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FINAL REPORT

on
Ion-Plating of Solar Cell Arrays
Encapsulation Task - LSA Project 32

Illinois Tool Works, Inc.
Venture Group
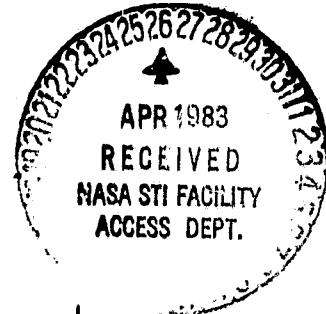1427 Holmes Road
Elgin, Illinois 60120

Contract Number 955506

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Prepared by:

Jack C. Volkers, Ph.D.
Technical Director

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PREFACE

This Final Report describes the results of work performed from December 1, 1979 to October 31, 1982 at the Endurex Ion Plating facility of Illinois Tool Works Inc., Elgin, Illinois, E. Grant Swick, Director and Contract Liaison. The Principal Investigator was William R. Conley and the Technical Director was Jack C. Volkers, Ph.D. Others who participated either directly or indirectly in this work were:

P. Lawson	–	Solar Power Corporation
N. Mardesich	–	Spectrolab Inc.
R. Staehle	–	University of Minnesota Corrosion Consultant
W. Taylor	–	Spectrolab Inc.
G. White	–	Illinois Tool Works Consulting Engineer

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SECTION I

SUMMARY

The ITW contract was initiated in December, 1979 to investigate, develop and demonstrate the capability to produce operational solar cells having metallizations and anti-reflective (AR) coatings deposited by gasless ion plating, which will separately and/or in combination with a low-cost encapsulation system, meet the LSA project life, cost and performance goals.

Under this contract, ITW has developed the capability to produce operational solar cells, both N on P and P on N types, with ion plated metallizations. Further, the ability to deposit AR coatings by ion plating has been demonstrated. The performance characteristics of solar cells thus produced has been equal to that of control cells finished with conventional metallization systems. Additionally, SAMICS analysis have shown that such process can meet cost requirements. Although life tests have not been performed, corrosion tests which have been performed imply that solar cells with ion plated metallization and AR coating will be much less susceptible to corrosion of the electrodes than will solar cells with conventional metallizations and AR coatings.

SECTION II

INTRODUCTION

A. THE GASLESS ION PLATING PROCESS

Various processes and techniques have been developed over the last century for depositing metallic films in vacuum. These processes can generally be grouped into the following categories:

    i.   Physical Vapor Deposition-PVD (including those processes which involve only the evaporation and condensation of metal in a vacuum)

   ii.   Sputtering (including DC, rf, bias and magnetically enhanced sputtering processes)

  iii.   Ion Plating (including DC and rf ion plating which takes place at a pressure of argon or other gas generally greater than 1×10^{-3} Torr. These processes are generally referred to as "Mattox Ion Plating" after Don Mattox[1] of Sandia National Lab.

Although each of these three techniques has certain advantages for particular applications, Endurex Gasless Ion Plating[2] has special advantages that set it apart as a unique process that still retains many of the better features of the others. Figure 1 shows a schematic of this process. The depositant atoms are evaporated from the source into an rf field, where they are ionized and then accelerated by a DC field toward the substrate. Approximately 50% of the depositant
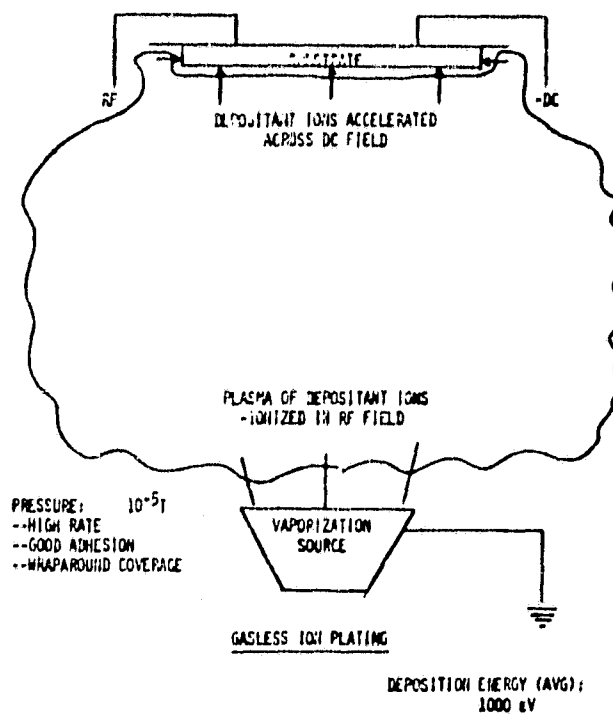
FIGURE 1: Schematic diagram of Gasless Ion Plating,
showing attachment of rf and DC power
supplies to substrate holder.

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is ionized and the average energy of deposition is about 1,000 eV, compared to <1 eV for PVD which is severely limited for applicati ns where adhesion of the depositant is important. One can quickly see that argon entrapment and polyatomic depositions which are characteristic of Mattox Ion Plating are eliminated and therefore the physical properties of the film approach those of the pure material. In contrast to sputtering, this method is also capable of high deposition rates and wrap-around or out of line-of-sight coverage. Thus, gasless ion plating is seen as superimposing the high rates possible from PVD onto many of the qualities of sputtering and Mattox ion plating while alleviating their shortcomings.

From the early work of Mattox, ion plating has attracted wide attention because of its extraordinary adhesion. The Endurex gasless ion plating process continues in this tradition. Not just adhesion in a limited sense, or application, but adhesion of a wide variety of materials and combinations onto an equally broad range of substrates (some presently considered unplateable by any process). This affords unusual versatility for the Endurex plater. Metals or non-metals or both simultaneously may be plated with little change in system parameters. One of the unfortunate facts learned in the course of the present work is that good adhesion is not sufficient, nor even necessary, to provide low contact resistance metallization on solar cells. This does not suggest, however that adhesion is not

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important. It is unlikely that life goals can be met without ex-
cellent adhesion of the metallization to a solar cell.

