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Thin EFG Octagons

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Summary

The participation of Mobil Solar Energy Corporation in Phase 2A - Process-Specific Issues of the Photovoltaic Manufacturing Technology (PVMaT) Initiative program commenced on April 1, 1992. This effort has as its objective to advance the manufacturing line capabilities in crystal growth and laser cutting of its unique EFG octagon technology and so reduce the manufacturing costs of 10 cm × 10 cm polycrystalline silicon EFG wafers.

This report summarizes the significant technical improvements in EFG technology achieved in Phase 1 of this program, and the success in meeting the program milestones. Technical results are reported for each of the three main program areas:

> **Task 1 - Thin octagon growth (crystal growth)** - to reduce the thickness of the octagon to an interim goal of 250 microns during Phase 1, with an ultimate goal of achieving 200 micron thicknesses.
>
> **Task 2 - Laser cutting** - to improve the laser cutting process, so as to produce wafers with decreased laser cutting damage at increased wafer throughput rates.
>
> **Task 3 - Process control and product specification** - to implement advanced strategies in crystal growth process control and productivity designed to increase wafer yields.

Highlights achieved in each task are described briefly in this report.

Task 1 - Crystal growth investigations in the Mobil Solar Phase 1 program were aimed at aiding and accelerating the transition from growth of 400 micron to 300 micron thick octagons in the Mobil Solar pilot line operation, while carrying out the research needed to achieve the Phase 1 interim goal of production of 250 micron thick wafers. The former task consisted of improving yields and productivity of 300 micron thick octagon tubes and wafers. The work on 250 micron thick tubes has stressed development of fundamental process understanding that will allow specification of EFG technology needed for a wafer thickness reduction to 200 microns set as the goal for Phase 3.

Task 2 - In the laser cutting area, an increased throughput laser station has been designed and a prototype of material handling system tested. The fundamentals of the laser beam interaction with silicon material have been investigated in order to define conditions under which high speed cutting with reduced damage and increased wafer edge strength can be obtained.

Task 3 - In process control, methods to deploy sensors for on-line material property control are being investigated, and as-grown wafer specifications developed for thickness, flatness, residual stress and wafer electronic properties.

Introduction

Mobil Solar Energy Corporation currently practices a unique crystal growth technology[1] for producing crystalline silicon sheet, which is then cut with lasers into wafers. The wafers are processed into solar cells and incorporated into modules for photovoltaic applications. The silicon sheet is produced using a method known as Edge-defined Film-fed Growth (EFG), in the form of hollow eight-sided polygons (octagons) with 10 cm faces. These are grown to lengths of 5 meters and thickness of 300 microns, with continuous melt replenishment, in compact furnaces designed to operate at a high sheet area production rate of 135 cm^2/min. Each tube in cut into 10 cm $\times$ 10 cm wafers by a high-speed laser, which eliminates the need for slicing or grinding that is wasteful of material.

The present Photovoltaic Manufacturing Technology (PVMaT) three-year program seeks to advance the manufacturing line capabilities of the Mobil Solar crystal growth and cutting technologies. If successful, these advancements will provide significant reductions in already low silicon raw material usage, improve process productivity, laser cutting throughput and yield, and so lower both individual wafer cost and the cost of module production.

Material Requirements

The successful implementation of process technology for the photovoltaic manufacturing program is critically related to a number of EFG material characteristics. First, the mechanical yield of processing wafers into solar cells and encapsulating them into panels depends upon the strength and the flatness of the wafers. Wafer strength is determined by the residual stress in the material, as well as the length of microcracks created at the wafer edge during laser cutting. Edge cracks can propagate as the wafers are flattened during processing, thus lowering mechanical yield. It is also important to improve wafer flatness during growth in order to facilitate automated wafer transfer between processing steps.

The local electronic characteristics of an EFG solar cell are correlated to the local thickness of the wafer. This results in the conversion efficiency being related to wafer thickness, so variations in thickness uniformity can also affect solar cell efficiency. Hence it is important to control tube thickness uniformity during growth to reduce variations in cell performance and hence raise overall cell efficiency.

Finally, the wafer should contain an optimum level of interstitial oxygen (O_i) for maximum conversion efficiency. Interstitial oxygen is incorporated during crystal growth by adding controlled amounts of carbon monoxide (CO) to the argon ambient. Since the degree of O_i incorporation can vary from run to run, it is necessary to evaluate and modify growth conditions in order to provide a process that will reduce this variation.

Program Goals

The objective of this program is to advance PV manufacturing technology by reducing wafer thickness and cost of crystal growth and laser cutting in Mobil Solar's EFG octagon technology--thereby reducing the cost of module production.

Mobil Solar has undertaken to meet this objective, during a three-year effort, by reducing the EFG wafer thickness by 50%, increasing the throughput of laser cutting of silicon octagon tubes into wafers, increasing the edge strength and thus the yield of wafers, and evaluating integrated computer-aided control programs for the Mobil Solar crystal growth manufacturing line that can enhance productivity.

This report summarizes the significant technical improvements in EFG technology achieved in Phase 1 of this program, and the success in meeting program milestones.

Progress in Technology Development

The technical work in this program is structured into three main tasks:

Task 1 - Thin octagon growth (crystal growth)
Task 2 - Laser cutting
Task 3 - Process control and product specification

Program goals for each task are summarized in Fig. 1. Highlights of work performed and results achieved under each task are reviewed in the following sections.

Task 1: Thin EFG Octagon Growth

The EFG process yields a tubular octagon sheet product that eliminates the need for the sawing, grinding, and polishing required to obtain uniform thickness and flat substrates when silicon wafers are produced by conventional processes such as ingot growth or casting.[2] However, the EFG process also requires that stringent measures be taken to control factors--inherent to the crystal growth process--that affect the as-grown material geometry.[3]

The following sections describe efforts under each of the Phase 1 subtasks.

Subtask 1.1 Thickness Uniformity

EFG wafer thickness variations originate from a number of sources and are conveniently categorized according to their origins. These are:

1. Transient thickness variations, predominantly associated with changes in the thickness differential between the octagon face center and edge. Typically, the earlier tubes grown tend to have thinner corners, but these corners become thicker as the number of tubes grown increases. These variations are caused by heat transfer nonuniformities in the die and susceptor.

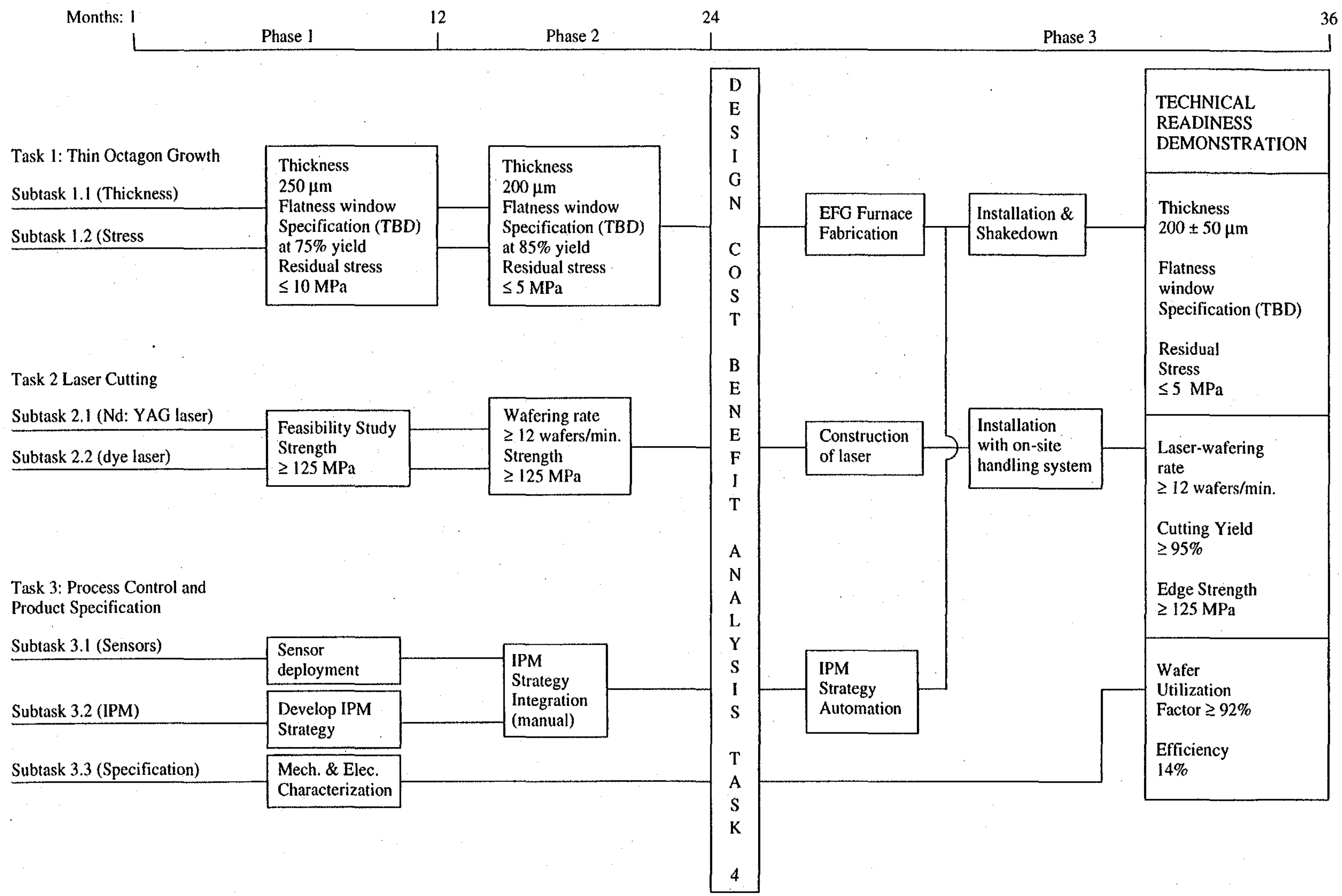

Figure 1. Program Goals Summary – See text for definitions of terms

2. Systematic variations around the octagon perimeter which appear to be periodic. These are related to coil placement and the temperature distribution in the melt. Unfavorable combinations of these variables lead to a significant amount of unmelted silicon in the crucible. The resulting temperature nonuniformities are a dominant source of periodic and near-periodic circumferential thickness variations.

3. Longitudinal variations along the length of the tube. These are influenced by the melt recharge, temperature and tube weighing control systems associated with the melt replenishment operation.[4]

Efforts are planned to develop specifications on thickness nonuniformity based on yield requirements as the thickness is lowered through the three phases of the program to the target of 200 microns in Phase 3. A target level of ±50 microns for allowable thickness variations has been tentatively set for the 200 micron thick 10 cm × 10 cm wafer to be produced in Phase 3. Subtask 3.3 on product specification will assist in establishing criteria for thickness variations of EFG wafers as thickness is decreased.

