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DRL No. 86/DRD No. SE

DOE/JPL - 955244 - 99/2

Line Item No. 7

Distribution Category UC-63

(NASA-CR-62179)	DEVELOPMENT OF LOW COST	N79-31757
CONTACTS TO SILICON SOLAR CELLS	Semiannual	
Report, 15 Oct. 1978 - 31 May 1979	(Optical	
Coating Lab., Inc., City of)	74 p	
HC A04/MF A01		Unclas
	CSCL 10A G3/44	31880

DEVELOPMENT OF LOW COST CONTACTS TO SILICON SOLAR CELLS

SEMI-ANNUAL REPORT

FOR PERIOD COVERING

15 OCTOBER 1978 to 31 MAY 1979

BY

P. A. ILES AND D. P. TANKER

JPL CONTRACT NO. 955244

OPTICAL COATINGS LABORATORY, INC.
PHOTOELECTRONICS DIVISION
15251 EAST DON JULIAN ROAD
CITY OF INDUSTRY, CA 91746



"The JPL Low-Cost Silicon Solar Array Project is sponsored by the U. S. Department of Energy and forms part of the Solar Photovoltaic Conversion Program to initiate a major effort toward the development of low-cost solar arrays. This work was performed for the Jet Propulsion Laboratory, California Institute of Technology by agreement between NASA and DOE."

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ABSTRACT

The seven (7) months of the original contract have been completed. A number of different electroless plating systems have been evaluated in conjunction with copper electroplating and a final contact system has been settled on.

All tests have involved simultaneous deposition of front and back contacts using a standard silicon cell material throughout the contract. Cells with good adhesion and good curve fill factors have been obtained using a palladium-chromium-copper metallization system. Forty (40) 2 1/4" diameter cells, which incorporate the palladium-chromium-copper metallization system, have been delivered to JPL.

As an additional experiment to the contract, the final copper contact system was evaluated to determine if the copper would migrate at elevated temperatures. Results indicate that copper does, indeed, migrate at elevated temperatures causing cell output degradation and that further work is needed to produce a reliable copper-based metallization system for solar cells.

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INTRODUCTION

This contract involves the evaluation of the technical feasibility and effective cost of a copper plating system for the manufacture of solar cells for high volume production of low cost solar array (LSA) modules.

Contacts have been identified as one of the most important but also one of the most expensive steps in making solar cells. Presently space and terrestrial cells are made with the standard titanium-palladium-silver contact system developed in the early sixties. This system, though expensive, has shown long-term reliability and presently is the only contact system believed to be able to last the twenty year lifetime goal, as described by the LSA project. Studies show that cell metallization is an area where large reductions in cell process costs can be obtained. The present Ti-Pd-Ag contacts are evaporated under a high vacuum, which alone, mainly due to the low throughput, is an expensive process. Also, metals like silver which are currently used in thicknesses of 3-10 microns are very expensive, and especially so when coupled with the large amount of wasted metal involved in the evaporation process. Therefore a new contact system should (A) use a high through-put technique, (B) should use a metal or metals that are inexpensive as compared to silver as the main current carrier, and (C) should have very low wastage of metals.

There are only two candidate contact systems that meets this criteria. First there is the print-on contact. This method uses a silk-screen mask which in conjunction with a printed conductive ink, prints contacts on the cell in the desired pattern. The printed ink, next has to be sintered at temperatures ranging from 450-750°C depending on the formulation of the ink and the cell processing sequence. Reliability has been the major problem with this system since control of the silicon-contact interface is very difficult. Also the printed cells have sometimes exhibited non-ohmic contacts, contact peeling problems, as well as degradation of the cells after severe heat treatments. All the present print-on contact inks contain a large percentage of silver making a low cost contact system difficult to obtain. Waste of the contact metal, though much lower than with evaporation, is still a problem, due to lack of control of the contact thickness and the wastage of the ink, left on the silk screen. The second contact system is electroless plating. In a plating system, metals are only deposited on the cell where required. The first layer of metal (the metal-silicon interface) can be controlled to get good adhesion and good cell performance. Using standard semiconductor metals such as silver or nickel, plating has proven to be a reliable low cost system.

This contract involves a study of the use of copper as the chief current carrying conductor for solar cells, replacing silver to reduced the contact cost further. Since copper is easily plated electrolessly and is relatively cheap, it is the prime candidate for this task. The only other cheap metal of good conductivity is aluminum, but it cannot be easily plated and is very difficult to solder for the cell interconnects.

During the last seven (7) months a copper based plating system has been developed. Work has centered on funding a plating procedure that would yield contacts that have good adhesion and conductivity. The metals as well as the different plating baths have been identified resulting in an adherent high quality contact. However, the problems with using copper are not limited only to the plating baths and contact adhesions, but also to long term cell performance.

From heat treatment experiments conducted during this contract, copper has been shown to cause degradation problems with the cells. The reputation of copper in being a fast diffuser in silicon appears to be true. If the copper could be blocked from migrating, a low cost contact system would be in hand. These fundamental problems with copper will be addressed in the second phase of the contract in a search for the proper barrier metals.

TECHNICAL DISCUSSION

During the duration of the contract a number of very important observations have been made. This section will discuss these observations and will show how they have effected the experimental work.

Plating Techniques

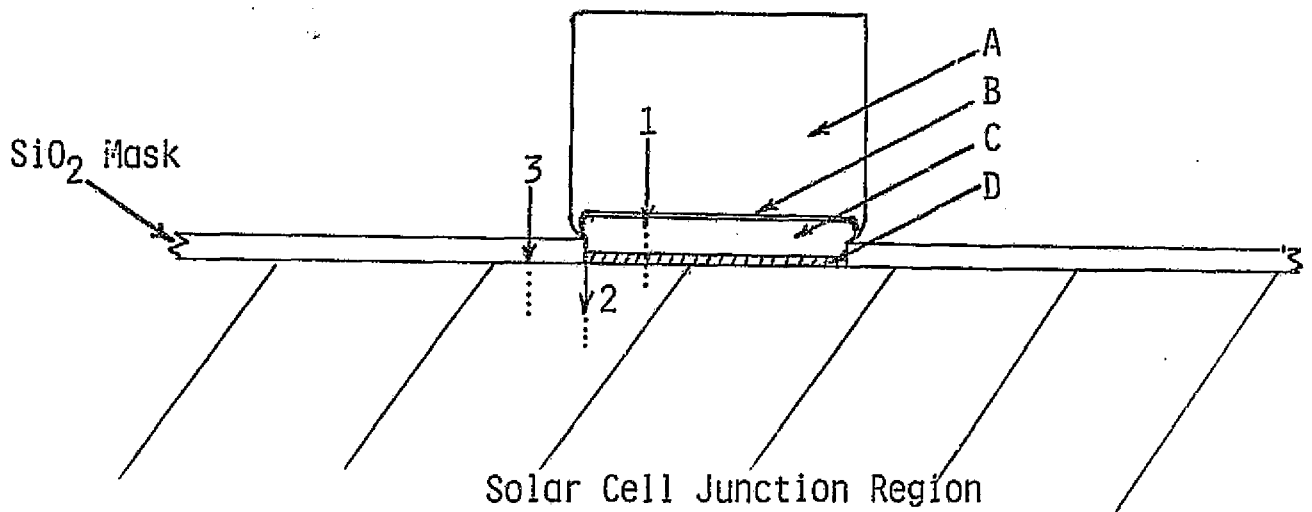
A large number of different plating techniques were used, but it has been shown that when copper is present, great care has to be taken to keep the copper from the silicon junction region.

Heat treatment tests have shown that the copper layer can cause problems when the cells are introduced to elevated temperatures. The results of these tests will be shown in the experimental section. Analytically, looking at the possible problems, a number of different modes of degradation can be identified.

Figure 1 shows the different possible modes of copper migration possible with our present contacting system. Mode one is identified as the diffusion of copper through the chromium layer. Mode one was observed in the contact tests as copper migrated through a dense evaporated chromium layer. It is certain that this will be more of a problem on a less dense material such as plated chromium. Mode two

FIGURE 1

Modes of Copper Migration



NOTE: MODE 1: Migration through chromium layer
 2: Migration at plating edge
 3: Migration through plating mask

Layer A: Electrolytic copper
Layer B: Electroless copper
Layer C: Electroless chromium
Layer D: Immersion Palladium

is identified as edge leakage around the chromium layer. This was not thought to be a problem on the evaporative tests, but could possibly be a problem in the plated system due to undercutting of the photoresist of the present process. Thickness of the chromium layer certainly may give some control on these problems, but a plated material which doesn't allow the copper to migrate would, of course, be the final solution. Mode three is identified as the possible diffusion of copper through the plating mask. Since on the standard substrates for plating, the plating mask has also been used as an antireflection coating, the thickness of the mask has been limited to 750-1000 angstroms. With a layer this thin, pinholes or direct diffusion of copper could cause serious cell performance problems.

Work is now being directed to look at these possible modes of degradation and find techniques of preventing them, compatible with the plating process.

The standard plating substrate must be prepared properly for the contact plating. The proper masking of the fronts of the cells has been discussed but since we are dealing with simultaneous plating of the fronts and backs, it has to be noted, some preparation of the backs is also required. If the outer edges of the cell are plated, the front and back contacts of the cell will be shorted together. This

makes it necessary to mask the outer edges of the cell from the plating solutions (or to include an edge clean-up operation after the plating is completed).

Sensitizing

It became obvious early in the plating work that sensitizing the silicon surface properly was the most important step of the process. If this step was not done correctly, the cells would have (A) poor adhesion, (B) high contact resistance, and (C) improper plating in later steps.

Sensitizing in our process is provided by the thin palladium layer from the immersion palladium bath. For example, it was found that to produce good plating from the chromium bath, the thin palladium layer should be in high small clumps. If there were, instead, a uniform smooth palladium layer, good plating repeatability became a problem and was coupled with poor adhesion of the chromium layer.

Plating Rates

The plating rates are important, of course, for obtaining a high throughput process. However, very high plating rates can adversely affect the adhesion of the plated layer.

The chromium bath rates were controlled by the temperature of the bath as well as concentrations of certain chemicals in the bath. Experiments showed the layers deposited

at high temperatures (100°C) were very stressed, leading to surface peeling problems. By decreasing the temperature and the rates, a more adherent layer was obtained. Also we found it important, in slowly plating the first layer of a metal, say with the electroless copper, and then increasing the plating rate as the layer became thicker.

Electrolytic Plating

With electrolytic plating, an electrode must touch the plated contact on the cell in order to commence plating. Since this contact spot usually does not plate (result of shielding by the electrode), a broken guideline or busbar could result. In the future a special small pad area connected to the grid pattern, will be included in the contact pattern which would eliminate this problem.

EXPERIMENTAL

Plating Mask

Early in the contract the ability to mask the cells properly to provide the required metal pattern was found to be a difficult task. Table 1 shows the results of different mask materials used with the final sequence. Silicon nitride appears to be the only material able to stand up to Bath A without the photoresist. The other plating baths were not corrosive to the masks, making plating easy after Bath A.

However, the masking material must serve other functions as well. With the Motorola system of palladium-nickel-solder, the silicon nitride plating mask is also a cell antireflection coating. Beside these, the mask for our contact system will have to prevent copper contamination of the silicon junction region (Mode 3 in the Technical Discussion Section). This may require thicker layers of masking materials, than just a 750 angstroms layer used for a standard antireflection coating. Certainly, some flexibility here (possibly in cell efficiency) will be needed to guarantee good long term cell performance.

TABLE 1

PLATING MASK RESULTS

PLATING MASK	RESULTS	BATH TYPE	FAILURE REASON
Positive Photoresist	3 2 0	A B C	Became brittle with heat Dissolved
CVD - SiO ₂	0 3 3	A B C	Etched
SiO - Evaporated	0 3 3	A B C	Etched and plated palladium
Ta ₂ O ₅ - Evaporated	0 3 3	A B C	Plated palladium everywhere
Si ₃ N ₄ - Low Temperature CVD	2 3 3	A B C	Slightly etched

NOTES: 0-poor, 1-fair, 2-good, and 3-excellent.