Another advantage generally discussed for Gasless Ion Plating
is its ability to yield wrap-around or out-of-line-of-sight coverage.
Since solar cells have a basically flat geometry, this characteristic
is advantageous only in mask and system design.

Unless specified otherwise, "ion plating" will refer to Gasless
Ion Plating when used in this report.

B. HISTORICAL BACKGROUND

The reader is referred to contract number 954728 to Endurex
Corporation, Dallas, Texas. (Endurex Corp. was acquired by ITW in
March, 1978.) This contract was for the investigation of ion plating
for depositing AR coatings on solar cells. Specifically to develop
the ability to deposit a continuous film of silicon monoxide, etc.,
over the metallization to provide both anti-reflectance for the solar
cell and corrosion protection for the metallization.

The result of that work was the discovery by SEM analysis that
conventional metallization systems are too porous to be protected
in this manner. Not even ion plating could be expected to encapsu-
late such metallization. It was expected however that if the metalliz-
ation could be deposited in a dense, non-porous film, e.g. by ion
plating, then an ion plated AR coating might be used to encapsulate
it, affording corrosion protection.

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It then became necessary to develop ion plated metallization techniques for solar cells to provide the form of metallization necessary for the ion plated AR coating protection scheme. The ITW contract was initiated in December, 1979 to investigate, develop and demonstrate the capability to produce operational solar cells having metallizations and anti-reflective (AR) coatings deposited by gasless ion-plating, which will separately and/or in combination with a low-cost encapsulation system, meet the LSA project life, cost and performance goals.

SECTION III

TECHNICAL DISCUSSION

A. METALLIZATION SYSTEMS

Solar cells are typically made by starting with a silicon wafer which has a particular contaminant (dopant) inherent in the material. This dopant may be either a P-type or an N-type dopant. (P-type doped silicon uses positive holes as the majority current carriers; N-type uses negative electrons as majority carriers. P-type dopants include boron and aluminum; N-type dopants include Phosphorous and arsenic.) By creating a front surface of opposite dopant type, an effective diode is created. Electricity is produced by photon stimulation of the minority carriers which cross the junction (N-P interface) and can not cross back.

Then there are two distinct varieties of single-junction solar cells: P on N type, where the P-type front surface is diffused into N-type silicon; and N on P type, where the N-type front surface is diffused into P-type silicon. It would be naive to expect that one metallization system would work on both types of cells. Therefore we have developed separate systems for the two types of cells. Additionally, the characteristics of the fronts and backs of the various cells are such that one can not expect that what works on the front of one type cell will work on the back of any cell, etc. Then four distinct metallizations are necessary; one for the front and another for the back of two distinct solar cell types.

This work was begun by creating a list of candidate metals and systems of metals which could be investigated for solar cell metallization. The criteria used to create this list include:

1. Consistency with Cost Goals--this generally excluded precious and exotic metals, except for possible use in very thin films.

ii. Non-diffusing--there are several metals which diffuse readily into silicon, causing loss of efficiency because of contamination. If these materials are used, they must be used in conjunction with a suitable diffusion-barrier layer.

iii. Conductivity--Each metal or system of metals must be capable of producing surface resistivities of < 10 milliohms per square in a thickness within the capability of ion plating.

Once a candidate material system had been deposited on a solar cell by ion plating, another set of criteria came into effect including:

iv. Ease of Deposition--it seems little use to develop a system which is inherently difficult to ion plate.

v. Adhesion--although good adhesion is independent of good electrical contact, it does not seem probable that a system with poor adhesion can meet handling and encapsulation requirements or lifespan goals.

vi. Contact Resistance--it is obviously inappropriate to continue development of a metallization system which can not be used to make adequate electrical contact with the solar cell.

It is often advantageous to use a contact layer of a P or N
type dopant material on silicon of the same, P or N, type
silicon, e.g. aluminum on P silicon.

vii. Stress--because of the mode of deposition used and the tem-
perature of the deposited film, it is typical to have a
great deal of tensile stress in the film. This is most
noticably characterized by the film separating from the
solar cell. This usually occurs by causing the silicon
to fracture or separate under the metallization (silicon-
silicon failure rather than failure at the silicon-metal-
lization interface). Some systems prone to this kind of
failure can be corrected by keeping the high stress films
as thin as possible and by adding layers of a ductile
material, such as aluminum.

viii. Interconnectability--It is obvious that a metallization
system which disallows interconnection is of no use. In
the present work, "interconnectability" has implied "solder-
ability". An advantage of ion plating is the ability to
to deposit a solderable film over any other metallization.

Using these criteria, metallization systems were developed for
both P on N and N on P solar cells, which are discussed separately
below.

1. Metallization of P on N Solar Cells

The present work with P on N cells was accomplished using active
wafers supplied by Solar Power Corporation. These wafers were partially

processed in their production process and removed just prior to metallization. Sister cells continued through production to serve as control cells. Another major difference, besides being P on N, between Solar Power cells and those from other manufacturers is that the anti-reflective (AR) coating is inherent in their processing; so the active wafers which were supplied to ITW already had an AR coating.

There were several iterations involved in developing the techniques to determine the best metallization to deposit on these wafers; many of which involved the development of better packaging and shipping techniques for active wafers as well as for finished cells. It was found that any small abrasion on the front surface of an active wafer can cause a site for shorting the junction when the metallization is applied. In retrospect, this seems obvious; however, it was not so obvious at the time and can be understood when one considers that wafers or cells are seldom shipped at these points in the production process.

