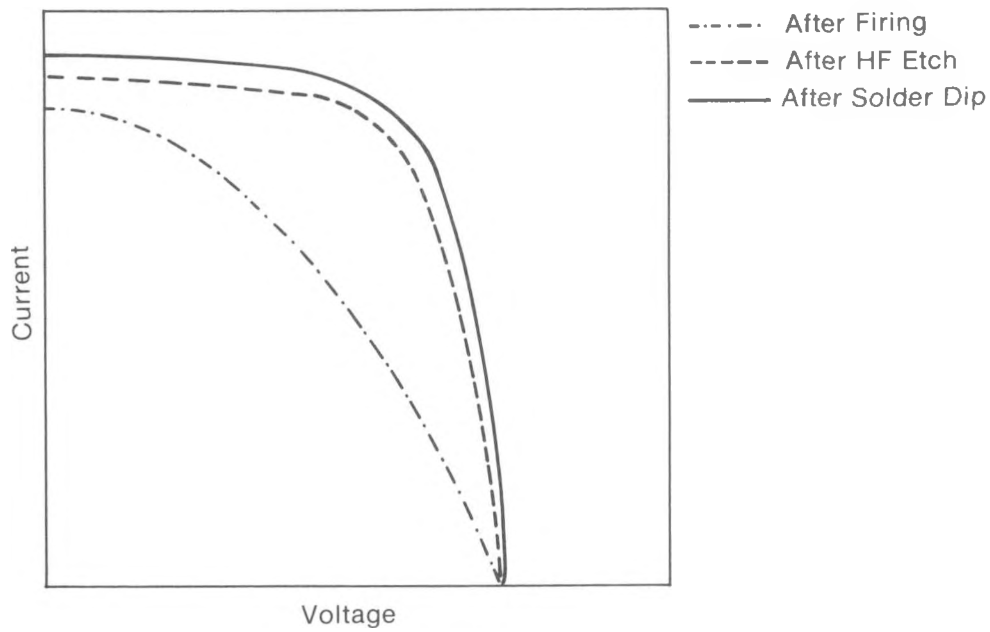


Figure 3-4. I-V Curves from a Typical Cell Showing the Difference in Cell Output After Firing, HF Etching, and Solder Dipping

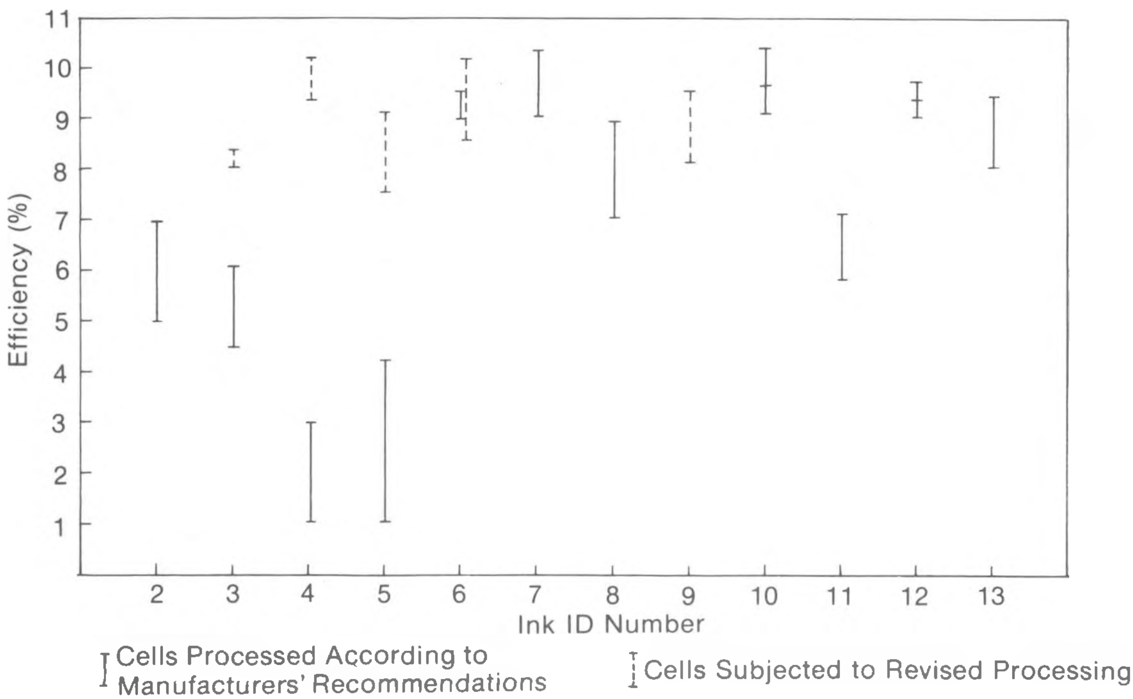


Figure 3-5. Ranges of Efficiencies from Cells Processed According to Ink Manufacturers' Recommendations and from Cells Subjected to Revised Processing

If a manufacturer's advice for ink processing fails to result in a good cell, one should not conclude that the manufacturer incorrectly determined how the ink should be processed for use on a solar cell. Inks behave differently on different cells. Processing usually will require some adjustments for cells that differ from those used to develop the processing recommendations. Parameters such as junction depth, texture etching, and other wafer fabrication steps will directly affect the optimal metallization process.

We made several types of revisions in the processing of different inks. The manufacturer of ink no. 3 advised us that an HF etch was not required. Although we tried many firing variations, obtaining a good cell using this ink necessitated an HF etch. Several cells used in this study were sent to the ink manufacturer, who also was unable to achieve good results without an HF etch. Possibly the junction depth was too shallow, or the textured surface was not compatible with the ink.

The recommended firing temperatures for inks no. 4 and no. 5 were not sufficiently high for the back contact of the cells; therefore, we raised the firing temperature. In another approach, we fired the back contact at about 600°C before printing the grid contact onto the cell. This procedure allowed us to fire the inks at the recommended temperature, but it also meant the cells were fired twice, resulting in more junction degradation. The manufacturer of ink no. 9 advised a fast-firing cycle in an IR furnace. No IR furnace was available, so we fired the ink as quickly as possible in the belt furnace.

The manufacturer of ink no. 6 advised solder dipping before etching. We found this advice valid, as HF etching of unsoldered cells caused the grids to lose adhesion before the cell output was improved. This ink was the only one surveyed with phosphate-based glass, which is more soluble in HF than borosilicate glasses. If the cells were solder-dipped before etching, the grid withstood a much longer etch. A 60-second etch was sufficient to improve the cell output without causing adhesion failure.

One interesting comparison involved inks no. 10, no. 11, and no. 12. These inks came from the same manufacturer. Ink no. 10 was the specially formulated solar cell ink, ink no. 11 lacked n-type dopant, and ink no. 12 had a lower glass content. Inks 10 and 12 produced higher-efficiency cells than undoped ink 11 when all were processed according to the manufacturer's recommendations. The low-glass ink could withstand solder dipping or HF etching, but not both--the grid on an etched cell came off immediately when it was soldered. Because of the success with soldering ink no. 6, we tried the same technique on no. 12. This ink, however, could withstand only ~20 seconds in HF before losing adhesion, a time insufficient for producing the desired improvement in power output.

3.1.5 Resistance Measurements

Series and contact resistance measurements were performed before and after the HF etch for several of the silver inks. Values varied, particularly before etching. All silver inks tested, however, were in the same range both before and after etching, except the phosphate-based ink, which showed lower resistance values before etching than the other inks. Typical values for the series resistance using Wolf and Rauschenbach's method ranged from 300 mΩ to 600 mΩ for as-fired cells. The dramatic improvement in the output of the cells following etching was reflected in (and chiefly due to) the decrease of the series resistance to 50-75 mΩ. These values were confirmed by another method using the dark current characteristics. The contact resistivity values determined were about 500 mΩ cm^2 before etch and 40 mΩ cm^2 after the etch. These values are consistent with those presented for thick-film metallization elsewhere [7]. Multiplying the contact resistivity by the grid area yields the contact resistance component of the series resistance. The voltage drop attributable to this contact resistance at the maximum power current is less than 2% of the typical V_{oc} (open-circuit voltage).

