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EFG Technology and Diagnostic R&D for Large-Scale PV Manufacturing

Final Subcontract Report
1 March 2002–31 March 2005

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NREL/SR-520-38680
October 2005

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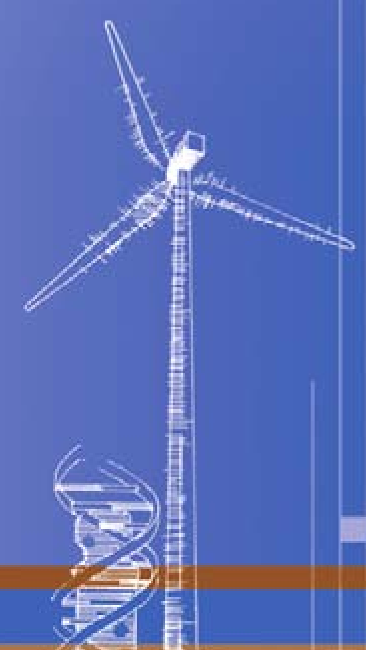

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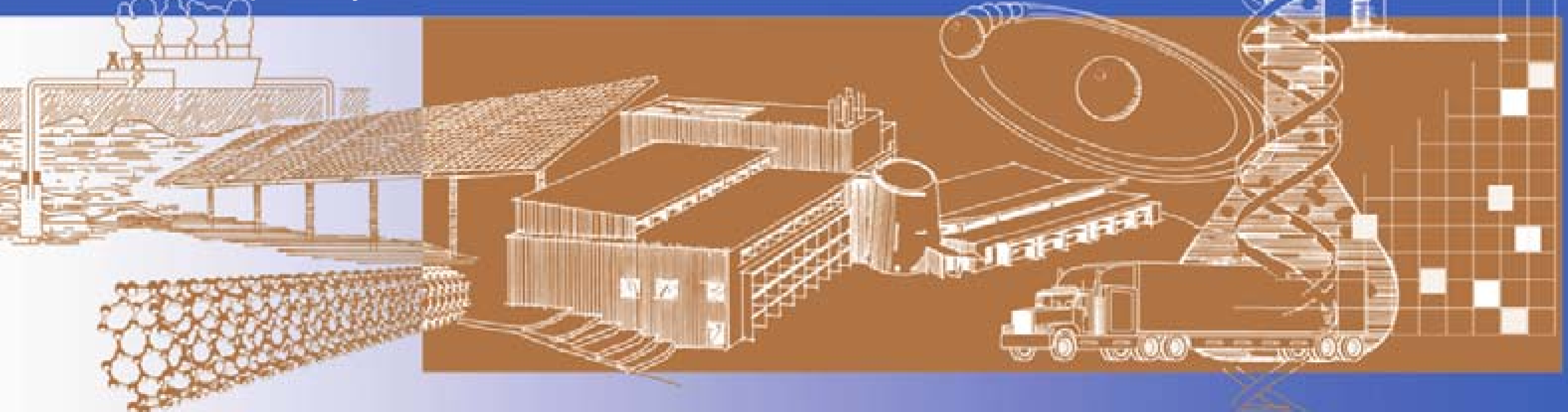

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1.0 Executive Summary

Our final report contains an overview and a summary of the work performed between March 1, 2002 and May 31, 2005 on this subcontract. The objective of this subcontract was to carry out R&D to advance the RWE SCHOTT Solar Inc. (RSSI), formerly ASE Americas, technology, processes, and performance of its wafer, cell, and module manufacturing lines, and help configure them for scaling up of EFG ribbon technology to the 50-100 MW PV factory level. EFG ribbon manufacturing continued to expand during this subcontract period and now has reached over a 40 MW capacity. EFG wafer products were diversified over this time period. In addition to 10 cm x 10 cm and 10 cm x 15 cm wafer areas, which were the standard products at the beginning of this program, R&D has focused on new EFG technology to extend production to 12.5 cm x 12.5 cm EFG wafers. Cell and module production also has continued to expand in Billerica. A new 12 MW cell line was installed and brought on line in 2003. R&D on this subcontract improved cell yield and throughput, and optimized the cell performance, with special emphasis on work to speed up wafer transfer, hence enhance throughput. Improvements of wafer transfer processes during this program have raised cell line capacity from 12 MW to over 18 MW. Optimization of module manufacturing processes was carried out on new equipment installed during a manufacturing upgrade in Billerica to a 12 MW capacity in order to improve yield and reliability of products.

Diagnostic equipment and methodology introduction and improvements for in-line monitoring of critical process parameters have been made in the EFG wafer, cells and module manufacturing areas. Techniques developed and successfully implemented in wafer production (EFG crystal growth and wafer laser cutting and etching) included pyrometer temperature control for the furnaces, in-line flatness monitoring using a buckle sensor, improved data collection and real time analysis for wafer quality and strength monitoring of laser cutting damage to optimize cutting and reduce etchant utilization. Other diagnostic techniques which were developed and brought to a level suitable for evaluation in manufacturing were crack detection, photoluminescence for wafer bulk lifetime evaluation, and a spectroradiometer for cell test calibration. Diagnostic techniques which were upgraded with the help of computer-automated data collection methods included resistivity measurements, bond strength testing, and module lamination process variable tracking.

New EFG growth and laser cutting technology for production of 12.5 cm x 12.5 cm wafers was successfully developed and implemented, and productivity per furnace increased by 25%. Furnace temperature field and stress models were developed and applied to assist in reducing stress during growth and for improving wafer yield. R&D was successful in identifying new laser technology with improved throughput and lowered damage in cutting. This now has been introduced into manufacturing to enhance throughput in the laser area by over 35%, and in producing improved wafer strength and allowing etchant use to be decreased by over 15%. Growth processes for thin EFG octagon tubes down to 250 microns were improved with the help of the models, and thin wafers were processed and made into modules to study factors and barriers in yield. Yields were improved to levels nearly up to those for normal thickness wafers in production. Wafer thickness now is being reduced incrementally in production to evaluate the improvements on a large volume production basis.

In other areas of work on this subcontract, the materials investigation for new encapsulants, backskins and reflecting medium/materials for reflector module design and construction was completed without identifying a robust manufacturing platform with which to proceed in pilot production. We completed introduction of a Computer Management and Maintenance System (CMMS) throughout the wafer, cell and module production areas. CMMS allows us to track production data including yield, throughput, and equipment uptime, performance, schedule maintenance work orders, and provide a searchable log on maintenance history. The CMMS system has been applied in conjunction with diagnostic sensors and techniques to assist in Statistical Process Control and machine Programmable Logic Controller (PLC) operation and performance tracking on

a daily basis throughout production and has become an important and indispensable feature in guiding our day-to-day manufacturing.

2.0 Program Scope

In the first phase, RSSI initiated R&D to develop concepts for and evaluate prototypes of in-line diagnostic equipment in the following areas: monitoring and control of crystal growth temperature fields, crystal (tube) thickness, crystal flatness, crack detection in wafers, bond strength at interconnects, and electronic quality. RSSI evaluated improvements of its wafer technology by carrying out R&D on growth of large octagons of diameters ~38 cm, as compared to the present ~ 30 cm diameter octagon, and on laser cutting of the tubes. We also investigated automation of statistical process control (SPC) methods and Programmable Logic Controller (PLC) monitoring for process and equipment control. A Computer Management and Maintenance System (CMMS) was created after evaluation of our requirements for data management and equipment monitoring in the wafer production area. The primary goals were to improve duty cycle and to assist in preventive maintenance functions. RSSI continued development of a prototype module using a reflector backing material. These results are described in our first annual report. [1]

Phase 2 activities included: continued evaluation and refinement of in-line diagnostic methods; advancement of EFG technology in crystal growth and cutting of large octagon tubes with 12.5 cm faces; continued development of reflector module technology; and implementation of approaches for utilizing intelligent processing methods based on the CMMS platform for data collection and management on the factory floor. Thermal and stress analysis methods were developed to assist in design and improvement of the crystal growth furnace and octagon growth process. A new generation of lasers was evaluated for production and demonstrated higher productivity and reduced cutting damage. Optimization of the acid etchant chemistry used for strengthening the as-cut wafers was carried out to both increase capacity of the etch line and decrease the volume of acid and waste materials produced. Reliability testing of new reflector materials was carried out and reflector design extended to module sizes up to 300 W. The CMMS platform was extended to the cell area and integrated with existing diagnostic techniques.

In Phase 3, we completed demonstration and installment of a number of diagnostic techniques throughout our manufacturing floor. R&D was completed on EFG crystal growth and cutting technology for production of 12.5 cm x 12.5 cm down to thicknesses of 250 microns. Optimization of equipment to raise yields and wafer quality for standard thickness products was carried out. The feasibility of production with EFG wafers as thin as 250 microns on a large scale was investigated. We carried out R&D work on enhancing the throughput of the new cell line through optimizing process steps at higher belt speeds and introduced and tested new design concepts in wafer transfer in the front metallization area, which had been a bottleneck up to this time. Reflector module R&D continued with an emphasis on developing a new materials base for larger module designs, and up to 50 W module sizes were constructed in order to study performance enhancement. We completed extension of our CMMS and data collection networks to module manufacturing and integrated it with the wafer and cell processing areas. Techniques for using PLC equipment information and SPC to enhance performance of our manufacturing were studied.

Papers on this subcontract work were presented at the 29th and 31st IEEE PV Specialists conferences summarizing the progress in our program, and these have been published in the Proceedings volume of the conferences. [2-4] Reviews of the progress of the R&D in our program were given at NREL, including papers at two NCPV DOE Program review meetings. [5-7] The work scope and work completed in individual tasks are described in detail below.

2.1 In-Line Diagnostics

The PV technology for expansion of RSSI's manufacturing facilities is based on production of multicrystalline silicon wafers by the Edge-defined Film-fed Growth (EFG) technique. This task addressed the development and evaluation of diagnostic needs and equipment for monitoring of the manufacturing line processes and product quality. The procedure used to address this task was as follows: (1) survey our requirements for diagnostic equipment, (2) inventory our available equipment, (3) evaluate the most promising methods for upgrading methods or equipment where needed, and (4) optimize and upgrade methods or equipment for monitoring and controlling critical process steps in the wafer, cell, and module manufacturing areas. The results of this effort are summarized in Table 1.

Table 1. Diagnostic methods and equipment upgraded or optimized during this program.

Area	Diagnostic approach(es)	Targeted procedure	Status
Wafers			
EFG furnace - die temperature	Remote pyrometer sensor	Continuous/automated	Installed and operative
Tube thickness	IR sensor	Continuous/automated	Vendor equipment identified and acquired for testing.
Tube flatness	Capacitance sensor	Automated – in-situ growth measurement	Installed and operative
Crack detection (both after laser cutting and at interconnect)	Acoustic or laser sensor	Automated	Ultrasonic vibration technique evaluated and equipment in test phase
Wafer Strength	Fracture twist test	Statistical/daily	Installed and operative
Cells			
Sheet resistivity	Four point probe	automated sampling	Manual entry to QC data base established
Bulk quality	PL or μ-PCD	PL/statistical- daily	Equipment acquired and in testing
AR thickness and n_R	Ellipsometer	<1 s/wafer, manual	Installed and operative
Cell tester spectrum	Spectroradiometer	Periodic calibration	Class A achieved
Modules			
IC bond strength	Pull test	Statistical/daily	Installed and operative
Glass	Defect inspection	Manual	Completed study and established procedures for automation
Lamination	Process control of temperature/pressure	PC based	PC monitoring equipment installed, procedures in development.
Wiring/Hi-pot testing	Continuity	Manual inspection	Procedures established and operative

Further details for a few of the items listed above are provided in the following sections. A general statement regarding the path taken for this work is that monitoring of manufacturing processes and product quality at RSSI has historically been carried out manually and with off-line methods. As the throughput of our equipment increases and demands are made to reduce labor costs, it is becoming more and more necessary to implement in-line, automated methods to monitor manufacturing processes and guide improvements. In our vertically integrated manufacturing facility, we are concerned here with diagnostic tools which span all areas from silicon preparation through module production. Requirements for on-line diagnostic techniques vary depending on the process step and the type of information that is required. Although, in principle, it would be ideal to sample each and every part with a given diagnostic approach, this is not possible in an actual manufacturing setting. We have studied, therefore, a variety of statistical sampling techniques for several of the monitored parameters. In general, there are several levels of diagnostics and controls available, ranging from operator-intensive manual operations to highly automated computer-aided measurements.