As described in the Task 1 Highlights section below, experimental growth runs and analysis during Phase 1 resulted in a new design of hot zone components, which eliminates the face-center-to-edge thickness variation across the octagon face, thereby producing wafers of more uniform thickness. In a separate subtask, we carried out a series of reviews to examine crystal growth furnace design to develop specifications for improved EFG octagon furnaces.

Subtask 1.2 Stress

Stress within the octagon is caused by nonuniformities and varying high axial gradients (of the order of 1000°C/cm) in the temperature field which create thermal stresses during growth.[5] These stresses produce plastic flow and dislocations which then further contribute to residual stresses in the EFG wafer. The most visible manifestation of stress is development of buckles, which are periodic deviations from flatness along an octagon face. These most often have a period of 10 cm and amplitudes that are as large as 2 mm in the extreme. Longer periods are also observed.

Implementation of controls for wafer buckling, as well as improvements in wafer flatness, are closely related to the ability to manipulate the temperature field (more specifically, its second derivative) in the region of greatest plasticity (generally above 1000°C) in post-growth cooling, and in the rate of cooling through the plastic region.[6] This region is located immediately above the die tip, indicated by an arrow in the schematic of the EFG octagon furnace (Fig. 2). Stress reduction requires detailed information of the temperature fields in close proximity--within about 5 mm--of the growth interface.

The central tasks of this work are to develop a better theoretical understanding of plastic buckling and to implement new experimental techniques to measure changes in temperature distribution in the growth interface region. The results will be used to formulate Intelligent Processing of Materials (IPM) strategies to control and minimize stress in the as-grown material. Some of the characterization and instrumentation techniques that will be applied to stress control in this subtask are being developed as part of the Task 3 effort.

As described in the Task 1 Highlights section below, modifications in the post-growth cooling profile of the octagon are expected to reduce stress and buckling, thereby increasing the wafer flatness. This result is one of the critical areas being evaluated in the analysis of the Technical Readiness Demonstration (TRD) runs performed at the end of Phase I.

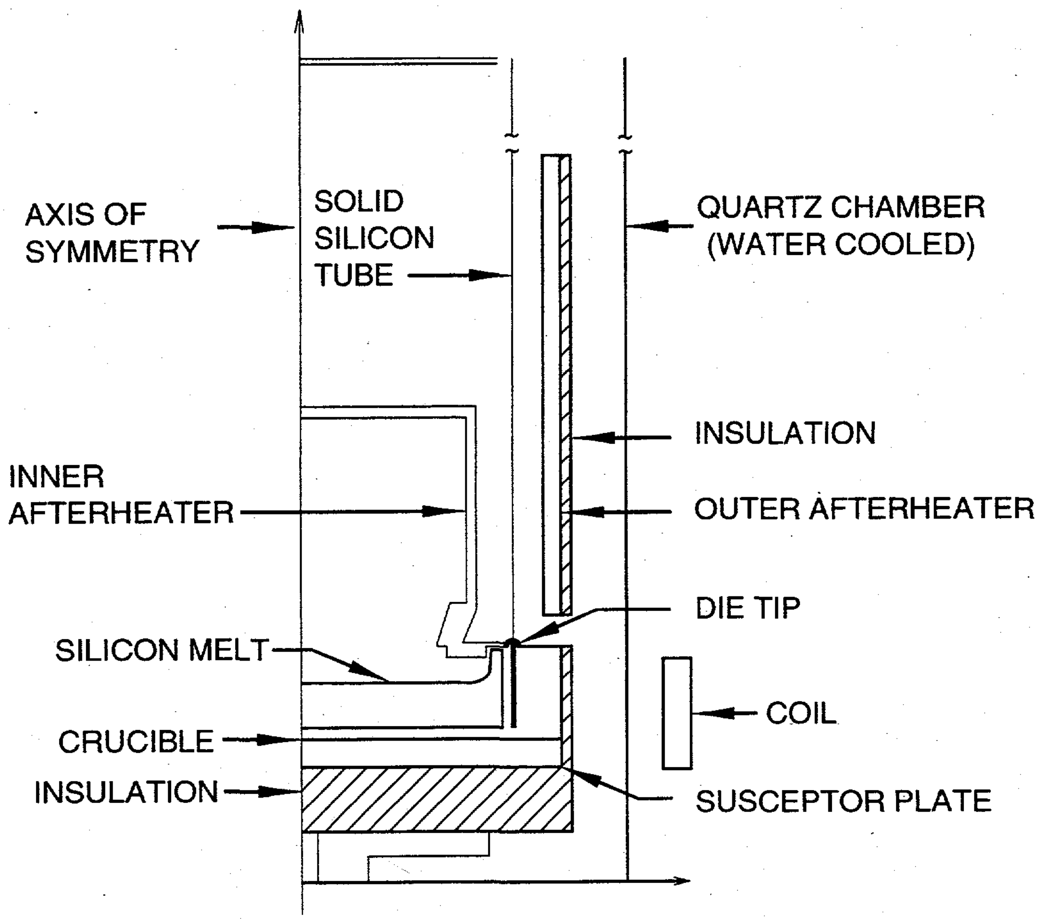

Figure 2. EFG octagon system furnace schematic.

Flatness specifications on thin EFG wafers that relate to mechanical yields (wafer breakage) will be refined during the remaining phases of the program. The relationship of yield to wafer edge strength, currently limited by the laser cutting process, will be studied as part of the Product Specification subtask in Task 3.

Task 1 Highlights

The central emphasis of the crystal growth task was on experiments carried out on two EFG octagon furnaces at Mobil Solar facilities during the year. This work was supported by lower-tier subcontractors who provided expertise in evaluation of equipment and theoretical models for growth behavior. Cost-effective improvements in EFG crystal growth technology which have demonstrated a potential to increase yields and productivity of 300 micron thick tubes and wafers include:

- a new design of hot zone components that eliminate a face-center-to-edge thickness variation across an octagon face and result in more uniform thickness wafers;

- modifications in the post-growth cooling profile of the octagon that reduce stress and buckling and so increase wafer flatness;

- identification of furnace design options to extend the length of a growth run with increased levels of carbon monoxide (CO) in the furnace ambient, which raises material oxygen levels and improves electronic quality;

- evaluation of new grades and purification methods for furnace graphite parts, which reduce parts cost and improve purity.

Together, these crystal growth advancements have the potential to improve the yield of acceptable wafers by 5%; increase the productivity in crystal growth by 10%; and increase the growth length by the order of 25%, with improved electronic quality (increased interstitial oxygen levels).

Support tasks have been successful in laying the foundations for significant advances in the crystal growth furnace designs needed for 200 micron thick wafer production. These include: establishment of specifications and testing of components for an advanced EFG crystal growth furnace; and investigation of EFG system computer models and carrying out analyses of furnace designs with magnetic, meniscus shape, temperature and stress field models. Competitive design reviews are under way with vendors for the crystal growth puller, automated control elements and associated equipment (seed alignment, weight control sensor, and power supply). The modeling subtask has resulted in an integrated comprehensive 2-d magnetic and thermal model, and a 3-d magnetic model representing the full EFG furnace and hot zone. These models have been successfully applied to assist in engineering design and evaluation of new EFG hot zones for thin octagon growth.

Task 1 Milestone Status

All the Phase 1 milestones listed for crystal growth were completed by the end of the first-year effort.

Task 2: Laser Cutting

The laser cutting work in Phase 1 was structured to study the feasibility of attaining program goals by two different routes:

(1) to improve existing cutting technology using Nd:YAG lasers, or
(2) to cut silicon with a new generation of line-focus dye lasers.

These two approaches provide very different options for meeting the cut wafer edge quality (strength) and throughput (wafering rate) objectives of the program shown in Fig. 1.

After feasibility studies and cost evaluation during Phases 1 and 2, the candidate laser technology best suited to meet the program goals and cost objectives will be selected for development and integration with tube-handling concepts in Phase 3.

Commercially available Nd:YAG lasers have the capability of achieving linear traverse speeds of more than 10 cm/s at the power levels necessary to cut through 200-400 micron thick silicon. In principle, this would allow a cut to be made around the perimeter of a 10 cm × 10 cm area in as little as 4 seconds, providing a processing rate of 15 wafers/min. However, maximum rates are not achieved in practice because of the limitations of tube- and wafer-handling mechanisms. Efforts to improve the cutting technology with these lasers thus involves advancing tube- and wafer-handling processes as well as improving the quality of wafer cut edges. This work is described under subtask 2.1 below.

High-power dye lasers have recently become available to allow accessing of new regimes for cutting silicon. These lasers provide the opportunity to work with line-focussed beams with sufficient energy to cut through octagons of the target thickness of 200 microns at the rates required. They have the potential to match and to exceed the wafering rates of the Nd:YAG lasers while at the same time improving wafer edge quality. In Phase 1 of this contract, efforts were undertaken at a lower-tier subcontractor's facility to demonstrate the feasibility of producing low damage line cuts with a dye laser. This work is described under subtask 2.2 below.

Laser cutting goals for the three year program are to demonstrate technology that will increase wafer cutting throughput rates while at the same time also improve the wafer edge strength of the thinner material. To achieve the desired throughput gains requires both improving wafer- handling technology and increasing the cutting speed. These improvements have to be accomplished while at the same time reducing laser damage in the cutting process.

The initial strategy for this task has been twofold: first, to carry out investigations with novel laser systems at lower-tier contractors' facilities in attempts to demonstrate the feasibility of cutting with reduced edge damage in Phase 1; second, to investigate new designs of wafer-handling at Mobil Solar in order to design and evaluate new concepts that will form the basis of throughput upscaling of the laser station to the wafering rates set for the Phase 3 objective, once the laser configurations producing the greatest improvement in edge quality are identified.

The following sections describe efforts under each of the Phase 1 subtasks.

Subtask 2.1 Nd:YAG Laser

Lasers have been used for cutting of EFG sheet silicon since 1980. Several types of lasers are currently being evaluated at Mobil Solar for their ability to meet cut quality and throughput objectives for the EFG octagon-based manufacturing technology. Laser system advancement is proceeding in parallel with development of octagon tube- and wafer-handling technology. The objective of this subtask is to determine the limits of cut edge quality and throughput available with new configurations of the Nd:YAG laser technology.

Results on edge quality studies with Nd:YAG lasers will be reported under the product specification section in Task 3 of Section 3. In this subtask we were concerned with:

- progress in design, testing and implementation of advanced tube and wafer-handling concepts for increasing throughput in a laser cutting station at Mobil Solar;
- success in reducing cutting damage with modifications in the Nd:YAG laser cutting configuration with a preheat beam, being carried out at a lower-tier subcontractor's facility, Lasag.

Results in these two tasks are described under Task 2 Highlights, below.

