Subcontractor Report

November 1999 • NREL/SR-520-27478

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Annual Report
5 August 1998 — 4 August 1999

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Summary

The PVMaT 5A2 program at ASE Americas is a three year program, which addresses topics in development of manufacturing systems, low cost processing approaches, and flexible manufacturing methods. The three-year objectives are as follows:

- Implementation of computer aided manufacturing systems, including Statistical Process Control, to aid in electrical and mechanical yield improvements of 10%
- Development and implementation of ISO 9000 and ISO 14000
- Deployment of wafer production from large diameter (up to 1 m) EFG cylinders and wafer thicknesses down to 95 microns
- Development of low damage, high yield laser cutting methods for thin wafers
- Cell designs for >15% cell efficiencies on 100 micron thick EFG wafers
- Development of Rapid Thermal Anneal processing for thin high efficiency EFG cells
- Deployment of flexible manufacturing methods for diversification in wafer size and module design.

In the first year of this program, the significant accomplishments in each of three tasks which cover these areas are as follows:

Task 1 - Manufacturing Systems: Key node analysis has been completed, Statistical Process Control (SPC) charting has been started, Design of Experiment matrices have been carried out on the cell line to optimize efficiencies, a capacity and bottleneck study has been performed, a baseline chemical waste analysis report has been prepared, and writing of Documentation and Statistical sections of ISO 9000 procedures have been more than 50% completed. A highlight of this task is that cell efficiencies in manufacturing have been increased by 0.4-0.5% absolute to average in excess of 14.2% with the help of Design of Experiment (DoE) and SPC methods.

Task 2 - Low Cost Processes: A 50 cm diameter EFG cylinder crystal growth system has been designed, constructed and tested to successfully produce thin cylinders up to 1.2 meters in length. A model for heat transfer has been completed. We have successfully deployed new nozzle designs and used them with a laser wafer cutting system with the potential to decrease cutting labor costs by 75% and capital costs by 2x. Laser cutting speeds of up to 8x have been achieved. Evaluation of this system is proceeding in production. Laser cutting conditions which reduce damage have been identified for both Q-Switched Nd:YAG and copper vapor lasers with the help of a breakthrough in fundamental understanding of cutting with these short pulse length lasers. We have found that bulk EFG material lifetimes are optimized when co-firing of silicon nitride and aluminum is carried out with Rapid Thermal Processing (RTP).

Task 3 - Flexible Manufacturing: Large volume manufacturing of 10 cm x 15 cm EFG wafers has been improved through development of laser cutting fixtures, adaptation of carriers and fabrication of adjustable racks for etching and rinsing facilities, and installation of a high speed data collection network. Fracture studies to develop methods to reduce breakage of wafers has been initiated. A module field studies program was started to collect data on field failures to help identify potential manufacturing problems. New encapsulants, which cure at room temperature, are being tested to improve flexibility and provide higher yields for thin wafers in lamination.

1. Introduction - PVMaT 5A2 Program Overview

We give here an overview of the progress made in the first year of a three year PVMaT 5A2 program at ASE Americas. ASE Americas is currently engaged in a rapid scale-up of EFG PV manufacturing capacity. Overall, wafer, cell and module capacity has grown fourfold in three years, from less than 1 MW/yr in 1994 to 4 MW/yr in 1997. Subsequently, wafer production has more than doubled with the installation of an additional 7 MW of EFG production furnaces. This represents a total output of more than the equivalent of 8 million 10 cm x 10 cm wafers annually. The EFG wafer manufacturing line has diversified so that both this previously standard area wafer and a larger 10 cm x 15 cm area wafer are now being produced. Building and infrastructure facilities are additionally completed to allow EFG wafer expansion to an annual capacity of 18 MW/yr. This rapid scale-up of EFG PV technology poses a number of technical and organizational challenges; we propose to attack the most essential of these challenges under PVMaT 5A2.

Technology improvements developed under PVMaT 2A (1992-1994) and PVMaT 4A2 (1995-98) were of critical importance in supporting the scale-up to commercial production. In the PVMaT 5A2 program at ASE Americas, we propose a multi-faceted technology development effort, which is aimed at implementing manufacturing line improvements to keep EFG PV products as low-cost PV leaders. We plan to introduce and integrate design, materials and processing improvements related to all major cost elements of the EFG PV module. These elements include new generations of EFG material growth processes and laser cutting technology, more efficient cell processing, and reduced cost module construction strategies, which match the key growing PV market applications. Under PVMaT 4A2, we demonstrated and developed EFG PV technology improvements in wafer manufacture aimed at better silicon feedstock utilization, improved purification for graphite to help raise solar cell efficiencies, longer EFG wafer furnace run-time approaches, and optimized laser cutting technology. In cell manufacturing, we installed data gathering and information tracking capabilities to support and allow demonstration and testing of Statistical Process Control (SPC) methodology, and demonstrated a low cost and environmentally advantageous glass etch process which dramatically reduces fluorine ion effluents. New module designs were developed and improved manufacturing methods were introduced. These have led to new product concepts. Advanced encapsulation technologies were evaluated for improving manufacturing yield and enhancing product field performance and lifetime.

In PVMaT 5A2, we will implement advances developed previously while we expand our manufacturing line. The higher capacity leverages the incremental advances and substantially enhances the competitiveness of EFG PV products. Specific tasks include implementation and utilization of SPC, and establishing a supporting system for data collection and documentation for processes (ISO 9000) and safety (ISO 14000), to cope with the large increase in manufacturing volume (Manufacturing Systems - Task 1). We plan to develop a new thin wafer technology using EFG cylinders, that have the potential to dramatically reduce the cost of EFG PV products (Low Cost Processes - Task 2). We also will develop and introduce methods to cope with increased manufacturing process diversity – both in wafers and in modules – which will allow intermediate product (wafer and cell) and module field performance tracking to be used to improve manufacturing processes (Flexible Manufacturing -Task 3). These elements are considered to be cornerstones for capturing the full cost and technical improvements of EFG PV, and assure well-controlled, high-yield, high-volume production.

