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PROCESS DEVELOPMENT FOR AUTOMATED SOLAR CELL AND MODULE
PRODUCTION

Task 4: Automated Array Assembly
Quarterly Report No. 1

By
C. R. Witham

April 18, 1978

Work Performed Under Contract No. NAS-7-100-954882

MBAssociates
San Ramon, California

MASTL

U.S. Department of Energy

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PROCESS DEVELOPMENT FOR AUTOMATED SOLAR CELL AND MODULE PRODUCTION

TASK 4: AUTOMATED ARRAY ASSEMBLY

Quarterly Report No. 1

JPL Contract No. 954882

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REPORT DATE: APRIL 18, 1978

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ABSTRACT

The objective of this program is to determine the state-of-the-art and to develop some of the technology required to allow for large volume and low cost terrestrial solar panel production. The baseline production facility being studied would provide for production of 200 megawatts of solar panels per year from an input commodity as sawn Czochralski wafers.

Initial analysis of available automation equipment applicable to the 1986 goals shows that most of the equipment will have to be of special design. The currently available equipment is designed for the semiconductor industry where process volumes are low. Maximum speeds are of the range of 100 to 200 wafers per hour. Using special equipment it appears feasible to produce the solar cells with 6 to 8 parallel production lines operating three shifts per day, seven days per week and to produce the encapsulated modules with 1 to 3 parallel production lines. Preliminary costs analyses show promise for reaching the 1986 price goals assuming a SAMICS wafer price of \$.28/wafer (1986 dollars).

Initial work has been done to study the applicability of a plasma process to perform back etch of the cells. This area shows promise for eliminating wet chemical etching procedures with attendant rinse and dry equipment and time required.

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1.0 INTRODUCTION

The scope of work under this contract involves specifying a process sequence which can be used in conjunction with automated equipment for the mass production of solar cell modules for terrestrial use. This process sequence is then critically analyzed from a technical and economic standpoint to determine the technological readiness of each process step for implementation. The process steps are ranked according to the degree of development effort required and according to their significance to the overall process. Those steps requiring the most development are to be worked with to demonstrate their feasibility to be used in such an automated process. Under this contract the steps receiving verification effort are: cell back etch, back contact metalization, automated cell array layup/interconnect, and panel edge sealing.

Work to date has involved specifying a baseline process sequence, describing each process step, and performing preliminary economic analysis on the sequence. Some initial work has also been done to assess the automation constraints associated with the production sequence. Some work has also been performed to reduce material costs for panel edge sealing, and to determine techniques for automated sealing material application.

2.0 TECHNICAL DISCUSSION

2.1 Process Sequence

A process sequence has been proposed with an input of four-inch Czochralski wafers (as sawn) and an output of encapsulated solar arrays. The proposed sequence is shown in Figure 2.1-1. This sequence has been analyzed for the feasibility of fully automated production techniques capable of producing 200 megawatts per year. (SAMICS baseline company size.) A target volume throughput per production line has been set by MBA at 3,000-3,600 cells per hour for the cell manufacturing lines, and 150-190 panels per hour for the module manufacturing line. This indicates a plant working three shifts per day, seven days per week, with 6 to 8 parallel cell lines and 1 to 3 parallel module lines.

There is a trade-off in any production line of this nature between batch and continuous process. For some processes where individual processing time is large in comparison to the desired production rates, wafers or materials must be handled in a parallel or batch mode. When processing times are shorter, continuous processes can be used. For the proposed cell fabrication sequence an automated batch process is shown in Figure 2.1-1 to the point in fabrication prior to contact printing. This batch mode is chosen because of the nature of the proven process steps currently being used by the cell manufacturing industry. Contact printing to final panel test and shipment is proposed to be a continuous process because of the nature of the steps involved.

In the proposed process it will be assumed that the wafers are purchased in such quantities that the containers they are received in are factory-specified and factory- or vendor-supplied. This will aid in simple materials input and handling at the start of the line.

Most of the cell making processes have had significant background work performed in the area of manufacturing equipment. Some of this comes from a technology transfer from the semiconductor industry. Much of the designed equipment, however, requires scaling

FIGURE 2.1-1
PROPOSED AUTOMATED SOLAR CELL FABRICATION PROCESS

and/or modification to reach program goals. Materials handling between processes in cell making requires work as well. It has been found that not much work has been done in the area of cell interconnect and panel layup. There is no transfer of technology in this area from the semiconductor industry, and deficiencies have been seen in currently available panels. This indicates that some effort should be directed at working with automation of cell interconnect and material handling.

