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HIGH RESOLUTION, LOW COST SOLAR CELL CONTACT DEVELOPMENT

Quarterly Technical Progress and Schedule Report

By
N. Mardesich

September 28, 1980

Work Performed Under Contract No. NAS-7-100-955725

Spectrolab, Inc.
Sylmar, California

U.S. Department of Energy

Solar Energy

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QUARTERLY TECHNICAL PROGRESS AND SCHEDULE REPORT

"HIGH RESOLUTION, LOW COST SOLAR CELL CONTACT DEVELOPMENT"

For the Period Ending September 28, 1980

Contract 955725

CDRL 2

Prepared for:

JET PROPULSION LABORATORY
4800 Oak Grove Drive
Pasadena, CA 91103

Prepared by:

N. Mardesich
Program Manager

Approved by:

William E. Taylor, Manager
Process Development and Engineering

of

SPECTROLAB, INC.
12500 Gladstone Avenue
Sylmar, California 91342

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1.0 SUMMARY STATEMENT

During the first quarterly period of this contract, Spectrolab has established the "MIDFILM"® process at Spectrolab, negotiated the subcontract with Ferro Corp. and is presently evaluating new powder compositions and resins.

A MIDFILM process sequence and equipment has been established. Four powder compositions and three resin formulations are under evaluation to produce and optimize process. Series resistance and interconnection soldering appear to be problem areas and are presently being resolved.

2.0 INTRODUCTION

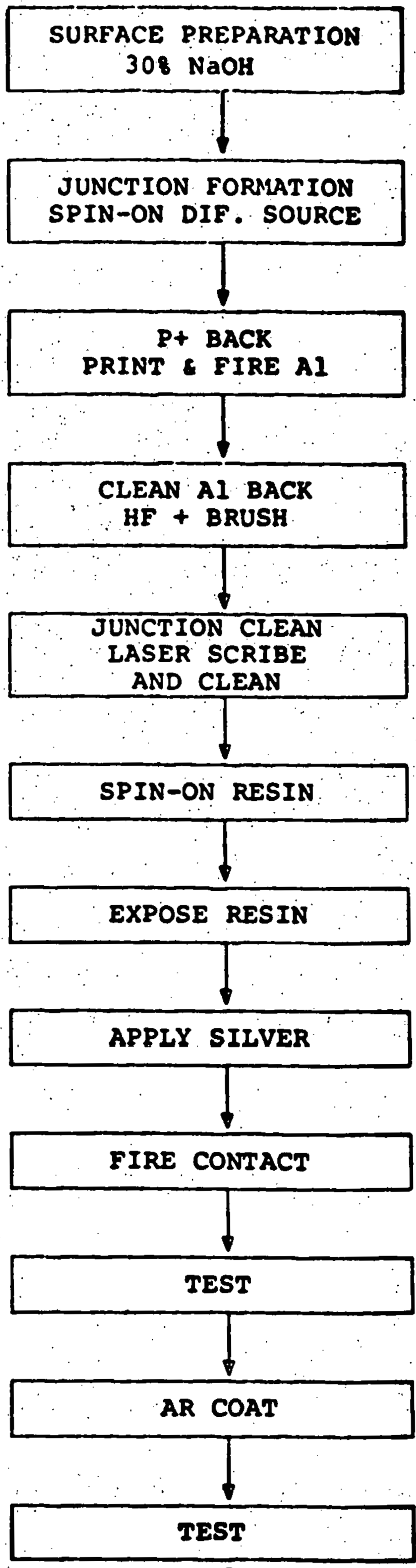
The first Quarterly Technical Progress and Schedule Report covers the period ending September 28, 1980. The scope of the contract covers the development and evaluation of forming solar cell collector grid contacts by the MIDFILM process. This is a proprietary process developed by the Ferro Corporation which is a subcontractor for the program.

The MIDFILM process attains line resolution characteristics of photoresist methods with processing related to screen printing. The surface to be processed is first coated with a thin layer of photoresist material. Upon exposure to ultraviolet light through a suitable mask, the resist in the non-pattern area cross-links and becomes hard. The unexposed pattern areas remain tacky. The conductor material is applied in the form of a dry mixture of metal and frit particles which adhere to the tacky pattern area. The assemblage is then fired to ash the photo-polymer and sinter the fritted conductor powder.

The baseline cell process sequence is shown in Figure 1. Effort was concentrated during this period on the establishment, optimization and identification of problem areas of the MIDFILM process.