Subtask 2.2: Dye Laser Feasibility Study

The objective of this subtask is to demonstrate the feasibility of cutting EFG silicon with a dye laser. This work is being carried out at a lower-tier subcontractor, Textron Defense Systems (TDS).

The TDS dye laser has a wavelength of 585 nm. A laser operating at this wavelength has not previously been used to cut silicon. The wavelength is a central parameter in laser cutting of silicon because the absorption depth for the beam (and hence the beam-material interaction volume) is a strong function of wavelength of the irradiation. The beam conditions of the dye laser are intermediate between the CO_2 and Nd:YAG lasers used at Mobil Solar and the excimer laser--insofar as beam energy density and pulse length combinations are concerned. This is illustrated in Fig. 3. This combination is an important factor in controlling the quality of the cut.

The TDS laser was chosen for this study primarily because of its ability to access an important high power regime in which silicon evaporates with minimal associated damage. Both the CO_2 and Nd:YAG "cut" the silicon by first bringing the silicon material surface to a melting condition, then expelling the melt using directed gas jets. As shown in Fig. 3 (in the area next to the vertical line), a single pulse will melt in its entirety a 300 micron thick substrate. Their pulse length range (100 to 500 microseconds) and energy density combinations are not sufficient to evaporate the silicon melt with minimum energy transferred into the zone around the melted region by thermal diffusion. The extent of the thermal diffusion zone determines the microcrack length[7] which sets the current limit to the edge strength of the EFG wafer.[8] The beam conditions for the excimer laser can also access the desirable regime for cutting which involves evaporation. The dye laser has an added advantage in that it does not require special facilities to handle toxic chemicals because it operates with a non-toxic rhodamine dye, or special optical components.

The TDS dye laser operates at 4 microsecond pulse length and can attain peak power levels above 6 J/pulse. At this energy level evaporation of silicon should be initiated. The beam at the cavity exit has dimensions of 0.5×8 cm, and with suitable optics can be easily focussed to a line of 10 cm $\times$ 100 microns, as will be desired in high speed cutting of 10 cm $\times$ 10 cm EFG wafers. In the feasibility studies, due to availability of focussing optics, the beam has been focussed to a line 5 cm $\times$ 100 microns.

The energy density achieved by the dye laser under these operating conditions provides the potential to meet both the quality and throughput goals of this task (see Fig. 1). The anticipated beam-material interaction mechanism through which dye laser cutting proceeds, when evaporation is included, is illustrated in Fig. 4. At a power density of 400 J/cm^2, there is enough energy for melting and evaporation to a depth (δ) of about 30 microns of silicon. At the same time, a thermal diffusion zone, D_T, will form due to energy that is absorbed beyond the evaporated region, and that which diffuses beyond the melt-solid boundary during the time of the laser irradiation. This depth can be up to 13

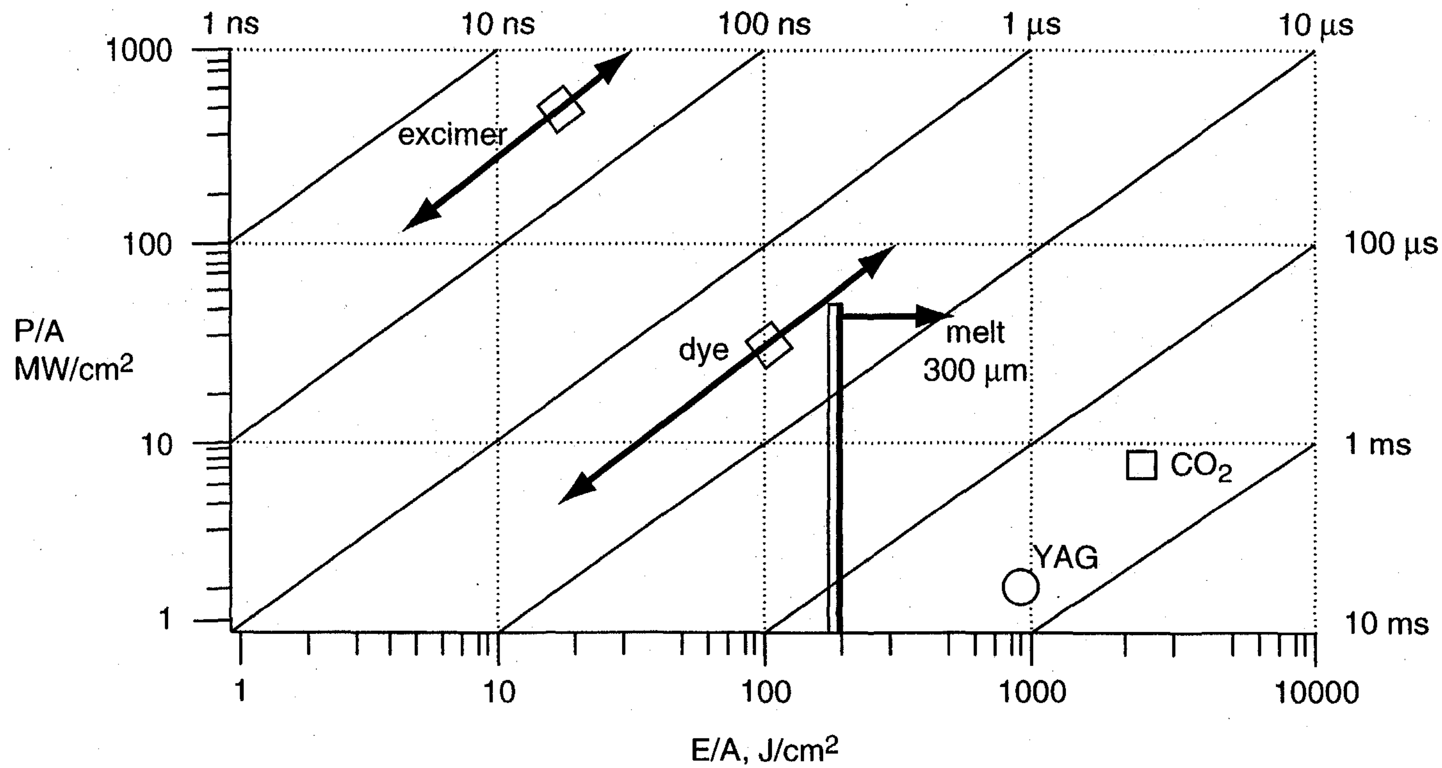

Figure 3. Laser Power and pulse length operating regimes.

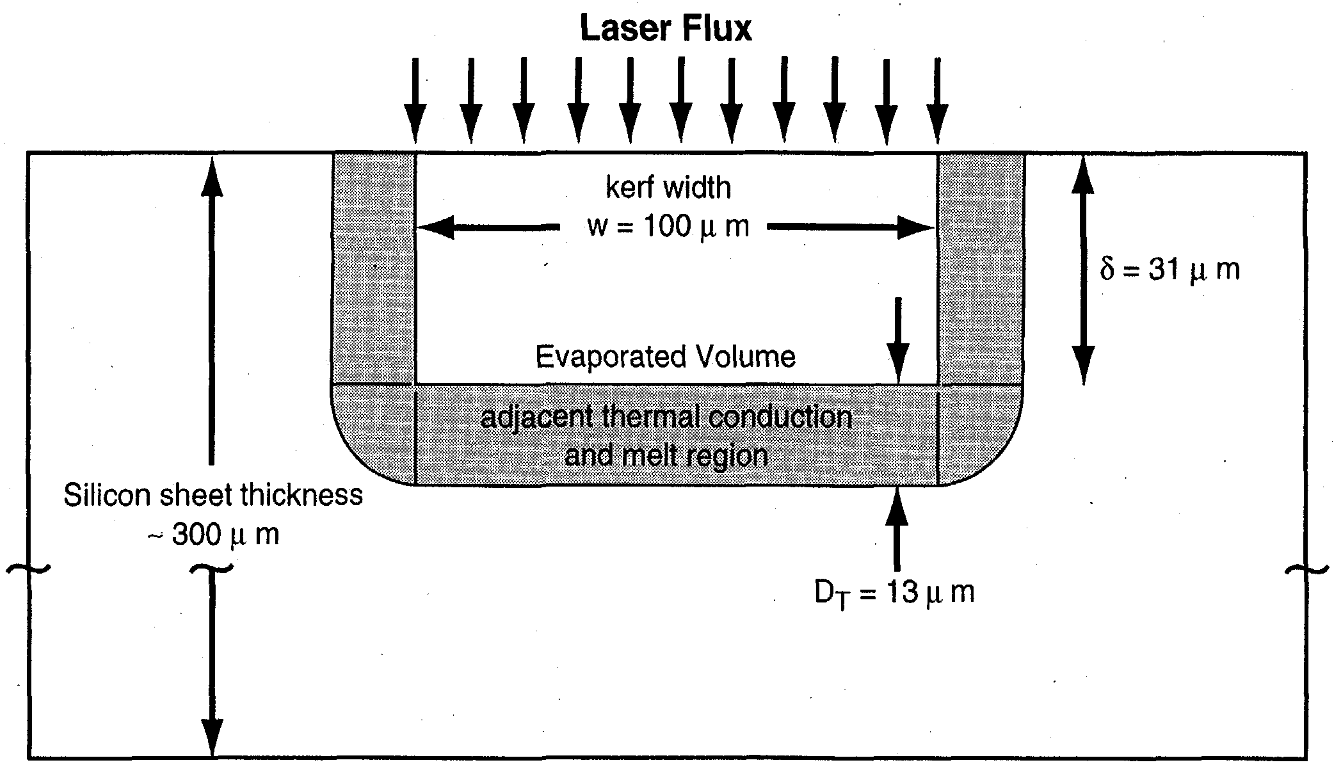

Figure 4. Laser beam-material interaction mechanisms.

microns in the available time of 4 microseconds. The strategy for achieving an energy distribution that creates the most favorable conditions for minimizing the edge damage requires that the evaporation depth be maximized while at the same time the melt depth and thermal diffusion zone are minimized. This simple analysis presents an idealized situation. We are examining the possibility of modeling this process to provide some guidance to the experiments and a more realistic picture of the complex dynamic effects taking place in competition between evaporation, melting, and thermal diffusion.

A second favorable aspect of operating in this dye laser cutting regime is the possibility of high throughput rates. With the potential of removing up to 30 microns of silicon per pulse, of the order of 10 pulses will cut through a 200 micron thick wafer. This laser has achieved repetition rates of 10 pps, and this makes wafering rates at the program target of 12 per minute within reach.

Results of the dye laser study are described in the following section, Task 2 Highlights.

Task 2 Highlights

Among the highlights in Task 2 are:

- The design of an improved throughput laser cutting station and wafer handling mechanisms have been completed. A prototype of this design has been tested, and final design for extensive on-line testing is under way. This design will increase the laser station throughput by a factor of two from current levels, and identify design options that may be viable for further upscaling in wafer handling rates.

