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COMMERCIALIZATION OF A THICK FILM SOLAR CELL

Final Technical Report for the Period September 15, 1980—April 30, 1981

By
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MASTER

Work Performed Under Contract No. AC02-77CH00178

Johnson Controls, Inc.
Milwaukee, Wisconsin

U.S. Department of Energy

Solar Energy

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Abstract

No technical problems were encountered in the preparation of screen printed cadmium sulfide layers. High conductivity (less than 5 ohm cm resistivities) adherent layers could be produced on 7059 glass, Nesatron and tin oxide coated glass. No macro pinholes were observed in thick films.

Solar cells produced from screen printed CdS had a maximum open circuit voltage of 0.44 volt and a maximum observed short circuit current of 8 ma per cm² under AM 1 illumination. A maximum cell efficiency of 2.2% was obtained. This performance is not felt to be a limitation produced by the screen printing approach but to be reflective of an unoptimized procedure for producing Cu₂S on the CdS film and the lack of a suitable post thermal treatment technique.

Further work is warranted on the sintering of CdS films and the conditions required to produce optimum CdS grains and Cu₂S layers.

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1.0. Introduction

The objective of this program is to evaluate the use of screen printing as a technique for producing large area solar cells. The attributes of screen printing which make this approach of interest are that screen printing (1) is a well established technique in the electronics industry with well established requirements; (2) has a demonstrated capability for producing large areas of electronic quality films with good fidelity; (3) provides a means for separating the conditions for film deposition from those required for sintering, providing control, for example, over microstructure; and (4) has a high material utilization efficiency. Possible disadvantages of screen printing may be that the starting material must be reduced to powder form and that a fugitive organic vehicle is used. The fact that efficient small area cells can be produced by screen printing has been reported in the literature (1, 2).

The work presented in this report is an extension of a previous one year contract. Previous work has shown that films of cadmium sulfide and cadmium telluride can be produced which have a film thickness of approximately 10 microns and resistivities in the range of 10 ohm cm. The work presented here represents an attempt to optimize the previous results to produce cadmium sulfide solar cells.

2.0. Experimental

2.1. Materials

Most of the materials used on this contract have been described in detail in the final report for the previous contract ⁽³⁾. The materials listed here are those not previously described.

Cadmium sulfide was obtained from G.E. Chemical Products Plant (Luminescent Grade, #118-8-2) as well as previously reported Materials Research Corporation material. Table 1 contains the results of our emission analysis which shows no contamination within the limits of detection of that instrument.

Two types of conductive glass substrates were used. One had an indium oxide coating and was obtained from PPG Inc. under the trade name of "Nesatron" glass. The substrates were one inch by three inches by 1/16 inch. The other substrate used had a tin oxide conducting coating and was produced by Photon Power Inc. These measured one inch by three inches by 0.1 inch and had a sheet resistivity of 10 ohms per square. A maximum transmission of light (87% transmission) occurred at 4700 angstroms.

All other chemical used have been previously described ⁽³⁾.

2.2. Equipment

Equipment used in addition to that already described is described in the following.

Electrical measurements of the solar cells produced were performed using a SMP 66 Wenking function generator in conjunction with a MP 75 Wenking potentiostat and a Bascom-Turner series 8000 version 3.5 c 8-channel digital recorder equipped with a model 40008 4-channel amplifier. A one kilowatt Schoeffel solar simulator with a xenon lamp provided AM 1 radiation as monitored by a photo detector manufactured by International Light, Inc. (model IL 510 M).

In addition to the three zone, controlled atmosphere, four-inch belt kiln manufactured by the Lindberg Company a three inch Mullite tube furnace manufactured by Hevi-Duty Electric Company was used for hydrogen firings and hydrogen thermal treatments. Vacuum and air heat treatments were performed in a Challenger furnace manufactured by the K. H. Huppert Company. Hydrogen flow rates were generally under 200 cubic centimeters per minute. An oxygen analyzer manufactured by Teledyne (Trace Oxygen Analyzer) was used to monitor the oxygen content of the atmosphere in the flowing belt furnace. The oxygen concentration in the center zone was generally maintained below 100 ppm.

Thermal analysis of the cadmium sulfide ink was performed using a Du Pont 1090 thermal analyzer. The study of the change in dark current with temperature was performed in a Delta oven attached to a liquid nitrogen tank.

The formation of copper sulfide on the cadmium sulfide film was performed in a plastic glove bay manufactured by Ventron for Alfa Products, inflated with argon.

A Beckman DB-G grating spectrometer was used to determine the transmission of the tin oxide coated glass. This spectrometer proved to be unsatisfactory for measuring the transmission spectra of CdS because it uses a single detector for both the sample and reference beams, precluding mounting the CdS film directly in front of the detector so that the scattered light could be detected.