Masks are rated only in their ability to hold up to the plating solutions.

Baths: A - Immersion Palladium
 B - Chromium Bath
 C - Electroless Copper

Plating Experiments

During the duration of the contract only one type of silicon substrate was used. This was 7-14 ohm-cm, P-type silicon material. It had a chemically polished front with a 25 ohm/square phosphorus diffusion. The back had an aluminum paste alloy for a rough surface texture as well as a back surface field. All aluminum was removed by etching down to the silicon before plating. Cells were 2x2 cm in size for easy evaluation work.

The first plating experiments were conducted to test plating copper directly onto the silicon surface. This set of experiments only succeeded after using a palladium-tin sensitizer (Appendix B, Solution A) before plating on the cell, but the copper was never adherent enough for further tests.

The second plating system developed was a gold-copper system (see Appendix A). Gold was thought to be a good material to make the copper stick on the silicon and gold plating solutions were readily available. Later when a quick cost analysis showed a 500 angstroms layer, only on the back of the cell would cost about \$.08/watt in material cost alone, this direction of research was abandoned. A few adherent cells were made, however, leading us to believe a search for good sticking metal was the correct direction in the research.

A careful scan of the metals available for electroless plating in conjunction with their thermal expansion characteristics, suggested chromium would be the best material for this job. Since chromium is an alternative to titanium in evaporative contacts the choice seemed an obvious one. The first electroless chromium bath (Bath A, Appendix C) was found to be hard to control and gave very non-uniform chromium layers. A second bath (Bath B, Appendix C) was found, which gave much better results, but only when the silicon surface had been properly sensitized by the tin-palladium solution (Appendix B). This layer, however, had very poor adhesion before heat treating which led us to believe a better sensitizer was needed. The immersion palladium bath (Appendix E) developed by Motorola, gave very promising results when used with Bath B. Since the palladium layer left was very adherent and the new sensitizing bath was also void of tin, a element known to have low eutectic temperature with silicon, the research appeared to be headed in the right direction. With minor modifications, of the palladium bath, uniform and reliable chromium plating was now routine. After the chromium layer was plated, the cells were sintered and then plated in the electroless copper solution (Appendix B, Solution C). This commercial electroless copper bath was only used to make the electrolytic copper layer more adherent. The 500 angstroms layer generated from this copper bath made a very uniform and consistent layer

for the electrolytic bath to plate. The thin electroless plated copper layer was then electrolytically copper plated to a thickness between 4-6 microns. Figure 2 shows a typical I-V plot of a cell made with the palladium-chromium-copper sequence (full sequence is shown in Appendix F). This cell had a CVD SiO₂ layer which led to about 25-30% increase in current from its antireflection effects. This layer was used only as a plating mask, not as an optimum antireflection coating.

Since the electroless palladium baths had been developed by Motorola, it was thought a palladium-palladium-copper cell should also be studied (see Appendix G). The cells were quickly made and Figure 3 shows a typical I-V plot of one of these cells. The only concern of using thick palladium for a contact metals is that palladium is relatively expensive. Other groups (such as Westinghouse) have also done work looking at the copper migration problem and have found palladium does not act as a very good barrier.

Another important test of contact quality is the contact pull test. In this test small wires were soldered to different areas of the cells (front and back). The cells were put in a special chuck where the wire could be freely pulled perpendicular to the silicon surface while the pull strength

FIGURE 2
Plated Palladium-Chromium-Copper

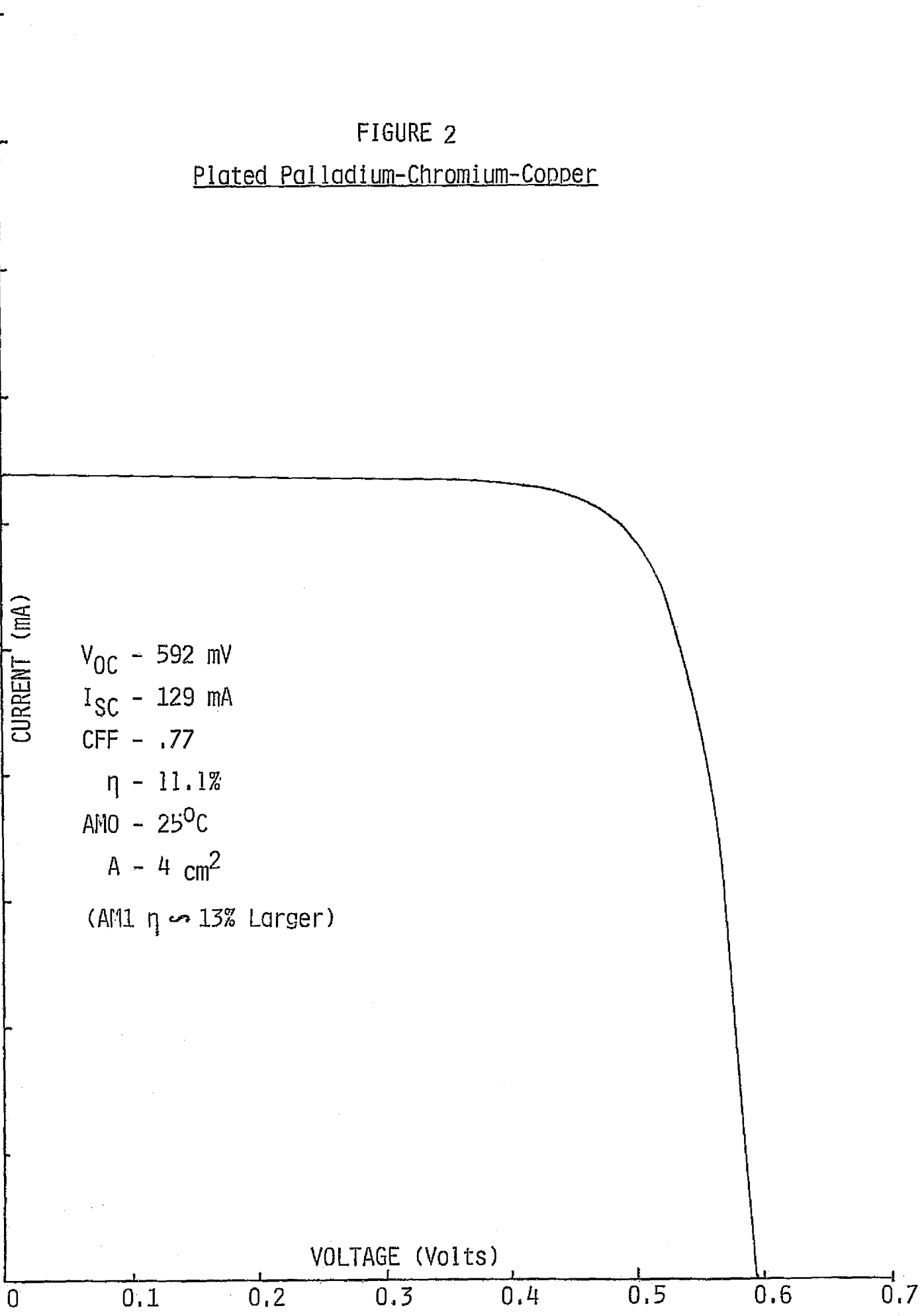
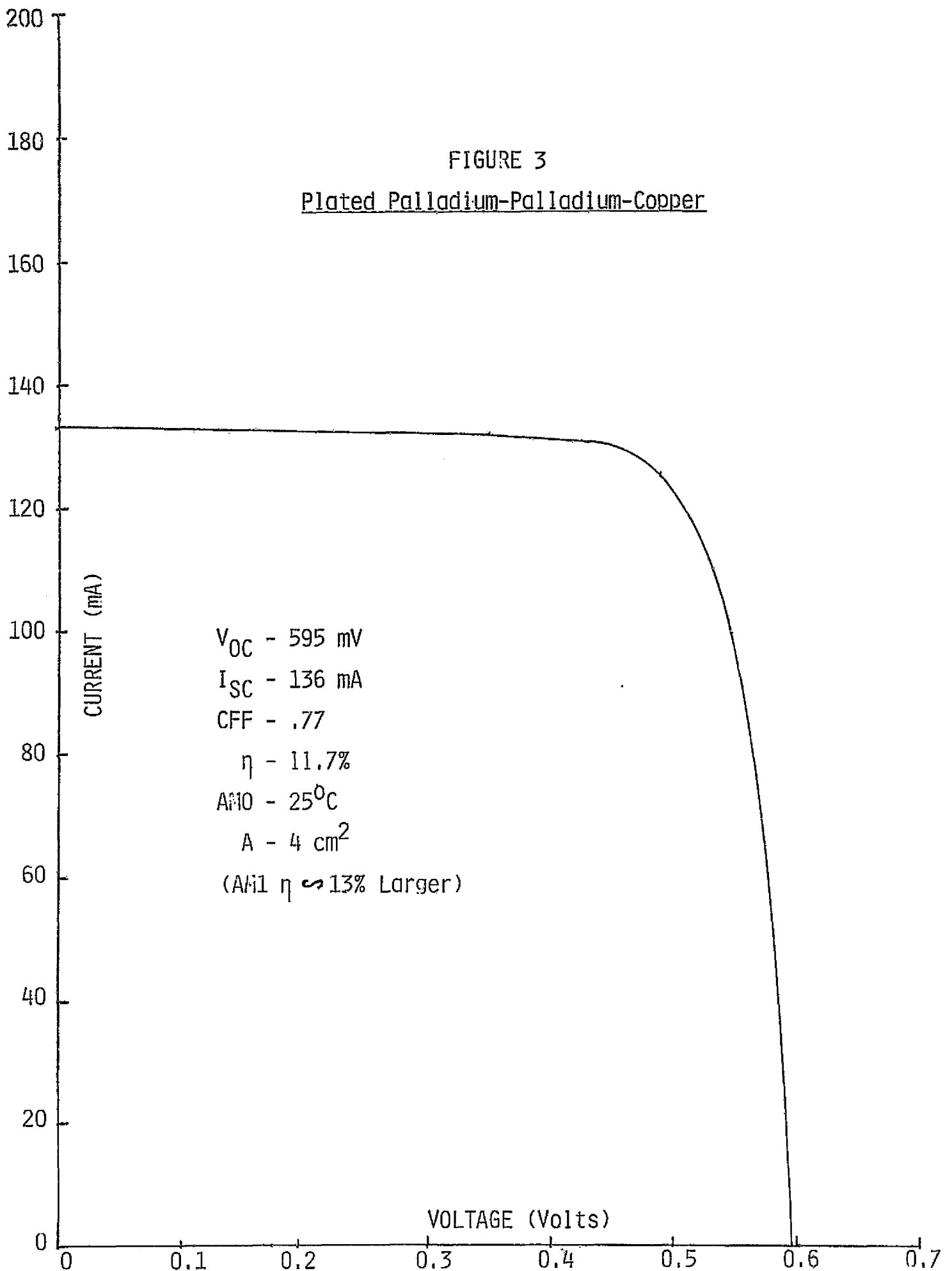


FIGURE 3

Plated Palladium-Palladium-Copper



was being measured. Since the pull strength is directly related to the area (assumed linear until the contact or the silicon breaks), the size of the soldered area was then measured after pulling and the pull adjusted to a constant $.02 \text{ cm}^2$ area. Table 2 shows the results of the pull strength test on four different contact types. All tests pulled some silicon with the contact or broke the silicon samples during the pull. It is believed that if a textured front surface is used, even better adhesion will be obtained.