- A new laser has been identified which has improved wafer edge strength. This laser will be installed in a cutting station at Mobil Solar for extensive testing in an on-line environment in Phase 2.

- The cutting of silicon wafers using a dye laser has been demonstrated for the first time at rates needed to attain program goals. Detailed studies of the laser beam-material interaction show that beam power levels are not sufficient to reach the evaporation threshold for silicon, at which edge damage could be eliminated and wafer edge strength maximized. Further studies will be done to find means to increase the power level and to control the ejected silicon debris.

- Some encouraging wafer strength improvements, from about 45 to 60 MPa, as measured by a fracture twist test, have been demonstrated with a low divergence high beam quality Nd:YAG laser. While the as-cut edge strength levels are still low, we find that the target wafer edge strength of 125 MPa set for Phase 1 is approached after these wafers are given a silicon etch treatment. However, the improved strength wafers are obtained at reduced power levels and resultant lower cutting speeds. The ongoing work will concentrate on demonstrating means to obtain increased wafer strength with higher power lasers.

Task 2 Milestone Status

Milestone M-1.24 in the laser cutting task was not completed as planned in Phase 1. There are delays of 3 to 6 months because priorities for the design and installation of the laser station wafer-handling equipment and testing of a new laser have been shifted to Phase 2. This is not expected to impact the Phase 3 goals.

Task 3: Process Control and Product Specification

The programs in this task are structured to provide support in areas of sensor development, crystal growth process control improvements, and wafer characterization for the work objectives described above in Tasks 1 and 2 (see Fig. 1). This support is to culminate in implementation of advanced concepts in on-line material property monitoring and crystal growth process control via Intelligent Processing of Materials (IPM) strategies, which lead to increased yield and productivity in fabrication of 200 micron thick EFG wafers in Phase 3.

The following sections describe efforts under each subtask under Task 3 in Phase 1.

Subtask 3.1: Sensor Development

Sensor development programs address feasibility testing and implementation of new approaches to monitor and measure EFG material geometric characteristics and material properties. A number of these will be designed for on-line use in the crystal growth process, among them interface temperature field and meniscus shape measurement, local thickness measurement, and buckle mapping.

Progress made toward these goals is described under Task 3 Highlights later in this section.

Subtask 3.2: Intelligent Processing of Materials (IPM) Strategy

The goal of this subtask is to integrate process models, sensor technology, and process control concepts to develop advanced furnace control elements involving the implementation of IPM strategies for maintaining high yields and productivity in growth of 200 micron thick EFG octagons. A schematic outline of the various control elements is given in Fig. 5. Specific milestones for this subtask are not due until Phase 2 of this program, at which time integration will start of successful elements from the top row of Fig. 5 into the crystal growth process control structure.

Progress made toward these goals is described under Task 3 Highlights later in this section.

Subtask 3.3: Product Specification

As-grown wafer property specifications being addressed in this subtask include: thickness and thickness uniformity, flatness and edge strength, residual stress, and electronic quality.

A number of the wafer acceptance criteria depend on the nature of complex relationships among the above material attributes. A specific example for thickness, flatness and edge strength of relevance is illustrated in Fig. 6. Here the edge stress (vertical axis) generated in flattening an idealized cylindrically curved wafer of given warp and thickness has been calculated and is plotted as a function of thickness. This stress will ultimately limit mechanical yield in a given process step where flattening of the wafer is required. It is encouraging to find that the edge stress developed in flattening thinner wafers of a fixed warp by a given applied load is lower than for thicker ones. As wafer thickness is reduced, edge strength improvements need to be related to the flatness specification by considering such interactive effects.

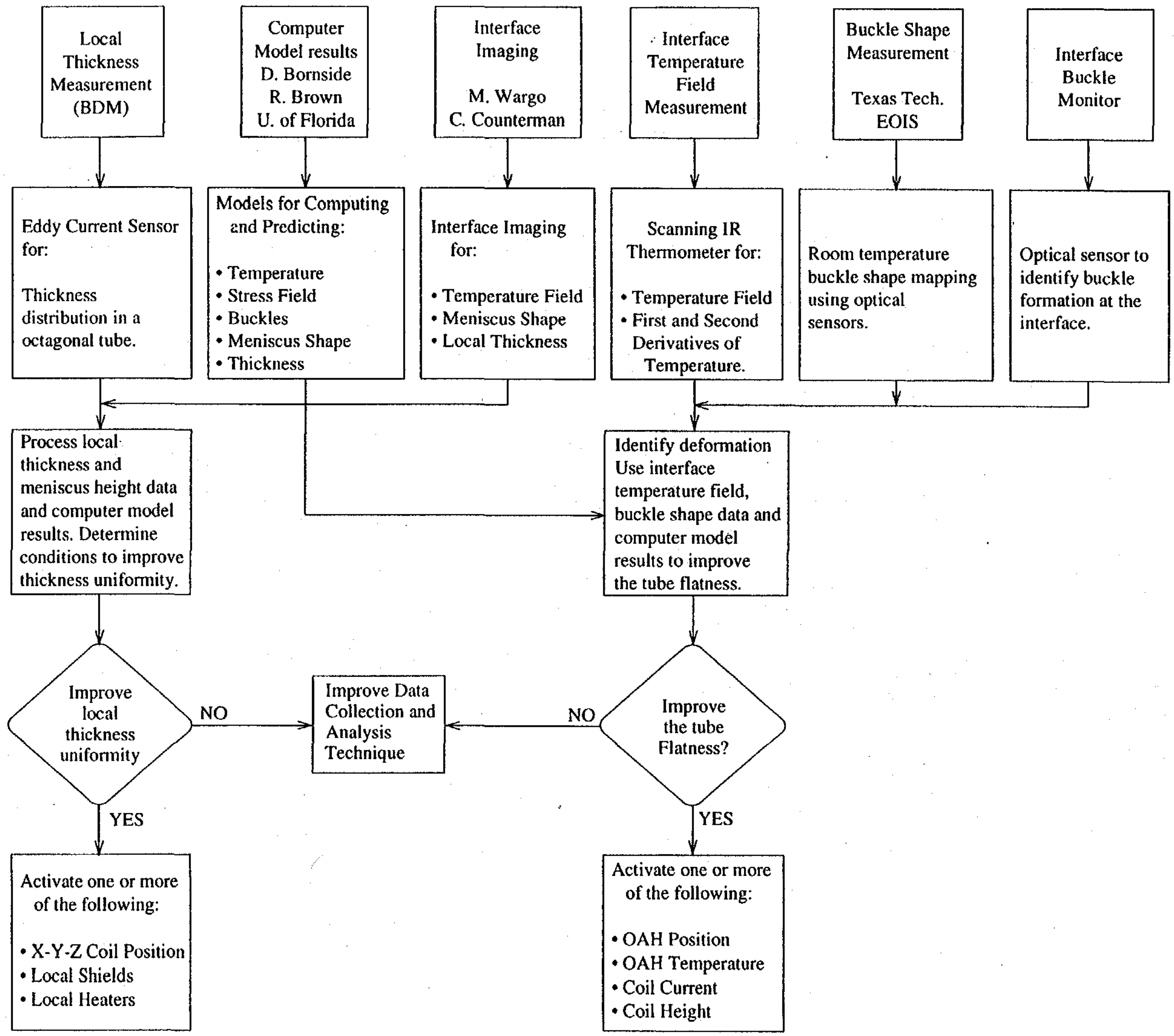

Figure 5. IPM implementation flow diagram.

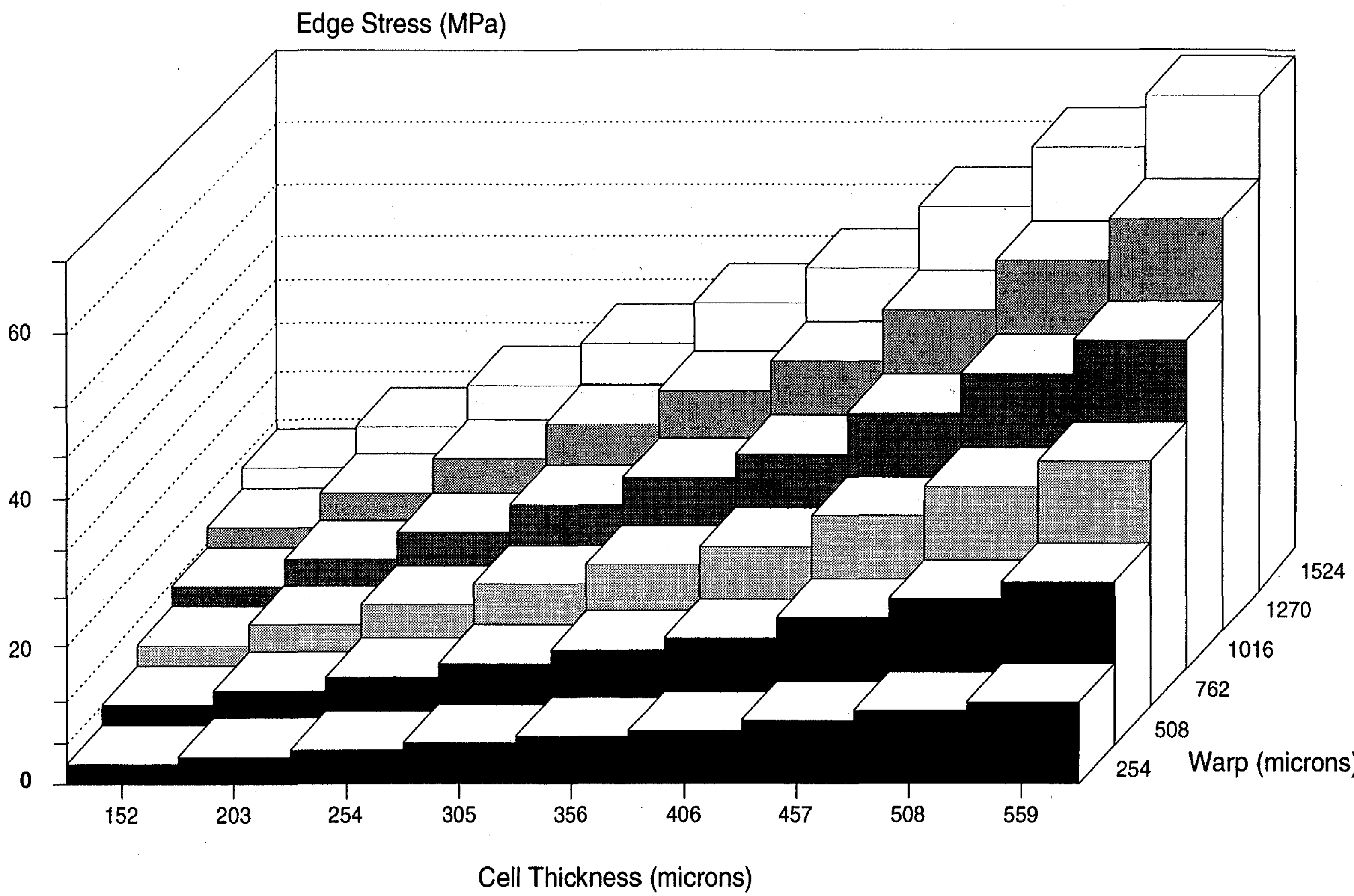

Figure 6. Edge stress in flattened cylindrical profile for various thickness and warp.