2. Task Objectives and Work in Progress

2.1 Task 1 - Manufacturing Systems

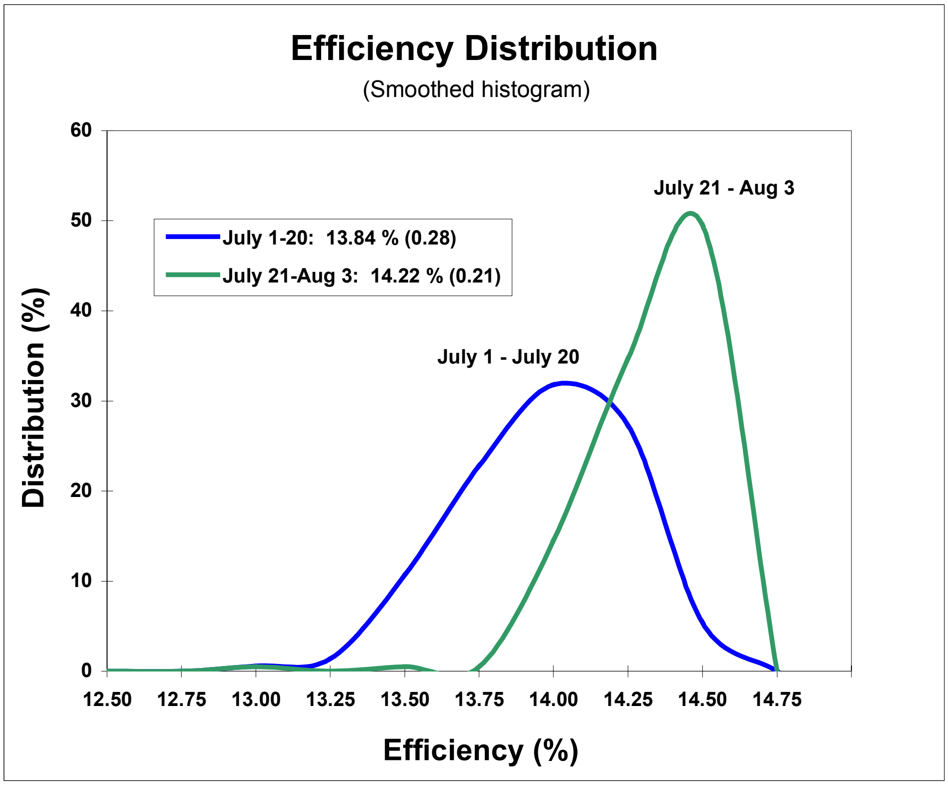
This task addresses efficient manufacturing management systems essential to achieving high-yields at high production volumes. We propose to implement process feedback, statistical process control, documentation procedures and ISO 14000 Certification. These manufacturing management systems improvements are absolutely essential to efficient, cost-effective manufacturing, and this task is a core activity of our PVMaT 5A2 work plan. The goal in pursuing these manufacturing management improvements is to incrementally lower costs, reduce waste and increase production output, and to lay a solid foundation for more substantial improvements made possible by implementation of the above-mentioned technology enhancements in high-volume production. Examples of such an infrastructure are statistical process control, total preventative maintenance, product quality enhancement, and industrial ecology.

Subtask 1.1 - Mechanical and Yield Loss. We have started to plan implementation of infrastructure improvements using SPC methodology by first focusing on the area of cell efficiency in the EFG cell line. The cell efficiency provides one of the highest leveraging elements in cost reductions, and takes on added importance with increasing volume. Reduction of mechanical and electrical yield loss requires identification of critical manufacturing steps that directly affect end product performance, utilization of the manufacturing database to track critical data in real time enabling manufacturing optimization, and implementation of a Total Preventative Maintenance (TPM) program throughout the factory. Initial planning in this area involves work on setting up of control charts and documentation for elements 4.5 (documentation) and 4.20 (Statistical Techniques) of ISO 9000.

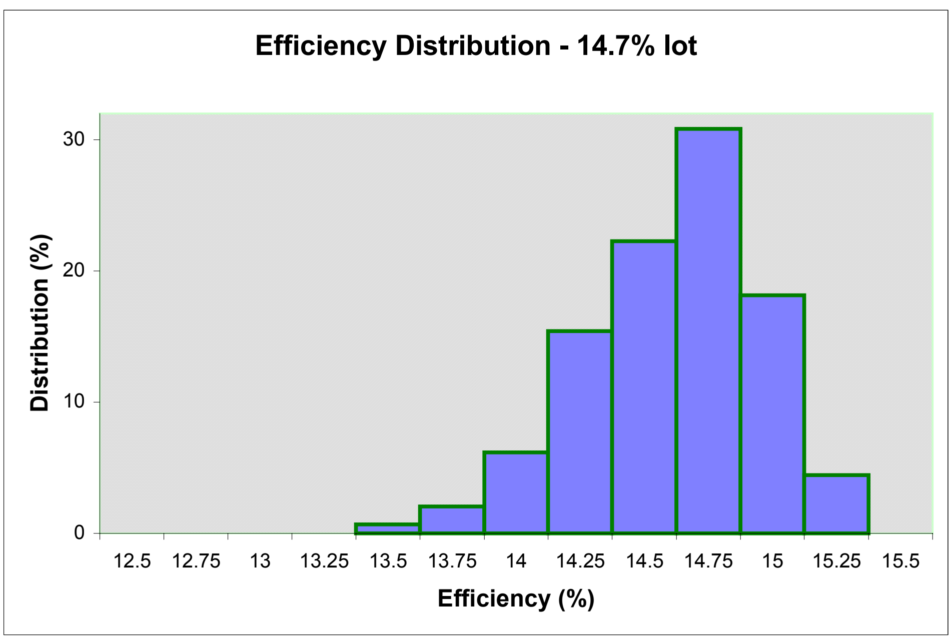
Year 1 Accomplishments: A highlight of our manufacturing activities in cell production this year has been a significant increase in cell efficiencies. We have been implementing recommendations arising from the Design of Experiments (DoE) which we have performed in the past. These, together with some equipment upgrades, have started to make an impact on cell efficiency on the production line. At the start of the program in August, 1998, the average cell efficiencies were generally in the range of 13.5 to 13.7%. Most recently, we have achieved a record average for a two week period of about 14.2%, as shown in Fig. 1a. This graphs shows the percent of solar cell lots which have a given efficiency level, and represent tens of thousands of cells.

Consistent with the boost in average solar cell efficiency has been the occurrence of record high lots. A histogram of one of the highest lots, averaging 14.7%, is shown in Fig. 1b.

Subtask 1.2 - Statistical Process Control (SPC). This task of using SPC and DoE's to improve the manufacturing of solar cells at ASE Americas falls within the goal of providing and using *efficient* manufacturing management systems to achieve high yields of quality product at high production volumes. A basic concept in SPC is that "continuous improvement" is not haphazardly made, but is targeted in a prioritized manner, focusing on those areas whose output is most sensitive to the success of the final product.



(a)



(b)

Figure 1. a) Histogram of cell efficiency results for production lots. b) Histogram of individual cells for the highest lot.

Defining and redefining what the "key nodes" are for the processes used to manufacture a product are a continuous activity. Currently ASE Americas is in the process--through the use of DoE's—of confirming which areas are key nodes, then focusing on SPC charting and the use of control action plans at these areas.

Accompanying the Control Charts are "Control Action Plan's" (CAP's). These essentially are flowcharts which define what the operator should do when the process has produced an out-of-control condition. Each CAP is being developed by engineering personnel with operational staff input. The CAP will then be executed by the manufacturing personnel on the floor. Before a control chart is implemented on-line, everyone using the chart is trained on how to use and read the chart, as well as how to follow the CAP. The CAP's developed include different actions for different conditions (i.e. out-of-control high vs. out-of-control low).

Year 1 Accomplishments: Implementation of SPC charts and CAP's was started: this has involved the statistical tracking of process outputs, document creation, and training of manufacturing personnel to maintain the charts and implement corrective actions, when needed. Their use has increased the robustness of the manufacturing process and is helping to establish a system to identify process excursions prior to catastrophic yield loss events. In addition, we performed four Design of Experiments to identify the key nodes in the cell manufacturing areas of: i) finger width and firing temperature; ii) temperature and belt speed for front metal firing; iii) antireflection (AR) coating; and iv) the diffusion temperature profile.

Subtask 1.3 - Flexible Manufacturing. Manufacturing Systems implementation in the wafer and module areas include the definition, development and implementation of quality and management systems that are built on controlled documents and calibration standards that are traceable to primary and secondary standards. Metrics for equipment performance (uptime, repair time, waiting for parts, qualification time) will be developed and tracked in the new electronic database system. These systems will add stability to the manufacturing process and will be used to document acceptable ranges of variability of all key parameters, and enable systems to come on line in a controlled fashion.

Year 1 Accomplishments: An initial effort in this area concentrated on developing metrics for equipment performance: a capacity and bottleneck study was completed which helped to identify several bottleneck areas which could be reduced. The results were reported in a confidential Deliverable Report D-1.3.10.

