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Mobil Solar Energy Corporation 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 describes the work carried out at Mobil Solar in the first six months of this program in three areas: (1) crystal growth - to reduce the thickness of the octagon to 200 microns; (2) laser cutting - to improve the laser cutting process to produce wafers with decreased laser cutting damage at increased wafering throughput rates; and (3) process control and product specification - to implement advanced strategies in crystal growth process control and productivity designed to increase wafer yields.

Crystal growth experiments and furnace design reviews are currently being carried out in support of a reduction of octagon and wafer thickness from 400 to 300 microns on the Mobil Solar pilot production line. The experimental work has successfully identified means to improve thickness uniformity, and to reduce the deleterious impact of ambient-related effects which have caused reduction in crystal growth productivity and yield. Octagon tubes of 250 micron thickness are being grown on an experimental basis in order to establish baseline laser cutting and flatness yields. The current main obstacle to improving 250 micron thickness EFG material yields to the targets set for the end of Phase 1 arises on account of the buckling produced by thermal stress. Programs are under way to study these causes both theoretically and experimentally, and to identify improvements that will reduce the buckling.

The work in progress in the laser cutting program has as its main objectives to reduce laser cutting damage so that EFG wafer edge strength increases by a factor of three, and to increase the wafering rate to 12 wafers/minute. Currently, CO_2 lasers are being used to establish cutting baseline yields for 300 and 250 micron thick octagons. Feasibility studies on the use of new configurations of Nd:YAG lasers and on the suitability of using a dye laser to cut EFG wafers have been initiated with lower-tier subcontractors. The objective for Phase 1 is to demonstrate improved edges strength with one of the new laser cutting approaches. Initial experiments with the dye laser have succeeded in producing 5 cm long line cuts through 300 micron thick silicon. Design reviews have been held to evaluate means for improving the tube and wafer cutting equipment and to identify approaches for increasing wafer cutting throughput.

A task on process control and product specification is examining means to improve crystal growth process control through utilization of advanced sensor concepts and Intelligent Processing of Materials (IPM) strategies. Bench-top demonstrations of the feasibility of using optical means to map buckles on EFG wafers have been successful, and on-line testing of these concepts is scheduled. Other sensor techniques that are being studied for on-line applications include an eddy current method for local thickness measurements, and interface imaging systems for measurement of temperature fields, meniscus shape (thickness control variable) and stress parameters, strain and buckling amplitudes. Product specification tasks are being supported by lower-tier subcontractor studies of residual stress measurement techniques and of correlations of laser cutting damage to edge strength.

Table of Contents

Figure and Table Captions

Introduction

The objective of the Photovoltaic Manufacturing Technology (PVMaT) program at Mobil Solar Energy Corporation is to advance the manufacturing line capabilities in crystal growth and laser cutting of its unique Edge-defined- Film-fed Growth (EFG) octagon technology,[1] and so reduce costs of 10 cm × 10 cm polycrystalline silicon EFG wafers. This advancement is to be accomplished through a decrease in the silicon material usage, by improvements in crystal growth productivity, and by increasing laser throughput and overall wafer yields. The technical goals include: decreasing octagon wall thickness from 400 to 200 microns, implementing advanced crystal growth control strategies, and deploying new laser cutting technology with an increased wafering rate and improved wafer strength. When incorporated into Mobil Solar's production line, these advances will significantly decrease the costs of its wafer and module manufacturing operation. In addition, such advances will open up new possibilities for Mobil Solar to enter into world markets for polycrystalline silicon wafers at a level that would greatly undercut current wafer prices.

This report describes the technical tasks and objectives, and the progress made toward achievement of milestones in the work carried out at Mobil Solar in the first six months of the program. The technical work is structured into three main tasks: 1. Thin octagon growth, 2. Laser cutting, 3. Process control and product specification. The phasing of the work and the goals of the tasks in the three years of the program, and the task relationships to the overall objectives of the PVMaT program are outlined in Fig. 1.

Progress in Technology Development

The significant results and progress made in this reporting period in work toward the technical objectives of the main tasks are discussed in the following sections. A milestone and deliverables listing for these objectives is provided in Table 1.

Task 1: Thin Octagon Growth

The customary sawing, grinding and polishing actions used to obtain uniform thickness and flat substrates in conventional silicon wafer production processes by ingot growth or casting[2] are obviated by the sheet nature of the product tube resulting from the EFG process. However, a consequence of this advantage is that stringent measures must be taken to control factors, inherent to the crystal growth process, affecting the as-grown material geometry.[3]

Subtasks 1.1 (Thickness Uniformity) and 1.2 (Stress) address the material problems in crystal growth that need to be resolved in order to produce acceptable 10 cm × 10 cm EFG wafers as octagon wall thickness is decreased to 200 microns. Variations in wafer properties of primary concern are of several types: thickness nonuniformity, buckling (i.e., deviations from flatness) and residual stress. The program intermediate goals for Phases 1 and 2 (see Fig. 1) are to maintain thickness uniformity, flatness and stress criteria that produce acceptable wafers for Mobil Solar's pilot line production while the octagon wall thickness is at the same time being reduced to the 250 and 200 microns, respectively, required at the end of these Phases. Wafer specification criteria on thickness uniformity, flatness and residual stress addressing Phase 3 goals are to be concurrently established through the work in task 3.

