Periodic Progress Report

RESEARCH AND DEVELOPMENT OF ELECTROFORMED ALUMINUM
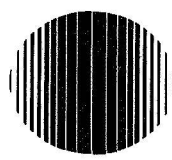SOLAR CELL CONTACTS AND INTERCONNECTS

Prepared for

California Institute of Technology
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, California 91103
Attention: Mr. Mark Beckstrom

JPL Contract No. 952485

EOS Document 4039-Q-1   21 October 1969

ELECTRO-OPTICAL SYSTEMS

A XEROX COMPANY

PASADENA, CALIFORNIA 91107 · 213/351-2351

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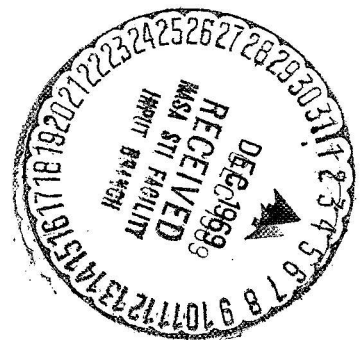
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ABSTRACT

Work is reported on aluminum-contact solar cells using the
aluminum electroforming technology. The results of studies
in photoresist masking, optimization of the plating process,
and the effects of sintering are reported. The production
of electroformed aluminum-contact cells with greater than
10% AMO efficiency is reported, using SiO antireflection
coating and no cover slips.

CONTENTS

SECTION 1

INTRODUCTION

This report covers the technical progress accomplished under JPL Contract 952485, "Research and Development of Electroformed Aluminum Solar Cell Contacts and Interconnects," for the period of June 5 to October 4, 1969. The program is divided into three main tasks. These are:

    I.   Development of Electroformed Aluminum Contacts

    II. Development of Electroformed Aluminum Intercell Connectors

    III. Fabrication of Multicell Matrix

The tasks are to be accomplished consecutively. All the effort in this period has been devoted to Task I. The primary program objective is to develop a one-step process of electroforming the contacts and interconnections of solar cells. The achievement of such a goal will reduce solar array costs. The resultant solar array will be lighter in weight and will withstand higher temperatures, since no soldering will be required. The technical goals are to improve solar cell performance and increase the reliability of solar cell contacts and interconnects.

SECTION 2

SUMMARY

All the process parameters for fabricating the ·electroformed aluminum
contact solar cell from n/p silicon wafers were individually investi-
gated. The individual parameters, which include masking, electrodeposi-
tion, and silicon monoxide antireflection (AR) coating, were optimized
and integrated in producing a desirable electroformed aluminum contact
solar cell. The results of these studies have led to the following
conclusions:

    a. The photoresist technique produces the most durable and de-
finitive mask.

    b. The most desirable aluminum contact material is obtained when
it is electrodeposited under the following conditions:

Aluminum bath composition:

      $AlCl_3$: 3.4 molar

      LiAlHg: 0.3 molar

      Solvent: anhydrous ether

Current density: 15 A/ft^2

Temperature: 22° to $25^\circ C$

    c. A contact adhesive strength of > 2,000 grams (Hunter pull tester)
is obtained when the aluminum electrodeposit on the silicon
wafer is heated for two minutes in a $350^\circ C$ oven.

    d. The cell peak power increases 15% to 17% (η increases $\approx 1.8\%$).
When a 1400-angstrom layer of silicon monoxide AR coating is
applied to the bare electroformed aluminum contact solar
cells.

    e. The "weak knee" and V_{oc} of the electroformed aluminum contact
solar cells can be improved by etching the edges of the cell
in hydrochloric acid, which probably removes the minute amount
of aluminum electrodeposited across the n-p junction.

Electroformed aluminum contact solar cells produced by the process as
developed during the reporting period have an efficiency of greater
than 10% at AMO.

SECTION 3

TECHNICAL EFFORT

3.1 CHOICE OF SILICON WAFER

A solar cell is composed of two entities: the silicon wafer and the metal contacts. In selecting a silicon wafer to be combined with electroformed aluminum contacts, one must consider the following: (1) the surface finish of the wafer, i.e., whether the surface is active or inactive, (2) the depth and conductance of the diffused layer, and (3) standardization, i.e., whether the cell is capable of being compared with some known cell.

The conventional Ti-Ag contact cell uses a polished surface. The accepted reasons for this are that the diffusion profile normally follows the surface profile, therefore, a polished surface probably results in a new uniform diffusion layer or a "straight" junction, and vapor deposition of Ti-Ag is better onto a polished surface than rougher surfaces. In the electroformed aluminum contact, a rougher surface is more desirable because the roughness tends to anchor the aluminum and thus prevent the curling up of the grids and premature peeling of the contacts.

No definite conclusions can be made as to how the diffused layer characteristics of a rough surface compare to those of a polished surface. Recent results of Tsai[*] indicate that there is no significant difference in shallow phosphorus diffusion profiles in silicon between the lapped (rougher) surfaces and the polished surfaces. The diffused layer has been fixed at 0.3 micron to provide a shallow junction for the highest efficiency. The sheet resistivity of such material composite is fixed at 34 ±12 ohms/square.

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[*]Joseph C. C. Tsai, "Shallow Phosphorus Diffusion Profiles in Silicon," Proc. IEEE, Vol. 57, No. 9, September 1969.

The other consideration in selecting the silicon wafer is that the performance of the finished cell with electroformed aluminum contacts can be directly compared with an acceptable flight-type Ti-Ag contact solar cell. It is no coincidence that the silicon wafer used as the starting material has the same specified properties as the MM'69 solar cell bulk material. It was chosen so that the performance of the finished cell with the electroformed aluminum contact can be compared directly with an acceptable flight-type Ti-Ag contact solar cell. The diffused n/p silicon wafers have been procured with the following specified properties:

Dimensions: 2 cm x 2 cm x 0.1 cm

Finish: lapped finish on p side and 5μ finish on the active side.

Base resistivity: 1 to 3 ohm-cm

Diffused junction depth: ≈0.3μ

Sheet resistance: 34 ±12 ohms/square

3.2 THICKNESS OF CONTACTS AND CONTACT GEOMETRY

The thickness of the aluminum contacts must be evaluated on the basis of electrical resistance (potential drop), stress, and weight. It has been calculated that the electrical resistance is at an acceptable level if the thickness is approximately 0.0005 inch. This calculation is presented in Appendix A.

