FINAL REPORT

IMPROVED SOLAR CELL CONTACTING TECHNIQUES

Contract No. 952144

Prepared for:

California Institute of Technology
Jet Propulsion Laboratory
Pasadena, California

February 1969

ION PHYSICS CORPORATION IPC
A Subsidiary of High Voltage Engineering Corporation
BURLINGTON, MASSACHUSETTS

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by:

R. W. Sudbury and K. A. Stirrup

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ABSTRACT

Work is reported on aluminum, nickel and copper contacted solar cells using ion beam sputtering technology. Apparent damage to the cells during contacting and the effect of annealing is reported. Environmental tests were made at high temperature and humidity. Aluminum contacted solar cells were fabricated with greater than 10% AMO efficiency for an uncoverslipped CeO_2 antireflection coated cell. Solderless interconnection of aluminum contacted cells was made by ultrasonic bonding of ribbons that could withstand a 1750 gram pull perpendicular to the solar cell.

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SECTION 1
INTRODUCTION

1.1 Contract Goals

Solar cell contacts have undergone little improvement over the years, the only major change being from plated Au and Ni to evaporated Ti-Ag contacts made and proven by the Bell System on the Telestar-Satellite.[1] The advantages of Ti-Ag contacts were immediately recognized and more recently disadvantages. The contact system is not giving the environmental stability required. Recent tests by Gereth and Fisher indicate this is due to the inherent anode-cathode relationship of Ti-Ag.[2]

Solder coating of the Ti-Ag contacts has retarded the degradation or at least made the problem difficult to detect. The disadvantage of solder coated cells are well-known as to the limited temperature excursion possible and the increase in weight.

This program involved Ion Physics Corporation's (IPC) ion beam sputtering technique as a new method of making electrical contacts to silicon solar cells and the contact materials investigated were aluminum, nickel, and copper.

The goals were:

(1) high efficiency cells

(2) contact reliability

(3) solderless interconnection techniques

All three areas were investigated with emphasis on aluminum contacted solar cells.

1.2 Deposition Technique

The work described in this report resulted from an investigation into improvement of solar cell contacts by contact deposition using ion beam sputtering.

1.2.1 Ion Beam Sputtering

IPC's ion beam sputtering technique is capable of depositing conductors and dielectrics.[3] While the mechanisms are not well understood, high vacuum sputtered materials leave the target with high kinetic energy and penetrate into the substrate. The energy of the sputtered particles is distributed but the distribution has not been measured for the system used on this program. An energy distribution should result in a graded interface. Conventionally rf sputtered metals are not expected to have the range nor intensity of ion beam sputtered materials. The sputtering ions have much higher energies (30 keV versus 1-2 keV), and consequently the sputtered atoms are expected to have higher energies. This coupled with the better vacuum means the atoms arrive at the substrate with high energies relative to conventional sputtering.

An additional feature of ion beam sputtering is that deposition can be made in the 10^{-5} to 10^{-4} torr pressure range resulting in deposits virtually free of occluded gases.

1.2.2 Sputtering Equipment

The basic sputtering system is diagrammed in Figure 1. This system consists of a highly developed ion source and electrostatic lens system producing a focused, accelerated (30 keV) argon beam. Oblique incidence of this beam on an appropriate target in the deposition chamber sputters target material onto a substrate mounted near and parallel to the target.

A photograph of the actual apparatus is shown in Figure 2. This machine is capable of sputtering currents up to 10 mA. During deposition the temperature of the substrate can be controlled and the target is water cooled. The energy of the accelerated ion can be adjusted but operated at approximately 30 keV.

The sputtering rate for this system varies with the particular material in use, however, for the materials on this program, aluminum, nickel and