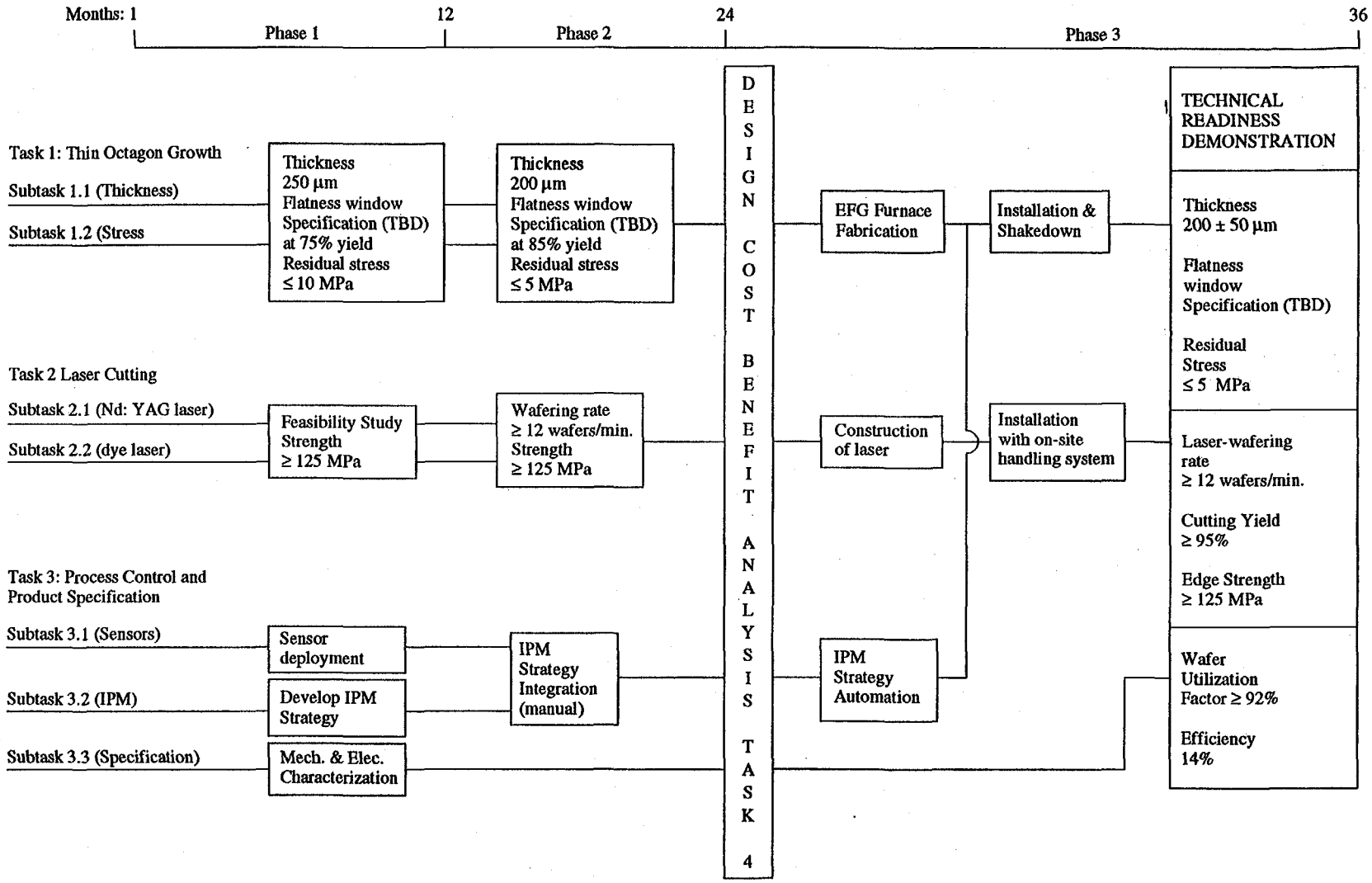


Figure 1. Program Goals Summary – See text for definitions of terms

Table 1. Milestones and Deliverables Schedule for Phase 1 of Mobil Solar PVMaT Program.

PHASE I

End of the First Quarter

m-1.1 Complete investigation of die and susceptor design to improve thickness uniformity on 300 μm thick octagons (Task 1)

m-1.2 Complete investigation of outside afterheater temperature as a means to control stress in 300 μm thick octagons (Task 1)

m-1.3 Deliver 36 samples (12/month) of EFG-grown Si wafers for mechanical characterization under deliverable D-1 (Task 3)

End of the Second Quarter

m-1.4 Complete investigation of coil design to improve thickness uniformity (Task 1)

m-1.5 Complete investigation of outside afterheater position as a means of controlling stress (Task 1)

m-1.6 Complete the hot-zone design that minimizes deleterious ambient effects while maintaining productivity and yield (Task 1)

m-1.7 Complete development of 3-d Magnetic Model (Task 1)

m-1.8 Complete Crystal Growth Furnace Design Review I (Task 1)

m-1.9 Deliver 36 Samples (12/month) of EFG-grown Si wafers for mechanical characterization under deliverable D-1 (Task 3)

End of the Third Quarter

m-1.10 Complete investigation of new graphite material and coatings to improve thickness uniformity (Task 1)

m-1.11 Complete investigation of transverse temperature field as a means to control stress (Task 1)

m-1.12 Test and debug the hot-zone assembly design that minimizes deleterious ambient effects for growth of 300 μm thick octagons and demonstrate performance standards acceptable for pilot line conditions (Task 1)

m-1.13 Complete Crystal Growth Furnace Design Review II (Task 1)

m-1.14 Complete Testing and Debugging of Coil Manipulator (Task 1)

m-1.15 Complete Testing and Debugging of a movable outer afterheater (Task 1)

m-1.16 Complete Evaluation of the parametric 2-d magnetic thermal model of the EFG System (Task 1)

m-1.17 Complete Evaluation of laser cutting facility for 300 μm thick octagons under pilot line conditions (Task 2)

m-1.18 Complete measurement of interface temperature field (Task 3)

m-1.19 Complete feasibility study on the interface Buckle Monitor (Task 3)

m-1.20 Deliver 36 samples (12/month) of EFG-grown Si wafers for mechanical characterization under deliverable D-1 (Task 3)

m-1.21 Deliver 12 samples of EFG-grown Si wafers for characterization of their electronic quality under deliverable D-2 (Task 3)

End of the Fourth Quarter

m-1.22 Complete the Phase I portion of the effort under Task 1 (Task 1)

m-1.23 Complete Crystal Growth Furnace Design Review III (Task 1)

m-1.24 Complete evaluation of Nd:YAG laser cutting facility for 250 μm thick octagons under pilot line conditions at increased wafering rates (Task 2)

m-1.25 Complete feasibility study on improving wafer edge strength for cutting with Nd:YAG laser to ~125 MPa (Task 2)

m-1.26 Complete feasibility study on improving wafer edge quality with a line cut from a dye laser to ~125 MPa (Task 2)

m-1.27 Complete the Phase I portion of the effort under Task 2 (Task 2)

m-1.28 Deliver 36 samples (12/month) of EFG-grown Si wafers for mechanical characterization under deliverable D-1 (Task 3)

m-1.29 Deliver 12 samples of EFG-grown Si wafers for characterization of their electronic quality under deliverable D-3 (Task 3)

m-1.30 Complete feasibility study of Interface Imaging (Task 3)

m-1.31 Complete feasibility study of On-Line Buckle Shape Measurement (Task 3)

m-1.32 Complete interim flatness & quality specifications, 250 μm wafer (Task 3)

m-1.33 Complete the Phase I portion of the effort under Task 3 (Task 3)

m-1.34 Complete the Phase I portion of the effort under Task 4 (Task 4)