Having overcome the above problems and reduced the candidate systems to only a few, several solar cells were made with efficiencies equal to or better than the controls. Of course the best cells were made using metal strips applied as busbars and solder-dipped; however, adequate cells were made using only ion plated conductors. Figure 2 shows IV curves for several ion-plated solar cells compared to the controls.
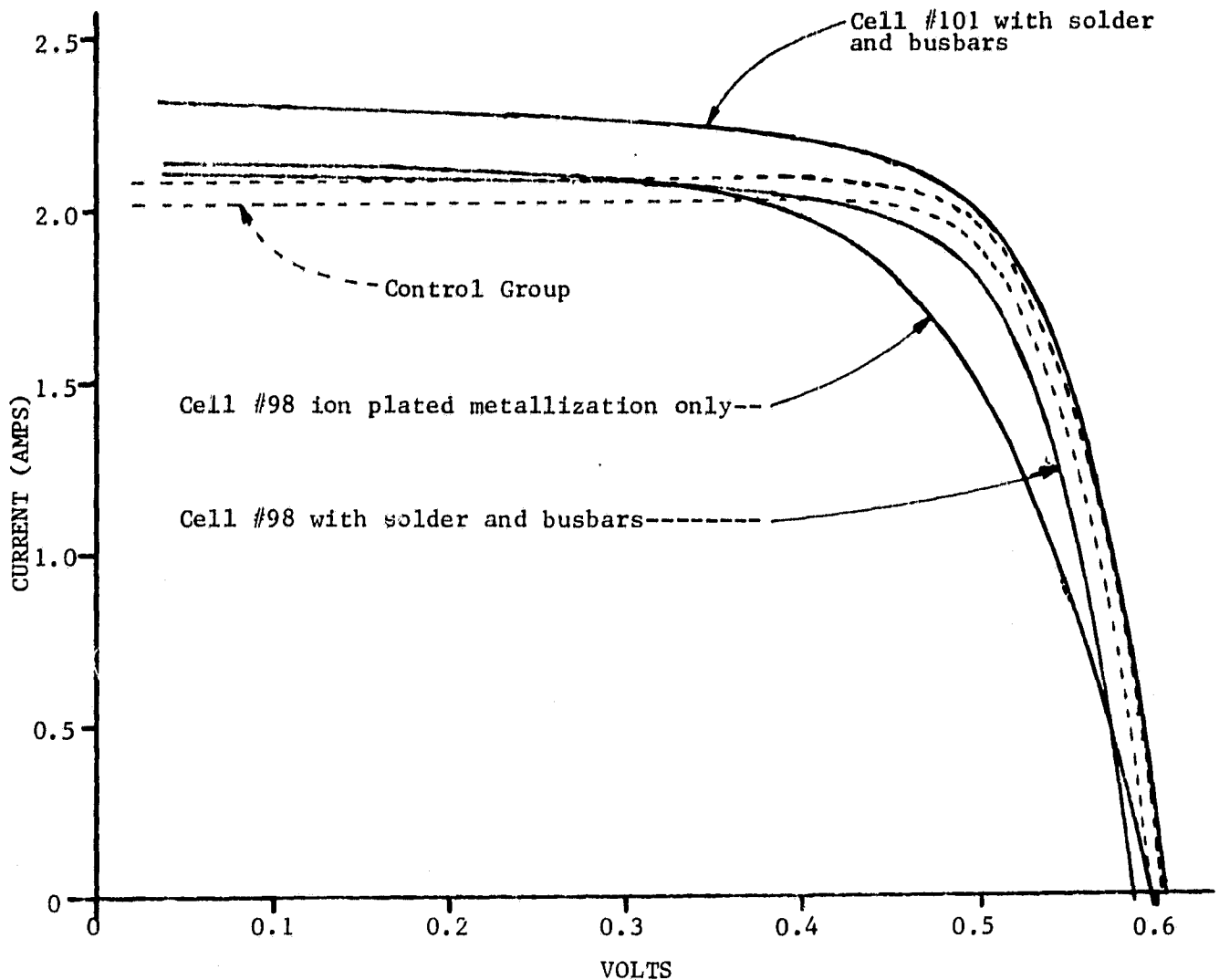
FIGURE 2: Comparison of P on N type solar cells commercially produced by Solar Power Corporation (controls) to those with ion plated metallization. Control group consisted of ten cells -- highest and lowest have been omitted. Cell #101 had narrower grid lines due to offset in plating masks. Note the effect of solder and busbars.

Although the efficiency of the ion plated cells in some cases surpasses that of the controls, the shape of the IV curve is noticably rounded at the corner near the peak power point. (This is indicative of a lower diode fill factor). One concludes that this is somehow a result of the ion plating process; however, many hours of investigation were unable to produce any correlation to any of the process parameters. Additionally, the higher efficiency of some cells could be attributed to somewhat narrower grid lines which resulted from either 1) a slight misalignment of the physical mask (see section III C for further discussion) or 2) a clearing of the edge of the grid lines by solder dipping (i.e. Fuzzy edges which shaded active area but contributed little to conductivity were dissolved and removed by the molten solder.).

The most successful metallization systems for the P on N cells supplied by Solar Power Corp. was determined to be as follows:

Front Surface:	1-3	kA	Nickel
	50-200	kA	Copper
Back Surface:	1-3	kA	Titanium
	10	kA	Alumium
	50	kA	Copper

A flash of tin was sometimes used over both surfaces to preserve solderability. As stated earlier, solder-dipping, especially in combination with additional busbar strips increased the performance of the cells by lowering the series resistance. It should be noted that solder-dipping will probably not fit within allowable cost parameters.