Wafer production diagnostics: Since several expansions have already been completed in EFG wafer production (comprised of crystal growth and laser cutting processes), the diagnostics development is the most mature there. CMMS (see Section 2.4) was the first to be installed and demonstrated in crystal growth and laser cutting, and automated data collection has been established for a number of process parameters. Process control software has been installed on crystal growth furnaces for monitoring certain growth variables on a continuous basis – such as temperature and buckle amplitude on a given tube face. (The latter parameter is a measure of the flatness of the tube face, which has a relation to the flatness of wafers cut from the tube.) A method suitable for measuring thickness on-line during tube growth simultaneously on all faces of the octagon has been demonstrated. This equipment has been purchased and will be installed on one furnace for optimization and integration into control algorithms. This method allows thickness measurement of the growing tube *in situ*.

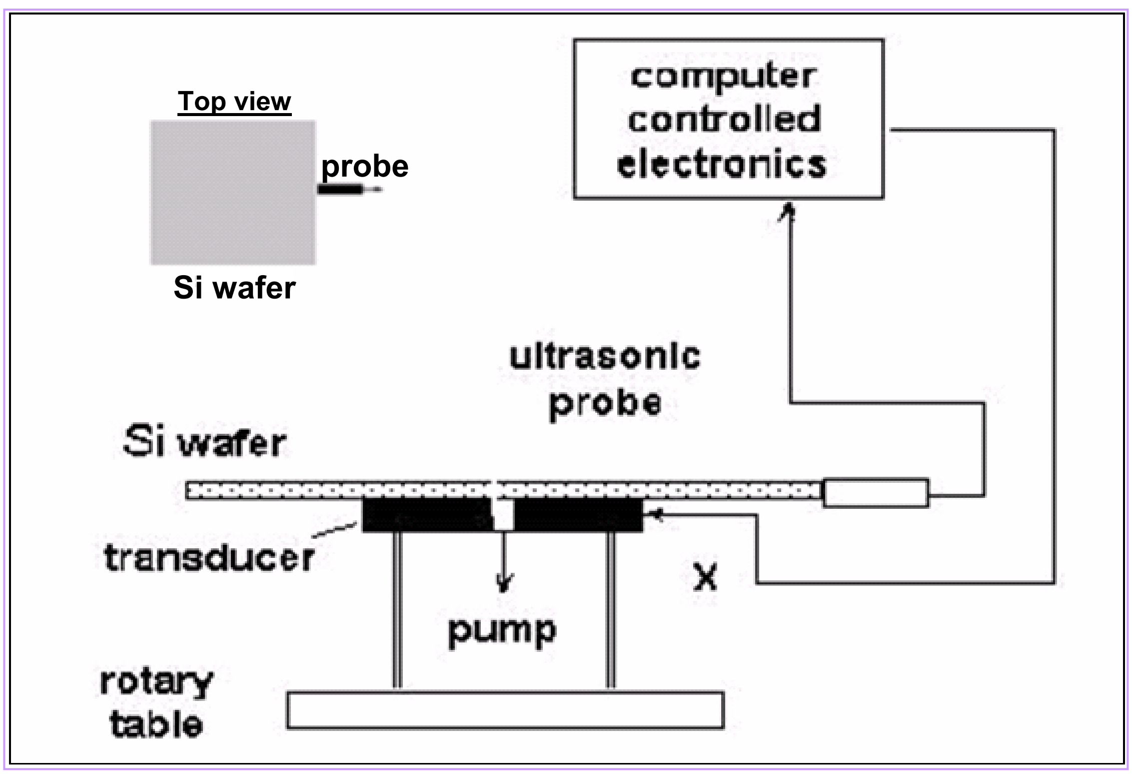


Figure 1. Ultrasonic crack detection apparatus schematic. [Courtesy of the University of South Florida (USF)].

In the laser cutting area, investigation into several methods resulted in identification of ultrasonic crack detection technology as the best candidate to provide accurate data on crack generation during cutting and simultaneously meet future throughput needs. Equipment was specified which could scan a wafer or cell in 1-2 s and hence be used in an in-line setting. R&D was carried out in a lower-tier subcontract at the University of South Florida to develop and demonstrate a manual test station which has the potential to be automated for production line use. A schematic of this equipment appears in Fig. 1.

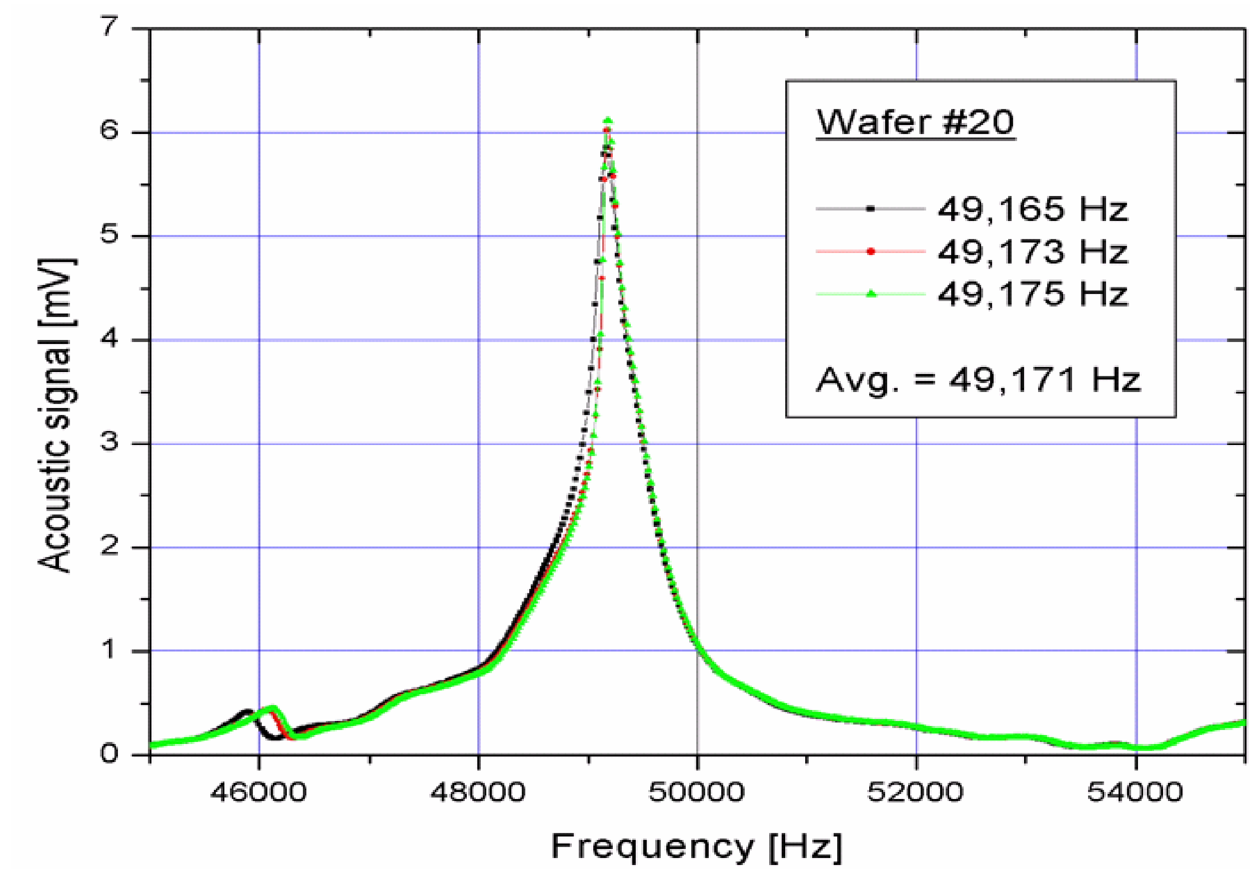


Figure 2. Multiple scans of a silicon wafer by ultrasonic crack detection apparatus showing excellent reproducibility. [Courtesy of the University of South Florida].

Both cracks and residual stress cause shifting of the resonance frequency of the induced acoustic signal emanating from a wafer tested in the apparatus, as well as a broadening of the resonance. The extent of the shifting and broadening depends upon the stress level and the length of the crack. It is straightforward to automate this system to provide a pass/fail analysis for cracks of a user-adjustable crack length. An example of an EFG wafer resonance frequency spectrum obtained with the system, described above, is shown in Fig. 2. Measurements repeated multiple times on the same wafer show excellent reproducibility, as the three scans made here indicate. Both wafers and cells can be analyzed with this method.

Cell Line Diagnostics: Diagnostics were upgraded to aid in enhancing the throughput for a new cell line, comprised of diffusion through cell test processes, which was installed at RSSI's facilities in Billerica in 2003 (Fig. 3). Its original capacity was estimated at 12 MW/yr. One program task was to adjust processing conditions and upgrade process equipment to first reach a 2.7 s per wafer cycle time, and then a 2.3 s per wafer cycle time, the latter pushing the nominal line capacity to 18 MW/yr. The correlation between cycle time and capacity is provided in Table 2. Cell line capacity can also be increased by increasing the wafer area. Long range targets call for cycle times to be reduced to the order of 1-1.5 seconds for 12.5 cm x 12.5 cm wafers–using the same basic technology set existing today, with the necessary modifications to obtain the faster cycle times– resulting in single line capacities exceeding 50 MW/yr. [2]

Figure 3. New cell line at RWE SCHOTT Solar in Billerica.

Table 2. Capacity parameters for RWE SCHOTT Solar cell line upgrades

Cell Technology	Cycle time (s)	Parts per hour*	Annual capacity
Baseline 2002	3.6	1000	~12 MW
New Billerica line	3.0	1200	14 MW
- upgrade 1 (achieved)	2.7	1325	16 MW
- upgrade 2 (achieved)	2.3	1550	18 MW
Long term goal	1.2	3000	55 MW*

** The last capacity value assumes introduction of 12.5 cm x 12.5 cm wafers.[See also Ref. 2]*

The specifications which set the wafer transfer/cycle times for the processing equipment simultaneously constrain diagnostic tools which are to be used on-line if parameters are to be monitored on a continuous basis. It has been found that, in general, the cell line can be maintained without needing to continuously monitor wafer or cell properties per se; rather, process parameters such as temperatures, relative humidity, water flows, chemical flows, and air pressures are what need to be continuously monitored to maintain process control on the line. Automated access to these parameters was built into the PLC monitoring systems of the new equipment. This allows now to: 1) set warning and out-of-specification parameter limits beyond which the equipment will sound an alert or alarm; 2) store machine parameters and process settings on a regular time interval to enable the display of historical trending, and 3) provide the capability for remote monitoring of process values.

At a minimum, diagnostics tools for monitoring wafer and cell properties must have cycle times which are sufficiently fast to enable operators to make statistical sampling during their work. Sheet resistivity provides a good example of such a diagnostic tool we examined and updated to better meet the needs of our new cell line. While we do not need to check every wafer for sheet resistivity, our sampling means were upgraded by replacing our four-point probe with a newer, easier to use and maintain model. We also provided a data entry terminal, which both calculates the averages and stores the information into a database for later retrieval and trend analysis. Ellipsometrical measurement of our AR coating film thicknesses and index of refraction is another example where upgrading was in order. In this case, our equipment was too slow to minimize operator wait time when the new cell line was initially procured, as the information is needed quickly during routine start-ups to make adjustments to bring the process to within specifications. A new ellipsometer was identified and procured, which brought the measurement time down from 45 s on the older equipment to < 1 s on the newer equipment, easily meeting our needs.