Thickness reduction in the octagon from the standard 400 microns practiced for some time at Mobil Solar has been proceeding in stages. The main focus in the past six months has been completion of the switch from 400 to 300 micron wall thickness octagon production. Work on subtasks of this program to be reported below has helped to define improved growth configurations that are being incorporated in the pilot production line as part of this changeover. The current status of projects and progress made toward milestones are reported next.

Thickness Uniformity - Subtask 1.1

The allowable limits for thickness nonuniformity for thin EFG wafers are currently not defined. They are in large measure dependent upon the nature of the yield losses encountered in solar cell and module production processes. Efforts are planned to develop specifications on thickness uniformity 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 $\pm$ 50 microns for allowable thickness variations has been tentatively set for the 200 micron thick 10 cm $\times$ 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 to 200 microns.

The work on the crystal growth objectives in this subtask is currently focussed on improving growth technology and material uniformity in the changeover to the intermediate octagon target thickness of 300 microns. Some preliminary work on 250 micron thick tubes has been initiated. In the remainder of Phase 1, the crystal growth experiments will be redirected toward growth of the target 250 micron thick material as necessary to address and achieve the goals of Phase 1 of the program (see Fig. 1).

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 octagon face center to edge thickness differential. Typically earlier tubes tend to have thinner corners in the beginning and then progressively become thicker as the number of tubes grown increases. These variations are caused by heat transfer nonuniformities in the die and susceptor.

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 resultant 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]

None of these manifestations depend on the actual thickness being grown. The results below are for growth of 300 micron thickness tubes except as noted otherwise.

Work and successes toward particular milestones completed in this reporting period are as follows:

Milestone m-1.1. Modified hot zone components have been designed, fabricated and tested which have led to a reduction by nearly a factor of two in thickness variations due to heat transfer effects (1 above) between the center and the edge of the octagon face. The improved designs are currently being evaluated for suitability for use in a pilot production environment. When these studies are completed, the new designs will be incorporated permanently into the crystal growth systems to be used in Phases 2 and 3 to grow 200 micron thick octagons. The concepts will be reported at a later time pending an investigation on whether patents will be filed on these designs.

Milestone m-1.4. Studies of the coil configuration needed to address thickness variations as in 2 above have been completed to fulfill this milestone. An octagonal shaped coil was designed, fabricated and tested in order to examine its impact on the face-center-to-edge thickness profile. It was found that the desired impact on the thickness variation was not attained, and the use of this coil will be discontinued.

Milestone m-1.6. Several solutions to alleviating oxide problems within the furnace have been identified. The oxide arises when carbon monoxide is used to increase octagon bulk interstitial oxygen and enhance material electronic quality to levels required for 14% efficient thin solar cells.[5,6]

The cause for the onset of oxide deposits has been elusive, and they appear to come and go randomly. When severe, they increasingly interfere with the growing tube as the run progresses, and produce large amplitude buckle-like perturbations. The result is an early termination of runs, with a loss in yield and productivity. In one solution identified, the build up of oxides with time has been essentially eliminated through a change in the materials used in the furnace. The other solution involves modifications in the design of the furnace configuration. The costs and benefits associated with these alternatives will be evaluated in the next quarter. The modifications in furnace designs proposed for solving this problem will be reported later pending an evaluation on whether patents will be filed.

Milestone m-1.8. The initial crystal growth design review (I) has been completed. The main elements of this review dealt with detailing the configuration, controls system for melt replenishment, and power supply for an improved EFG crystal growth furnace. These designs will contribute toward better axial thickness control (item 3 above). The task of preparing detailed specifications for this furnace constitutes the work to be done for the second review scheduled in the next quarter. As part of this effort, a furnace redesign is underway to extend the octagon face width to allow an increase in the EFG wafer dimension from the current 96 to 100 mm.

Milestone m-1.10. New graphite material and improved purification methods for graphite components are being evaluated for use as EFG hot zone components. This work has two aspects. A new grade of graphite is available, and material has been ordered and will be fabricated into dies for testing. The new mode of fabrication of this material gives it an improved uniformity of material properties, e.g., thermal conductivity and electrical resistivity, which are in turn important in controlling the homogeneity of the temperature and induced heat distributions. Improvements in this area may help to reduce systematic as well as some random thickness variations around the perimeter of the octagon, and hence directly contribute toward achieving the goals of subtask 1.2. In a second aspect, graphite purification technology is being evaluated to examine its relation to growth performance and productivity as well as for its potential to contribute toward program goals on maintaining and improving as-grown material electronic quality. Purification spans all aspects of growth performance related to reproducibility, productivity and quality. Results on material electronic quality evaluation related to improvements in graphite materials will be reported in Task 3 milestones scheduled for later in Phase 1.

Stress - Subtask 1.2

Stress acting on the octagon originates in nonuniformities and high axial gradients (of the order of 1000°C/cm) in the temperature field which create thermal stresses during growth.[7] These stresses produce plastic flow and dislocations which then further contribute to residual stress 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 means of controlling the buckling and improvement in flatness is closely related to ability to manipulate the temperature field, more specifically, its second derivative, in the region of greatest plasticity (generally above 1000°C) in the post-growth cooling, and in the rate of cooling through the plastic region.[8] This region is located immediately above the die tip, indicated by an arrow in the schematic of the EFG octagon furnace configuration in Fig. 2. Stress reduction requires detailed information on the temperature fields in close proximity, within about 5 mm, of the growth interface. This information currently is not available. 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 utilized to formulate Intelligent Processing of Materials (IPM) strategies to control and minimize octagon stress. Some of the characterization and instrumentation techniques that will be applied to stress control in this subtask will be developed in Task 3.