A thickness of 0.5 mil would provide a pore-free, continuous layer of aluminum. The voltage drop across the grid line (MM'69 solar cell configuration) is 9.0 mV. Further considerations are: (1) the stress experienced for this thickness of aluminum on a 15-mil silicon wafer during thermal shock cycling; and (2) the required mechanical properties of the aluminum for a reliable contact. A calculation shows that the stress experienced in the thermal shock cycling is about three times the yield strength of the aluminum. However, the elongation of the
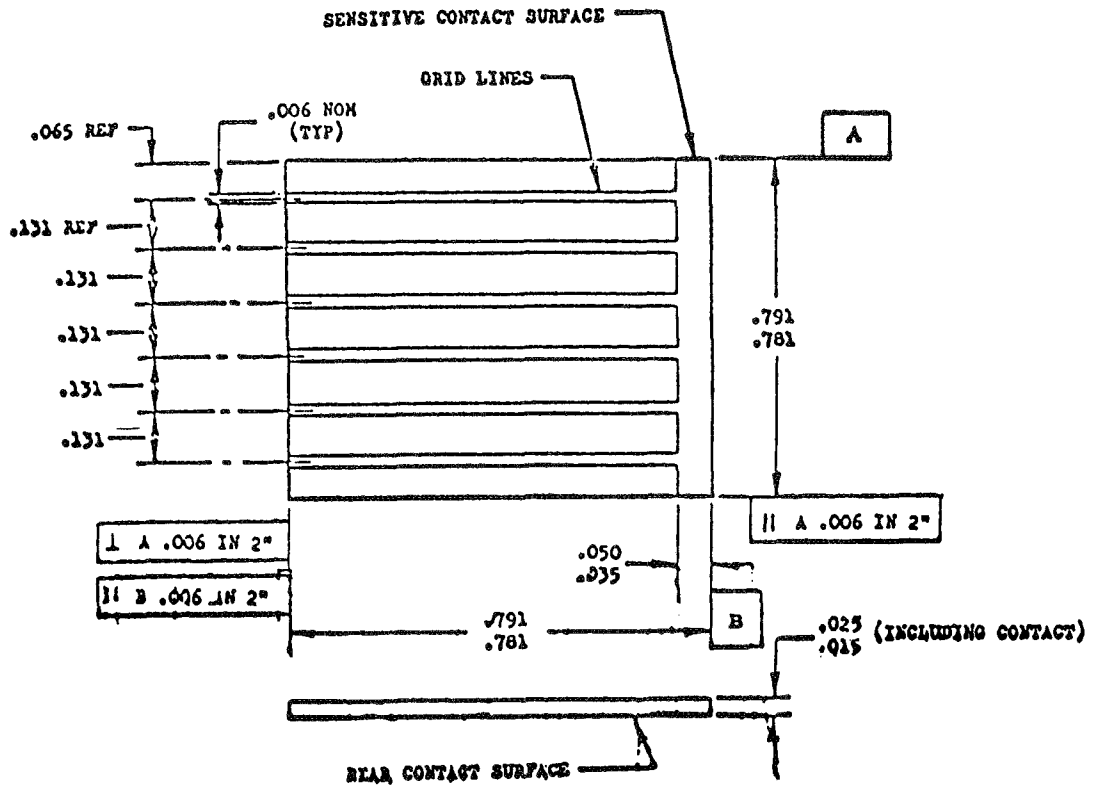
electrodeposited aluminum with this yield strength and modulus is approximately 26%. Thus, failure of the aluminum-silicon bond due to yield is prevented by the compensating flexing due to the high elongation of the aluminum. These calculations of thermal stress in the aluminum-silicon bond are presented in Appendix B.

Initially, the contact configuration was that specified for the MM'69 cell (Fig. 1). The contact has been modified several times to correct for plating over the cell edge, which caused shunting, and to upgrade the cell performance. The final evolved contact geometry configuration is shown in Fig. 2. The ohmic bar contact is relocated approximately 10 mils from the edges to lessen the probability of the electroformed aluminum growing over the edges. The grid lines are properly tapered so that a more uniform voltage drop is maintained over the entire length of the grid.

3.3 MASKING STUDIES

Several different techniques for masking the silicon wafers were evaluated during the reporting period. The three types of masking materials tried were photoresist, polyethylene emulsion, and rubberized ink. Masking is required to define the areas to be plated and thus achieve the desired contact configuration. The three major requirements for the masking material are that it must: (1) be stable in the electrolyte, (2) offer good definition, and (3) be easy to apply.

The polyethylene emulsion is a slurry of fine raw polyethylene powder in alcohol. To make a polyethylene mask, the required deposition areas are first screened off. The polyethylene emulsion is brushed on and the piece is heated at 125°F for 20 minutes. During the heating period the alcohol is evaporated and the raw polyethylene is cured. The screen is peeled off and the unscreened area is covered with a thin sheet of polyethylene.

SENSITIVE CONTACT SURFACE

GRID LINES

.006 NOM (TYP)

.065 REF

A

.131 REF

.131

.131

.131

.131

.791
.781

⊥ A .006 IN 2"

‖ A .006 IN 2"

‖ B .006 IN 2"

.050
.035

.791
.781

B

.025 (INCLUDING CONTACT)
.015

REAR CONTACT SURFACE

I. Material:
    Phosphorous diffused "P" doped silicon .

NOTES: Optical Coating:
    a. Silicon monoxide.
    b. Minimum reflectivity in the 0.6 - 0.8 micron region .

NOTES: 1. Part Number Example . . . . DS 116-1

2. Mechanical and Electrical Characteristics:
    See Procurement Specification.

3. Dimensions are in inches, unless otherwise specified.

4. Part marking shall be per Procurement Specification and consist
    of the following information:
    a. Part number (see Note 1.)
    b. Serial number.
    c. Date Code.
    d. Manufacturer's identification.