A new diagnostic tool evaluated and introduced for routine use in the cell line during this program was the spectroradiometer, which was used to measure and adjust the lamp spectrum in cell testing. Reliable and reproducible procedures were established to provide rapid assessment of the lamp spectrum, to check the quality of new lamps, to monitor lamp life, and to diagnose equipment malfunctions. This improved the accuracy of cell test data. In Fig. 4, the lamp spectrum is plotted over the course of its useful life, showing that while the total lamp output is kept constant, there is a decrease in output at the near UV end of the visible spectrum, and an increase in output at the near IR end of the spectrum. This knowledge helps us to judge the accuracy of our testing and subsequent binning for module fabrication. Degradation effects are tracked, as in this case the light output falls into Class A during its initial hours, falling into Class B for the near IR region as the lamp ages. The spectroradiometer was used to obtain the data necessary for working with our suppliers to achieve a Class A spectrum, which is now routinely maintained in manufacturing.

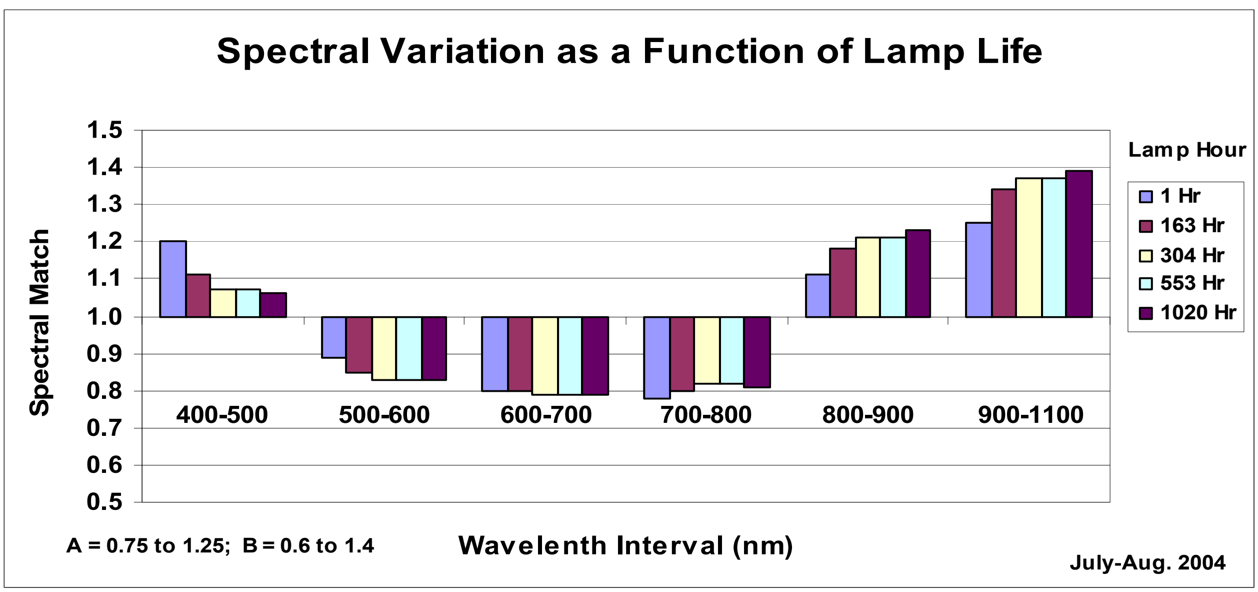


Figure 4. Spectral aging for solar simulator lamp in new cell line as determined using a spectroradiometer.

Room temperature photoluminescence (RTPL) was selected as a potential method for monitoring minority carrier lifetimes because of its flexibility to be applied throughout the manufacturing line, from as-grown wafers to cells, and can be used to assess process improvements and improve cell efficiencies [7]. Figure 5 gives an example of a map of an EFG wafer made with this method. While methods such as microwave photoconductivity decay are conventionally used to measure lifetimes, they generally either require special sample preparation or are limited to certain process steps where they can be suitably applied.

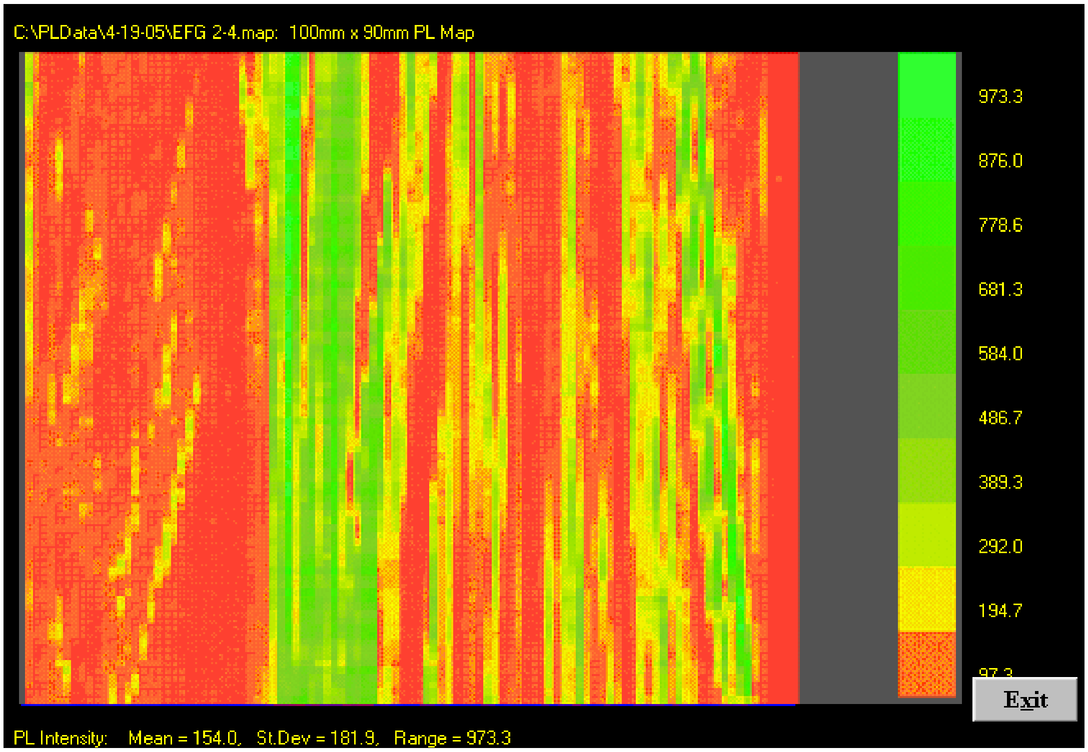


Figure 5. Full area photoluminescence mapping of an EFG silicon wafer.

PL measurements have particularly proven helpful for diagnosing impurity variations in crystal growth. Specifically, with 40 different growth furnaces, it is not practical with the new high speed, high volume cell line to track the efficiencies of individual tubes of 400 wafers each. Production staff can more efficiently run the cell line at lot sizes of 100,000-200,000 wafers each. However, keeping track of individual tube lots before cell fab is standard practice. Thus, by taking PL measurements on wafers just after the Si etch step, at a point where the furnace and tube identity is still known, we have found that statistically meaningful differences can be found from furnaces with variations in impurity levels. The band-to-band PL signal strength shows good correlation with resulting cell efficiencies in experiments where both measurements were tracked. Getting the PL data is also timelier than getting cell data and involves no interruption to the cell line, also increasing throughput on average. We now can optimize crystal growth variables while minimizing the number of experiments which would otherwise be needed to improve material quality.

Module Line: New module equipment was evaluated, installed, and made operational during this program. This included several interconnect machines and laminators. R&D was carried out to update in-line diagnostics for this new manufacturing equipment. Work was carried out to automate data collection for both the strength of the interconnection to busbars and the backside solder pad locations. An example of the type of SPC charting which resulted is given in Fig. 6, which depicts the performance of bond strength for two different interconnect machines. The lower control limit

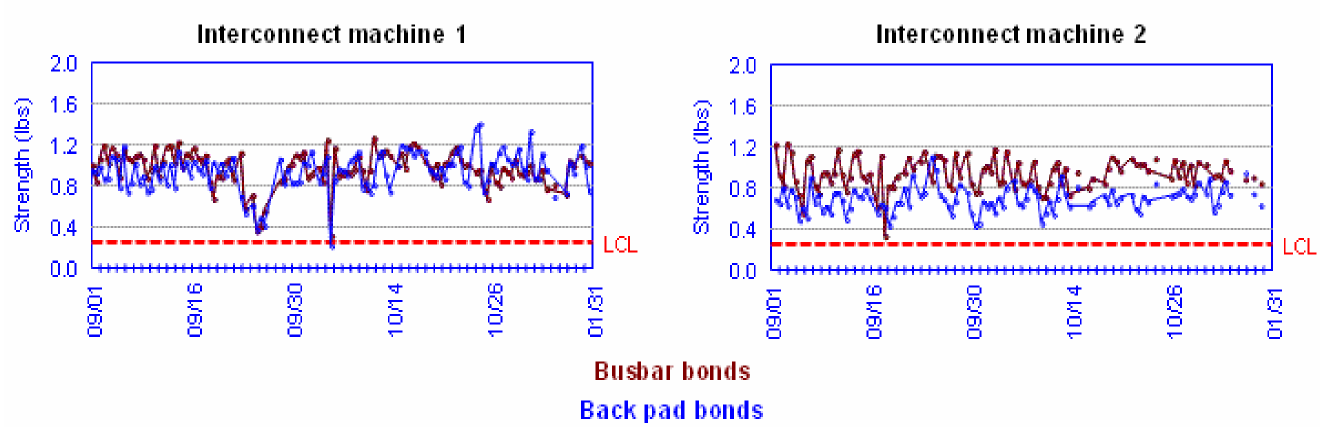


Figure 6. Bond strength SPC charts for two interconnect machines in module manufacturing.

(LCL) of 0.25 pounds ensures good product reliability. While there are some small performance differences between the two machines, both provide performance well beyond the minimum requirements. The SPC charting is shown to be a good diagnostic tool in assessing the product quality in our high speed module manufacturing environment and to increase operator awareness of the need to evaluate equipment performance and material quality.

In summary, this task has demonstrated prototype equipment for in-line temperature field monitoring; control algorithms for crystal growth and EFG tube thickness and flatness measurement; in-line equipment for detecting cracks in wafers and cells; and statistical methods to use in the application of wafer fracture strength testing. Methods for bulk electronic quality measurements using PL, resistivity sampling after diffusion, bond pull strength testing for interconnect evaluation, and cell calibration have also been implemented. The use of diagnostic tools has been helpful in maintaining quality while we have upgraded our cell line capacity from 12 to 18 MW.

2.2 EFG Manufacturing Technology Scale Up

A central focus of our program over its 3 years has been to extend EFG wafer production to 12.5 cm x 12.5 cm wafer sizes by completing the development of a new generation of large diameter EFG furnaces for growth of octagons with 12.5 cm faces, as well as laser cutting stations capable of handling and cutting these octagons. This development was initiated in our previous PVMaT program, where feasibility of growth of a 50 cm diameter EFG tube was demonstrated. As a result of the developments in the competitive marketplace, this feasibility demonstration was channeled into R&D on demonstrating manufacturing readiness of a larger diameter EFG furnace, increasing productivity by 25% over the standard 10 cm face octagon already in production.

The design and improvement of the EFG octagon growth technology has been supported and accelerated through the development and application of temperature field and residual stress models of the EFG growth process and the furnace. The larger dimension EFG wafer has made it possible to expand EFG wafer-based production with 12.5 cm octagons and extend this advantage to cell and module production using EFG wafers, and helps maintain the competitive position of EFG technology with respect to ingot-based technologies. The increase in scale of the octagon crystal in comparison to the 10 cm face EFG tube is illustrated in Fig. 7 below.

Laser station productivity was enhanced and labor costs decreased by 35% by R&D on a new generation of higher cutting speed lasers and the improvement of cut patterns to decrease average cut time per wafer. We summarize below the work and accomplishments of this task in bringing the larger diameter octagon and laser cutting technology to yield and quality levels which are competitive with those of the mature 10 cm x 10 cm EFG wafer manufacturing in Billerica.