Subtask 1.4 - ISO 14000 Certification. This work will formalize safety and environmental issues within a framework of acceptable practices and gain recognition for the photovoltaic industry for leadership in this area. This certification mandates that the manufacturing line be developed to be consistent with minimizing its effect on the environment through fundamental understanding of the chemical usage, waste and environmental impact of the manufacturing process. It also mandates a system to be developed that enables continuous improvement, training, and reporting on safety and environmental issues. We plan to use developments on the EFG manufacturing line as a template to structure and formalize our environmental concerns within the comprehensive and generic approach provided by ISO 14000.

Year 1 Accomplishments: Initial work in this area consisted of working on the Documentation and Statistical sections of ISO 9000. A summary of the progress in given in the chart in Fig. 2

below. A second accomplishment was the development of a database for baseline material and chemical usage information. A confidential Deliverable Report D-1.2.6 on the baseline chemical usage was completed in the first year of this work.

Cost reduction in Task 1 over the three year program will be achieved through decreasing the variability in products (wafers, cells, modules) and optimizing their performance. We expect to improve average rated cell efficiency by 5-10% (relative) by reducing the amplitude and duration of efficiency swings experienced in the past. We plan to stabilize machine performance and enhance throughput at near the maximum capability of the line demonstrated on an interim basis in the past. This will reduce labor costs by 10% on average. The overall module cost reduction in manufacturing from such stabilization of operating conditions and achieving optimal values is expected to be about 10%. As noted above, one of the main accomplishments in the first year toward these goals has been to achieve the target of a 5-10% (relative) efficiency improvement in the cell manufacturing line.

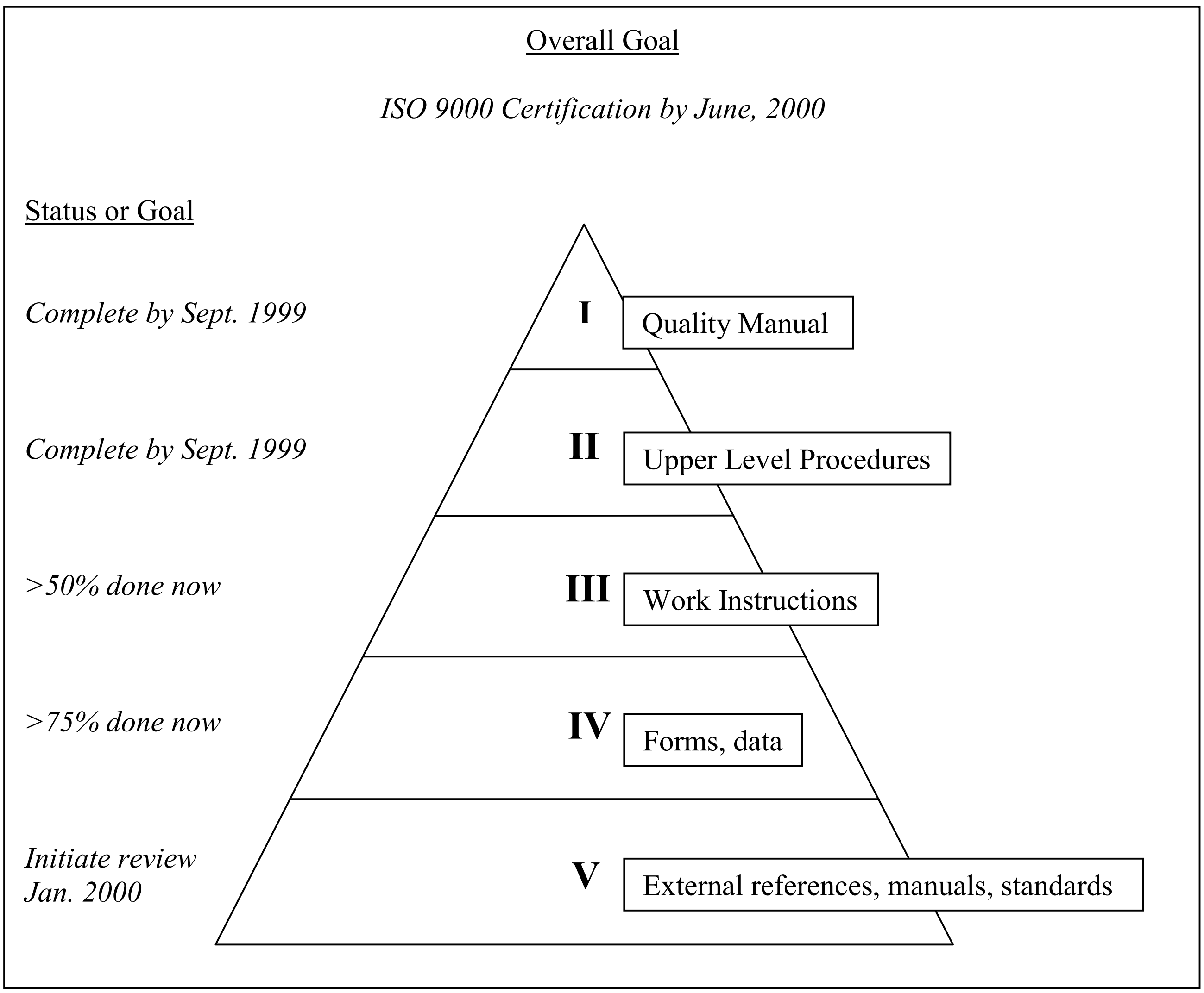


Figure 2. Summary of ISO 9000 certification work.

2.2 Task 2 - Low Cost Processes

In this Task, we are working to develop and implement advanced EFG technology. We are in the process of testing a new generation of lasers which reduce as-cut wafer edge damage, deploying a very high speed laser in production, and deploying a plasma etch process to remove edge damage in place of acid. The latter will reduce etchant consumption, hence lower the volume of hazardous processing materials usage and waste generation.

We are also exploring higher-risk, higher-reward opportunities for radically reducing x-Si PV module costs through introduction of new processing and thinner wafers. We are investigating new cell processing approaches using Rapid Thermal Processing (RTP) techniques, and planning to develop manufacturing methods for wafers down to 100 micron thicknesses. To date, we have been successful in growing large 50 cm diameter EFG cylinders. In Year 2, we will study the feasibility and cost advantages of extending the diameter to 1 meter and carrying out the emitter diffusion during crystal growth. The goal in pursuing these configurations is to demonstrate over a 50% reduction in manufacturing costs of the EFG wafer.

Subtask 2.1 - Laser cutting. Improvements in laser technology are central to raising EFG manufacturing line mechanical yields and introduction of thinner EFG wafers. The current EFG wafer laser cutting process introduces damage in the wafer edge. This makes the wafer susceptible to increased levels of breakage as its thickness is decreased, and necessitates use of a costly acid damage-removal etch. The two main aspects of our program on lasers are: i) to evaluate new short pulse length laser technology that will provide reduced damage cutting for thin wafers; and ii) to demonstrate large, up to 75%, reductions in labor in laser cutting of current thick wafers, through use of high power lasers that can increase the cutting speed in production by up to 8x.

An initial task in the laser program was to design and construct an R&D laser station for testing of new laser concepts. Nd:YAG laser cutting of wafers from EFG grown silicon tubes has been in use for a number of years in manufacturing at ASE Americas. However, availability of a laser station for R&D work was constrained by production pressure, which prevented up to now in-house testing of new laser technologies.

The main requirements and goals sought for our advanced laser cutting station were:

1. An improved cutting speed to improve throughput and reduce cost per wafer.
2. Improved edge quality (edge smoothness and reduced micro-crack damage).
3. Flexible system control, mechanics and optics to permit the use of different laser types and a wide range of operating parameters.
4. On-line inspection capability of laser cuts.