5. Packaging:
    See Procurement Specification.

6. Acceptance:
    Acceptance testing as required per Procurement Specification.

7. This standard takes precedence over documents referenced herein .

Figure 1. Solar Cell-Silicon Photovoltaic
(Taken from JPL DS 116)

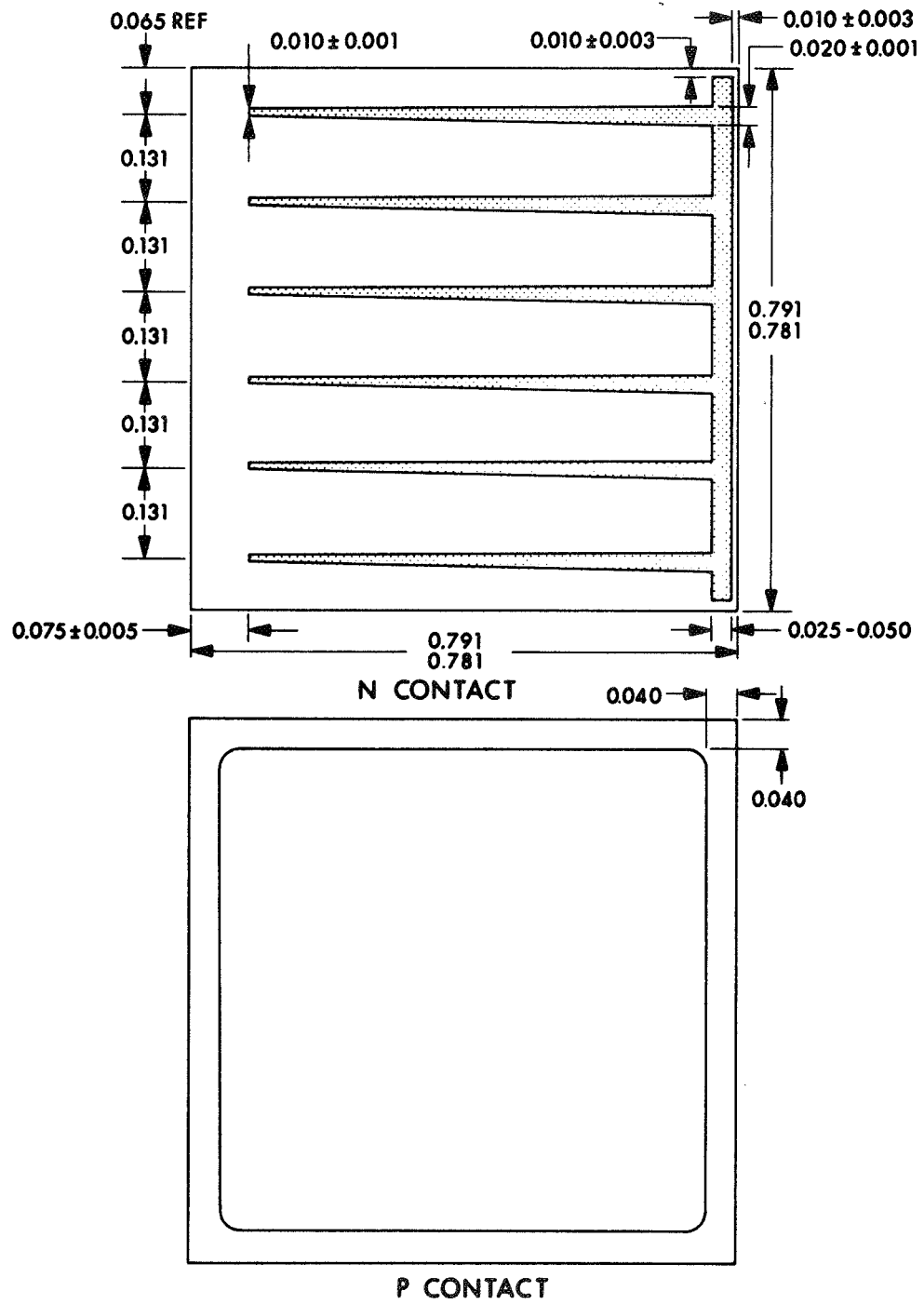0.065 REF
0.010 ± 0.001
0.010 ± 0.003
0.010 ± 0.003
0.020 ± 0.001
0.131
0.131
0.791
0.781
0.131
0.131
0.131
0.131
0.075 ± 0.005
0.791
0.781
0.025 − 0.050

N CONTACT

0.040
0.040

P CONTACT

Figure 2. Solar Cell with Tapered Grid Lines

36057

It was found that the polyethylene coating offers insufficient definition for thin grid lines. The ink was tried only once and was discarded because it decomposes in the plating solution.

The photoresist technique appears to provide both good definition and compatibility with the ethereal electrolyte. Some of the first samples have shown some pores, but this porosity has been practically eliminated by proper adjustment of the combination of the viscosity of the photoresist material and the spin rate. Occasionally there were a few specks of aluminum deposited through the mask, but they usually came off with the subsequent stripping of the mask. The procedure for masking silicon wafers using the photoresist technique is presented in Appendix C.