2.2 Process Step Descriptions

The process sequence will be taken one step at a time with a description given and problems discussed.

2.2.1 Incoming Inspection

This step is used to standardize and control wafers which may be received from several vendors. Measurements will be made of the diameter and resistivity of the incoming wafers using non-contacting techniques. Wafer thickness and diffusion length will also be measured on a sample basis. Each lot of cells will be characterized by prediction of expected efficiency based on variations in thickness, area, resistivity and diffusion length of the input material. Information from this step will be input into a central processor to keep track of the data and enable simplified process control.

Operation of this station would be as follows: Prior to measurement, a machine should be adapted to unpackage the wafers and send them via conveyor to the inspection point. Assuming that the wafers are contained in a special cassette (possibly 50 to 100 wafers, closely spaced) a handling machine would feed the wafers to each in-line measuring location. At each location a currently available measuring sensor will be brought to the wafer. This sensor is merely a modular part of a slower currently available system with a modification to enable it to access the wafers at a higher speed. Since there is more than one test required, some could be done simultaneously or some could be done serially. The wafer will probably be in the machine for longer than one second, but if the indexing cycle for serial events is one second, a production rate of one per second can be achieved.

2.2.2 Etch and Clean

The silicon used is as sawn Czochralski wafers. This step will etch the saw damaged surfaces from the wafer as well as texture etch the wafers to make them less reflective. This process will be performed in a batch mode due to the time required in the etch solutions. The batch will be transferred between etchant and cleaning baths using automated materials handling equipment. This process will therefore require little or no direct labor. This step will perform the following functions:

- Receive cassettes from receiving inspection
- Load and immerse the cassettes in the etching solution for the proper time
- Move the cassettes for rinsing and cleaning
- Dry the wafers
- Transport the cassettes to drying.

Preliminary analysis indicates that the batches can be made large enough to reach a target of 3,600 cells per hour per line. Careful process control will be required to set process times relative to incoming inspection results. A cassette or boat-stacking machine will be required to assemble the cassettes coming from inspection into the proper batch configuration.

2.2.3 Drying

Current techniques for drying wafers coming from a wet chemistry step involve loading cassettes into centrifugal drying equipment and spin drying in a heated nitrogen atmosphere. The centrifugal drying equipment currently available off-the-shelf will handle volumes on the order of 1,200 wafers/hour. These dryers are not designed for interface with automated handling equipment. Therefore modifications must be made to enable this equipment to handle larger batches, and be loaded automatically. An alternative solution may be to dry the batches of wafers with a blow dryer without a centrifugal spin. This could be performed with the cassettes moving on a conveyor.

This process step, therefore, receives the batches of cassettes from the etch and clean station and configures the batch to be either loaded for a centrifugal dry or a blow dry. The cassettes are then output to the diffusion step.

2.2.4 Diffusion

This step will diffuse batches of wafers to provide a uniform junction on one side of the wafer. The objective will be to minimize the amount of diffusant deposited on the back side of the wafers. The station will have to transfer wafers from plastic etch cassettes into quartz cassettes for back-to-back diffusion. The quartz boats will automatically be inserted into a diffusion furnace for POCl_3 diffusion and automatically withdrawn at the end of the cycle. The equipment for this chemical vapor deposition reaction is well-developed and very reliable. The systems which are currently available provide automated diffusion atmosphere control as well as automated quartz boat pulling into and out of the furnace tubes. Interface machinery will be required to load the full quartz cassettes onto the boat pulling mechanisms.

A furnace with multiple diffusion tubes will be required to meet the target of 3,600 cells per hour.

An alternative approach to junction formation may be to ion implant the wafers. It should be noted that this process requires relatively high cost equipment, and equipment to operate at the target volumes requires some development. The diffusion furnace was chosen for a baseline here because of its current availability and performance.

The diffused wafers must be removed from the quartz boats and their positions reversed, such that the diffused surfaces are facing each other. This is done to prepare the cassettes for back etching where the portions diffused on the back of the wafers must be removed without removing the junction on the front. The machine which performs this wafer reversal function can be designed to sample the wafers with a four-point probe inspection to provide quality control on the diffusion process parameters.

2.2.5 Back Etching

To remove the diffused portions of the backs of the wafers, several techniques are available. One currently being used is to liquid etch the back of the wafer. However, in a high throughput process sequence such as this, it is desirable to remove the time and materials requirements attendant with another wet chemistry step. It is believed that plasma etching can be successfully used to remove unwanted POCl_3 from the backs of diffused wafers. The equipment used should be operated in a batch mode, with the batches being automatically loaded into the plasma vacuum chamber.