Scaling Up the Final Process

With the palladium-chromium-copper system working on a small scale (plating on $2 \times 2 \text{ cm}^2$ cells), the next requirement of the contract was a scale up, to a size closer to a production type effort. We decided to use some available $2 \frac{1}{4}$ " diameter cells. These cells would not require bath sizes as large as with 3" diameter cells, but the baths would still have to be increased in size by a factor of six. Maintaining the standard type of silicon material, a batch of silicon wafers (not of the best quality) were used since they were immediately available. Usually when the silicon material quality is in question, the indication is in the quality of the cells back surface field. With these cells after aluminum alloy, a number of them

TABLE 2
CONTACT ADHESION

CONTACT TYPE	MODE	AREA	PULL STRENGTH	
			FRONT	BACK
Ti-Pd-Ag	Evaporated	.02 cm ²	200 gm*	236 gm [†]
Cr-Cu	Evaporated	.02 cm ²	117 gm*	250 gm [†]
Pd-Cr-Cu	Plated	.02 cm ²	83 gm*	220 gm [†]
Pd-Pd-Cu	Plated	.02 cm ²	170 gm*	280 gm [†]

*Pulled Some Silicon

†Cell Broke

Cell Substrate: 7-14 ohm-cm P-Type - Chemically Polished Front -
 Al Alloyed Back

showed problems resulting in the shorting out of the cells, indicating the material had some crystallinity problems. Working with the scaled-up baths, no fundamental problems occurred. The cells were processed in lots of ten (10), since our small heat treat furnace could only accommodate five (5) cells at a time.

The immersion palladium bath worked just as before, even with the large number of cells processed. Over seventy-five (75) 2 1/4" cells were sensitized in this one bath. The depletion rate of this bath appears to be quite low.

The electroless chromium bath (when used successively) depleted very quickly. After only the first twenty (20) cells, the plating rate decreased several orders of magnitude. It was found, however, if 3.5 grams of sodium hypophosphite was added after every ten (10) cells the bath plating rate would remain relatively consistent. Up to forty (40) cells have been plated in one bath. But another problem appeared as this bath became older. The masked areas of the cell became plated with dark deposits of loose material. This appears to be a problem stemming from the depletion of other chemicals in the bath. Work is still being conducted on refining this bath. Chromium baths typically can be used up to a week with proper replenishing of the used chemicals⁽¹⁾.

The electroless copper bath worked repeatably and did not seem to deplete during this test. A problem, however, arose with the electrolytic copper bath, but only involving the size of the power supply. With the present supply only a few cells could be plated at one time. The size of this supply could be increased for the ability to plate a large number of cells at one time. Figure 4 shows a typical I-V plot from one of these large cells. The front electrode thickness was increased to 10 microns on this cell to lower the high series resistance. The photomask that was used was the only one readily available for the cell size. It was designed for a silver thickness of 10 microns for a good cell fill factor (CFF) (plated thickness of copper of 15 microns, would yield a CFF of 77% with this mask). In the future a new mask will be designed to require only 5 microns of copper for cells generating a 77-78% curve fill factor. Table 3 shows a group of five cells taken in random from the forty (40) cells delivered to JPL. Only one cell, No. 4, was shunted. This is believed to be from an aluminum alloy problem, not from cell contact problems.

FIGURE 4

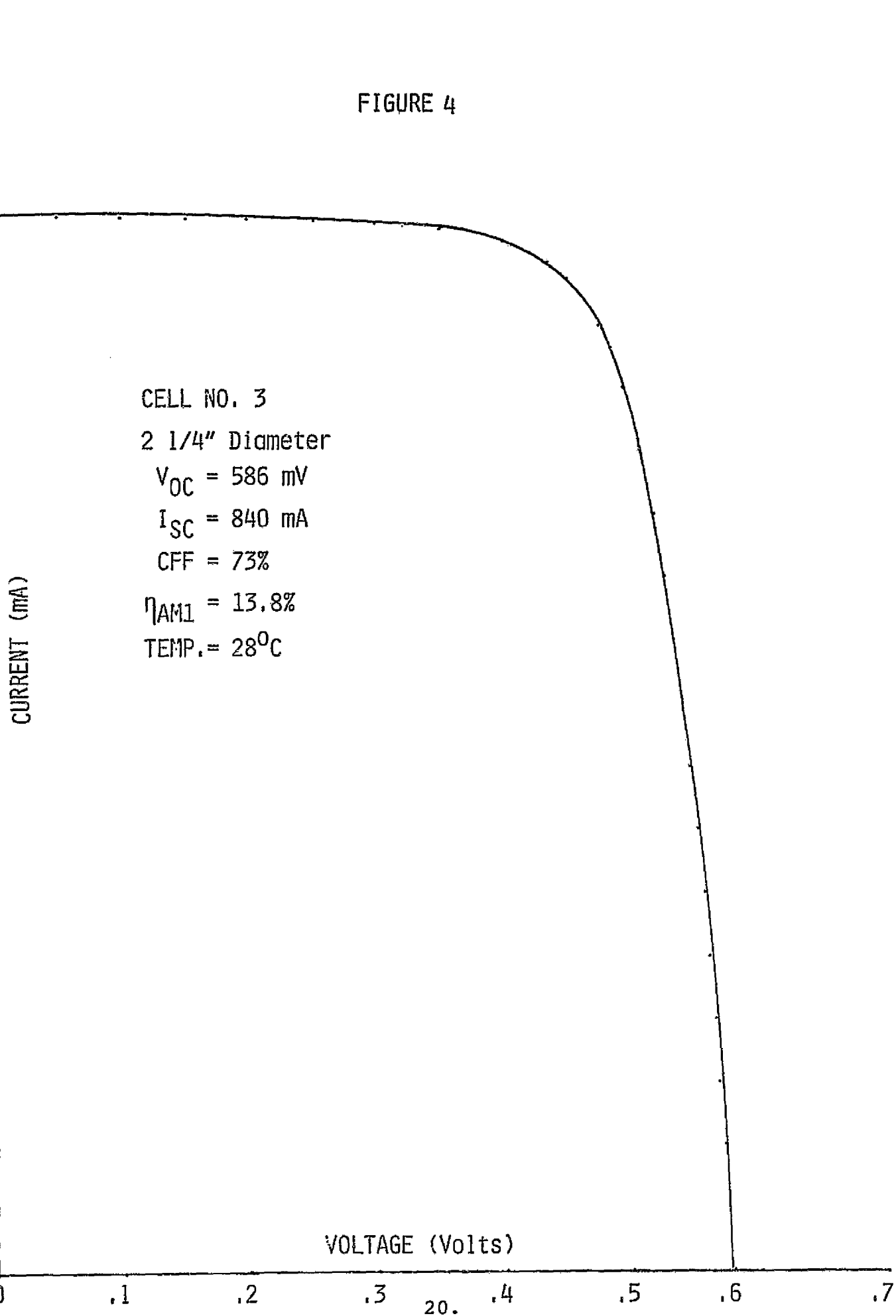


TABLE 3
SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: 2 1/4" Solar Cells With Pd-Cr-Cu Plated Contacts

TEST CONDITION: AMI
TEMPERATURE: 28°C

DATE: 15 May 79

NO.	V_{OC}	I_{SC}	I_{SCB}	I_{SCR}	I_{Max}	V_{Max}	P_{Max}	CFF	η	AREA
	mV	mA	mA	mA	mA	mV	mW	%	%	cm ²
1	586	840	---	---	750	470	352.5	72	13.7	25.7
2	585	850	---	---	755	470	354.9	71	13.8	25.7
3	579	840	---	---	755	470	354.9	73	13.8	25.7
4	454	817	---	---	550	260	143	39	5.6	25.7
5	586	868	---	---	760	460	349.6	69	13.6	25.7

Cells had only approximately 30% current increase due to the CVD SiO₂ (only a plating mask). These are five cells taken in random from the forty (40) cells delivered to JPL.

EVAPORATION EXPERIMENTS

After the new plated contact system was well developed, the question of long term reliability of cells with copper contacts was still unresolved. Simple heating (400-500°C) of the plated cells produced lower V_{OC} and CFF but sometimes the thick copper layer would peel (probably due to the sudden changes of temperature with the differences in linear expansion of the metals). It was decided in order to closely control the metal layers, that is to eliminate any plating variables such as thickness or bath impurities, a heat treatment test of evaporated chromium-copper system would be conducted. The first test (Test No. 1) was done on cells made previously as a comparison in efficiency of the plated cells. These cells were put through a limited heat treat cycle with temperatures ranging from 400-500°C. The cells had 1000 angstroms of chromium, 500 angstroms of copper and then a 4-6 microns layer of copper plated. Table 4 shows the cell data before the heat treatments. Cells were heated in nitrogen (for 5 minutes) at 400, 450 and 500°C. Table 5 shows the cell data after the heat treatments. Some of the cells appear to remain about the same, where the others degraded severely. Since this test included only cells with plated copper, a more controlled test was needed. Table 6 shows the different contact cell groups and test parameters of Test No. 2. Notice there were two groups of

TABLE 4

SOLAR CELL ELECTRICAL DATACELL DESCRIPTION: Cr-Cu Evaporated Contacts With Plated Cu Before Heat Treats (2x2 cm)Test No. 1 (1000 Angstroms Chromium)TEST CONDITION: AMOTEMPERATURE: 28°CDATE: 8 March 1979

NO.	V_{OC}	I_{SC}	I_{SCB}	I_{SCR}	I_{Max}	V_{Max}	P_{Max}	CFF	η	AREA
	mV	mA	mA	mA	mA	mV	mW	%	%	cm ²
A1	601	133.2	51.9	81.2	117.3	500	58.65	.73	10.9	4
A2	600	128	46.2	82	117	500	58.65	.76	10.8	4
B1	600	129.7	48	82	116.9	500	58.45	.75	10.8	4
B2	599	127.4	48.4	79	110.4	500	55.2	.72	10.2	4
C1	502	134.3	52.3	82.4						
C2	599	128.8	47	82	115	500	57.5	.75	10.7	4

These are 2x2 cm² cells with the standard plating substrates.

The cells will be heat treated as follows: A - 400°C, 5 minutes in N₂

B - 450°C, 5 minutes in N₂

C - 500°C, 5 minutes in N₂

TABLE 5

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Cr-Cu Evaporated Contacts With Plated Cu After Heat Treats (2x2 cm)Test No. 1 (1000 Angstroms Chromium)TEST CONDITION: AMOTEMPERATURE: 28°CDATE: 13 March 1979

NO.	V_{OC}	I_{SC}	I_{SCB}	I_{SCR}	I_{Max}	V_{Max}	P_{Max}	CFF	η	AREA
	mV	mA	mA	mA	mA	mV	mW	%	%	cm ²
A1	593	133	52.1	80.9	114	450	51.3	.65	9.5	4
A2	594	128.4	47.1	81.5	114	495	56.4	.74	10.4	4
B1	596	129.5	48.6	81.4	117	490	57.3	.74	10.6	4
B2	593	127.4	48.9	78.5	109	480	52.3	.69	9.7	4
C1	400	134.3	52.4	82	106	235	24.9	.47	4.6	4
C2	593	129.3	47.9	81.6	114	485	55.3	.72	10.2	4

These are 2x2 cm² cells with standard plating substrates.

The cells were heat treated as follows: A - 400°C, 5 minutes in N₂

B - 450°C, 5 minutes in N₂

C - 500°C, 5 minutes in N₂

TABLE 6

EVAPORATED CONTACT TEST NO. 2

GROUP NO.	CONTACT TYPE
1	Cr-Cu (1000 \AA Cr - 5000 \AA Cu)
2	Cr-Cu-Plated Cu (4-6 microns)
3	Ti-Pd-Ag (only 2000 \AA Ag)
4	Ti-Pd-Ag-Plated Ag (4-6 microns)

Sets from each group were heated at 400°C, 450°C, and 500°C for 5 minutes in Nitrogen.