3.0. Technical Discussion

3.1. Thermal Analysis of Cadmium Sulfide Ink

The cadmium sulfide ink used to screen print CdS films was characterized by thermogravimetric analysis. A Du Pont 1090 Thermal Analyzer was used for this work. Figure 1 shows the results. Three distinct weight losses can be seen. One is below 200°C. Another occurs between 200 and 400°C, and the last is between 400 and 700°C. Table 2 presents the observed and anticipated weight losses for each temperature range. Closer analysis of these data shows that not all the solvents were removed below 400°C. The weight loss below 200°C was less than anticipated and in the range 200 to 400°C was greater than anticipated. Further, the TGA curve shows that there is an additional wave in the 200-400°C range. Two solvents are used in the ink - α -terpineol and butyl "Carbitol" acetate. The α -terpineol is completely lost below 200°C while some of the butyl "Carbitol" acetate remains and is slowly lost in the next temperature zone along with the plastic binder. The other disparities between the observed and anticipated weight losses are within experimental error in preparing the inks.

Based on the above analysis under the experimental conditions used to fire the cadmium sulfide layers all the binders and solvents should be removed.

3.2. Cadmium Sulfide Films

Films of cadmium sulfide were prepared using various loadings of the cadmium chloride flux and a variety of firing temperatures and times. Table 3 contains a summary of the results obtained along with references to the appropriate SEM photographs for each set of conditions. Films prepared using twenty volume percent cadmium chloride are shown in Figures 2 through 9. Sintering at best is minimal. The films appear to be very porous. At the 630°C firing con-

dition larger grains appear on the surface of the film. These features are not present at 552°C or 600°C. At 653°C the surface grains are larger and have well defined facets. The resistance of the film fired at 653°C is higher than that of the films prepared at lower temperatures. The large surface grains are less prominent when the flux content is thirty volume percent, see Figures 10 through 17. These films are more continuous even at 552°C and at 600°C. Again by 630°C surface grains appear which by the 653°C firing are very pronounced and which appear to have the effect of lowering the sample conductivity. Parallel features are noted when the flux level is forty volume percent, see Figures 18 through 23. All films produced with this quantity of flux are better sintered than the corresponding film produced at lower flux levels. Resistances of the films produced with thirty and forty volume percent cadmium chloride are equivalent, see table 2.

Films were also produced with two layers of cadmium sulfide in place of three. Generally, the sintering is not as good as in the corresponding three-layer films, see Figures 24 through 29. The thickness of the fired films is almost the same as for the three-layer films even though they contain only two-thirds of the material and the resistance is somewhat higher.

One cadmium sulfide film was fired for 100 minutes to see if the surface grain growth would continue and whether these grains would ultimately sinter together. Figures 30 and 31 show that additional grains formed and that the grains did increase in size (compare with Figures 22 and 23). The grains do not appear to be sintering together and the resistance increased during this prolonged firing and surface adhesion was low.

X-ray analysis of some of the films containing large grains on their surface showed the presence of cadmium oxide. SEM work was performed to determine the location of this oxide. Figure 32 is an SEM photograph of a cadmium

sulfide film produced at 653°C using 20 volume percent cadmium chloride flux. This sample was chosen for oxygen analysis because of the spacing of the grains on its surface. Figure 33 is an oxygen map of the same area shown in Figure 32. Figure 34 is an oxygen line scan (EDAX) across the film. From these results it is apparent that the large crystals on the surface of these films are cadmium oxide.

Reviewing the photographs presented shows that the information of these surface crystals is favored by the following conditions: high firing temperatures, long firing times, and low flux concentrations.

To avoid the formation of oxide on the films, films were produced at temperatures below 630°C with firing times of less than 50 minutes and flux concentrations of 30 volume percent or greater.

The Teledyne Trace Oxygen Analyzer was used to monitor the oxygen content in the kiln during firing. When the flow of nitrogen was five cubic feet per hour to the first zone and zero and one cubic feet per hour to the next two zones, the oxygen content of the center zone was 10,000 ppm. Increasing the flow rates to 10, 0, 5 cubic feet per hour to the three zones maintained the oxygen content in the center zone below 100 ppm. All cadmium sulfide films fired under these flow conditions were lighter yellow in color and no oxide content could be detected by x-ray diffraction analysis. All subsequent firings used these modified nitrogen flow rates to the various zones in the three zone furnace.

Films were prepared using G.E. luminescent grade cadmium sulfide in place of the Materials Research Corporation's. Figures 37 and 38 are scanning electron micrographs (SEM) of the G.E. CdS. Its small particle size and freedom from any particle agglomeration permitted direct usage without

pretreatment required by the Materials Research Corporation's material.