Flatness specifications on thin EFG wafers that relate to mechanical (wafer breakage) yields are to be determined (viz., TBD in Fig. 1) in the course of this program. The relationship of yield to wafer edge strength, currently limited by the laser cutting process, will be studied under the work planned in the Product Specification subtask in Task 3.

Work under way to address the milestones in subtask 1.2 in this reporting period is described next.

Milestone m-1.2. The outer afterheater temperature near the die tip (see Fig. 2) is a measure of the degree to which manipulation of octagon interface temperature fields can be made. A number of design parameters control the afterheater temperature distribution. In, addition, its location, viz., its height above the die tip region, is an important variable for controlling the temperature field in the octagon. All of these parameters are scheduled to be investigated in the course of the work in this subtask.

In the current phase of the study, the maximum operating temperature at the tip of the afterheater was monitored with a pyrometer, and its effects on buckling observed at a qualitative level, pending the development of more advanced sensor technology. The latter will be needed to give the quantitative picture of the interface temperature field and its relationship to buckling which is to be eventually used in developing control strategies for residual stress and flatness reduction.

A number of tubes were grown with a range of afterheater temperatures, and resulting wafer flatness was monitored. The maximum temperature which could be studied is restricted by growth stability considerations. As temperature is raised, interface gradients promoting stability are reduced concurrently with the desired decrease in the second derivative of the interface temperature profile, which determines the stress. The observations suggested that the minimum buckle amplitude was not always achieved at the highest afterheater operating temperature, but occurred at temperatures below the maximum reached. Although a number of 300 and 250 micron thick tubes were cut and wafers inspected, reliable data has not been obtained to date to quantify these relationships. This may have been the result because the thickness uniformity of the material was additionally affected, as is discussed further below, and this has precluded continuing this direction of investigation for the time being.

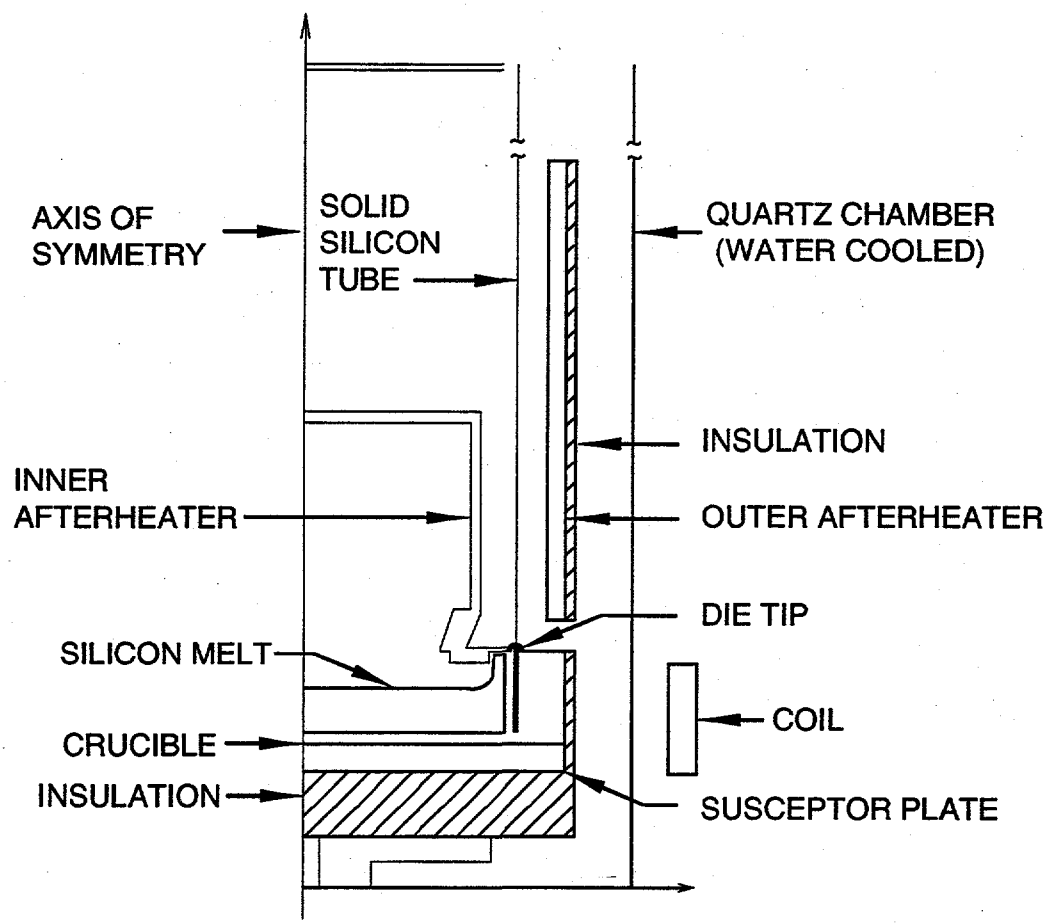


Figure 2. EFG octagon system furnace schematic.

Milestone m-1.5. Experiments were carried out with the outer afterheater at several different elevations with respect to the die top. These placements had to be carried out manually and it was found that the current design does not allow for precise or reproducible placement of the afterheater. There is a need to develop more flexible and robust outer afterheaters, and several options have been proposed and will be tested in future work to be done in this subtask.

Milestone m-1.7. Development of a 3-dimensional magnetic field model for calculating induced heat distributions in the current design of octagon hot zone was completed through a collaborative effort with a lower-tier subcontract at STM Consulting. More details are given below.

Lower-tier Subcontractor Activity in Support of Task 1

The work of lower-tier subcontractors addresses milestones in Table 1 that are due in later quarters of Phase 1. The following reports summarize the progress toward these milestones.

Milestone m-1.7: 3-d Magnetic Modelling - STM Consulting. Both of the above subtasks are supported by investigations of the three dimensional temperature field in the EFG growth system. This is required to better understand means by which to: 1. eliminate the thickness variation across the octagonal face, i.e., the thick corners and the thin face centers and the corner thickness transient, i.e., the progressive thickening of the corners with growth length; and 2. modify the temperature field (axial and transverse) to minimize the thermal stress in the growing octagon. The temperature distribution in an induction heated EFG system, as used in the current program, is dependent on the heat induced within the components of the system, and thus requires solution of the magnetic field and heat transfer equations for the entire growth furnace. The induced heat distribution, obtained from the solution of magnetic field equations, will be used as an input to compute the 3-d temperature distribution in the EFG system.