Groups 1 and 3 plated-up after heat treatments for proper comparison.

each type contact system, chromium-copper and titanium-palladium-silver. One group used evaporated metals together with plated metals (copper or silver) while the other used evaporated metals only. The cell groups were marked C - for evaporated chromium-copper, CP - for evaporated chromium-copper-plated copper, T - for evaporated titanium-palladium-silver (2000 angstroms silver), and TP - for evaporated titanium-palladium-silver-plated silver. These four groups of cells were used to separate the effects of plating, namely the mode (3) identified in the discussion section. Table 7 shows a summary of typical cells from each group after the 400 and 500°C heat treatment. Appendix H lists all the data from Test No. 2 showing the cell parameters before and after the heat treatments. Also the cells without plated metal were plated after the heat treating tests for easy comparisons with the other cell data. Results show cells which indicate very little degradation with the 400°C heat treat. But with the 500°C heat treat, degradation was apparent from all the cells with copper contacts. Cells that had plated copper, degraded much worse than the evaporated-only chromium-copper cells, indicating it was bad for the copper to directly touch the silicon surface. Since even the evaporated chromium-copper showed some degradation, it was apparent that mode one was operating with this contact test. Figure 5 is a forward bias dark I-V plot of typical cells taken from Test No. 2 heated at 400°C.

TABLE 7
SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Chromium-Copper Evaporated Heat Treat Tests (2x2 cm)

Test No. 2 (1000 Angstroms Chromium)

TEST CONDITION: AMO

TEMPERATURE: 28°C

DATE: 23 March 1979

NO.	V_{OC}	I_{SC}	I_{SCB}	I_{SCR}	I_{Max}	V_{Max}	P_{Max}	CFF	η	AREA
	mV	mA	mA	mA	mA	mV	mW	%	%	cm ²
GROUP 1										
400°C	594	143	51	91	130	.5	65	.76	12	4
500°C	554	141.7	50	92	104	.385	40	.51	7.4	4
GROUP 2										
400°C	597	144	51.6	93	133	.495	65.8	.77	12.2	4
500°C	302	141	50	90	103	.16	16.5	.39	3	4
GROUP 3										
400°C	594	146	50	96.3	135	.495	66.8	.77	12.4	4
500°C	597	148	51	97.6	136	.5	58.4	.77	12.7	4
GROUP 4										
400°C	596	147.8	50	97.5	134	.495	66.3	.75	12.3	4
500°C	595	146	53	93	132.5	.49	64.9	.75	12	4

FIGURE 5

Heat Treat Results - Dark I-V Plot

Test No. 2

400°C-1000 Angstroms Chromium

CURRENT (mA)

1000

1000

10

1

.1

.01

.001

.0001

0.1

0.2

0.3

0.4

0.5

0.6

0.7

VOLTAGE (Volts)

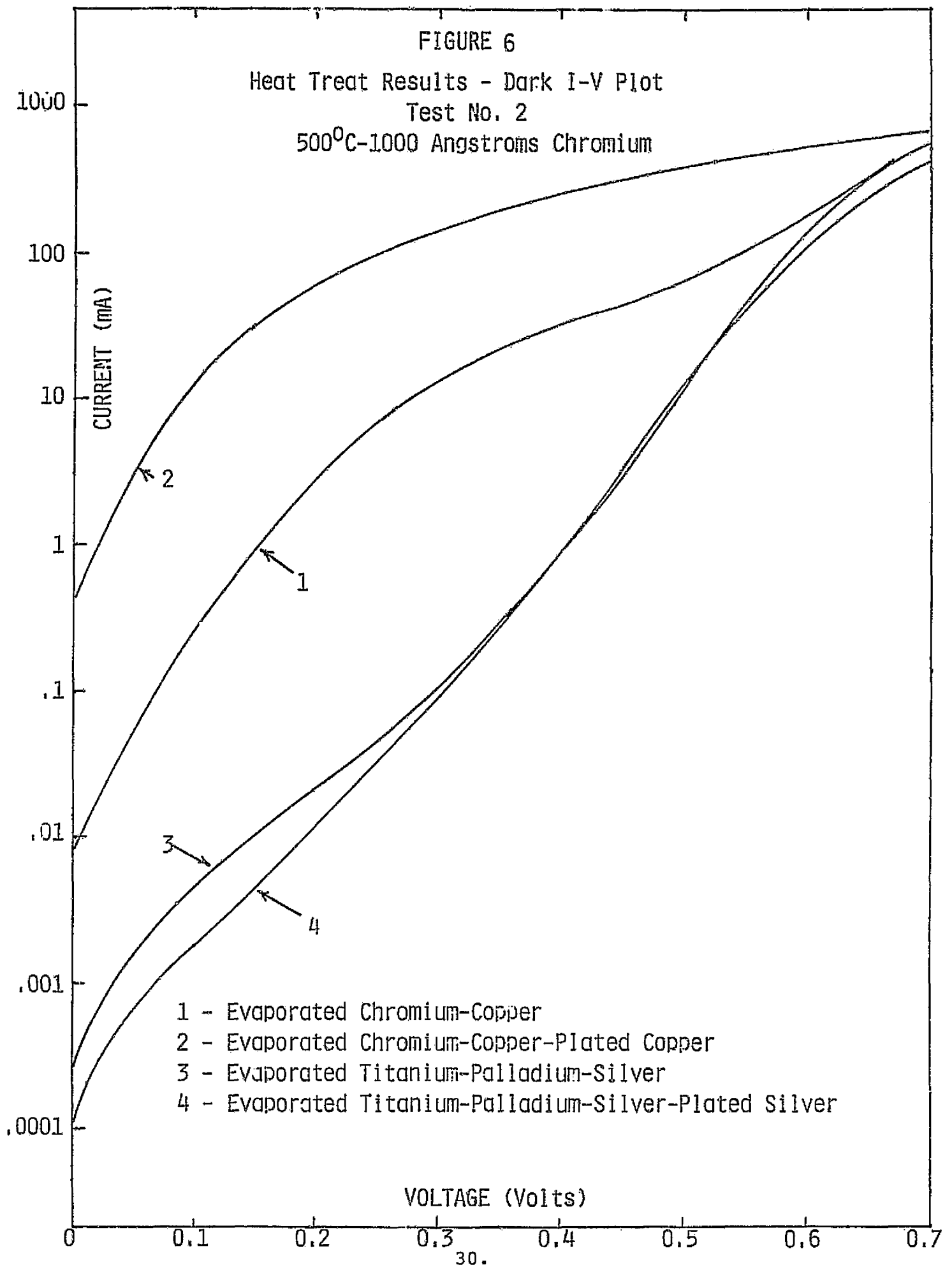
- 1 - Evaporated Chromium-Copper
- 2 - Evaporated Chromium-Copper-Plated Copper
- 3 - Evaporated Titanium-Palladium-Silver
- 4 - Evaporated Titanium-Palladium-Silver-Plated Silver

There appears to be little difference between the groups. Figure 6 shows the results from cells of the 500°C heat treating, indicating again that the copper cells degraded. Notice on Table 7 the red and blue current responses (I_{SC_R} and I_{SC_B}) were unchanged even after the severe 500°C heat treat. From the dark I-V data and the unchanging current levels, conclusions of the effects of copper migration can be made. It appears that the copper is migrating and creating acceptor states in the depletion region of the cell. This would have the effect of lowering the V_{OC} as well as the reducing the curve fill factor. However, one should note, the lifetime of the silicon in the bulk and in the junction region was unchanged as indicated by the red and blue response.

Test No. 3 was designed to look at the effects of the same tests in Test No. 2 but with an increase in thickness of the chromium layer to 2000 angstroms. Only groups 1, 2 and 4 were used from Test No. 2. Groups 3 and 4 in Test No. 2 were basically control groups. When little difference was seen between them, it was thought only group 4 would be needed as a control to Test No. 3. Table 8 shows a summary of the data for the 2000 angstroms chromium test. A full accounting of the data is in Appendix I. Figure 7 shows the forward bias dark I-V data for cells from Test No. 3 heated at 400°C. Notice as before there is very little

FIGURE 6

Heat Treat Results - Dark I-V Plot
Test No. 2
500°C-1000 Angstroms Chromium



- 1 - Evaporated Chromium-Copper
- 2 - Evaporated Chromium-Copper-Plated Copper
- 3 - Evaporated Titanium-Palladium-Silver
- 4 - Evaporated Titanium-Palladium-Silver-Plated Silver

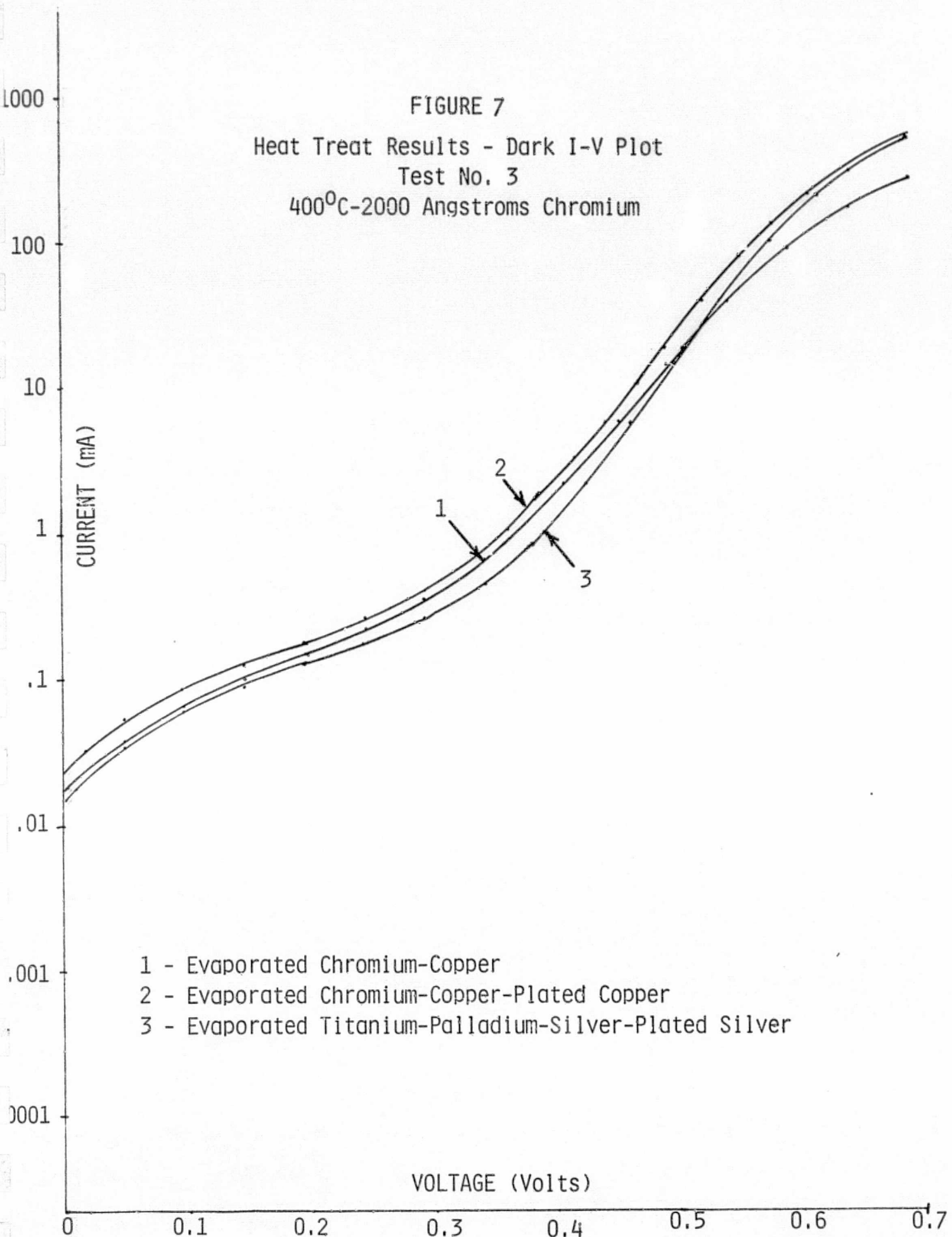
VOLTAGE (Volts)

TABLE 8

SOLAR CELL ELECTRICAL DATACELL DESCRIPTION: Evaporated Test No. 3, Chromium-Copper - 2000⁰A Chromium (2x2 cm)TEST CONDITION: AMOTEMPERATURE: 28⁰CDATE: 9 May 1979