One of the Task 1 objectives is to monitor residual stress and demonstrate that it does not exceed 10 MPa. Several approaches to measure residual stress have been evaluated. One promising method is described in a report given in Appendix B. Preliminary results indicate that residual stress in EFG wafers are considerably below the 10 MPa level set as an objective for Phase 1.

The program objectives require that EFG wafer electronic quality be sufficient to have the potential to produce 10 cm × 10 cm 14% efficient solar cells. This capability has been demonstrated for a significant number of solar cells on a research level with 300 micron thick octagons.[9] Wafer minority carrier lifetimes will be monitored and small batches of cells made on an experimental basis as material thickness decreases throughout the program to check the impact of crystal growth developments on this material capability. A program is being developed to establish as-grown wafer electronic property monitoring and measurement techniques.

Highlights of Task 3 results are described in the following section.

Task 3 Highlights

Sensor Development

Several sensor prototypes have been evaluated for their suitability for on-line operation:

- *An optically-based interference technique for buckle shape mapping.* Competing approaches are being evaluated. Both techniques have overcome problems associated with EFG material reflectivity and surface irregularity, and on-line testing to map buckles have been successful.

- *An eddy current sensor for on-line measurement of tube wall thickness distributions.* The conventional mode of utilization of a low-frequency (of the order of 10 MHz) probe has been shown not to be practical. Alternate approaches are being explored and show promise.

- *Interface imaging sensors for measurement of growth interface response in meniscus shape and temperature fields and stress and thickness control.* An imaging system has been specified and successfully tested. Temperature calibration procedures are being developed.

- *An interface-region strain measurement technique.* Initial efforts to obtain good quality images of the crystal near the interface have not succeeded.

Intelligent Processing of Materials (IPM)

Task 3 activities will be integrated into the crystal growth effort with the implementation of advanced concepts in on-line material property monitoring and process control via Intelligent Processing of Materials (IPM) strategies, which can enhance yield and productivity in production of 200 micron thick EFG wafers in Phase 3. IPM will undertake integration of process models, sensor technology and process control concepts. A flow diagram showing the implementation plan for IPM was shown in Fig. 5. Additional information about the IPM effort is shown in Appendix A.

Product Specification

Highlights of material characterization/specification efforts include:

- Residual stress measurements. A Shadow Moire interferometric technique has been used to obtain estimates of residual stress in EFG wafers. Further calibration and verification of the applicability of this method for use with polycrystalline silicon is in progress (see Appendix B).

  A second project in this area is attempting to obtain residual stress in uncut tubes using holographic interferometry to detect strain changes around a drilled hole.

- Wafer edge strength. A statistical fracture twist test, developed at Mobil Solar, is being used routinely to monitor microcracks in the edges of laser-cut wafers.

- Diffusion length and lifetime. Several techniques have been explored for monitoring electronic quality and correlating to solar cell performance. Among those being considered are the Photoconductive Decay (PCD) for lifetime, and the Surface Photovoltage (SPV) technique for minority carrier diffusion length.

Task 3 Milestone Status

The Technical Readiness Demonstration detailed in milestones m-1.22, m-1.27, m-1.31, and m-1.34 will continue into Phase 2 of the program, as described in the following section.

Technical Readiness Demonstration (TRD)

Cost-effective improvements in EFG crystal growth technology have been demonstrated in individual instances during Phase 1. Designs have been tested in growth of small numbers of tubes and with experimental wafer cutting. The most significant results of these experiments are summarized in Table 1. All numbers are normalized to current baseline pilot production yields (set at 100%). The results demonstrate that these design improvements have the potential to produce material with increased yields and productivity at a 300 micron tubes thickness (yields greater than 100% in Table 1) and also meet the property specification satisfying Phase 1 goals for 250 micron thick material (greater than 75% yield).

The trial Technical Readiness Demonstrations (TRDs), which will continue into Phase 2, are planned as more extensive tests of new furnace design concepts. The scope of the TRDs and the milestones they address are outlined in Table 2. We have currently completed two growth runs of the TRD series; however, results were not available at the time of this writing. The TRDs will produce statistically significant numbers of EFG wafers meeting the required material specifications. They will also allow evaluation of the potential of the design changes to produce a consistent impact over longer periods of growth, representative of pilot production. Finally, the TRD will also help establish procedures for a similar effort scheduled for 200 micron thick material at the end of Phase 3.

Table 1. Laser Cutting and Flatness Results.†

300 Microns Thick Tubes

Tube	Condition of Growth	Laser Yield %	% Passed 1000 μm window	% Passed 650 μm window*	Comments
Prod. 1992 Average	Pilot line	100	100	Not used	Acceptable flatness yield and thick corners
Experimental - Improved Thickness Uniformity					
26T41-05	New susceptor	101	100	50.0	Lowered flatness yield and
39T21-03	New susceptor	104	96	65.0	reduced corners thickness
40T21-02	New susceptor	102	98	98	-same-
41T21-01	New susceptor	100	100	100	-same-
Experimental - Improved Flatness and Thickness Uniformity					
51T21-01	New IAH	85	105	--	Improved flatness yield and
51T21-02	shield & new	104	108	71.2	reduced corners thickness
51T42-01	susceptor	92	108	79.0	-same-
51T42-02	-same-	103	109	78.0	-same-
51T42-03	-same-	102	107	78.0	-same-

Experimental 250 Microns Thick Tubes

Tube	Condition of Growth	Laser Yield %	% Passed 1000 μm window	% Passed 650 μm window*	Comments
Poor Flatness and Thickness Uniformity					
16T21-04	T(OAH)=1170			23.0	Poor flatness and thick
37T21-06	T(OAH)=1190	93	96	57.4	corners
Improved Flatness and Thick Corners					
19T21-05	T(OAH)=1245 thick corners	102	100	61.0	Good flatness with thick corners
Poor Flatness and Improved Thickness Uniformity					
41T21-03	New susceptor	68	74	19.0	Unacceptable flatness with
41T21-04	New susceptor	75	68	22.0	thin corners
41T21-05	New susceptor	92	79	40.0	-same-
41T21-06	New susceptor	85	72	21.0	-same-
Improved Flatness and Thickness Uniformity					
51T21-03	New IAH	100	95	67.0	PVMaT program flatness
51T21-04	shield & new	96	102	65.0	goals satisfied and thin
51T42-04	susceptor	75˙	100	72.0	corners

† Percentages are normalized to Mobil Solar 1992 pilot production levels for 300 microns thick wafers.
* Not normalized.
˙ Low laser yield due to handling loss.

Table 2. Scope of Trial TRDs.

PHASE I TECHNICAL READINESS DEMONSTRATION

INTERNAL PROGRAM
MILESTONES m-1.22, -1.27, -1.31 AND -1.34

Objectives:

1) To establish procedures for evaluating thin octagon and wafer production in preparation for Phase 3 TRD

2) To compare wafer cutting yield and material characteristics and properties on statistical basis for 250 and 300 micron thick EFG material

3) To evaluate new furnace designs for improved thickness uniformity, reduced stress and increased productivity

Approach:

a) Two growth runs of 4–5 days under pilot line conditions, 16 tubes per run, half 250 and half 300 micron thick tubes

b) Cutting of tubes with improved laser conditions to optimize edge strength

c) Statistical comparison of 250 and 300 micron thick wafer properties (residual stress, flatness, thickness uniformity, edge strength)

Status:

i) Furnace parts ordered with improved designs for lowering stress, increasing productivity

ii) New laser and laser station not available

iii) Planning for March TRD completed

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Appendix A

Report on Implementation of Intelligent Processing of Material (IPM) Strategy for EFG Wafer Production

S. Rajendran, Mobil Solar Energy Corporation

Distribution Date: March 31, 1993

1. Introduction

The mechanical yield of processing EFG wafers into solar cells and encapsulating them in panels depends on the strength and the flatness of the wafers. The strength of a wafer is determined by the residual stress in the material and the length and density of microcracks created during laser cutting. The propagation of the edge cracks due to the flattening of the wafers during the processing lowers the mechanical yield. Further, automating the wafer transfer between processing steps becomes complicated due to the non-flatness of the EFG wafers. Hence, it is important to improve the flatness of the EFG tubes during growth.

The local electronic characteristics of an EFG solar cell are correlated to the local thickness of the wafer. The dependence of the wafer local thickness on the conversion efficiency limits the ability to maximize of cell efficiency. Hence the thickness uniformity of the tubes is another important characteristic that needs to be controlled during growth.

The interstitial oxygen (O_i) level in the wafer should be at an optimum level for maximum conversion efficiency. The interstitial oxygen is incorporated during the crystal growth by adding controlled amount of CO to argon ambient. The degree of O_i incorporation in the silicon tube changes from run to run in an unknown way. Hence, it is necessary to control the concentration of CO in the ambient to get the optimum level of O_i in the wafers.

The wafer characteristics discussed above can not be corrected after the octagonal tubes are grown. In EFG process development, all the thermal and mechanical components are designed to produce the best possible thickness uniformity, flatness and O_i level. However, due to the subtle variations in the properties of the raw materials and the time dependent interaction between the silicon melt and the graphite, there are variation in the quality of the tubes produced. These variations are not addressed by the normal process control algorithms.

Reducing the variation in the product quality is addressed by the Intelligent Processing of Materials (IPM) concept. The flow diagram of IPM strategy is shown in Figure A1. Sensors to measure the local thickness of the tubes, the flatness and the interstitial oxygen level during growth are developed and/or procured to implement IPM strategies. The measured quantities, the results of the predictive process models and the empirical observations on the process are being integrated into computer algorithms to correct the growth process as part of Task 3 of the Mobil Solar PVMaT program.