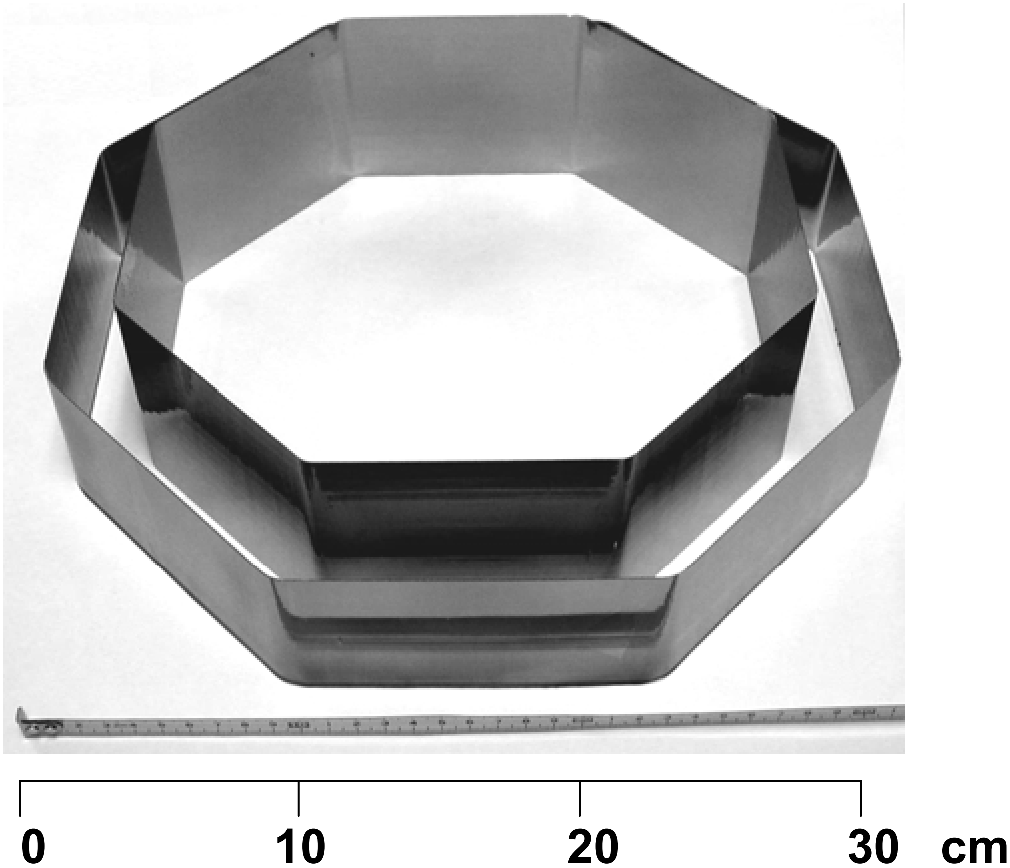


Figure 7. Perspective on the size of the 10 cm and 12.5 cm EFG octagon tubes.

Crystal Growth. We completed and demonstrated competitive cost levels for 12.5 cm-face width EFG octagon growth in order to produce wafers at a throughput and yield sufficient to justify the initiation of large scale manufacturing of 12.5 cm x 12.5 cm EFG wafers. In-line diagnostics developed in the task above were applied to raise 12.5 cm wafer quality, both with respect to mechanical and electronic characteristics, and we achieved a level of productivity in these areas on par with our current production 10 cm octagon growth systems. One aspect of this work has involved developing sensors which improve furnace temperature control and which track wafer flatness during growth, as noted in the diagnostics development task. Another aspect was support work for improving hot zone designs and shortening the engineering steps and time required to develop new crystal growth concepts, which was carried out with the help of lower-tier, university subcontracts. Magnetic field and thermal models of the EFG large diameter system hot zone were developed and applied to engineering design by Stony Brook University. The temperature field information was used to guide stress analysis of the growing tube at another subcontract at Harvard University in order to improve material properties of wafers.

In Phase 1 of our program, EFG furnace development work focused on improving the design of the EFG furnace for production of 12.5 cm x 12.5 cm wafers. A prototype furnace design was recommended for production at the end of Phase 1, and we continued to improve and optimize the design throughout Phases 2 and 3. This effort has culminated in a production line of about 15 MW for 12.5 cm EFG wafers. Octagon tubes with 12.5 cm faces are now being routinely grown in a manufacturing setting to lengths of 6 m, with average growth speeds of 1.5 cm/min (0.6 in/min). While production EFG furnaces were being constructed, installed and optimized, the concurrent

R&D work focused especially on improvement of wafer properties in areas of better thickness uniformity and reduced residual stress. As a result of improvements, the average thickness of 12.5 cm x 12.5 cm EFG wafers produced in manufacturing has now been reduced from 400 microns at the start of the program to 300 microns while maintaining yields acceptable for a high volume manufacturing facility.

At the same time, we have concentrated in the latter stages of our program to grow and characterize tubes at a 250 micron thickness level in order to ready this reduced thickness EFG wafer for introduction into manufacturing. The thickness non-uniformity encountered in this R&D and traced to shortcomings in the present furnace design became a critical near-term issue that made it clear that 250 micron thickness EFG wafers could not be produced with yields suitable for production without additional furnace hot zone redesign. While stress limitations to growth lead also to unacceptable non-flat or buckled ribbon as thickness decreases, it can be mitigated by slowing down the growth speed and sacrificing productivity in the short term, while solutions to stress reduction are developed. The issue of thickness uniformity requires improved thermal balance in the hot zone, involving strategies such as on-line thickness measurement diagnostics, feedback loops for *in situ* growth modifications, improved mechanical alignments of furnace hot zone components, and dynamic modifications of heat transfer/isotherms during growth during transient phases of growth. All these elements are being addressed in crystal growth furnace redesign in developing them further to raise yields of 250 micron thick wafers to ready the thinner EFG wafer technology for production.

An example of the progress we made on improving flatness of the thinnest 12.5 cm octagon tubes down to the range of 200-250 microns through application of our combined thermal and stress analysis techniques and diagnostic tools is illustrated in Fig. 8 below. Three hot zone configurations designated by G8, E3 and G27 denote furnace hot zones with successively improved tube material characteristics and flatness achieved by modifying the hot zone components through repeated iterative application of the stress analysis, as well as the furnace and growth models. At the start of

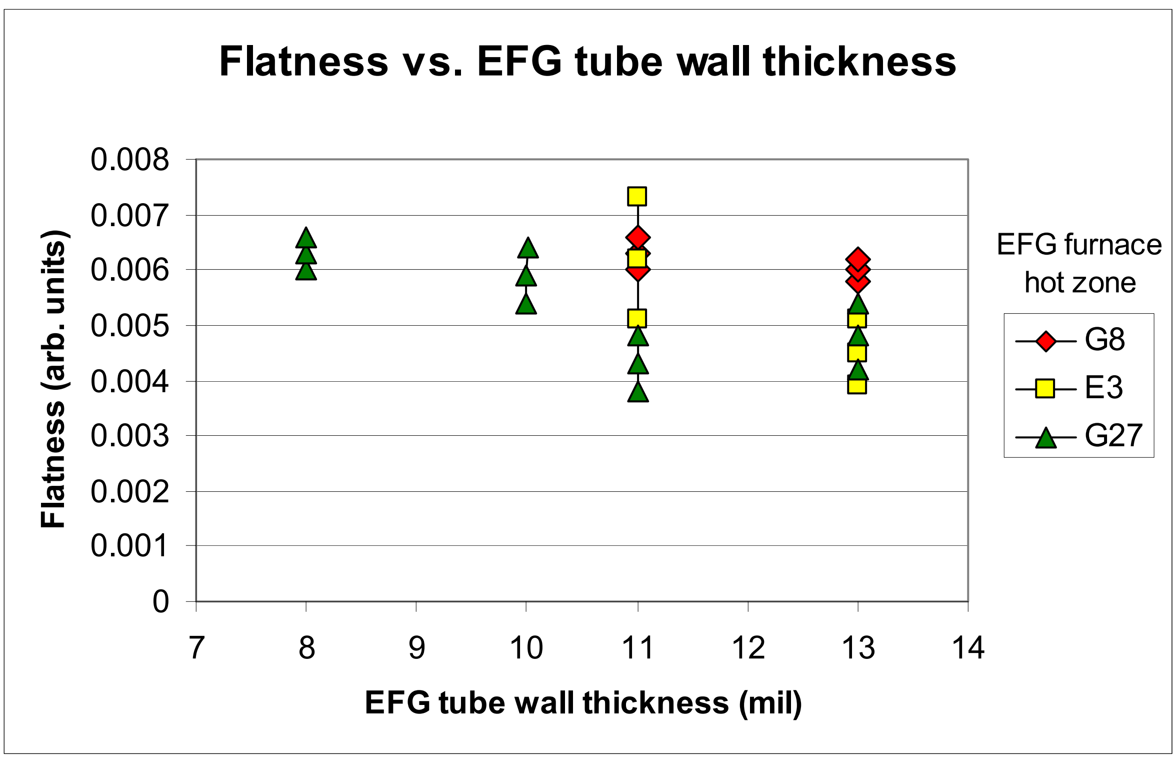


Figure 8. Plot of flatness metric as a function of tube wall thickness. A level of approximately 0.002 corresponds to a flatness yield of > 98%. All runs are for a 12.5 cm EFG furnace.

our program, our baseline hot zone configuration, G8, was capable of achieving flatness metrics of only about 0.006. By the end of the program, the best configuration, G27, lowered this metric to the range of 0.004-0.005. Equally important, we now are capable of producing much thinner tubes in the range of 200-250 microns from G27 with flatness no worse than that of the starting baseline 400 micron (16 mil) material made from G8, and the flatness of 275 micron (11 mil) tubes from G27 is as good as that of thicker tubes from G27.

Thin wafer acceptance in manufacturing depends not only on the wafer properties, but also on the ability of equipment in cell and modules manufacturing to handle thinner wafers. A separate task was organized to study the impact that the decrease in wafer thickness has on yield in various critical steps of the overall manufacturing line. This effort is discussed later in this report.

While the major R&D challenge for the task of high volume manufacturing of both larger and thinner EFG wafers has been to lower stress, an equally challenging effort was to improve the thickness uniformity of the wafers. The source of wafer non-uniformity arises from thermal asymmetries around the perimeter of the tube, which makes narrowing the range of the thickest to thinnest wafers produced an important task in improving the performance of EFG wafers in cell and module manufacture. In the current design of the 12.5 cm furnace, we have determined that we have reached the limit of uniformity that can be achieved with adjustments in a single main heating coil. These limits also apply to plans for a 15 cm face-width octagon furnace based on the same 12.5 cm face octagon EFG furnace design and technology. We have thus concluded that the larger face octagon would not be capable of performing at yield and throughput levels that are cost effective until these problems are resolved through a redesign of the crystal growth equipment.

Laser Cutting Technology R&D. Cost reductions in laser cutting are primarily driven by labor content. We have explored more effective utilization of lasers, evaluated a new generation of high speed lasers, and studied the concept of cutting simultaneously on opposite sides of the tube with two lasers in this program. A higher speed laser was introduced and successfully tested in production in Phase 2 of our program. This laser can cut up to 1.6 in/s as compared to 1 in/s of the current production laser, and has a higher duty cycle due to a more robust design and use of fiber optics cables in place of mirrors for beam delivery. Together with a streamlining of the cut pattern for the wafers in order to remove dead time, this laser has been demonstrated to lead to greater than a 20% increase in capacity of a laser station, with a commensurate 35% decrease in labor costs, surpassing program goals.

We have developed a design and written specifications for a new laser station, which could employ two lasers to double wafer production rates per station. The economics of retrofitting our production lasers is not favorable at this time, although this design strategy will be useful for future EFG wafer factory expansions.