The thermal stress reduction requires the optimization of the transverse temperature profile across the face of the octagonal tube. The design of the bottom ring of the outer afterheater is critical to control the transverse temperature profile. The 3-d magnetic model results will be used in exploring the outer afterheater design that minimizes the thermal stress.

<u>Status</u> In the first step in establishing a comprehensive magnetic and temperature field modeling capability, STM consulting has completed development of a parametric 3-d magnetic model of the EFG system using the software, MSC/XL and MSC/EMAS.

The model is being used to study the effect of furnace design changes on the magnetic field and induced heat distribution. This study includes the effect of coil position, of the afterheater design and of the susceptor design.

The preliminary results of the 3-d magnetic modelling completed by STM to date expedited the progress towards achieving milestones m-1.1 and m-1.4 for improving the thickness uniformity, by identifying the dominant mechanism that causes the transverse thickness variation along the octagonal face.

Milestone m-1.14: Coil Positioner - Advanced Automation. The placement of the hotzone (die, susceptor and insulation) with respect to the coil, the differential expansion of graphite parts and the variation in the property of the graphite parts used manifest as thickness variation around the octagonal tube. As discussed under subtask 1.1 some of the thickness variations could be corrected by adjusting the coil with respect to the hot zone.

An adjustable induction coil positioner is being developed by the subcontractor. The coil will allow adjustment in all three perpendicular directions to be controlled by a computer. The in-plane adjustments of the coil will allow manipulation of the circumferential thickness variation. The axial adjustment of the coil will be used to modify the temperature distribution and hence the stress. It is anticipated that the added flexibility allowed by this coil will help in dealing with the complex interactive effects that couple thickness and stress manipulation, as discussed elsewhere.

Status The design and engineering phase of the project is complete. A comprehensive parts list and engineering drawings are available. The parts are being procured. The system will be assembled and tested in the next quarter.

Milestone m-1.18: Interface Temperature Field Measurement. Work toward this milestone has not yet been started and its completion date is likely to slip into the fourth quarter.

Milestone m-1.19: Interface Buckle Monitor. This program consists of two parts. An in-house effort is planned to set up an interface imaging system that will allow determination of the buckle amplitude in a region of the growing octagon tube within 5 mm of the growth interface. This will provide guidance to experimental efforts to study factors producing stress and buckling and give complementary information to the monitoring techniques that will become available from the work being done toward milestone m-1.30 (see Task 3). Work on this milestone has not yet been initiated and its completion date is very likely to slip into the fourth quarter.

In a separate effort, lower-tier subcontractor work at Texas Tech University is attempting to demonstrate the feasibility of using an laser-based optical method to measure strain near the growth interface. This program has been initiated with Professor J. Cardenas-Garcia of the Optomechanics Research Laboratory of the Department of Mechanical Engineering. Equipment has been acquired and bench-top testing has been started.

Milestone m-2.5 (Phase 2): EFG Process Modelling & Die Design - R.A. Brown & D. Bornside. A thermo-capillary model of an EFG system is being developed to better understand the interaction between various operating parameters, such as the induction coil currents, the outside afterheater (OAH) position on the temperature distribution close to the solid/melt interface - and the meniscus height. The temperature distribution close to the solid/melt interface of the growing tube determines the residual stress and the flatness and the meniscus height determines the local thickness of the tube.

The chief strategy to reduce the thermal stress in the growing octagon is to lower the second derivative of temperature at the solid/melt interface region. This is done in practice by increasing the OAH temperature, which generally lowers the second derivative of the axial temperature in the solid. However, any such change in the afterheater region affects the temperature distribution in the silicon melt in the meniscus region also. If there is an increase in the temperature in the melt next to the solid/melt interface, then this could increase the first and second derivatives of the axial temperature field in the solid silicon. Hence the effect of increasing the OAH temperature on the derivatives of the axial temperature profile is not clearly defined from these first principle arguments alone. Application of thermo-capillary model will provide information to understand these coupled effects, and help define a strategy to minimize the stress-producing second derivatives of the temperature field.

In making system modifications either to reduce stress or attain growth of the thinner 200 micron thick octagons, it is necessary to maintain edge definition at the corners of the octagonal tubes. The rounding of the corners results in waste of material and lowers the processing yield. The die-tip design parameters,

such as the width, height, capillary width among others, that control the radius of the corners will be studied by the extension of the 2-d thermo-capillary model to the third dimension. The 3-d thermo-capillary model to be developed will also shed light on the importance of the surface tension on controlling the thickness of the corners.

Status The geometry of the model that includes the meniscus region, the inside afterheater, the outside afterheater, the susceptor and the die has been meshed. Provisions are made in the model to include the induced heat computed using the magnetic models being developed at STM, as described above.

Milestone m-2.9 (Phase 2): Buckling and Residual Stress in EFG Silicon - P. Mataga. The non-flatness and the magnitude of the residual stress in an EFG wafer are manifestations of the net strain field accumulated, during the growth process, when the silicon tube is subjected to plastic deformation. The subcontractor is adapting existing models to compute the residual stress in the tube and developing new concepts to study the formation of buckles.

The temperature distribution in the silicon tube and the growth velocity determine the thermal stress field and hence control the residual stress and the flatness of the wafers. In the current program, the temperature distribution in a growing silicon tube will be manipulated by varying the outside afterheater design, temperature and position. The temperature distribution computed from the magnetic, thermal and the thermo-capillary models will be used as an input to the residual stress models and the resulting residual stress will be used as inputs to the buckle models. Thus, the sensitivity of the residual stress and the propensity to buckle formation to a furnace component design/process variable can be followed through both experimentation and computation. The computational results will be used to determine the optimum axial and transverse temperature profile needed to minimize the residual stress and the buckles in 200 micron thick octagons.

Status A post-doctoral candidate has been hired by Professor P. Mataga at the Department of Aerospace Engineering, Mechanics and Engineering Science of the University of Florida. Setting up of the model to perform the stress calculations is currently under way.

