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Annual Technical Progress Report, 5 July 1995 - 4 June 1996

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Executive Summary

Iowa Thin Film Technologies, Inc.'s (ITF) goal is to develop the most cost effective PV manufacturing process possible. To this end we have chosen a roll based manufacturing process with continuous deposition and monolithic integration.

Work under this program is designed to meet this goal by improving manufacturing throughput and performance of the manufactured devices. The following efforts were the focus of work during the first year:

- The capability of sputtering a high quality Zn(Al)O was developed. A wide range of variations were investigated to allow us to implement this material as a reflection enhancement layer in devices. All efforts resulted in an increase in shunt defects in the devices. Work will continue on this task.

- Increased deposition rates for the ZnO top contact deposition were successfully implemented. Preliminary work was done on implementing single pass operation of this system. A throughput increase of 50% has been achieved.

- To allow a reduction in area loss due to interconnects, improvement in registration and ink line width were required. These improvements have been achieved.

- A new alignment process and sensor were developed to improve the speed and accuracy of registration for the patterning processes. This technique proved highly successful and has been fully implemented on the scriber. The sensors have been installed on the printer and implementation of the new process is in progress.

- A new Silver ink composition has been developed which allows finer print lines and lower series resistance.

- An overall improvement in area utilization of 8% has been demonstrated to date. Also, throughput improvements of 30% on the scriber and 70% on the printer have been realized.

- Water based insulator inks were evaluated for compatibility with our process. One candidate was found which shows promise.

- Use of roll based lamination was investigated and tested as a means to reduce the cost of assembly.

- Straight roll lamination capability using pressure sensitive adhesives and thermally activated bonding was developed. This process works well with a range of candidate materials. Laminated assemblies will be life tested to determine long range stability. This approach yields at least a 4-fold increase in throughput.

- Use of the standard EVA/Tefzel encapsulant with a roll laminator was evaluated. This process requires a post bake following rolling. The best method for this post bake is still under investigation.

During the next year ITF will focus on the following: continued efforts at implementing the back reflector; optimization of performance and deposition rates in the new tandem machine; development of single pass capability in the TCO and metalization systems; implementation of the new alignment process on the printer; and development of an automated cutting and busbar attachment system to go with the roll laminator.

1.0 INTRODUCTION

The following ANNUAL TECHNICAL PROGRESS REPORT has been prepared under Subcontract ZAF-5-14271-4 with the Midwest Research Institute National Renewable Energy Laboratory Division. This Phase I/year one annual report covers the performance period of July 5, 1995 through June 4, 1996.

1.1 Background

The Department of Energy (DOE), in cooperation with the U.S. photovoltaic (PV) industry, has the goal of enhancing the U.S. PV industry leadership in the world market. To further this goal, the Photovoltaic Manufacturing Technology (PVMaT) project was initiated in FY 1991 to assist U.S. industry in the improvement in module manufacturing processes and the substantial reduction of module manufacturing cost. PVMaT's partnership with industry is being implemented in phased procurements to support continued progress as each phase accomplishes its objectives. Phases 1, 2, and 3 have been successfully implemented beginning with Phase 1 in 1991.

Phase 4A, the PVMaT addressed in this subcontract, addresses areas of research and development including issues related to cost-effective PV end-products, including module manufacturing, flexible manufacturing approaches, systems integration, and balance of systems. This subcontract represents an R&D in approach under Phase 4A2, Product Driven PV Module Manufacturing Technology, and is planned as a three (year) effort. It is directed toward R&D on PV module manufacturing process technology (with no funding for acquisition of production line equipment).

During this Phase 4A2 subcontract, Iowa Thin Film Technologies, Inc. (ITF) was to focus on increasing the throughput of their metalization, a-Si deposition, laser-scribing and welding processes and on reducing the overall module manufacturing costs on the ITF production line by 68%. Efforts to accomplish these goals will be focused on replacing the ITF TiN layer with a less absorbing layer ZnO layer; investigating alternate sources for the supply of Zn and O in the ZnO growth process; designing and implementing a web steering system machine control programs; identifying new laser operating parameters to optimize the laser beam scan speed and study alternative processes for the scribing; developing a new water-based insulating ink printing and roll based laminating processes for the ITF production line; designing and implementing baffles for the isolation of deposition regions; studying alternative methods of welding shunts in cell-interconnects; and automating the final process steps of busbar attachment and web cutting.

1.2 Objectives

The objective of this subcontract over its three year duration is to improve overall module performance, increase the throughput of the metalization, a-Si deposition, laser-scribing, and welding processes and to reduce the overall module manufacturing costs of the ITF production line by 68%.

The Phase I/ year one task efforts were aimed at a 30% to 40% overall reduction in the cost of module manufacturing for the ITF production line.

1.3 Approach

Phase I of the three one-year subcontract phases began in July 1995 and continued through June 1996. Phase I/ year one project activities focused on task efforts which included: increasing the throughput of the metalization, a-Si deposition, laser-scribing and welding processes; replacing the ITF TiN layer with a less absorbing ZnO layer; designing and implementing a web steering system for feeding the web onto the printer platen; establishing new laser operating parameters to optimize the laser beam scan speed; and developing a new insulating ink printing and roll-based laminating process for the ITF production line. Phase I activities were divided into four tasks :

Task 1: Roll Based Deposition Throughput Improvement for Back Contact Layer
Task 2: Improvements in Laser-Scribing, Welding, and Printing Process Throughput
Task 3: Substrate and Materials Cost Reduction
Task 4: Development of a Roll Based Laminating Process

Phase I activities and accomplishments are described below organized under the four tasks.

2.0 PHASE I ACTIVITIES AND ACCOMPLISHMENTS

2.1 Task 1: Roll Based Deposition Throughput Improvement for Back Contact Layer

Phase I Task 1 efforts were aimed at back reflector improvement and deposition throughput improvement. Fabrication parameters and techniques to allow replacement of the current TiN layer with a ZnO layer sputtered from a metal target would be developed. Parameters would be established which produce a ZnO layer with less than 3% absorption (over 400-700nm) at a deposition rate compatible with metalization system web speeds of 2-ft/min. The effect of this layer on full device operation would be evaluated. Modifications would be made to the fabrication process to eliminate any increases in contact resistance or shunt defect density. Parameters would be established for maximum acceptable deposition rates for each layer made in the new single-pass tandem deposition system based on material quality and dust formation.

It was expected that this task would result in replacement of the TiN layer with a less absorbing ZnO layer leading to a device current improvement of 25% to 35%, and provide data for optimizing the operating parameters for the new ITF a-Si tandem deposition system. Percentages of cost reduction cited in the following tasks have a component due to this improvement.

2.1.1 Texture control

Total reflectance of light off the back contact and back contact texture are both critical to achieving the highest efficiency of collection of red light. High total reflectance minimizes loss of light by absorption at the back surface and texture provides scattering which increases the path length before reaching the front surface and creates the possibility of total internal reflection of light when it reaches that surface. In addition to the optical performance, the back contact must also be stable and have a good mechanical bond to the substrate.

To guarantee the best reflectance and optimum scattering, it is important to have a characterization method. It is one of the advantages of a roll based process that such a characterization method can be incorporated into the deposition system to monitor film quality and control deposition parameters. We have worked at developing such a system.

We initially evaluated the specular and diffuse reflectance of good and poor substrate material using a He-Ne laser and a moveable silicon detector to establish the sensitivity of the method. Figures 1-A and 1-B show the data for the "good" (Fig. 1-A) and "poor" (Fig. 1-B) samples in this experiment. It is evident that both the total specular reflectance and the ratio of diffuse to specular reflectance can be measured and correlated with substrate quality.

To establish a capability of monitoring texture during processing within the deposition chamber, a system was constructed which uses a laser diode along with 4 silicon detectors at fixed angular positions. A diagram of this system is shown in Figure 2. This system provides 4 data points which can be used to monitor the efficiency of scattering of red light. Figure 3 shows data from this setup overlaid on the prior data. From this it is clear that the 4 data points taken are adequate to indicate the full scattering response and be used as a quality control check on system operation.

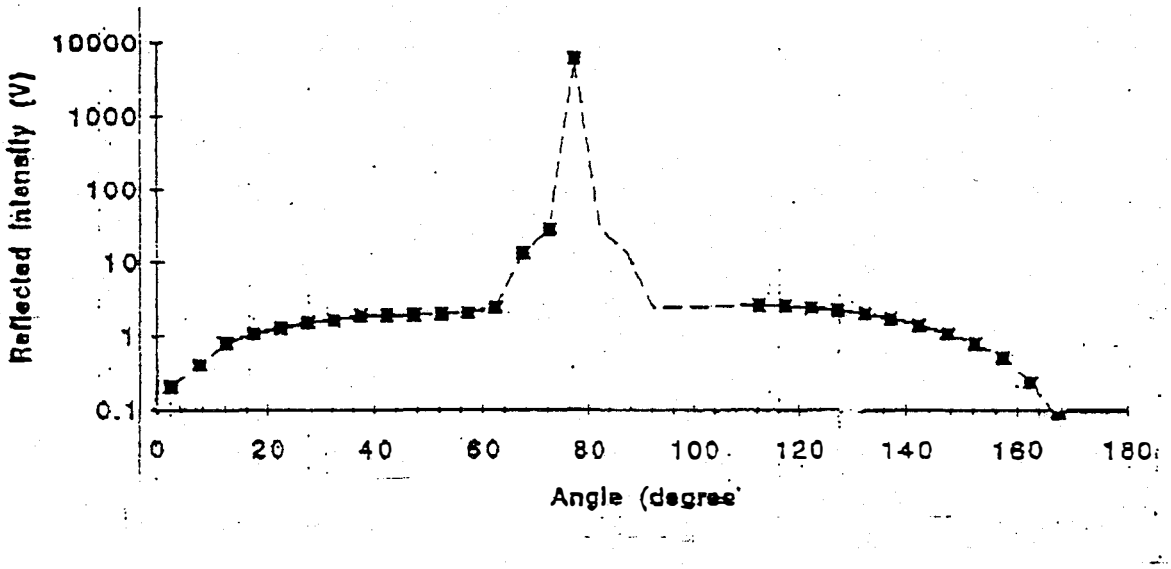


Figure 1-A. Specular and diffuse reflectance of a "good" sample.