The station would receive the back-to-back wafers in aluminum cassettes from the diffusion process, automatically load them into and remove them from the plasma etch system. The wafers would then be removed from their cassettes and sent in a continuous mode to the contact metalization processes. Inspections could be performed on a sample basis of the wafers coming from the etch system to insure proper etching of the desired surfaces.

Another technique which shows some promise is to eliminate a back etching process through proper back wafer surface preparation and metalization. This step would then consist of removing the edges of the wafer, possibly through mechanical means in a continuous mode.

2.2.6 Wafer Contacting

The most promising technique for wafer metalization at this time appears to be thick film printing. This can be performed at rates approaching the target using currently available screen printing equipment. The front contact is more critical than the back due to the reduced contact area. Therefore the back contact should be printed and dried first.

This process step receives wafers in a continuous mode on a conveyor and successively prints and dries a back contact. The wafers are then turned front to back with relatively simple handling

equipment, and a front contact is screen printed to each wafer successively. The two contacts can be fired simultaneously if they are both of the same material (silver) or they may require separate firing stages if the back contact is not of the same material.

2.2.7 Anti-Reflective Coating

This process step receives cells in a continuous mode from the contacting processes on a conveyor. There are several techniques which can be used to apply a controlled thickness of an anti-reflective material. Sputtering is currently being done at very large rates in the automotive industry. It appears that this technique would be a feasible technique to reach the target production of 3,600 cells/hour using tantalum or indium tin oxide.

Other techniques which can be used are a belt furnace CVD process or plasma reactions. Both of these techniques appear to be a feasible solution to AR coating deposition.

The output of this process step will be finished cells on a conveyor to be tested and sorted for module use.

2.2.8 Cell Test, Sort and Buffer Storage

This step is required for quality control and process monitoring. The station receives the finished cells with exposed ohmic contact pads, ready for lead bonding.

The station will isolate each cell and individually measure its performance. Based on performance the cell is sorted by class or rejected. Each class is separated, marked and loaded into a "class" cassette. The failure mode will be identified on rejected cells. This data is reported through the central process controller to provide parameter adjustments.

This process is simple to automate, using a probe and a microprocessor to control and record the data. No difficulty is expected to reach a 3,600 cell per hour rate.

The cells, after they are sorted into relative efficiency classes can be put into buffer storage. This allows enough cells of the same performance ratings to be accumulated so that they can be put into the same module. This is required to gain maximum efficiency from each module system. The buffer storage is inherently a batch process since the cells are accumulated into a sorted batch.

It is expected that after the production system has been experimented with in a high volume production environment, that overall process control will yield more uniform results. This is a desirable feature to seek in order to remove the requirement for a batch storage. In this case, the test station would merely be an accept/reject decision station as far as the mechanics of the product flow are concerned.

The output of this station is therefore working solar cells, and these could be either packaged for shipment to a module manufacturing company, or they could be input directly to a cell encapsulating line located within the same facility.

2.2.9 Cell Layup and Interconnect

This process is used to take the cells from batch storage or from a continuous conveyor to be layed up into a panel. This process may involve some substeps depending upon the process technique chosen (see Figure 2.1-1).

One technique which shows some promise of greatly simplifying the materials handling tasks is to form a subassembly consisting of a row of cells interconnected into a ribbon. This could be done by positioning the cells onto a strip of mylar containing pressure sensitive adhesive. Concurrently or just prior to this placement, leads could be soldered or bonded to the backs of the cells. These would lay on the front of a cell already attached to the ribbon and a series bond or solder could be made between cells. The pacing operation appears to be bond forming between the cells and the interconnect pieces. Several techniques exist to perform this function: soldering (with solder paste

dispensing or printed solder pads), ultrasonic soldering or contact welding. At this point in time, soldering with solder paste dispensing is being considered as the most reliable technique.

Using this ribbon subassembly technique, each ribbon in turn would be placed into an array and connected in parallel to a buss bar. These components are all automatically placed on the encapsulating substrate or superstrate, in this case probably a glass superstrate.

Other techniques are available for panel layup and interconnect. Another technique which shows some promise is to lay up the cells into an array possibly in an interconnect fixture. This would allow the cells to be laid up in conjunction with array interconnect pieces. The connections between elements could then be made all at once, possibly in a solder reflow arrangement with atmospheric control. This could reduce electrical connection time by doing them all simultaneously. However, it should be noted that cell and interconnect positioning time may be larger due to the larger distances which must be traversed by an automated positioning tool.