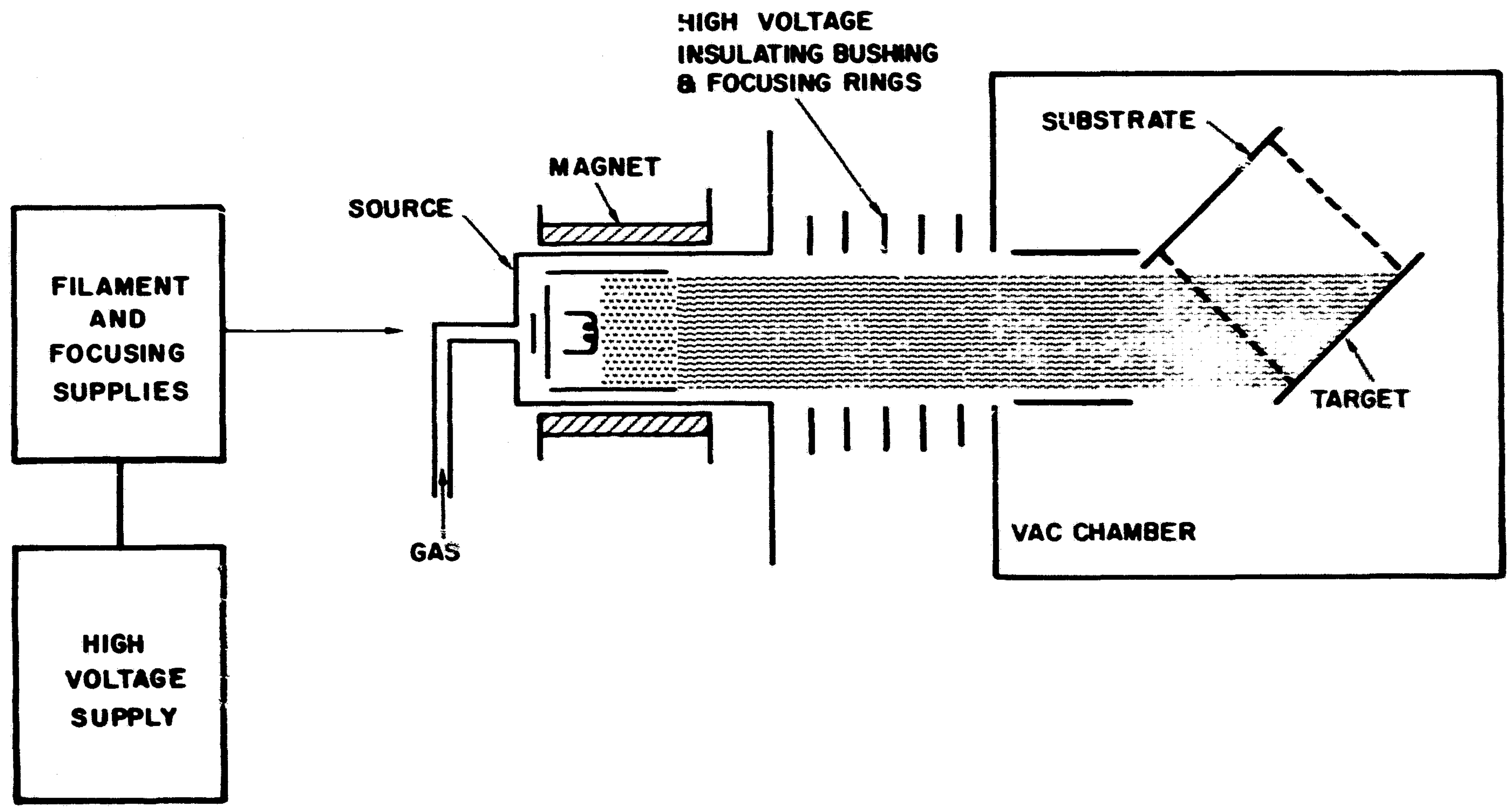

Figure 1. High Current Sputtering System Schematic

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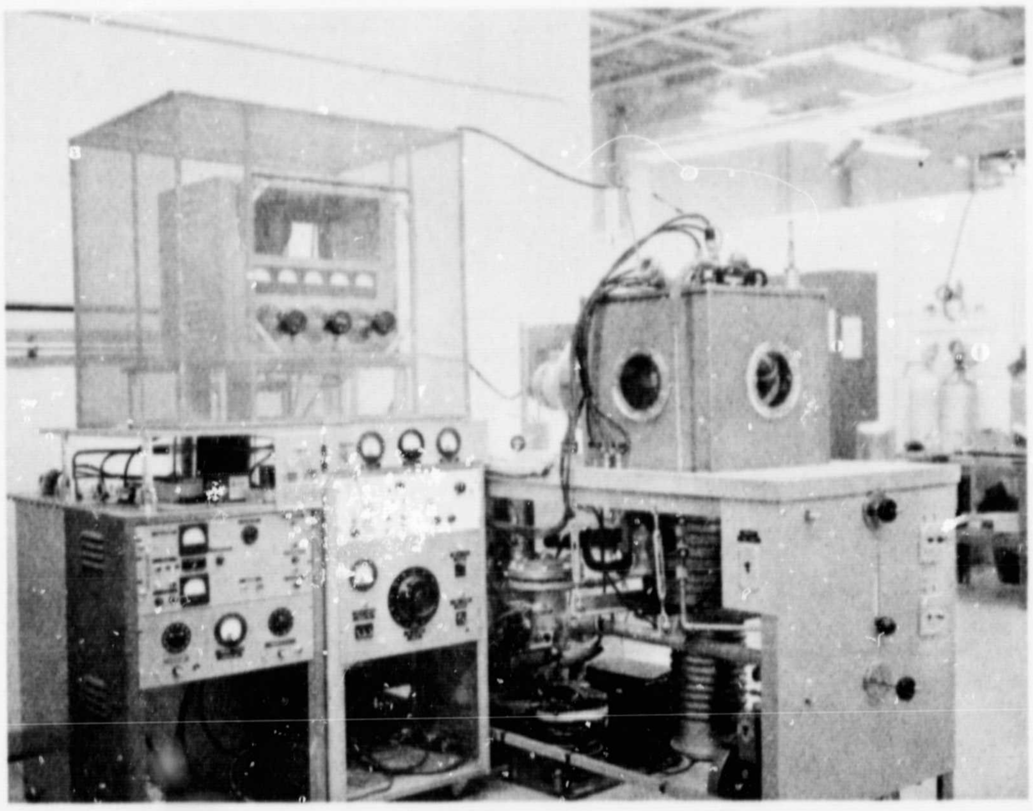

Figure 2 IPC High Voltage High Current Sputtering Apparatus

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copper, the rate of deposition of the sputtered material was approximately 2,000 Å per hour with a typical vacuum of 8×10^{-5} torr in the deposition chamber.

1.2.3 Deposition Parameters

The deposition parameters were kept constant during all work on this program. The vacuum in the chamber during deposition was typically 8×10^{-5} torr. The ion beam current was approximately 10 mA at an energy of 30 keV.

This system shown in Figure 2 and diagrammed in Figure 1 has a target size of 4 x 8 inches and a substrate to target spacing of 12 cm. The sputtering rate varies with the particular material used as a target, but for the materials used on this program an approximate rate of 2,000 Å per hour was observed for the conditions described.

1.3 Evaporated Aluminum Contacts

At the time this program was started, IPC had undertaken, for the Air Force, a research program for radiation hardened solar cells under Contract F33615-68-C-1164. One facet of that program was to develop aluminum contacted solar cells and the method investigated was vacuum evaporation. The details of this effort are described elsewhere.[4, 5]

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SECTION 2

EXPERIMENTAL RESULTS

2.1 Contact Deposition

The contacting of solar cell with contacts of Al, Ni and Cu has been investigated. All the contacts for solar cells fabricated with these metals on this program were deposited by IPC's ion beam sputtering process.

The front contact configuration of 14 fingers was obtained by sputtering through a proprietary bimetallic mask, as shown in Figure 3. The fingers are tapered from 4 mils wide at the bar to 1 mil which is not indicated in the figure. This mask requires heating to 150°C to obtain close contact between the solar cell and mask as a result of the bimetallic action.

Another front mask was fabricated from Molybdenum. This was intended to be rigid and eliminate the heating requirement which could promote oxide formation. The new mask readily became stressed and creased and, in general, failed to give good contact definition on the solar cell. After several attempts the Molybdenum mask was abandoned and the bimetallic mask used exclusively.

The entire backs of the cells were contacted and no mask was required.

It is possible to have several sputtering targets in the system and rotate them into the beam as required. This enabled multi-metal coatings to be deposited without exposing the cells to atmosphere. In addition, the system is equipped with a shutter enabling the target to be sputter-cleaned before deposition begins.

Initially it was thought that the energetic particles being deposited would help clean the surface of the solar cell, but solar cell cleanliness prior to contacting was found to be very critical. This sputtering system is not equipped for glow discharge cleaning which might have alleviated the problem. Careful cleaning plus a high pressure solvent cleaning prior to loading was utilized.