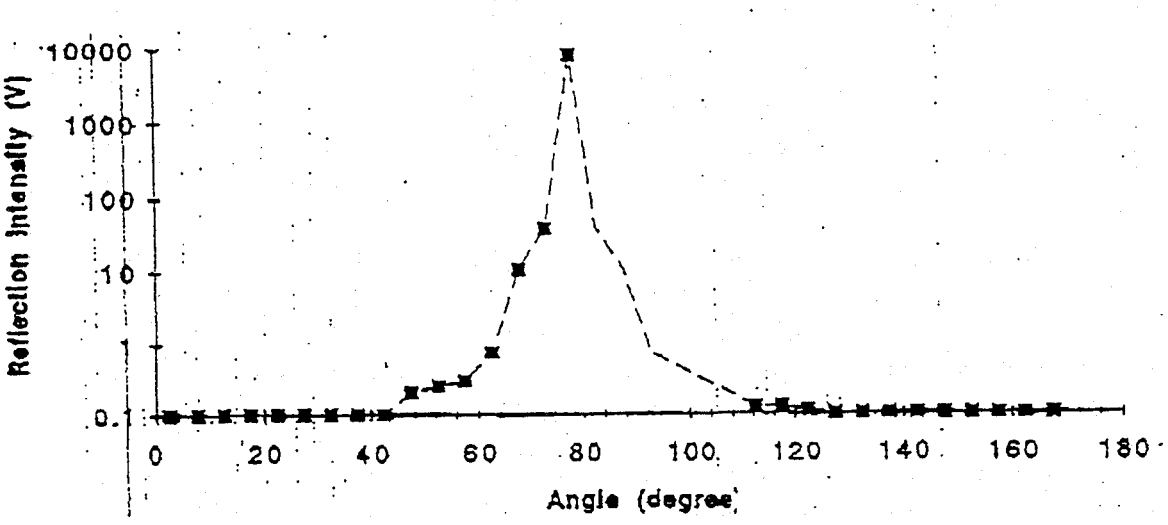


Figure 1-B. Specular and diffuse reflectance of a "poor" sample.

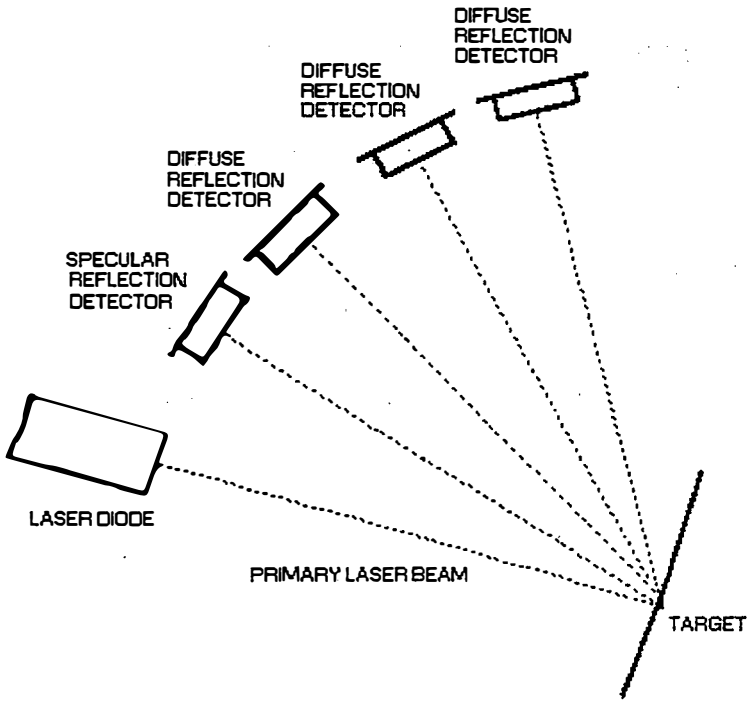


Figure 2. Diagram of the specular and diffuse reflectance measurement system constructed with a laser diode with 4 silicon deflectors.

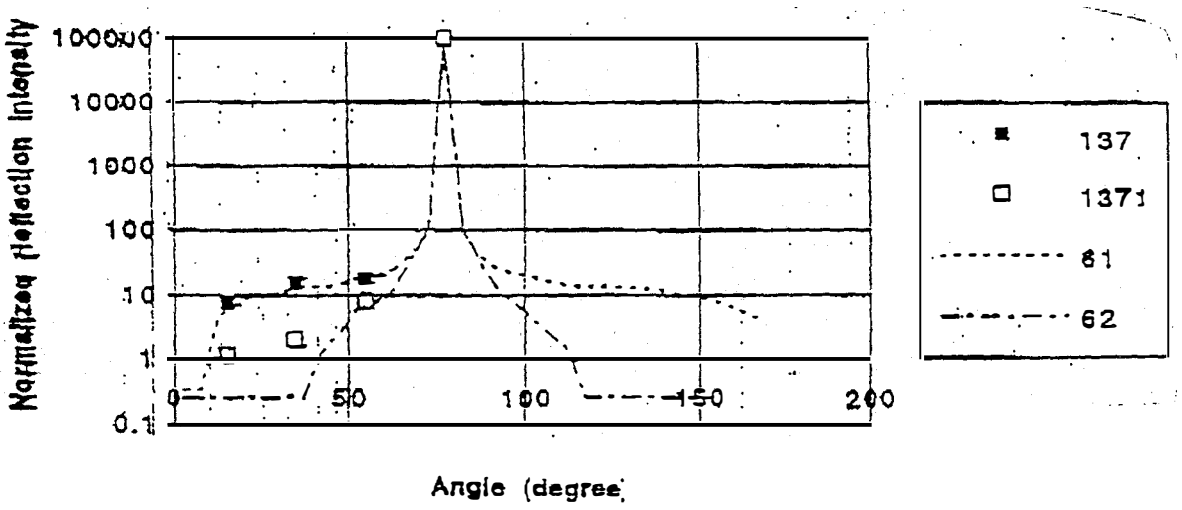


Figure 3. Test results using the laser diode system with 4 silicon deflectors overlaying the previous test data.

2.1.2 Back Surface Reflection Enhancement

Zinc oxide is being developed as an alternative to titanium nitride as the intermediate layer between the aluminum base metal/reflector/electrical conductor and the silicon layers for photovoltaic cells. ZnO has optical benefits that can enhance the reflectance of light from the base of the cell improving the overall efficiency of the cell, however, silicon may have adhesion and electrical shorting problems to the ZnO layer.

Initially, a zinc, 2% aluminum target was installed in the PTS for deposition onto a polyester web. Polyester was used because it is transparent to the wavelengths of light of interest and allows for transmission spectra tests. Zinc oxide is deposited from a metal target using a reactive sputtering technique in an argon/oxygen atmosphere. Various pressures and argon/oxygen ratios were investigated. Deposition was controlled at 400 watts power, web speed at 2 inches/min. and with no applied heating. After deposition of the ZnO, resistance and optical transmission measurements were made. Table 1 below shows a comparison of results with variations in the % oxygen, total pressure, target potential and resistance. (Resistance was measured using a digital multimeter with the probes touching the film with approximately a 1 inch separation.)

Table 1. Comparison of test results with variations in the % oxygen, total pressure, target potential, and resistance.

Sample #	% Oxygen	Total Pressure (mTorr)	Target Potential (volts)	Resistance (ohms)	Notes on Color
148-9930	100	5.05	268	*	clear
148-9880	88.7	4.79	267	*	clear
148-9840	67.3	4.65	266	*	clear
148-9800	50.6	4.78	266	*	clear
148-9760	34.2	4.53	272	*	clear
148-9720	21.7	4.61	271	2.3 Meg	clear
148-9671	10.3	4.38	276	105 K	clear
148-9520	6.7	4.30	318	770	clear
148-9485	7.4	5.11	341	370	very slight
148-9453	7.1	5.50	330	252	clear
148-9438	6.2	5.96	332	360	very slight
148-9403	5.8	6.38	327	385	brown
148-9376	7.8	4.10	320	416	slight
148-9282	6.8	3.67	335	380	brown

* indicates infinite resistance.

Thickness measurements were made on samples 148-9485, 9453, and 9438. These were found to be 1K Å, 2.4 K Å,, and 2.2 K Å, respectively.

From these measurements, the conditions of 5.5 mTorr and 7.1% oxygen was deemed the most favorable for deposition of the conductive transparent oxide.

Transmission spectra were taken on these films and the results are included in Appendix A. The samples with high, or infinite, resistance are very transparent indicating little deposition, i.e., low deposition rates. The lower resistance samples show a transmission peak at about 1000 nm, tapering off at longer wavelengths. At higher wavelengths the clear samples show a stable transmission at shorter wavelength to approximately 500 nm where transmission diminishes. The brown colored samples show a transmission peak at 1000 nm but also decrease at shorter wavelengths, probably due to absorption by metallic zinc.

Laboratory results have shown that the ZnO layer incorporated between the back metal contact and the n+ layer can significantly enhance reflection and therefore the collection efficiency of red light. To date, ITF has been unable to incorporate this in our roll based pilot manufacturing line. Attempts to incorporate a sputtered ZnO layer have resulted in shunted cells or a very high leakage current while CVD ZnO has produced a barrier. Figure 4 below shows an I-V curve of such a device.

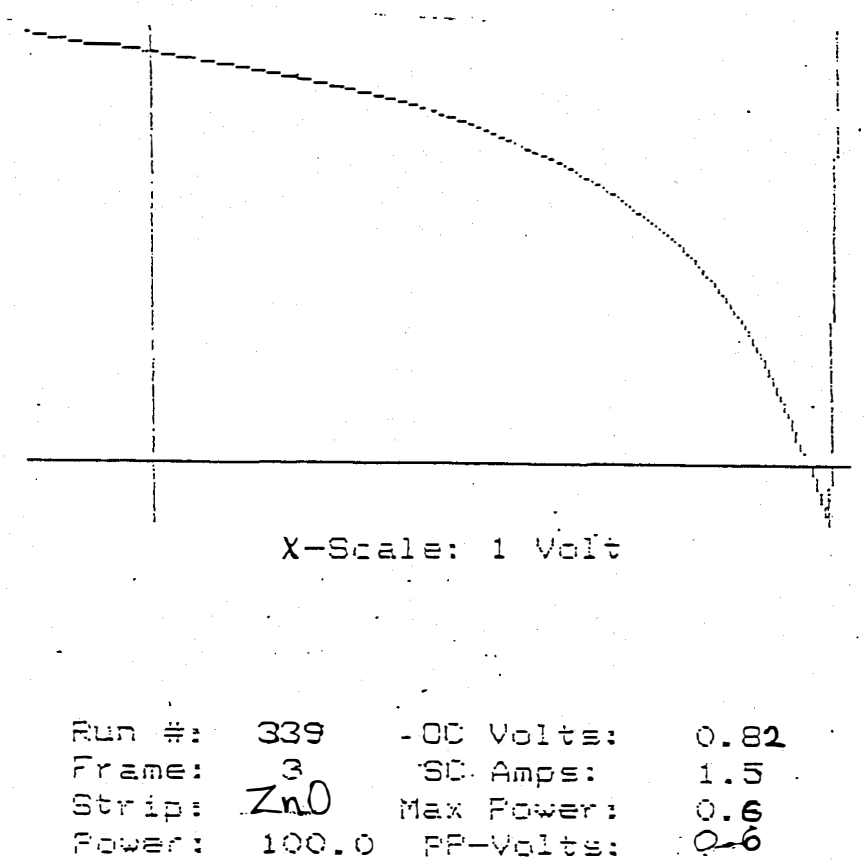


Figure 4. I-V curve for submodule with ZnO reflective layer.