NO.	V_{OC}	I_{SC}	I_{SCB}	I_{SCR}	I_{Max}	V_{Max}	P_{Max}	CFF	η
	mV	mA	mA	mA	mA	mV	mW	%	%
GROUP 1									
400 ⁰ C	591	138.4	47.0	92	122	460	56.1	69	10.4
500 ⁰ C	586	136.4	45.3	91	117	440	51.5	64	9.5
GROUP 2									
400 ⁰ C	590	138.3	49.2	89.6	128	495	63.4	78	11.7
500 ⁰ C	569	137.6	49.9	87.1	110	465	51.4	65	9.5
GROUP 3									
400 ⁰ C	595	140.8	47.7	93.4	130	500	65	78	12
500 ⁰ C	592	138.4	47.1	91.3	126	480	60.5	74	11.2

FIGURE 7
Heat Treat Results - Dark I-V Plot
Test No. 3
400°C-2000 Angstroms Chromium



- 1 - Evaporated Chromium-Copper
- 2 - Evaporated Chromium-Copper-Plated Copper
- 3 - Evaporated Titanium-Palladium-Silver-Plated Silver

VOLTAGE (Volts)

change in the curves, especially at .3 volts region controlled by space charge effects. Figure 8 shows the same plots for cells heated at the 500°C level. The Group 1 cell showed a very small change in the current at the .3 voltage level as compared to the same plot in Test No. 2, Figure 6. The Group 2 cell again showed a large change at the .3 voltage level, but still smaller than the comparable plot from Test No. 2, Figure 6. Again the data seems to indicate that plated copper is touching the silicon surface caused by the poor plating mask. Table 9 shows a comparison of changes in V_{OC} over the temperature range and dark current at .3 volts for the different groups with the same thicknesses. This clearly shows a decrease in the changes caused by the 500°C heat treat by the increased thickness of the chromium. Figures 9 through 12 show plots of the different tests using only thickness as a variable within the same groups. Using a linear approximation, a chromium thickness approximately 2500 angstroms should stop the copper migration for the 5 minutes heat treat. The assumption that the data went linearly was only made because only two data points were available from this limited test. Still, the four sets of data does show consistent decreased changes of parameters with the increasing chromium thickness. Certainly this type of data will be very useful in characterizing different possible barrier metals for copper.

FIGURE 8

Heat Treat Results - Dark I-V Plot
Test No. 3
500°C-2000 Angstroms Chromium

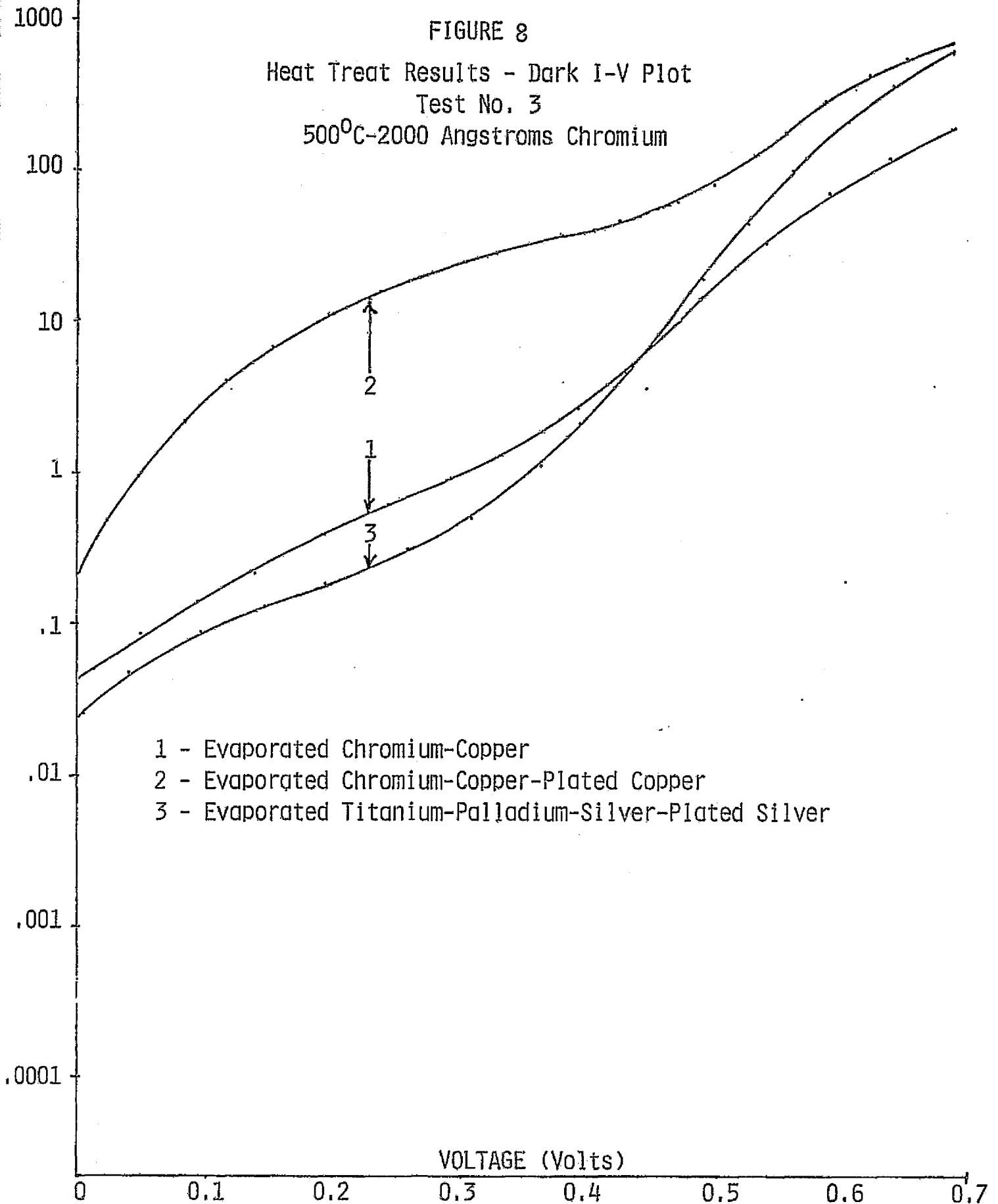


TABLE 9

COMPARISON OF TEST NO. 2 RESULTS TO TEST NO. 3 RESULTS IN CHANGE OF V_{OC} AND IN ABSOLUTE CHANGES OF THE FORWARD BIAS, DARK CURRENT AT .3 VOLTS AND WITH DIFFERENT TEMPERATURES AND THE SAME THICKNESSES

TEST NO.	GROUP NO.	V_{OC} (400-500°C)	DATA AT .3 VOLTS
2	1	29.2 mV	9.1 mA
	2	259.3 mV	199.3 mA
3	1	7.4 mV	.4 mA
	2	34 mV	29.5 mA

NOTE:

- Group 1, Test No. 2: Cells have 1000 $\overset{\circ}{\text{A}}$ Cr-5000 $\overset{\circ}{\text{A}}$ Cu
- Group 2, Test No. 2: Cells have 1000 $\overset{\circ}{\text{A}}$ Cr-5000 $\overset{\circ}{\text{A}}$ Cu-4 Plated Cu
- Group 1, Test No. 3: Cells have 2000 $\overset{\circ}{\text{A}}$ Cr-5000 $\overset{\circ}{\text{A}}$ Cu
- Group 2, Test No. 3: Cells have 2000 $\overset{\circ}{\text{A}}$ Cr-5000 $\overset{\circ}{\text{A}}$ Cu-4 Plated Cu