The present systems used in manufacturing spend only approximately 50% of their time in cutting. The other 50% of the time is consumed by tube handling, wafer unloading and other overhead. Thus, a doubling of the linear cutting speed, for example, would only yield a productivity improvement of 25% if all other operations were to be kept constant. (We will not address these machine overhead issues, which will be of concern only when the laser is operated in production.)

The issue of cutting speed is being addressed in two distinct phases. In the first phase, we have attempted to achieve an approximate doubling of the cutting speed without significantly changing the laser type or system presently employed at ASE Americas in manufacturing. In the second part of this work, we have started a program to evaluate a family of high power CO_2 lasers. Because of the increased level of damage associated with the higher power of these lasers, it also has become necessary to develop a replacement for the acid etch used to remove laser edge damage. A plasma etch process has been evaluated and shows great promise as a replacement for acid for all lasers.

Doubling of the cutting speed involves increasing the sophistication of laser power utilization, together with some increase in the available laser output power. The first option was discussed in detail in Deliverable Report D-1.1.3. We also evaluated a higher power model laser. This gave an average power output increase of approximately 15% without changing the laser cavity characteristics. The low divergence option is retained in order to achieve the smallest practical beam spot size with this model laser. In the second phase, we achieved even higher cutting rates in excess of 50 cm/s. This required a motion system capable of high acceleration. The design included the use of a high performance beam positioning system specifically designed to support high speed cutting. The capability for beam shaping and pulse shaping is imbedded in system design to allow improvements in wafer edge quality (reduced edge roughness and micro-crack damage) to be realized. The deployment and testing of specially designed ‘assist gas’ nozzles developed in PVMaT 4A2 was part of this effort. These achieve much higher impact of the assist gas on the wafer surface while reducing the net force.

Flexible system control, mechanics and optics are achieved by the design of the laser beam delivery system permitting the use of laser coupling by fiber optics or traditional mirrors. For ease of controlling the entire system (laser, beam positioning, beam delivery and assist gas nozzle) under changing experimental conditions, a new software platform has been selected as high level control programming software. This choice will also facilitate easy introduction and integration of a final cutting system into manufacturing.

In order to enable rapid evaluation of laser cutting results and system setup a vision system having through-the-laser-beam focusing lens illumination and viewing has been included in the system design. It is anticipated that incorporation of this feature will ultimately enable on-line quality control of the wafer cutting process in manufacturing.

A photograph of the new R&D cutting facility is shown in Fig. 3. A short pulse length Q-Switched laser has been purchased after extensive testing, and has become the foundation of the R&D station to develop low damage cutting for thin cylinders.

In PVMaT 4A2, we carried out a feasibility demonstration of a new generation of lasers which could reduce edge damage on wafers significantly. One of the lasers identified, which has a high potential for low damage cutting, is the copper vapor laser (CVL). Now under PVMaT 5A2, a lower tier subcontract was initiated with the University of New Hampshire to carry out a development of CVL technology for thin EFG cylinder cutting. This is a one year program. The challenges that this work is facing is the demonstration of the cost effectiveness of the technology, both through defining a reliable and consistent cutting process and equipment configuration, and in reducing the high capital cost of the copper vapor laser by achieving required throughput rates.

An alternative to the CVL laser is a new generation of short pulse length Nd:YAG lasers which were identified in the PVMaT 4A2 program for their potential for higher speed cutting than possible with the current CVL technology. We were able to demonstrate that reduced damage cutting was possible with one laser model, but it is not known whether this low damage cut can be sustained under production conditions.

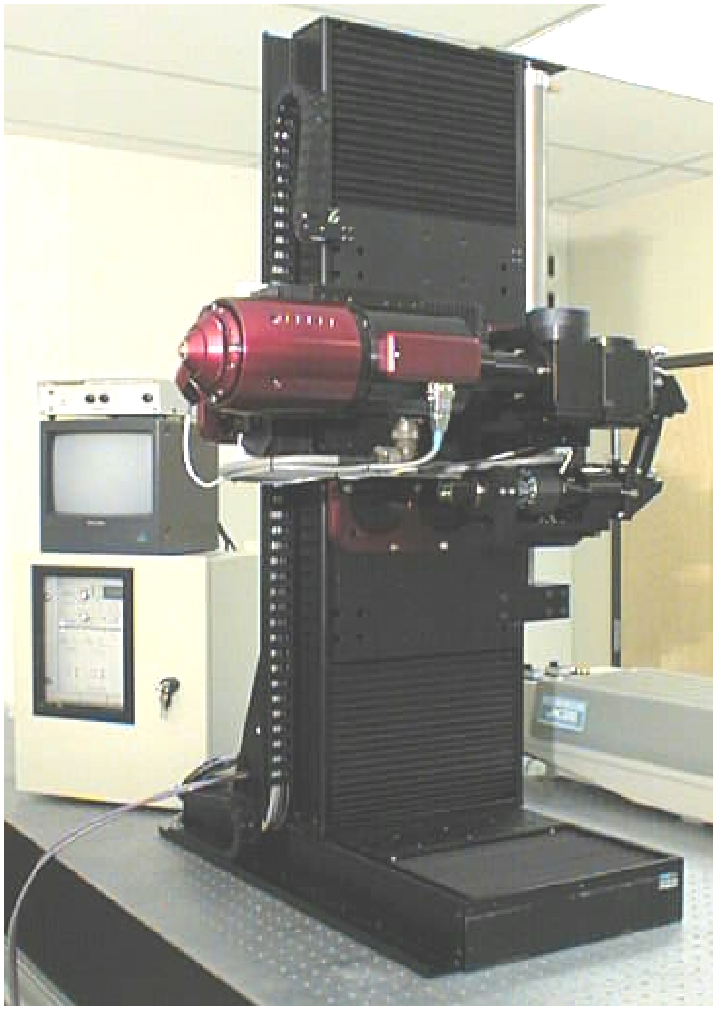


Figure 3. Photograph of new R&D laser cutting station.

In the course of advanced laser development in this program we have pursued several options in parallel. First, we need to establish the operating parameters for the supersonic nozzle. In order to do this, we obtained a new design of short pulse length Q-Switched Nd:YAG laser on a rental basis. With this laser, we explored a regime where we previously found a higher quality cut could be obtained at moderate cutting speeds comparable to those for the current systems. This higher quality cutting is necessary for the EFG cylinder crystals, which are being produced now, as described in Subtask 2.3. Very promising results have been obtained with this laser, and it now has been purchased and will be used for in-house cutting of thin cylinders on the R&D station. We plan to evaluate this laser side by side with the Cu vapor laser to determine which is the best option for cutting the cylinder.

Finally, we also are investigating the possibility of using a CO_2 laser which is capable of cutting at 5-10 times the current speed. With this laser, the edge quality is not expected to be improved. However, we hope to combine this technology with a wafer edge treatment, which has shown promise to remove all laser cutting damage and provide a high quality wafer edge for cell processing. A 250 W CO_2 laser been installed on the production line and is in the process of being optimized. This laser brings a number of advantages. It is a new generation of gas dynamic CO_2 lasers. These are very compact and easy to install, and have a totally sealed cavity designed for operation with low maintenance and a high degree of reliability. The cavity has been demonstrated to last for about 10,000 hours, after which time it is taken out and sent back to the manufacturer for refurbishing.