3.1.6 Adhesion Testing

Our method of measuring adhesion strength yielded inconsistent values. The mechanism of failure--the stud pulling out the pad and silicon or the pad separating from the silicon surface--gave more informative data. Figure 3-6 shows failures from both mechanisms. In general, adhesion was acceptable (silicon fracture) with the as-fired cells. Following either etching or soldering, most inks still demonstrated acceptable adhesion, but after both etching and soldering, many cells showed poor adhesion. Loss of adhesion accelerated further for the cells subjected to the environmental test.

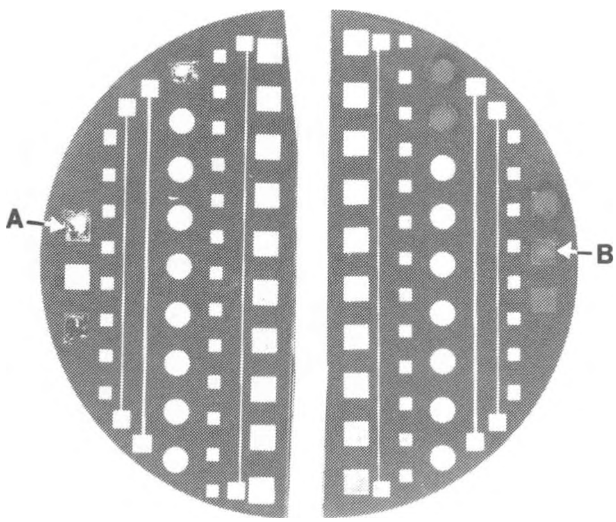


Figure 3-6. Failure Modes Resulting from Adhesion Testing
(A) Acceptable adhesion: Si breaks away
(B) Unacceptable adhesion: pad peels off of Si

3.1.7 Environmental Testing

The 24 cells subjected to the environmental stress test showed two markedly different results. Tested cells were in several stages of processing; some had been etched, some had been etched and soldered, and some were still in the as-fired state. The electrical output for etched-only cells worsened considerably after the week of heat and humidity. Figure 3-7 shows a typical set of I-V curves before and after the stress test of etched-only cells. Surprisingly, the output of cells lacking an HF etch increased. A plausible explanation for this phenomenon is that water attacks glass: in the humid environment of the test chamber, the water vapor in the heated air etched the glass in the silver film in much the same way as HF does. This same explanation predicts the decrease in the performance of the etched cells. We found that over-etching decreases the electrical performance, probably by destroying the film's adhesion. This finding was supported by contact resistance measurements that indicated an increase after a certain optimal etch time. The environmental test led to excessive etching of the previously etched cells.

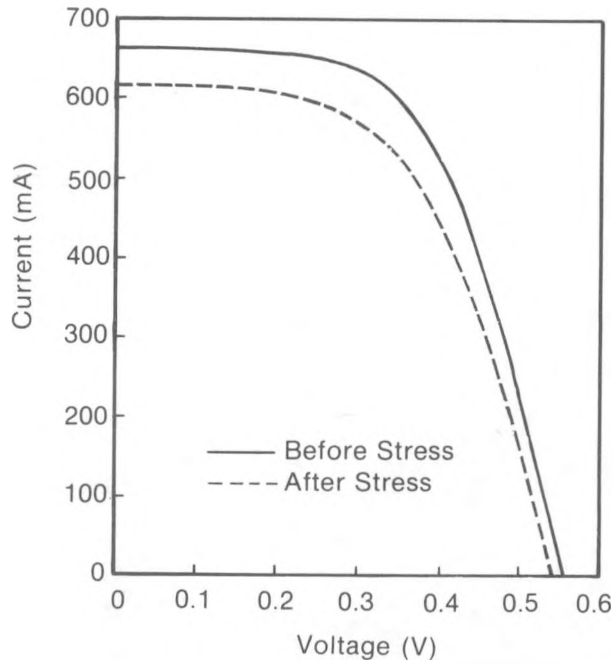


Figure 3-7. I-V Curves of Cell Before and After Environmental Stress

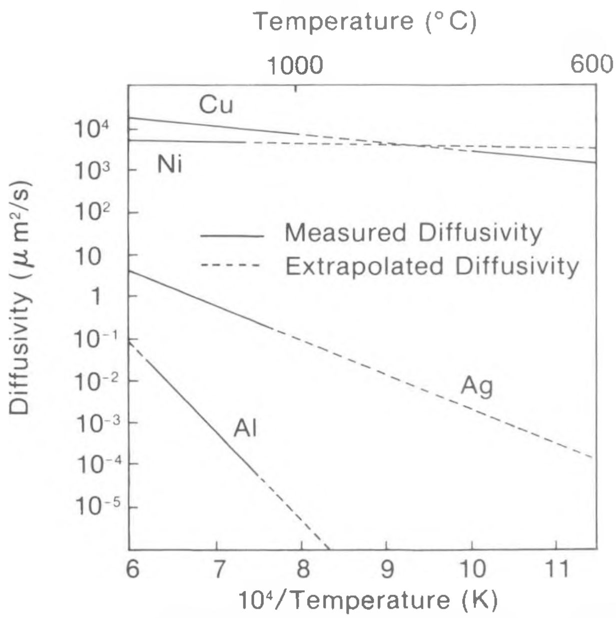
3.1.8 Data Collection

At the onset of this study, data sheets were designed to record the data collected. These sheets are reproduced in abbreviated format, one for each ink tested, in Appendix D. The sheets indicate data taken during the processing that gave the best results for each ink.

3.2 BASE-METAL INKS

Eight nonnoble-metal inks were tested during this study: two copper-based, four nickel-based, one aluminum-based, and one chromium-based. All were designed for firing in air.

Many problems arose when the base-metal inks were used for the top grid contact. The primary problem was the high diffusivity of these metals in silicon. Since the n-layer of the solar cell is thin (~0.3 µm in the cells tested), a metal that readily diffuses into silicon will soon intrude into the p-n junction, raise the generation-recombination rate in the junction and adjacent bulk, and shunt the junction. The diffusivities of various base metals in silicon are compared to silver in Fig. 3-8. With the exception of the chromium-based ink, all the base metal inks tended to diffuse through the n-layer and short the junction.



SOURCE: Grove [8] and Research Triangle Institute [9]

Figure 3-8. Diffusivities of Copper, Nickel, Silver, and Aluminum in Silicon as Measured and Extrapolated to a Typical Firing Temperature (600°C)

Another severe problem with the base-metal inks was a high series resistance. To replace a silver-based ink, a nonnoble-metal ink must perform nearly as well as the silver in providing electrical contact to a solar cell. I-V curves for cells with base-metal grids showed the electrical outputs to be limited by a high series resistance. Firing the inks in a nitrogen atmosphere produced no significant change. Plating over the grid with copper and then coating with solder reduced series resistance, but not sufficiently to get a good solar cell. The lowest series resistance obtained was 200 mΩ, but typical values were closer to 1 Ω. Examination of the I-V curves also indicated a low shunt resistance. The best cell output obtained with base-metal ink is shown in Fig. 3-9. This I-V curve is from a cell printed with a nickel-based ink, fired at 600°C, copper-plated on the grid, and then solder-coated over the Cu plating.