Figure 1

MIDFILM PROCESS SEQUENCE



3.0 TECHNICAL DISCUSSION

3.1 PROCESS SEQUENCE

During this first quarter a standard process sequence was established (Figure 1) in order to evaluate the MIDFILM process. This process sequence is essentially the same process used on another JPL contract (#954853). The cell size is 2.1 in. x 2.1 in. (28.45 cm^2) and is laser scribed from a 3 inch round (100) Czochralski type wafer.

3.2 MIDFILM EQUIPMENT

The essential equipment for applying the MIDFILM contacts has been established at Spectrolab, Inc. The resin is applied with an eye dropper to the center of the wafer and spun with a Headway Research, Inc. spinning system. The cell and mask pattern is held in position with a vacuum, while the resin is being exposed with a Xenon solar simulator. The silver and frit is then applied by sifting through a screen and rubbing it out. The contacts are sintered by firing them in an IR furnace.

3.3 FERRO TECHNOLOGY TRANSFER

During August Ferro Corporation employees visited Spectrolab to establish subcontract and transfer necessary technological information. A new modified resin was evaluated at Spectrolab during this period. It became necessary to modify the solvent base of the resin in order to avoid environmental problems which would be encountered with the toxic solvents used in the original resin. This modified resin performed very well except that it was sensitive to humidity. After about three hours, the dried resin on a wafer began to absorb moisture. This resin has been modified again to give a 10-hour shelf life when dried on wafers.

3.4 PROCESS OPTIMIZATION

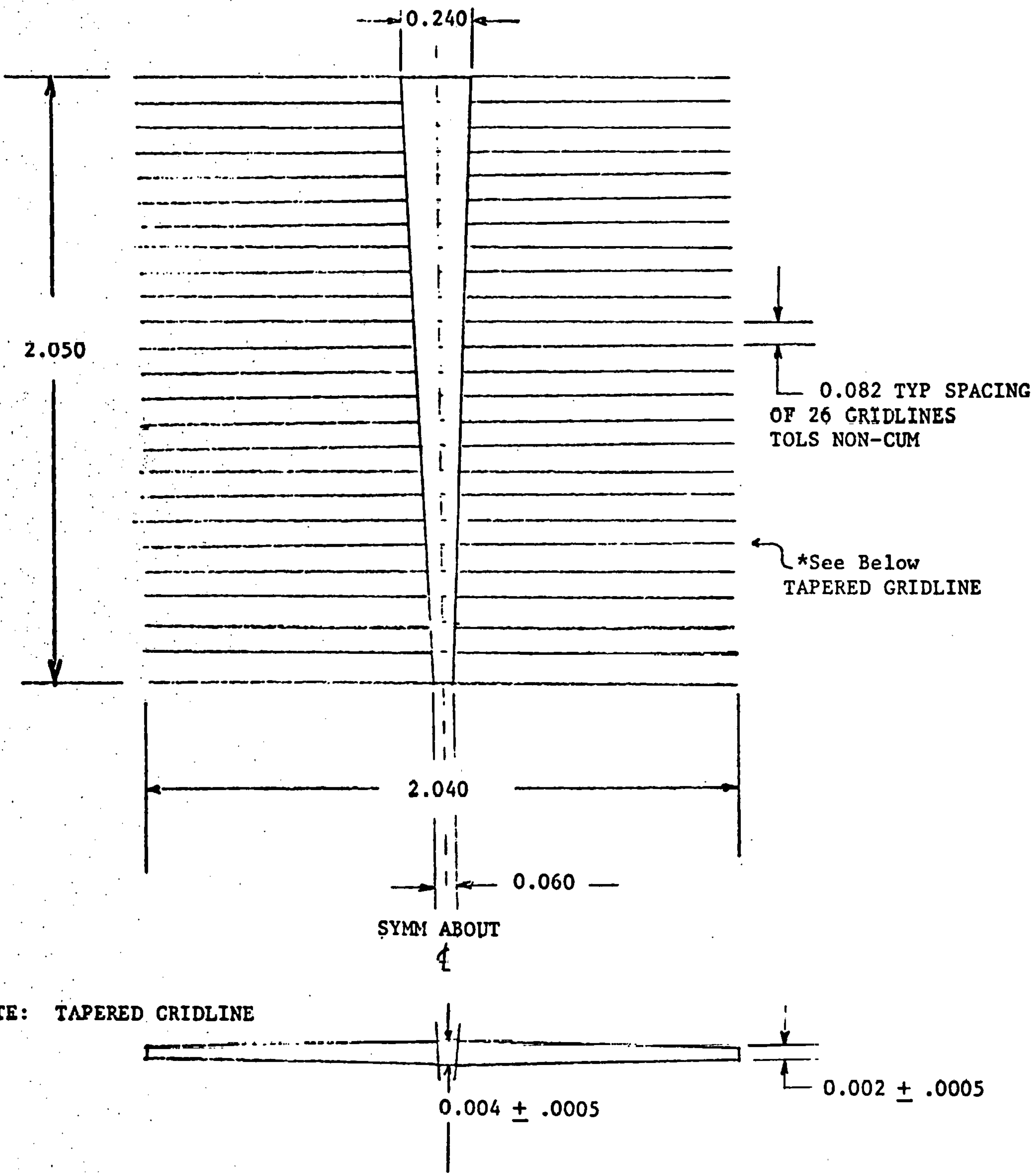
During this last quarterly period a number of metallization powder compositions were evaluated, Table 1. All powders were based on TFS (Thick Film Systems, Inc.) spherical type powders and frit from 3347 TFS paste, the paste used for screen printing thick film contacts. The three resins evaluated are listed in Table 2. The contact grid pattern is shown in Figure 2 and a series resistance calculation for this pattern is given in Appendix 1.