To minimize the possibility of internal shorting caused by through pores thicker films were prepared by multiple screening. Figures 39 and 40 are SEM photographs of the cross section of a multilayered CdS film fired at 600°C for 30 minutes using a flow rate of 5, 0, 1 cubic feet per hour to the three zones. All six layers of CdS were fired at one time. The elongated features seen in Figure 4 were later determined to be TPA 85--the plastic surface coating which was stretched over the cross section during fracture. Figures 41-44 are of a CdS film on 7059 glass which was prepared by first printing and firing four layers and then applying and firing two additional layers. This sample was then etched in HCl (10 seconds) and dipped in Cu_2Cl_2 (12 seconds in 65°C Cu_2Cl_2 solution). The open circuit voltage of the resultant cell was 0.14 volts under AM 1 radiation. Figures 43 and 44 are copper line scans and a copper map (energy) of this film. It clearly shows through penetration by the copper.

Figures 45-48 are SEM photographs of six layers of CdS fired on Nesatron glass (In_2O_3 coated glass). Firing conditions were 30 minutes at 600°C with flow rates of 5, 0, 1 cubic feet per hour to the three zones. The film was then dipped in 100°C Cu_2Cl_2 solution for three seconds without any pre-etch. Pre-etching would cause the CdS film to separate from the indium oxide coated glass. The copper line scan shown in Figure 11 indicates through penetration of the copper to the indium oxide coated glass on the left side of the picture. This accounts for the low open circuit potential for this cell, 0.16 volts. Figure 48 shows an indium line scan showing that the indium oxide layer was neither affected by the firing conditions used nor did it diffuse into the CdS layer.

Figures 49 through 52 are SEM photographs of one of the first CdS films produced on Photon Power's tin oxide coated glass. On the left side of Figure 49 the half micron thick continuous film is the tin oxide layer. Close examination of Figure 50 shows that one can distinguish the set of four fired layers from the two subsequently fired surface layers. The grain size of the lower four layers is larger than that in the top two layers. It appears that the grains in the lower layers grew in during the firing of the upper layers. Figures 51 and 52 are reversed in orientation with the tin oxide coated glass on the right side of the photograph. Figure 52 clearly shows that the tin oxide is localized in its original position and that tin did not migrate.

Figures 53 and 54 show the effect of firing six layers of CdS at once on tin oxide coated glass. Blisters are seen to form during the firing process. Presumably a surface crust was formed before all the organic binders were removed. Gases were then formed which caused the blistering.

Figures 55-59 are SEM photographs of a CdS cell consisting of a CdS layer formed by firing two layers on top of four previously fired layers. Tin oxide coated glass was used as a substrate and an eight second Cu_2Cl_2 dip without pre etching was used. The open circuit voltage under AM 1 radiation was 0.40 volts. In Figure 55 the features extending over the glass on the right side of the photograph are fragments of the TPA-80 plastic coating. In Figure 56 the two fired layers are visible in a ratio of thickness of 2:4 with the surface layer having a smaller grain size than the lower layer. Figure 57 shows the portion of the sample used for the two following copper maps. Figure 58 is an energy copper map and shows only scatter. Using a wavelength map shown in Figure 59 the copper can clearly be seen to be isolated on the surface of the CdS film. This correlates well with the higher open circuit

voltage of 0.40 volts. The improvements in the copper dipping technique is responsible for this improved performance. All dipping processes are currently performed in an argon filled plastic glove bag.

Figures 60-65 are photographs of six layers of CdS fired at one time on tin oxide coated glass. As had previously been observed blisters were formed during firing. The open circuit voltage of this cell was 0.22 volts with evidence of pinholes which occurred at the blisters. Figure 63 is a copper wavelength map of this cell showing that the copper was localized on the cell surface. Shorting, accounting for the low open circuit voltage, occurred through the macro pinholes at the blisters.

Figures 64-68 show a four layer CdS film with an additional two layers of CdS fired on its surface. The substrate is In_2O_3 coated glass. The open circuit voltage was 0.38 volts. Figure 65 shows the disparity of grain sizes between the two layers, with appreciably greater grain sizes in the lower layer. Figure 66 shows that during fracture of the cell to expose the cross-section separation of the top from the bottom layer occurred in places. Figure 68 is a copper wavelength map showing that the 8 second dip in the Cu_2Cl_2 solution produced general penetration of the copper into the film.

Figures 69 through 72 show six CdS layers fired at once on indium oxide coated glass. Figure 71 shows extensive copper penetration into the CdS layer. The open circuit voltage for this cell was 0.34 volts. The surface film seen in Figure 72 is the plastic coating (TPA-85) coating on the areas masked against copper.

The general conclusions which can be drawn based on the SEM work are that printing a separate layer of CdS over a prefired base layer seems to produce a larger-grained lower layer. This grain growth may be due to the

migration of the CdCl_2 flux into the lower layer during the early stages of sintering of the top layers. The problem encountered in multiple firings when using the indium oxide coated glass as a substrate was that the glass warped during the initial firing and was often broken while attempting to print another layer over the top. Putting down six layers and firing at one time often resulted in blistering. When tin oxide coated glass is used as a substrate no warpage is encountered and multiple firing is relatively simple to accomplish. The possibility of increasing the grain size in the film by printing a CdCl_2 layer over CdS failed because the CdCl_2 was lost before appreciable growth could occur.