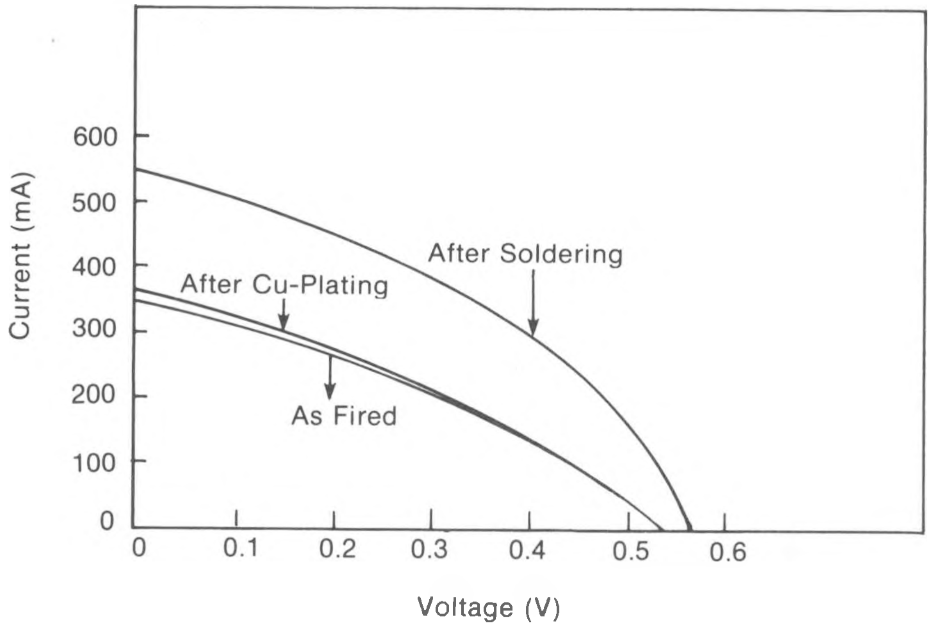


Figure 3-9. I-V Curves for a Solar Cell With Screen-Printed Nickel Top Contact. After soldering, the cell efficiency was 5.25% and the fill factor was 0.38.

A third major problem with the nonnoble-metal inks was that most could not be soldered directly. If, as with most silver-based inks, a solder coating is necessary for increasing cell output and protecting the grid, the lack of solderability is an obvious shortcoming. Even if solder-coating the grid is not necessary, interconnection of cells in modules is facilitated by soldering. Unfortunately, the solutions to this problem involve additional processing steps, such as plating copper over the grid to make it solderable.

SECTION 4.0

CONCLUSIONS

4.1 SILVER-BASED INKS

Our study supports two conclusions: first, that thick-film metallization provides a viable, low-cost alternative to other metallization systems; and second, that a variety of commercially available inks can be processed for effective solar cell contact material.

The low cost and effectiveness of silver-based inks has been verified by previous cost analyses and the performance results reported in this paper. Several cells used in this study were covered by a conventional evaporated Ti-Pd-Ag technique in order to compare thick-film and vacuum-evaporated contacts. These cells were 10% efficient, and those produced with thick-film contacts typically were equally efficient (using Kelvin-probe measurements). These findings were confirmed when antireflection coatings were applied to cells using thick-film and conventional contacting. Both types of cells were ~12% efficient. Combined with the economic studies [2] and reliability analysis [10] performed at Clemson University for the Low-Cost Solar Array Program at Jet Propulsion Laboratory, these results show that the thick-film technique offers an inexpensive alternative for contacts for terrestrial solar cells.

As Figs. 3-2 and 3-5 show, only 3 or 4 of the 12 inks tested gave unsatisfactory results. It is important to note that processing modifications were usually necessary to obtain good results; with optimized processing even those three or four inks might be acceptable. The processing parameters must be fully examined and if necessary, modified to fit the requirements of the cell structure to be contacted. Inks that could be compared directly showed that the best results are obtained with ink containing some semiconductor dopant. Doping should lower the contact and series resistances of the metallization, and these resistances constitute the major drawback of the thick-film system. Although HF etching also solves this problem, it is not an attractive solution because it can create other problems, e.g., impaired adhesion. An examination of the HF etch mechanism and its effects on the adhesion and environmental stability of the thick-film inks is now underway.

4.2 BASE-METAL INKS

The study of the base-metal inks was inconclusive. No processing sequence for any of the base-metal inks tested resulted in good electrical contact. Since most of the cost of thick-film metallization for solar cells today is for silver [2], costs could be reduced substantially if a suitable material less expensive than silver was substituted. With ink and/or cell modifications, the use of base-metal inks is still possible. We doubt, however, that the savings obtained from using a base-metal ink rather than a silver ink will ever outweigh the cell efficiency loss resulting from the diffusion problems caused by copper inks or the higher bulk resistances in nickel and other non-noble-metal inks.

SECTION 5.0

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APPENDIX A

LETTER SENT TO INK MANUFACTURERS DESCRIBING STUDY OBJECTIVES AND PARAMETERS

SERI

Solar Energy Research Institute
1617 Cole Boulevard
Golden, Colorado 80401
(303) 231-1000

SERI

December 12, 1979

Dear Sirs:

In an effort to provide current information on available conductor inks for solar cell application, we are establishing a program to analyze those inks and report the results in the open literature. We hope this will provide the manufacturers of solar cells valuable information and further impetus to accept the thick film process as an established procedure in manufacturing.

To make this project tractable, we are confining our investigation exclusively to front grid contact materials. The printing and analyses will be done on photovoltaic cells which have been obtained from a single manufacturer. This manufacturer has provided cells of the following characteristics:

Start Wafer;	1-3Ω-cm Boron Doped Single Crystal Silicon
Texture Etch;	30% NaOH @ 80°C for 20 min. 2% NaOH for 20 min.
Junction Formation;	Phosphorous diffused by Phosphine gas with a 50 minute drive-in. This provided a surface resistivity of 30-40Ω/□
Etch;	40/60 Nitric/HF
Back Contact Printed & Dried;	Using a Ag based ink with 2% Al for ohmic contact

These cells will then be printed with the appropriate material suggested by you.

The testing done on the inks and finished cells will include at least the following. Printing will be done using an AMI Presco Model 435 Automic Screen printer. A grid pattern using both 5 mil and 10 mil line widths will be printed on the cells. The cells will then be processed, following your specifications for drying and firing as closely as possible. The firing will be done in a Watkins Johnson Multi-Atmosphere 4 Zone Belt Furnace (Model 4CM38). Following the firing step, any further recommended processing of the cell will be adhered to. Efficiency calculations for the cells will then be made, as well as solderability and adhesion testing of the metallization. A moisture degradation test and thermal shock test (both yet to be defined) will also be done on the finished cells.

As most ink manufactureres who have dealt with solar cell manufactureres are aware, it is common to follow the firing process with a quick HF etch to improve the cell output efficiency (often by a factor of two). As this appears to be a very critical step, it is important that you clearly state the parameters of this etch, if needed. It is commonly agreed by most cell manufacturers that the elimination of this step is very important. (Indeed, some manufacturers feel they have alleviated this problem by a high-temperature, close to 850°C, firing process for a very short period in an IR furnace. We do not have IR furnace capabilities, but can attempt such short firing cycles on the above mentioned furnace if specified.) Regardless of the post-firing etch, if needed, we will attempt to follow the recommended procedures as closely as possible.

Front grid metallizations to date have been most successful when employing inks of Ag based compositions, when fired at as low a temperature for as short a time period (thereby not disturbing the diffused junction) as possible. Due to the costs of these systems, the photovoltaic industry is encouraging the development of base metal ink systems. We will be glad to test, and encourage the submittal for analysis, any commercially available inks which might satisfy the needs of the P.V. industry. However, since we hope to provide as large a statistical sampling as possible, we ask that you limit candidate materials to no more than two or three ink suggestions. Also, in the spirit of providing useful information to cell manufacturers, we also ask that the materials suggested be limited to either commercially available materials, or soon to be available.

Please feel free to contact us in the event of any questions you might have regarding this study. We hope to finish the analysis by April of 1980, so your prompt reply will be appreciated.