The prime candidate mechanisms for producing the high leakage currents were identified as follows: 1) The n layer deposition might reduce the ZnO and let Zn diffuse into the device destroying the barriers; 2) Spikes of ZnO may form which protrude through the cell to provide shunt paths; 3) Small pieces of the ZnO might separate from the underlying metal and flake of causing pinholes, shunting the device; 4) The ZnO might affect the nucleation of the micro-crystalline n+ layer, reducing the thickness below the needed level.

To help distinguish between these effects, SIMS was performed on samples of the devices fabricated on ZnO covered Al substrate. Figure 5 shows the results of this profile. No Zn is visible before the back contact is reached. The back interfaces look close to what is desired. If Zn had diffused far into the device, it should be visible in this scan.

If pinholes or ZnO spikes existed in the scanned area, one might expect a low level Zn signal to be evident early in the scan. As this was not apparent from the scan, if they do exist, they must be a very small percentage of the total area.

A wide range of experiments were carried out to determine the source of the shunts. Deposition temperature, power and ZnO film thickness were varied and devices examined for correlations between these parameters and shunt level. No correlation was found.

An amorphous n+ layer was substituted for the standard microcrystalline layer to investigate the possibility that the high deposition power and H2 etching associated with the microcrystalline layer were causing damage. A range of deposition powers and doping levels were used for the amorphous n+ layer. No reduction of shunt level was seen with these changes.

To further investigate the effect of the interface with the silicon layer, a TiN layer was deposited over the ZnO layer as a barrier before fabrication of the silicon layers. This configuration was shown to have shunts also.

During the course of these experiments, one correlation was observed: the shunt level increased with the occurrence of physical damage that results from poor handling. While this is true for all substrate combinations, the sensitivity seemed much higher for the ZnO coated back material. It may be that the mechanical strength or interface bonding strength of the ZnO is enough lower than the TiN that it is susceptible to mechanical damage. This weakness would be more noticeable on our flexible substrate than on a more rigid material.

Our continued course of action will be to look at less conductive ZnO which would result in higher resistance leakage paths and to look for alternatives to ZnO which would have similar optical properties, but would have stronger mechanical properties. If the shunt paths are very small physically (indicated by the lack of Zn signal early on the SIMS), a higher resistance material should severely limit the amount of current that they could drain off. Prime candidates for replacing the ZnO are Titanium oxide and Titanium oxy-nitride. These were chosen because of the previously demonstrated ability of TiN.

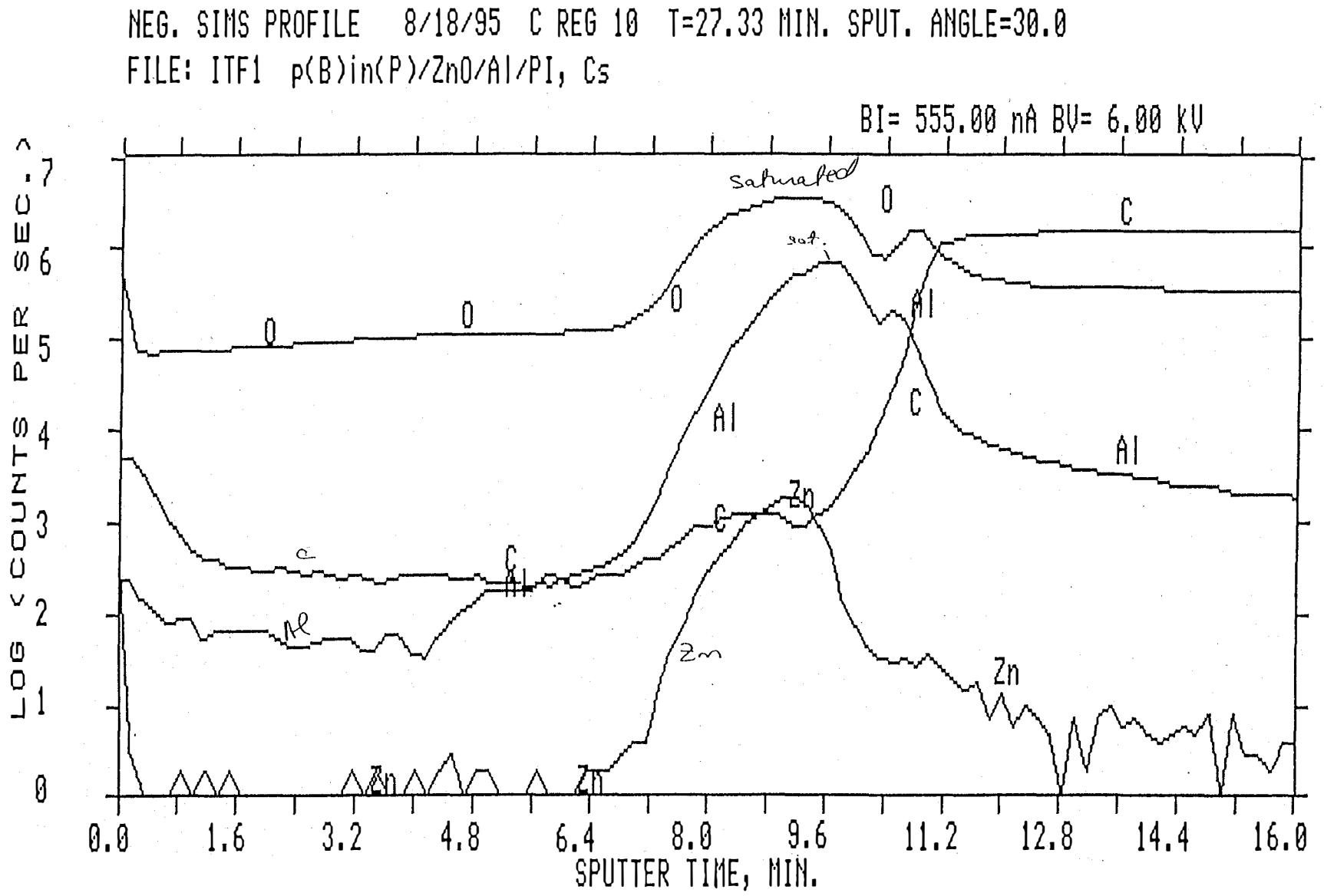


Figure 5. SIMS profile of device samples fabricated on ZnO covered Al substrate.

2.1.3 Improved Throughput of ZnO Top Contact Deposition

The basic property requirements of the TCO are:

1. A sheet resistance of 10 ohms/sq. or better
2. Optical absorption of 5% or less averaged over the response spectrum of the a-Si solar cell
3. Good electrical contacts to the p+ silicon layer and the Ag ink contacts
4. Low manufacturing cost.

Improvement of the throughput on the ZnO deposition system is an important cost improvement. A number of mechanisms for increasing throughput were investigated during this phase including increasing deposition temperature to increase the deposition rate and reduce sheet resistance. It is important that the increase in deposition rate not be accompanied by an increase in optical absorption.

Figure 6 shows a plot of sheet resistance vs. deposition temperature with web speed and gas flows held constant. It appears that by increasing the deposition temperature from our current level of 175 C to 195 C, sheet resistance drops by nearly a factor of 2. This would allow doubling of the web speed through the system provided that the optical and mechanical properties of the ZnO were not degraded.

Figure 7 shows the absorption curve taken from a sample deposited at 195 C. Although the absorption increases as the wavelength goes below 450 nm, the average absorption between 400 and 700 nm is about 5% which is quite reasonable. Mechanically, the films deposited at 195C adhere well to the substrate and show no signs of failure.

2.2 Task 2: Improvements in Laser-Scribing, Welding, and Printing Process Throughput

Phase I Task 2 efforts were aimed at improvements in laser-scribing, welding, and patterning system processes throughput. Several wide-field-of-view sensors would be evaluated, and candidates selected and implemented to speed up web registration under computer control. This would include the development of new software to incorporate the wide-field detectors into the alignment process and any redesign of laser and printer platens that became necessary. ITF would also examine photoelectric detectors, linear arrays and position sensor detectors for use in registration mark positioning. Resultant detection schemes and alignment processes would be incorporated into both the printer and laser scriber in the ITF production line processes steps.

Iowa Thin Film Technologies, Inc. would also design and implement a web steering or tracking system for feeding the web onto the printer platen. The ink line widths would be decreased in the printing steps to 0.3 mm or less. Several technologies including position sensitive detectors (PSDS), would be evaluated and the best candidate selected for the computer system currently controlling web drive. New laser operating parameters to optimize laser beam scan speed would be established. In addition, the laser scriber would be optimized for maximum throughput in conjunction with the detectors and software. Possible hardware changes such as stepper motor and gearing changes for their potential for reducing overall process time would be evaluated.

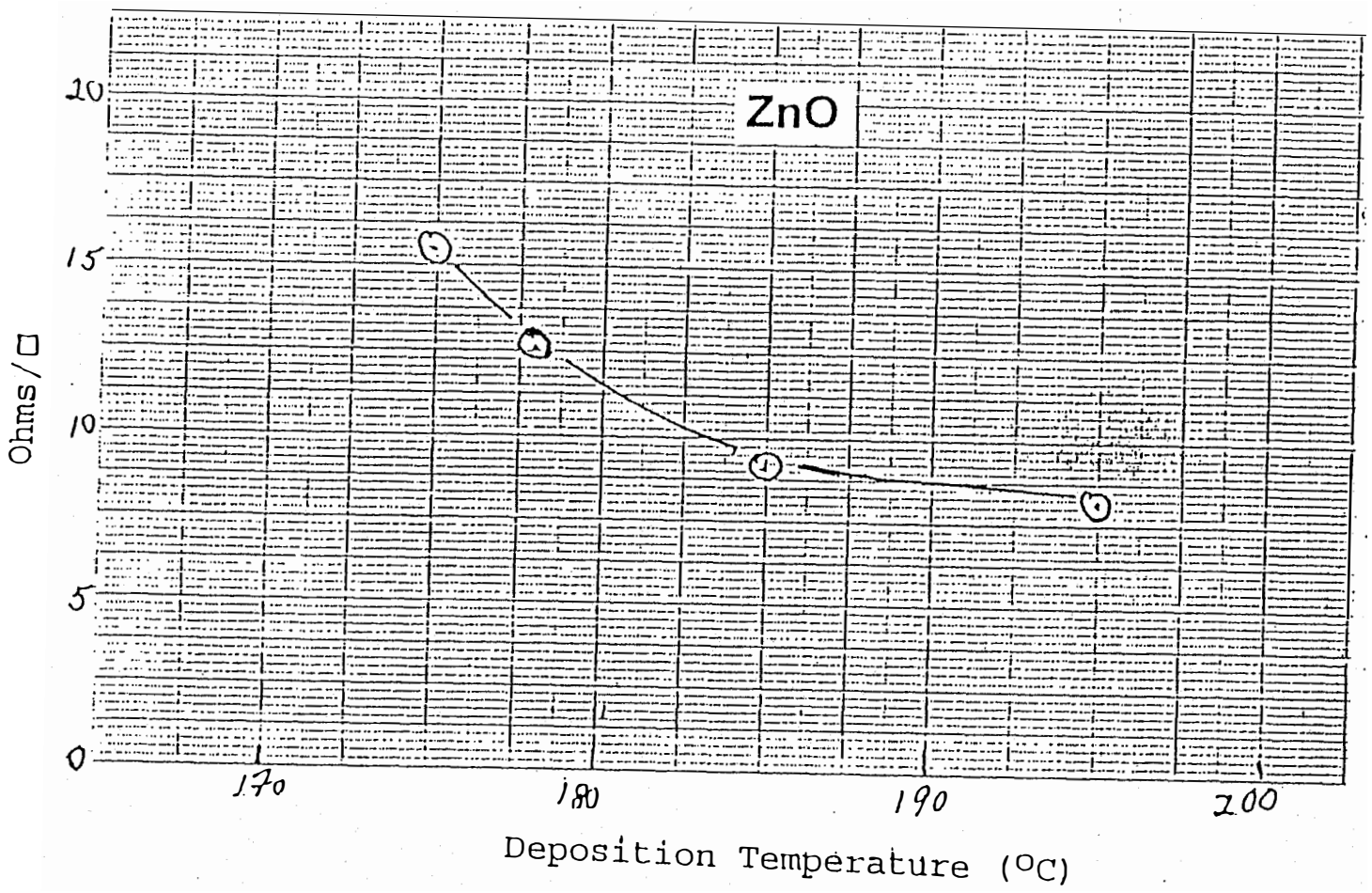


Figure 6. Plot of sheet resistance vs. deposition temperature with web speed and gas flows held constant.