3.4 OPTIMIZATION OF THE ELECTROFORMING PROCESS

The complete electroforming process may be divided into three phases: (1) the preplating treatment, (2) the electrodeposition of the aluminum, and (3) the removal of the electroformed aluminum contact solar cell from the mandrel (holding fixture), shown in Fig. 3. There are two steps in the preplating treatment: (1) removal of surface dust and grease with solvents and (2) removal of surface oxide with etchant. A variety of solvents can be used, but cleaning the wafers ultrasonically in trichloroethylene is the method adopted because this particular cleaning step is also suitable for use in the masking process, utilizing common equipment and material. The degreased wafer is lightly etched in a mixture of ammonium fluoride and hydrofluoric acid (10:1 by volume) to remove surface oxide. The etching solution is diluted with successive portions of ethyl alcohol and finally is washed with anhydrous diethyl ether. Because of the number of electrolysis tests involved, a special electrolysis test cell has been designed so that as many as ten such cells can be connected in series during an experimental run. A diagram of the plating test cell is shown in Fig. 4.
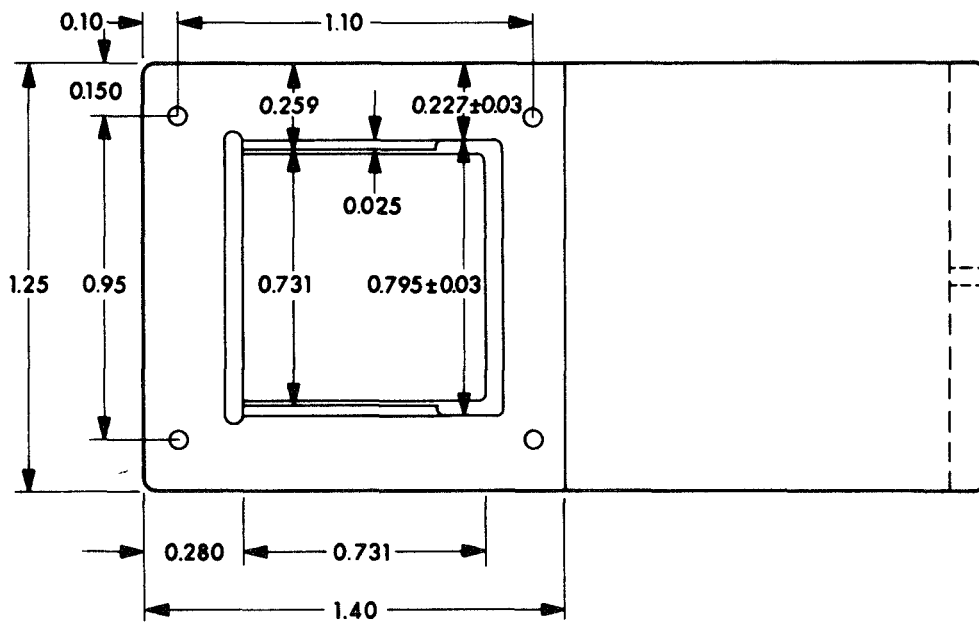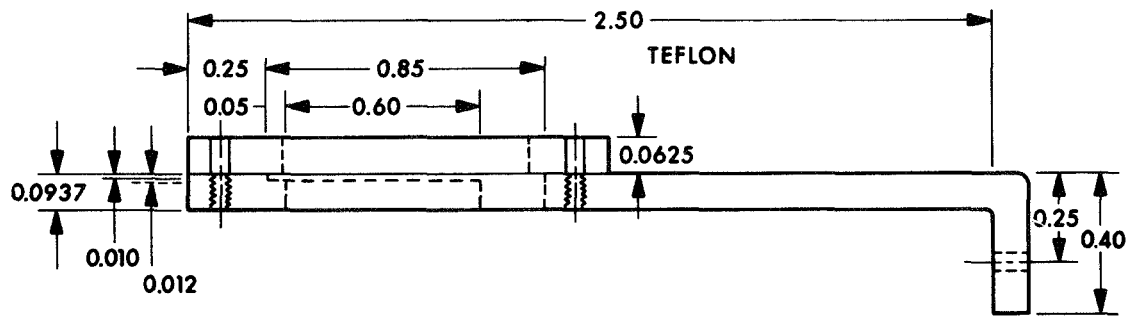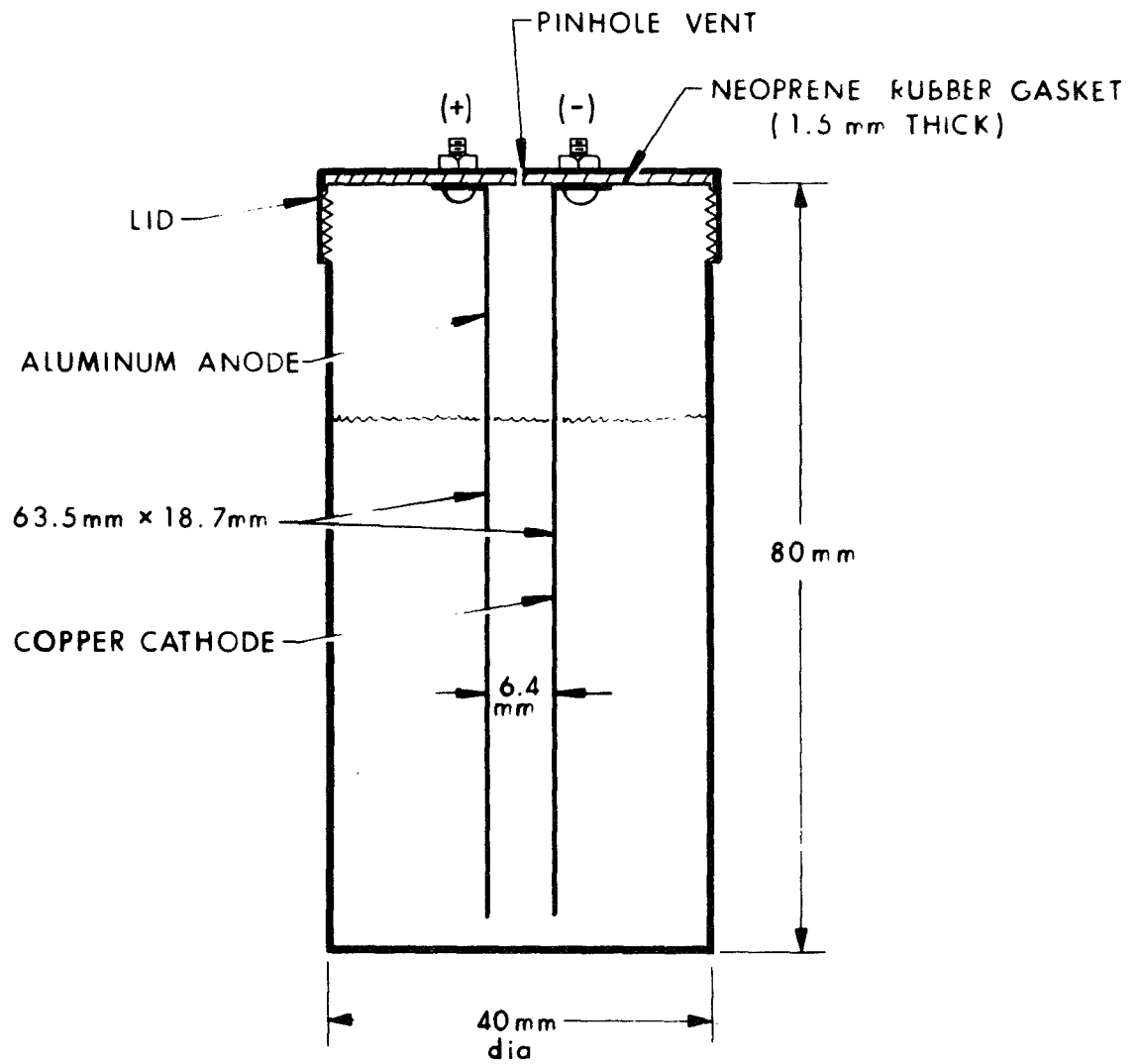
Figure 3. Plating Fixture

PINHOLE VENT

(+)   (−)

NEOPRENE RUBBER GASKET
(1.5 mm THICK)

LID

ALUMINUM ANODE

63.5mm × 18.7mm

COPPER CATHODE

6.4 mm

80 mm

40 mm dia

ELECTRODE AREA = 6.05 cm^2

Figure 4. Plating Test Cell

In the electrodeposition study, three plating baths were evaluated by comparing the quality of the thin layers of aluminum electrodeposited and the relative mechanical properties of the aluminum. The pyridine additive bath produces the highest tensile yield strength. However, the pyridine itself was found to be incompatible with the masking material. The mixed ether also has better mechanical properties than the National Bureau of Standards (NBS) bath, but at a thickness of about 0.5 mil the electrodeposit has some pores. The aluminum electrodeposited from the NBS bath has a yield strength of only 11,000 psi but provides a pore-free deposit at 0.5 mil. Also, the photoresist mask is stable in this bath.