Problems and Concerns - Task 1

Significant concerns have been raised during the work in both subtasks 1.1 and 1.2. These relate to interactive effects between variables used to modify the temperature distributions relevant to improving thickness uniformity and reducing stress. In the first instance, the design solutions found to reduce thickness nonuniformity in meeting objectives of milestone m-1.1 in subtask 1.1 above also produced increases in stress. This manifested in greater buckle amplitudes in the octagon and an increase in the nonflatness of the cut wafers.

There are several possible causes for these results. Thinning of the corners of the octagon reduces resistance to buckle formation. Thus a certain degree of thickness increase at the octagon corner may be desirable to take advantage of the stiffening effect against buckling at a corner. The reduction in interface isotherm curvature produced in making the corners thin, e.g., hotter, if it were to result in transverse temperature gradient modification in the crystal, also could lead to increased thermal stress. Finally, the design change implemented to reduce the face-center-to-corner thickness variation resulted in a slight change in operating temperature used in steady-state growth. These temperature changes all have the potential to contribute to increased stress and buckling. An effort is being formulated to examine these interactive effects.

A second problem area has arisen in the course of meeting the milestones m-1.2 and 1.5 in subtask 1.2. Varying the afterheater temperature and/or its location produced undesirable changes in the crucible temperature distribution. In particular, varying levels of unmelted silicon were produced in the bulk melt. This adversely influenced the thickness uniformity around the perimeter of the octagon. The unmelted silicon results from a failure of all the silicon, added to the melt while the tube is being grown to melt, and is caused by radial temperature gradients in the crucible.[9] These become particularly severe when the temperatures in the outer afterheater region are increased as is believed to be desirable to reduce stress. This relationship is currently under study. A solution will have to be found to eliminate the unmelted silicon to allow systematic optimization of conditions minimizing stress and thickness nonuniformities to be carried out independently.

Task 2: Laser Cutting

The laser cutting work planned for the main subtasks in Phase 1 is structured to study the feasibility of attaining program goals by two different routes: improving existing cutting technology using Nd:YAG lasers, or cutting silicon with a new generation of line focus dye and CO_2 lasers. These two approaches provide very different options for meeting the cut wafer edge quality (strength) and throughput (wafering rate) objectives of the program (see Fig. 1). After feasibility studies and cost evaluations in Phases 1 and 2, the candidate laser technology best suited to meet the program goals as well as 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 over 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 $\times$ 10 cm area in as little as 4 seconds, providing a 15 wafers/min rate. However, maximum wafering rates available at the laser output are not reached in practice because of the limitations of tube and wafer handling mechanisms. The work on improving the cutting technology with these lasers thus involves advancing tube and wafer handling processes as well as improving wafer cut edge quality. This program is described in the report in subtask 2.1 below.

High power 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 the current Phase of this contract, efforts are under way 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. Future comparisons to line cutting with a high power CO_2 laser are scheduled in Phase 2.

Laser cutting objectives for this task involve demonstrating improved quality in cutting, as measured using a fracture twist test (10), and increasing the wafering rate for 200 micron thick EFG octagons (see Fig. 1). There were no intermediate milestones due for the laser cutting subtasks for the first six months of the program. The following sections describe progress toward meeting third quarter and year end objectives in the various subtasks.

Nd:YAG Laser - Subtask 2.1

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 in Section 3. Here the status is given of programs on: (i) progress in design, testing and implementation of advanced tube and wafer handling concepts for increasing throughput in a laser cutting station at Mobil Solar, and (ii) on means of 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.

Milestones m-1.17 and m-1.24 - Laser Cutting Station. A significant part of the initial work in this area was in preparation for an internal engineering design review of all facets of the current laser cutting and wafer handling technology, and of proposals for new advanced increased throughput systems. The main components of this technology include the tube and wafer handling equipment, the laser autofocus unit, and the computer-based interface control system. The design review was completed in August. As a consequence, a number of concepts have been selected for evaluation, and are currently being worked on. A cutting station layout has been completed. Designs for advanced tube and wafer handling have been completed and various components are being fabricated for individual testing.

Milestone m-1.25 - Nd:YAG Laser Evaluation. A program has been initiated at Lasag to evaluate various limits of Nd:YAG laser cutting technology. This involves testing of several options that offer to combine improved cut edge quality with increased throughput. Two laser types are being evaluated: a conventional low beam divergence point focus laser; and a slab laser which operates with an elongated rectangular beam. In each case, cutting with and without a preheat and/or postheat beam will be evaluated for its potential to decrease edge damage. This program has just been initiated and results are not yet available. The new cutting station facility is scheduled to be available for evaluation of cutting of 250 micron thick octagon tubes in the last quarter of Phase 1. It is planned to rent a Lasag Nd:YAG laser and to install it for testing with various components of the tube handling system at that time. This laser will then be used for on-site testing in the Phase 2 program with the more advanced Nd:YAG laser configurations, under evaluation at Lasag for the remainder of Phase 1, which show promise for meeting the program goals.

Dye Laser Feasibility Study - Subtask 2.2

The objective of this program 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, hence the beam-material interaction volume, is a strong function of wavelength of the irradiation. The beam conditions available place it 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 evaporation with minimal associated damage becomes possible. Both the CO_2 and Nd:YAG "cutting" processes proceed via first bringing the silicon material surface to a melting condition and then expelling the melt using directed gas jets. As shown in Fig. 3 by the vertical line, a single pulse will melt in its entirety a 300 micron thick substrate. Their pulse length range (100 to 500 microseconds)