Figures 73 through 82 are current-voltage scans of $\text{CdS-Cu}_2\text{S}$ solar cells. The SEM photographs shown in Figure 69 through 72 pertain to the performance shown in Figure 73, and those of Figures 45 through 59 to the current-voltage shown in Figure 80. The object with these cells was to obtain as high open circuit potentials as possible to prove that pinhole-free films could be produced by screen printing. At this point no attempts were made to optimize current collection as to minimize contact problems.

Figures 70 and 71 show line scans for indium and cadmium in the CdS films printed on Nesatron glass. The broadness of the indium line is related to the size of the area analyzed (~ 2 microns). Indium does not seem to have been affected by the CdS film and essentially no interdiffusion has occurred.

3.3. Copper Sulfide Barrier Formation

The technique used to form the copper sulfide layer on the CdS cells described above was the "Wet Process" technique involving the dipping of the masked cells in a hot Cu_2Cl_2 solution. The procedure is more of an art than a science.

A comparison was made of the technique used at Westinghouse and Delaware. Only terse information is available on the actual procedures used (4). Suitable results were only obtained using the Delaware procedure. Comparing this procedure with the previous procedures, the following conclusions were obtained:

1. Pre-etching of the cadmium sulfide in hydrochloric acid is required. Hot etching in concentrated HCl resulted in total dissolution of the cadmium sulfide film. Using 55% HCl resulted in satisfactory surface preparation.
2. Hot Cu_2Cl_2 solution (60°C) is required to produce suitable copper sulfide layers.

At this point the best cells are produced using a cadmium sulfide film prepared at 600°C using a 40 minute firing cycle, etched in 55% HCl solution, and dipped in a hot (60°) solution containing 6 g Cu_2Cl_2 , 2 g NaCl per liter for 10 seconds.

Variations of this procedure were attempted. Conducting the entire operation in an argon filled glove bag gave slightly more consistent results provided that the samples were not stored in the glove bag before dipping. The high humidity in the glove box adversely affected the adhesion of the CdS films. Decreasing the dip time to 6 to 8 seconds also seemed to give more consistent results. Table 5 gives the typical variability in electrical performance of cells produced in one batch. Minor changes in technique used in inserting the cells into the dip bath and removing excess solution from the surface of the cells resulted in substantial changes in performance. If larger runs were to be made, automation of the dipping process could be expected to eliminate this variability. The use of the "Dry Process" or evaporated Cu_2Cl_2 deposition onto the CdS may also produce more consistent results.

3.4. Thermal Treatment

Figure 83 shows the effect of a variety of thermal treatments on the performance of a CdS solar cell on indium oxide coated glass. The initial performance is shown in curve 1. Treatment for two hours in hydrogen at 160°C reduced both the open circuit potential and the short circuit current, as is shown in curve 2. Heating the cell for two hours in air at 160°C increased both the short circuit current and the open circuit potential (curve 3), though not to the original value. A layer of gold was evaporated over the back of the cell on both the Cu_2S layer and that portion of the In_2O_3 coated glass that did not contain the CdS film. Curve 4 shows that the open circuit potential was slightly decreased and the short circuit current was increased over the original value. A subsequent thermal treatment, 160°C for one hour in air, resulted in a further increase in short circuit current. The latter result is more likely due to the formation of a better contact between the gold and the cell.

Because of the limited time remaining in this contract, only a limited number of thermal treatments could be performed. Invariably the open circuit voltage was reduced, in many cases to zero.

Usually an air firing of one hour at 160°C after the hydrogen treatment resulted in a cell which had higher short circuit current and slightly lower open circuit potential than the cell had before hydrogen treatment. This type of behavior has also been noted by Westinghouse ⁽⁵⁾ for cells that were not treated to remove absorbed water prior to hydrogen treatment. Time did not permit exploration of this avenue.

3.5. Hall Measurements

Cadmium sulfide films were prepared on 7069 glass for Hall measurements to be performed at SERI. No results of these tests have been received as of the writing of this report.

3.6. Hydrogen Firing

Attempts were made to fire screen printed cadmium sulfide films in pure hydrogen. Experience with nitrogen firing suggested that at least 550°C be used to get appreciable sintering of the CdS and for the removal of the Cd₂Cl₂ flux. A limited number (10) of hydrogen firings were attempted. Firings below 350°C resulted in bright yellow films with no adhesion to the substrate. Higher firing temperatures resulted in complete reduction of the CdS to cadmium metal. Time did not permit further study of firing temperatures and nitrogen-hydrogen mixtures.