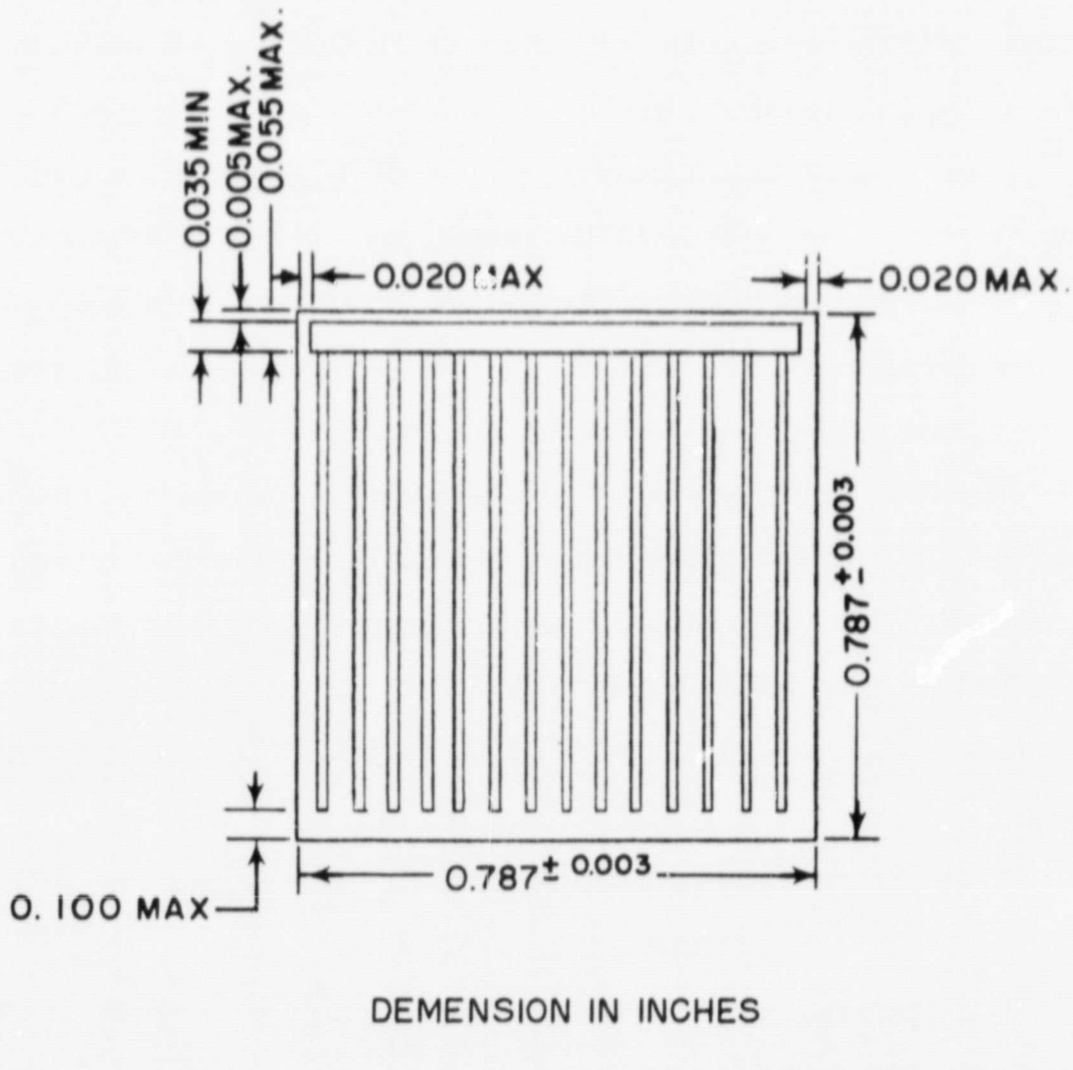

Figure 3. 14 Finger Mask

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The cleaning procedure found to be successful that was utilized on the program involved the following steps:

(1) ultrasonic washing (Alconox)

(2) swabbing

(3) cleaning in a solution of ammonium hydroxide and hydrogen peroxide

(4) HF dip

(5) rinse

(6) spray cleaning (Cobehn)

These steps were carried out with visual inspection and careful handling.

All contacts were made to n-on-p silicon solar cells fabricated by the Implion® process. Contact depositions are described in Section 1.2.3. The base material was 10 ohm-cm and the cells were nominally 15 mils thick. The concentration in the "n" region was approximately 5×10^{19} with the "n" region being typically 0.25 μm deep.

2.1.1 Aluminum Contacted Solar Cells

Solar cells were first fabricated with aluminum contacts. Problems were encountered with peeling of the Al contacts. This was observed primarily on the rear surface, however, on a few of the cells the fingers and bar on the front surface lifted off on tape testing.

Al was sputtered onto both surfaces on several groups of cells. The Al thickness on the back surface was held between 2 and 3 microns, however, the deposit on the front surface ranged from 1 to 5 microns over the various runs.

The electrical data on the group of 20 cells fabricated with 2 micron thick front Al contacts is shown in Table 1. Finger resistance measurements were made on these cells by measuring the resistance of 2/3 the length of a finger down from the bar. Normally, IPC's Ti-Ag contacted solar cells

Table 1. Sputtered Al Contacted Cells
(2 x 2 cm Cells CeO_2 Coating)
(Test Conditions: AMO 25°C)

	Before Anneal			After 450°C Anneal		
	I_{SC}	$I_{0.43}$	V_{OC}	$I_{0.43}$	V_{OC}	$\eta\%$
1	128	112	0.548	114	0.549	9.2
2	129	120	0.550	121	0.550	9.8
3	131	125	0.550	125	0.550	10.1
4	126	76	0.513	120	0.545	9.7
5	124	93	0.532	116	0.544	9.4
6	126	64	0.496	105	0.520	8.5
7	127	86	0.520	98	0.517	7.94
8	129	116	0.540	121	0.546	9.8
9	130	112	0.534	119	0.562	9.6
10	132	119	0.546	122	0.552	9.9
11	127	76	0.516	106	0.529	8.57
12	124	100	0.532	115	0.540	9.30
13	128	40	0.488	109	0.531	8.80
14	128	113	0.532	122	0.543	9.90
15	132	85	0.510	121	0.540	9.80
16	126	106	0.531	118	0.544	9.55
17	132	121	0.549	125	0.551	10.1
18	134	118	0.543	122	0.548	9.9
19	122	78	0.546	89	0.545	6.7
20	130	103	0.547	119	0.547	9.6

have finger resistance of less than 5 ohms. For the group of cells with 2 microns of Al the resistance was generally found to be 6 to 10 ohms, averaging approximately 8 ohms.

As shown in Table 1 the solar cells were subjected to a one hour heat treatment at 450°C in forming gas. This was an extension of some work done previously on Contract F33(615)-67-C-1158, in which it had been found that a 250°C heat treatment improved the characteristics of sputtered Al cells. The 450°C heat treatment was found to have, in general, a more marked effect even though some of the cells failed to improve. The main result of this treatment was to significantly reduce the series resistance of the cells, and to slightly increase the open circuit voltage. This resulted in a large improvement in many cases of the current at 0.43 volt. Increasing the temperature to 550°C did not result in any additional change. It appears that two distinct mechanisms are involved with different threshold temperatures. It is probable that the mechanism at 450°C is a bulk effect, as this is a typical temperature at which bulk damage anneals out. It has also been shown[6] that N/P Si solar cells are susceptible to surface damage under low energy bombardment. It is possible that such damage is present after contact sputtering, and is annealed out at 250°C.

A typical I-V characteristic curve from a cell from Table 1 is shown in Figure 4. This curve was obtained from a carbon arc solar simulator with an electronic ratio comparator to correct the data to AMO 25°C. A series resistance of 0.5 ohm was measured for this cell, with a curve factor of 0.735. This compares to a series resistance of about 0.4 ohm and a curve factor of 0.75 for a Ti-Ag contacted cell. The curve factor[7] is defined as maximum power as determined from the I-V characteristic divided by the product of the open circuit voltage and short circuit current. The series resistance was measured from the slope of the I-V characteristic. Two of the cells in Table 1 exceeded 10% efficiency, but did not meet the requirements that the current at 0.4 V should be less than 2.1 mA down from the short circuit current.