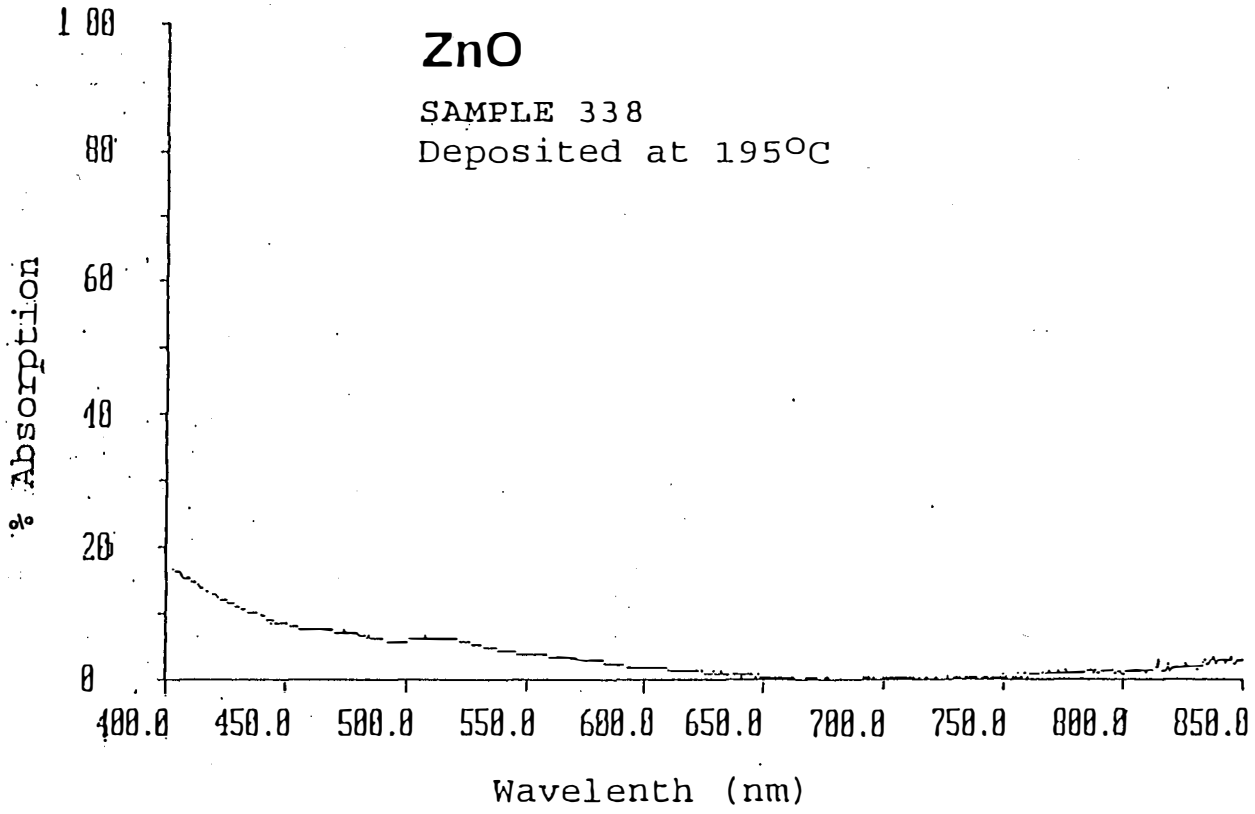


Figure 7. Absorption curve of a CVD ZnO sample deposited at 195 C.

This task, in conjunction with Task 6 and Task 11, is expected to result in an increase in throughput of the laser and printer systems, and a 17% overall reduction in $/W cost of module manufacturing for the laser-scribing, welding, and printing process steps. Further implementation of the results from this task are expected under activities outlined in Task 6 and Task 11.

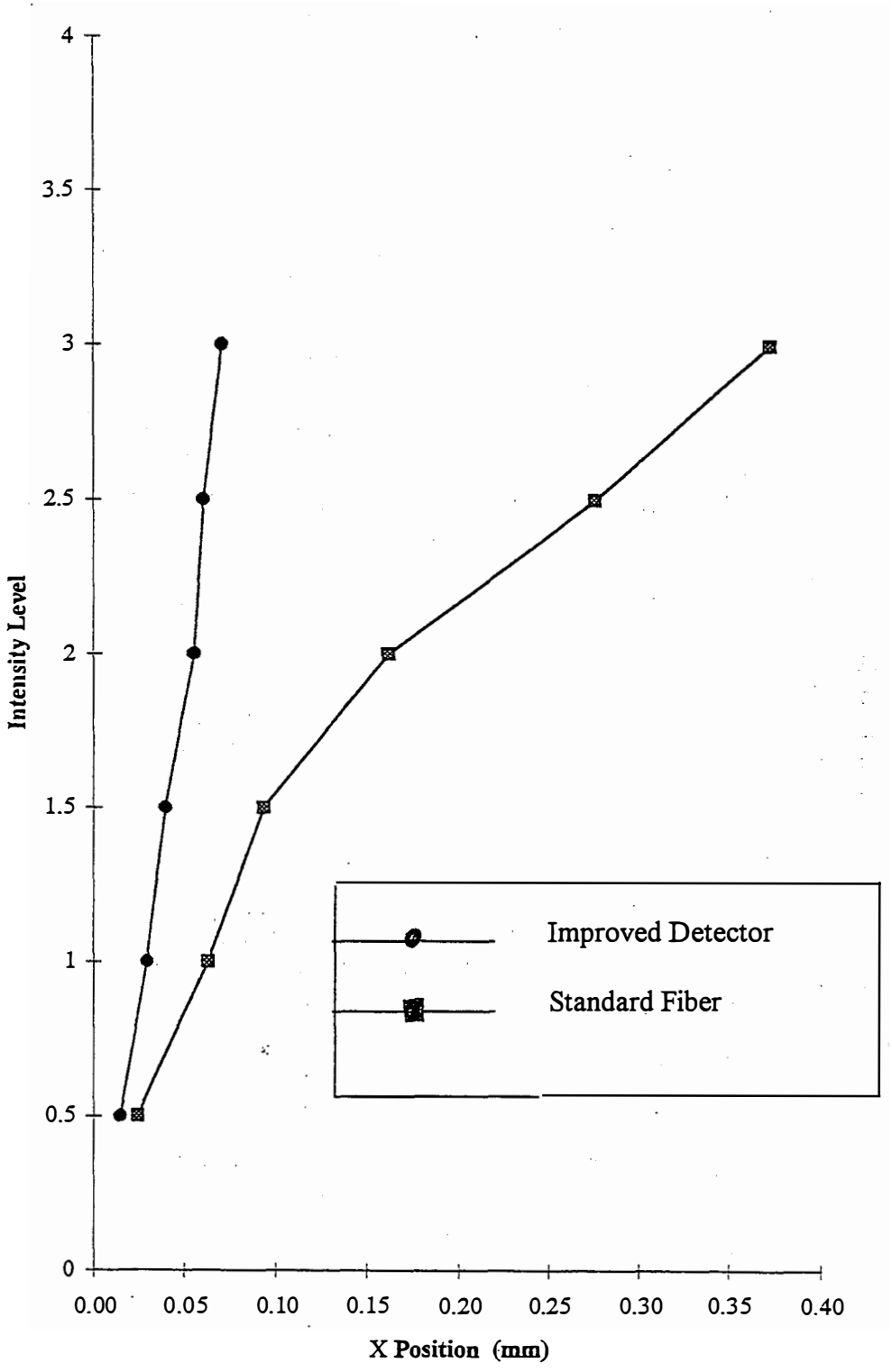
The following activities and accomplishments resulted from work done to date on Task 2:

Throughput improvements with the roll-to-roll laser scriber/welder and screen-printing modules are determined by a) improvement in submodule alignment and b) improvements in unit submodule processing time.

The scriber and printer have similar alignment technologies, both in hardware and software used. Common to both scriber and printer are stepper and servo motors for web motion over a platen and fiber optic sensors. The scriber probes are mounted on an x-y stage that aligns with and moves relative to the web on the scribing platen. Previously, the printer screen had been hand adjusted to maintain alignment with the web. However, under this development contract, the screen printer is to be mounted on an x-y stage that automatically aligns with and moves relative to the web on the printing platen. The software for the web movement, movement, and fiber optic detector registration is also similar for the scriber and printer. There exists a great variety of optical detection schemes for web alignment. They vary greatly in complexity and cost, ranging from over $20,000 for CCD camera systems to as little as $100 for fiber optic sensors. All claim resolutions smaller than 0.02 mm (1 mil). In each of these systems, the registration capability is dependent on the accuracy of the mechanical system integration and alignment. For optical systems, the smaller the resolution the smaller the depth of focus, which is a source of concern with a moving bouncing web. Thus the final decision for a wide field sensor must be made along with how the final mechanical registration is to be achieved.

For the laser scribing system, a solution has been found with a transmission fiber optic system using proprietary improvements. Previously, the resolution was 0.025 mm, but suffered from fiber optic light scattering caused by ZnO crystallite diffraction in the region of the registration mark. This resulted in a final registration reproducible only to 0.15 mm with the standard fiber optic system. Several improvements to the fiber optic system were evaluated. Figure 8 shows a graph showing a comparison of the position resolution of the final improved system with the original system. This graph indicates that a registration of 0.02 mm should be possible with a 0.5 fiber light intensity resolution. This new system achieves routine registration 0.05 mm. This larger value is not caused by the intensity resolution. Investigation has shown that the registration marks are not parallel lines. As can be seen in the micrograph shown in Figure 9, there is an oscillation present that can be as large as 0.040 mm. It is believed that this oscillation limits our current registration reproducibility to the 0.05 mm value. The oscillation is caused by mechanical resonance with x-y stage and has been greatly reduced by mechanical damping to a massive wall structure. Improvements in limiting damping in future scriber systems will involve: 1) using high precision x-y tables, 2) massive support structures, and 3) coupling the support structures to a massive wall for additional damping.