3.7. Cadmium Telluride on Cadmium Sulfide

A two micron thick cadmium telluride layer was deposited by screen printing on top of a 10 micron thick fired CdS layer. Scanning electron micrographs failed to resolve the two layers (Figures 84 and 85). However, the tellurium and sulfur maps shown in Figures 86 and 87 clearly show the positions of these layers and are evidence that minimal interaction between the layers has occurred.

Figures 88 through 91 are SEM photographs of a film of cadmium telluride (one layer) cofired on four layers of CdS. The CdTe layer did not contain any CdCl₂ flux but the CdS layers contained 30 volume percent CdCl₂. The penetration of the tellurium into the CdS is shown in the tellurium line scan shown in Figure 91. In addition blisters were formed during the firing similar to what had been encountered when firing six-layer CdS films. The prefiring of the CdS layer before addition and firing of the CdTe appears to be a preferred approach.

References

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2. N. Nakagama, H. Matsumoto, A. Nakano, S. Ikegami, H. Uda, and T. Yamashita, Japan J. of Appl. Phys., 19, 703-712 (1980).
3. G. D. McDonald (Johnson Controls), "Commercialization of a Thick Film Solar Cell," Final Report, 9-15-79 to 9-14-80.
4. J. R. Szedon, F. A. Shirland, J. A. Stoll, and H. C. Dickey (Westinghouse), "Development of CuS/CdS Thin Film Solar Cells," 1st. Technical Progress Report, February 1980.
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Table 1Spectrographic Analysis of GE Luminescent Grade CdS

♦ ♦ ♦ G L O B E U N I O N ♦ ♦ ♦

♦♦♦ MATERIALS TEST LABORATORY SPECTROGRAPHIC REPORT ♦♦♦
 CORP. ADDRESS 1XE DATE 12/17/80
 PHONE 2366

PHOTO PLATE # 2019.2

MTL #8012-0134 EXPOSURE 10

T&R SHEET # 80-12/45

ELEMENT

CONCENTRATION
 IN % BY WT OF SAMPLE AS RECEIVED BY MTL

CUST. IDENT. ♦♦♦♦ CdS - Lot 1142A

13 ALUMINUM	< .003
51 ANTIMONY	< .010
33 ARSENIC	< .100
56 BARIUM	< .100
83 BISMUTH	< .010
48 CADMIUM	> 1.000
20 CALCIUM	< .050
24 CHROMIUM	< .003
27 COBALT	< .005
29 COPPER	< .005
79 GOLD	< .010
26 IRON	< .003
50 LOTIN	< .003
50 LOTIN	< .003
25 MANGANESE	< .0010
12 MAGNESIUM	< .003
30 MERCURY	< .100
28 NICKEL	< .003
78 PLATINUM	< .033
14 SILICON	< .002
47 SILVER	< .0010
11 SODIUM	< .050
22 TITANIUM	< .010
23 VANADIUM	< .003
40 ZIRCONIUM	< .010
30 ZINC	< .050

THE ACCURACY OF THESE RESULTS AT THE 95% CONFIDENCE LIMIT IS APPROXIMATELY + OR - 50% OF THE AMOUNT PRESENT AT THE .01% LEVEL. THE ACCURACY DECREASES SUBSTANTIALLY AS THE ELEMENT CONCENTRATION APPROACHES THE CURRENT SPECTROGRAPHIC DETECTION LIMIT.

THIS ANALYSIS HAS BEEN CORRECTED FOR ANY CONTAMINATION INTRODUCED BY THE REAGENTS USED IN THE SAMPLE PREPARATION. THIS INFORMATION IS AVAILABLE UPON REQUEST.

Table 2
Analysis of TGA Curve

<u>Temperature</u> <u>°C</u>	<u>Percent Weight Loss</u>		<u>Fugitive</u> <u>Species</u>
	<u>Observed</u>	<u>Anticipated</u>	
200	28.25	29.94	Solvents
200 - 400	10.71	9.98	Plastic
400 - 680	20.88	21.53	CdCl ₂
Residue	40.16	38.55	CdS

Table 3Performance of CdS Films Relative to Conditions of Preparation

<u>CdS Layers</u>	<u>Firing Temp. °C</u>	<u>Firing Time Min.</u>	<u>Flux Content v/o</u>	<u>Resist. kohms</u>	<u>Thick- ness microns</u>	<u>SEM Photo Figures</u>	<u>V_{oc} volts</u>	<u>Heat- treated V_{oc} volts</u>
3	552	40	20	20	18	2, 3	--	--
3	600	40	20	10	15	4, 5	--	--
3	630	37	20	20	15	6, 7	.02	--
3	653	40	20	150	13	8, 9	.05	--
3	552	35	30	2.5	15	10, 11	.15	--
3	600	40	30	3	15	12, 13	.22	--
3	630	35	30	4	15	14, 15	.05	.12
3	653	40	30	24	13	16, 17	.10	--
3	550	30	40	2.7	10	18, 19	.22	.33
3	600	33	40	3	13	20, 21	.21	--
3	653	40	40	24	10	22, 23	.03	--
2	630	37	20	200	13	24, 25	.02	--
2	630	37	30	50	10	26, 27	.23	--
2	630	37	40	8	10	28, 29	.07	.18
3	653	100	40	498	--	30, 31	--	--