In the above exercises, an important discovery was made concerning the conductivity of ion plated films as a function of thickness. It was found that such conductivity was not directly proportional to thickness as simplistically predicted. SEM analysis revealed that the well known columnar growth characteristic of vacuum deposited films causes a decrease in transverse conductivity (along the plane of the film). This becomes more pronounced as the thickness becomes greater. Although we were unable to exactly quantize this effect it is clear that there is a definite factor of diminishing returns which would help to optimize the thickness of metallization deposited in production. An alternate optimization might be to use ion plating in conjunction with another process, e.g. electroplating. It is reported in section III D that even with metallization totally applied by ion plating, the project cost goals can be satisfied.

2. Metallization of N on P Solar Cells

Having successfully metallized P on N cells, it was expected that the metallization of N on P cells would be straightforward. Such was not the case. After many months of effort trying to develop a metallization system to make a good contact with the P-type back surface, it was found that this could only be accomplished by interdiffusing a P-type dopant material into the back surface.

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In the process which was developed, aluminum is used as the contact metallization and the diffusion is produced by depositing copper over the aluminum at f deposition rate which causes melting or near-melting of the aluminum; the source of heat being the latent heat of fusion of the copper as it deposits as a vapor and undergoes phase transformation to a solid. Although the temperature on the surface is at or near the melting point of aluminum, ~600°C, this temperature is localized and short-lived, less than one minute. We were unable to attribute any ill effects to diffusing in this way. The copper over the aluminum, in addition to supplying the necessary energy to make a good contact, also reduces series resistance and provides a solderable surface.

The work reported here was done using active wafers supplied by Spectrolab. Unlike the P on N wafers from Solar Power, because of process differences, these wafers could not simply be pulled from production lots, metallized, and reinserted. It was necessary to have special wafers processed for this work. Again, control cells were removed from the lot and metallized by conventional techniques, but the resulting cells are not the same as Spectrolab production.

Once a suitable back surface metallization was developed, the front surface metallization was straight forward. Chromium is used as the adhesion-contact layer with an overlayer of aluminum for conductivity and stress relief, followed by Copper for additional conductivity and solderability.

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Figure 3 shows I V curves of some of the cells metallized at ITW compared to controls finished at Spectrolab. It should be noted that the curves for the control cells were made at a much earlier time than those of the ion plated cells. During this time, the controls were destroyed. The calibration of the control runs is now questioned by Spectrolab and since the runs can not be repeated, Spectrolab has advised an adjustment to the data to correct the miscalibration. This adustment is reflected in Figure 3. The much lower currents of these cells when compared to the previous ones is a result of the 2 X 2 inch square format rather than the 4 inch round format.

The metallization systems used for these cells were as follows:

Front surface:	1	kA Chromium
	10	kA Aluminum
	50-200	kA Copper
Back Surface:	10	kA Aluminum
	50	kA Copper

This was, in fact, the only system which was found to perform for N on P solar cells.

Because of the many months developing this technique, there was no time to further optimize N on P cell performance. The rounded corners and low fill factors which were seen on several of the cells are indictive of the high series resistance which occurs as a result of insufficient plating thickness. None of these cells, including those which equal the controls, were solder-dipped.
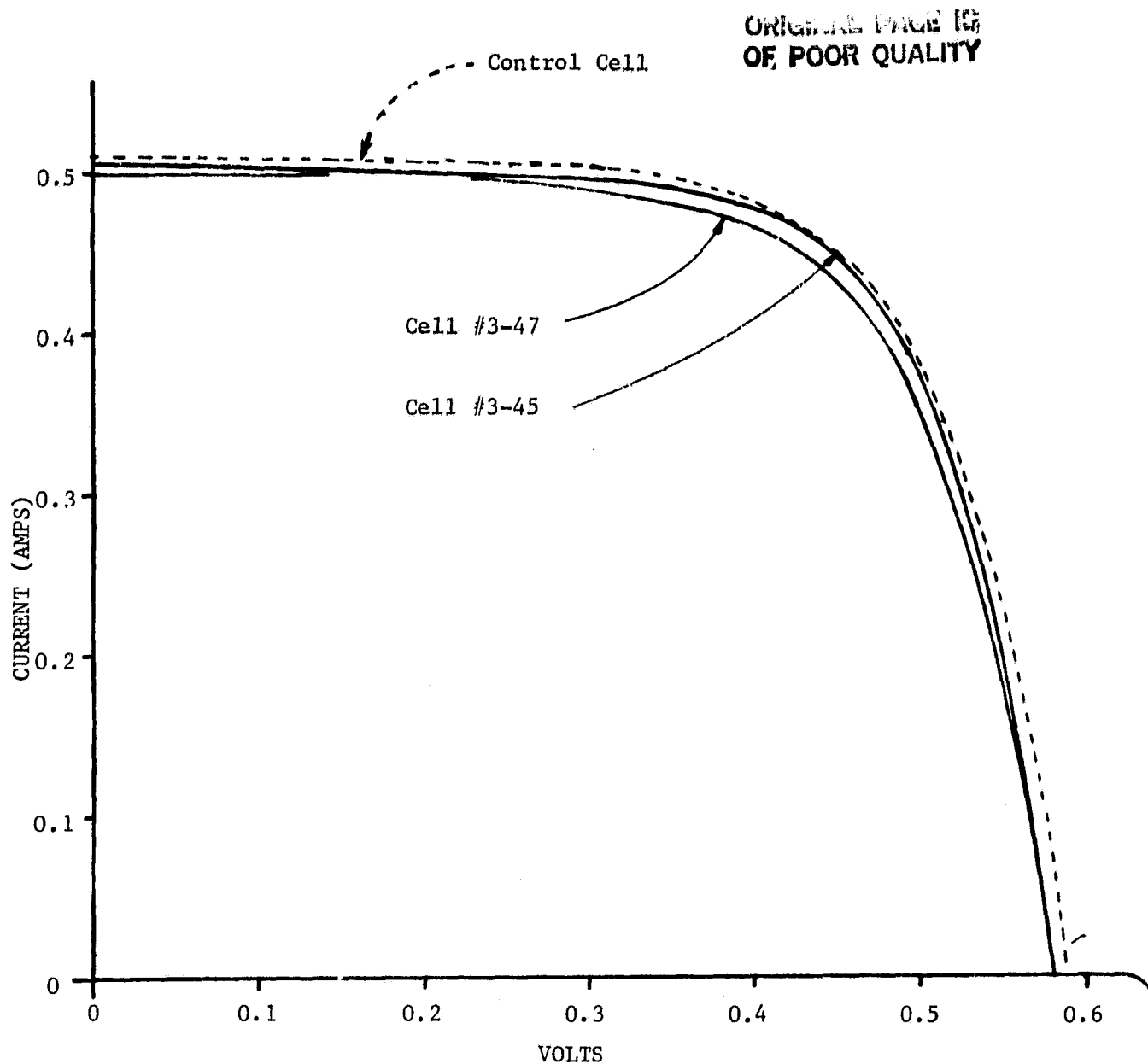
FIGURE 3: Comparison of N on P type solar cells with conventional metallization (controls) prepared by Spectrolab, Inc. to cells with ion plated metallization. Control curve has been nomalized to reflect change in calibration. Ion plated cells are ion plated only, no solder or busbars.