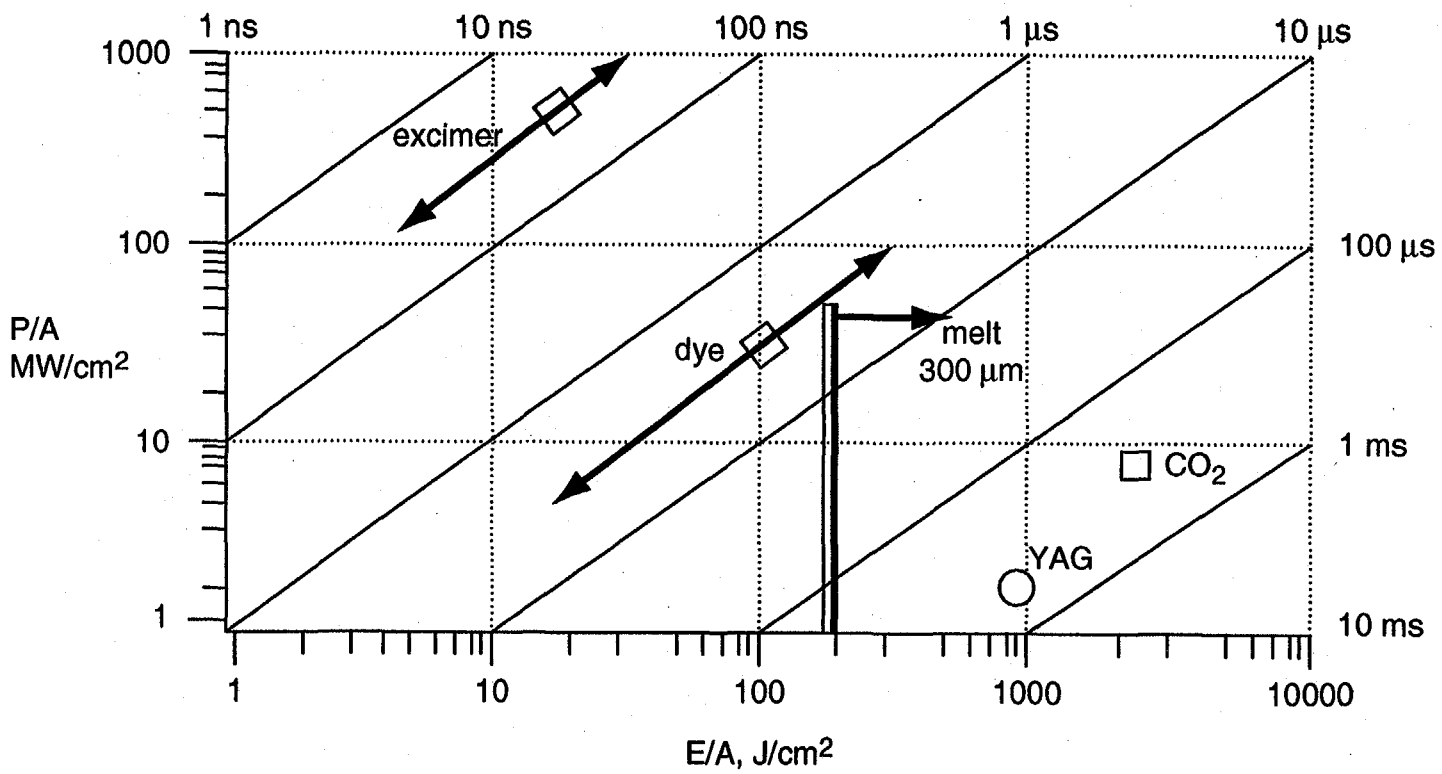


Figure 3. Laser Power and pulse length operating regimes.

and energy density combinations are not sufficient to evaporate the silicon melt and thus minimize the energy transferred into the zone around the melted region by thermal diffusion. The extent of the thermal diffusion zone determines the microcrack length[11] which sets the current limit to the edge strength of the EFG wafer.[10] 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.

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 × 100 microns, as will be desired in high speed cutting of 10 cm × 10 cm EFG wafers. In the feasibility studies, due to availability of focussing optics, the beam has been focussed to a line 5 cm × 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 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. The possibility is being examined of carrying out modeling of 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 demonstrated achieved repetition rates of 10 pps, and this makes wafering rates at the program target of 12 per minute within reach.

Milestone m-1.26 Status. The dye laser cutting configuration has been set up and preliminary tests carried out to successfully demonstrate its ability to cut silicon. Beam energies have been achieved that cut through both CZ and EFG test wafers of 300 micron thickness in 15 to 20 pulses over a line of 5 cm. Indications are that "cutting" is occurring with the evaporation of the silicon. Some residual melt was detected on the walls of the cut. The extent of the melt formed and its relation to other cutting parameters will be explored during the remainder of this Phase 1 study. It is anticipated that 5 cm square wafers will be produced in sufficient quantities to test whether the available operating regimes of beam parameters can produce wafers with edge strengths that come close to the desired program targets.

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 production of 200 micron thick EFG wafers in Phase 3. The following reports describe the status of work toward various milestones in Task 3.