Table 4
Summary of Cell Performance

<u>CdS Layers</u>	<u>Firing Temp. °C</u>	<u>Firing Time Min.</u>	<u>Flux Content v/o</u>	<u>Resist. kohms</u>	<u>Thick- ness microns</u>	<u>SEM Photo Figures</u>	<u>V_{oc} Volts</u>
6	600	30	40	2.0	23	39, 40	--
6	610	45	40	2.504	23	41, 42	.14
6	610	45	40	2.504	23	43, 44	.14
6	600	30	40	2.270	--	45, 46	.16
6	600	30	40	2.270	--	47, 48	.16
6	600	25	40	122	31	49, 50	--
6	600	25	40	122	31	51, 52	--
6	600	25	40	136	33	53, 54	--
6	600	25	40	122	31	55, 56	.40
6	600	25	40	122	31	57, 58	.40
6	600	25	40	122	31	59	.40
6	600	25	40	136	33	60, 61	.22
6	600	25	40	136	33	62, 63	.22
6	600	40	40	32	28	64, 65	.38
6	600	40	40	32	28	66	.38
6	600	40	40	32	28	67, 68	.38
6	600	40	40	91	23	69, 70	.34
6	600	40	40	91	23	71, 72	.34

Table 5Electrical Performance of Cells Produced in One Batch

<u>V_{oc}</u>	<u>I_{sc}</u>
0.40	2.2
0.39	1.8
0.38	2.2
0.42	1.4
0.26	1.3
0.36	1.5
0.20	0.4
0.33	0.9

Sample: CDS INK

Size: 37.35 mg

Rate: 10 DEG.C/MIN

Program: Advanced Playback V1.0

TGA

Date: 14-Nov-80 Time: 13:39:27

File: REAX.05

Operator: TRISCHAN

Plotted: 17-Nov-80 11:17:54

Figure One

DuPont 1090

Figure 2. Low magnification SEM photograph of 3-layer CdS film fired at 552°C for 40 minutes, originally containing 20 volume percent CdCl₂.

Figure 3. High magnification SEM photograph of 3-layer CdS film fired at 552°C for 40 minutes, originally containing 20 volume percent CdCl₂.

Figure 4. Low magnification SEM photograph of 3-layer CdS film fired at 600°C for 40 minutes, originally containing 20 volume percent CdCl₂.

Figure 5. High magnification SEM photograph of 3-layer CdS film fired at 600°C for 40 minutes, originally containing 20 volume percent CdCl₂.

Figure 6. Low magnification SEM photograph of 3-layer CdS film fired at 630°C for 37 minutes, originally containing 20 volume percent CdCl₂.

Figure 7. High magnification SEM photograph of 3-layer CdS film fired at 630°C for 37 minutes, originally containing 20 volume percent CdCl₂.

Figure 8. Low magnification SEM photograph of 3-layer CdS film fired at 653°C for 40 minutes, originally containing 20 volume percent CdCl₂.

Figure 9. High magnification SEM photograph of 3-layer CdS film fired at 653°C for 40 minutes, originally containing 20 volume percent CdCl₂.

Figure 10. Low magnification SEM photograph of 3-layer CdS film fired at 552°C for 35 minutes, originally containing 30 volume percent CdCl₂.

Figure 11. High magnification SEM photograph of 3-layer CdS film fired at 552°C for 35 minutes, originally containing 30 volume percent CdCl₂.

Figure 12. Low magnification SEM photograph of 3-layer CdS film fired at 600°C for 40 minutes, originally containing 30 volume percent CdCl₂.

Figure 13. High magnification SEM photograph of 3-layer CdS film fired at 600°C for 40 minutes, originally containing 30 volume percent CdCl₂.

Figure 14. Low magnification SEM photograph of 3-layer CdS film fired at 630°C for 30 minutes, originally containing 30 volume percent CdCl₂.

Figure 15. High magnification SEM photograph of 3-layer CdS film fired at 630°C for 30 minutes, originally containing 30 volume percent CdCl₂.

Figure 16. Low magnification SEM photograph of 3-layer CdS film fired at 653°C for 40 minutes, originally containing 30 volume percent CdCl₂.

Figure 17. High magnification SEM photograph of 3-layer CdS film fired at 653°C for 40 minutes, originally containing 30 volume percent CdCl₂.

Figure 18. Low magnification SEM photograph of 3-layer CdS film fired at 550°C for 30 minutes, originally containing 40 volume percent CdCl₂.