3. General Techniques

Table 1, below, summarizes the ion plated metallization systems
which have been shown to produce solar cells equal to or better than
those with conventional metallization. All of these films are depos-
ited by straightforward ion plating techniques with the possible
exception of the N on P back surface which requires careful control
of the deposition rate, although the technique is otherwise the same.
The remainder of this section contains a step-by-step procedure as
used to make a deposition of any of the films in table 1. Although
this process has been performed on only one wafer at a time, there
are no limitations in the process which disallow production type
processing. In Section III D, a machine is proposed which would
metallize both sides and apply AR coating in a continuous production
process.

TABLE I: Metallization systems for ion plated contacts on front
and back surfaces of P on N and N on P wafers.

WAFER TYPE	FRONT SURFACE	BACK SURFACE
P on N	1-3 kA Nickel 50-200 kA Copper	1-3 kA Titanium 10 kA Aluminum 50 kA Copper
N on P	1 kA Chromium 10 kA Aluminum 50-200 kA Copper	10 kA Aluminum 50 kA Copper

ION PLATING PROCEDURE

i.) Start with clean vacuum system and evaporation sources. If sources are reused, be sure they are not contaminated from previous run.

ii.) Load material into evaporation sources. Since we are using tungsten coils and firing to completion, material must be loaded for each deposition. As many as four sources were available for this work.

iii.) Inspect wafer for oxide layer or other contamination. Like any other metallization system, ion plating can not make contact through dirt on SiO_x.

iv.) Place wafer on magnetic chuck and install mask. In this work, a magnetic chuck was used to hold the mask in close contact with the wafer.

v.) Place chuck under shutter. In the particular geometry used herein, the substrate was rotated on a platform from under a stationary shutter. The evaporation sources were placed in order along the path of rotation.

vi.) Close chamber and evacuate to a base pressure of $\sim 5 \times 10^{-5}$ Torr.

vii.) Admit argon to a pressure of $\sim 5 \times 10^{-4}$ Torr.

viii.) Apply rf and DC power to cause back-sputtering and surface activation.

ix.) Remove argon from system.

x.) Start heating first evaporation source. When evaporation begins and stable plasma is established...

xi.) Rotate platform to place wafer under first source. As first source nears completion...

xii.) Start second source. As plasma is established...

xiii.) Rotate wafer to second source. (The best procedure is to grade the sources so that both sources are on together for a short time; this assures a good interface.)

xiv.) Continue in this way from source to source.

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Special Note: As previously discussed, successful contacts on the back surface of N on P cells requires that the copper layer be deposited at a controlled rate. The geometry and process used herein required that 50-60 kA copper be deposited in $\sim$ 20 seconds.

xv.) When last source is depleted, turn off all sources and rf and DC power supplies.

xvi.) Cool. An objective study of cooling times was not performed in this work. Obviously, one would not wish to admit oxygen or air while the wafer is at elevated temperatures (which will be no higher than $\sim 200^0$ C within a few seconds of shut-off). But it might be quite allowable to admit some other gas, e.g. nitrogen, immediately.

xvii.) Vent vacuum chamber.

xviii.) Remove wafer.

B. INVESTIGATION OF ION PLATED AR COATINGS

Anti-reflective coatings have been deposited by vacuum deposition for several years. So it does not seem unusual that ion plating be used for this purpose. The present work, however, included efforts to 1) investigate the ability to increase cell efficiency by use of a new (not easily deposited by other processes) or more functional (e.g. conductive) AR coating and 2) to investigate the encapsulating effect of ion plated AR coatings when deposited over ion plated metallization. Unfortunately, the development of the various metallization systems required considerably more time and effort than was originally allotted, thus diminishing the available resources for work on AR coatings. Despite the difficulty, however, some very meaningful work was done especially in the encapsulation area.

1. AR Coating Techniques and Materials

The technique used for deposition of AR coatings is very similar to the one described in Section III.A.3., with the following exceptions:

i) For many AR materials, a different evaporation source is used to prevent large pieces from "jumping" out of the source. In the present work, a "baffle-box" supplied by R. D. Mathis and Co. was employed.

ii) A make up gas is required for certain materials, e.g. Al_2O_3, which decompose at evaporation temperatures. The pressure of this gas was $\leq 5 \times 10^{-4}$ Torr.

iii) Most importantly, since AR coatings are effective only at very specific thickness, the thickness of the deposit must be precisely controlled. In this work, the thickness was controlled by running the evaporation source at a specific power level and calibrating thickness to the time of exposure to the source. As in the previous work, the substrate could be rotated out from under and in behind a stationary shutter.