FIGURE 9
GROUP NO. 1

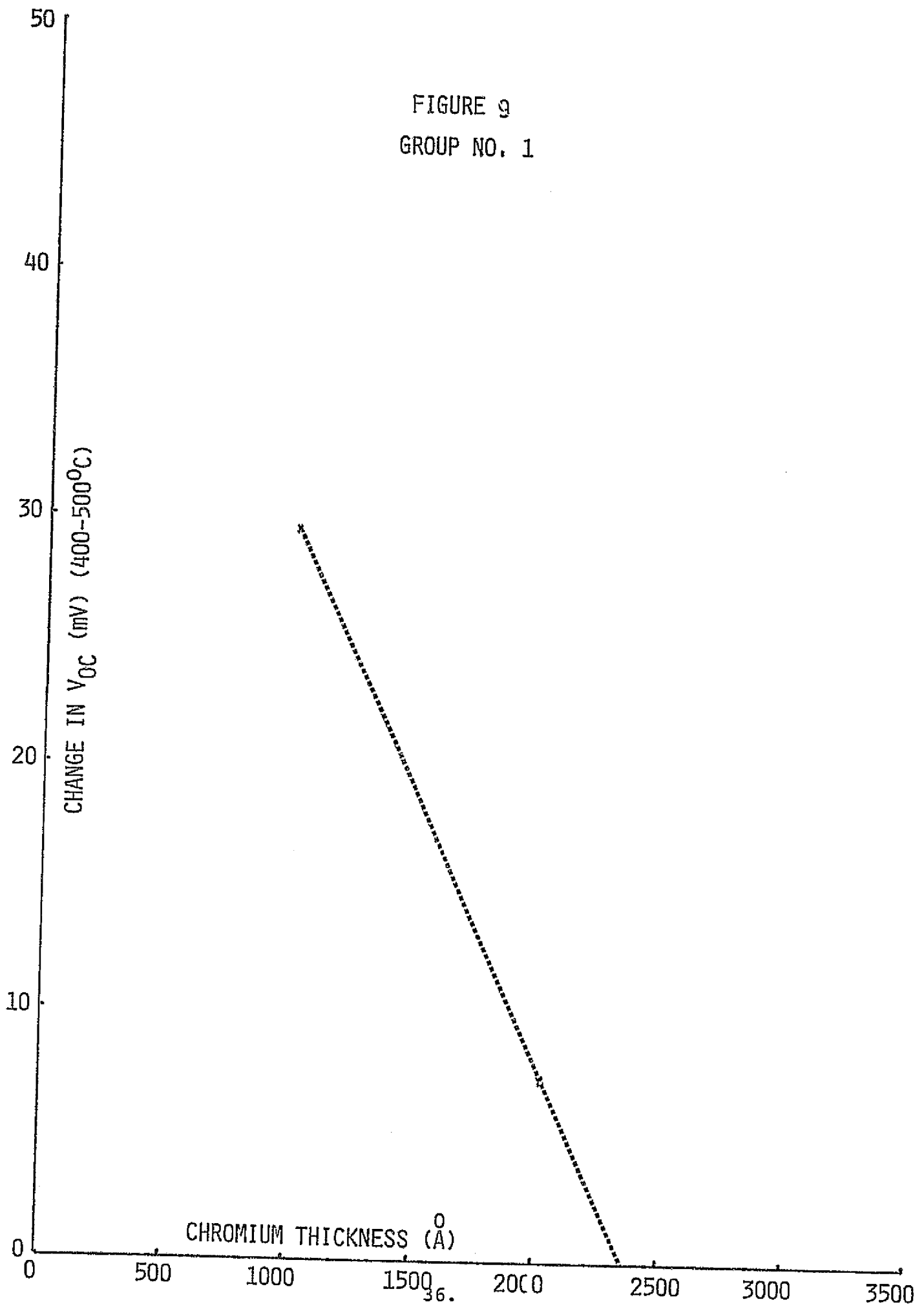


FIGURE 10
GROUP NO. 2

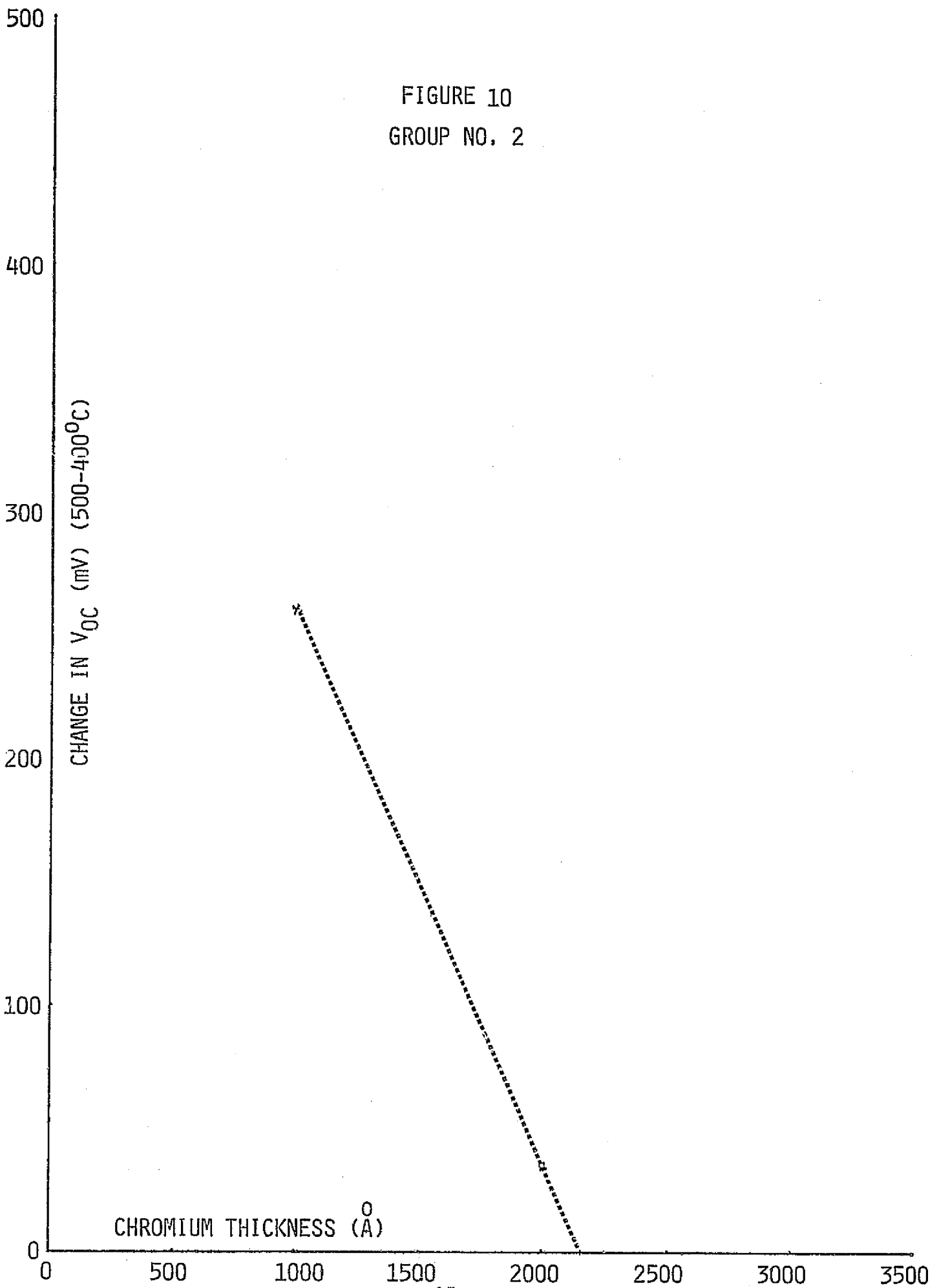


FIGURE 11
GROUP NO. 1

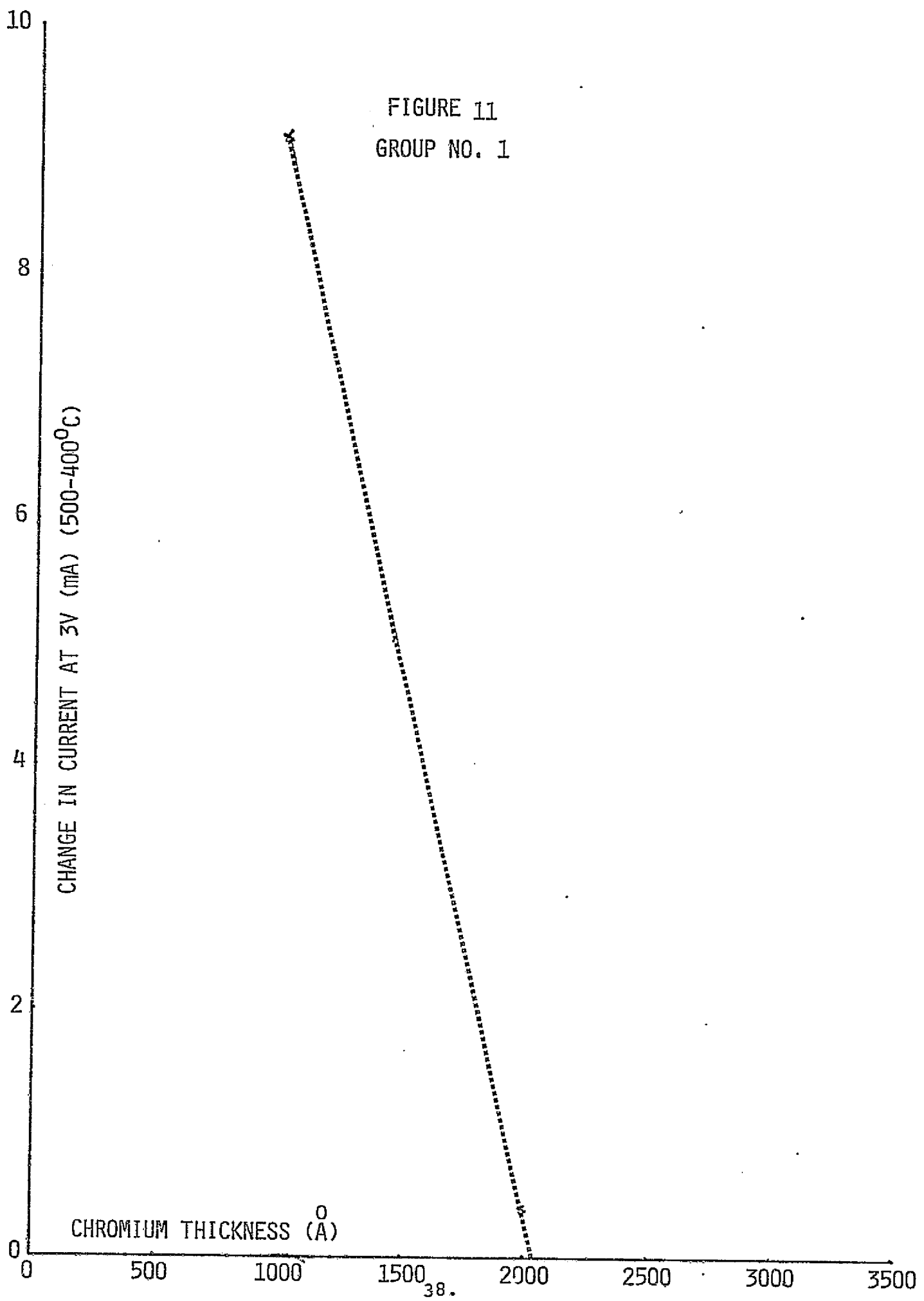
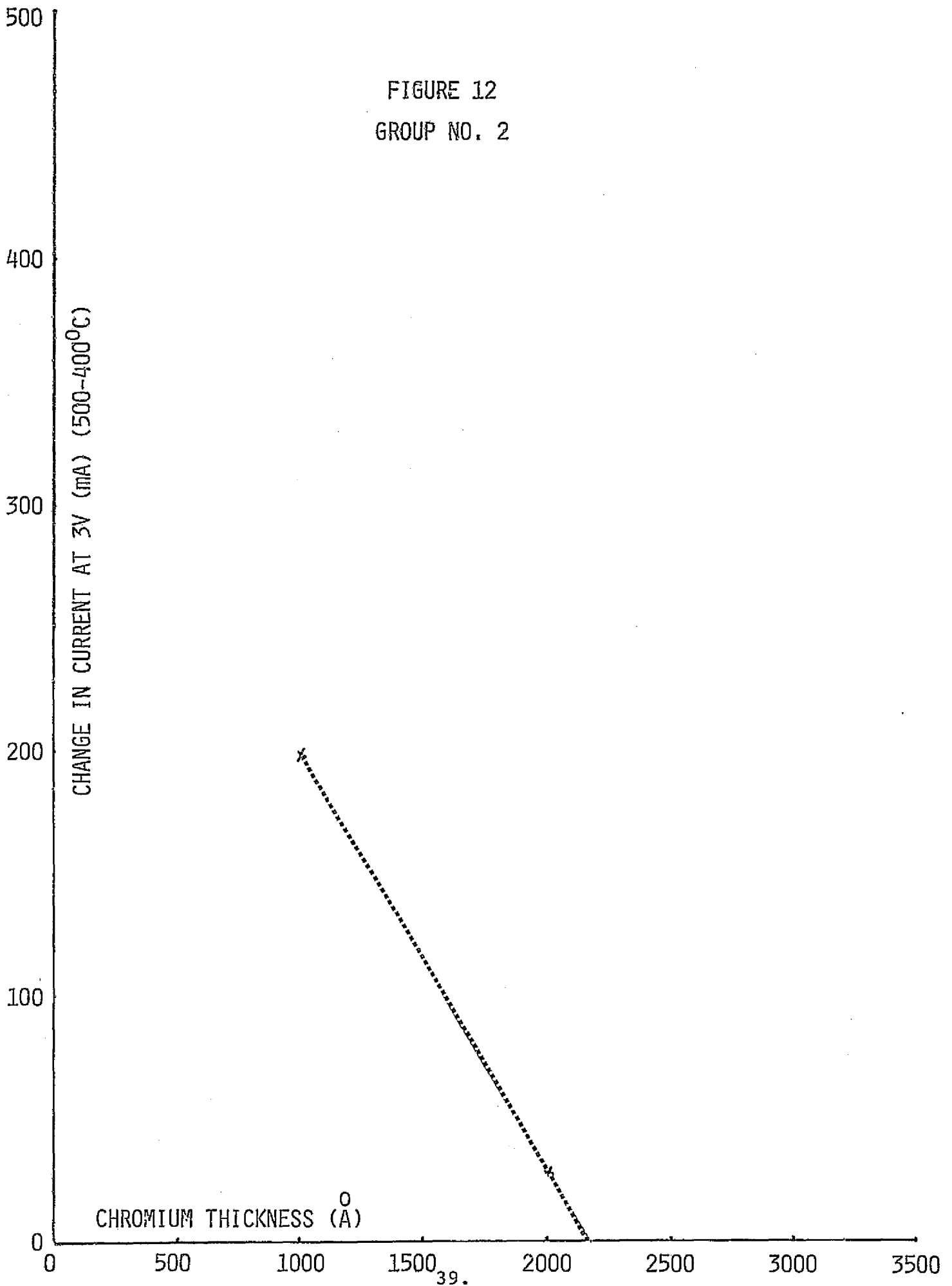