The time required for the scriber to register is about 2 seconds. This time should be compared with the 200 seconds of scribing motion. Thus, registration time is only 1% of the time required



prepared by M.Noack

Figure 8. Comparison of standard and improved fiber optic detectors.

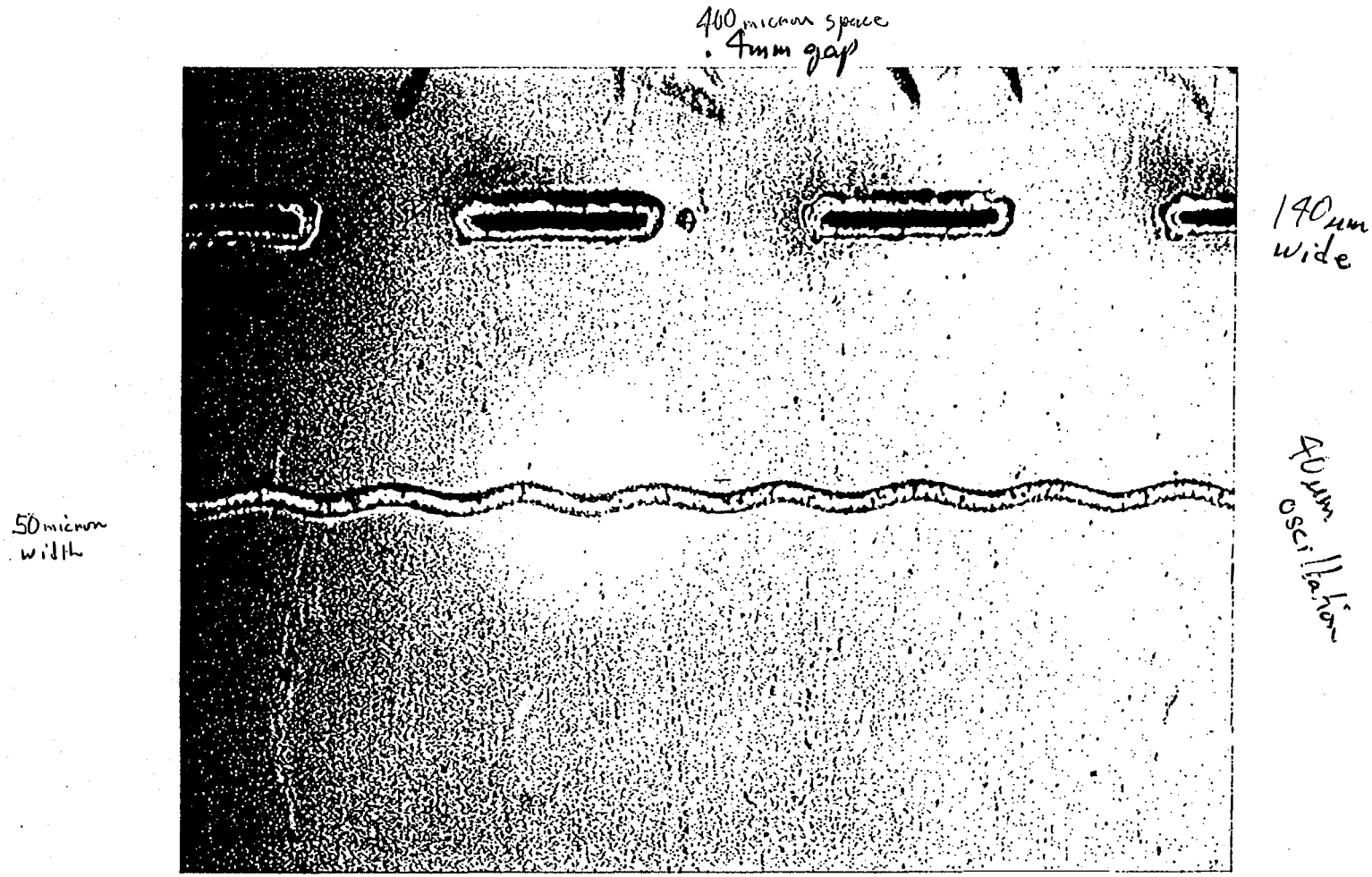


Figure Micrograph of laser scribe lines showing oscillation.

for processing a module. Further improvement to reduce the registration time will not result in significant cost savings. The scribing motion time can be reduced by increasing the number of scribing beams and beam speed.

For the printer system, registration reproducibility is limited by non-uniform advancement of the web, or "hopping." To reduce "web-hop" and achieve better registration modification of the mechanical system will be required. Nevertheless, the improved fiber-optic system was incorporated with the printer system resulting in marked improvement in registration (+/- 0.05 mm). With the completion of the x-y mechanical screen registration mentioned above, an alignment of +/- 0.02 mm (1mil) is achievable.

Table 2 below shows a list of sources for alignment errors for the scriber and printer for original (pre-contract), current, and expected (post-contract) alignment accuracies. Expected decreases in scribed line variations will reduce to better x-y stages and more massive mountings. Current and

Table 2. Sources of alignment errors for the scriber and printer for original, current, and accuracies.

Sources of Alignment Errors

Scriber

	Web Hop	Head Location	Line Wobble	Line Bow	Line Spread
Original	+/- 0.1 mm	+/- 0.01 mm	+/- 0.02 mm	+/- .025 mm	+/- 0.05 mm
Current	-	+/- 0.01 mm	+/- 0.02 mm	+/- .025 mm	+/- 0.05 mm
Expected	-	+/- 0.01 mm	+/- 0.01 mm	+/- .01 mm	+/- 0.01 mm

Printer

	Web Hop	Screen Stretch	Screen Location
Original	+/- 0.1 mm	+/- 0.05 mm	-
Current	+/ - 0.05mm	+/- 0.05 mm	-
Expected	-	+/- 0.02 mm	+/- 0.01 mm

expected decreases in printer web hop are due to platen vacuum modifications. The preceding discussion on approaches to improve web alignment accuracy and speed is summarized on the next page, in Table 3. The improvements are operational on the scriber and in development on the printer.

These alignment methods register to a laser scribed "tic" mark at the head of a submodule area. Adjustments in printing are presently done through manual inspection of printed registration using CCD cameras. Final adjustment of the print screen is done to align through scribe lines (other than the scribed "tic" marks) to the printed registration marks. This process is followed for both the insulator and silver ink prints. Variations in screen pattern, such as those caused by screen stretching, is visually integrated for the best fit to the overall area of the submodule. These adjustments are slight, on the order of 0.05 mm. An automated CCD camera pattern recognition system could inspect printed submodule frame areas as they emerge from the printer and make automatic "best fit" adjustments to the screen frame position. This is the next level of registration complexity and expense.

Additional improvements in printer process throughput can be obtained by reducing the percentage area loss due to the cell interconnect area and silver ink current collecting finger area. The base (pre-contract), current, and goal (post-contract) percent area loss due to interconnect and finger grids is summarized in Table 4. Throughput is improved by reducing this "dead" area because the power per unit aperture area increases for constant web linear throughput speed in the printer. Further discussion of the reduction of the amount (and cost) of Ag ink will be found in the "Task 3" section below.

2.3 Task 3: Substrate and Materials Cost Reduction

Phase I Task 3 efforts were aimed at substrate and materials cost reduction. New water based insulating ink would be selected for the patterning process to replace the current organic solvent based insulator ink and to reduce solvent emissions. The critical evaluation of candidates for this ink would include the right absorption properties, the right vaporization characteristics, low outgassing, and the ability to provide an adequate laser beam stop for the TCO cut with a single print. ITF would select candidate inks with low outgassing from various databases. Candidate inks would be printed on silicon coated web, baked, and then have ZnO deposited on them for evaluation. ITF would then determine the suitability of ink outgassing properties by comparing electrical conductivity of the ZnO near an ink line with ZnO conductivity some distance away from the printed region. ITF would also evaluate the adequacy of candidate inks as a beam stop both optically (through microscope evaluation of the scribing trench) and electrically (through testing for isolation).

This task was expected to result in the development of an insulating ink for incorporation into the ITF production line and reduce environmental concerns regarding solvents.

Table 3. Approaches to improve web alignment and speed.

ORIGINAL PLAN

- Advance web to alignment position
- Web motion stopped when led detector triggered
- Slow process. Response time limits accuracy

⇓

FIRST ALTERNATIVE APPROACH

- Advance web to alignment position
- Wide field detector watches approach, slows web near end
- Faster and more accurate process
- Still limited by web "hop"

⇓

IMPROVED ALTERNATIVE

- Advance web to approximate position and lock down
- Processing head is aligned to final web position using led detectors
- Excellent processing speed , excellent accuracy
- Operational on scriber
- In development on printer

Table 4. Percent area loss due to interconnect and finger grid areas.

Percentage Area Loss

Base

Insulator Ink Width: .6mm Weld Line Width: .8mm
Finger Width: .7mm Alignment Tolerance: .15mm

	Finger	Interconnect	Total
2 cm	7%	10%	17%
4 cm	7%	5%	12%

Current

Insulator Ink Width: .6mm Weld Line Width: .6mm
Finger Width: .5mm Alignment Tolerance: .15mm

	Finger	Interconnect	Total
2 cm	5%	9%	14%
4 cm	5%	4.5%	9.5%

Goal

Insulator Ink Width: .3mm Weld Line Width: .4mm
Finger Width: .4mm Alignment Tolerance: .075mm

	Finger	Interconnect	Total
2 cm	4%	5%	9%
4 cm	4%	2.5%	6.5%

The following activities and accomplishments resulted from work done to date on Task 3:

In order to accomplish a subgoal of this task- to minimize environmental impact by reducing or eliminating solvents in the printing process- the use of UV curable or water-based/water soluble inks was examined. A thorough search for suitable UV-curable inks, involving contact with a large number of vendors, revealed that 1) there are presently no conducting Ag based UV-curable inks available, and that 2) none exist that have good adhesion to glassy surfaces like that of a-Si or plastic surfaces. The search for suitable products continues in hopes that new UV-curable products will appear on the market.

In regards to water-based/ water-soluble inks, after intense searching, it appears that no such conducting Ag ink exists. In regards to insulator inks, a water-based/water soluble ink was sought to replace the current organic solvent-based epoxy insulator ink to reduce solvent emissions. Basic properties for an insulator ink to be used in the ITFT process were good bonding to a glass-like Si surface and the ability to withstand a temperature of 178 C during ZnO deposition. End use of the ZnO deposition coverage, electrical conductivity, and laser beam stopping ability were to be determined after the candidate insulator inks were determined to possess basic bonding/temperature properties.

After a great deal of searching, no water-based ink was found to meet all basic requirements but one solvent containing ink was found which met the requirements and was water-soluble. This water-soluble ink eliminates the use of solvents for clean-up. Also, because this ink is not catalytically cured, the unused portions can be collected from the screen and reused eliminating additional waste. Preliminary results with this water soluble ink indicates that there is no problem with ZnO deposition coverage over the ink.