Using the above techniques with small modifications for various deposition materials, several AR coating materials were deposited. These included:

i. Indium-tin oxide $(InO)_x \cdot (SnO)_4$, ITO

ii. Aluminum Oxide Al_2O_3

iii.	Tantalum pentoxide	Ta_2O_5
iv.	Magnesium difluoride	MgF_2
v.	Silicon monoxide	SiO

Of these, only the first, ITO, is a conductive material. ITO, tin oxide doped with indium is a transparent material which can have a bulk resistivity approximately the same as that of the diffused front surface of a solar cell. Then the extra thickness of conductive material can reduce the series resistance associated with transverse current above the junction. In the present work, there was little effort dedicated toward the development of ITO deposition techniques. It was expected that the conductive AR would be used to enhance the performance of good cells.

The Al_2O_3 and TaO_5 coatings were deposited in an atmosphere of $\sim 5 \times 10^{-4}$ T of oxygen since both decompose at evaporation temperatures. Although some success was attained, the deposition was difficult in that the stoichiometry of the film was difficult to control. Additionally, their relatively high indices of refraction require even greater control of film thickness since the window of tolerance is reduced in size. Because of these difficulties, and since other candidates were available without these disadvantages, further work on Al_2O_3 and TaO_5 was postponed.

Both MgF_2 and SiO have been used for optical AR coatings on glass, deposited by vacuum evaporation, for many years. Depositing these materials by ion plating techniques should provide excellent adhesion

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to both the silicon wafer and the metallization pattern, as well as provide complete coverage of microscopic edges, steps, etc. Both these materials have been deposited successfully in the present work. However, SiO was chosen as the primary candidate for the encapsulation work reported below, mostly because of its lower index of refraction (n=1.4) which allows both a wider acceptance window and a thicker film. One assumes that a thicker encapsulating film can only be a benefit in protecting the metallization underneath it.

2. Corrosion Tests on AR-encapsulated Metallization

In order to determine the effectiveness of SiO films as an encapsulant, a series of wafers were metallired on both sides with a titanium-copper metallization pattern. These wafers were suspended in a 100% relative humidity environment for up to six hours at temperatures of 85-90^{0}C.

The results of these test were quite 'ramatic. They are tabulated in table 2. The side without the ion plated AR coating shows signs of tarnish, etc. even after only one hour. After six hours, it was severly corroded. The protected side, on the other hand, showed no signs of deterioration of the metallization after six hours, although the AR coating itself appeared to "yellow" on some of the wafers.

Of course, on such a limited data base, one must be careful of his conclusions. But certainly positive evidence in support of the original hypothesis has been demonstrated. If a front surface

TABLE II: Comparison of the effect of exposure to 100% humidity
at 85°C on the surfaces of a silicon wafer with Ti-Cu
metallization, one surface being coated with 1 kA SiO
by ion plating. NE: No significant effect.

WAFER	EXPOSURE TIME (hours)	COATED SURFACE 1 kA SiO	UNCOATED SURFACE
3-30	1	NE	Tarnished Appearance ↓
3-28	2	NE	↓ ↓
3-26	3	NE	↓ Effects of ↓ corrosion
3-29	4	Slight yellow appearance (AR was deposited in two depositions. Places covered by only one layer showed NE.)	↓ increse with ↓ exposure ↓ ↓ ↓ ↓
3-21	6	NE	Severely Corroded

protection system could be developed in which the AR coating provided
encapsulation of the metallization, then the requirements on other
members of the system could be relaxed. This could well lead to the
ability to use even less expensive encapsulation materials.

C. OPTIMIZATION OF GRID PARAMETERS

Anyone who has ever done even a quick analysis of how to in-
crease solar cell efficiency by adjusting the metallization grid has
quickly come to two conclusions, specifically:

i) The grid lines should be as narrow as possible.

ii) The metallization pattern should be as conductive as
    possible.

A more sophisticated analysis will trade off these elements
against increased cost etc., but the above statements are . ver
doubted.

Once practical (cost compatible) limits can be assigned to the
minimum line width and the minimum resistivity of the metallization,
a computer may be utilized to determine the optimum parameters
for the grid, e.g. line spacing, bus width and spacing etc. The
computer analysis in the present work was performed by Dale Burger
at JPL.

1. Process Limitation.

As reported in section III.A.3, the present work involves the
use of physical masking techniques. (It is a simple exercise to cal-
culate the expense of photo-masking, etc. to find that such techniques
are too expensive to be compatible with LSA cost goals.) The physical
masks which we are using can be made to be reusable indefinitely and
require little incremental expense once they are fabricated. Then the
question of minimum line width requires the consideration of two
criteria: i) Through how small a slot can ion plating be deposited?
And ii) How small a slot can be made economically?

The answer to the first question is determined by how thin the
mask material can be, since one expects to deposit economically to
about 2 times the slot width. Experience in the present work has shown
that the mask should be at least .006" in thickness with a second
mask (which may have larger solts) over the first to receive the
extraneous metallization which will be deposited indiscriminately.
This metallization would cause warpage of the thin mask. Then the slot
could be a minimum .003" in width.

Producing masks in quantity, however, with .003" slots can be
very expensive. Masks used in the present work were made by wire EDM
with a minimum of .007" width. This technique is not practical for
production quantities. The only production process which might pro-
duce the desired masks economically is chemical etching. The SAMICS

analysis in section III.D. uses chemically etched masks. However, in the present work a very inexpensive masking system was developed.

The least expensive way to put slots in a metal sheet is by stamping. Once a die is made, the incremental cost of each successive pattern is little more than the cost of the material. Although the registration (position) of a slot can be held within a very small tolerance in stamping, the width of a slot can not be so small that the punch would be too weak to be useful. Figure 4 shows a cross-sectional view of how the accuracy of placement characteristic of stamping can be used to provide a masking technique for slots much thinner than could be made in a simple stamping. With this geometry masks for grid lines of .002"± .001" in width can be economically produced.