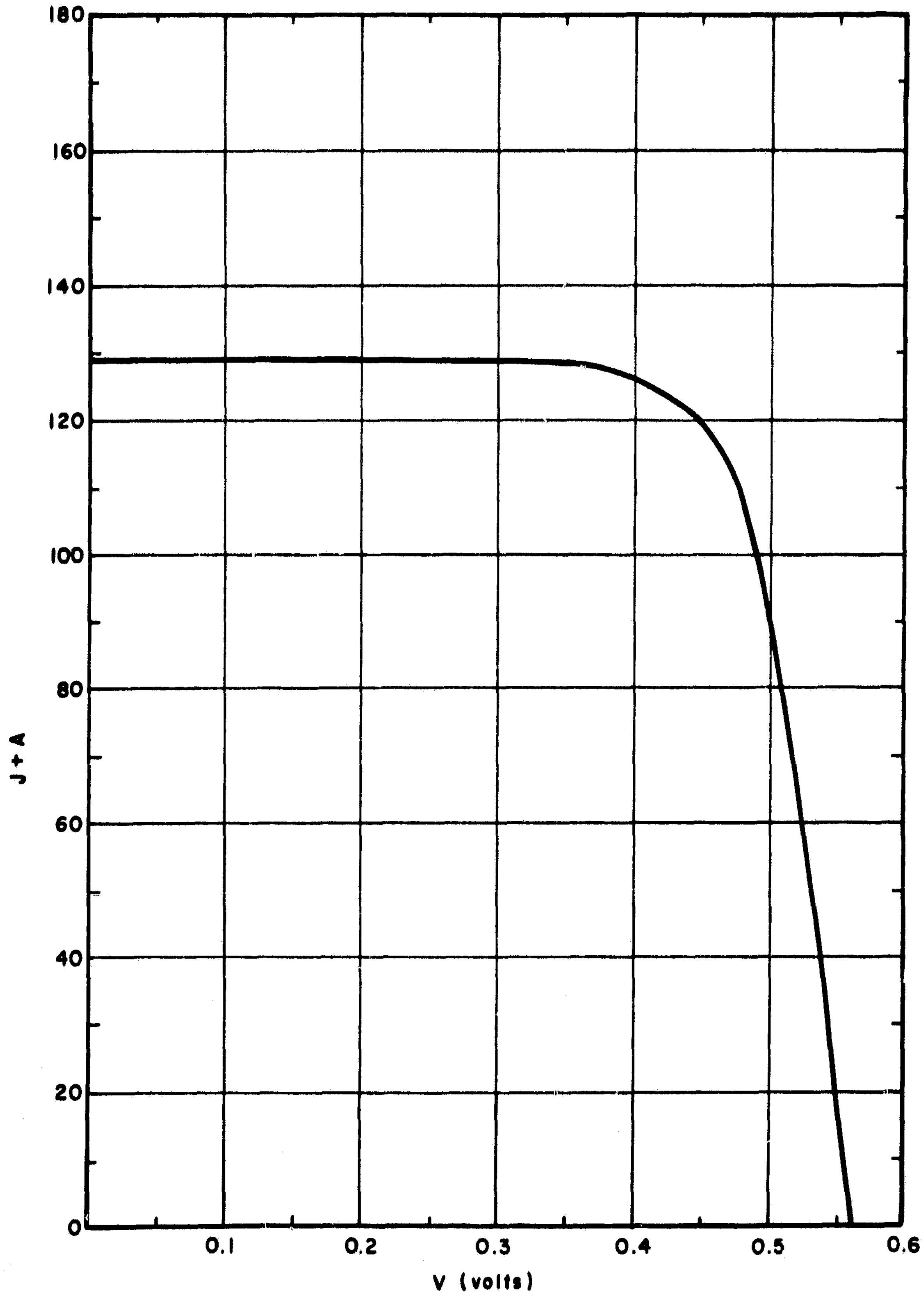

Figure 4. I-V Characteristic Curve, 2 Micron Sputtered Al (2 x 2 cm CeO_2 Coating) (Test Conditions: AMO 25°C)

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To reduce the contribution of the contacts to the cell series resistance, some cells were made with sputtered Al contacts 5 microns thick on the front surface. The finger resistance on these cells was measured at about 5 ohms, however, the contacts exhibited poor mechanical contact possibly due to cleaning problems. Most of these cells failed at the tape test prior to electrical testing. The electrical data on those cells that passed the tape test is given in Table 2.

A group of 9 cells was fabricated with 2 microns of sputtered Al, and the heat treatment was extended to 550°C. The cells were separated into 3 groups of 3 cells each which were treated at 450°C, 500°C and 550°C. The data from these cells is shown in Table 3. No significant variation in the electrical data was observed as a function of temperature. A heat treatment cycle at 450°C was retained as a standard post sputtering procedure and typical results are reported in Table 4.

2.1.2 Nickel Contacted Solar Cells

Previous work at IPC on sputtering nickel had included one attempt to sputter Ni contacts under the deposition condition used on this program and described in Section 1.2.3. In that experiment Ni over 1 micron thick had spontaneously split. For this reason, the first group of cells made with sputtered Ni contacts was limited to 0.7 micron of Ni. The electrical data obtained from these cells is presented in Table 5. These cells exhibited series resistance problems, which are inevitable with such low thicknesses of Ni. The open circuit voltages were also about 10% lower than for a regular Ti-Ag cell. The data on these cells is also presented after application of an antireflective CeO_2 coating. It was observed that excess leakages occurred after this coating was applied, however, this was found to be caused by the cleaning process prior to the coating. By cleaning the cells ultrasonically in a detergent, Alconox, it was found that Ni was being removed and redeposited on the cell edge, thereby increasing the leakage current. This step was dropped and replaced by a high pressure solvent spray cleaning step. To investigate the possibility of improving

Table 2. 5 Micron Sputtered Front Al Contacts (No Antireflection Coating) (Test Conditions: AMO 25°C)

	I_{SC}	$I_{0.43}$	V_{OC}
1	96	24	0.540
2	105	47	0.522
3	97	46	0.538
4	69	--	0.530

Table 3. 2 Micron Sputtered Al
(2 x 2 cm, No Antireflection Coating)
(Test Conditions: AMO 25°C)

	Cell	I_{SC}	I at 0.43 V	V_{OC}
450°C	1	99	88	0.549
	2	36	19	0.555
	3	100	83	0.541
500°C	4	96	88	0.538
	5	98	87	0.539
	6	100	85	0.541
550°C	7	99	84	0.538
	8	99	93	0.547
	9	98	68	0.532

Table 4. Sputtered Al Contacts
(2 x 2 cm, No Antireflection Coating)
(Test Conditions: AMO 25°C)