ITFT will continue to search for suitable water-based/water-soluble inks as new products appear on the market. We have established good communication with a number of screen printing supply vendors who are on the lookout for appropriate new products.

In an effort to reduce waste and minimize environmental impact, ITFT is investigating less expensive, reusable inks to compare against the currently used standard non-reusable 2-part epoxy insulator ink.. One such solvent-based ink is a slower drying but suitable 1-part epoxy. Its ZnO deposition and beam stopping qualities have been demonstrated. By using newly designed forced air heated drying ovens, drying time will hopefully be reduced. The reduction in waste ink and waste ink containers will be significant with this 1-part epoxy ink.

In regards to Ag ink development, the ITFT baseline Ag ink was not able to be printed in 0.3 mm lines. A major problem is that most Ag inks are designed to make ohmic contact to ITO or metal films. No Ag ink "as is" that ITFT has evaluated, has been found to make good contact with ZnO TCO's. Hence, we have modified standard inks with proprietary additives and evaluated a range of alternative compositions. Our foremost goal is to provide low contact and line (bulk) resistance, hopefully down to a 0.3 mm line width. A series of coupons consisting of web coated with a-Si/ZnO, were printed with various test ink compositions. Test results are shown in Table 5 on the following page. A second Ag ink product from a second ink vendor, the "alternative vendor " ink, consists of ink mixed with the same additives as the baseline ink but has the

Table 5. Ag inks test results

Ink	Contact Res. Initial	Contact Res. 2 wks @ 125C	Line Resistance
Baseline ink	1.65	8.59	4.0
Alternative Vendor	2.15	5.43	3.8
New ink #1	0.74	2,13	2.0
New ink #2	2.29	0.67	2.2
New ink #2.2	4.59	0.41	1.9

advantage of a 40% reduction in cost for the base Ag ink. New ink, #1, uses the same , earlier, Ag ink vendor's ink product as the baseline but has different additives that survive long term baking at 125 C. New inks #2 and #2.2 use the second Ag vendor ink product with the different additives as in new ink #1. New ink #2 and variation #2.2 are the best candidates for both improved performance and reduced cost.

2.4 Task 4: Development of a Roll Based Laminating Process

Phase I Task 4 efforts were aimed at evaluation of the potential of existing roll-based laminating technologies and equipment taking into account versatility and capacity. A prime candidate for laminating material and technology would be selected. Pressure sensitive adhesives (PSA) would be evaluated taking into account the potential active species within the PSA that might lead to corrosion. Thermal adhesives would be evaluated taking into account the limited film-compression time in a roll based lamination process. This task was expected to lead to the development of a roll based laminating process for the ITF production line and a significant reduction in module assembly costs.

The following activities and accomplishments resulted from work done to date on Task 4:

2.4.1 Improvements in module assembly process

The following steps were taken with the objective of reducing module assembly costs and resultant overall module encapsulation cost reduction without sacrificing performance/value . The original process (and lamination industry standard) involved: 1) cutting each one of the component pieces (including submodule, busbar, strain relief, encapsulant, and cover tape); 2) assembling the pieces; 3) vacuum laminating assembly; 4) trimming; and 5) attaching a wire connection. The new system consists of 1) cutting the sub module and busbar attachment; 2) roll laminating the assembly; 3) die cutting out the module; and 4) attaching a junction box.

The first part of this task involved a search for a manufacturer that produced a suitable roll laminator which could be incorporated into the present production line for ITF's module encapsulation. Several candidate roll lamination techniques were identified. The two most suitable for ITF lamination needs were a roll laminator, as shown in Figure 10, that used heated rollers to heat the material just before it was pressed together and a roll laminator that used shoe type preheaters to preheat the material before it was laminated as shown in Figure 11. Each system had benefits and drawbacks. The heated roll laminator (Figure 10) provided contact heating as long as the material was in contact with the nip roller so preheat time could be adjusted by determining how much of the circumference of the nip roller the material covered. Drawbacks to this system included web tracking problems and applying heat to a rolling nip mandrel. The shoe type preheater system (Figure 11) eliminates the web tracking problem and the difficulty of applying heat to a rotating member. The one drawback to the shoe preheat roll laminator is that the plastic laminate is dragged across the preheaters under tension causing scratch marks on candidate plastic laminates including Dupont's Tefzel®.

A number of manufacturers make base machines that could accomplish roll lamination. However, in the industrial roll laminator or converters industry, most of the roll laminator nip rollers will only adjust to a .020" minimum distance between the rollers, for two heated Teflon nip rollers which makes it impossible to laminate a .005" module. Two paper lamination industry (i.e. ID's, sheet paper, etc.) laminator manufacturers make the second shoe type preheater roll laminator where the laminate is dragged around the heated shoe then nip rolled together. The nip rollers are constructed with a rubber surface and can be set to give a negative nip roller distance (so the rollers are pressed against each other). This type of laminator is useful for laminating both thin and thick laminates. Most of the laminate testing was done using a shoe preheater type roll laminator.

2.4.2 Selection of a prime candidate material for roll lamination

The initial designs showed a down web lamination process putting down the bus bar and conductive adhesive simultaneously (refer to Figures 10 and 11). This system will not work for laminating modules in Tefzel® with the adhesive EVA (ethylene vinyl acetate) from Springborne Laboratories or Richmond Technology due to the adhesive's cure time. These adhesives require both pressure and heat for approximately 5 mins to reach an acceptable gel content, approximately 85%. This gel content is what is considered for "curing." Curing is impossible to accomplish in a nip roller where the contact time negligible. However Tefzel®/EVA encapsulation can be nip rolled to set the EVA adhesive and eliminate air pockets/bubbles. The remaining obstacle is curing the EVA.

Three methods were tested to cure the EVA after it had been roll sealed. The first involved compressing sealed modules and baking them in a oven following these steps: 1) modules were assembled with bus bars on the sides; 2) the completed module and bus bar were sealed with Tefzel®/EVA in the heated roll laminator and cut to length; 3) the final step was compiling a large number of modules, pressing them, and placing the entire stacked array in a large oven for final curing. Curing time varied with the size of the array and the number of stacked modules.

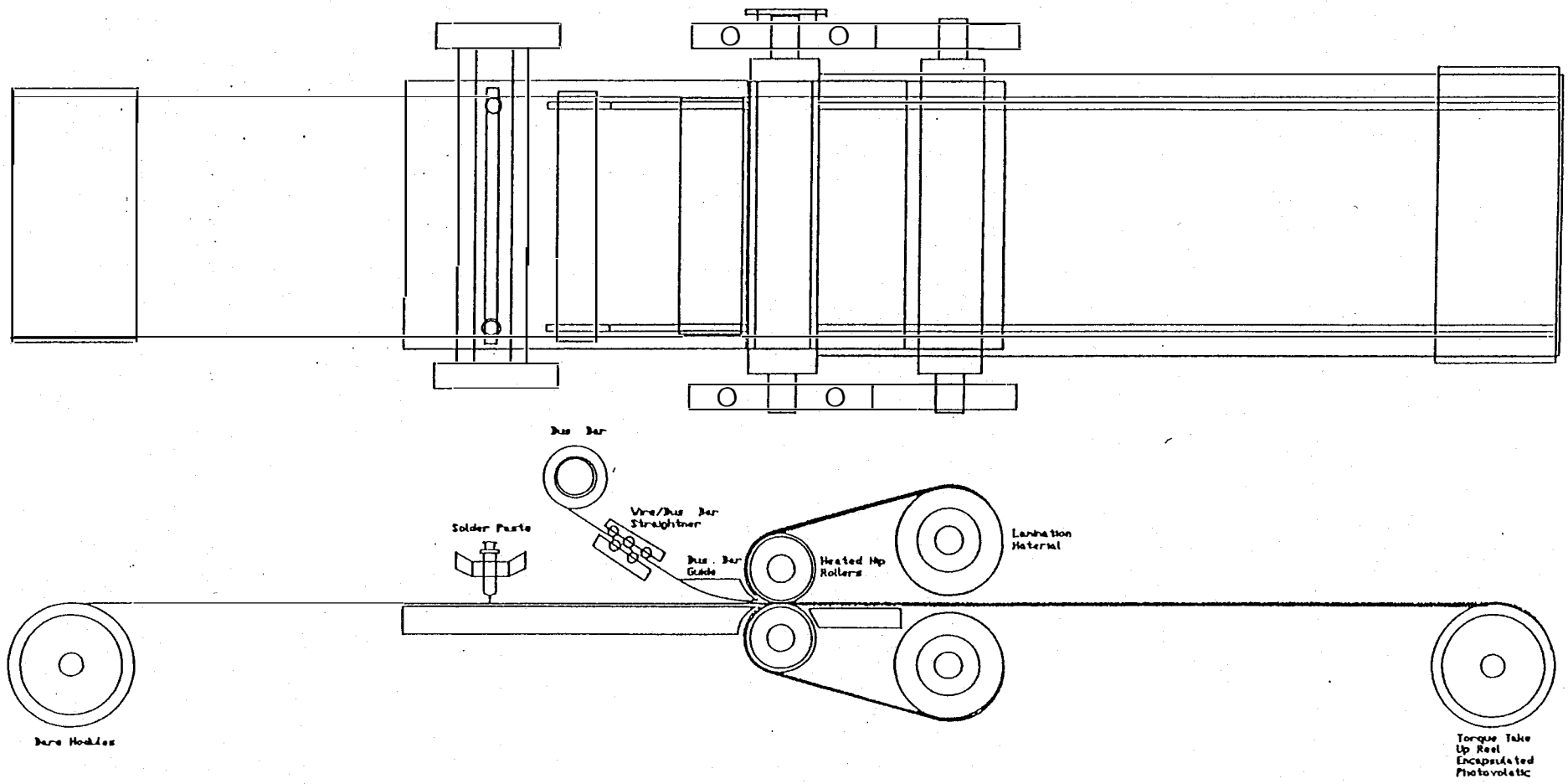


Figure 10. Roll laminator that uses heated rollers.