A goal of our effort during this period was to optimize the NBS bath to increase the yield strength with minimum alteration in other mechanical properties and chemical characteristics. It was found that by changing the lithium aluminum hydride concentration from 0.5 molar to 0.3 molar, the yield strength is increased to 15,000 psi. The modulus of elasticity remained unchanged at 9×10^{-6} psi, the elongation decreased from 26% to 24%, and the photoresist mask remained stable. The aluminum plating bath to be used in this program will be referred to as the modified NBS bath. Its chemical composition is as follows:

Aluminum chloride	3.4 molar
Lithium aluminum hydride	0.3 molar
Solvent (anhydrous diethyl ether)	

The plating parameters required to be investigated using the modified NBS bath are current density and temperature. The most desirable plating conditions would consist of plating in the shortest possible time at ambient temperature. These conditions correspond to electrodepositing at the highest permissible current density but with an acceptable temperature rise contributed by the accompanying I^2R heating. Current density not only is directly related to the process time but also determines

the grain size of the electrodeposit. The current density effects of the modified NBS bath were observed to be as follows for a deposit of 0.5-mil thickness:

Current Density (A/ft^2)	Appearance of Deposit
1 - 5	Contained pores; larger grain
10	Fewer pores and smaller grain than at 5 A/ft^2
15	No pores; fine grain
20	No pores; fine grain
30	No pores; fine grain; excessive gassing at the anode

The platings at 10 to 25 A/ft^2 were all acceptable. A current density of 15 A/ft^2 was selected because at around 20 A/ft^2 external cooling is required to extract the I^2R heat and prevent too rapid and too large a temperature rise from ambient temperature.

The third phase of the electroforming process is the removal of the electroformed aluminum contact silicon wafer from the mandrel (wafer holding fixture). No problems were encountered in the single-cell operation. Thin sheets of aluminum were formed around the edge of the silicon wafer due to bridging at the areas of electrical contact to the mandrel. However, the wafer is easily separated by cutting the bridging aluminum.

3.5 ADHESION OF THE ALUMINUM ELECTRODEPOSIT TO SILICON SURFACE

Adhesion of electroformed aluminum to the silicon wafer was evaluated using commercially available silicon wafers for the solar cell. These cells are normally lap finished on the back side and mirror polished on the active side. Aluminum platings were electrodeposited on both surfaces to observe any differences in adhesion. The adhesion was poor on

the polished side and fair on the lapped side. The pull test value for the lapped side was approximately 800 grams. The aluminum could be easily rubbed off from the polished side.

The low adhesive strength of the samples tested above indicates that a sintering step is necessary. Plated samples were sintered in an auto-clave at 320°C for 2 minutes. Pull tests performed on the aluminum on both the polished side and the lapped side were all valued at about 1800 grams. The failure modes were either cracking of the silicon wafer or pulling off a chunk of the silicon. There were no failures due to peel-ing off the aluminum from the silicon surface on the sintered samples. For this program a surface finish of 5 microns is used instead of a polished surface. With the 5-micron finish surface, premature peeling of contacts (i.e., presintering) is completely eliminated. The effects of sintering temperature-time profile and liquid nitrogen thermal shock on adhesive strength are presented in Table I.

The results of this study indicate that a postplating sintering operation at 350°C for 2 minutes should be used.

3.6 SILICON MONOXIDE COATING

The final step in the fabrication of the electroformed aluminum contact solar cell is the addition of a silicon monoxide AR coating.

The spectral response of a silicon solar cell was found to be greatly dependent on the thickness of this coating. The coating enhances the response of the visible region and is peaked for minimum reflection at about 0.6 micron. During this reporting period, the silicon monoxide coating was done by an outside vendor. However, preparations are being made in the EOS solid-state laboratory to coat the electroformed aluminum silicon wafers.

TABLE I

EFFECT OF SINTERING TEMPERATURE AND TIME ON ADHESIVE STRENGTH
OF ELECTROFORMED ALUMINUM ON SILICON WAFERS

Type of Wafer		Surface Finish	*PULL TEST VALUE (GRAMS)							
			No sintering	No sintering; LN$_2$ shock	300°C, 2 min	300°C, 2 min; LN$_2$ shock	350°C, 2 min	350°C, 2 min; LN$_2$ shock	400°C, 2 min	400°C, 2 min; LN$_2$ shock
Nondiffused		5μ	550	500	1875	1825	2025	2100	2050	2075
Diffused	n	5μ	500	500	1750	1750	2150	2150	1975	2050
	p		1300	1200	1850	1800	2300	2225	2150	1950

* Pull test procedure for electroformed aluminum on silicon wafer:

  (1) Solder No. 22 AWG tinned copper lead to center of aluminum-plated wafer.

  (2) Perform pull test using Hunter tensile tester.

The aluminum-plated and sintered cells will be cleaned and coated with an optimum thickness of SiO using the following procedure:

(1) Ultrasonically clean cells in isopropanol three times.

(2) Vapor degrease with trichloroethylene.

(3) Load into coating jig; place jig in vacuum system.

(4) Heat cells to approximately 300°C (to remove any organics present on the surface).

(5) Cool to less than 100°C.

(6) While monitoring cell I_{sc}, evaporate SiO at approximately 1400Å perminute.

(7) When cell I_{sc} maximizes (after about 1 minute), close shutter to end deposition (thickness $\approx$1400Å).

(8) Remove from vacuum.

3.7 ELECTROFORMED ALUMINUM CONTACTED SOLAR CELL FABRICATION SCHEME

The steps involved in the EOS electroformed aluminum contact solar cell process are the following:

(1) Apply photoresist.

(2) Degrease in trichloroethylene.

(3) Deoxidize in NH_4F-HF etchant.

(4) Rinse in isopropyl alcohol.

(5) Final rinse in ether.

(6) Mount wafer in fixture.

(7) Electrodeposit in ethereal electrolyte.

(8) Separate plated wafer

(9) Wash with water.

(10) Remove mask with stripper.

(11) Wash with water.

(12) Rinse with acetone.

(13) Sinter in oven at 350°C for 2 minutes.

(14) Apply SiO AR coating.