Advantages in operating parameters, besides the obvious one of high cutting speed, are derived from a number of desirable characteristics. The beam divergence is much reduced and the pulse length is shorter than the Nd:YAG lasers currently in use, contributing to a comparable heat affected zone (HAZ) even though the power level is double that of the YAG. This is combined with a capability to operate at high repetition rates up to 10 kHz, compared to about 225 Hz for the YAG. These operating parameters provide the capability to cut at speeds in excess of 4 in/s, a fourfold increase over production YAG-based technology. A second higher power (500 W) CO_2 laser is also available and will be evaluated next, which was shown to allow cutting speeds of over 10 in/s to be reached in a laboratory demonstration. At present, the motion tables in place in production limit us to speeds of 8 in/s. Even at this level, we expect that labor costs in laser cutting will be reduced by over 50% as throughput per station is raised by over a factor of two. This will reduce wafer manufacturing costs by nearly 10%.

This CO_2 laser had been tried previously in cutting of EFG octagons without success (September and October, 1996, Monthly Reports under PVMaT 4A2 subcontract No. ZAF-6-14271-13). The failure was due to the buildup of slag at the laser beam exit, which produced unacceptable roughness, microcracks and fracture/spalling of edge material, and led to low processing yields. In these previous trials, the failure was traced to inadequacies of the gas delivery system. In the cutting mode common to the YAG and CO_2 lasers, the laser melts a cylindrical cavity through the thickness of the wafer, but there is not enough energy supplied to the melted region to vaporize and expel the melt. Melt expulsion is carried out by the assist gas. The nozzle design used at that time limited operating assist gas pressures to about 40 psi, which was not sufficient to cleanly blow out the debris from the kerf area. In laboratory tests, on the other hand, operation at 80 psi with the sample well supported from the back, showed that at higher gas flows the slag at the laser beam exit was eliminated and a good edge was obtained. At this high pressure under production conditions, however, all but the thickest octagons fractured during cutting.

These inadequacies of the nozzle design led to a new program in the second and third years of our previous PVMaT 4A2 program to study nozzle configurations and examine the causes for limitations in the melt removal. This program was very successful in arriving at two new design concepts of nozzle configuration. These concepts have now been combined and demonstrated in the nozzle currently being used with the CO_2 laser, which can cut with gas pressures up to 80 psi without generating undue force on the work piece. The new supersonic "net zero force" nozzle is primarily responsible for the improved operation seen with the CO_2 laser.

Our plan for year 2 is to develop and optimize the cutting conditions with the high speed system. This work also involves evaluating the etching process which is best suited to removing the damage for the CO_2 laser cut wafer.

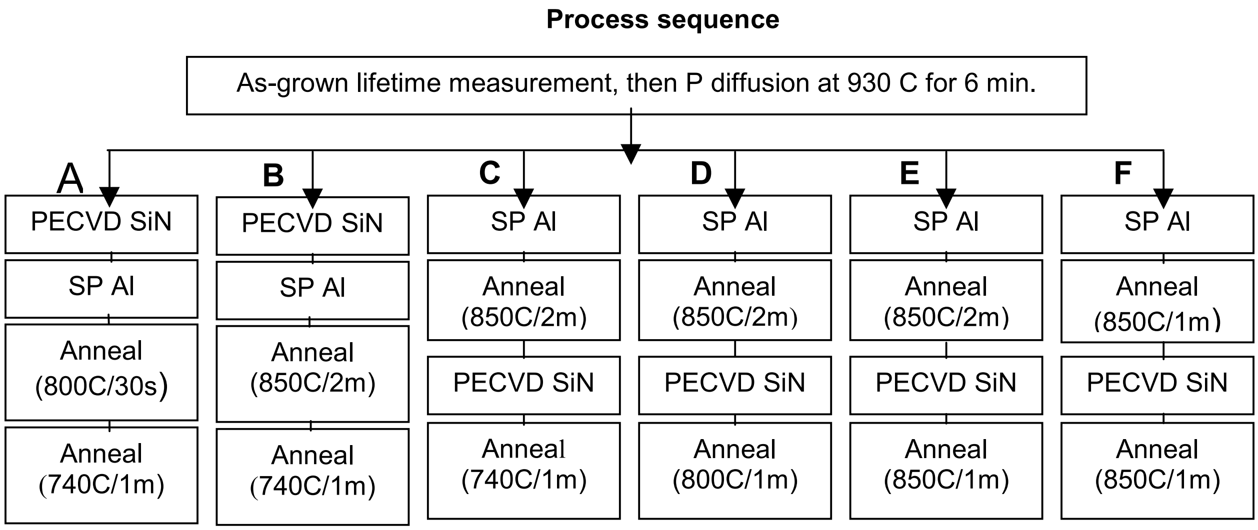
Year 1 Accomplishments: Both the Q-Switched Nd:YAG and the copper vapor laser have been demonstrated to be able to achieve cutting speeds of about 0.5 in/s on a 100 micron thick wafer. This has involved a breakthrough in understanding of the fundamentals of cutting with short pulse length lasers. Cutting improvements are undergoing patent review and will not be reported at this time. This advance has made cutting with the short pulse length laser a viable candidate for low damage cutting of thin cylinders.

The CO_2 laser with the new gas nozzle configuration has been shown to be able to cut at speed up to 4 in/s under production line conditions, and will be tried out in a full evaluation in manufacturing.

Subtask 2.2 - Cell Efficiency. EFG PV cells have reached the 14% level in commercial production with the help of programs carried out in PVMaT 4A2, about 5 - 10% (relative) lower than conventional x-Si wafer-based PV technologies. In this subtask we will look for techniques to further investigate advanced processes to close this performance differential while maintaining EFG's cost advantage, and extend these processing techniques to be applicable to thin EFG wafers (100-150 microns). The objective will be to demonstrate technology to raise solar cell efficiency by 10% (relative). We have started to study cell designs which can be applied to produce thin high efficiency cells. The goal for Phase I is to achieve the 15% level. We have negotiated a three-year program to be carried out at the Georgia Institute of Technology (GIT) to evaluate if rapid thermal processing (RTP) can help us achieve these goals. The initial work in the first year at GIT concentrates on process development. Its goals are to define process sequences and identify equipment for improving cell efficiency through development of an alternate diffusion process, and to apply the selective emitter concept in EFG cell processing. The key challenge in applying these techniques to EFG will be to find an approach that is both cost-effective and can be integrated into the current EFG cell line. In the second and third years, successful candidate processes will be tested in a production environment. The overall module cost reduction from work in these improvements under Task 1 is expected to be about 15% (relative).

Year 1 Accomplishments: A number of matrix experiments have been carried out at GIT on evaluation of RTP methods for optimizing EFG wafer base lifetime. The results of an experiment to study the effects of RTP processing on lifetime upgrading of EFG wafers are summarized in Figure 4. Cases A and B involve simultaneous firing of silicon nitride and aluminum, and give the most lifetime enhancement, whereas C though F involve sequential firing and do not show as much potential for bulk lifetime enhancement.

Subtask 2.3 - Thin EFG Cylinder. Cylindrical shapes allow rotational movement in the dies, which in turn improves thermal uniformity, hence wafer thickness control and uniformity. Cylindrical shapes also improve laser cutting efficiency and allow thinner wafers to be processed with high yields so as to provide higher materials use efficiency. If cylinder growth is combined with on-line emitter diffusion by incorporating phosphorus diffusion sources into the EFG growth furnaces, this eliminates the costly and yield-critical processing steps of etching and diffusion in the cell line, and removes critical steps in wafer handling. The overall module cost reduction from work in breakthrough opportunities may be upwards of 50% (relative), i.e. cutting EFG PV costs in half. Given the existing cost advantage of EFG wafers relative to wafer-based x-Si PV technologies, a halving of EFG costs would dramatically change the overall commercial prospects for PV relative to other energy sources.