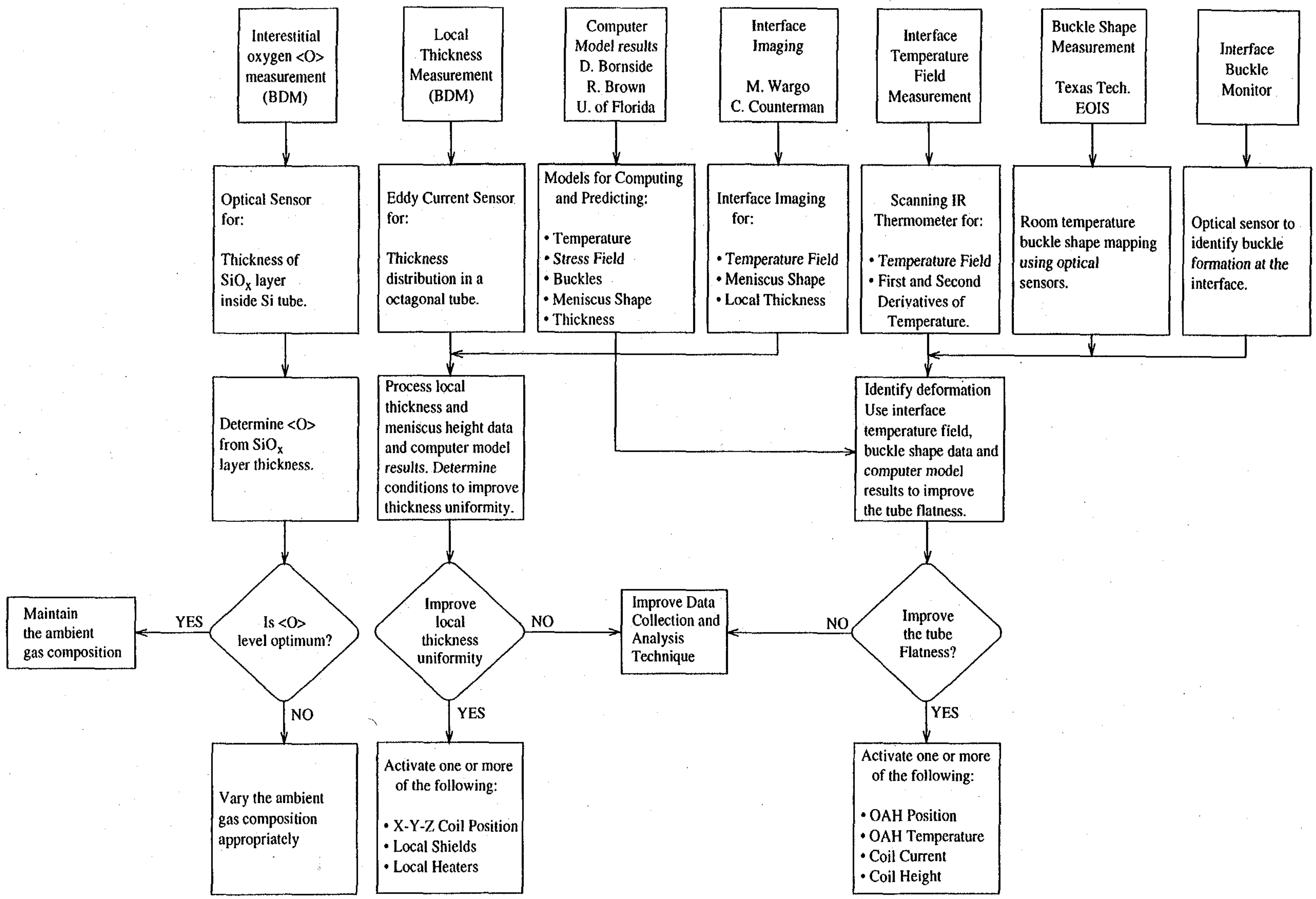


Figure A1. IPM implementation flow diagram.

The current status of the development of the different concepts shown in Figure A1 and the future work on implementation are discussed in this report. The technical issues involved in controlling the wafer quality, such as the thickness uniformity, the interstitial oxygen and the flatness are discussed in Section 2. The overall strategy of executing the IPM concept is discussed in Section 3 and the current status of sensor development and IPM is summarized in Section 4.

2. Wafer Quality Control

2.1 Local Thickness: In the current EFG process, the **average thickness** of an octagonal tube is maintained constant by controlling the heat dissipated in the hot zone. The average thickness of a face of the tube varies predominantly due to uneven heat dissipation around the susceptor and the die. Hot faces tend to be thin and cold faces tend to be thick. The location of hot and cold faces of the tube vary from tube to tube and run to run due to the variation in the thermal and the electrical properties of the graphite used. The thick and thin faces could be eliminated by adjusting the in-plane induction coil position with respect to the perimeter of the solid/melt interface.

A typical thickness distribution at the bottom of the first 5 m long tube, grown from a set-up, is shown in Figure A2a. The x-axis represents the location around the octagonal tube and the y-axis represents the local thickness. Seventeen measurements were taken on each face of the octagonal tube. It is clear from the figure that face 6 is the thinnest and the face 2 is the thickest. The induction coil position was then adjusted to improve the thickness uniformity. The thickness uniformity of the tubes grown after the coil adjustment improved significantly as shown in Figures A2b and A2c.

Frequent adjustment of the coil position, based on the thickness distribution around the tube, will improve the thickness uniformity of the wafers produced. A thickness sensor that measures the local thickness of the silicon tube during growth is not readily available. Developing an optical technique of measuring the local thickness of the silicon tube is currently pursued by one of the sub-contractors.

The surface topology of a face of the octagon, obtained with an optical technique, and the surface line scan gathered with a laser based proximity sensor are shown in Figures A3a and A3b respectively. The flatness of an octagonal face is indicative of the thickness of the face: thin faces tend to be buckled more than thick faces. In the absence (under development) of a local thickness sensor, it is proposed here that the flatness of the faces be used to compute the position the coil to improve thickness uniformity. The algorithm to collect the flatness data, process the information and compute the coil movement are currently under development. For a given hot-zone design, proper coil positioning is expected to improve the thickness uniformity and the flatness of the tube. The coil placement algorithm together with the other hot-zone modifications are expected to eliminate the fraction of the wafers rejected by the MSEC pilot line for flatness and thickness.

2.2 Flatness: The fraction of 250 microns thick wafers, grown under identical conditions, passing through a 650 microns wide window vary by as much as 30 percentage points. The reasons for the variations are not clear. Identifying non-flatness during growth and correcting it by manipulating the temperature field and the growth speed are being pursued in Task 3. The algorithms that will be implemented to improve the flatness yield are not yet finalized. The material discussed below, defines studies that will be conducted to determine optimum method of on-line flatness control.

Fig. A2a

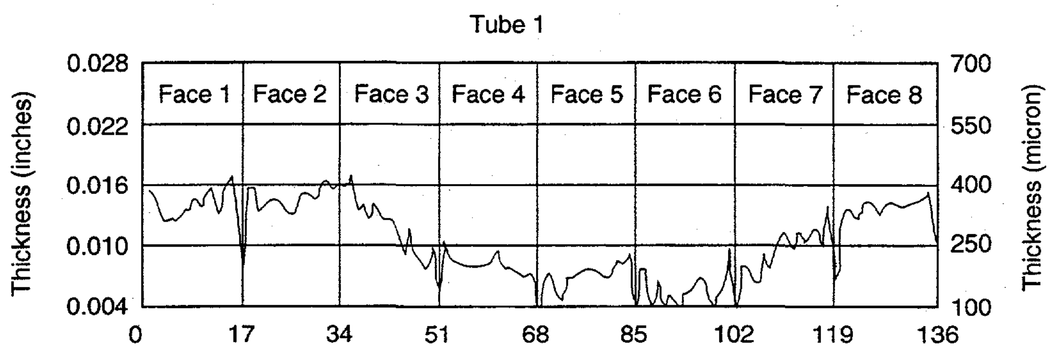


Fig. A2b

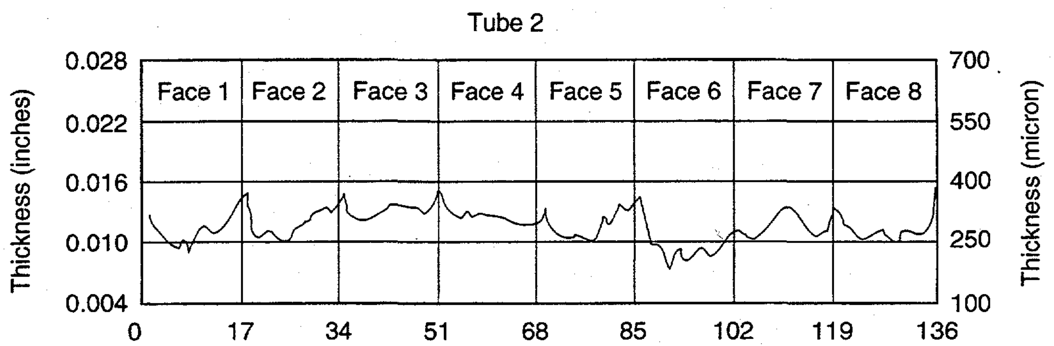
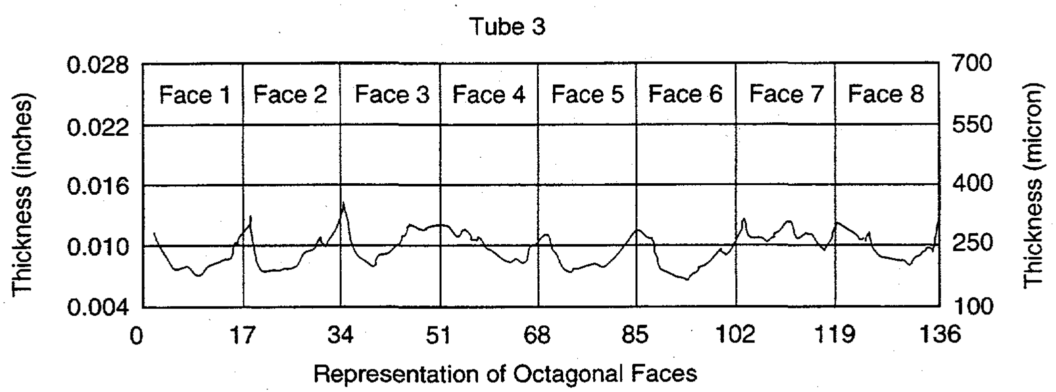