Initial evaluations of the powder compositions 1 and 2 were accomplished using Ferro RC 4851 type resin, which contains toxic solvents. The wafers were fired at 675, 700 and 725°C for 30 seconds. The best results occurred at 675 and 700°C. At 725°C the open circuit voltage (V_{oc}) and short circuit current (I_{sc}) was reduced. Powder composition 1 had a lower I_{sc} and higher series resistance than powder composition 2.

To determine the optimum firing conditions a number of times were used to fire wafers at 650 and 675°C, Table 3. These cells had poor V_{oc}, but the best firing times appear to be 30 and 45 seconds. A repeat of a portion of the previous run, Table 4, indicates optimum firing conditions occur near 675°C for 30 seconds.

Further tests using Ferro resin RC 4851 have been discontinued. During Ferro's visit to Spectrolab, a new resin, RW 3190, was evaluated using 675°C for 30 seconds as the firing condition for composition 2. Table 5 gives the tabulated results of this evaluation. Figure 3 is a typical I-V curve of these cells. Series resistance measurement for the typical cell was 100 mΩ and a profilometer trace of the gridline by Ferro indicated a 13 to 16 μm thick fired silver gridline. The new RW 3190 resin appeared to be humidity sensitive. Ferro has modified the resin to assure 10-hour shelf life when dried on a wafer, resin RG 4933.

Figure 2



DIMENSIONS ARE IN INCHES

TOLERANCES: XXX = ± .003

PART NO. 6325-01

FRONT CONTACT
GRIDLINE PATTERN
(MIDFILM)

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Table 1

Evaluated Silver Powder Compositions

1. 98% TFS Spherical Type Powder;
   2% 3347 TFS Frit
   (3347-B)

2. 97% TFS Spherical Type Powder;
   3% 3347 TFS Frit
   (3347-C)

3. 95% TFS Spherical Type Powder;
   5% 3347 TFS Frit
   (3347-D)

4. 90% TFS Spherical Type Powder;
   10% 3347 TFS Frit
   (3347-E)

Table 2

Evaluated Resins

1. Ferro RC 4851
2. Ferro RW 3190
3. Ferro RG 4933

Table 3

RUN M-8-2-8

(No AR Coating)

Powder 3347-C

Fire Time (sec.)	Fire Temperature 650°C				Fire Temperature 675°C			
	V_{oc} (mV)	I_{sc} (mA)	I_{500} (mA)	R_{shunt} (Ω)	V_{oc} (mV)	I_{sc} (mA)	I_{500} (mA)	R_{shunt} (Ω)
120	565	564	352	135	553	610	409	132
	555	609	450	278	553	606	509	208
	561	582	397	116	556	596	478	192
60	556	583	359	208	556	613	453	294
	558	561	417	114	552	662	457	156
	559	587	438	156	558	621	467	93
45	555	580	442	227	560	655	444	208
	562	681	562	500	560	673	490	384
	567	649	465	294	562	634	515	294
30	565	679	494	357	565	680	552	125
	563	662	530	417	576	680	419	93
	565	662	502	263	560	653	492	116

Table 4

RUN M-8-3A-8

(No AR Coating)