Simultaneous (A,B) vs. sequential anneals (C-F) for SiN and Al-BSF, by a lamp-heated belt furnace. Lifetime improvements are shown below.

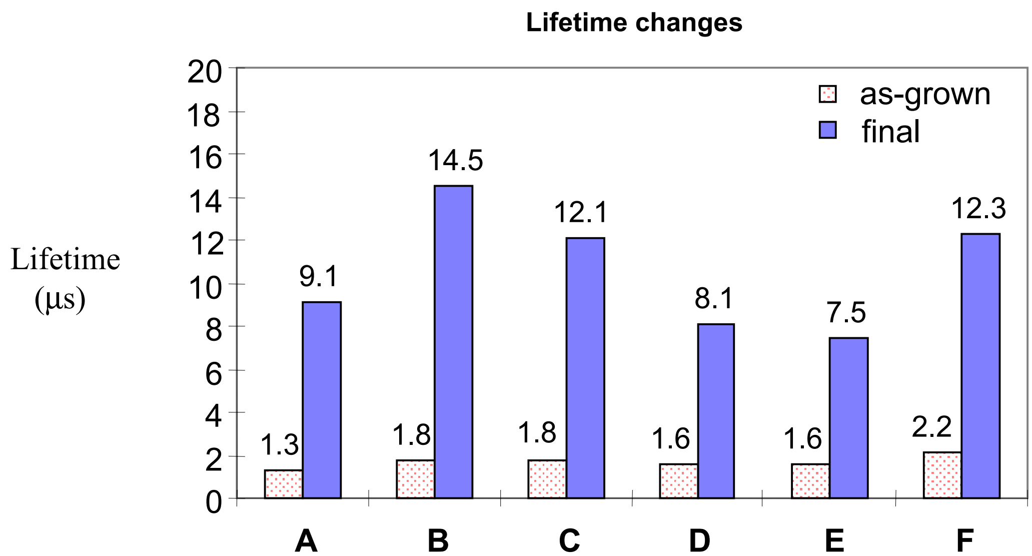


Figure 4. Comparison of bulk lifetimes before and after processing for various sequences.

Year 1 Accomplishments: We have completed a design program for a 50 cm diameter EFG crystal growth system, and the system has been built and thoroughly tested. Initial growth experiments were extremely successful. The first growth runs produced several tubes each. The longest was 1.2 meters. Growth was stable and reproducible. Growth with rotation showed that there is an asymmetry in the rotation axis alignment, which resulted in ridges on the cylinder surface. Difficulties with the weight and thickness control software prevented growth of material below about 400 microns because manual control had to be used. This problem has been fixed by changing the load cell calibration, and growth trials are continuing.

Photographs of the EFG furnace and tube are shown in Figs. 5 and 6 below. The striations on the tube seen in Fig. 5 arise from a misaligned axis of rotation. Fig. 6 shows a section of a completed tube.

Figure 5. Large diameter EFG tube in the process of growing.

Figure 6. View of 50 cm diameter EFG cylinder after completion of growth. The section shown is 33 cm tall; full tubes are as long as 120 cm. This section was grown without rotation.

Crystal growth - Modeling. Development of a growth model is underway at the State University of New York (SUNY)-Stony Brook in parallel to the experimental growth program. They have developed a comprehensive heat transfer model to use in engineering design work on large diameter configurations. We also have hired a consultant to develop a stress model for cylinder growth. One of the goals will be to maximize throughput, which involves achieving growth conditions which permit the highest possible pulling speed with the lowest acceptable stress. This work will be integrated with the furnace and hot zone modeling program at SUNY in the second year of the program.

Initial calculations of stress and dislocation distributions in the cylindrical geometry have been made to establish a baseline case and to validate the model. They show, as known for earlier studies, that the stress and dislocation density levels are reduced by an order of magnitude or more from those in the plane sheet case. The test temperature profile is shown in Fig. 7 along with results for the stress and dislocation density in Figs. 8 and 9. The maximum values of shear stress obtained are in the range of 10 MPa for the cylinder. In the case of the plane sheet geometry such as the octagon they may be as high as 200 MPa.

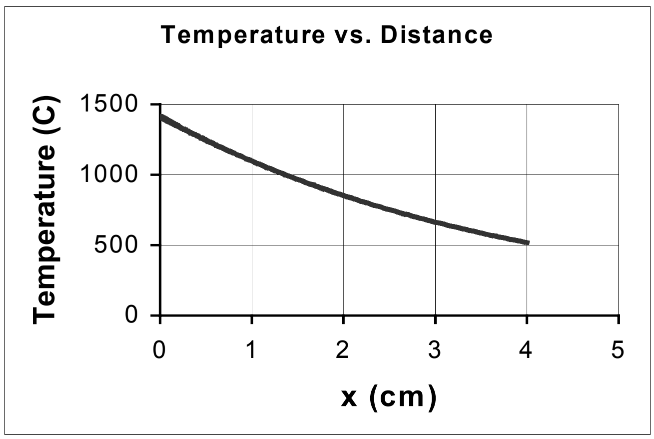


Figure 7. Temperature distribution in the crystal cylinder along growth direction (x) used in the stress analysis.

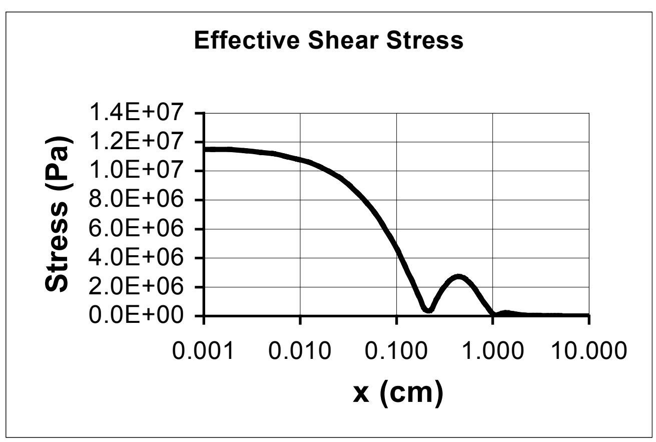


Figure 8. Effective shear stress as a function of distance from the growth interface (x=0).

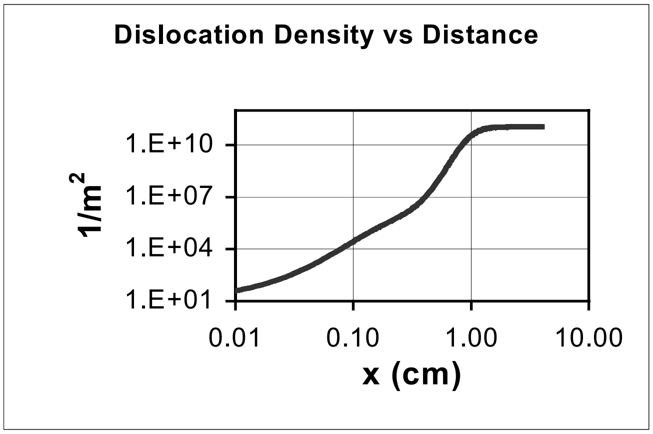


Figure 9. Dislocation density as a function of distance from the growth interface (x=0).

2.3 Task 3 - Flexible Manufacturing

This task has worked on improving the manufacture of larger EFG wafers, and on module failure analysis. The goals in pursuing such product design and fabrication improvements are to deliver better value to the customer, to better respond to customer requirements, and to achieve longer field service life and lower field failure rates.