Fig. A2c



The Thickness Uniformity of the Tubes Improve with Coil Adjustments

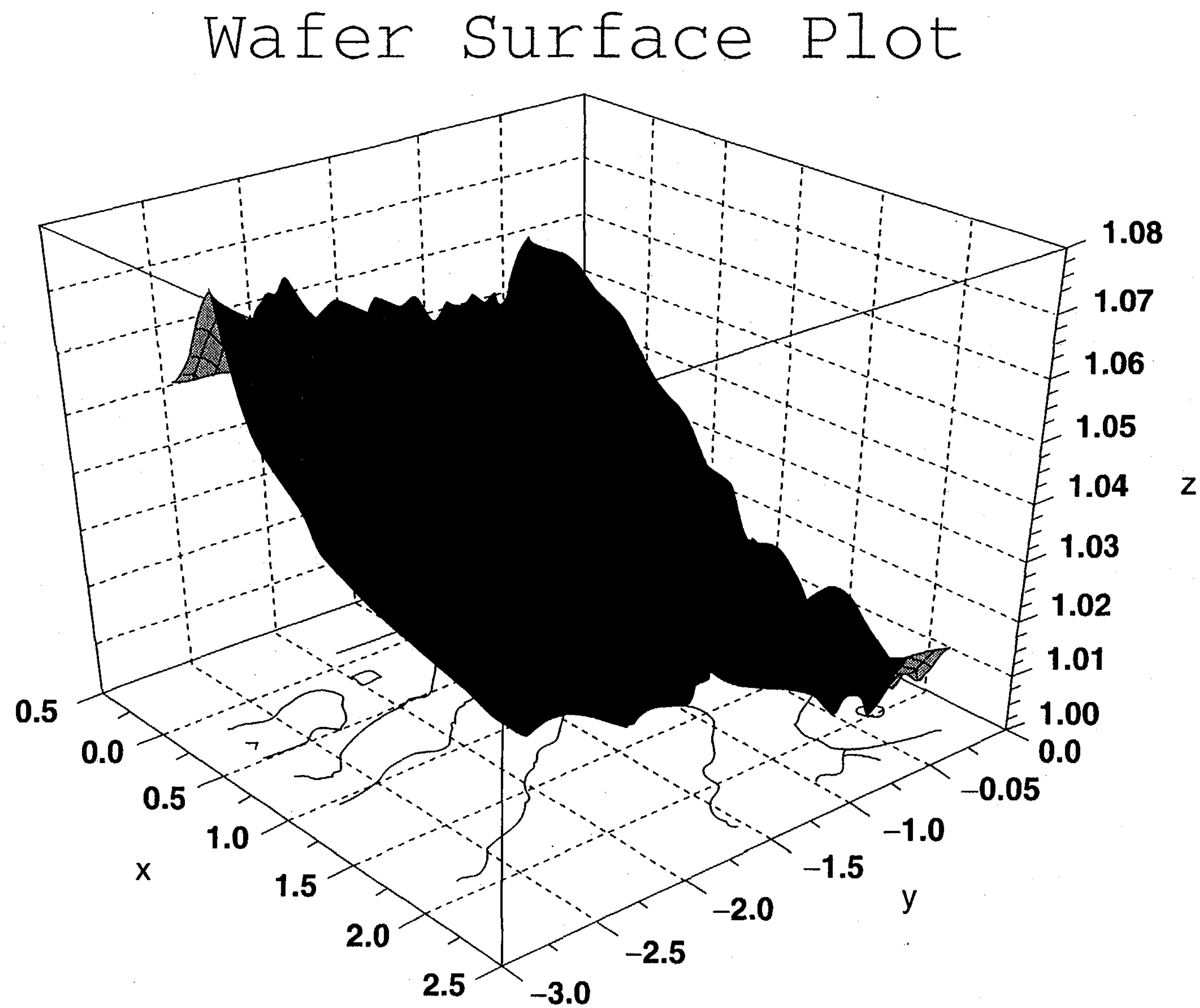


Figure A3a. Surface Topology of a Wafer.

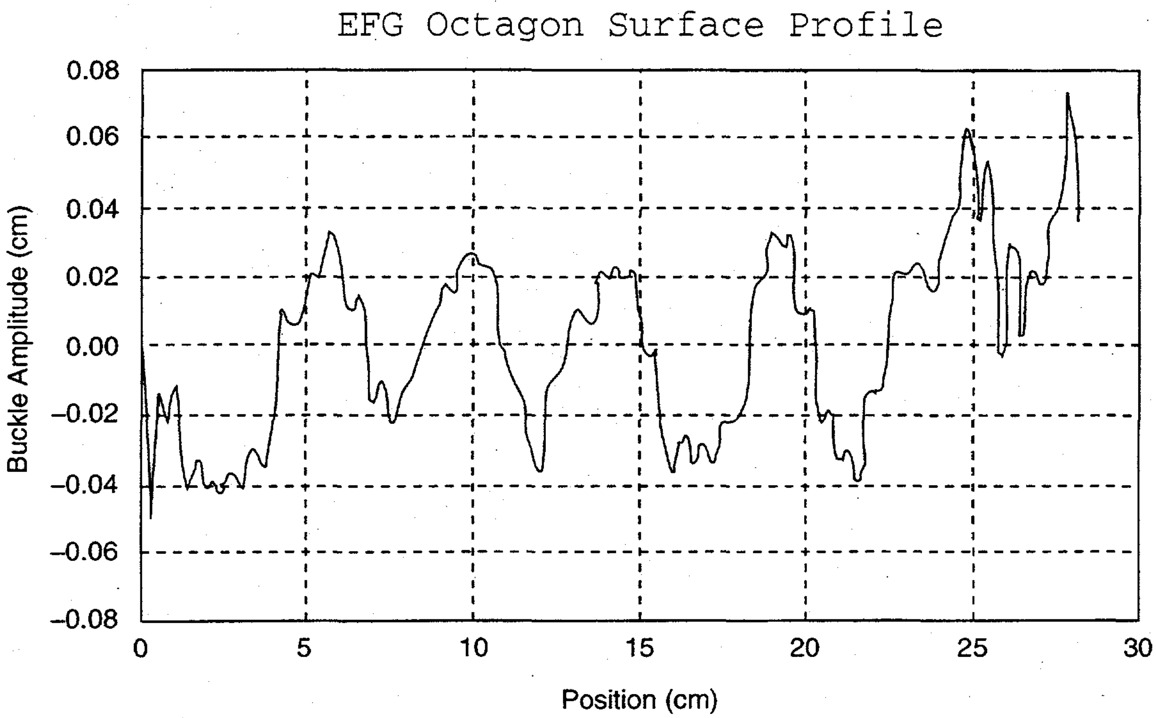


Figure B3b. Si Surface Profile Obtained With a Laser Based Proximity Sensor

The flatness of a tube is affected by the temperature at the bottom of the Outside AfterHeater (OAH), the position of the OAH with respect to the die-tip, and the length of the tube grown and the growth speed. Unraveling the relationship between these variables and the buckle amplitude is the focus of Task 1.

Empirical evidences indicates that the flatness of a tube varies with growth length along a tube after growth is initiated. The amplitude of the buckles is large during certain period, approximately between 17" and 60" growth. Methods of improving the flatness during this period of growth by varying the OAH temperature and position, and the growth rate, are being considered.

Independent control of the OAH temperature will facilitate the implementation of flatness control. An algorithm to control the OAH temperature is currently being developed. Once an algorithm for independent control of the OAH temperature is derived, the feasibility of varying the OAH temperature as a function of growth length will be investigated.

The growth rate is held constant and the thickness is controlled by manipulating the power dissipated in the operation of the current EFG system. The flatness of a tube is sensitive to growth rate and the flatness improves with the lowering of the growth speed. The growth rate cannot be varied without affecting the thickness of the tube with the current process control algorithm. Hence an algorithm that changes the growth rate without affecting the thickness will be developed for flatness control.

The results from the growth process modelling carried out by D. Bornside (MIT) and from the residual stress and the buckle formation computations done by P. Mataga (U. of Florida) will be combined to determine the best OAH temperature and position as a function of the length of tube grown. The computational results will be incorporated in on-line flatness control.

2.3 Interstitial Oxygen: The interstitial oxygen (O_i) level should be optimum for maximum solar cell conversion efficiency. Normally, the interstitial oxygen level in the wafer depends on the concentration of CO in the argon ambient during growth. However, the efficiency of O_i incorporation in the wafer is dependent on the graphite purification process used by the vendors and other subtle variation in the graphite properties which are beyond the control of MSEC. Hence it is necessary to measure the O_i level during growth and correct it, if necessary.

The O_i level in the EFG wafer is normally measured by the FTIR technique. Adopting the equipment for on-line is one of the avenues that is currently considered. Introducing CO in the growth ambient forms a layer of SiO_x at the inside surface of the octagonal tube. A correlation between the O_i and the thickness of SiO_x layer has been established. Hence methods of measuring the SiO_x layer thickness are being investigated. Once a sensor to measure the O_i during growth is identified, the algorithm to manipulate the CO concentration to control O_i level will be deployed.

3. Implementation of IPM

The objective of IPM strategy, as applied to EFG system, is to implement on-line controls that improves the thickness uniformity and the flatness of the Si tubes and maintains the optimum interstitial oxygen (O_i) level during growth. In devising a control strategy, it is important to recognise the widely varying time scales involved in the process. For example, the average thickness of a tube changes faster due to a change in the heat dissipated in the susceptor compared to the local thickness change caused by the differential accumulation of silicon carbide. Of course, if the local thickness variation is due to the local temperature alone, then the local thickness will respond as fast as the average thickness to a power level change.

A flow diagram of a possible scheme for implementing the process and product control of EFG Si tubes is given in Figure A4. The response of the average thickness of the tube to a variation in processes parameters, such as the susceptor temperature, pull velocity and etc., is very fast. Hence the process parameters need to be supervised and updated in frequent time intervals. It is proposed that the control of the process variables be carried out by a PLC. The quality of a tube need to be monitered relatively over a long period of time before corrective actions could be taken. Further, computational modelling results and other data bases could be required along with the sensor information to make corrective actions. Hence it is proposed a 486 based computer or a similar computer be used for the product control actions, which is essentially collecting information on the quality of the a tube, computing the values of the process variables and communicating them to the PLC.

In the current EFG process, the pull rate is held constant and the average thickness of the octagonal tube is controlled by manipulating the power induced in the susceptor-die assembly through a cascading loop. A constant silicon melt level in the crucible is maintained by establishing a mass balance between the weight of the tube grown and the weight silicon pellets fed into the crucible. The power dissipated in the susceptor, the pull rate and the mass of the silicon fed into the system need to be adjusted over a short time interval for proper control, i.e. the frequency of control action is high. The algorithm to perform the process control, as described above, has been established. The inputs and the outputs currently used for process control are noted in Figure A4.

The algorithm to control the product attributes such as the local thickness distribution, the flatness and the interstitial oxygen level in tube are currently being developed. New process parameters that affect the quality of the tube, such as the coil position, the OAH temperature and position and the CO concentration will be monitered and corrected, as a part of the product control algorithms. The inputs and the outputs required to control these parameters are identified in separate blocks in Figure A4. The function of the product control loop is to **collect** the data from various sensors and to **compute** the optimum setting of the process parameters, i.e. determine the best position for the coil to improve the thickness uniformity, the CO concentration for the optimum O_i level and the OAH position and temperature required for minimizing the buckles and **communicate** the information to the PLC. The values of the process parameters will be updated by the algorithm residing in PLC. The product attributes need to be monitored continuously but the time interval between updates for corrective actions will be of the order of a few minutes.