Powder 3347C

Fire Temp. (°C)	Fire Time (sec)	V_{oc} (mV)	I_{sc} (mA)	I_{500} (mA)	R_{sh} (Ω)
650	45	596	695	423	625
		592	708	362	250
		596	723	430	357
650	30	598	701	435	152
		596	727	390	278
		596	732	432	333
675	30	598	731	442	313
		596	679	455	238
		594	685	405	294

Table 5

RUN M-8-cB-8

(No AR Coating)

Powder 3347C

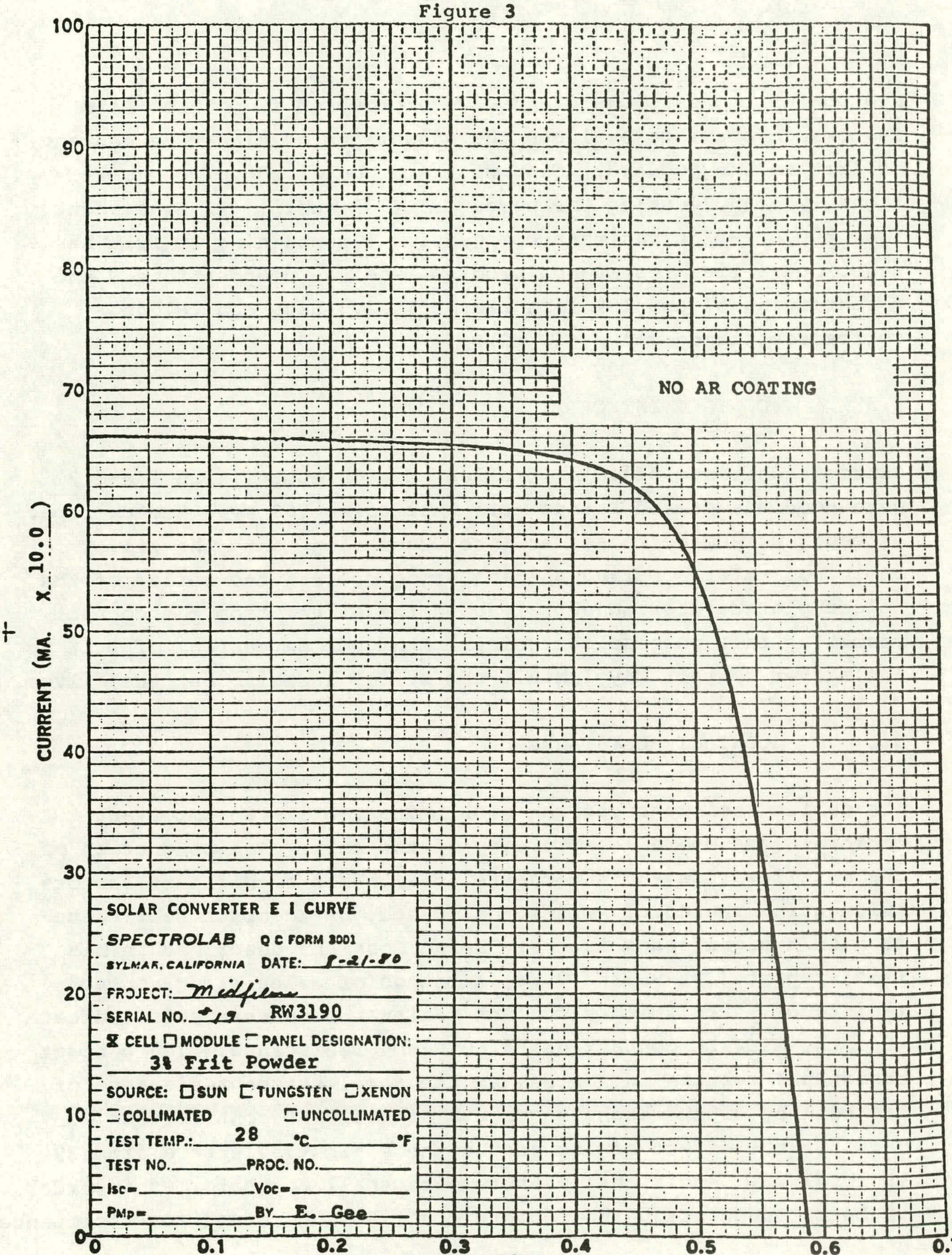
New Modified Resin (RW 3190)

Fire Temperature 675°C

Fire Time 30 sec.