Subtask 3.1 – Large EFG Wafers. The trend in x-Si wafer technology is towards larger wafers so as to decrease cell processing costs, by (in effect) amortizing unit cell processing costs over larger areas. Conventional ingot/block + sawing wafer technologies are limited by ingot/block size and/or by maximum sawing length. EFG technology is not so limited; EFG wafers could conceivably be cut to produce a wafer encompassing the full length of an EFG tube or cylinder. The first step toward larger wafers at ASE Americas will be to expand our product offering to include 10 cm x 15 cm wafers in addition to the standard 10 cm x 10 cm wafers now available. We need to develop – for this expansion of wafer size – a strategy for laser cutting station modifications and wafer handling that are high yield and cost effective for producing larger rectangular EFG wafers.

Wafer fracture during cutting and processing is a major contributor to productivity losses in manufacturing. We initiated under this task a study to identify the causes of mechanical yield loss for wafers throughout the crystal growth and laser cutting areas. The initial work set up a baseline on the regular size 10 cm x 10 cm wafers. The goal of this work will be to understand better the processing steps which are most detrimental to fracturing wafers, and pay attention particularly to which steps both in wafer cutting and cell processing are going to be of highest concern as we produce thinner wafers. We also will test out a diagnostic technique utilizing sonic testing for cracks being developed at an institute in Germany. Cracks in EFG wafers are propagated from the damaged laser cut edge into the interior of the wafers during handling and loading of carriers. They do not extend sufficiently far to be visible or to lead to fracture of the wafer into several pieces. However, they greatly weaken the wafer and give it a high probability that it will fracture in subsequent cell processing, interconnect or module fabrication. These wafers are a major contributor toward mechanical yield losses and also impact throughput, because frequently line operation must be interrupted to clear the broken wafer pieces. The purpose of this study will be to determine which steps in cutting and handling of wafers result in the most frequent generation of these cracks, and where the sonic diagnostic technique would be the most effective to apply in order to remove cracked wafers from the processing stream.

We are addressing mechanical yield losses for EFG wafers by evaluating a proprietary method with which to remove the damaged region of the wafer edge after it is laser cut. This would reduce the incidence of cracks propagating to fracture in handling, and raise overall mechanical yield, and contribute toward the goals of reducing chemical usage in the ASE Americas' manufacturing line (reported under Subtask 1.4 above) by reducing acid etch requirements. Currently the laser damage is removed by a costly and environmentally undesirable acid etch process. As we are going to higher volumes with our wafer expansion, this process becomes a bottleneck and expansion of manufacturing equipment becomes very costly. One approach already being studied above (Subtask 2.1) is to reduce the damage through utilization of new laser technologies – the copper vapor or short pulse length YAG lasers. However, the improved edge quality and stronger wafer that is produced by these lasers generally comes at the expense of reduced throughput. Cutting speeds with these new lasers cannot be enhanced, and may generally be lower, as has already been encountered for the copper vapor laser. Although the latter will be an acceptable means of cutting for the new thin cylinder material, where the most important aspect is that the cut be made with minimal damage so the cylindrical wafer can be flattened, it will not be able to reduce labor costs with the current Nd:YAG technology already in manufacturing as a result of decreased throughput. The alternative approach to reduce costs both in laser cutting and in etching, which has potential to remove the larger amounts of edge damage that arise from the higher speed lasers, uses an atmospheric plasma etch.

We plan also as part of this task to develop statistical methods to measure and compare wafer manufacturing processes for the different size wafers, and closely coordinate our research with customer requirements for wafer edge quality and strength.

Year 1 Accomplishments: Full operation of a new 7 MW expansion of the EFG wafer production line was achieved this year at ASE Americas. This involves growth and cutting of the equivalent of over 5 million 10 cm x 10 cm wafers on an annual basis. The facility produces both 10 cm x 10 cm and 10 cm x 15 cm wafers. Under the PVMaT program task, we carried out design modifications and testing of fixtures for large wafer cutting, as well as for the etching and rinsing of the larger wafers produced from this facility. Installation of SQL server hardware also was completed for the crystal growth area. This will allow collection of data from the manufacturing floor and integration of production information with other parts of the production line for cells and modules.

To date we have carried out several feasibility studies with the new plasma process. Edge damage removal is very uniform, and wafers can be coin-stacked to achieve very high machine throughput rates. Wafers after etching have as high fracture strengths in fracture twist testing as those fully etched with our current silicon acid etch step. One drawback is that a residue film is left on the edge of the etched wafer. To date, we have found we can remove it with a diluted acid to preserve efficiency and cosmetics in the finished solar cell. However, even with this dilute acid clean we will be able to reduce waste products in the etching step by over 80%. We will continue to evaluate the plasma etch process with larger scale experiments in Year 2 of this program, and develop specific designs to allow high throughput and cost effective processing to justify deployment of this process in manufacturing.

Subtask 3.2 – Modules. As EFG PV products accumulate field exposure and as EFG PV products are applied in an increasingly wide array of applications, it is inevitable that some field failures will occur. It is important to promptly analyze any failures and quickly translate the lessons learned into manufacturing improvements. In this Subtask, we will establish feedback systems from end users and field failure information that tie field experience back to the manufacturing process. We plan to develop the capability to close the loop between the manufacturing process and the observed product defects to be corrected. Fundamental to achieving improvement in high volume manufacturing will be the establishment of Failure Analysis and Root-Cause-of-Failure capabilities.

Year 1 Accomplishments - Module Field Studies: We have developed an initial strategy for field evaluations and module failure studies with a consultant. The basis of this strategy is a compilation we have made of field failures, customer comments and warranty claims. The initial task of the consultant is to develop a database involving manufacturing variables and field conditions (e.g., location, installation type, and environment) so that the failures can be charted and correlations examined.

Subtask 3.2 -Encapsulants. One task under PVMaT 4A2 successfully evaluated new encapsulants, and provided future options for manufacturing, both for reduced costs and expectations for a longer module field lifetime. This work had two purposes. One was to develop an improved encapsulant to overcome some shortcomings in the current encapsulant in use in the ASE Americas manufacturing line. Tests were successfully completed and recommendations to manufacturing have been made. Test modules with this encapsulant will be included as part of the above field study program to compare them to our existing product line. The second PVMaT 4A2 objective was to examine options provided by resin encapsulants which are liquid at room temperature. Several of these also have very fast cure times using UV light. These are desirable both to provide flexibility in manufacturing with respect to increasing throughput and improving yield of current products, and to increase yields with thin wafers. We have previously found that the stiffness and the relatively long process cycle time of our current encapsulant were limitations which are crucial to overcome if we are to successfully reduce module manufacturing costs with future thin EFG wafer technology. Several alternatives were identified, and some already have been under test.

Year 1 Accomplishments - Encapsulants: We have set up facilities to make prototype modules with a liquid resin which shows the most promise to use with thin EFG wafers. Coupons and small modules have been made with his encapsulant, to be tested side by side with the other materials currently under evaluation within the company, and examine process variants which may be valuable to use with curved wafers.

Initial accelerated testing of small coupons made with the new encapsulant has been completed. The results are shown in Figure 10. We find some degradation of transmission after about 4 months equivalent exposure time under Arizona conditions. However, we also find that there was cracking of the encapsulant layers between the glass slides in these coupons. This was not seen in the cell coupons we have made. We believe this has occurred because the encapsulant films were too thin, and more samples will be made to continue the testing.

Field studies in installations with ac modules will be included in the module program in Year 2. The overall module cost reduction from work in this Task is expected to be about 5% (relative), and help drive introduction of new customer-driven product offerings.