Sincerely,

Steve Hogan

Steve Hogan

Kay Firor

Kay Firor

SH,KF:bfs

APPENDIX B

RESPONDING INK MANUFACTURERS AND INKS OBTAINED

Manufacturer	Ag Ink	Base-Metal Ink
Cermaloy, Cermet Division Union Hill Industrial Park West Conshohocken, PA 19428	S4450	--
DuPont Electrochemicals Department 1007 Market St. Wilmington, DE 19889	Experimental Ag	--
Electro Materials Corporation 605 Center Ave. Mamaronek, NY 10543	Silver 92	--
Electro-Oxide Corporation 6620 Lakeside Road West Palm Beach, FL 33411	6103 6105	-- --
Electro-Science Laboratories, Inc. 2211 Sherman Ave. Pennsauken, NJ 08110	590C 595 --	2590 2554 2560
Englehard Industries, Inc. 1 West Central Ave. East Newark, NJ 07029	E422S	E575A
Materials Science and Technology 801 Newton Ave. and Division Camden, NJ 08103	-- --	2303 2301
Plessey, Electronic Materials Division 320 Long Island Expressway, So. Melville, NY 11746	LP80-4630 LP80-4683 LP80-4684	-- -- --
Thick Film Systems, Inc. 324 Palm Ave. Santa Barbara, CA 93101	3347 --	5514 5517

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APPENDIX C

CONTACT RESISTANCE MEASUREMENTS

Contact resistance was measured in three ways. Figure C-1 shows the pattern used for contact resistance measurements. The series of grid lines (A) were used for two techniques while the concentric circles (B) were used for the third technique.

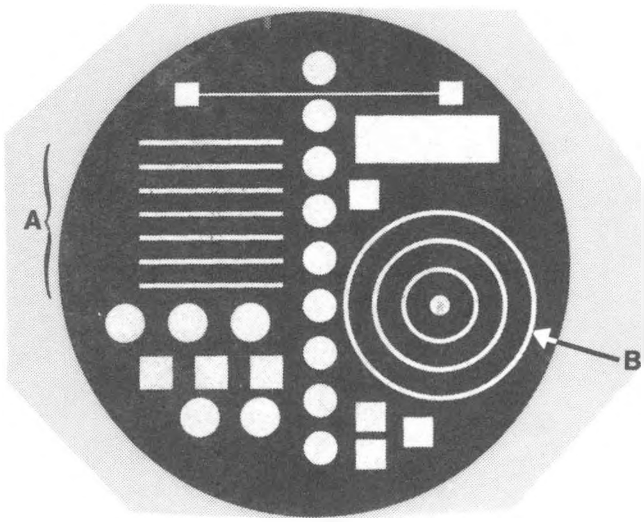

Figure C-1. Pattern Used for Contact Resistance Measurements

The first technique used four of the grid lines. A current was injected in the outer pair while the voltage was read across the inner pair. The current source was then placed between one line of the outer pair and the farthest line of the inner pair. Figure C-2(a) illustrates this set of hookups. Figure C-2(b) shows the simplified equivalent circuit of the setup. The four-pad arrangement shows that the voltage measured is the result only of the current flowing through R_{Si}, the sheet resistance of the silicon. Because the ideal voltmeter draws no current, there can be no voltage across either R_c, the resistance due to the ink-to-silicon interface. This means that

$$V_1 = IR_{Si} \quad .$$

When the hookup is set to the three pads, the voltmeter now registers the voltage drop across both the silicon resistance and one of the equivalent contact resistors; that is,

$$V_2 = I(R_{Si} + R_c) \quad .$$

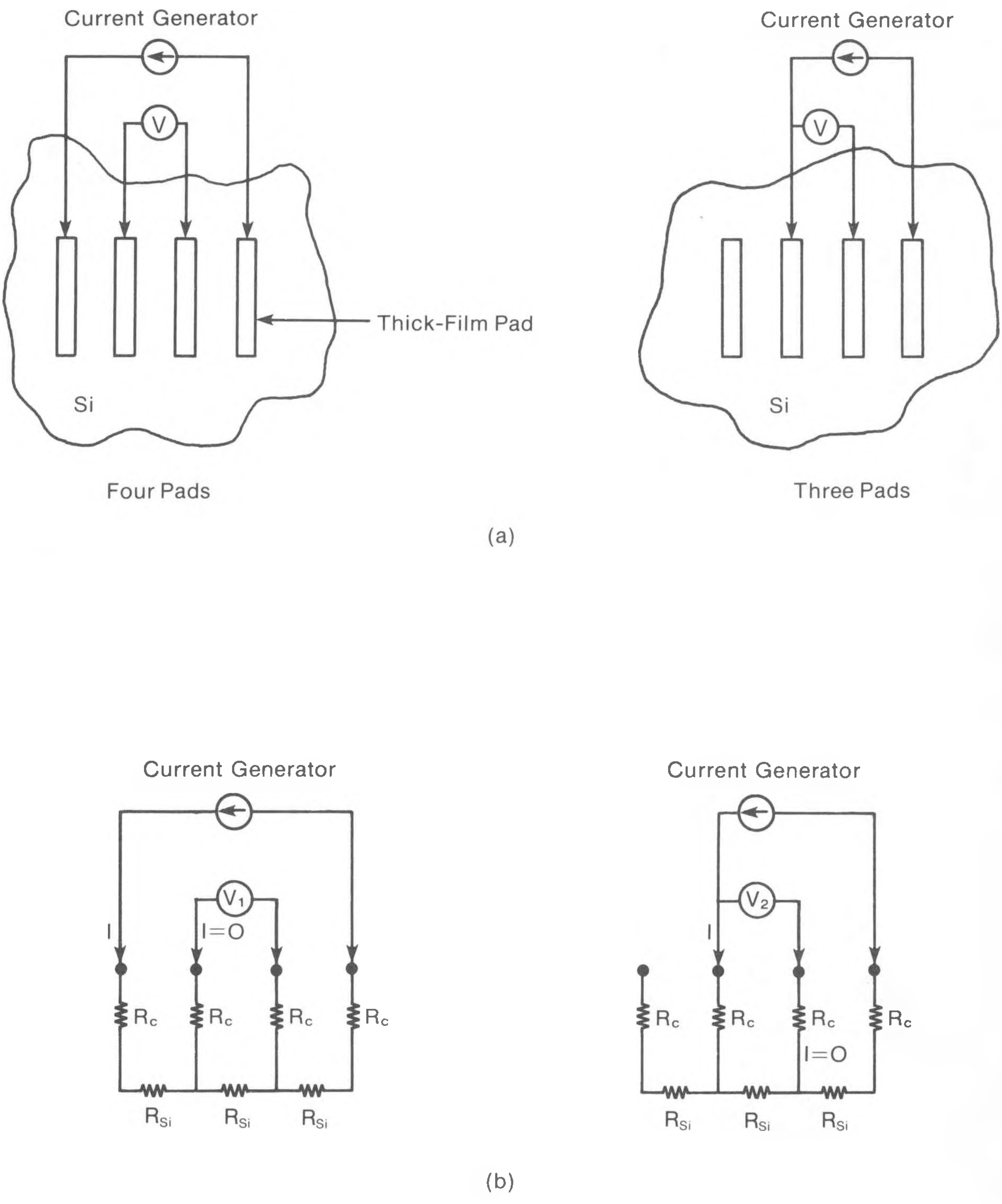

Figure C-2. Schematic of Physical Hookups for Contact Resistance Measurement (a) Using Three and Four Conductor Pads; (b) Equivalent Circuits of the Setups

The value of contact resistance is simply computed using the difference in the two voltage readings (note that $V_2 > V_1$):

$$V_2 - V_1 = I(R_{Si} + R_c) - IR_{Si} = IR_c \quad ;$$

therefore,

$$R_c(\Omega) = \frac{V_2 - V_1}{I} \quad .$$

The contact resistivity is then computed by multiplying R_c by the area of one pad:

$$\rho_c \ (\Omega \ cm^2) = R_c A \quad .$$

The second technique follows the same principle with one improvement. The first technique assumes a constant current density under all the pads. This assumption ignores the possibility of current-spreading, which would give a lower current density under middle pads. For long pads of low resistance compared to the silicon resistance this is a close approximation. However, any current-spreading effect can be avoided by using the concentric circle pattern, which assures a uniform current density under all pads. The hookup is identical to the first method and the calculation reduces to

$$R_c = \frac{V_2 - V_1}{I} \quad ,$$

and

$$\rho_c = R_c A \quad ,$$

where A is the area of the ring that shares the voltage and current probe.