Cell	I_{SC} (ma)	I_{MP}	V_{MP}	V_{OC}	η%	R_S (ohms)*	R_{Shunt} (ohms)*
1	95.6	79.0	0.43	0.546	6.15	0.835	225
2	91.5	75.5	0.43	0.545			
3	87.8	75.0	0.43	0.543	6.0	0.71	225
4	90.5	83.0	0.43	0.540	6.7	0.65	215
5	92.0	88.0	0.43	0.548	7.1	0.52	500
6	95.4	89.2	0.43	0.545	7.2	0.71	400
7	98.0	91.5	0.43	0.550	7.4	0.675	300
8	98.0	72.0	0.410	0.537	5.55	1.09	28
9	102.0	80.0	0.43	0.540	6.5	0.735	100
10	100.4	76.0	0.43	0.545	6.18	0.75	60
11	100.0	0		0.05			
12	96.0	72.0	0.43	0.540	5.85	0.83	50
13	99.2	76.0	0.43	0.540	6.15	0.83	63
14	93.0	80.0	0.43	0.530	6.50	0.715	55
15	103.4	82.0	0.40	0.530	6.20	0.93	65
16	98.0	90.0	0.43	0.543	7.28	0.75	300
17	96.0	85.0	0.43	0.542	6.9	0.78	200
18	96.4	74.2	0.43	0.538	6.0	0.92	94
19	100.2	84.0	0.43	0.540	6.8	0.735	68

* from I-V Curve

Table 5. Ni Contacted Solar Cells
(0.7 Micron Ni Both Surfaces by Sputtering)
(2 x 2 cm Cells) (Test Conditions:
AMO 25°C)

	Before CeO_2			After CeO_2		
	I_{SC}	I_{43}	V_{OC}	I_{SC}	I_{43}	V_{OC}
1	97	44	0.496	117	46	0.516
2	97	50	0.514	124	56	0.521
3	87	29	0.490	101	39	0.515
4	91	50	0.516	128	59	0.525
5	97	48	0.516	130	64	0.525
6	100	52	0.509	121	76	0.513
7	96	39	0.489	112	40	0.527
8	93	37	0.496	117	54	0.541
9	98	53	0.522	127	58	0.523
10	94	32	0.492	116	52	0.529
11	97	50	0.518	124	52	0.513
12	100	47	0.517	124	52	0.517
13	96	25	0.467	124	54	0.514

Avg I_{SC} before CeO_2 = 95.6 mA   Avg V_{OC} before CeO_2 = 0.503 V

Avg I_{SC} after CeO_2 = 120.5 mA   Avg V_{OC} after CeO_2 = 0.521 V the cells by heat treatment, one cell was fired at 400°C for 20 minutes. A slight increase in open circuit voltage resulted, however, large flakes of Ni peeled off in the process. The Ni was observed to fracture within itself, leaving a thin layer behind on the Si. This indicated that a good Ni to Si bond existed. Typical maximum power point on these cells was 0.34 V with low efficiencies up to 6.4%.

Two further experiments were performed on cells with sputtered Ni, both designed to reduce the series resistance. Twelve solar cells were fabricated with 3 microns of Ni to check the previous observation that the Ni split if it were deposited in excess of 1 micron. This effect was verified, to the extent that no electrical data was obtainable from these cells. Both front and back surfaces exhibited extreme loss of Ni and in many cases the entire finger pattern peeled off intact during tape testing while leaving a thin layer of Ni behind. In the second experiment to reduce series resistance, 0.5 micron of Ni was sputtered onto 13 solar cells, which was then overlaid by 2 microns of sputtered Al. The electrical data obtained from these cells with no anti-reflective coating is given in Table 6. Normal short circuit currents were obtained from these cells, however, low open circuit voltages and high series resistance values were still present.

2.1.3 Copper Contacted Solar Cells

Cells produced with Cu contacts sputtered as described in Section 1.2.3, were found to have very poor mechanical and electrical characteristics. Electrical test results are listed in Table 7 for two groups of cells with sputtered copper contacts, sputtered on successive runs. Group A contained 5 solar cells and Group B 6 solar cells. Excessive peeling occurred at the scribing for Group A when the cells were being cut to 2 x 2 cm cells after contacting and both short circuit currents and open circuit voltages were found to be very low. Cells from the "A" group were used in heat treatment tests, however, even greater peeling of the copper resulted after heating.

Table 6. Sputtered 2 Micron Al Over 0.5 Micron Ni
(2 x 2 cm, No Antireflection Coating)
(Test Conditions: AMO 25°C)

Cell	I_{SC} (ma)	I at 0.43 V	V_{OC} (volts)
1	99	18	0.450
2	98	35	0.473
3	97	32	0.469
4	99	21	0.453
5	98	32	0.462
6	96	49	0.491
7	96	--	0.427
8	98	--	0.420
9	99	--	0.430
10	98	23	0.459
11	99	30	0.463
12	100	--	0.433

Table 7. 2 μm Sputtered Copper Contacts
(2 x 2 cm, No Antireflection Coating)
(Test Conditions: AMO 25°C)

Cell	I_{SC}	I at 0.43 V	V_{OC}
A1	16	--	0.25
A2	16	--	0.27
A3	8	--	0.4
A4	91	16	0.52
A5	7	--	0.4
B1	67	28	0.558
B2	20	--	0.540
B3	81	22	0.536
B4	57	13	0.562
B5	91	--	0.08
B6	86	--	0.10

A group of cells fabricated with Cu contacts deteriorated grossly as the copper turned black during a soak in trichlorethylene to remove the cells from a tape backing used in the sputtering system. The short circuit currents and open circuit voltages were improved on the "B" group of cells. An ohmic contact had been made, but high series resistance was encountered.

2.2 Contact Resistance

The contact resistance of the solar cell aluminum silicon interface has been measured. To measure the contact resistance to the 10 ohm-cm p-type silicon, both surfaces of a wafer were coated and the resistance measured. Allowing for the resistance of the bulk silicon the contact resistance per unit area was calculated. For sputtered aluminum heat treated at 450°C for 30 minutes the contact resistance was found to be 8×10^{-2} ohm-cm^2. Contact resistance for Ti/Ag measured by the same technique was 5×10^{-2} ohm-cm^2.

An approximate value for contact resistance to the high doped front n-type region was obtained by depositing metal stripes on the surface of the shallow n-type region. The stripes 16 mils wide were deposited in closely spaced pairs by use of the mask shown in Figure 5. Separation between stripes of each pair was varied from 16 to 40 mils in 8 mil increments. The resistance between the pairs of stripes was measured and plotted as a function of spacing. By extrapolating back to zero spacing an approximation to the contact resistance can be found. As this procedure does not account for non-uniform current flow through the aluminum-silicon interface and the silicon resistance under the contact, the value obtained will be higher than the true value. By using the same technique for both Al and Ti/Ag comparison data was obtained.

The contact resistance of Al to the front of the solar cell was extrapolated to be 8×10^{-2} for sputtered aluminum after the heat treatments described. This is higher than the 2×10^{-2} ohm-cm^2 value found by the same technique for Ti/Ag.