It is believed that panel layup and cell interconnect has had the least amount of work directed to it. This is because wafer handling and processing has been studied in the past for other semiconductor applications. Interconnect techniques and hardware design as well as cell positioning must be studied to approach a more optimal technique.

2.2.10 Panel Test and Encapsulation

After layup and interconnection, the panels should receive a brief electrical test to insure electrical integrity prior to encapsulation. This must be done so that rejected panels have the capability to be reworked. Information from testing would also be input into a central process controller for process parameter adjustments.

Encapsulation process techniques vary according to the encapsulating system used. Many types of encapsulating materials are feasible, being traded off by performance and cost features. For the

purposes of this process sequence and step descriptions, the encapsulating system chosen is a glass superstrate with a polyvinyl buturate (PVB) binder or pottant, and a protective plastic (mylar) back cover. This process station would therefore receive interconnected panels, laying on a glass superstrate. This subassembly is transported to this station on a conveyor. The process step here would include adding sheets of PVB and protective plastic preparatory to bonding the panel elements together.

The bond is made by heating the sandwich to approximately 275°F while pulling a moderate vacuum on the system to eliminate entrapped air. The heating and vacuum application require a relatively large time allocation, and therefore to reach a target production rate of 190 panels per hour special measures must be taken. This may involve either a carousel arrangement where the panels are in the encapsulating machine for a longer period, but the input/output rate matches the 190 panels per hour. The other technique is to do the bonding in a batch mode, heating and pulling a vacuum on several panels simultaneously. This technique requires a buffer storage for panels coming from the layup and test phase and generally increases the process complexity.

2.2.11 Trimming and Edge Sealing

This step receives panels from the encapsulation step and trims any flash remaining from the encapsulant system. Trimming is required to prepare the edge surfaces for application of an edge sealant and/or a framing element. Attaining process speeds for trimming to reach the target of 190 panels/hour does not appear difficult, however, no off-the-shelf equipment has been found.

Edge seal is required to prevent moisture intrusion into the panel from the edge, as well as to prevent panel delamination at the edges. Edge sealing also could be used as an edge support depending upon the characteristics of sealant used. Edge sealing is especially important to be used in conjunction with the baseline encapsulating system proposed here, as the PVB is moisture sensitive.

Initial edge sealing studies point toward the possible use of a hot melt adhesive application system. Several different types of sealants are available with varying properties, one of the most promising being a butyl sealant which is currently being used for thermoplane window glass insulating systems. An advantage of melted sealant application is the short cure time required for the applied sealant bead. This appears to be on the order of 5 to 10 seconds, depending upon the material used. This type of application system also interfaces well with an automated production system as has been demonstrated by numerous can labeling, box gluing, and other packaging techniques being used in industry. It is believed that the desired production rate can be easily met. The materials should be studied further in order to reduce the costs as low as possible while preserving the minimum performance requirements.

2.2.12 Frame Installation

This step receives a panel from the edge sealing station via a conveyor and installs a prefabricated frame to the panel. This step could possibly be incorporated with the edge sealing process in order to seal the edge and bond the frame at the same time. The machine configuration and process technique used depend upon the frame design and upon the encapsulation system. A production volume of 190 panels per hour does not pose any difficult problems in this process.

2.2.13 Final Test and Packaging

With the panel encapsulated and framed, it must have a final test to insure its readiness for shipment. The timing is not too critical, as there is 19 seconds allocated per panel for test. A pulsed solar simulator should be used, and a performance label can be made and applied at this process station. The final performance data should be input into the central processing system to keep process controls updated.

Packaging does not pose too many problems, as long as the system handles the glass panels properly. Considerations for packaging and shipping should be taken into account when designing framing. The panels should probably be palletized, possibly with the same packing that the input glass comes with.

2.3 Automation Constraints

Initial study has been made to determine how automated production affects the processes, and how the materials handled affect the type of automation equipment used. In any automated system there are trade-offs between personnel usage and equipment usage. The automated system is usually chosen because of economic factors involved. However, automated machinery is often chosen solely because of the uniformity and reliability of the product produced.