3.8 PERFORMANCE OF ELECTROFORMED ALUMINUM CONTACT SOLAR CELLS

During this reporting period, aluminum contact solar cells have been fabricated by the electroforming technique. Both the front bar-grid contacts and the back "p" contacts were electroformed simultaneously. For the front bar-grid contacts a photoresist mask with the pattern shown in Fig. 1 was used. The thickness of all the electroformed aluminum contacts was 0.0005 ±0.0001 inch.

The history and electrical characteristics of 10 cells fabricated with 0.5 mil of aluminum are shown in Table II. The table indicates the improvement of cell performance after the 10-minute heat treatment at 240°C and after SiO coating.

Figure 5 shows the I-V characteristic curves for cell No. 6. These curves and the data in Table II were taken on a tungsten simulator at AM1. The efficiency as shown in Fig. 5 at V0.400 is 11.82% at AM1. When converted to AMO using a facter of 1.18, the efficiency is 10%. As noted from the I-V curves in Fig. 5, the "weak knee" and relatively lower Voc are indications of shunt current. The shunt current is probably caused by a minute quantity of aluminum plated over the edges and forming a bridge across the junction. Methods which will be used to eliminate this bridging are (1) locating the ohmic bar contact away from the edges and (2) etching the edges of the electroformed contact solar cells in hydrochlonic acid to remove any aluminum electrodeposited onto and/or across the junction.

TABLE II

CHARACTERISTICS OF ELECTROFORMED ALUMINUM
CONTACT CELLS (2 x 2 cm), SiO AR COATED

| Cell No.	Bare Cell			Bare Cell Heated 10 min in 240°C Oven			SiO Coated Cell		
	I_{sc}	$I_{0.400V}$	V_{oc}	I_{sc}	$I_{0.400V}$	V_{oc}	I_{sc}	$I_{0.400V}$	V_{oc}
1	103.4	84.8	0.553	106.0	94.1	0.565	121.6	109.3	0.569
2	107.0	99.8	0.568	108.3	106.0	0.583	122.9	118.2	0.585
3	103.3	90.1	0.567	105.8	99.2	0.578	122.2	113.0	0.580
4	101.8	90.5	0.538	103.1	89.8	0.536	119.1	101.7	0.537
5	103.8	89.5	0.566	106.8	98.6	0.577	121.9	112.4	0.579
6	101.8	94.4	0.570	103.4	98.6	0.576	117.8	111.8	0.578
7	106.8	97.2	0.565	108.0	100.6	0.573	123.0	111.2	0.580
8	94.4	87.2	0.566	95.6	89.0	0.570	111.4	106.8	0.578
9	102.2	91.5	0.562	104.7	90.2	0.563	119.6	108.0	0.572
10	102.4	91.8	0.553	103.2	93.8	0.564	118.0	111.3	0.572
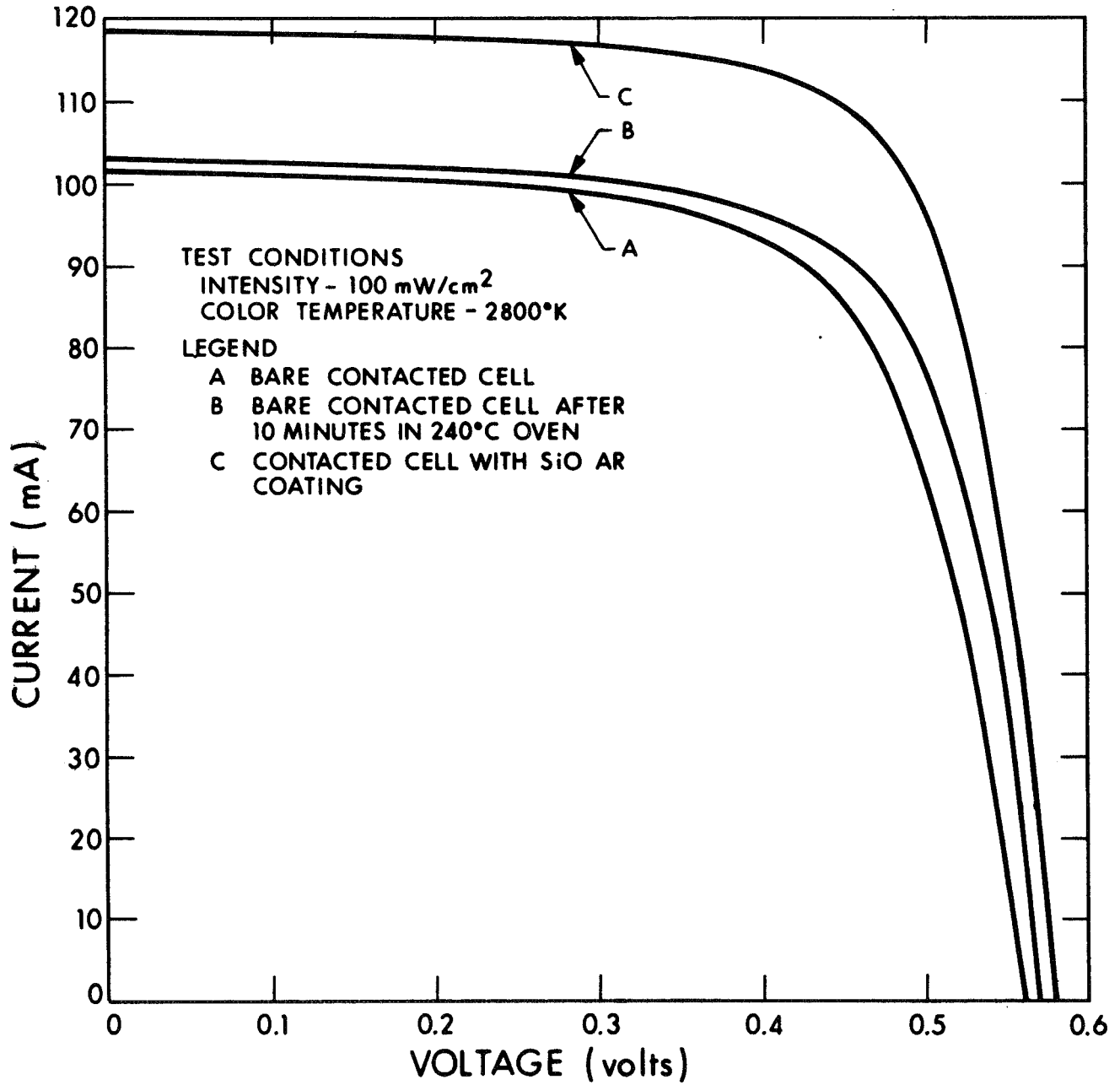
Figure 5. I-V Characteristic Curves of Electroformed
Aluminum Contact Solar Cell

SECTION 4

PLANS FOR NEXT PERIOD

Electroformed aluminum contact solar cells will be fabricated by the optimized process developed in this reporting period. A group of 50 cells will be subjected to the prescribed environmental testing. Task II, Electroformed Aluminum Interconnector, will be commenced.