Other improvements in laser technology have come with the help of applying diagnostic methods for testing of wafer strength (Table 1) and improved information collecting networks, facilitated by CMMS. The four point twist test described in a previous report [1] has been applied successfully to identify deficiencies in laser focusing and equipment malfunctions, such as in wafer backpad alignment, and wafer etching shortcomings. This method is now routinely used in the manufacturing line for wafer mechanical strength monitoring. As a result, we have been able to optimize EFG wafer strength and increase the average strength as measured by the fracture twist test diagnostics by a factor of two with respect to the beginning of the program. This has contributed to a decrease of mechanical yield losses by a relative 40% in the cutting step alone. It is estimated that several more percent absolute in mechanical yield improvements have come from raising the average performance level and reducing variability in the cut EFG wafer strength through laser performance optimization.

In summary, on the basis of the work we have carried out in this program, we conclude that growth and cutting of 250 micron thick EFG wafers up to 12.5 cm dimensions can be carried out at levels acceptable to carry on trials on a manufacturing scale. However, additional gating factors on the acceptance of the thinner wafers in manufacturing remain in the cell, interconnect and module areas for a number of reasons: EFG wafer strength after laser cutting, buckling/flatness, and residual stress. Emphasis in R&D now has shifted to carry out large scale studies of yield of wafers in our cell and module fabrication areas at wafer thicknesses of ~250 microns. These experiments will provide data and arrive at firm conclusions as to what modifications in process steps and in the cell and module manufacturing equipment are necessary to accommodate thinner EFG wafers than we process currently.

2.3 Reflector Module

This task continued R&D on a reflector module design demonstrated and patented on a previous DOE/NREL subcontract [1]. This design effectively decreases the silicon required per unit of module output. The central objective of this task was to reduce the cell requirements by 25%, while maintaining the rated baseline module output power. Additionally, this task developed and reported on a manufacturing strategy for reflector modules, data on encapsulant and backskin evaluations, and a manufacturing floor layout for production of the reflector module.

In the reflector module, a light-reflecting film is placed behind the cells. This film concentrates incident light, falling in intentionally large spaces left between cells, back onto the cells. Figure 9 shows a reflector module with a preferred design, which incorporates thirty-six 5 cm x 10 cm cells with an R&D embodiment of a test reflector material showing in the approximately 2.5 cm spaces between the cells. The cost benefit from use of the light enhancing film results from a reduction in the number of cells required to attain a specific power from a specific module area compared to the number required in a standard design terrestrial module of equal power and area.

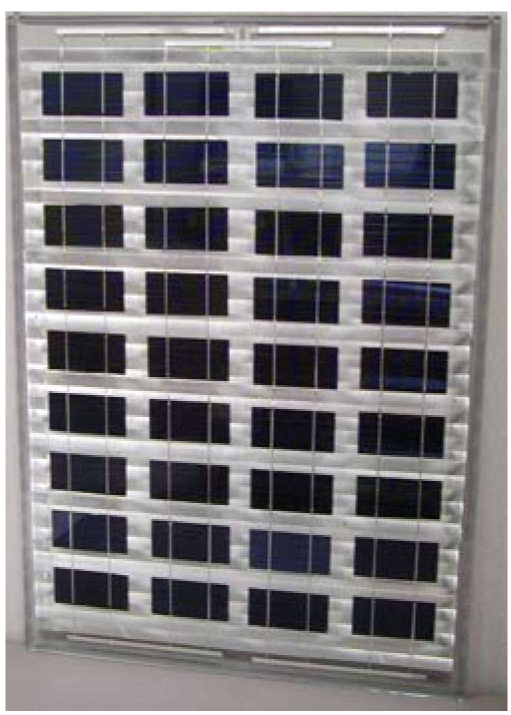


Figure 9. Reflector module incorporating thirty-six 5 cm x 10 cm EFG cells.

In Phase 1, RSSI carried out investigations on reducing module costs by completing a design and fabrication of a number of prototypes of a reflector module with a novel backskin material. In Phase 2, the work effort included scaling up module design to a 300 W module size, while developing manufacturing methods for modules of the type shown in Figs. 9 and 10 for outdoor performance verification and for environmental testing in both outdoor exposure and in accelerated temperature/humidity cycling. Stress analysis of various laminate material combinations was carried out to evaluate safety factors in design and determine stress-related causes of module failure in reliability testing.

Prototype reflector modules were manufactured and provided to NREL for performance verification at regular intervals during the program. Reliability problems were first seen in larger modules with the construct of a single glass and backskin shown in Fig. 10. Stress analysis was undertaken through a collaboration with Harvard University to determine stresses arising in the laminate which could affect module reliability, and it was determined that the chosen materials produced stresses that likely lead to delamination of the kind seen in the environmental tests. Significant glass/encapsulant interface stresses were found to arise as a result of thermal expansion mismatch between several commercial backskin materials and the glass. The tensile interface stress generally may be compensated by compressive stress imposed in framing. Thus, a frameless module configuration would be undesirable; furthermore, it has the potential for delamination at the module edges under the action of this mismatch stress if the glass/encapsulant bonding strength were to be reduced by any means, e.g. by defective manufacturing processes (poor priming) or environmental degradation in the field (moisture). We completed this analysis with other encapsulant/backskin material systems, which have the potential for reduced interface stress.

As a result of a concern for module reliability due to the potential for delamination predicted by the modeling, the R&D in the last year of the program investigated material compatibility issues associated with encapsulant and backskin materials, as well as on the effect of chemical effects at encapsulant-glass interfaces and alternate backskin/encapsulant systems. Significant mitigation of risk related to stress build up and delamination potential was not accomplished, and an acceptable design and materials base for commercialization of the reflector module were not found.

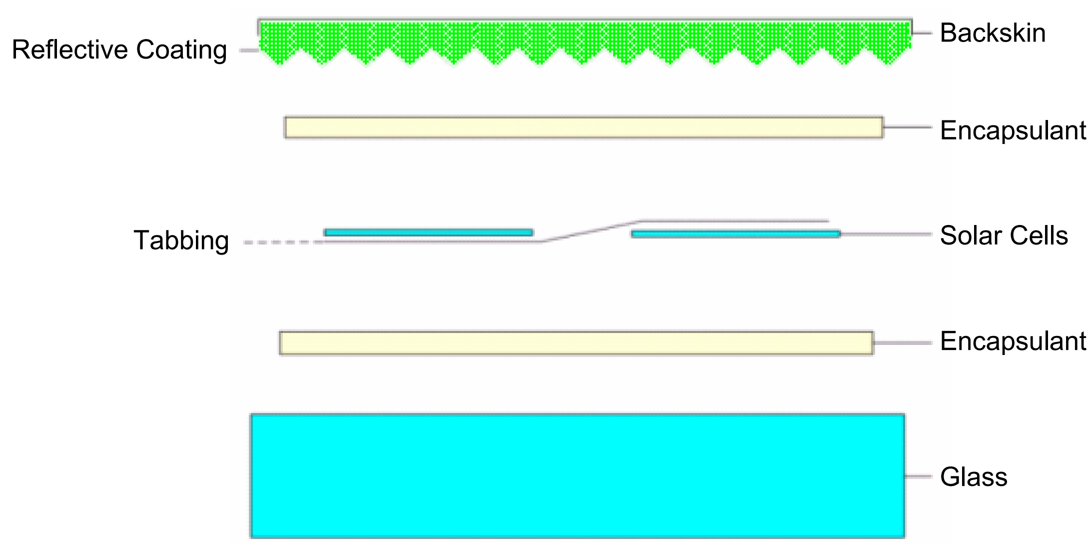


Figure 10. Schematic of reflector module laminate layout.

2.4 Intelligent Processing

This task had three main aspects: (1) to develop a Computer Maintenance Management System (CMMS) at RSSI in all three manufacturing areas (wafers, cells, modules); (2) to automate manufacturing diagnostic tools and Statistical Process Control (SPC) techniques; and (3) to utilize the benefits of these intelligent processing techniques to increase throughput, efficiency, yield, and reduce acid waste. Each aspect is described in further detail below.

Development of a Computer Maintenance Management System (CMMS). The main goal behind implementing the CMMS was to reduce overall manufacturing cost and improve operation efficiency. Details of the CMMS system architecture were described in our first year annual report [1]. The main features of the architecture are as follows. At its foundation are relational databases stored on central SQL servers. Internet technology provides a gateway for users to access the database. Accepted programming languages were used to build the front-end user interfaces. Querying rules are implemented both through stored procedures in the SQL servers and class libraries in the codes. The user interfaces are presented as a series of HTML pages. The system is deployed on RSSI's existing communications intra-network. This eliminates the need for deployment of special programs on each individual client computer: all that is needed for a client computer to run the program through a web browser, such as Internet Explorer or Netscape Navigator. Since it is on our intranet and not the internet, the system is secure. The system can also be accessed from overseas corporate locations.

Main subsystems of the CMMS include:

- Repair order requests and tracking
- Repair parts inventory management
- Automated PM scheduling
- Equipment Downtime Tracking
- Utility monitoring and control, and
- Wireless access

Examples in some of these areas follow.

Repair order requests and tracking. Work orders track the requester, the request, those doing the repair, the work done, the downtime, parts used, and whether the work order was Urgent (U), Normal (N), or Preventive (P). One can query the system in many different ways, with hyperlinks and indexes providing for quick gateways to additional information. The example provided in Fig. 11 provides a list for different pieces of equipment used in Cell Fabrication, showing the frequency of each type of work order which occurred in a user-selected period, here defaulted to the last 30 days. Clicking on the equipment link provides summaries of each work order including a work order number, and further clicking on a work order number provides all details associated with that work order.

Repair Parts Inventory Management. This system module consists of: a barcode labeling system; a wireless inventory auditing capability with a handheld PC or PDA; and the software modules for ordering, receiving, and tracking machine parts. Figure 12 demonstrates a minimum balance report off the machine parts inventory system. It shows records of machine parts that have quantities on-hand below certain specified minimum threshold values. The system alarms users by highlighting the row of the machine part in red if an order has not been placed for that part. Other screens call up part orders placed between two given dates, listing purchase order numbers, order dates, vendor information, and order status. Clicking on the PO number links to the details page of that particular

Closed WO | Index | Start: | End: | Submit

# of Work Orders by Machine: Last 30 Days

MachineID	Machine	U	N	P
2107	AR Coater2	3	9	1
2106	AR Pallet Loader	2	2	3
2108	AR Pallet Unloader	1	0	0
2001	AR1 Bottom	0	5	1
2002	AR1 Top	2	6	1
2003	AR2 Bottom	0	6	0
2109	Back Metal Loader	0	4	0
2110	Back Metal2	4	13	0
2117	Cell Tester2	13	6	0
2104	Diffusion Furnace2	1	0	0

Figure 11. Compilation of work orders of varying priority over a one month period in Cell Fabrication.

order. Also listed on the screen is information on the number and percentage of the orders that were placed as emergency. Emergency orders may require added cost or cause extended equipment downtime.

Automated Preventive Maintenance (PM) Scheduling. The Automated PM Scheduling system consists primarily of a PM Tasks table, a PM Schedule table, and a series of class libraries codes and SQL stored procedures. Users first create and enter the PM tasks to the task table for each machine category, e.g. growth pullers, laser cutters, or cell testers, etc. A step-by-step procedure instruction is also created for each PM task. The PM task defines the frequency of the scheduling for each machine category, and the type of PM to be performed by technicians or production operators. After a PM task has been entered into the system, a new PM schedule can be created for an individual machine by entering the PM Task ID, the machine ID, and the time when the first PM task is to be performed. A PM scheduling screen with this information tabulated for any time period can be called up by the user. The table in the screen updates each time it is open. Overdue PM schedules are highlighted in red. Clicking on any entry on the Task ID column brings up the individual PM task information page, which then links to a step-by-step instruction page for that particular PM task.