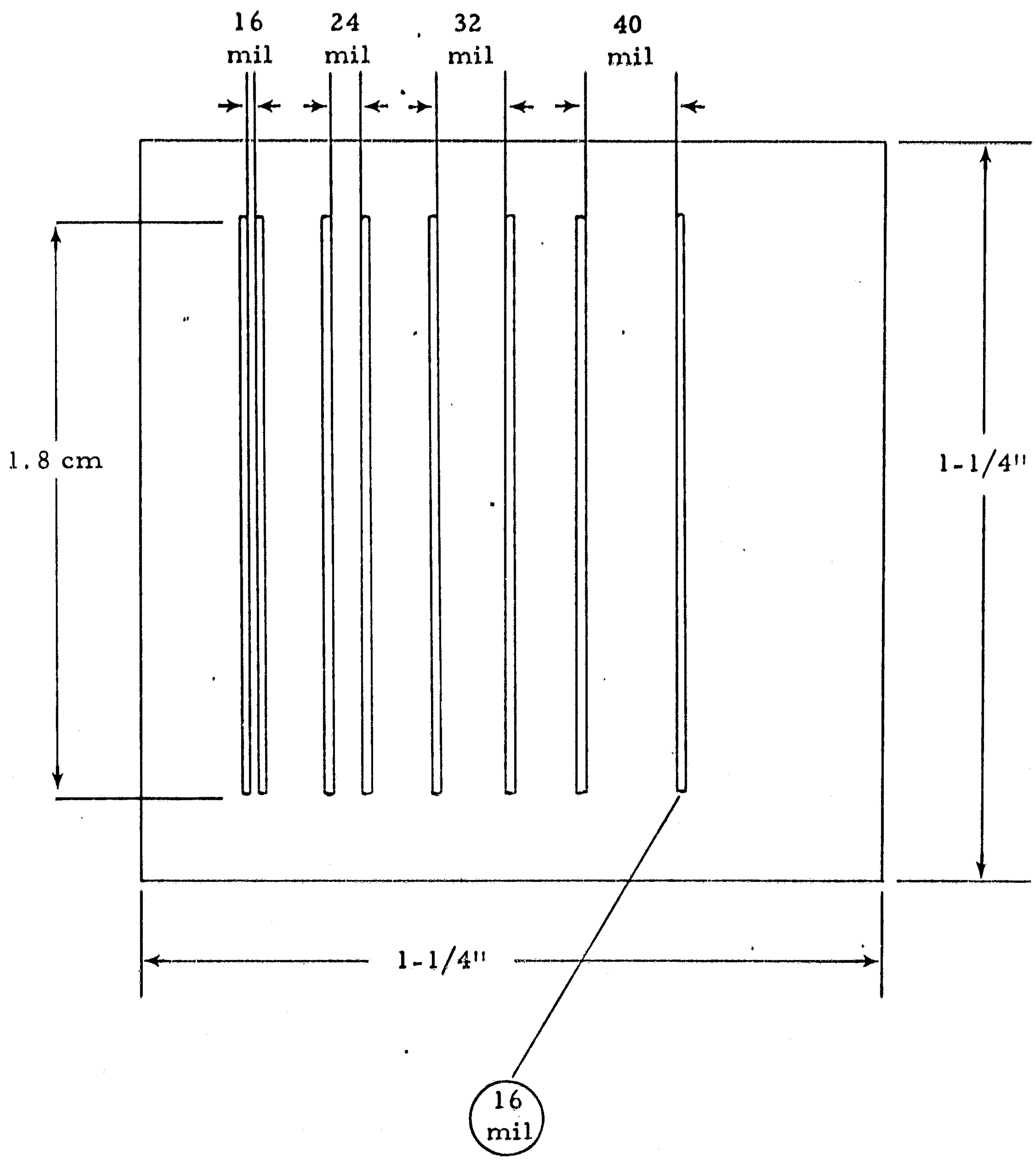

Figure 5. Sputtering/Evaporation Mask

The evaporated aluminum series resistance measured by the technique of Wolf and Rauschenbach[8] with a ΔI of 10 mA was found to be typically between 0.4 ohm and 0.5 ohm, which is similar to values of series resistance for Ti/Ag.

The bulk resistivity of the Al was found by measuring the resistance of one of the fingers, of which all the dimensions were known. A value of 13.0 microhm-cm was obtained which compares to a value of 2.7 microhm-cm for crystalline Al.

Attempts were made to measure the contact resistance of Ni and Cu in the same way. In both cases, however, it was found that the measured resistance between fingers did not increase uniformly with finger separation. This can only be interpreted to mean that the contact resistance varied randomly from one finger to another. A contact resistance of approximately 1 ohm/cm^2 was indicated for Cu and Ni. In the case of Ni, this contrasts markedly with the contact resistance obtainable with electroless Ni, which has been shown to be about the same as for Al.[9]

2.3 Solderless Interconnection

As aluminum appeared to be the best contact material under investigation the bonding of solderless interconnections to Al was investigated. The successful technique used on this program for achieving an Al-to-Al bond was by ultrasonic welding. Parallel gap welding methods were investigated, however, surface oxides prevented good consistent welds being achieved. In addition, the Al contact was somewhat thin for this process, and often vaporized at times removing with it some of the underlying silicon.

In ultrasonically bonding no difference was detected in bonding to evaporated or sputtered Al contacts. A difference in bonding to the rear surface was detected as it became difficult to consistently bond to the rear surface with the same settings from cell to cell. This is believed due to the roughness of the rear surface which had been polished with 5 μm grit. A problem of repeatability on the front surface was found to be due to the antireflection coating when the coating covered the contact.

Ultrasonic bonding was initially investigated using IPC's ultrasonic bonder with 1 mil and 3 mil Si doped Al wire, and ribbon of various dimensions but good bonds were not consistently obtained. It became apparent that this equipment did not offer sufficient pressure or tip alignment control. Equipment was developed by Unitek/Weldmatic of Monrovia, California after discussions with IPC. Using this equipment, 2 mil Al foil was bonded to both surfaces of Al contacted solar cells. The bond area was approximately 1/16 inch in diameter. Figure 6 shows a solar cell with ultrasonically bonded foil tabs. These initial bonds were made at the Unitek plant, and were tested on a Unitek pull tester in a test parallel to the cell. In all cases, the Al foil broke before the bond failed.

Bonds were also made using 3 x 10 mil type 1100 annealed Al ribbon. In pull tests similar to those for the 2 mil foil, the ribbon failed before the bond was affected. The force required was 200 grams. Figure 7 shows a photomicrograph (50X) of the bonded ribbon. These bonds were made with a tip force of 28 ounces and a time of 0.16 second and 9.5 watts.

Electrical test results for the sputtered contacted solar cells before and after leads were ultrasonically bonded to the front and back contacts are shown in Table 8. A slight degradation in performance was observed and may have been due to contacting, but these cells were mailed across the United States twice between test. Recent test with evaporated aluminum contacts, from the program described in Section 1.3, indicate bonds can be made without electrical degradation.