APPENDIX A

CONTACT THICKNESS VERSUS RESISTANCE CALCULATIONS

For the straight grid line contact, a conservative estimate of the voltage drop can be made by using the following assumptions:

(1) The current collected by one grid line (total of six) is $\frac{140 \text{ mA}}{6}$ or 23.3 mA.

(2) The voltage drop is calculated at the midlength of the grid line.

The voltage drop is related to the thickness by the following equations:

$$E_G = I R_G$$

$$R_G = \frac{\rho \ell}{Wt}$$

where

ρ = resistivity of Al

ℓ = length of grid

W = width of grid

t = thickness of grid

For l = 0.95 cm,

  w = 0.015 cm,

  ρ = 2.62 x 10^{-6} ohm-cm, and

  I = 2.33 x 10^{-2} A,

$$E_G = \frac{I \rho \ell}{wt} = \frac{(2.33 \times 10^{-2})(2.62 \times 10^{-6})(0.95)}{(0.015)(t)}$$

$$E_G = \frac{3.87 \times 10^{-6}}{t}$$

At 0.001 in. or 0.0025 cm, the voltage drop is 1.55 mV, and the values of E_G corresponding to other thickness are as follows:

t(in.)	E_G (mV)
0.001	1.55
0.0005	8.75
0.0001	15.5

For practical purposes, both a pore-free continuous layer of aluminum and an acceptable resistance are obtained when the electrodeposited layer is approximately 0.00125 cm.

THERMAL STRESS IN ALUMINUM-SILICON BOND
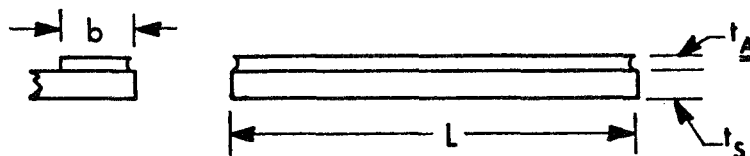
35454

Coefficients of thermal expansion:

$$\alpha_{aluminum} = 13.1 \times 10^{-6} \text{ in./in. } ^{o}F$$

$$\alpha_{silicon} = 1.8 \times 10^{-6} \text{ in./in. } ^{o}F$$

Modulus of elasticity

$$E_{aluminum} = 9.0 \times 10^{6} \text{ psi (electroformed)}$$
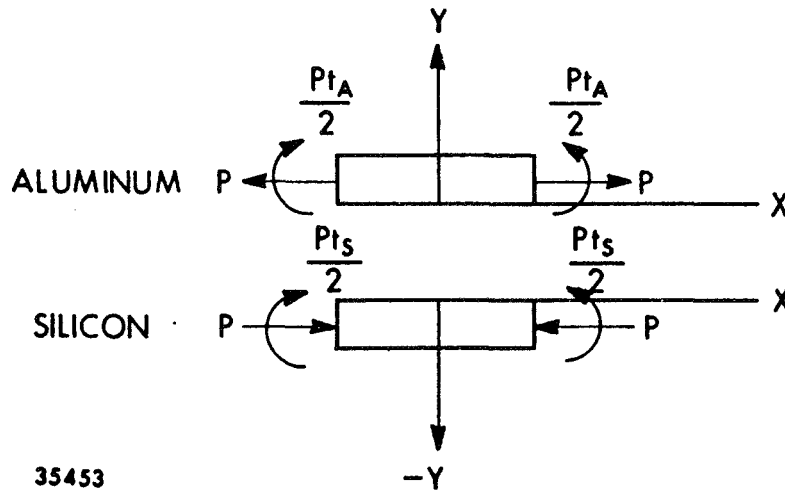
$$E_{silicon} = 15.5 \times 10^{6} \text{ psi}$$

Derivation of equation for stress at bondline

Define $\Delta T = T - T_{AMB}$

T_{AMB} = temperature during plating ^{o}F

T = temperature (independent variable) ^{o}F

Free-Body Diagrams

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The axial displacements are

$$\mu_{AL}(y) = \alpha_{AL}\,\Delta T + \frac{P}{E_{AL}\,t_A\,b} - \frac{1}{\rho 1}\left(y - \frac{t_{A1}}{2}\right) \tag{1}$$

$$\mu_{S1}(y) = \alpha_{S1}\,\Delta T - \frac{P}{E_{S1}\,t_S\,b} - \frac{1}{\rho 2}\left(y + \frac{t_{S1}}{2}\right) \tag{2}$$

Where,

$$\frac{1}{\rho 1} = \frac{M}{E_{AL}\,I_{AL}} = \frac{P\,t_{AL}}{2\,E_{A1}\left(\frac{1}{12}\,b\,t_{AL}^{\,3}\right)} = \frac{6\,P}{E_{A1}\,b\,t_{AL}^{\,2}} \tag{3}$$

$$\frac{1}{\rho 2} = \frac{M}{E_{S1}\,I_{S1}} = \frac{P\,t_{S1}}{2\,E_{S1}\left(\frac{1}{12}\,b\,t_{S1}^{\,3}\right)} = \frac{6\,P}{E_{S1}\,b\,t_{S1}^{\,2}} \tag{4}$$

At $y = 0$ $\mu_{AL}(y) \equiv \mu_{S1}(y)$

$$\therefore\ \alpha_{AL}\,\Delta T + \frac{P}{E_A\,t_A\,b} + \frac{t_A}{2\rho 1} = \alpha_{S1}\,\Delta T - \frac{P}{E_{S1}\,t_S\,b} - \frac{t_S}{2\rho 2} \tag{5}$$

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Substituting (3) and (4) in (5) and solving for P gives

$$P \left(\frac{1}{E_A \, t_A \, b} + \frac{1}{E_S \, t_S \, b} \right) = (\alpha_{S1} - \alpha_{AL}) \, \Delta T - 3P \left(\frac{1}{E_{AL} \, t_{AL} \, b} + \frac{1}{E_{S1} \, t_S \, b} \right)$$

$$P = \frac{(\alpha_{S1} - \alpha_{AL}) \, \Delta T}{4 \left(\frac{1}{E_A \, t_A \, b} + \frac{1}{E_S \, T_S \, b} \right)}$$