The strategy to control the local thickness uniformity automatically has been developed and will be implemented within the first quarter of phase 2. Once a sensor that measures the O_i level during the growth is identified, the procedure to control the O_i level by manipulating the mass flow rate of CO into the argon stream will be deployed.

The details on the strategy to control the flatness during growth are being developed. Varying the growth rate and the OAH temperature and position as a function of the length of the crystal is one of the avenues currently considered. Hence emphasize is placed on devising algorithms that holds the thickness constant while varying the velocity and the OAH temperature.

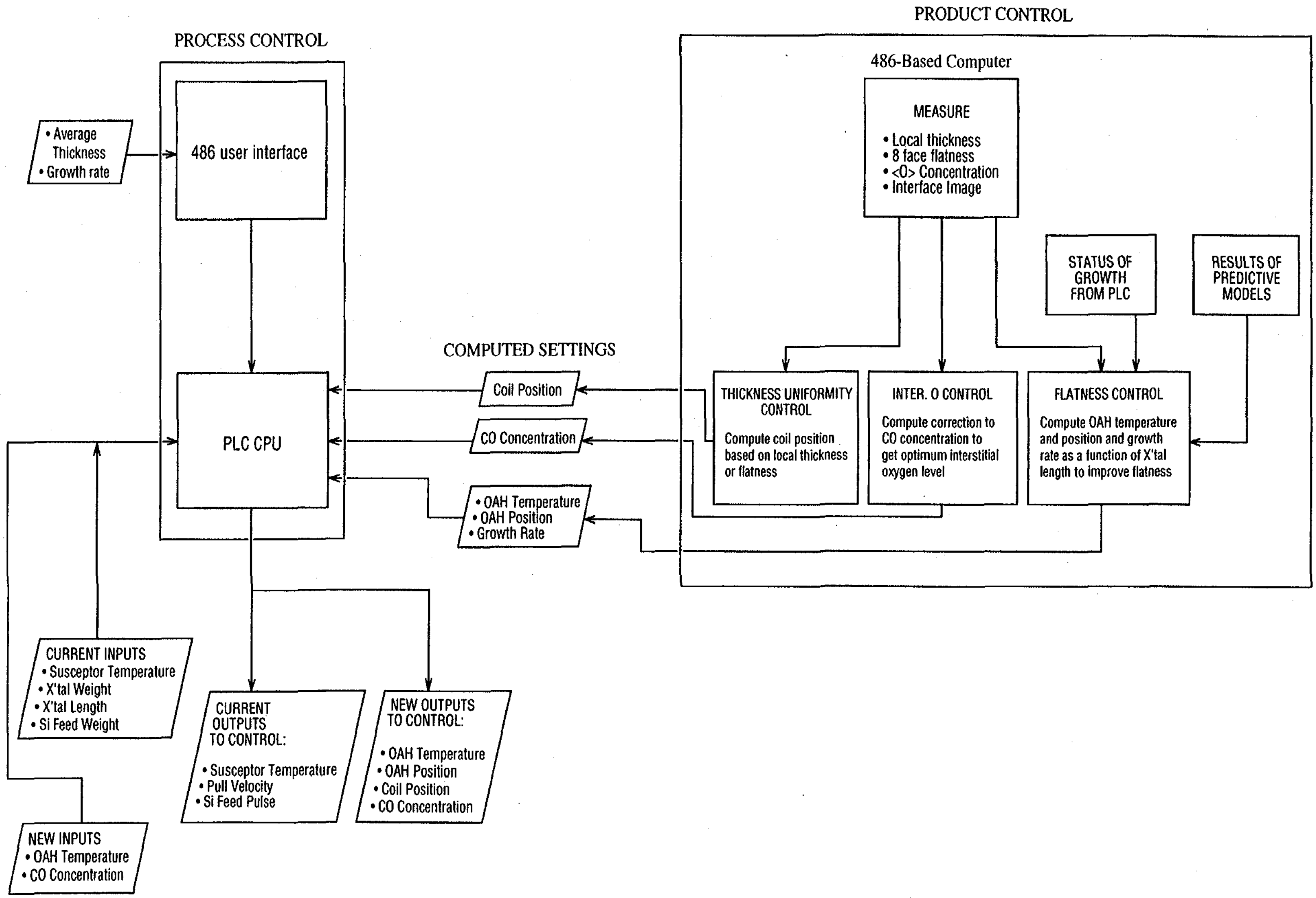


Figure A4. Flow Diagram for the Process and the Product Control During EFG of Octagonal Si Tubes.

4. Summary

* Implementation of on-line, local thickness control is well underway.

* Process control algorithms that facilitate the implementation of on-line flatness control are being developed.

* Efforts are taken to procure and develop sensors to measure the local thickness, flatness and the interstitial oxygen level during growth.

Acknowledgements

Contributions to the technical results described in this report are gratefully acknowledged from J. Crowley and F. Feda of Mobil Solar.

Appendix B

Measurement of Residual Stresses in EFG Wafers

Status Report

prepared for

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by

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February 5, 1993

Summary

This project was initiated in June 1992 as an outgrowth of previous work by the PI on development of optical and analytic methods to obtain the in-plane residual stresses of circular Cz wafers and rectangular EFG wafers.[1] The experimental method involves use of the shadow Moiré technique to obtain out-of-plane deflections due to known loads and the calculation of in-plane residual stresses over large spatial areas by the use of unique analytic techniques that describe the stresses in terms of the deflections. Within the last six months, a calibration test has been developed for circular Cz wafers, and a new analytical technique for extracting in-plane stresses from measured deflections has been developed, tested and applied to 90 mm diameter circular EFG wafers. Preliminary measurements of the in-plane residual stresses in six circular EFG wafers have been made. The maximum in-plane stresses ranged from 0.9 to 1.9 MPa, and these stresses were tensile.

The PI has changed university affiliations. The project will be transferred over a period of three months to the Georgia Institute of Technology.

Technical Status

The technical status of the project can be summarized as follows:

1. A new and improved analytical formalism has been developed to extract the in-plane residual stresses from deflections of a thin, flat wafer centrosymmetrically loaded, with the outside edge pressed against a knife-edge support. An example of the analytical expression for the in-plane residual stresses at the center of the wafer is given by

$$\sigma_{rs} = 0.4E\left(\frac{h}{a^2}\right)[1 + w_o(0)/w_m(0)]$$

   where σ_{rs} is the in-plane residual stress, h is the wafer thickness, a is the radius from the center to the knife-edge, E is Young's modules and $w_o(0)$ and $w_m(0)$ are the theoretical and measured deflections at the center of the wafer.

2. A calibration experiment of the technique has been completed. A circular ring that can be used to impose in-plane compressive stresses has been fabricated and applied to a 100 mm Cz (111) silicon wafer. Strain gauges were positioned on the ring, and the ring was compressed. The strains measured by the gauges were converted to stresses and these were compared to the stresses obtained by the optical technique. The correspondence of these stresses was within 10%.

3. Six circular EFG wafers were provided by Mobil Solar and the in-plane stresses were measured. The in-plane residual stresses at the center of the wafers where the stresses are expected to be the largest were determined using average thicknesses and the values of Young's modulus and Poisson's ratio for (111) single crystal silicon. The results are shown in Table I below.

Table I. In-Plane Residual Stresses of Circular EFG Wafers at the Center of the Wafer.

Wafer #	Average Thickness (mm)	σ_{rs} (MPa)
1	0.28	1.21
2	0.30	1.47
3	0.29	1.47
4	0.30	1.43
5	0.31	0.86
6	0.29	1.93

There is not any trend in stress variation with thickness observable, although the overall variation from 0.28 to 0.31 mm is too small to be conclusive. Thinner material than is now being grown will be tested in the next phase, and stress related to other growth variables such as growth speed, oxygen and resistivity. The stresses are considerably below the Phase 1 objective of 10 MPa so that this material variable appears to be well controlled at present.

References

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Abstract

We report here on the Photovoltaic Manufacturing Technology (PVMaT) Initiative program at Mobil Solar Energy Corporation for Phase 1, covering the period from April 1992 to March 1993. Mobil Solar is developing advanced technology for growth and laser cutting of 200 micron thick Edge-defined Film-fed Growth (EFG) octagons that will reduce the manufacturing costs of 10 cm × 10 cm polycrystalline EFG silicon wafers and modules. Factors have been identified in crystal growth which impact on thickness uniformity and yield of wafers. Steps have been taken to evaluate process improvements and wafer and module cost reductions in growth and cutting of 300 micron thickness EFG wafers on the production line. The work on intermediate target 250 micron thickness octagons has focused on fundamental process understanding to allow specification of EFG technology needed for a wafer thickness reduction to 200 microns set as the goal for Phase 3. Specifications for new EFG furnace configurations and laser cutting equipment have been completed and testing under pilot line conditions is scheduled to take place in Phase 2.

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4. Title and Subtitle Thin EFG Octagons	5. Publication Date January 1994
	6.
7. Author(s) J.P. Kalejs	8. Performing Organization Rept. No.
9. Performing Organization Name and Address Mobil Solar Energy Corporation Billerica, Massachusetts	10. Project/Task/Work Unit No. PV450101
	11. Contract (C) or Grant (G) No. (C) ZM-2-11040-3 (G)
12. Sponsoring Organization Name and Address National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401-3393	13. Type of Report & Period Covered Technical Report 1 April 1992 - 31 March 1993
	14.

15. Supplementary Notes
NREL technical monitor: R. Mitchell

16. Abstract (Limit: 200 words)

This report summarizes the significant technical improvements in edge-defined film-fed growth (EFG) technology achieved in Phase 1 of the PVMaT project and the success in meeting the project guidelines. Technical results are reported for each of the three main program areas. (Task 1) Thin octagon growth (crystal growth)—investigations were aimed at aiding and accelerating the transition from the growth of 400-μm to 300-μm-thick octagons, while carrying out the research needed to achieve the Phase 1 interim goal of the production of 250-μm-thick wafers. This work stressed development of fundamental process understanding that will allow specification of EFG technology needed for a wafer thickness reduction to 200 μm. (Task 2) Laser cutting—in this area an increased throughput laser station was designed, and a prototype of a material handling system was tested. The fundamentals of the laser beam interaction with Si material were investigated in order to define conditions under which high speed cutting with reduced damage and increased wafer edge strength can be obtained. (Task 3) Process control and product specification—methods to deploy sensors for on-line material property control are being investigated and as-grown wafer specifications are being developed for thickness, flatness, residual stress, and wafer electronic properties.

17. Document Analysis

a. Descriptors
manufacturing ; wafers ; crystal growth ; edge-defined film-fed growth ; octagons ; photovoltaics ; solar cells

b. Identifiers/Open-Ended Terms

c. UC Categories
270

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