Figure 19. High magnification SEM photograph of 3-layer CdS film fired at 550°C for 30 minutes, originally containing 40 volume percent CdCl₂.

Figure 20. Low magnification SEM photograph of 3-layer CdS film fired at 600°C for 33 minutes, originally containing 40 volume percent CdCl₂.

Figure 21. High magnification SEM photograph of 3-layer CdS film fired at 600°C for 33 minutes, originally containing 40 volume percent CdCl₂.

Figure 22. Low magnification SEM photograph of 3-layer CdS film fired at 653°C for 40 minutes, originally containing 40 volume percent CdCl₂.

Figure 23. High magnification SEM photograph of 3-layer CdS film fired at 653°C for 40 minutes, originally containing 40 volume percent CdCl₂.

Figure 24. Low magnification SEM photograph of 2-layer CdS film fired at 630°C for 37 minutes, originally containing 20 volume percent CdCl₂.

Figure 25. High magnification SEM photograph of 2-layer CdS film fired at 630°C for 37 minutes, originally containing 20 volume percent CdCl₂.

Figure 26. Low magnification SEM photograph of 2-layer CdS film fired at 630°C for 37 minutes, originally containing 30 volume percent CdCl_2 .

Figure 27. High magnification SEM photograph of 2-layer CdS film fired at 630°C for 37 minutes, originally containing 30 volume percent CdCl_2 .

Figure 28. Low magnification SEM photograph of 2-layer CdS film fired at 630°C for 37 minutes, originally containing 40 volume percent CdCl₂.

Figure 29. High magnification SEM photograph of 2-layer CdS film fired at 630°C for 37 minutes, originally containing 40 volume percent CdCl₂.

Figure 30. Low magnification SEM photograph of 3-layer CdS film fired at 653°C for 100 minutes, originally containing 40 volume percent CdCl₂.

Figure 31. High magnification SEM photograph of 3-layer CdS film fired at 653°C for 100 minutes, originally containing 40 volume percent CdCl₂.

Figure 32. SEM photograph of 3-layer CdS film fired at 653°C for 40 minutes, originally containing 20 v/o CdCl₂.

Figure 33. Oxygen map of same film shown in figure 32.

Figure 34. Oxygen scan of 3-layer CdS film fired at 653°C for 40 minutes, originally containing 20 v/o CdCl₂.

Figure 35. Indium line scan of CdS film on indium oxide coated glass.

Figure 36. Cadmium line scan of CdS film on indium oxide coated glass.

Figure 37. G.E. luminescent grade CdS SEM, high magnification.

Figure 38. G.E. luminescent grade CdS SEM, low magnification.

Figure 39. Cofired six-layer CdS film on 7059 glass, low magnification.

Figure 40. Cofired six-layer CdS film on 7059 glass, high magnification.

Figure 41. Four layers plus two layers of CdS on 7059 glass, low magnification.

Figure 42. Four layers plus two layers of CdS on 7059 glass, high magnification.

Figure 43. Copper line scan of four layer plus two layers of CdS on 7059 glass.

Figure 44. Copper map (energy) of four layers plus two layers of CdS on 7059 glass.

Figure 45. Cofired six layers of CdS on Nesatron glass, high magnification.

Figure 46. Cofired six layers of CdS Nesatron glass, low magnification.

Figure 47. Copper line scan of cofired six layer CdS on Nesatron glass.

Figure 48. Indium line scan on cofired six layer CdS Nesatron glass.

Figure 49. Four layers plus two layers CdS on tin oxide-coated glass, high magnification.

Figure 50. Four layers plus two layers of CdS on tin oxide-coated glass, low magnification.

Figure 51. Four layers on two layers of CdS on tin oxide-coated glass showing area of tin map.

Figure 52. Tin map of four layers on two layers of CdS on tin oxide-coated glass.

Figure 53. Cofired six layers of CdS on tin oxide-coated glass, low magnification.

Figure 54. Cofired six layers of CdS on tin oxide-coated glass, high magnification.

Figure 55. Four layers plus two layers of CdS on tin oxide-coated glass, high magnification.

Figure 56. Four layers plus two layers of CdS on tin oxide-coated glass, low magnification.

Figure 57. Four layers plus two layers of CdS on tin oxide, area used for copper maps.

Figure 58. Four layers on two layers of CdS on tin oxide, copper energy map.

Figure 59. Four layers on two layers of CdS on tin oxide, copper wavelength map.

Figure 60. Cofired six layer CdS film on tin oxide-coated glass, high magnification.

Figure 61. Cofired six layer CdS film on tin oxide-coated glass, low magnification.

Figure 62. Cofired six layers CdS film on tin oxide-coated glass, area for copper map.

Figure 63. Cofired six layers CdS film on tin oxide-coated glass, copper wavelength map.

Figure 64. Four layers plus two layers of CdS or In₂O₃ coated glass, high magnification.