	V_{oc} (mV)	I_{sc} (mA)	I_{500} (mA)	R_{sh} (Ω)	R_{series} (mΩ)	Comments
	590	675	550	-	100	
	596	701	516	143	-	
	589	686	541	85	-	
	587	650	492	77	-	Poor ohmic coverage
	593	666	531	94	-	
	590	658	555	63	-	
	591	628	530	60	-	
	590	661	545	37	-	
	584	502	437	74	-	Under exposed resin
	594	698	533	35	-	
	580	622	497	42	-	
Ave.	591.3	665.4	553.1	69.9		
σ	5.1	27.0	18.0	36.6		

Figure 3



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New powder compositions 3 and 4 were procured from Thick Film Systems in order to evaluate the advantages of higher percentage of frit in the powders. Figure 4 is a comparison of compositions 1, 3 and 4 using the newest RG 4933 resin. It is evident from these I-V curves that composition 1 containing 2% frit has a serious series resistance problem, whereas compositions 3 and 4 containing 5% and 10% frit respectively, have equivalent series resistance values (≈ mΩ).

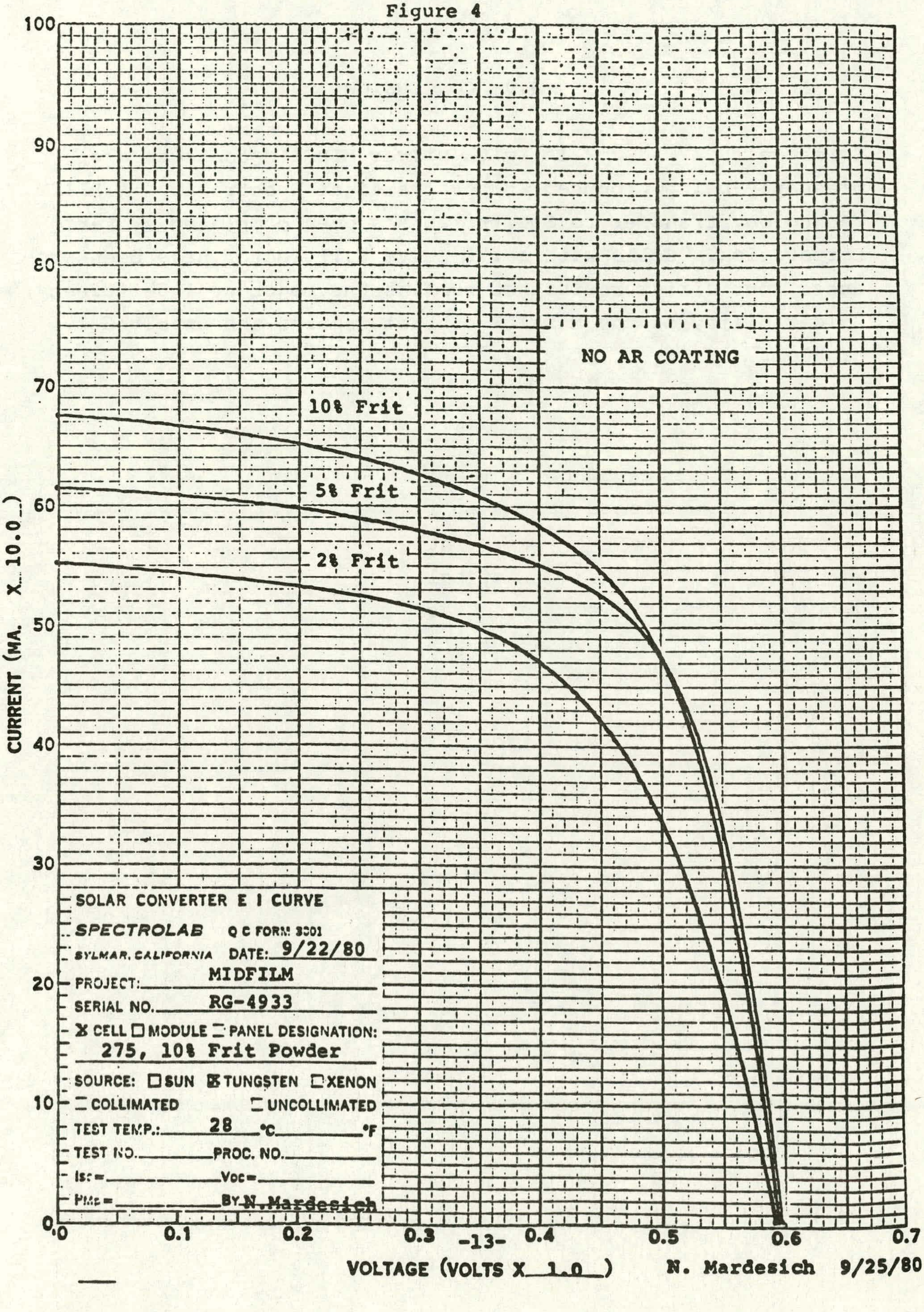
3.5 CONTACT INTEGRITY

Contact adherence of cells fabricated with composition 1 and 2 were good and passed a tape pull test using 600 type Scotch tape. Attempts were made to solder interconnections onto the silver ohmic collector. During the soldering process the reflow of the solder plated interconnects leached the silver from the contact, resulting in a poor solder joint. A higher percentage of frit in the silver contact may inhibit the solder leaching out the silver.

3.6 CONTACT RESISTANCE

The series resistance of the MIDFILM contact is an important factor in the overall efficiency of the cell. The conduction of the metallization and the contact design are significant factors influencing the total series resistance, but contact resistance is also a significant factor. Bernd Ross has described in his final report (JPL-955164 79/4) a method of