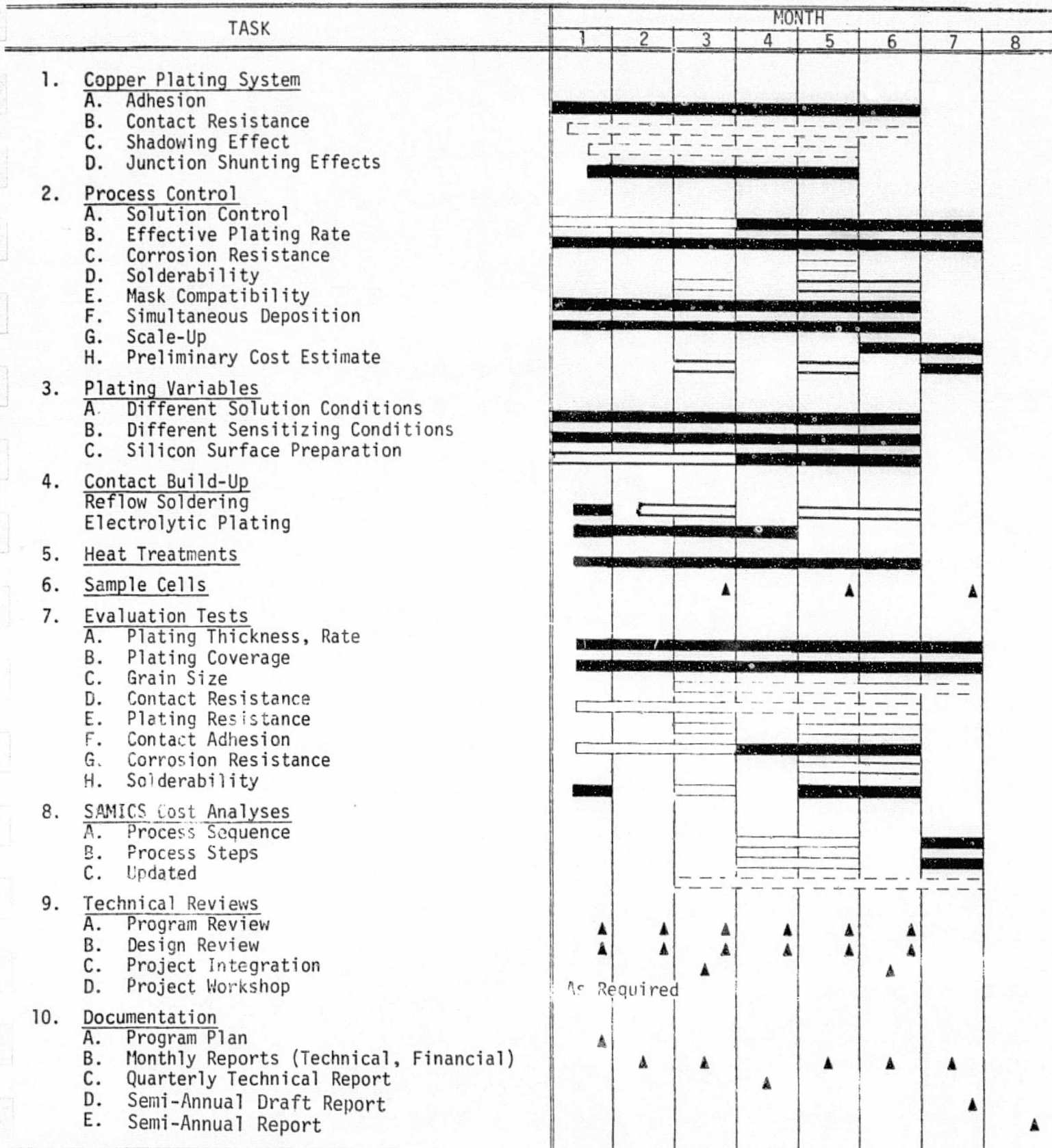
FIGURE 12
GROUP NO. 2



CONCLUSION

A new electroless plating system of palladium-chromium-copper has been developed. But questions of the cells long term reliability are still unresolved. Techniques will have to be developed to control the thick copper contact in keeping it from the active regions of the cells. This will be the main effort in the contract extension. Metals will have to be found that will reliably keep the copper from the cells over long periods of time. When these metals are found, they will have to be incorporated into the present plating process.

MILESTONE CHART



LEGEND [Solid Bar] Scheduled [Dashed Bar] Continuing [Solid Bar] Completed

APPENDIX A

GOLD CYANIDE SOLUTION

200 ml Deionized Water

2 gm Gold Cyanide

10 ml 48% HF

Use at room temperature under a bright light for 2 minutes.

This solution was discussed on Page 11. Use was discontinued due to high cost.

APPENDIX B

COMMERCIAL PLATING SYSTEM

- A) Dynaplate Activator 120
- B) Dynaplate Conditioner 101
- C) Dynaplate 240 Electroless Copper

All solutions made by Thiokol/Dynachem Corporation.

Use at room temperature.

This bath is used in the final contact sequence, but only Bath C. The thin layer of copper generated from this bath, makes the electrolytic copper adhere better. See Process Specifications for Baseline Procedures, May 31, 1979, Contract No. 955244.

APPENDIX C

ELECTROLESS CHROMIUM BATHS

Bath A

Chromium Fluoride	15	gm/l
Chromium Chloride	1	gm/l
Sodium Citrate	7.5	gm/l
Sodium Hypophosphite	7.5	gm/l

The operating temperature was 85-95°C.

Bath B *

	<u>2x2 cm Cell</u>	<u>2 1/4" Cell</u>
Deionized Water	200 ml	1800 ml
Chromium Acetate	6 gm	42 gm
Nickel Acetate	.4 gm	28 gm
Sodium Citrate	8 gm	56 gm
Sodium Glycolate	8 gm	56 gm
Sodium Acetate	4 gm	28 gm
Sodium Hypophosphite	5 gm	35 gm

The operating temperature was 85-90°C.

*This bath formulation was selected for the final chromium plating sequence. See Process Specification Procedures for plating formulations and operating conditions, Contract No. 955244, dated May 31, 1979.

Formulations taken from "Electroless Plating Today" by Dr. Edward B. Saubestre.

APPENDIX D

ELECTROLYTIC COPPER SOLUTION

Deionized Water	1000 ml
H ₂ SO ₄	30 ml
CuSO ₄	200 ml

Solution used at room temperature. Cells plate ~.3 microns per minute at 7 mA/cm².

This solution was used in final contact sequence. See Process Specifications for Baseline Procedures, May 31, 1979, Contract No. 955244.

APPENDIX E

MOTOROLA'S PLATING SOLUTIONS

Immersion Palladium Bath*

	<u>2x2 cm Cell</u>	<u>2 1/4" Cell</u>
Deionized Water	300 ml	1800 ml
PdCL	.05 gm	.3 gm
HCL	1 ml	6 ml
NH ₄ F	20 ml	120 ml

Mixed in a sonic bath and used at room temperature in the dark.

Electroless Palladium Plating Bath⁺

Deionized Water	830 ml
HCL	4 ml
PdCL ₂	2 gm
NH ₄ CL	27 gm
NAH ₂ PO _d 2H ₂ O	6 gm
NH ₄ OH	160 ml

*Bath was used in final process. See Process Specification Procedures for plating formulations and operating conditions, Contract No. 955244, dated May 31, 1979.

⁺Bath only used for certain experiments. Palladium costs were too high.

APPENDIX F

CHROMIUM-COPPER PLATED CONTACT PROCEDURE

1. Standard 2x2 cm substrates or 2 1/4" cells.
2. Photoresist and etch.
3. Immersion palladium bath (Appendix E).
 - a) Five (5) seconds 6% HF.
 - b) Immersion palladium bath for 5 minutes in the dark.
 - c) Scrub cell with Q-tip, deionized water rinse.
 - d) Remove photoresist with acetone.
 - e) Heat treat 15 minutes at 400°C in N₂.
4. Electroless chromium bath (Appendix C).
 - a) Five (5) seconds 6% HF.
 - b) Deionized water rinse 5 seconds.
 - c) Immerse cells for 15 minutes, rinse deionized water.
 - d) Heat treat 15 minutes at 400°C in H₂.
5. Dip in 6% HF 5 seconds and then 5 seconds dip in deionized water.
6. Immerse in Dynachem electroless copper solution for 5 minutes at 35°C.
7. Plate in electrolytic copper solution for 20 minutes at (7 mA/cm²) for plating front and back simultaneously. Procedure plates 4-6 microns of dense copper.

For more detailed procedure see Process Specification Procedures, Contract No. 955244, dated May 31, 1979.

APPENDIX G

PLATED PALLADIUM-PLATED COPPER PROCEDURES

1. Standard 2x2 cm substrates.
2. Photoresist and etch.
3. Immersion palladium bath (Appendix E).
 - a) Five (5) seconds 6% HF.
 - b) Immersion palladium bath for 5 minutes.
 - c) Scrub with Q-tip, deionized water rinse.
4. Electroless palladium bath (Appendix E)
 - a) Five (5) seconds in 6% HF.
 - b) Immerse in bath for 2 minutes at 40°C.
 - c) Heat treat 400°C in N₂ for 15 minutes.
5. Dip in 6% HF for 5 seconds and rinse in deionized water for 5 seconds.
6. Electroless copper bath (Appendix B) for 2 minutes.
7. Electrolytic copper bath (Appendix D)
 - a) Twenty (20) minutes at 7 mA/cm² for 4-6 microns layer.

Process abandoned in favor of Pd-Cr-Cu of Appendix F largely because Pd-Cr-Cu is a more cost effective plating sequence.

APPENDIX H

FULL LISTING OF DATA GENERATED
FROM THE CONTACT HEAT TREAT TESTS

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: EVAPORATIVE Test 2 Cr-Cu system (500°C 5min N₂)
(1000 Å Cr)
 TEST CONDITION: AMO
 TEMPERATURE: 28°C DATE: 3/23/79

NO.	V _{OC}	I _{SC}	I _{SCB}	I _{SCR}	I _{Max}	V _{Max}	P _{Max}	CFF	η
	mV	mA	mA	mA	mA	mV	mW	%	%
C3	562	141.4	50	91.4	108	395	42.7	54	7.9
6	560	142.4	50.4	91.7	104	375	39	49	7.2
9	565	143.8	52.4	91.6	104	375	39	48	7.2
CP3	429	142.3	50.4	91.5	90	240	21.6	35	4.0
6	302	140.6	50.4	90	103	160	16.5	39	3.0
9	273	139.8	48.4	91.5	101	135	13.5	36	2.5
T3	581	99.6	45.7	78.4	58	400	23.2	40	4.3
6	583	136.0	47.1	92.6	86	390	33.5	42	6.2
9	582	130.5	48.9	93.0	79	390	30.8	41	5.7
TP3	595	146.0	53	93.1	132.5	490	64.9	75	12
6	593	144.4	49.7	94.8	131	480	62.9	73	11.6
9	590	141.2	47.4	93.2	131	480	62.9	75	11.6

Note: Cell Area 4cm²

57

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: EVAPORATIVE TEST 2 Cr-Cu system (450°C 5m IN N₂)
(1000Å Cr)
 TEST CONDITION: AMO
 TEMPERATURE: 28°C DATE: 3/23/79

NO.	V _{OC}	I _{SC}	I _{SCB}	I _{SCR}	I _{Max}	V _{Max}	P _{Max}	CFF	η
	mV	mA	mA	mA	mA	mV	mW	%	%
C2	588	144.5	52.3	92.4	124.	430	53.3	63	9.9
5	572	142.7	51.2	91.7	101	415	41.9	51	7.8
8	586	140.7	48.4	92.7	105	415	43.6	53	8.1
CP2	589	143.1	51.6	91.5	125	485	60.6	72	11.2
5	592	139.4	47.4	91.7	124	490	60.8	74	11.3
8	592	137.0	46.2	90.4	124	490	60.8	75	11.3
T2	583	105.3	49.0	81.4	61	405	24.7	40	4.6
5	585	126.3	47.5	93.6	78	385	30	41	5.6
8	581	98.5	46.4	77.5	58	400	23.2	41	4.3
TP2	590	145.8	50.9	94.7	132	445	58.7	68	10.9
5	591	145.0	52.2	92.8	130	440	57.2	67	10.6
8	591	144.3	52.2	92.6	133	490	65.2	76	12.1

NOTE: CELL AREA 4 CM²

58.