Type 1100 Al ribbon 5 mils thick and 62 mils wide pulled away in a perpendicular pull test at 900 grams. Soft aluminum ribbons, 3 mils thick and 320 mils wide bonded to Al contacts 2 μm thick with 3 ultrasonic bonds have withstood pull testing perpendicular to the cell up to 1750 grams. The ribbon did not pull off under this force, however, this is the limit of the IPC pull tester. Limited test on a different tester indicates a 2,000 gram pull test

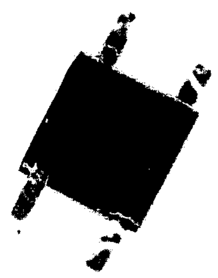

Figure 6 Aluminum Contacted Solar Cell with 2 mil Foil Leads Attached by Ultrasonic Bonding

2-898

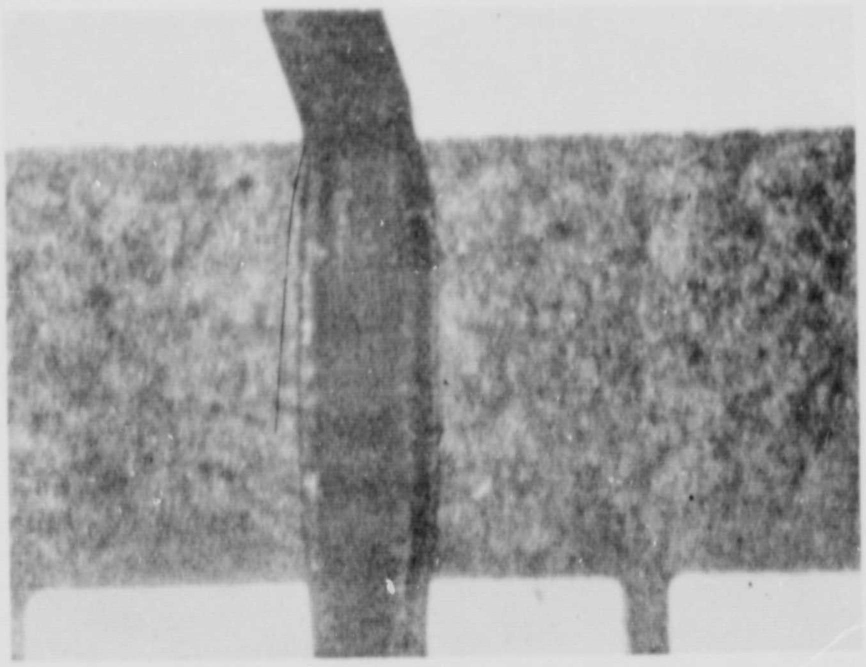

Figure 7 Ultrasonic Bonded
3 x 10 mil Ribbon (50X)

2-899

Table 8. Electrical Performance of Al-to-Al Bonded Cells (Test Conditions: AMO 25°C)

Cell No.	Before Bonding			After Bonding		
	I_{SC}	$I_{0.43\ V}$	V_{OC}	I_{SC}	$I_{0.43\ V}$	V_{OC}
1	100.0	83.0	0.541	101.0	79.0	0.530
2	100.0	85.0	0.541	102.0	80.0	0.532

requirement can be met. A slightly wider ribbon and an extra weld could be used if required. Area of the welds was approximately 62 mils in diameter. The bonding for these tests was accomplished using tip pressure in the 7 ounces and times of approximately 1.8 seconds. A frequency sweeping circuit was used and the 12 watt power setting on the power supply.

2.4 Environmental Testing

Environmental testing was performed both at IPC and at an independent laboratory. The IPC humidity chamber was employed in an initial test. This chamber was capable of 60°C and 95% RH, and a group of 6 solar cells was subjected to this environment for 30 days. The data from this test is presented in Table 9. None of the cells, which included sputtered Ni and Al, and evaporated Al, degraded. A similar test performed on Ti-Ag contacted cells showed degradation of a few percent on the cells tested.

Toward the end of the program, more comprehensive testing was performed by the Acton Environmental Testing Corporation. This laboratory provided a test environment for testing at 5°C and 95% RH for 2 hours followed by a drop in temperature to 0°C for 4 hours and the high temperature testing that followed was limited to 82°C and 95% RH for 30 days. Cells tested included sputtered and evaporated Al, sputtered Ni, Al over Ni, and Ti-Ag contacts. The data before and after the test is presented in Tables 10 through 13. Extensive degradation between 25 and 30% power degradation occurred on all the cells with the exception of the cells with Ni contacts. Considerable discoloration was visible on all the cells with Al contacts, due to partial removal of the CeO_2 antireflective coating. Loss of this layer is believed responsible for the drop in short circuit current on these cells. This CeO_2 problem was not found on the Ti-Ag contacted cells, although the output of these cells fell significantly. The Al contacted cells were found to have "soft" CeO_2, presumably due to a poor quality deposition at the CeO_2 station.

The environmental test was rerun on cells with sputtered Al contacts. This test followed the same test pattern, but was conducted for 15 days

Table 9. IPC Environmental Testing Studies
(Test Conditions: AMO 25°C)

Type of Cell	Before Testing			After 30 Days at 60°C and 95% RH		
	I_{SC}	I at 0.43 V	V_{OC}	I_{SC}	I at 0.43 V	V_{OC}
1 Sputtered Ni + CeO_2	70	23	0.514	73	25	0.511
2 Sputtered Ni + CeO_2	118	61	0.552	121	65	0.552
3 Sputtered Al Bare	95	85	0.541	97	88	0.541
4 Evaporated Al + CeO_2	132	127	0.551	133	129	0.551
5 Evaporated Al + CeO_2	133	121	0.556	134	122	0.556
6 Sputtered Al over Ni	97	33	0.477	98	50	0.494

Table 10. Sputtered Al Contacts
(Test Conditions: AMO 25°C)

	Before Testing			After Environmental Testing		
	I_{SC}	$I_{0.43}$	V_{OC}	I_{SC}	$I_{0.43}$	V_{OC}
1	128.0	81.6	0.544	94	48	0.534
2	134.7	97.5	0.556	95	49	0.545
3	135.3	-	0.40	113	68	0.541
4	131.3	92.2	0.551	120	75	0.544
5	129.2	93.8	0.548	112	70	0.543
6	132.0	113.1	0.540	134	89	0.538
7	141.4	87.1	0.529	107	61	0.528
8	135.0	119.1	0.552	129	89	0.547
9	133.5	108.6	0.555	116	82	0.550
10	131.2	91.5	0.547	107	72	0.542
11	138.8	109.3	0.547	119	75	0.538

Before Testing	After Environmental Testing
Avg I_{SC} = 133.6 mA	Avg I_{SC} = 112.5 mA
Avg $I_{0.43}$ = 90.3 mA	Avg $I_{0.43}$ = 70.5 mA
Avg V_{OC} = 0.533	Avg V_{OC} = 0.541

Environmental Test Schedule

5°C	95% RH	2 Hours
0°C		4 Hours
82°C	95% RH	30 Days

Table 11. Evaporated Al Contacts
(Test Conditions: AMO 25°C)