Figure 65. Four layers plus two layers of CdS on In₂O₃ coated glass, medium magnification.

Figure 66. Four layers plus two layers of CdS on In_2O_3 coated glass, low magnification.

Figure 67. Four layers plus two layers of CdS on In₂O₃ coated glass, area for copper map.

Figure 68. Four layers plus two layers of CdS on In₂O₃ coated glass, copper wavelength map.

Figure 69. Six layer CdS film on indium oxide coated glass, high magnification.

Figure 70. Six layer CdS film on indium oxide coated glass, low magnification.

Figure 71. Six layer CdS film on indium oxide coated glass, copper wavelength map.

Figure 72. Six layer CdS film on indium oxide coated glass showing TPA-85 coating.

Figure 73. Cofired six layers of CdS on In_2O_3 coated glass.

Cell	CdS- Cu_2S
Substrate	Nesatron
Temperature	28°C
Illumination	$7.8 \times 10^3 \text{ lm/ft}^2$
Area	1 cm^2
Cell number	137138139140141142-0-153-72
Heat treatment	none
Date	01/22/81

Figure 74. Cofired six layers of CdS on In_2O_3 coated glass.

Cell	CdS- Cu_2S
Substrate	Nesatron
Temperature	28°C
Illumination	$7.8 \times 10^3 \text{ lm/ft}^2$
Area	1 cm^2
Cell number	137138139140141142-0-153-54
Heat treatment	none
Date	01/22/81

Figure 75. Four layers plus two layers of CdS on coated In_2O_3 glass.

Cell	CdS-Cu ₂ S
Substrate	Nesatron
Temperature	28°C
Illumination	$7.8 \times 10^3 \text{ lm/fg}^2$
Area	1 cm ²
Cell number	137138139140-0-151141142-0-153-73
Heat treatment	none
Date	01/22/81

Figure 76. Four layers plus two layers of CdS on coated In₂O₃ glass.

Cell	CdS-Cu ₂ S
Substrate	Nesatron
Temperature	28°C
Illumination	7.7×10^3 lm/ft ²
Area	1 cm ²
Cell number	137138139140-0-151141142-0-153-58
Heat treatment	none
Date	01/22/81

Figure 77. Four layers plus two layers of CdS on In_2O_3 coated glass.

Cell CdS- Cu_2S

Substrate Nesatron

Temperature 28°C

Illumination $7.8 \times 10^3 \text{ lm/ft}^2$

Area 1 cm^2

Cell number 137138139140-0-151141142-0-153-37

Heat treatment none

Date 01/22/81

Figure 78. Four layers plus two layers of CdS on tin oxide coated glass.

Cell	CdS-Cu ₂ S
Substrate	tin oxide coated glass
Temperature	28°C
Illumination	7.8×10^3 lm/ft ²
Area	1 cm ²
Cell number	137138139140-0-152141142-0-154-48
Heat treatment	none
Date	01/22/81

Figure 79. Four layers plus two layers of CdS on tin oxide coated glass.

Cell	CdS-Cu ₂ S
Substrate	tin oxide coated glass
Temperature	28°C
Illumination	7.8×10^3 lm/ft ²
Area	1 cm ²
Cell number	137138139140-0152141142-0-154-47
Heat treatment	none
Date	01/22/81

Figure 80. Four layers plus two layers of CdS on tin oxide coated glass.

Cell	CdS-Cu ₂ S
Substrate	tin oxide coated glass
Temperature	28°C
Illumination	7.8×10^3 lm/ft ²
Area	1 cm ²
Cell number	137138139140-0-152141142-0-154-36
Heat treatment	none
Date	01/22/81

Figure 81. Four layers plus two layers of CdS on tin oxide coated glass.

Cell	CdS-Cu ₂ S
Substrate	tin oxide coated glass
Temperature	28°C
Illumination	7.8 x 10 ³ lm/ft ²
Area	1 cm ²
Cell number	137138139140-0-152141142-0-154-35
Date	01/22/81

Figure 82. Four layers of CdS on In_2O_3 coated glass.

Cell	CdS- Cu_2S
Substrate	Nesatron
Temperature	28°C
Illumination	$7.8 \times 10^{+3} \text{ lm/ft}^2$
Area	1 cm^2
Cell Number	137138139140-0-151
Heat Treatment	none
Date	01/15/81

Figure 83. Thermal treatments of CdS cell.

Figure 84. Low magnification SEM of CdTe on CdS

Figure 85. High magnification SEM of CdTe on CdS

Figure 86. Tellurium map of CdTe on CdS

Figure 87. Sulfur map of CdTe on CdS

Figure 88. Cofired CdTe-CdS film, low magnification.

Figure 89. Cofired CdTe-CdS film, intermediate magnification.

Figure 90. Cofired CdTe-CdS film, high magnification.

Figure 91. Cofired CdTe-CdS film, tellurium line scan.