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: EVAPORATIVE Test 2 Cr-Cu CONTACTS (HEATED 400°C IN N₂)
 (1000 Å Cr) 5 min

TEST CONDITION: AMD
 TEMPERATURE: 28°C DATE: 3/23/79

NO.	V _{OC}	I _{SC}	I _{SCB}	I _{SCR}	I _{Max}	V _{Max}	P _{Max}	CFF	η
	mV	mA	mA	mA	mA	mV	mW	%	%
C1	592	144	51.8	92.6	128	455	58.24	68	10.8
C4	573	143.9	52.8	91.7	101	420	42.4	51	7.9
C7	591	144.8	53.4	91.6	130	455	59.2	69	11.0
CP1	593	142.7	52.9	90.1	129	500	64.5	76	11.9
CP4	597	144.0	51.6	93.0	133	495	65.8	77	12.2
CP7	592	141.2	49.7	91.6	122	495	60.4	72	11.2
T1	585	134.3	49.8	96.7	81	395	32.0	41	5.9
T4	589	133.5	51.6	97.0	81	395	32.0	41	5.9
T7	585	109.7	50.3	84.8	65	395	25.7	40	4.8
TP1	596	147.8	50.2	97.5	134	495	66.3	75	12.3
TP4	595	145.8	48.5	97.3	133	490	65.17	75	12.1
TP7	596	145.8	48.2	97.7	133	490	65.17	75	12.1

NOTE: CELL AREA 4 cm²

59.

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: EVAPORATIVE Test 2 Cr-Cu system before heat TREAT
(Copper Cells) (1000Å Cr)
 TEST CONDITION: AMO
 TEMPERATURE: 28°C DATE: 3/23/79

NO.	V _{OC}	I _{SC}	I _{SCB}	I _{SCR}	I _{Max}	V _{Max}	P _{Max}	CFF	η
	mV	mA	mA	mA	mA	mV	mW	%	%
C1	591	143.9	—	—	128.5	445	57.18	67	10.6
2	593	145.8	—	—	127.0	430	54.6	63	10.1
3	593	143.2	—	—	128.5	445	57.18	67	10.6
4	594	144.2	—	—	129.0	450	58.05	68	10.7
5	594	144.7	—	—	129.0	450	58.05	68	10.7
6	589	144.3	—	—	122.0	415	50.63	60	9.4
7	593	144.7	—	—	129.0	455	58.7	68	10.9
8	588	141.6	—	—	110.0	405	44.6	54	8.2
9	592	145.9	—	—	120.0	410	49.2	57	9.1
CPI	594	143.1	—	—	132.0	490	64.7	76	12.0
2	594	144.0	—	—	132.0	490	64.7	76	12.0
3	598	144.4	—	—	132.0	495	65.3	76	12.1
4	597	144.4	—	—	132.0	500	66.0	77	12.2
5	596	140.7	—	—	129.0	495	63.9	76	11.8
6	595	143.1	—	—	131.0	495	64.8	76	12.0
7	596	141.1	—	—	129.5	500	64.8	77	12.0
8	595	138.3	—	—	126.5	500	63.3	77	11.7
9	595	141.6	—	—	129.5	500	64.8	77	12.0

Note: Cell AREA 4 cm²

60.

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: EVAPORATIVE TEST 2 Cr-Cu SYSTEM Before HEAT TREAT
 (TiPdAg CELLS)

TEST CONDITION: AMD
 TEMPERATURE: 28°C DATE: 3/23/79

NO.	V _{OC}	I _{SC}	I _{SCB}	I _{SCR}	I _{Max}	V _{Max}	P _{Max}	CFF	η
	mv	mA	mA	mA	mA	mV	mW	%	%
T1	591	147.0	—	—	113	410	46.3	53	8.6
2	588	125.8	—	—	74	405	30.0	41	5.5
3	587	115.8	—	—	68	400	27.2	40	5.0
4	596	149.2	—	—	108	410	44.3	50	8.2
5	593	145.1	—	—	107	410	43.9	51	8.1
6	590	144.4	—	—	107	410	43.9	51	8.1
7	591	135.1	—	—	83	390	32.4	41	6.0
8	586	116.2	—	—	67	405	27.1	40	5.0
9	589	145.8	—	—	107	415	44.4	52	8.2
TP-1	598	147.8	—	—	134	485	64.9	74	12.0
2	593	147.5	—	—	134	465	62.3	71	11.5
3	601	150.4	—	—	137	485	66.4	74	12.3
4	597	145.5	—	—	135	480	64.8	75	12.0
5	596	148.1	—	—	134	460	61.4	70	11.4
6	598	148.8	—	—	135	480	64.8	73	12.0
7	597	145.9	—	—	133	490	65.2	75	12.1
8	594	147.9	—	—	137	485	64.4	76	12.3
9	594	144.4	—	—	132	485	64.0	75	11.9

CELL AREA 4 cm²

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: EVAPORATIVE Test #2 PLATE-UP RESULTS AFTER
HEAT TREATS CELLS T1-9 (Ag) C1-9 (Cu)
 TEST CONDITION: AMO
 TEMPERATURE: 280C DATE: 3/27/79

NO.	V _{OC}	I _{SC}	I _{SCB}	I _{SCR}	I _{Max}	V _{Max}	P _{Max}	CFF	η
	mV	mA	mA	mA	mA	mV	mW	%	%
C1	594	142.5	50.8	91.8	129	495	63.9	75	11.8
2	591	143.5	51.7	92	129	495	63.9	75	11.8
3	554	141.7	50.1	91.7	104	385	40	51	7.4
4	579	143.6	52.3	91.5	106	455	48.2	58	8.9
5	572	142.5	51.0	92	104	435	45.2	56	8.4
6	531	143.1	50.7	92.4	102	350	35.7	47	6.6
7	594	143.3	52.7	90.8	130	500	65	76	12
8	589	140.2	48.2	92.3	123	485	59.7	72	11
9	564	144.4	52.3	92.0	106	420	44.5	55	8.2
T1	594	146.1	49.5	96.8	135	495	66.8	77	12.4
2	594	144.1	48.7	95.6	130	480	63.7	74	11.8
3	595	140.7	45.8	95.0	129	490	63.2	76	11.7
4	597	148.2	51.0	97.6	136	503	68.2	77	12.7
5	593	141.7	47.2	95	129	495	63.9	76	11.8
6	592	139.2	46.7	92.7	130	495	64.4	78	11.9
7	598	145.8	49.6	96.3	135	495	66.8	77	12.4
8	595	141.4	46.2	95.5	130	495	64.4	76	11.9
9	591	142.0	48.4	93.7	130	490	63.7	76	11.8

NOTE: Cell Area 4cm²

APPENDIX I

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: EVAPORATIVE Test # 3 Cr-Cu System NO HEAT TREATS
(2000Å) Cr

TEST CONDITION: AMO
 TEMPERATURE: 280C

DATE: 5/9/79

NO.	V _{OC}	I _{SC}	I _{SCB}	I _{SCR}	I _{Max}	V _{Max}	P _{Max}	CFF	η
	mV	mA	mA	mA	mA	mV	mW	%	%
C1	594	135.5	45	90.8	119	440	52.4	65	9.7
2	591	141.2	49.6	92.4	123	440	54.1	64	10
3	593	137.6	45.9	91.7	124	460	57	70	10.6
4	596	142.1	49.6	92.7	128	465	59.5	70	11
5	595	145.1	53.3	82.3	128	465	59.5	69	11
6	595	141.1	48.6	92.8	127	460	58.4	70	10.8
7	593	135.1	44.8	90.6	117	435	50.9	64	9.4
8	597	139.1	47.5	91.9	122	455	55.5	67	10.3
9	594	135.0	44.4	90.5	120	450	54	67	10.0
10	594	136.6	46	90.5	124	470	58.3	72	10.8
CP1	598	135.2	44	90.4	121	500	60.5	75	11.2
2	591	137.5	47.7	89.7	126	500	63	78	11.7
3	593	143.7	53.7	90.1	130	500	65	76	12
4	596	138.3	41.8	90.8	127	500	63.5	77	11.8
5	597	133.1	44.6	89.5	121	500	60.5	76	11.2
6	596	141	49.1	91.6	128	500	64	76	11.9
7	592	133	45.7	87.7	120	505	60.6	77	11.2
8	592	139.7	51.4	88.7	127	505	64.2	78	11.9

Note: Cell Area 4 cm²

64.

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: EVAPORATIVE TEST #3 Cr-Cu SYSTEM NO HEAT TREATS
(2000 Å Cr)
 TEST CONDITION: AMO
 TEMPERATURE: 28°C DATE: 5/9/79

NO.	V _{OC}	I _{SC}	I _{SCB}	I _{SCR}	I _{Max}	V _{Max}	P _{Max}	CFF	η
	mV	mA	mA	mA	mA	mV	mW	%	%
TP1	598	145	51.4	93.6	130	505	65.7	76	12.2
2	596	140	48.5	91.8	130	500	65	78	12
3	598	141.3	49	92.8	130	500	65	77	12
4	597	140.1	47.3	93.1	127	500	63.5	76	11.8
5	595	137.6	46.1	91.6	125	500	62.5	76	11.6
6	596	137.3	46.4	91.4	125	500	62.5	76	11.6
7	595	137.2	45.7	91.8	125	495	61.9	76	11.5
8	597	144	50	93.9	132	500	66	77	12.2
9	597	139.9	48.3	92.3	130	500	65	78	12
10	596	138.2	46.7	92.2	126	500	63	76	11.7

CELL AREA 4 cm²

65.

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Evaporative Test #3 (Cr-Cu system (400°C N₂ 5m))
(2000 A Cr)
 TEST CONDITION: AMO
 TEMPERATURE: 28°C DATE: 5/9/79

NO.	V _{OC}	I _{SC}	I _{SCB}	I _{SCR}	I _{Max}	V _{Max}	P _{Max}	CFF	η
	mV	mA	mA	mA	mA	mV	mW	%	%
C1	593	136.2	45.3	91.2	115	440	50.6	63	9.4
2	589	142.2	48.7	92.6	124	440	54.6	65	10.1
3	591	138.4	47	91.9	122	460	56.1	69	10.4
4	595	142.7	50.4	92.6	128	465	59.5	70	11.0
5	593	145.6	53.7	92	128	465	59.5	69	11.0
CP1	596	136.6	46	91.1	124	490	60.8	75	11.3
2	590	138.3	49.2	89.6	128	495	63.4	78	11.7
3	592	144	54.5	89.7	132	500	66	77	12.2
4	594	139.2	48.8	90.7	130	500	65	79	12.0
TP1	594	145.4	52.4	93.5	132	500	66	76	12.2
2	596	141.6	49.2	92.4	130	500	65	77	12.0
3	597	142.3	50.1	92.9	132	500	66	78	12.2
4	595	140.8	47.7	93.4	130	500	65	78	12.0
5	594	138.7	46.6	92.1	128	500	64	78	11.9

CELL AREA 4 cm²

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: EVAPORATIVE TEST #3 Cr-Cu system (500°C N₂ 5m)
(2000 Å Cr)

TEST CONDITION: AMD

TEMPERATURE: 28°C

DATE: 5/9/79

NO.	V _{OC}	I _{SC}	I _{SCB}	I _{SCR}	I _{Max}	V _{Max}	P _{Max}	CFF	η
	mV	mA	mA	mA	mA	mV	mW	%	%
C6	582	139.7	49.4	90.1	124	440	54.6	67	10.1
7	582	134.9	44.7	89.9	112	410	45.9	58	8.5
8	591	139.6	47.9	91.7	122	440	53.7	65	9.9
9	586	136.4	45.3	91.0	117	440	51.5	64	9.5
10	583	134.7	46.1	87.9	122	445	54.3	69	10.0
CP5	558	133.1	45.8	87.0	90	405	36.5	49	6.7
6	569	137.6	49.9	87.1	110	465	51.2	65	9.5
7	543	130.7	45.8	84.6	84	390	32.8	46	6.1
8	566	136.6	51	85.5	102	460	46.9	61	8.7
TP6	594	137.6	46.8	90.8	124	495	61.4	75	11.4
7	592	137.3	45.9	91.3	124	495	61.4	76	11.4
8	591	141.2	50.1	90.6	127	500	63.5	76	11.8
9	586	138.4	48.8	89.6	126	480	60.5	75	11.2
10	592	138.4	47.1	91.3	126	480	60.5	74	11.2

CELL AREA 4cm²

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