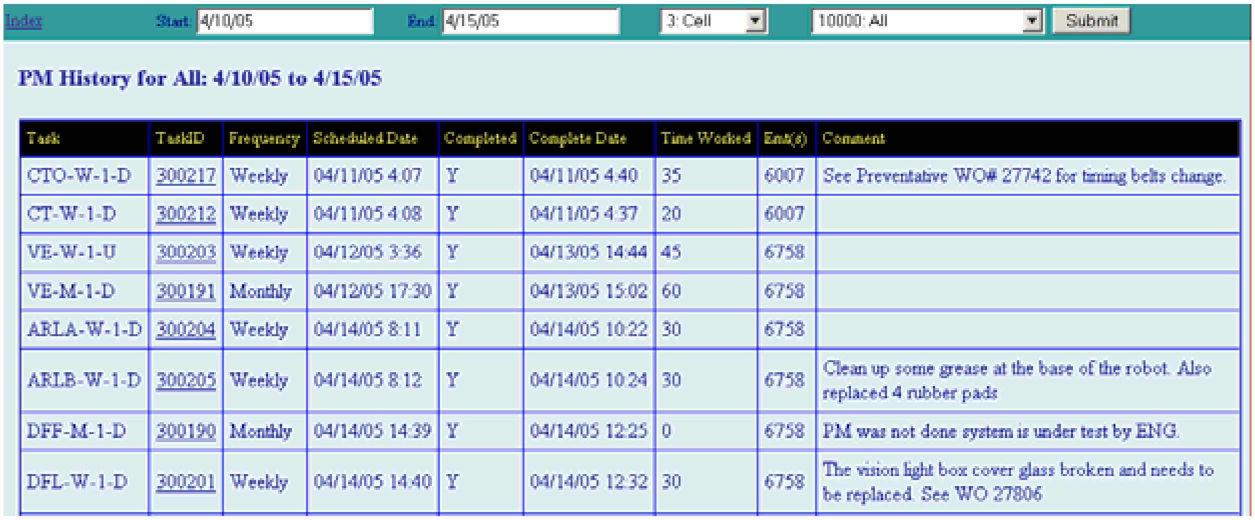
Min Balance Report — Tuesday, May 04, 2004 1:49 PM

Part#	Part Name	Max Qty	Min Qty	OnHand	OnOrder	Order Date	Due Date	Price	Cost
1001724	belt, drive belt 10T5/1000BFX	24	3	1	15	2004-04-29		$12.40	$186.00
1002122	Lamp, Ushio type JC 24V20W G4	25	2	1	20	2004-04-26	2004-05-10	$4.07	$81.40
1000217	MAC Valve 24VDCX5.4W	10	2	1				$38.50	
1002051	Motor, DC gearmotor (Pittman)	125	10	2	100	2004-03-19		$81.19	$8,119.00
1000249	Shield, Bent with tube 100mm Rt	4	2	1	2	2003-11-26		$279.95	$559.90
	Total Cost:								$8,946.30

Lines Min-Balanced/On-Order: 5/4. % of Min-Balanced Lines: 0.2

Figure 12. Parts Inventory Minimum Balance Report; highlighted row indicates item which requires reordering.

After a PM task is complete the actual time worked on the PM task by a technician or an operator is entered into the system. The system then automatically generates the next PM schedule for the same task on that machine based on the frequency of the given PM task. The system also allows for rescheduling of any PM task that has been entered for any given machine. It also provides reports to summarize PM history for a given machine or manufacturing area in any time period. An example of a PM history report for a subset of equipment in Cell Fabrication is shown in Fig. 13.



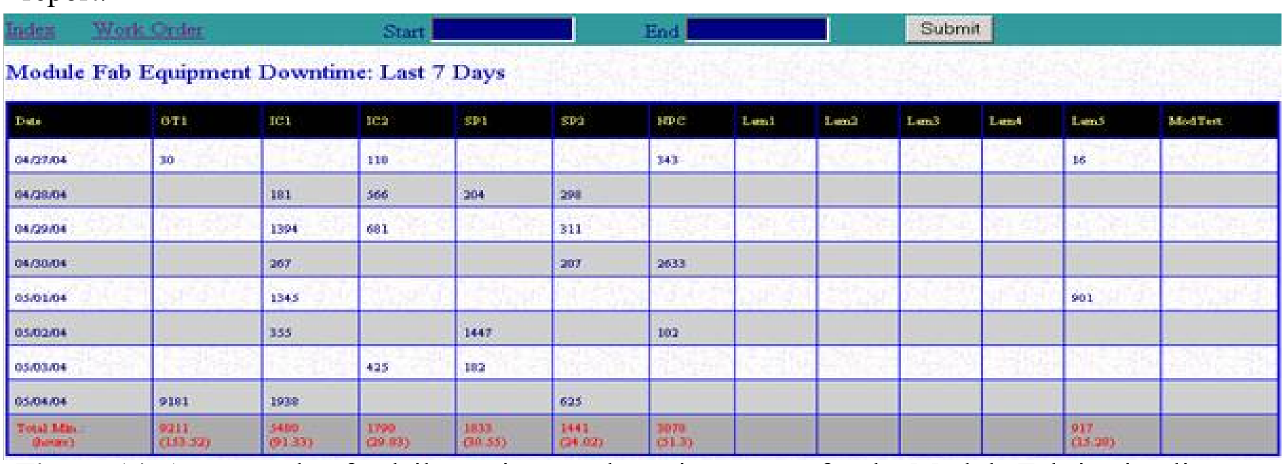
Index Start 4/10/05 End 4/15/05 3: Cell 10000: All Submit

PM History for All: 4/10/05 to 4/15/05

Task	TaskID	Frequency	Scheduled Date	Completed	Complete Date	Time Worked	Emp(s)	Comment
CTO-W-1-D	300217	Weekly	04/11/05 4:07	Y	04/11/05 4:40	35	6007	See Preventative WO# 27742 for timing belts change.
CT-W-1-D	300212	Weekly	04/11/05 4:08	Y	04/11/05 4:37	20	6007	
VE-W-1-U	300203	Weekly	04/12/05 3:36	Y	04/13/05 14:44	45	6758	
VE-M-1-D	300191	Monthly	04/12/05 17:30	Y	04/13/05 15:02	60	6758	
ARLA-W-1-D	300204	Weekly	04/14/05 8:11	Y	04/14/05 10:22	30	6758	
ARLB-W-1-D	300205	Weekly	04/14/05 8:12	Y	04/14/05 10:24	30	6758	Clean up some grease at the base of the robot. Also replaced 4 rubber pads
DFF-M-1-D	300190	Monthly	04/14/05 14:39	Y	04/14/05 12:25	0	6758	PM was not done system is under test by ENG.
DFL-W-1-D	300201	Weekly	04/14/05 14:40	Y	04/14/05 12:32	30	6758	The vision light box cover glass broken and needs to be replaced. See WO 27806

Figure 13. Example of a PM history report for a portion of the Cell Fabrication area.

Downtime Tracking. The downtime tracking system derives time values from the Work Order system built into the CMMS. Figure 14 is an example of a daily Module equipment downtime report.



Index Work Order Start End Submit

Module Fab Equipment Downtime: Last 7 Days

Date	OT1	IC1	IC2	SP1	SP2	NPC	Lam1	Lam2	Lam3	Lam4	Lam5	ModTest
04/27/04	30		110			343					16	
04/28/04		181	566	204	298							
04/29/04		1394	681		311							
04/30/04		267			207	2633						
05/01/04		1345									901	
05/02/04		355		1447		102						
05/03/04			425	182								
05/04/04	9181	1938			625							
Total Min. (hours)	9211 (153.52)	5480 (91.33)	1790 (29.83)	1833 (30.55)	1441 (24.02)	3078 (51.3)					917 (15.28)	

Figure 14. An example of a daily equipment downtime report for the Module Fabrication line equipment.

Automation of Manufacturing Diagnostic Tools and Statistical Process Control (SPC) Techniques. The overall objective of this task was to develop a data and information-gathering network capable of accessing various sensors and diagnostic equipment, along with accessing data already collected by individual equipment programmable logic controller (PLC) functions. The networking capability was already established as a result of our preexisting Manufacturing Information System and the CMMS discussed in the previous section. Specific work done on this task was to provide the necessary equipment interfaces to collect the data available at each machine.

Where possible, this was done. One example of this is the work done to gather pull strength measurements into our data collection system. As the pull strength tester had a built-in capability of sending a signal corresponding to the bond strengths through a serial port into a PC, this value could be collected automatically by querying for this signal. Other information, such as operator, date, weight of the cell, etc., was to be gathered via an operator interface of a similar format to others used at RSSI for data collection. Figure 15 shows the equipment and the interface screen created for this

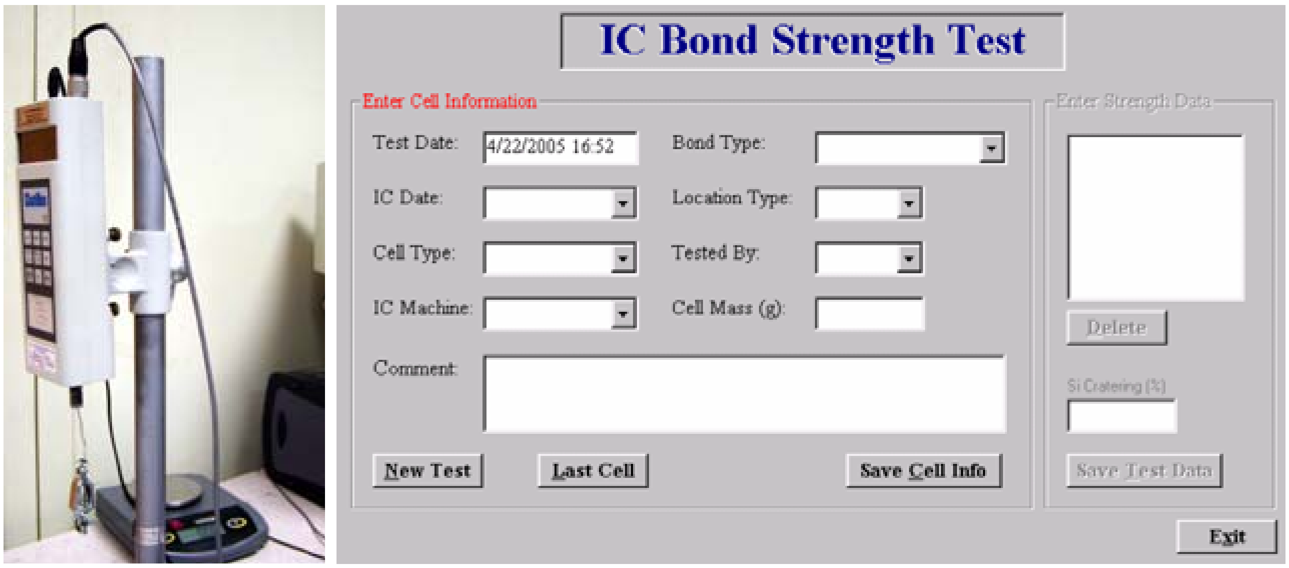


Figure 15. Apparatus and operator interface for data collection of bond strengths for cells in Module Fabrication area tested as for interconnection (IC) quality control.

purpose. The strength measurement itself automatically appears in the square box at the right after the measurement is made and a button on the pull strength apparatus touchpad is entered. The data collected from this measurement assesses the bond strength for the interconnection tabbing to busbars and back pads on our cells. This information is collected on a daily basis by manufacturing operators. SPC charting of the now on-line data is one of the options available through our Manufacturing Information System, as in Fig. 6 above.

In other cases, PLC data obtained directly from production machines was collected for diagnostic purposes, either from sensors added to the equipment or via sensors or gauges already provided by the manufacturer and read within the machine PLC. An example of this is a system created to provide on-line monitoring for several of our laminators. Temperature readings from thermocouples, lower and upper chamber pressures, etc. are directed to the PLC, and the data is then pulled at regular intervals. A visualization screen of this data was provided with remote access so that process engineers and support technicians can more easily make process improvements or troubleshoot the equipment.

Another example of PLC data collection is for the wafer counts collected from robots handling each wafer or cell in the cell line. This data is continuously collected and can be tracked to specific assigned lot numbers. Lot numbers are tracked via run sheets with bar code labels which operators scan in, ensuring accurate information. Comparison of the counts at different robots in the manufacturing line allows a means of automatically collecting yield information for a given lot, once all the wafers have passed through the line and the lot number is closed out. This data provides us with yields between the diffusion and back metalization steps, as well as between the back metalization and the cell test steps.