The third method for contact resistance measurements utilizes the lines again. In this method, a current is impressed through the outermost pads, and the voltage is read from one of the outermost pads to the various other patterns. Figure C-3(a) shows the measurement setup. One then plots the voltage versus distance (pad number) as shown in Fig. C-3(b). A least squares fit (straight line) through the data points, intercepting the voltage axis, gives the equivalent contact voltage. The contact resistivity is then determined using $\rho_c = R_c A$, where $R_c = V_c/I$ and A is the pad area. This method assumes the contact resistance to be a part of each measurement and hence is a linear addition to all the voltage values. Variations of this technique, using well-defined unequal pad intervals, yield even more precise measurements [1,2].

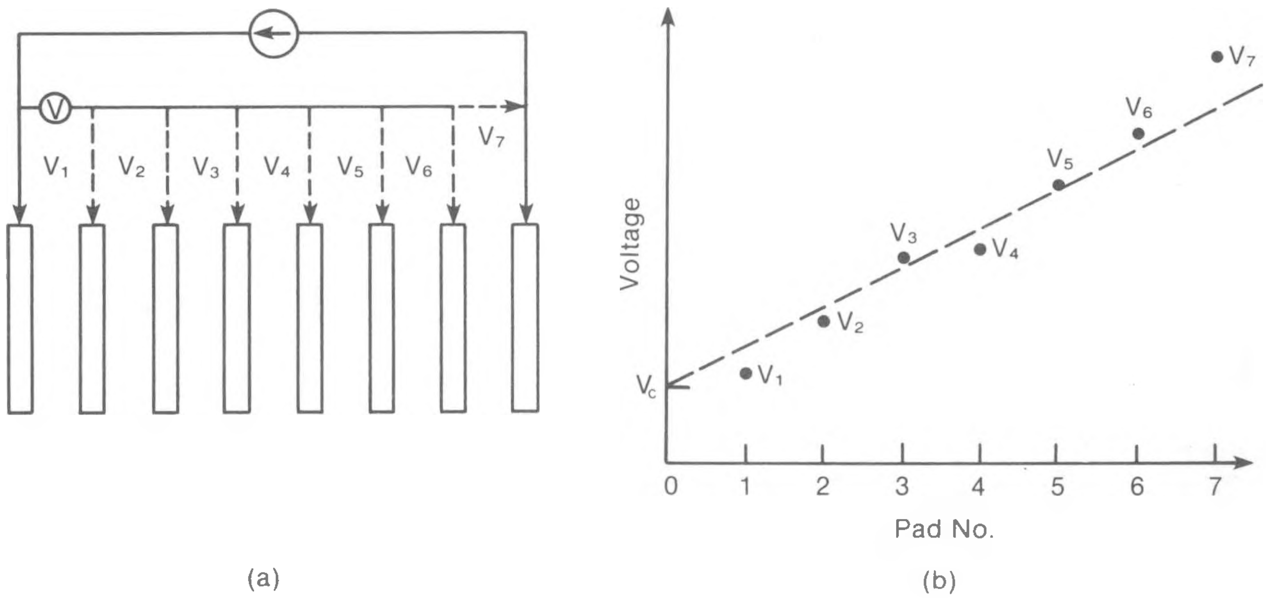

Figure C-3. (a) Schematic of Physical Hookups for Contact Resistance Measurement Using Eight Grid Lines; (b) Plot of Voltage vs. Distance for Straight-Line Approximation

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APPENDIX D

DATA SHEETS ON BEST PROCESSING PARAMETERS OBTAINED

NOTE: The electrical testing of cells was performed under 100 mW/cm^2 irradiance at 28°C, using an ELH bulb simulator. The HF etching was carried out at room temperature and followed by a 10-min rinse in deionized water. When cells were soldered, 2% Ag, tin-lead solder was used at 210°C; the dip time was 3 seconds.

INK: Ag ID No.: 2

Printing

Screen number: 103-F-10 #2
5-mil line print: good
Ink cleanability: poor
Comments: Thinning would help. Double-printed all samples.

Drying

Ambient settling time: 15 min
Drying time (under IR lamp): 8 min; temperature: 160°C
Ink flow: good
Comments: --

Firing

Furnace settings:

Zone:	1	2	3	4
Temperature (°C):	612	593	589	627
% Power:	100	70	70	70

Profile no.: 68
Time in furnace: 18 min
Atmosphere: air; flow rates: 20/40/20
Comments: --

Post Firing

Appearance: OK

Cell no.:	1	2	3	4	5
V_{oc} (V):	0.512	0.475	0.527	0.540	0.514
I_{sc} (mA):	144	196	217	233	221
η (%):	0.8	1.1	1.4	1.4	1.3
FF:	0.25	0.26	0.27	0.25	0.26

HF Etching

Bath age: ~ 12 runs
Etch time

Cell no.:	1	2	3	4	5
Time (s):	8	10	12	60	60

HF concentration: 5%
Comments: 12 s may not be long enough. Cells 4, 5 soldered before etch.

Post Etching

Cell no.:	1	2	3	4	5
V_{oc} (V):	0.548	0.507	0.536	0.547	0.533
I_{sc} (mA):	585	587	587	581	578
η (%):	5.9	5.0	6.2	6.7	6.1
FF:	0.41	0.37	0.44	0.47	0.44

Soldering

Flux: Cell 4, Kester 1587; cell 5, Kester 1544
Solderability: poor to fair
Comments: Cells 4 and 5 soldered before etch.

Post Soldering

Cell no.:	3	4	5
V_{oc} (V):	0.549	0.542	0.542
I_{sc} (mA):	609	571	522
η (%):	6.9	5.6	4.3
FF:	0.46	0.40	0.35

INK: Ag ID No.: 3

Printing

Screen number: 103-F-10 #1
5-mil line print: fine
Ink cleanability: good
Comments: --

Drying

Ambient settling time: 10 min
Drying time (under IR lamp): 10 min; temperature: 110°C
Ink flow: good
Comments: --

Firing

Furnace settings

Zone:	1	2	3	4
Temperature (°C):	300	620	610	630
% Power:	20	100	100	100

Profile no.: 72
Time in furnace: 13 min
Atmosphere: air; flow rates: 20/40/20
Comments: Try lower temperature but keep firing fast--this ink should not need HF etch.

Post Firing

Appearance: fine

Cell no.:	1	2
V_{oc} (V):	0.574	0.561
I_{sc} (mA):	445	354
η (%):	3.2	2.6
FF:	0.28	0.30

HF Etching

Bath age: --
Etch time: 60 s
HF concentration: 5%
Comments: Etch done after solder dip.

Post Etching

Cell no.:	1	2
V_{oc} (V):	0.584	0.568
I_{sc} (mA):	603	587
η (%):	8.0	8.3
FF:	0.51	0.56

Soldering

Flux: Kester 1544
Solderability: fair
Comments: Solder dipping improved outputs, but not enough.

Post Soldering

Cell no.:	1	2
V_{oc} (V):	0.585	0.571
I_{sc} (mA):	672	618
η (%):	5.9	6.1
FF:	0.36	0.38

INK: Ag ID No.: 4

Printing

Screen number: 103-F-10 #2
5-mil line print: OK
Ink cleanability: OK
Comments: 325-mesh screen has tendency to clog.

Drying

Ambient settling time: 8 min
Drying time (under IR lamp): 5 min; temperature: 110°C
Ink flow: poor
Comments: --

Firing

Furnace settings

Zone:	1	2	3	4
Temperature (°C):	627	603	593	617
% Power:	100	70	70	70

Profile no.: 55
Time in furnace: 22 min
Atmosphere: air; flow rates: 15/35/15
Comments: Fired at temperature higher than recommended.

Post Firing

Appearance: OK

Cell no.:	1	2	3	4	5
V_{oc} (V):	0.581	0.586	0.580	0.570	0.575
I_{sc} (mA):	525	450	557	483	348
η (%):	4	3.3	4.7	3.7	2.5
FF:	0.29	0.28	0.33	0.30	0.28

HF Etching

Bath age: ~ 15 runs
Etch time:

Cell no.:	1	2	3	4	5
Time (s):	8	10	12	60	60

HF concentration: 5%
Comments: Solder dip, followed by 90-s HF. Gave good results.