calculating contact resistance. Preliminary contact resistance measurements indicate that the MIDFILM contact has a 30 $\Omega\text{-cm}^2$ resistance. The contact resistance results in increasing the total series resistance of the cell by 32 mΩ which is quite a significant contribution. This has the effect of increasing the series resistance from 39 mΩ to 71 mΩ. Additional measurements shall be performed in order to better understand the factors contributing to contact resistance.

Figure 4



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4.0 CONCLUSION

Solar cells (2.1" x 2.1") with silver MIDFILM contacts are presently being produced and evaluated at Spectrolab. MIDFILM technology transfer to Spectrolab has been completed by Ferro Corporation. Cells with a .73 curve fill factor have been produced, but series resistance remains the major cell deficiency. Solderability of the MIDFILM contact remains the unsolved problem.

APPENDIX A

CALCULATION OF SERIES RESISTANCE

A) BASE MATERIAL RESISTANCE

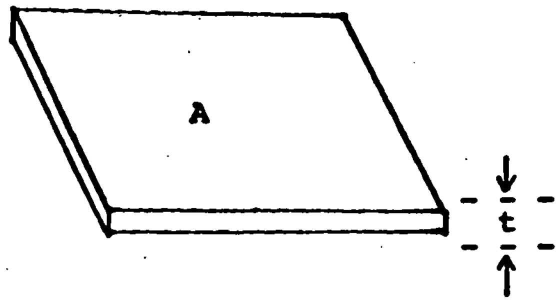
R = resistance

ρ_{Si} = resistivity of silicon

t = thickness of wafer

A = area of wafer

$$R_B = \frac{\rho_{Si}\, t}{A} \qquad (1)$$



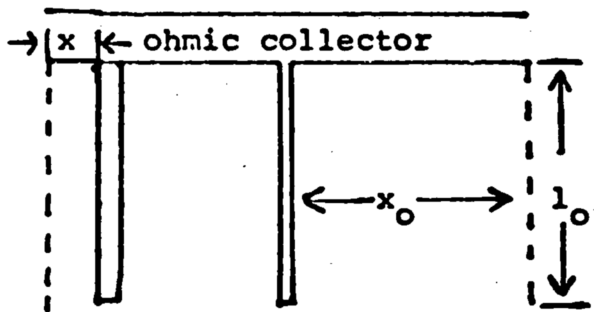
B) RESISTANCE OF DIFFUSED SURFACE LAYER

ρ_s = surface resistivity

l_o = length of grid line (assuming grid lines go to edge of wafer)

x_o = half distance between grid lines

j = current density*



The element of power loss over an element of silicon dx, is the square of the current entering that element times the resistance of that element dx.

$$dp = (j l_o x)^2 \cdot \left(\rho_s \frac{dx}{l_o}\right) \qquad (2)$$

$$dp = j l_o \rho_s\, x^2 dx \qquad (3)$$

integrating over the half distance between grid lines (x_o) gives the total voltage drop to the midpoint.