In other cases where computer interfacing with the diagnostic equipment to our database was not easily automated, data is entered manually into screens otherwise similar to the one in the preceding figure. This includes quality control parameters such as: material removed in silicon etch, sheet resistivity, AR coating thickness and index of refraction, grid finger widths, busbar finger widths, and interconnect crimp heights.

Utilization of the benefits of intelligent processing techniques to increase throughput, efficiency, yield, and reduce acid waste. As a demonstration of the benefits of employing the preceding intelligent processing techniques into our manufacturing line, the following specific goals were established:

- demonstration of 14.5% efficiency over a large lot of 2000+ cells
- reduction in yield loss of 10% in wafers, cells, and modules
- reduction in acid use for our laser-cut edge strengthening step of 10%
- increase in throughput of 10% in the new cell line
- develop means for processing 250 micron thin wafers with high yield

A discussion of the accomplishments towards the goals in each of these tasks follows.

14.5% cell performance goal

A critical factor used as an aid in achieving this objective was the application of production line diagnostics, and also making use of the CMMS and data collection network. Front metal firing, in particular, was made more stable through optimization of the Proportional-Integral-Derivative (PID) parameters on the firing furnace; these parameters can now be monitored remotely using via the furnace PLC via a connection made to our in-house data collection network. Following this work, production efficiencies were stabilized at a 14% efficiency level and above in our new cell line. Subsequent to this, for a short interval, we ran the AR coating step under conditions shown to be superior to our standard process (at the expense of being more labor intensive) and obtained 14.3% efficiency for 13,000 cells, with a distribution as shown in Fig. 16.

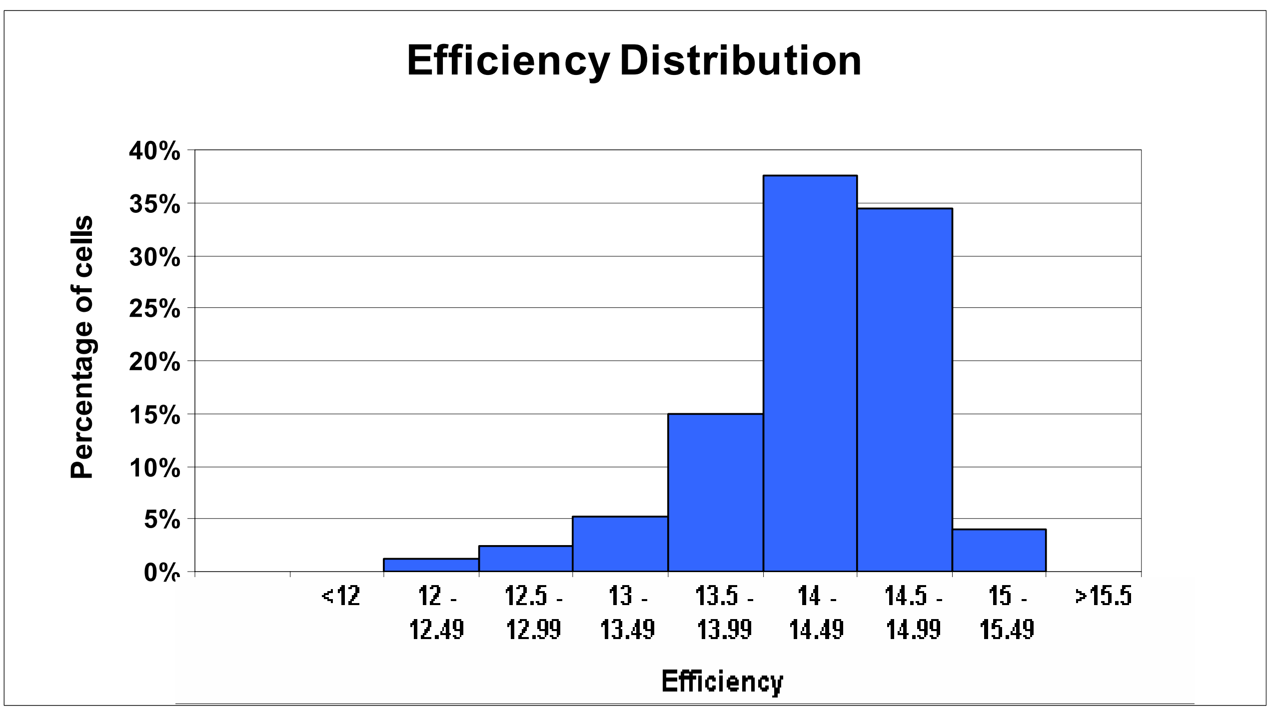


Figure 16. Cell efficiency distribution for 13,000 production cells averaging 14.3%.

We next explored a new processing variable regime using average thickness 250 micron wafers, which provide higher Voc and Jsc. An initial trial group of 500 10 cm x 10 cm area wafers was processed and monitored, maintaining the same improvements in process control previously discussed. This lot achieved a 14.7% lot average with the following parameters:

Table 3. Cell performance for first batch of 500 cells of 250 micron thickness for the high efficiency demonstration experiment.

	J_{rev} (mA/cm^2)	V_{oc} V	J_{sc} (mA/cm^2)	FF	PP (mW/cm^2)	ρ_s (ohm-cm^2)	ρ_{sh} (ohm-cm^2)	Qty. Out
Average	0.24	0.595	32.42	0.763	14.72	1.17	2749	425

A second lot of 2000+ wafers was processed and gave the following parameters:

Table 4. Cell performance for 2000+ cells of 250 microns average thickness for the high efficiency demonstration experiment.

	J_{rev} (mA/cm^2)	V_{oc} V	J_{sc} (mA/cm^2)	FF	PP (mW/cm^2)	ρ_s (ohm-cm^2)	ρ_{sh} (ohm-cm^2)	Qty. out
Average	0.23	0.597	32.15	0.757	14.53	1.33	2898	2006

Finally, other areas of processing, which we had been experimenting on in small scale, were combined for a larger experiment. In this final experiment for this task, we combined selected silicon feedstock, explored a range of bulk resistivities, a range of sheet resistivities and a range of firing conditions for the metalization. The best subgroup of 30 cells averaged 14.9%. The overall collection of almost 900 cells averaged 14.66%, as given below.

Table 5. Cell performance for 900 cells in the high efficiency optimization experiment.

	J_{rev} (mA/cm^2)	V_{oc} V	J_{sc} (mA/cm^2)	FF	PP (mW/cm^2)	ρ_s (ohm-cm^2)	ρ_{sh} (ohm-cm^2)	Qty. out
Average	0.36	0.599	32.25	0.759	14.66	1.24	1873	889

It is anticipated that by confirming and extending the optimal conditions gradually into production, cell line efficiencies of 14.5% level will be achieved in the near future.

10% yield improvement on the wafer, cell and module lines

Through a combination of improvements implemented during the 3 years of this program, yields in our Wafer Fabrication department (growth, laser cutting, and etching) have steadily increased, as shown in Fig. 17. The relative reduction in yield losses has greatly exceeded the 10% goal set for this program.

In the cell line, efficiency and throughput stabilization were the primary goals after the initial introduction of the new cell line equipment. It was not until mid-2004 that yield issues became a focus, working on each process step and making improvements to weak areas. The mechanical yield improvements achieved are shown in Fig. 18. Here too, the relative reduction in yield losses greatly exceeded the 10% goal set for this program.

We also instituted new procedures and operator training, resulting in improved yield in module manufacturing. As we have changed standardized methods to evaluate yield losses over this

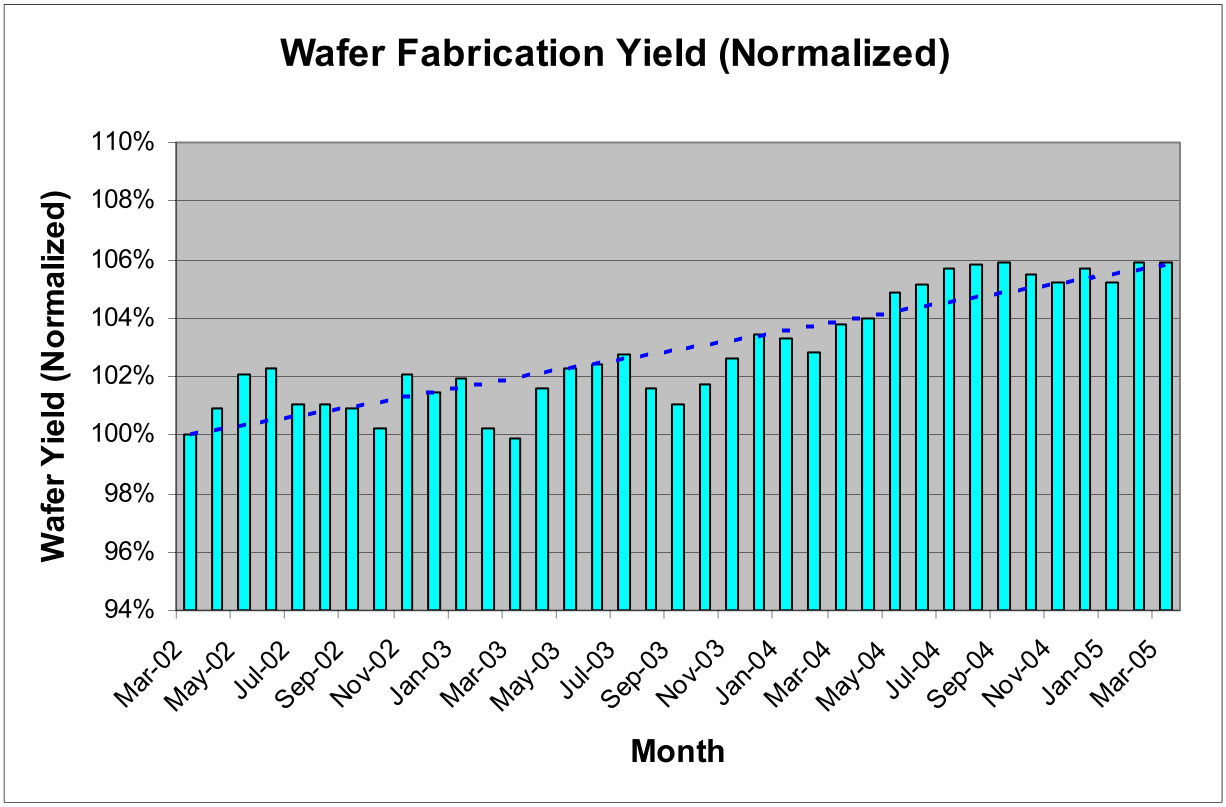


Figure 17. Wafer fabrication yield improvements over the 3 years of this program.

time period, we do not have as accurate a baseline with respect to which we can calculate yield improvements. As such, the data set does not represent a fair comparison over previous years and changes in yield for this area could not be fairly assessed. Such work will occur beyond the end of this program.