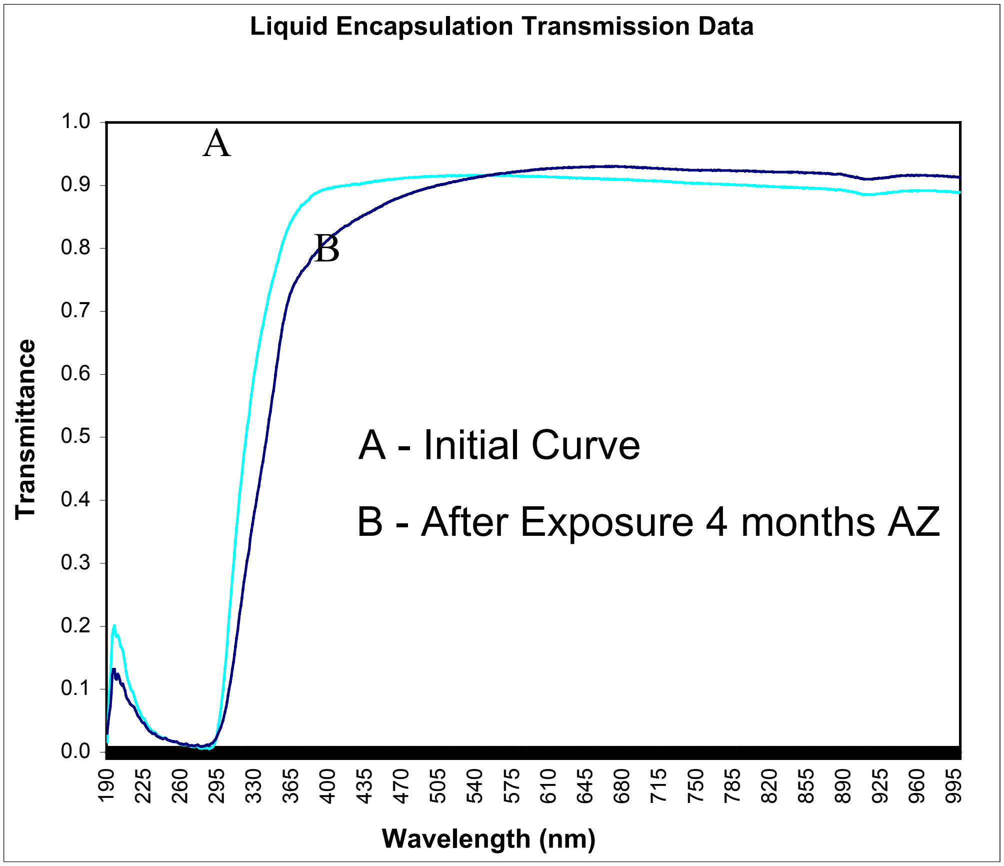


Figure 10. Transmission data for the new encapsulant after 4 months Arizona equivalent accelerated UV exposure.

3.0 Highlights of the Year 1 Program

The main accomplishments of the first year program at ASE Americas have been:

- Cell efficiencies in the ASE Americas manufacturing line are improved to over 14% with the help of application of Design of Experiments and Statistical Process Control methods. An 0.4-0.5% increase in absolute efficiency has resulted in a 5% decrease in manufacturing costs of modules.
- Growth of 50 cm diameter EFG cylinders of 1.2 m length is demonstrated. Tube wall thicknesses down to 200 µm on average have been achieved, with small segments down to as low as 75 microns in thickness.
- New laser technologies were demonstrated to give: i) up to 8x higher speed cutting in manufacturing, with the potential to reduce labor costs in cutting of up to 75% and to cut capital costs for new equipment in half; ii) low damage cutting with short pulse length lasers and new methods to control ejected material.

4.0 Future Work

Year 2 work in the various tasks of the ASE Americas' PVMaT program which is being considered:

Task 4 – Manufacturing Systems:

- Complete ISO 9000 certification and "gap analysis" on ISO 14000
- Extend SPC to areas outside of cell manufacturing to achieve:
  - Integration of computer aided manufacturing systems
  - Demonstration of additional 5% reduction in yield losses
- Demonstrate 10% reduction in chemical waste
- Develop new diagnostics in support of SPC in areas of photoluminescence and stress measurement (University of South Florida)

Task 5 – Low Cost Processes

- Improve thickness uniformity for 50 cm diameter EFG systems
- Develop rotation mechanism for reproducible growth of large diameter EFG cylinders at thicknesses down to 95 microns
- Demonstrate potential for 4x productivity improvements - evaluate limits of rotational and pulling rate stability
- Validate stress model and develop optimal low stress growth system (with SUNY-Stony Brook)
- Evaluate potential for high quality and 16% solar cells on thin wafers (with Georgia Institute of Technology)
- Design viable 1 meter diameter EFG system

Task 6 – Flexible Manufacturing

- Develop database for quality control procedures for EFG wafer manufacturing area
- Integrate SPC in wafer and cell areas
- Deploy alternative plasma etch with reduced wafer damage and acid wastes
- Complete evaluate of sonic detection methods for wafer yield tracking
- Extend data base and field evaluations on glass fracture and power loss
- Apply metrics for reliability and quality control to manufacturing
- Demonstrate liquid encapsulant with small modules
- Evaluate modifications of liquid encapsulant for application in spraying mode

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13. ABSTRACT *(Maximum 200 words)*
This report describes work performed by ASE Americas researchers during the first year of this Photovoltaic Manufacturing Technology 5A2 program. Significant accomplishments in each of three task are as follows. Task 1 - Manufacturing Systems: Researchers completed key node analysis, started statistical process control (SPC) charting, carried out design-of-experiment (DoE) matrices on the cell line to optimize efficiencies, performed a capacity and bottleneck study, prepared a baseline chemical waste analysis report, and completed writing of more than 50% of documentation and statistical sections of ISO 9000 procedures. A highlight of this task is that cell efficiencies in manufacturing were increased by 0.4%-0.5% absolute, to an average in excess of 14.2%, with the help of DoE and SPC methods. Task 2 – Low-Cost Processes: Researchers designed, constructed, and tested a 50-cm-diameter, edge-defined, film-fed growth (EFG) cylinder crystal growth system to successfully produce thin cylinders up to 1.2 meters in length; completed a model for heat transfer; successfully deployed new nozzle designs and used them with a laser wafer-cutting system with the potential to decrease cutting labor costs by 75% and capital costs by 2x; achieved laser-cutting speeds of up to 8x and evaluation of this system is proceeding in production; identified laser-cutting conditions that reduce damage for both Q-switched Nd:YAG and copper-vapor lasers with the help of a breakthrough in fundamental understanding of cutting with these short-pulse-length lasers; and found that bulk EFG material lifetimes are optimized when co-firing of silicon nitride and aluminum is carried out with rapid thermal processing (RTP). Task 3 - Flexible Manufacturing: Researchers improved large-volume manufacturing of 10-cm x 15-cm EFG wafers by developing laser-cutting fixtures, adapting carriers and fabricating adjustable racks for etching and rinsing facilities, and installing a high-speed data collection network; initiated fracture studies to develop methods to reduce wafer breakage; and started a module field studies program to collect data on field failures to help identify potential manufacturing problems. New encapsulants, which cure at room temperature, are being tested to improve flexibility and provide higher yields for thin wafers in lamination.

14. SUBJECT TERMS
photovoltaics ; Photovoltaic Manufacturing Technology ; PVMaT ; manufacturing systems ; low-cost processes ; flexible manufacturing ; edge-defined, film-fed growth; EFG ; high volume

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