*As a first approximation of power loss, the current density (j) is assumed to be independent of distance from gridline.

$$\Delta p = j^2 \rho_s l_o \int_o^{x_o} x^2 dx$$

$$= 1/3\ j^2 \rho_s l_o\ x^3 \Big|_o^{x_o}$$

$$\Delta p = 1/3\ j^2 \rho_s l_o\ x_o^3 \qquad (4)$$

The total resistance over the half distance between grid lines is;

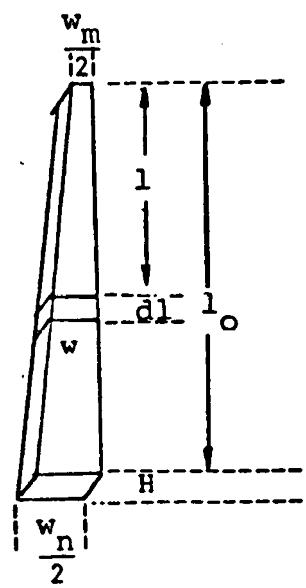
$$R = \frac{\Delta p}{j^2 l_o^2\ x_o^2} \qquad (5)$$

$$= \frac{\rho_s\ x_o}{3 l_o} \qquad (6)$$

These areas of half distance between grid lines are all in parallel.

$$R_D\ (\text{total}) = \frac{\rho_s\ x_o}{3 l_o} \div \text{number of areas} \qquad (7)$$

C) RESISTANCE OF GRID LINES



ρ_{AG} = resistivity of silver paste
l_o = length of grid lines (assuming grid lines go to end of wafer)
w_m = minimum width of grid line
w_n = maximum width of grid line
x_o = half distance between grid lines
j = current density

Considering one half the grid line, the element of power loss over an element of grid line dl, is the square of the current entering that element times the resistance of that element dl.

$$dp = (x_o\ j\ l)^2 \cdot \left(\frac{\rho_{AG}\ dl}{WH}\right) \qquad (8)$$

$$dp = \frac{j^2\ \rho_{Ag}\ x_o^2\ l^2 dl}{WH} \qquad (9)$$

w can be expressed as

$$w = \frac{l\ (w_n - w_m) + l_o w_m}{2\ l_o}$$

Integrating over the whole grid line, and taking each side of the grid as two resistors in parallel:

$$P = \frac{4\ l_o\ x_o^{\ 2}\ j^2\ \rho_{Ag}}{H} \int_o^{l_o} \left[\frac{l^2 dl}{l_o w_m + l(w_n - w_m)}\right]$$

Form of

$$\int_o^c \frac{x^2\ dx}{a + bx} = \frac{x^2}{2b} - \frac{ax}{b^2} + \frac{a^2}{b^3}\ \ln\ (a + bx)$$

(except where b approaches 0.)

$$P = \frac{4\ (j^2 x_o^{\ 2} l_o^{\ 2})\ l_o\ \rho_{Ag}}{H(w_n - w_m)} \left[{}^1\!/_2 = \left(\frac{w_m}{w_n - w_m}\right) + \left(\frac{w_m}{w_n - w_m}\right)^2 l_n \frac{w_n}{w_m} \right]$$

(except where $w_n \approx w_m$)

Then the resistance over the whole grid line becomes:

$$R = \frac{\Delta P}{4j^2 l_o^{\ 2} x_o^{\ 2}}$$

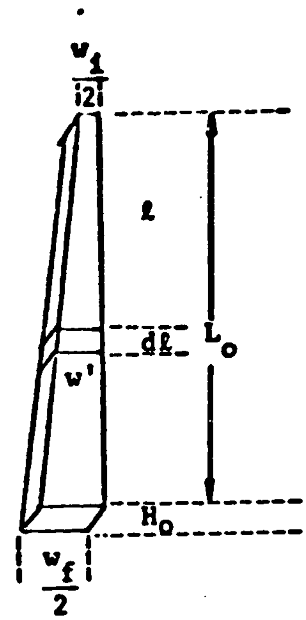
R_G (Total) = R/v

v = number of grid lines

$$R_G \text{ (Total)} = \frac{l_o \rho_{Ag}}{vH(w_n - w_m)} \left[{}^1/_2 = \left(\frac{w_m}{w_n - w_m}\right) + \left(\frac{w_m}{w_n - w_m}\right)^2 l_n \frac{w_n}{w_m} \right]$$

(except where $w_n \approx w_m$)

D) OHMIC COLLECTOR



ρ_{Ag} = resistivity of silver paste

l_o = average distance between ohmic and edge of cell

w_i = minimum width of ohmic collector

w_f = maximum width of ohmic collector

L_o = length of ohmic collector

j = current density

Considering one half the cell, the element of powder loss over an element of ohmic collector $d\ell$, is the square of the current entering that element times the resistance of the element $d\ell$.