	Before Testing			After Environmental Testing		
	I_{SC}	$I_{0.43}$	V_{OC}	I_{SC}	$I_{0.43}$	V_{OC}
1	137.6	-	0.350	113	-	0.298
2	123.4	95.6	0.544	126	90	0.536
3	129.4	112.9	0.550	124	80	0.544
4	141.8	84.4	0.532	116	44	0.512
5	137.6	-	0.448	131	-	0.400
6	131.5	-	0.127	110	-	0.108
7	133.1	-	0.440	123	-	0.386
8	117.0	104.0	0.549	122	94	0.540
9	134.6	109.6	0.556	134	83	0.551
10	138.[illegible]	90.3	0.530	143	67	0.517
11	123.8	49.4	0.510	117	-	0.480
12	134.8	89.8	0.547	124	38	0.538

Avg I_{SC} = 131.9	Avg I_{SC} = 123.0
Avg $I_{0.43}$ = 62.1	Avg I_{SC} = 42.5
Avg V_{OC} = 0.474	Avg V_{OC} = 0.450

Environmental Test Schedule

5°C	95% RH	2 Hours
0°C		4 Hours
82°C	95% RH	30 Days

Table 12. Ti-Ag Contacts
(Test Conditions: AMO 25°C)

	Before Testing			After Environmental Testing		
	I_{SC}	$I_{0.43}$	V_{OC}	I_{SC}	$I_{0.43}$	V_{OC}
1	134.4	117.3	0.548	116	42	0.539
2	131.5	125.5	0.554	118	42	0.542
3	132.8	124.3	0.553	118	43	0.542
4	133.8	123.6	0.552	134	73	0.546
5	132.0	122.8	0.545	136	79	0.543
6	131.4	126.5	0.560	130	48	0.554
7	133.7	125.7	0.552	136	77	0.540
8	132.6	126.3	0.560	136	54	0.541
9	134.3	128.3	0.563	133	57	0.551
10	133.5	126.1	0.556	119	49	0.544
11	132.0	125.0	0.554	107	50	0.542
12	136.0	125.1	0.552	105	57	0.543
13	135.6	126.6	0.559	87	31	0.548
14	133.8	125.4	0.549	77	31	0.529

Before Testing	After Environmental Testing
Avg I_{SC} = 133.4	Avg I_{SC} = 118.0
Avg $I_{0.43}$ = 125.1	Avg $I_{0.43}$ = 52.0
Avg V_{OC} = 0.554	Avg V_{OC} = 0.543

Environmental Test Schedule

5°C	95% RH	2 Hours
0°C		4 Hours
82°C	95% RH	30 Days

Table 13. Sputtered 0.7 μm Ni Contacts
(Test Conditions: AMO 25°C)

	Before Testing			After Environmental Testing		
	I_{SC}	$I_{0.43}$	V_{OC}	I_{SC}	$I_{0.43}$	V_{OC}
1	70.9	24	0.508	70.0	22	0.505
2	119.8	63.2	0.552	119.0	58.0	0.546
Sputtered 2 μm Al Over Sputtered 0.7 μm Ni						
	98.2	46.2	0.492	990	37.0	0.494

Environmental Test Schedule

5°C	95% RH	2 Hours
0°C		4 Hours
82°C	95% RH	30 Days

instead of the 30 days on the first test, in order to complete it prior to the end of the program. No antireflection coating was used on the Al sputtered contacted cells. The results of this test are presented in Table 14. No degradation resulted.

In the second environmental test run evaporated Al contacted cells were included with SiO_2 and CeO_2 coating to investigate the effect of the antireflection coating. These solar cells included solar cells from a previous pilot line test where the junction depth had been varied. In that test implantation energy was being varied to change junction depth. The variation in junction depth was 0.08 μm to 0.3 μm. As junction depth is not a normally specified parameter, these cells were tested and placed in inventory. The cells with shallow junction, approximately 0.1 μm, degraded significantly. This effect of degradation varying with junction depth masked the effect of the SiO_2 and CeO_2 coating.

Following the humidity test, some of the cells from this test were subjected to the thermal shock test. These cells were subjected to 20 cycles between the extremes of 200°C in cotton seed oil and -196°C in liquid nitrogen. The cells were removed from one extreme and immediately placed in the other extreme so that the temperature rate of change far exceeded the minimum of 100°C per minute.

Two of the sputtered Al contacted cells shattered during testing. Such shattering is seldom observed, and the explanation for it is not known. It would appear unlikely, however, that it could be caused by the contacts as the aluminum is only 2 μm thick.

All contacts were subjected to tape testing with Scott No. 810 tape. When peeling did occur it could generally be observed prior to tape test. All electrical results presented in this report are for cells that passed tape test. Normally at tape testing, close to 100% of Ti-Ag contacted cells pass. This same result has been observed for cells produced with aluminum contact as described in Section 1.3. With sputtered aluminum contacts the lots varied

Table 14. Environmental Test - 15 Days
(Test Conditions: AMO 25°C)

	Sputtered Al Contacts - No Antireflective Coating					
	Before Testing			After Environmental Testing		
	I_{SC}	$I_{0.43\ V}$	V_{OC}	I_{SC}	$I_{0.43}$	V_{OC}
1	104	80	0.539	104	78	0.530
2	94	50	0.519	100	50	0.505

Environment Test Schedule

5°C	95% RH	2 Hours
0°C		4 Hours
82°C	95% RH	15 Days

from 50% to 100% of the cells passed table test. All nickel contacted cells with less than 1 μm passed tape testing. Insufficient numbers of copper contacted cells were tested but severe peeling occurred frequently.

SECTION 3
CONCLUSIONS

Solar cell contacts were fabricated by ion beam sputtering using aluminum, nickel and copper as contact materials. Test data for these cells has been compiled and evaluated. Of the materials deposited by this technique, Al resulted in the highest quality cells, but none of the cells fabricated had the efficiency of present state-of-the-art Ti-Ag contacted solar cells.

An interpretation of the improvement of aluminum contacted cells with annealing is that energetic particles have caused damage to the crystal structure in the sputtering process. The annealing temperature used was 520°C to avoid problems with the Al-Si eutetic at higher temperature.

In environment tests the sputtered Al contacted solar cells and sputtered Ni contacted solar cells were superior to Ti-Ag cells manufactured by IPC in terms of electrical degradation.

High vacuum sputtered nickel contacts indicated environmental stability. The nickel films deposited by ion beam sputtering were highly stressed indicating this process is not suitable for manufacturing nickel contacted solar cells.

Solar cells can be fabricated with sputtered copper contacts but no conclusions can be drawn at this time as to the suitability of using ion beam sputtering for copper contacts.

Ultrasonic bonding was used to bond aluminum ribbons to the aluminum contacts. From the electrical test and contact pull and peel test it is concluded that ultrasonic bonding could be a satisfactory method of solderless contacting to aluminum contact solar cells.

Maintaining a good cell cleaning process prior to contacting was a severe problem with the sputtered contacted cells. Glow discharge cleaning prior to sputter would be expected to eliminate this problem.

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SECTION 4
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