Post Etching

Cell no.:	1	2	3	4	5
V_{oc} (V):	0.578	0.579	0.576	0.574	0.576
I_{sc} (mA):	615	642	635	635	654
η (%):	9.3	9.6	9.6	9.5	9.4
FF:	0.58	0.58	0.58	0.58	0.56

Soldering

Flux: 1544
Solderability: OK
Comments: --

Post Soldering

Cell no.:	1	2
V_{oc} (V):	0.576	0.584
I_{sc} (mA):	626	647
η (%):	9.0	10.2
FF:	0.55	0.60

Printing

Screen number: 103-F-10 #3
5-mil line print: good
Ink cleanability: OK
Comments: --

Drying

Ambient settling time: 7 min
Drying time (under IR lamp): 10 min; temperature: 100°C
Ink flow: good
Comments: --

Firing

Furnace settings

Zone:	1	2	3	4
Temperature (°C):	300	620	610	630
% Power:	20	100	100	100

Profile no.: 72
Time in furnace: 13 min
Atmosphere: air; flow rates: 20/40/20
Comments: --

Post Firing

Appearance: --

Cell no.:	1	2
V_{oc} (V):	0.552	0.567
I_{sc} (mA):	441	482
η (%):	3.1	3.9
FF:	0.28	0.31

HF Etching

Bath age: --
Etch time: 90 s
HF concentration: 5%
Comments: Etched after soldering.

Post Etching

Cell no.:	1
V_{oc} (V):	0.553
I_{sc} (mA):	618
η (%):	7.5
FF:	0.49

Soldering

Flux: Kester 1587
Solderability: good
Comments: --

Post Soldering

Cell no.:	1
V_{oc} (V):	0.548
I_{sc} (mA):	563
η (%):	4.4
FF:	0.32

Printing

Screen number: 103-F-10 #2
5-mil line print: good
Ink cleanability: fair
Comments: --

Drying

Ambient settling time: 5 min
Drying time (under IR lamp): 5 min; temperature: 90°C
Ink flow: good
Comments: Dark residue forms around lines.

Firing

Furnace settings

Zone:	1	2	3	4
Temperature (°C):	612	593	585	617
% Power:	100	70	70	70

Profile no.: 57
Time in furnace: 20 min
Atmosphere: air; flow rates: 20/40/20
Comments: --

Post Firing

Appearance: --

Cell no.:	1	2	3
V_{oc} (V):	0.585	0.588	0.588
I_{sc} (mA):	631	639	630
η (%):	6.5	7.0	7.2
FF:	0.39	0.41	0.43

HF Etching (after soldering)

Bath age: ~ 5 runs
Etch time: 90 s
HF concentration: 2.8%
Comments: --

Post Etching

Cell no.:	1	2	3
V_{oc} (V):	0.582	0.584	0.588
I_{sc} (mA):	623	625	620
η (%):	9.2	8.5	10.2
FF:	0.57	0.52	0.62

Soldering

Flux: Kester 1544
Solderability: good
Comments: --

Post Soldering

Cell no.:	3
V_{oc} (V):	0.580
I_{sc} (mA):	644
η (%):	9.1
FF:	0.54

Printing

Screen number: 103-F-10 #2
5-mil line print: good
Ink cleanability: OK
Comments: Both 1 and 2 double-printed.

Drying

Ambient settling time: 13 min
Drying time (under IR lamp): 10 min; temperature: 110°C
Ink flow: good
Comments: --

Firing

Furnace settings

Zone:	1	2	3	4
Temperature (°C):	602	583	579	617
% Power:	100	70	70	70

Profile no.: 74
Time in furnace: 15 min
Atmosphere: air; flow rates: 20/40/20
Comments: --

Post Firing

Appearance: --

Cell no.:	1	2
V_{oc} (V):	0.585	0.570
I_{sc} (mA):	499	331
η (%):	4.2	2.8
FF:	0.32	0.33

HF Etching

Bath age: 17 runs
Etch time: 7 s
HF concentration: 5%
Comments: --

Post Etching

Cell no.:	1	2
V_{oc} (V):	0.591	0.581
I_{sc} (mA):	629	638
η (%):	9.3	8.6
FF:	0.55	0.52

Soldering

Flux: Kester 1544
Solderability: excellent
Comments: --

Post Soldering

Cell no.:	1	2
V_{oc} (V):	0.592	0.586
I_{sc} (mA):	645	666
η (%):	10.3	9.8
FF:	0.60	0.56

Printing

Screen number: 103-F-10 #2
5-mil line print: good
Ink cleanability: fair
Comments: --

Drying

Ambient settling time: 10 min
Drying time (under IR lamp): 10 min; temperature: 110°C
Ink flow: good
Comments: --

Firing

Furnace settings

Zone:	1	2	3	4
Temperature (°C):	375	710	700	700
% Power:	20	100	100	100

Profile no.: 73
Time in furnace: 7 min
Atmosphere: air; flow rates: 20/40/20
Comments: "Spike" firing profile.

Post Firing

Appearance: OK

Cell no.:	1	2	3	4
V_{oc} (V):	0.566	0.554	0.534	0.548
I_{sc} (mA):	372	409	196	323
η (%):	2.5	3.0	1.3	2.2
FF:	0.27	0.29	0.28	0.28

HF Etching

Bath age: ~ 18 runs
Etch time: 10 s
HF concentration: 5%
Comments: Cells 3 and 4 soldered before etch (60 s).

Post Etching

Cell no.:	1	2	3	4
V_{oc} (V):	0.541	0.547	0.553	0.556
I_{sc} (mA):	588	607	567	573
η (%):	7.8	8.1	7.0	7.2
FF:	0.54	0.55	0.50	0.51

Soldering

Flux: 1544
Solderability: fair
Comments: --

Post Soldering

Cell no.:	1	2	3	4
V_{oc} (V):	0.563	0.564	0 552	0.560
I_{sc} (mA):	644	666	551	568
η (%):	8.9	8.9	4.6	5.2
FF:	0.55	0.53	0.34	0.37

INK: Ag   ID No.: 9

Printing

Screen number: 103-F-10 #2
5-mil line print: good
Ink cleanability: fair
Comments: --

Drying

Ambient settling time: 5 min
Drying time (under IR lamp): 10 min; temperature: 130°C
Ink flow: poor
Comments: --

Firing

Furnace settings

Zone:	1	2	3	4
Temperature (°C):	300	700	700	700
% Power:	40	100	100	100

Profile no.: 61
Time in furnace: 12 min
Atmosphere: air; flow rates: 20/40/20
Comments: --

Post Firing

Appearance: --

Cell no.:	1	2	3	4	5
V_{oc} (V):	0.577	0.573	0.576	0.575	0.554
I_{sc} (mA):	542	517	555	525	361
η (%):	4.3	3.8	4.8	4.0	2.4
FF:	0.31	0.28	0.34	0.30	0.27

HF Etching

Bath age: new
Etch time

Cell no.:	1	2	3	4	5
Time (s):	6	8	10	60	12

HF concentration: 5%
Comments: Cell 2 chipped (small piece); cell 4 etched after soldering.

Post Etching

Cell no.:	1	2	3	4	5
V_{oc} (V):	0.581	0.573	0.582	0.570	0.575
I_{sc} (mA):	572	570	600	504	590
η (%):	8.6	8.2	9.4	7.2	7.9
FF:	0.58	0.51	0.60	0.56	0.52

Soldering

Flux: Kester 1587
Solderability: good
Comments: Cell 4 soldered before etch.