$$dP = (l_o \ell j)^2 \cdot \left(\frac{\rho_{Ag}\, d\ell}{w' H_o}\right) \tag{13}$$

w' can be expressed as

$$w' = \frac{\ell(w_f - w_i) + L_o w_i}{2 L_o} \tag{14}$$

Integrating over the whole ohmic

$$P = \frac{4 L_o l_o^2 j^2 \rho_{Ag}}{H_o} \int_o^{L_o} \left[\frac{\ell^2\, d\ell}{L_o w_i + \ell(w_f - w_i)}\right] \tag{15}$$

Form of:

$$\int_{o}^{C} \frac{x^2\,dx}{a + bx} = \frac{x^2}{2b} - \frac{ax}{b^2} + \frac{a^2}{b^3} \ln (a + bx) \qquad (16)$$

(except where b approaches 0)

$$P = \frac{4(j^2\, l_o^2\, L_o^2)\, L_o\, \rho_{Ag}}{H_o(w_f - w_i)} \left[\tfrac{1}{2} = (\frac{w_i}{w_f - w_i}) + (\frac{w_i}{w_f - w_i})^2 \ln \frac{w_f}{w_i} \right] \qquad (17)$$

(except where $w_f \approx w_i$)

Then the resistance over the whole cell becomes:

$$R = \frac{\Delta P}{4j^2\, l_o^2\, L_o^2}$$

$$R_o \text{ (Total)} = \frac{\Delta P}{4j^2\, \ell^2\, L_o^2} = \frac{L_o\, \rho_{Ag}}{H_o\, (w_f - w_i)} \left[\tfrac{1}{2} + (\frac{w_i}{w_f - w_i}) + (\frac{w_i}{w_f - w_i}) \ln \frac{w_f}{w_i} \right] \qquad (18)$$

(except where $w_f \approx w_i$)

SAMPLE CALCULATION OF SERIES RESISTANCE FOR GRID PATTERN #6325-01, FIGURE

$\rho_{si} = 3.0\ \Omega\text{-cm}$

$t = 0.033$ cm

$A = 28.45\ \text{cm}^2$

$\rho_s = 35\ \Omega/\square$

$l_o = 2.54$ cm

$X_o = 0.104$ cm

$\rho_{Ag} = 4.77 \times 10^{-6}\ \Omega\text{-cm}$

$W_m = 0.005$ cm

$W_n = 0.01$ cm

$H = .85 \times 10^{-3}$ cm

$W_i = 0.152$ cm

$W_f = 0.610$ cm

$H_o = .85 \times 10^{-3}$ cm

$L_o = 5.18$ cm

Number of gridlines = 52

A) Base Material Resistance

$$R_B = \frac{\rho_{si}\ t}{A} = \frac{(3.0)\ (0.033)}{28.45}\ \Omega = 3.48\ \text{m}\Omega$$

B) Resistance of Diffused Surface Layer

$$R_o = \frac{\rho_s\ X_o}{3\ l_o} \div 104 = \frac{(35)\ (0.104)}{3(2.54)}\ \Omega \div 104 = 4.59\ \text{m}\Omega$$

C) Resistance of Gridlines

$$R_G = \frac{\rho_{Ag}\, l_o}{H\,(w_n - w_m)} \left[{}^1/_2 + \left(\frac{w_m}{w_n - w_m}\right) + \left(\frac{w_m}{w_n - w_m}\right)^2 \ln \frac{w_n}{w_m} \right] \div 52$$

where $w_n \gg w_m$

$$= \frac{(4.77 \times 10^{-6})(2.54)\Omega}{(.85 \times 10^{-3})(.005)} \left[{}^1/_2 = 1 + \ln 2 \right] \div 52 = 10.59 \text{ m}\Omega$$

D) Resistance of ohmic collector

$$R_o = \frac{\rho_{Ag} L_o}{H\,(w_f - w_i)} \left[{}^1/_2 = \frac{w_i}{(w_f - w_i)} + \left(\frac{w_i}{w_f - w_i}\right)^2 \ln \frac{w_f}{w_i} \right]$$

where $w_f \gg w_i$

$$\frac{(4.77 \times 10^{-6})(5.18)}{(.85 \times 10^{-3})(.458)} \left[{}^1/_2 = \frac{.152}{.458} + \left(\frac{.152}{.458}\right)^2 \ln \left(\frac{.610}{.152}\right) \right]$$

$R_o = 20.38 \text{ m}\Omega$

Total resistance of contact pattern is:

$3.48 + 4.59 + 10.59 + 20.38 = 39.04 \text{ m}\Omega$

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