2. Computer Optimization

Information regarding ion plated metallization patterns and standard parameters of the wafers in use were sent to Dale Burger at JPL for use in his CELCAL program. The information supplied for this analysis is as follows:

    i.   cell geometry: 100 mm diameter
                                        .51 mm thick

    ii.   bulk resistivity of Si: 1.0 $\Omega \cdot$cm

    iii.   surface resistivity
            of front surface: 30 Ω/sq.

TOP MASK

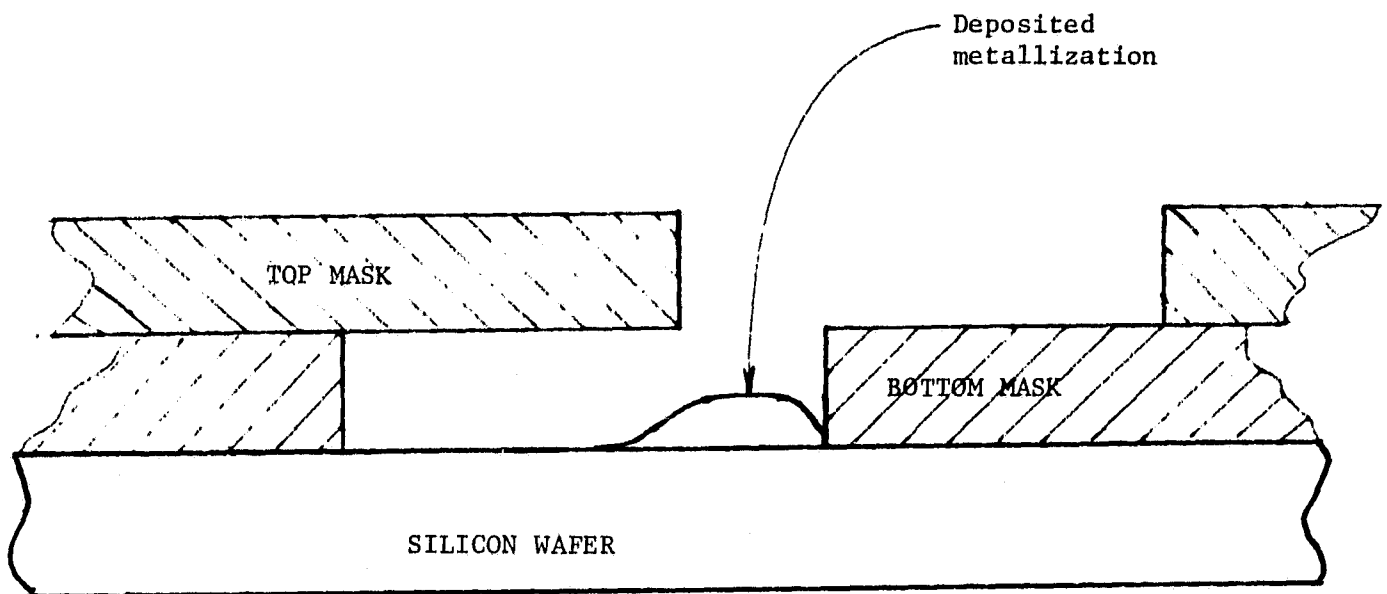Deposited
metallization

BOTTOM MASK

SILICON WAFER

FIGURE 4: Method of offsetting masks in order to make grid lines
narrower than slots in masks. Masks shown are .005"
in thickness; slots are .020" in width. Deposited
metallization is exaggerated about ten times vertically.
Using this technique, masks can be produced by an inex-
pensive process such as stamping.

iv. front metallization*:   1 kA Ni
                                30-100 kA Cu
                                1 kA Sn
                                $\rho = (.53t + 1.06)$ $\mu\Omega\cdot cm$
                                where t=Cu thickness
                                in microns

v.   back metallization: 3 kA Aluminum
                                50 kA Copper

vi. contact resistance
                    front: .012 Ωcm^2

                     back: .124 Ωcm^2

vii. line width
                 minimum: .002"

               tolerance: ±.001"

Using this information, Burger came up with "nominal" design

parameters assuming the application of .0025" copper bus strips.

These parameters are:

   i) front metallization
                thickness: 4 microns

  ii) line width: .003"±.001"
                                (.0076±.0025cm)

 iii) line spacing: .080"
                                (.200cm)

These parameters are, of course, for a round cell with buses-

not the expected configuration of mass produced cells of the future.

However, the ability to deposit fine lines and the use of computer

analyses of this type will together provide optimization of the grid

pattern for any cell geometry.

* It was reported in section III.A.3. that increasing thickness of
ion plating has decreasing effect on conductivity. This equation
for ρ reflects this effect and is roughly applicable to films of
1 to 7 μ in thickness.

D. SAMICS Analysis

Part of the objective of the present work is to show that ion plating as a process has the capability of meeting LSA cost goals for metallization and AR coating. Several economic analyses were conducted at ITW, based on 500 megawatts (Mw) per year, which showed ion plated metallization to cost about half the 1976 goals ($0.07/watt). However, it was decided that a detailed analysis using SAMICS be performed to see if a smaller production facility could produce ion plated cells economically.

In this exercise, a continuous ion plating machine would metallize and AR coat thirty-six solar cells per minute. Such a machine is shown in Figure 5. A plant using six such machines could produce 50 Mw of solar cells per year. Physical masks would be used and the facility would include a machine for cleaning the used masks. Initial cost of all equipment was projected to be $3.3 million and last for 10 years. Other inputs into the SAMICS program include utilities, direct and indirect labor, floorspace, materials used, etc. The process and materials envisioned for this analysis were essentially those reported in section III A and B although the exact metallization systems had not been determined. This is not seen as a significant perturbation on the analysis.