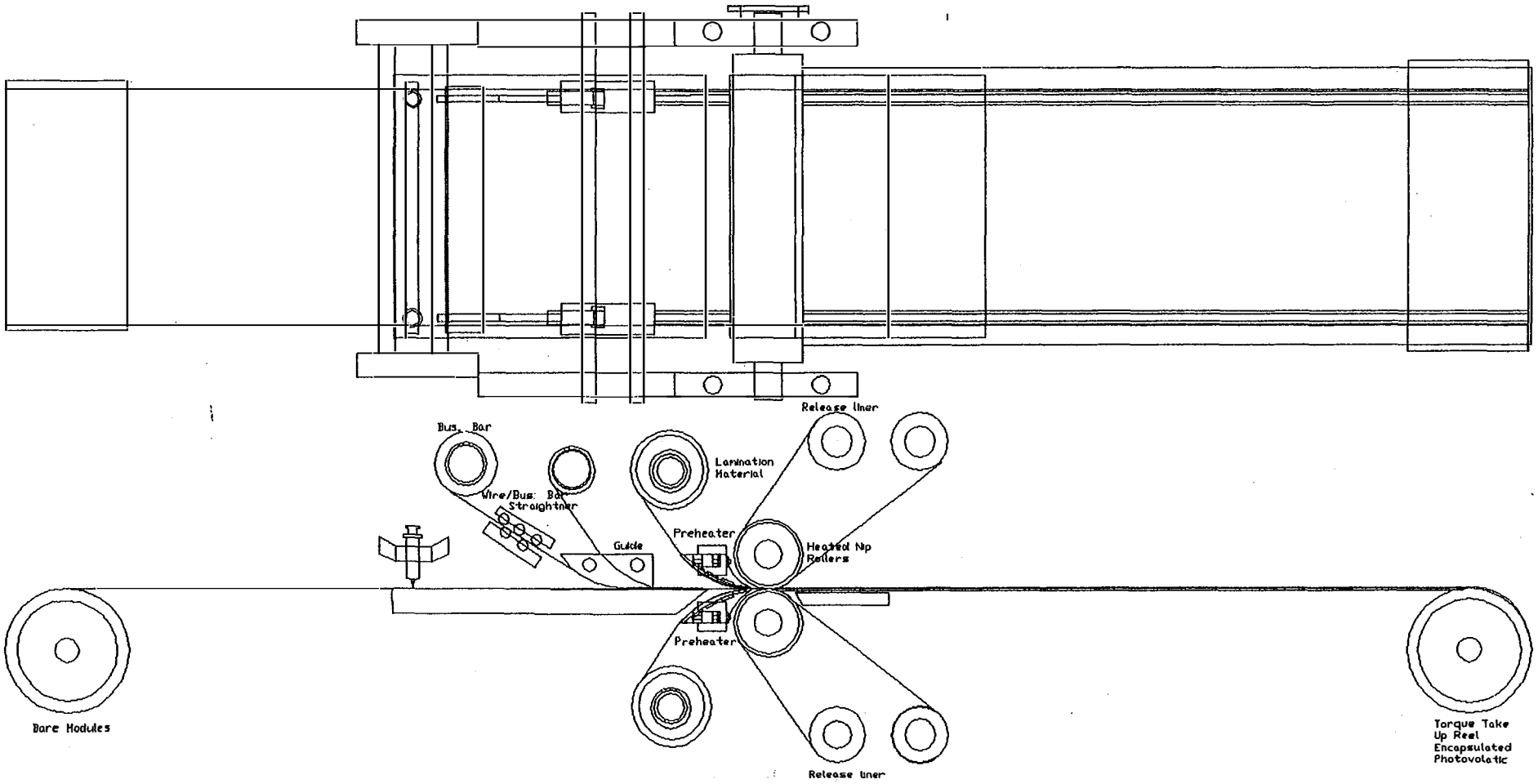


Figure 11. Roll laminator that uses shoe type preheaters.

The second system used a base plate, frame, and bladder to make up the lamination platen. This system is very similar to that of a production laminator with the main difference being that there is no internal heating and there is an open top. These steps were followed: 1) a module was assembled; 2) it was placed under the bladder and pumped down; 3) then the entire assembly was placed into an oven and baked until the time/temperature formula was satisfied curing the EVA. Lastly, 4) the assembly was removed from the oven and cooled under vacuum to room temperature.

The third system used the same module assembly as the second but, instead of a frame and bladder, a backing sheet of aluminum and a high temperature vacuum bag were used. The following steps were followed: 1) the module was assembled on a sheet of aluminum; 2) then the entire module/sheet is slipped into a large vacuum bag and pumped down; 3) then put into an oven until the EVA was cured. Finally the modules were allowed to cool under vacuum.

Each system was rated based on appearance, clarity, and flatness as is described in Table 6 below. As can be seen in this table, the roll laminated module (#1) lost some clarity because of scratches

Table 6. Comparison of three methods tested to cure EVA.

Procedure	Appearance	Clarity	Flatness	Bubble Formation
#1 Roll laminated and pressed				
Single	excellent	very clear	flat	no bubbles
Multiple	good	OK	flat	no bubbles
#2 Vacuum laminated				
frame and bladder	excellent	very clear	lumpy	no bubbles
#3 Vacuum laminated				
vacuum bag	excellent	very clear	flat	no bubbles

that were generated during the roll laminating process. However the single roll laminated module still looked better than the multiple layer group. Small wrinkles formed on the back of the multiple layer group. These wrinkles may have been caused by uneven roll lamination as the EVA had a tendency to get pressed down to the web by the rollers. To correct for this it may be necessary to set a minimum pinch distance to accommodate for the thicker EVA.

The vacuum lamination technique (#2) results were very clear in appearance but were also very uneven indicating uneven pressure in the laminator. This was resolved by building a laminator

with an offset base to accommodate for bladder stretch during pump down. This test laminator was flat on the bottom leaving no room for the bladder to go anywhere. The laminator that had a

recessed base laminated the modules very even and flat, resolving the problem with the initial test laminator.

The vacuum bag (#3 in Table 6) provided the best test results. The modules were very clear and very flat. However, finding commercially available vacuum bags large enough to build large modules will be key to adopting this process. The test lamination bags were disposable and fairly small. This last system is the system of choice as it provided the best results with the lowest run time and least cost. In addition, multiple laminations may be possible in vacuum bags but further experimentation will be required to verify.

The process of roll laminating other materials like pressure sensitive adhesives and thermal set adhesives is as follows: (1) place conductive metal foil tapes down on the modules' bus areas; (2) laminate the material in a roll laminator with a shoe type preheat system; and (3) cut out and test the finished modules.

The testing and evaluation of alternative materials for roll lamination involved two adhesive types: thermal set adhesives (TSA) and pressure sensitive adhesives (PSA). Some of the candidate adhesives that were evaluated were: thin Ethylene Vinyl Acetate (EVA/TSA); Ultra High Adhesion rubber (UHA/PSA); Silicone (PSA); Acrylic (PSA); and Polyethylene (TSA).

The two TSA's Polyethylene and thin EVA (1.5 mil) were roll laminated on a thermal laminator with shoe type preheats (Fig. 11). Both adhesives were used with a polyester film, the EVA was with 1.0 mil Poly, and the Polyethylene was used with UV stable polyester 1.0 mil and 2.0 mil. These laminates are commercially available and did not require that the adhesive be laminated to the film. Both of these adhesives work excellently in the laminator and in the resultant solar modules in terms of clarity, uniformity, ease of lamination, adhesion, and overall appearance (wrinkle/bubbles). Samples were tested in the thermal cycler and 80°C oven. Modules were also optically checked with a Lambda 9 wavelength/intensity system, and pretested laminated and retested. Again both materials performed excellently.

To find a suitable pressure sensitive adhesive, ten different samples were selected for testing. The testing criteria included clarity, adhesion, appearance, and opposition to bubble formation. All of the ultra high adhesion (UHA) rubber samples failed all testing criteria The UHA rubbers were yellow in appearance and clarity and while adhesion was excellent during lamination, after one month of temperature cycling the adhesive separated from the module and the film laminate. Bubble formation in the UHA rubber adhesive appeared as the roll started out at the beginning of the process and after lamination the bubbles were still prevalent Thus, the UHA rubber adhesives failed all testing criteria. The second adhesive type that was tested was the acrylic based PSA's. Testing produced varied results as shown in Table 7 on the following page. There were two test variations for each laminate. Those listed under the first variation, "CYCLER," were temperature cycled for 4 weeks with a swing from -40°C to 80°C. The frequency for a complete cycle was 2 hours 30 minutes with 1 hour at -40°C followed by 10 minutes of ramp up to 80°C then 1 hour at 80°C followed by an additional 20 minutes of cool down to -40°C and repeat. This frequency provided 9.6 cycles/day, 67.2 cycles/week, and approximately 268.8 cycles/month. The second testing variation was an 80°C oven. This test is used for an extreme heat test which seems

Table 7. Acrylic PSA's: test results shown by category

ACRYLIC PSA's

Testing conditions	Adhesive trade name	Clarity	Appearance	Adhesion	Wrinkle/Bubble	Sample#
Cycler trimmed	MWC #190	Clear	OK	FAIL	separated	1
Cycler 1/4" border	MWC #190	Clear	Good	EX	wrinkled	2
80°C trimmed	MWC #190	Clear	OK	FAIL	separated	3
80°C 1/4" border	MWC #190	Clear	Good	EX	wrinkled	4
Cycler trimmed	Avery 1115	Clear	Good	OK	few bubbles	5
Cycler 1/4" border	Avery 1115	Clear	Good	EX	wrinkled	6
80°C trimmed	Avery 1115	Clear	Good	OK	few bubbles	7
80°C 1/4" border	Avery 1115	Clear	Good	EX	wrinkled	8
Cycler trimmed	Sun Poly 23	Clear	EX	Good	Same as C.G.	9
Cycler 1/4" border	Sun Poly 23	Clear	EX	Good	Same as C.G.	10
80°C trimmed	Sun Poly 23	Clear	EX	Good	Same as C.G.	11
80°C 1/4" border	Sun Poly 23	Clear	EX	Good	Same as C.G.	12
Cycler trimmed	3M F9752PC	Clear	Good	EX	none	13
Cycler 1/4" border	3M F9752PC	VClear	Good	EX	wrinkled	14
80°C trimmed	3M F9752PC	Clear	EX	EX	none	15
80°C 1/4" border	3M F9752PC	Clear	Good	EX	wrinkled	16
Cycler trimmed	3M F9755PC	Clear	Good	Good	Separated ends	17
Cycler 1/4" boarder	3M F9755PC	Clear	Good	EX	wrinkled	18
80°C trimmed	3M F9755PC	Clear	EX	Good	Separated ends	19
80°C 1/4" border	3M F9755PC	Clear	Good	EX	wrinkled	20
Cycler trimmed	3M FC9469PC	Yellow	EX	Good	Separated ends	21
Cycler 1/4" border	3M FC9469PC	Yellow	Good	EX	wrinkled	22
80°C trimmed	3M FC9469PC	Yellow	EX	Good	Separated ends	23
80°C 1/4" border	3M FC9469PC	Yellow	Good	EX	wrinkled	24

to have the most profound effect on the adhesive/film interaction. This test has run for 6 weeks and is continuing to date.

Two different laminate styles were also tried. The first, "trimmed," meant the laminates were trimmed to the edges of the module. This allowed examination of the adhesion of the adhesive to the module without the edge/adhesive to adhesive interaction to possibly mask results The second laminate style , "1/4" border," allowed for a 1/4" edge seal around the module more closely representing an actual laminated module.