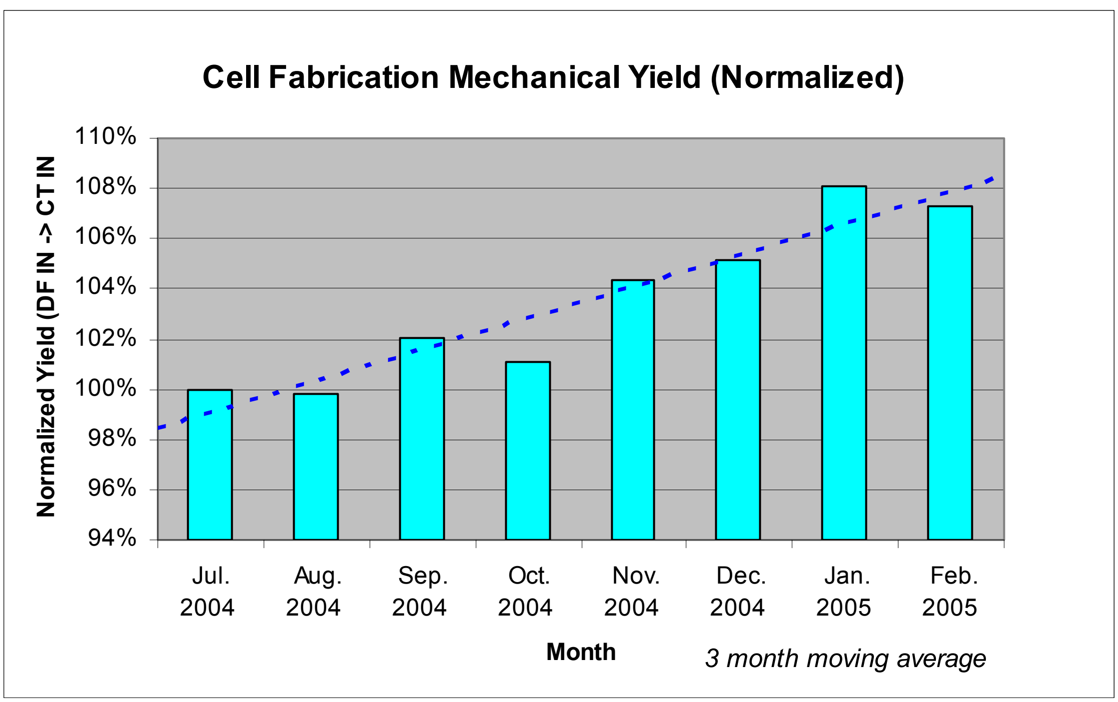


Figure 18. Cell fabrication yield improvements in Phase 3 of this program.

Overall, the yield improvements in the wafer and cell areas exceeded the program goal we set for this task, with the likelihood that additional but undocumented yield improvements were also achieved in module manufacturing.

10% reduction in acid consumption

We had previously reported on the use of a fracture twist test for wafers to diagnose laser cut quality arising both from laser out-of-focus conditions and from mechanical malfunctions of the tube and wafer handling equipment. One of the specific actions made as a result of the earlier studies was that an immediate increase in the minimum etch removal amount per wafer was necessary in order to achieve a revised and increased minimum target fracture strength.

Within the framework of the new etch target, we have demonstrated a 15% reduction in acid consumption *per micron of Si removed*. This was accomplished through a combination of changing the acid chemistry (to increase the aggressiveness of the acid) and increasing the initial temperature setpoint and temperature ramp rate to further increase the aggressiveness of the acid, while at the same time reducing the etch time by 30% to increase throughput. This allowed us to etch a greater amount of Si, when measured on a percentage basis, than the increase in acid per wafer required. Specifically, transitioning to 20% greater acid use has allowed us to etch 41% more microns of Si.

Recent checks of the fracture strength for our different lasers confirm that the changes made have brought the minimum strength up from ~125 MPa to ~135 MPa. Figure 19 shows the latest values for each production laser station. In addition, more laser stations are changing to the technology presently used only in Laser 19. These combined efforts will allow us to further cut down on acid use per wafer and yet maintain fracture strength.

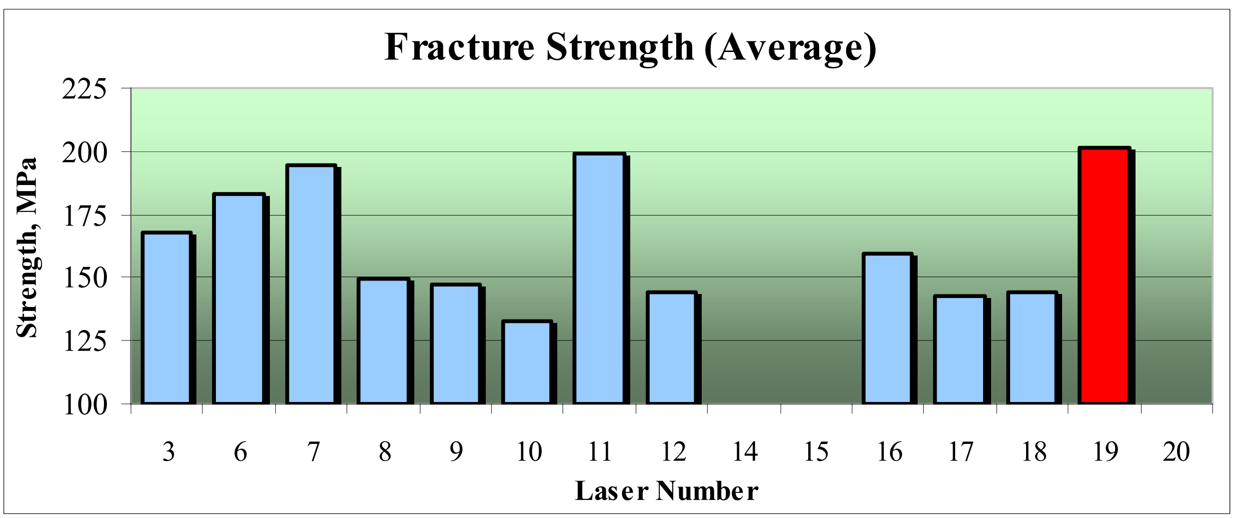


Figure 19. Fracture Strength of EFG silicon wafers cut on different laser cutting stations. Laser 19 represents a new cutting technology being substituted for older lasers.

10% increase in cell line throughput

We completed a number of upgrades of all stations in our new cell line and initially increased our baseline transfer time of 3.0 s per wafer to 2.7 s per wafer or better on all our equipment. This achieved the goal of a >10 % increase in throughput on the line relative to the baseline. We subsequently worked on further design changes to achieve an additional 10% increase in cell line throughput by reducing wafer transfer time to 2.3 s. The major hurdle here was to re-engineer wafer handling during the busbar writing step. This proved successful, and a major redesign of the previous bottleneck in front metallization has recently been completed. Refer to Table 2 in Section 2.1 for a summary of our throughput evolution and future goals.

Thin wafer yield study

We completed the goal of running 2000+ cells of nominal 250 micron thickness. The yield matched that achieved for regular 330 um thickness wafers. Each process step was carefully observed during earlier trial runs of 500 wafers each, and modifications at processing steps, primarily in the robots removing wafers from stack boxes, were made in order to maintain high yields with these thinner wafers. Eight full size 300 W modules have been made with these thinner wafers with high yield.

3. Summary

We have made advances in the technology, processes and capabilities of the wafer, cell, and module manufacturing lines at RSSI in the course of the R&D carried out on this program. The intent of R&D has been focused on improvements which will aid the scaling up of EFG ribbon technology to the 50-100 MW factory capacity level. Particular areas addressed included in-line diagnostics, throughput and yield enhancements, reflector module design exploration, and development of intelligent processing concepts through automating data collection and machine control and monitoring.

The R&D was carried out against a background of rapid EFG ribbon manufacturing expansions which have reached a 40 MW capacity level in EFG wafer production. This required both improvement of existing methods and development of cost competitive new technology. EFG wafer size was diversified to a 12.5 cm x 12.5 cm wafer, joining the 10 cm x 10 cm and 10 cm x 15 cm wafers which were the standard products at the beginning of this program. Cell and module production also has continued to expand in Billerica and more automated equipment has been brought in with different control and operational requirements. Work on our subcontract increased the throughput, yield and cell performance on a new 12 MW cell line installed in Billerica in 2003. A significant accomplishment was the introduction of modifications on the equipment and processes which raised the capacity to 18 MW without footprint modifications. R&D on module manufacturing processes was carried out on equipment installed during a manufacturing upgrade and capacity has now reached 12 MW. Yield and reliability of products was also improved.

Demonstration and introduction of new diagnostic techniques and improvements of existing equipment for in-line monitoring and/or measurement and control of critical process parameters was made in the EFG wafer, cells and module manufacturing areas. Techniques developed and successfully implemented in wafer production (crystal growth and wafer laser cutting and etching) include: pyrometer temperature control for the furnaces, in-line flatness monitoring using a buckle sensor, improved data collection and real time analysis for wafer quality monitoring, and wafer strength monitoring of laser cutting damage to reduce and control etchant utilization. In cell fabrication, sheet resistivity equipment was upgraded and an on-line database established. A spectroradiometer was acquired and data collection on the spectral output of the lamps used for cell testing has helped lead to improvements in quality and reproducibility of our cell test measurements. Diagnostic techniques for crack detection and photoluminescence for bulk lifetime evaluation were proven and equipment built to carry out R&D under manufacturing line conditions. Other diagnostic techniques were upgraded with the help of computer-automated data collection methods. These included resistivity measurements, and in the module area, bond strength testing and module lamination process parameter tracking.

The R&D efforts which enabled EFG growth and laser cutting for production of 12.5 cm x 12.5 cm wafers led to a productivity increase per growth furnace of 25% for new EFG wafer manufacturing capacity. Furnace temperature field and stress models were developed and applied to assist in reducing stress during growth and for improving wafer yield. R&D was successful in identifying laser technology with improved throughput and lowered damage in cutting. This was introduced into manufacturing to enhance throughput in the laser area by over 20% and reduce labor costs by 35%, as well as improve wafer strength. Modifications to the acid etching chemistry for reducing damage in EFG wafers prior to cell processing increased the effectiveness of our acid use by increasing silicon removal per unit volume of acid by more than 15%. Growth processes for thin EFG octagon tubes down to 250 microns were improved with the help of the models, and thin wafers were processed and made into modules to study factors and barriers in yield. Yields in thin EFG wafer processing were improved to close to those for wafers of normal thickness in production. Wafer thickness is now being reduced incrementally in full scale production to evaluate the improvements on a large volume production basis. Yield improvements were made in the wafer and cell line manufacturing processes of 10% and 15% respectively with respect to baselines established at the beginning of the program.

Materials investigations for new encapsulants, backskins and reflecting medium/materials for reflector module design and construction were completed but did not succeed in identifying a robust manufacturing platform with which to proceed to pilot production.

We completed introduction of a Computer Management and Maintenance System (CMMS) throughout the wafer, cell and module production areas, joining a previously existing Manufacturing Information System which was further upgraded. Together, these two systems allow us to: track production data including efficiency, yield, throughput; track machine data such as equipment uptime; schedule maintenance work orders; provide a searchable maintenance history; and track and guide preventive maintenance needs. The system has been applied in conjunction with diagnostic sensors and techniques to assist in SPC and PLC operation tracking on a daily basis throughout production and has become an important and indispensable feature of our regular business. The development of the computer-aided databases and machine and process tracking formed a critical component of the basis for improvement of all aspects of the EFG-base manufacturing lines for wafers, cells and modules.

Overall, based in part on the advancements made during this program, large gains in throughput and productivity have been achieved, whereby new options have been created for ramping up EFG technology to the 50-100 MW level and beyond.

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14. ABSTRACT *(Maximum **200 Words**)*

The objective of this subcontract was to carry out R&D to advance the technology, processes, and performance of RWE Schott-Solar's wafer, cell, and module manufacturing lines, and help configure these lines for scaling up of edge-defined, film-fed growth (EFG) ribbon technology to the 50-100 MW PV factory level. EFG ribbon manufacturing continued to expand during this subcontract period and now has reached a capacity of 40 MW. EFG wafer products were diversified over this time period. In addition to 10 cm x 10 cm and 10 cm x 15 cm wafer areas, which were the standard products at the beginning of this program, R&D has focused on new EFG technology to extend production to 12.5 cm x 12.5 cm EFG wafers. Cell and module production also has continued to expand in Billerica. A new 12-MW cell line was installed and brought on line in 2003. R&D on this subcontract improved cell yield and throughput, and optimized the cell performance, with special emphasis on work to speed up wafer transfer, hence enhancing throughput. Improvements of wafer transfer processes during this program have raised cell line capacity from 12 MW to over 18 MW. Optimization of module manufacturing processes was carried out on new equipment installed during a manufacturing upgrade in Billerica to a 12-MW capacity to improve yield and reliability of products.

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