PALATES ARE INVERTED & CONTRACT MASKING
SEPARATED FROM FRONT SURFACE

FRONT SURFACE
AR COATING

BACK SURFACE
COPPER: ~15C KÅ
BACK SURFACE
AL/TI ALLOY: 1 KÅ

FRONT SURFACE
TIN: 1 KÅ

FRONT SURFACE
COPPER: ~400 KÅ

FRONT SURFACE
NICKEL: 1 KÅ

25 INCHES SQUARE PALATE HOLDS 36
100MM CELLS, FRONT SURFACE DOWN
AGAINST CONTACT MASK.
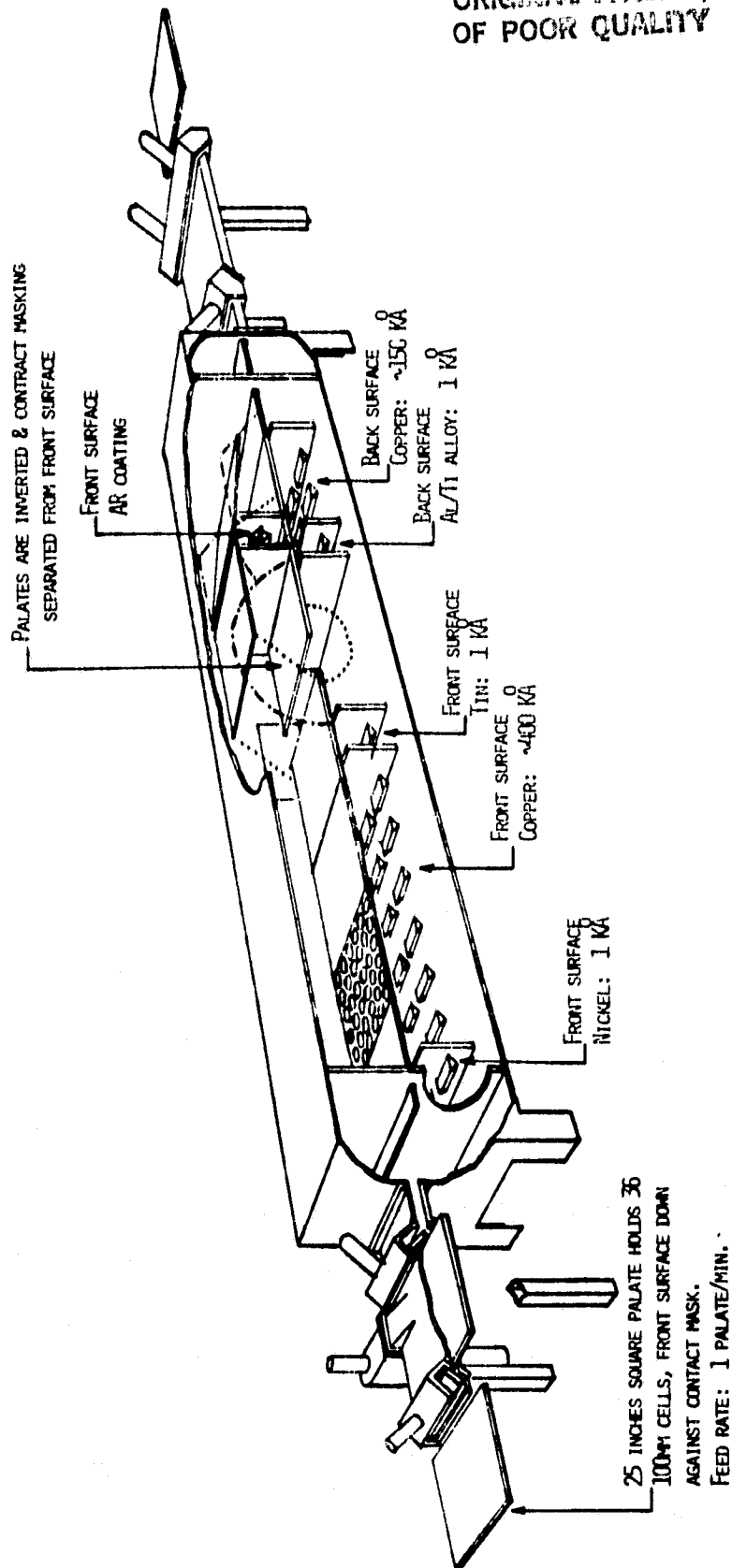FEED RATE: 1 PALATE/MIN.

FIGURE 5: Cutaway view of a conceptual machine for metallizing and AR coating solar cells.

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Having detailed the process and costs as much as was possible, the SAMICS program yielded $0.069/watt as the true cost of ion plated metallization and AR coating in 1980 dollars. This amount is within the acceptable limits for such costs. The only caveat which seems appropriate is that this analysis was for a 50 Mw facility--there are certain to be lost economies when production is based on a smaller scale.

SECTION IV

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

During the work on this contract, ITW has developed and defined an ion plating process by which solar cells can be metallized and AR coated yielding efficiencies equal to or better than state-of-the-art cells. ITW has suggested techniques which might be employed to produce cells of even higher efficiency. Additionally, it was demonstrated that ion plated AR films may be used as an effective encapsulant, offering primary protection for the metallization. It was also shown that ion plated metallization and AR coatings can be consistent with the project cost goals.

Although further development of ion plated metallization techniques might lead to improved cell efficiency, the greatest contribution to the eventual widespread use of photo-voltaic solar energy involving ion plating techniques may come from the encapsulating ability of ion plated AR films. The primary protection of the cell and metallization afforded by gasless ion plating may open the door to new and better encapsulation techniques which could ultimately change present array concepts and significantly reduce existing economic barriers. Certainly, the initial evidence in this report mandates further investigation of this application of ion plating.