Test results shown above in Table 7 were given under each category. In order to pass to the next phase of testing, the adhesive's Clarity had to be "clear". Samples 21-24 failed. For the Appearance, results above a "good" rating passed. All modules passed this criterion. As for Adhesion, nothing but "excellent" would be accepted so samples 1,3,9-12,17, and 19 were eliminated. Under the next category, Wrinkle/Bubble, any module that had bubble formation during the testing phase was eliminated, thus samples 5 and 7 failed. As for wrinkles, it was determined that most of the wrinkle formation was due to the shrinkage of the Tefzel film and was

not associated with the adhesive. This was the reason that a "good" rating passed in the appearance category. This testing criterion left the 3M 2 mil acrylic and 5 mil acrylic adhesives, modules 17 and 19, listed as "separated ends" under Wrinkle/Bubble. These "separated ends" were the result of the copper bus bar peeling off the module. The 1/4" border modules (samples 18 and 20) did not exhibit "separated ends," therefore, the 3M 5 mil acrylic passed all testing criteria. The "good" rating in Adhesion for 17 and 19 was given because of the separated ends. This rating was waved for the reason stated above.

Two silicone adhesives, a 4 mil silicone and a 2 mil silicone, passed all criteria. A little wrinkle appeared on the 1/4" border modules in both the 4 mil and the 2 mil adhesives but this wrinkle was less than in all other samples. Because of the overall performance of the silicone adhesives compared with that of other adhesives, the 4 mil silicon PSA was chosen to be the best candidate for the next phase of testing. The 2 mil 3M acrylic and the 5 mil 3M acrylic will continue to the next phase of testing as will the 2 mil silicone . In addition, any other adhesive that are received and pass initial testing will continue to the next phase of testing.

The next phase of testing involves checking the performance of a module before and after lamination. Raw material is tested by running an I-V curve using a four point probe under light conditions of AM 1.0. Five samples were tested, laminated, and retested. These five samples were strip numbers 3,4,5,6, and 8. The performance change overall was an increase from unencapsulated to encapsulated-- which seemed to mimic the Tefzel®/EVA performance change. Fill factors increased 2-3 points and power point current increased form 2% to 10%.

The overall best performance PSA was the 4 mil silicone, but pricing makes the acrylic very attractive. However the thin EVA's and Polyethylenes are far better than the best PSAs in terms of ease of assembly, and performance. Life expectancy of all the laminates tested showed that the Tefzel® film with 18 mil EVA still out performed all other materials in terms of optical clarity, UV resistance, and durability making this the best long term outdoor encapsulant. The UV stable polyesters with polyethylene TSAs appear the second best but further testing will be required as it could result that they might be a 5-10 year laminate with very low cost.

3.0 CONCLUSIONS AND FUTURE WORK

Work done during Phase I, year 1, aimed at achieving the overall program goal of developing the most cost effective PV manufacturing process possible, resulted in the following achievements and bases for efforts during Phase II, year 2.:

- The capability of sputtering a high quality Zn(Al)O was developed. Efforts will continue to improve the process quality.

- Increased deposition rates for the ZnO top contact deposition were successfully implemented. Preliminary work was done on implementing single pass operation of this system. A throughput increase of 50% has been achieved.

- Improvement in registration and ink line width were achieved.

- A new alignment process and sensor were developed to improve the speed and accuracy of registration for the patterning processes. This technique proved highly successful and has been fully implemented on the scriber. The sensors were installed on the printer and implementation of the new process will be accomplished shortly.

- A new silver ink composition has been developed which allows finer print lines and lower series resistance.

- An overall improvement in area utilization of 8% has been demonstrated to date. In addition, throughput improvements of 30% on the scriber and 70% on the printer have been realized.

- A candidate water based insulator inks has been found and tested which shows promise for use in the ITF process.

- Use of roll based lamination has been researched and tested and shows promise as a means to reduce the cost of assembly.

- Use of the standard EVA/Tefzel encapsulant with a roll laminator was evaluated. This process requires a post bake following rolling. The best method for this post bake will continue to be investigated in year 2.

- Straight roll lamination capability was developed using pressure sensitive adhesives and thermally activated bonding which works well with a range of candidate materials. This approach yields at least a 4-fold increase in throughput. Laminated assemblies will be life tested to determine long range stability.

Phase II, the second year of this three year effort, begins on July 5, 1996 and will run through June 4, 1997. During the next year Iowa Thin Film Technologies, Inc. will continue efforts at implementing the back reflector; optimize performance and deposition rates in the new tandem machine; develop single pass capability in the TCO and metalization systems; implement the new alignment process on the printer; and develop an automated cutting and bus bar attachment system to go with the roll laminator. During this second phase, ITF will continue with efforts begun in Phase I and will focus on task efforts designed to:

- increase the throughput of the metalization, a-Si deposition, laser scribing and printer processes;

- design and implement baffles for the isolation of metal deposition regions;

- investigate the limits of the ZnO deposition rate;

- develop new machine control programs;

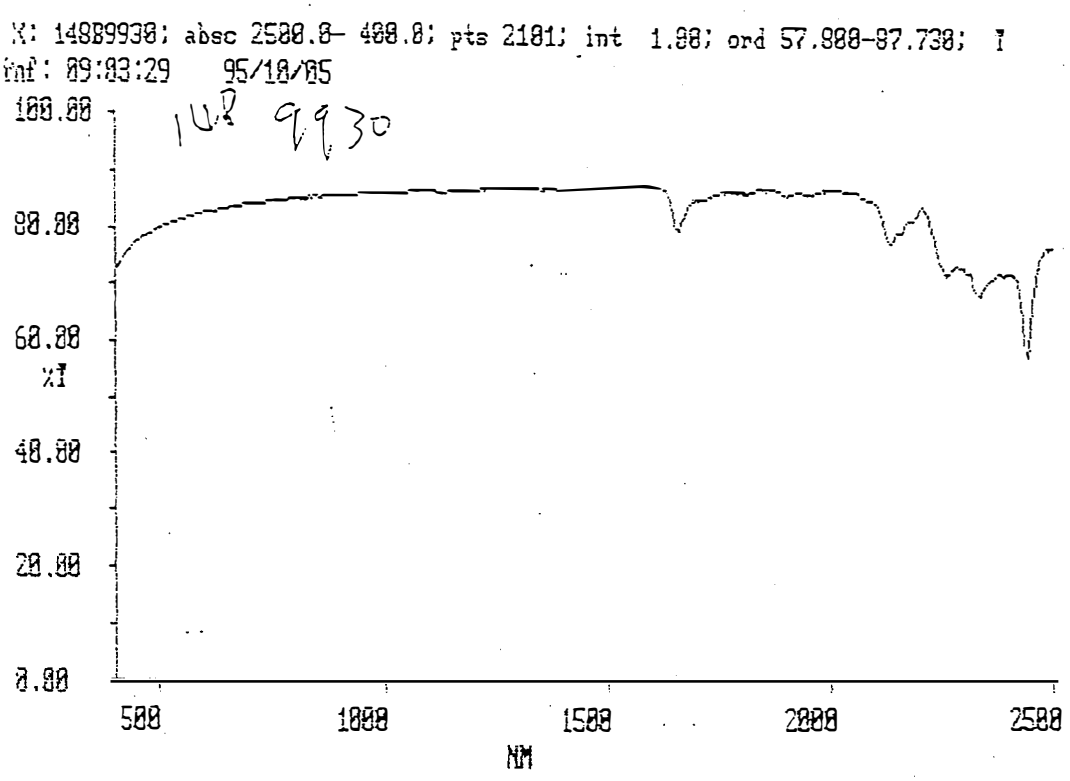
- identify new laser operating parameters to optimize the laser beam scan speed;

- integrate a new water based insulating ink into the patterning process; and

- automate the final process steps of bus bar attachment and web cutting.

Successful accomplishment of Phase II efforts will lead to continued effort under the Phase III, year 3 portion of this subcontract with the goal of increasing the throughput of the metalization, a-Si deposition, laser-scribing and welding processes; and reduce the overall module manufacturing costs on the ITF production line by 68%.

Appendix A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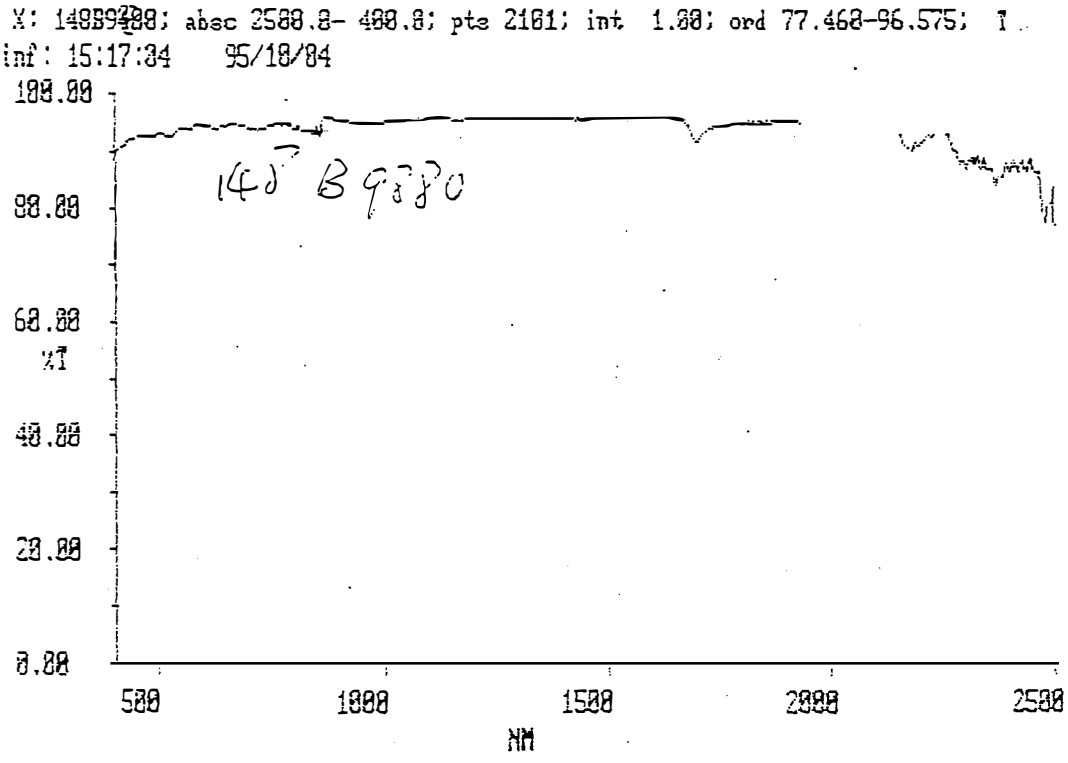
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13. ABSTRACT *(Maximum 200 words)*

Iowa Thin Film Technologies' goal is to develop the most cost-effective photovoltaic manufacturing process possible. During the first year, they developed the capability of sputtering a high-quality Zn(Al)O; successfully implemented increased deposition rates for the ZnO top contact deposition; improved registration and ink-line width to reduce area loss due to interconnects; developed a new alignment process and sensor to improve the speed and accuracy of registration for the patterning processes; developed a new Silver ink composition that allows finer print lines and lower series resistance; demonstrated an 8% overall improvement in area utilization; evaluated water-based insulator inks for compatibility with their processes; investigated and tested the use of roll-based lamination as a means to reduce the cost of assembly; developed straight roll lamination capability using pressure-sensitive adhesives and thermally activated bonding; and evaluated the use of the standard EVA/Tefzel encapsulant with a roll laminator.

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