Post Soldering

Cell no.:	4	5
V_{oc} (V):	0.566	0.574
I_{sc} (mA):	546	619
η (%):	6.3	9.5
FF:	0.45	0.59

INK: Ag   ID No.: 10

Printing

Screen number: 103-F-10 #2
5-mil line print: fair
Ink cleanability: excellent
Comments: --

Drying

Ambient settling time: 10 min
Drying time (under IR lamp): 10 min; temperature: 120°C
Ink flow: excellent
Comments: --

Firing

Furnace settings

Zone:	1	2	3	4
Temperature (°C):	612	593	585	617
% Power:	100	70	70	70

Profile no.: 57
Time in furnace: 20 min
Atmosphere: air; flow rates: 20/40/20
Comments: --

Post Firing

Appearance: chalky-white

Cell no.:	1	2	3	4	5
V_{oc} (V):	0.579	0.579	0.580	0.583	0.583
I_{sc} (mA):	365	320	350	330	393
η (%):	2.4	2.1	2.3	2.2	2.6
FF:	0.25	0.26	0.26	0.26	0.26

HF Etching

Bath age: 16 runs
Etch time: 6 s
HF concentration: 5%
Comments: Some yellowish discoloration around edges on Si surface.

Post Etching

Cell no.:	1	2	3	4	5
V_{oc} (V):	0.582	0.587	0.589	0.584	0.578
I_{sc} (mA):	660	648	650	657	650
η (%):	9.8	9.7	9.8	9.6	9.1
FF:	0.57	0.57	0.57	0.56	0.54

Soldering

Flux: Kester 1544
Solderability: good
Comments: Cells etched longer than 8 s lost adhesion.

Post Soldering

Cell no.:	1	4
V_{oc} (V):	0.578	0.579
I_{sc} (mA):	684	657
η (%):	10.3	9.6
FF:	0.58	0.56

Printing

Screen number: 103-F-10 #2
5-mil line print: good
Ink cleanability: good
Comments: --

Drying

Ambient settling time: 10 min
Drying time (under IR lamp): 10 min; temperature: 120°C
Ink flow: excellent
Comments: --

Firing

Furnace settings

Zone:	1	2	3	4
Temperature (°C):	612	593	585	617
% Power:	100	70	70	70

Profile no.: 57
Time in furnace: 20 min
Atmosphere: air; flow rates: 20/40/20
Comments: --

Post Firing

Appearance: good

Cell no.:	1	2	3	4	5
V_{oc} (V):	0.499	0.425	0.541	0.499	0.392
I_{sc} (mA):	344	357	317	235	318
η (%):	2.1	1.8	1.9	1.3	1.5
FF:	0.27	0.27	0.26	0.25	0.27

HF Etching

Bath age: ~ 18 runs
Etch time: 10 s
HF concentration: 5%
Comments: Cell 5 soldered before etching, but back contact not soldered; therefore, 90-s HF etch ruined back contact.

Post Etching

Cell no.:	1	2	3	4
V_{oc} (V):	0.494	0.467	0.549	0.510
I_{sc} (mA):	557	604	633	624
η (%):	2.1	4.4	7.1	5.2
FF:	0.27	0.35	0.46	0.37

Soldering

Flux: Kester 1544
Solderability: poor
Comments: --

Post Soldering

Cell no.:	1	4	5
V_{oc} (V):	0.510	0.533	0.433
I_{sc} (mA):	608	645	537
η (%):	5.8	6.9	3.4
FF:	0.42	0.45	0.32

INK: Ag   ID No.: 12

Printing

Screen number: 103-F-10 #2
5-mil line print: good
Ink cleanability: good
Comments: --

Drying

Ambient settling time: 10 min
Drying time (under IR lamp): 10 min; temperature: 100°C
Ink flow: excellent
Comments: --

Firing

Furnace settings

Zone:	1	2	3	4
Temperature (°C):	612	593	585	617
% Power:	100	70	70	70

Profile no.: 57
Time in furnace: 20 min
Atmosphere: air; flow rates: 20/40/20
Comments: --

Post Firing

Appearance: chalky white

Cell no.:	1	2	3	4	5
V_{oc} (V):	0.579	0.585	0.583	0.582	0.586
I_{sc} (mA):	590	573	552	519	579
η (%):	4.7	4.2	4.1	3.9	4.5
FF:	0.31	0.28	0.28	0.29	0.30

HF Etching

Bath age: 18 runs
Etch time: 8 s
HF concentration: 5%
Comments: Grid visibly darkened immediately upon contact with HF; cell-1 grid came off during blow-dry.

Post Etching

Cell no.:	2	3
V_{oc} (V):	0.585	0.585
I_{sc} (mA):	639	646
η (%):	9.7	9.0
FF:	0.58	0.53

Soldering

Flux: Kester 1587
Solderability: poor
Comments: Grid came off completely when soldering was attempted.

Post Soldering

V_{oc} (V): NA
I_{sc} (mA): NA
η (%): NA
FF: NA

Printing

Screen number: 103-F-10 #2
5-mil line print: good
Ink cleanability: fair
Comments: Occasional screen clotting.

Drying

Ambient settling time: 4 min
Drying time (under IR lamp): 5 min; temperature: 90°C
Ink flow: good
Comments: --

Firing

Furnace settings

Zone:	1	2	3	4
Temperature (°C):	612	593	585	617
% Power:	100	70	70	70

Profile no.: 57
Time in furnace: 20 min
Atmosphere: air; flow rates: 20/40/20
Comments: --

Post Firing

Appearance: --

Cell no.:	1	2	3	4	5
V_{oc} (V):	0.558	0.565	0.561	0.567	0.564
I_{sc} (mA):	337	503	394	503	434
η (%):	2.2	3.8	2.8	3.7	3.1
FF:	0.27	0.30	0.29	0.29	0.28

HF Etching

Bath age: 22 runs
Etch time

Cell no.:	1	2	3	4
Time (s):	6	8	10	10

HF concentration: 5%
Comments: --

Post Etching

Cell no.:	1	2	3	4
V_{oc} (V):	0.568	0.565	0.568	0.570
I_{sc} (mA):	624	643	659	655
η (%):	8.6	8.0	8.7	8.2
FF:	0.55	0.49	0.2	0.49

Soldering

Flux: Kester 1587
Solderability: good
Comments: --

Post Soldering

Cell no.:	3	4
V_{oc} (V):	0.564	0.563
I_{sc} (mA):	645	655
η (%):	9.4	9.1
FF:	0.58	0.55

Printing

Screen number: 103-F-10 #1
5-mil line print: good
Ink cleanability: excellent
Comments: Very smooth ink.

Drying

Ambient settling time: 5 min
Drying time (under IR lamp): 15 min; temperature: 125°C
Ink flow: good
Comments: --

Firing

Furnace settings

Zone:	1	2	3	4
Temperature (°C):	320	670	660	680
% Power:	100	70	70	70

Profile no.: --
Time in furnace: 12 min
Atmosphere: air; flow rates: 20/40/20
Comments: --

Post Firing

Appearance: OK
Cell no.:
V_{oc} (V):
I_{sc} (mA): Complete junction shunting, no curves obtained.
η (%):
FF:

HF Etching

Bath age: NA
Etch time: NA
HF concentration: NA
Comments: NA

Post Etching

Cell no.: NA
V_{oc} (V): NA
I_{sc} (mA): NA
η (%): NA
FF: NA

Soldering

Flux: NA
Solderability: NA
Comments: NA

Post Soldering

Cell no.: NA
V_{oc} (V): NA
I_{sc} (mA): NA
η (%): NA
FF: NA

Printing

Screen number: 103-F-10 #1
5-mil line print: good
Ink cleanability: good
Comments: Ink very runny.

Drying

Ambient settling time: 8 min
Drying time (under IR lamp): 15 min; temperature: 125°C
Ink flow: excellent
Comments: --

Firing

Furnace settings

Zone:	1	2	3	4
Temperature (°C):	582	563	559	597
% Power:	100	70	70	70

Profile no.: --
Time in furnace: 12 min
Atmosphere: air; flow rates: 20/40/20
Comments: --

Post Firing

Appearance: --

Cell no.:	1	2	3	4	5
V_{oc} (V):	0.072	0.068	Contact not made to Si.		
I_{sc} (mA):	18	21			
η (%):	Not worth taking.				
FF:					

HF Etching

Bath age: NA
Etch time: NA
HF concentration: NA
Comments: NA

Post Etching

Cell no.: NA
V_{oc} (V): NA
I_{sc} (mA): NA
η (%): NA
FF: NA

Soldering

Flux: NA
Solderability: NA
Comments: NA

Post Soldering

Cell no.: NA
V_{oc} (V): NA
I_{sc} (mA): NA
η (%): NA
FF: NA

Printing

Screen number: 103-F-10 #1
5-mil line print: good
Ink cleanability: good
Comments: Ink very runny.