Stress at the bondline (aluminum side tension)

$$S = \frac{P}{A} + \frac{Mc}{I}$$

$$= \frac{P}{t_A \, b} + \frac{P \, t_A \, (t_A/2)}{2 \left(\frac{1}{12} \, b \, t_A^3 \right)}$$

$$S = \frac{P}{t_A \, b} + \frac{3 \, P}{t_A \, b}$$

$$S = 4 \, \frac{P}{t_A \, b} = \frac{4}{t_A \, b} \; \frac{(\alpha_{S1} - \alpha_{AL}) \, \Delta T}{4 \left(\frac{1}{E_A \, t_A \, b} + \frac{1}{E_s \, t_s \, b} \right)}$$

$$S = \frac{(\alpha_{S1} - \alpha_{AL}) \, \Delta T}{\frac{1}{E_{AL}} + \left(\frac{t_{AL}}{t_s} \right) \frac{1}{E_{S1}}} = \frac{(\alpha_{S1} - \alpha_{AL}) \, \Delta T \, E_{A1}}{1 + \left(\frac{t_{A1}}{t_s} \right) \frac{E_{AL}}{E_{S1}}}$$

Evaluating (6) for the previously specified values for E, and α

$$S = \frac{-11.3 \, \Delta T}{0.11111 + \left(\frac{t_{AL}}{t_S} \right) 0.06451} = \frac{-101.7 \, \Delta T}{1 + \left(\frac{t_{AL}}{t_{S1}} \right) (0.58064)}$$

Silicon side

$$S = \frac{-11.3 \, \Delta T \, E_S}{\frac{t_S \, E_S}{t_A \, E_A} + 1} = \frac{-175.4 \; \Delta T}{1.72222 \left(\frac{t_S}{t_A} \right) + 1}$$

During the thermal shock cycling, the ΔT encountered is $388^{\circ}F$. The tension on the aluminum is

$$S = \frac{-101.7\ (388)}{1 + (0.018)(.58064)} = -39,100 \text{ psi.}$$

The aluminum will yield under this tension. The failure of the aluminum-silicon bond is prevented, however, by the stretching of the aluminum.

The elongation of the aluminum, including extension in the plastic region, must be:

$$\mu_{AL} = \alpha_{AL}\ \Delta T + \frac{P}{E_{AL} t_A b} + \frac{1}{\rho 1}\ \frac{t_{AL}}{2}$$

where

$$\frac{1}{\rho 1} = \frac{GP}{E_{AL}{}^b\ t_{AL}{}^2}$$

$$P = \frac{(\alpha_{S1} - \alpha_{AL})\ \Delta T}{4\left(\dfrac{1}{E_A t_A b} + \dfrac{1}{E_S t_S b}\right)}$$

$$\mu_{AL}\ (y = o) = \alpha_{A1}\ \Delta T + \frac{P}{E_{A1}\ t_{A1} b} + \frac{GP}{2E_{AL}{}^b\ t_{A1}}$$

$$\mu_{AL}\ (y = o) = \alpha_{A1}\ \Delta T + \frac{AP}{E_{A1}\ t_{A1} b}$$

$$= \alpha_{A1}\ \Delta T + \frac{(\alpha_{S1} - \alpha_{A1}\ \Delta T}{1 + \dfrac{E_{A1}\ t_{A1}}{E_{S1}\ t_{S1}}}$$

$$= \left[\frac{\alpha/AL + \dfrac{E_{AL}}{E_{S1}} \dfrac{t_{AL}}{t_{SL}} \alpha_{AL} + \alpha_{S1} - \alpha/AL}{1 + \dfrac{E_{A1} t_{A1}}{E_{Si} t_{Si}}} \right] \Delta T$$

$$\mu_{AL} = \left[\frac{\left(\dfrac{E_{AL}}{E_{S1}} \dfrac{t_{AL}}{t_{S1}} \right) \alpha_{AL} + \alpha_{S1}}{1 + \dfrac{E_{A1} t_{AL}}{E_{Si} t_{Si}}} \right] \Delta T$$

for

$$\frac{t_{AL}}{t_{S1}} \ll 1$$

$$\mu_{AL} = \alpha_{S1} \Delta T$$

$$\mu_{AL} = 2.8 \times 10^{-6} \Delta T$$

Exact solution for

$$t_{AL} = 0.0005 \text{ in.}$$

$$t_{S1} = 0.015 \text{ in.}$$

$$E_{AL} = 9.0 \times 10^{6} \text{ psi}$$

$$E_{S1} = 15.5 \times 10^{6} \text{ psi}$$

$$\alpha_{AL} = 13.1 \times 10^{-6} \text{ in./in. } ^{o}F$$

$$\alpha_{S1} = 1.8 \times 10^{-6} \text{ in./in. } ^{o}F$$

$$\mu_{AL} = \left[\frac{(0.01935)(13.1) + 1.8}{1 + 0.01935} \right] \Delta T \times 10^{-6}$$

$$\mu_{AL} = 2.0 \times 10^{-6} \Delta T$$

% elongation required $= 2.0 \times 10^{-4} \Delta T$

and at $\Delta T = 388^{o}F$

% elongation required $= 2.0 \times 10^{-4} \times 388 = 0.1\%.$

APPENDIX C

MASKING OF SILICON WAFER WITH THE
PHOTORESIST TECHNIQUE

1. Wash cells ultrasonically in:

   a. Alcohol (electronic grade isopropanol) 3 times.

   b. Trichloroethylene (electronic grade) 3 times.

   c. Acetone (electronic grade) 3 times.

   Dry.

2. Etch in HF (to remove P_2O_5-rich glass on front surface and lapping particles from rear).
   Rinse 3 times in DI H_2O.

3. Boil in H_2SO_4 10 min. (removes hard-to-remove organic materials).
   Rinse 3 times in DI H_2O.

4. Boil in HNO_3 10 min. (leaves surface very clean and hydrophilic).
   Rinse 3 times in DI H_2O.

5. Rinse 3 times in McOH.

6. Heat in furnace at $800^{\circ}C$ for 3 min. (removes OH groups from oxide surface and promotes resist adhesion.)

7. Coat rear surface with KMER. Dry.

8. Expose, develop, and bake.

9. Coat front surface. Dry.

10. Expose, develop, and bake.

   NOTE: There will be microscopic examinations of the patterns after each development.

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