The LSSA program has several goals and guidelines set to gauge performance. The 1986 goals involve a production of 500 megawatts per year for the entire industry. Depending upon the number of companies producing this total production, it is recommended that a target for full automation be aimed for. Under this system, the personnel of the plant would be involved in process monitoring and equipment maintenance. This type of system is feasible within the current technology, and depending upon the final processes used, will probably be the most cost effective as well.

The LSSA interim guidelines call for production rates which are lower, with a larger cost allocation for process completion. This type of production indicates a more labor intensive factory for optimal cost efficiency. In this case, much of the overall process control will be overseen by a production supervisor. Much of the materials transfer between process steps, and the loading of equipment will be done by hand. Interim production guidelines also point to obtaining as much off-the-shelf type of process equipment as possible. Off-the-shelf equipment which can be easily modified to increase production rates is also applicable. The equipment currently available does not readily interface with automatic materials handling between steps, and also rates

of currently available equipment are considerably slower as is discussed above. The 1986 goals will probably require specially-designed automation equipment in order to reach the capacity of flow desired.

For interim production, one type of equipment which appears to be applicable is the use of industrial robots. These are available for moderate cost, off-the-shelf and can be programmed to perform many of the handling tasks required in cell and panel production.

In handling the materials used within this production facility the first thing to note is that the parts used are relatively fragile (wafers, quartz boats, glass, etc.). This indicates that material holding and clamping techniques as well as acceleration/deceleration values must be carefully designed. Vacuum pickup techniques appear to be the most feasible for use in wafer transfer devices. During the batch mode portions of the process, handling is not as critical as the wafers are held in rigid cassettes.

The impact of automation will directly affect the types of processes chosen. For example, there are many techniques for applying contact metalization to the wafers, but screen printing is recommended because of the reduced number of process steps, the speed with which it can be performed, and the ease with which it can be performed automatically. In this way the desire for a high production volume has guided the selection of the process steps as described in Section 2.2.

2.4 Process Economics

The process sequence as described above has been analyzed according to the SAMICS guidelines. This initial economic analysis indicates that the proposed process sequence shows some promise of meeting the desired goals. The cell production facility (SAMICS Cellco) indicates a selling price for cells of approximately \$.28 to \$.34 each (1975 dollars) using 1986 cost guidelines, and therefore using a wafer buying price of \$.16/wafer (1975 dollars, four-inch diameter wafer). This is within the 1986 price goal allocations for cell production.

The price goals for the panel production facility (SAMICS Moduleco) appear to be a little bit more difficult to reach. Initial analysis indicates a module selling price of \$. 54/watt (1975 dollars). This was calculated on the basis of a cell buying price of \$. 347/watt (1986 goals, 1975 dollars). Allocations for encapsulation materials are small. Lower cost encapsulation systems with equal performance must be found to lower the overall costs. More study should also be done in the panel production facilities to determine if costs can be reduced through the use of new equipment and/or techniques.

These price figures, though preliminary, indicate the directions which must be taken for further study. They also indicate that it may be possible to reach the desired SAMICS goals from the standpoint of cell and module production costs.

3.0 CONCLUSIONS AND RECOMMENDATIONS

It has been found in analyzing the feasibility of a 200 megawatt (SAMICS baseline company size) production plant that only a few of the processes can directly use off-the-shelf equipment as it stands. Most applicable equipment that is available is designed and optimized for the semiconductor industry. The bulk of the equipment operates at production rates of 150 to 200 wafers per hour, maximum. This is not compatible with a facility which requires on the order of 24,000 wafers per hour, as this would require 120 pieces of equipment for each process.

By increasing batch sizes, scaling up equipment, and optimizing materials handling techniques, MBA feels it is feasible to perform many of the processes at rates of 3,600 wafers per hour, and in a few cases even higher.

This type of production indicates an increase over the currently available process equipment rates of 10 to 20 times. This is in reference to special equipment in contrast to interim off-the-shelf type of equipment. It is recommended that further concepting and experimentation be done with most of the processes to reach firm conclusions as to feasible rates.

Studies to date also indicate a difficulty in reaching the costs desired for encapsulating materials, as these are the major cost elements for the panel production facility. It has also been seen that some effort should be aimed at panel layup and interconnect, as these processes appear to lag developments in the other areas. New techniques will be required to reach the process speeds desired and still produce a reliable product.

The preliminary economic analysis indicates that work has been proceeding in the correct direction as costs are approaching the desired goals. It should be realized, however, that this analysis is preliminary and is subject to change and update as new cost reducing techniques and materials are discovered for use in this production facility.

4.0 NEW TECHNOLOGY

No new technology has been developed during this period.