Drying

Ambient settling time: 7 min
Drying time (under IR lamp): 15 min; temperature: 125°C
Ink flow: excellent
Comments: --

Firing

Furnace settings

Zone:	1	2	3	4
Temperature (°C):	582	563	559	597
% Power:	100	70	70	70

Profile no.: --
Time in furnace: 12 min
Atmosphere: air; flow rates: 20/40/20
Comments: --

Post Firing

Appearance: OK

Cell no.:	1	2	3	4	5
V_{oc} (V):	0.562	0.578	No current attained,		
I_{sc} (mA):	44	52	poor contact.		
η (%):	Not worth				
FF:	taking.				

HF Etching

Bath age: NA
Etch time: NA
HF concentration: NA
Comments: NA

Post Etching

Cell no.: NA
V_{oc} (V): NA
I_{sc} (mA): NA
η (%): NA
FF: NA

Soldering

Flux: NA
Solderability: NA
Comments: NA

Post Soldering

Cell no.: NA
V_{oc} (V): NA
I_{sc} (mA): NA
η (%): NA
FF: NA

INK: Ni ID No.: 23

Printing

Screen number: 103-F-10 #1
5-mil line print: good
Ink cleanability: excellent
Comments: --

Drying

Ambient settling time: 7 min
Drying time (under IR lamp): 10 min; temperature: 135°C
Ink flow: good
Comments: --

Firing

Furnace settings

Zone:	1	2	3	4
Temperature (°C):	542	523	519	557
% Power:	100	70	70	70

Profile no.: 69
Time in furnace: 18 min
Atmosphere: air; flow rates: 20/40/20
Comments: Cells prefired at 612°, 593°, 589°, and 627°C before printing to make sure back contact properly fired.

Post Firing

Appearance: --

Cell no.:	1	2
V_{oc} (V):	0.538	0.544
I_{sc} (mA):	19	6
η (%):	0.1	0.03
FF:	0.22	0.23

HF Etching

Bath age:
Etch time:
HF concentration:
Comments: --

Cell 2 was copper-plated, then solder-dipped.

Copper Plated

Cell no.:	2
V_{oc} (V):	0.552
I_{sc} (mA):	19
η (%):	0.09
FF:	0.19

Soldering

Flux: --
Solderability: poor
Comments: --

Post Soldering

Cell no.:	2
V_{oc} (V):	0.575
I_{sc} (mA):	100
η (%):	0.78
FF:	0.30

INK: Ag ID No.: 24

Printing

Screen number: 103-F-10 #1
5-mil line print: OK
Ink cleanability: good
Comments: Ink is grainy.

Drying

Ambient settling time: 10 min
Drying time (under IR lamp): 10 min; temperature: 90°C
Ink flow: poor
Comments: Residue spread at edges.

Firing

Furnace settings

Zone:	1	2	3	4
Temperature (°C):	587	568	564	602
% Power:	100	70	70	70

Profile no.: --
Time in furnace (min): 12 12 10 --
Atmosphere: air; flow rates: 20/40/20
Comments: --

Post Firing

Appearance: --

Cell no.:	1	2	3
V_{oc} (V):	0.514	0.503	0.541
I_{sc} (mA):	121	62	160
η (%):	Not taken		1
FF:			0.25

HF Etching

Bath age: NA
Etch time: NA
HF concentration: NA
Comments: NA

Post Etching

Cell no.: NA
V_{oc} (V): NA
I_{sc} (mA): NA
η (%): NA
FF: NA

Soldering

Flux: NA
Solderability: NA
Comments: NA

Post Soldering

Cell no.: NA
V_{oc} (V): NA
I_{sc} (mA): NA
η (%): NA
FF: NA

INK: Ni   ID No.: 25

Printing

Screen number: 103-F-10 #1
5-mil line print: good
Ink cleanability: good
Comments: --

Drying

Ambient settling time: 7 min
Drying time (under IR lamp): 10 min; temperature: 85°C
Ink flow: good
Comments: --

Firing

Furnace settings

Zone:	1	2	3	4
Temperature (°C):	562	543	539	577
% Power:	100	70	70	70

Profile no.: --
Time in furnace: 24 min
Atmosphere: air; flow rates: 20/40/20
Comments: --

Post Firing

Appearance: --

Cell no.:	1	2
V_{oc} (V):	0.56	0.55
I_{sc} (mA):	7	7
η (%):	Not worth taking.	
FF:		

HF Etching

Bath age: NA
Etch time: NA
HF concentration: NA
Comments: NA

Post Etching

Cell no.: NA
V_{oc} (V): NA
I_{sc} (mA): NA
η (%): NA
FF: NA

Soldering

Flux: NA
Solderability: NA
Comments: NA

Post Soldering

Cell no.: NA
V_{oc} (V): NA
I_{sc} (mA): NA
η (%): NA
FF: NA

Printing

Screen number: 103-F-10 #1
5-mil line print: good
Ink cleanability: good
Comments: Ink is reddish and smooth.

Drying

Ambient settling time: 10 min
Drying time (under IR lamp): 10 min; temperature: 105°C
Ink flow: excellent
Comments: --

Firing

Furnace settings

Zone:	1	2	3	4
Temperature (°C):	582	563	559	507
% Power:	100	70	70	70

Profile no.: --
Time in furnace: 16 min
Atmosphere: air; flow rates: 20/40/20
Comments: --

Post Firing

Appearance: OK

Cell no.:	1	2	3	4	5
V_{oc} (V):	0.523	0.499	V_{oc} and I_{sc} improve-		
I_{sc} (mA):	6	2	ments diametrically		
η (%):	Not taken		opposed.		
FF:					

HF Etching

Bath age: new
Etch time: 17 s
HF concentration: 5%
Comments: --

Post Etching

Cell no.:	1
V_{oc} (V):	0.503
I_{sc} (mA):	40
η (%):	Not
FF:	taken

Soldering

Flux: NA
Solderability: NA
Comments: NA

Post Soldering

Cell no.: NA
V_{oc} (V): NA
I_{sc} (mA): NA
η (%): NA
FF: NA

Printing

Screen number: 103-F-10 #1
5-mil line print: good
Ink cleanability: good
Comments: Prints nicely.

Drying

Ambient settling time: 7 min
Drying time (under IR lamp): 10 min; temperature: 125°C
Ink flow: OK
Comments: --

Firing

Furnace settings

Zone:	1	2	3	4
Temperature (°C):	612	593	589	627
% Power:	100	70	70	70

Profile no.: 69
Time in furnace: 20 min
Atmosphere: air; flow rates: 20/40/20
Comments: Firing in N_2 did not help.

Post Firing

Appearance: --

Cell no.:	1	2	3	4	5
V_{oc} (V):	0.536	0.514	0.511	0.507	0.500
I_{sc} (mA):	352	325	312	310	273
η (%):	2.5	2.2	2.0	2.0	1.7
FF:	0.29	0.29	0.28	0.29	0.28

HF Etching

Bath age: 15 runs
Etch time: 15 s
HF concentration: 5%
Comments: 20-s etch took grid off cell 4, and 10-s etch took grid off cell 3.

Post Etching (Cu plated on cells 1 and 2)

Cell no.:	1	2	3	4
V_{oc} (V):	0.540	0.367	0.530	0.534
I_{sc} (mA):	357	265	344	344
η (%):	2.6	1.2	2.4	2.5
FF:	0.30	0.28	0.30	0.30

Soldering

Flux: Kester 1544
Solderability: poor
Comments: --

Post Soldering (cell #5 soldered with In/Sn/Pb)

Cell no.:	1	2	5
V_{oc} (V):	0.558	0.434	0.465
I_{sc} (mA):	555	385	567
η (%):	5.25	2.2	3.5
FF:	0.38	0.29	0.29

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