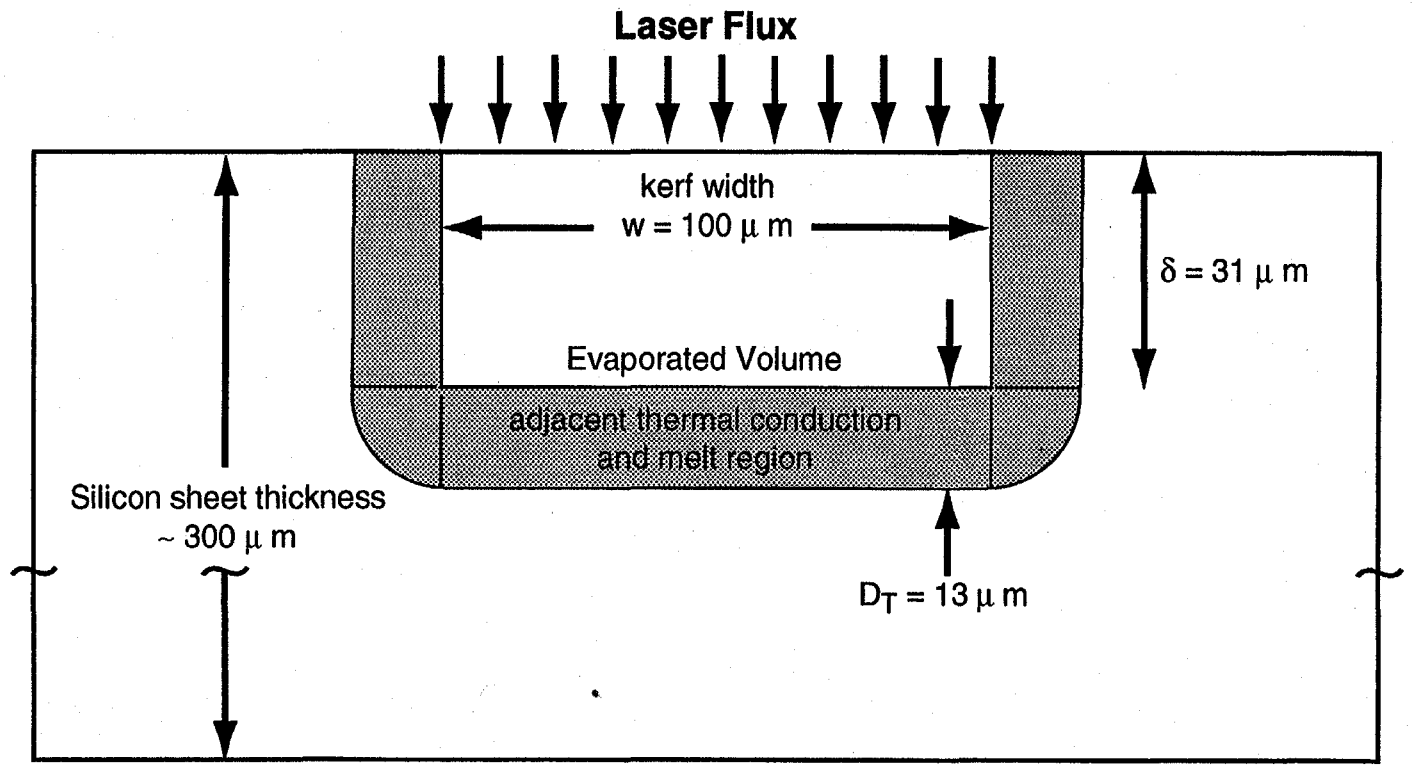


Figure 4. Laser beam-material interaction mechanisms.

Sensor Development - Subtask 3.1

Sensor development programs address feasibility testing and implementation of new approaches to monitor and measure octagon and 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 milestones for these techniques due in the fourth quarter and beyond was as follows:

Milestone m-1.30: Interface Imaging - M. Wargo and C. Counterman. Control of octagon thickness or stress in the EFG process requires understanding of the process dynamics taking place around the interface region, e.g., as noted above, of the local meniscus height that controls the local thickness of the octagonal tube and the interface temperature field that determines the thermal stress developed in the silicon sheet. Knowledge of the relationships between such local variables, furnace component design and operating conditions which are modified to effect these changes is crucial to establishing control systems that operate on the meniscus height and the temperature field.

An interface imaging system will be developed which has the capability to follow the effect of the process and design parameters on the meniscus height and the interface temperature field. This imaging system will allow the connection to be made between parameters such as the OAH temperature and its position and the main coil position, monitored by the design and controls engineers, and the meniscus height and the interface-region temperature fields.

The concepts developed in the interface imaging task will be valuable in two respects: to verify the computational models that will form the basis of control algorithms for advanced process control strategies to be developed in the IPM implementation in Phases 2 and 3 of this program; and as a diagnostic tool for increasing productivity of 200 micron thick octagons in the crystal growth operation in a factory setting.

<u>Status</u> The specifications for the components of the imaging system have been established. The components are being procured, and will be assembled for on-line testing in the next quarter.

Milestone m-1.31: On-line Buckle Shape Measurements. Two lower-tier subcontractors are working in separate and competitive efforts to demonstrate the feasibility of making on-line measurements of buckle shape and amplitude. Preliminary studies prior to this program's initiation with these contractors had indicated that a number of obstacles needed to be overcome in order to obtain reproducible and quantitative on-line mapping of octagon buckles. Each of the subcontractors offered some advantages. A fast and reliable means to monitor buckling is a central contributor toward success in the stress reduction program in subtask 1.2, studies. In order to increase the probability of success in this important task, both available approaches to measurement of buckling are being investigated in a preliminary feasibility study. A decision based on cost-effectiveness and flexibility of each approach will be made after the completion of the initial studies.

<u>Status</u> The preliminary work being carried out at Texas Tech University and EOIS in both cases have successfully demonstrated buckle shape imaging capabilities on 10 cm × 10 cm areas. The next phase of this work is to test the imaging concepts in on-line demonstrations on a growing octagon at Mobil Solar.

Milestone m-2.7: Local Thickness Measurement - BDM. In the current operation of the EFG crystal growth system, the tube thickness distribution is measured after the growth of every 5 m long tube and coil adjustments are manually made to improve the thickness uniformity. On-line coil adjustments, based on the growing octagonal tube thickness distribution, have the potential of improving the thickness uniformity of the tube. A sensor, based on eddy current phenomena, has been demonstrated to be capable of measuring the local thickness of the tube during the growth process. The feasibility of using this sensor to perform on-line thickness measurements on the octagon is being investigated by this lower-tier subcontractor.

The variation of the local electrical resistivity and the stand-off distance, the distance between the sensor and the silicon sheet surface complicate the eddy current measurement technique. Also, the optimal frequency of operation for the sensor needs to be determined.

Status The subcontractor is in the process of determining the optimal frequency range of the operation and the eddy current probe design through process simulation and experimentation.

Intelligent Processing of Materials (IPM) Strategy - Subtask 3.2

This subtask will undertake integration of process models, sensor technology and process control concepts to develop advanced furnace control elements via 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 previously described in other sections of this report 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.

Product Specification - Subtask 3.3

Areas of specification of as-grown wafer properties which are 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 that are to be developed 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. Wafer edge strength improvements need to be related to the flatness specification as thickness is decreased through consideration of such interactive effects in developing wafer specifications on geometric and mechanical attributes on thinner wafers.

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 recently been demonstrated for a significant number of solar cells on a research level with 300 micron thick octagons.[6] 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.

Progress toward milestone m-1.32 for material specification studies in this reporting period has been as follows:

Residual Stress. Calibration of an apparatus for measurement of residual stress in 10 cm × 10 cm EFG wafers has been started by Prof. S. Danyluk at the University of Illinois (Chicago). This measurement uses a Shadow-Moiré technique. It has been applied to study residual stress in circular Czochralski single crystal silicon wafers and must be adapted and evaluated for the square EFG wafer format. There is a further issue to be examined on whether the nonflatness and polycrystallinity of the EFG material will permit straightforward interpretation of fringe patterns and quantitative stress measurements to be made.

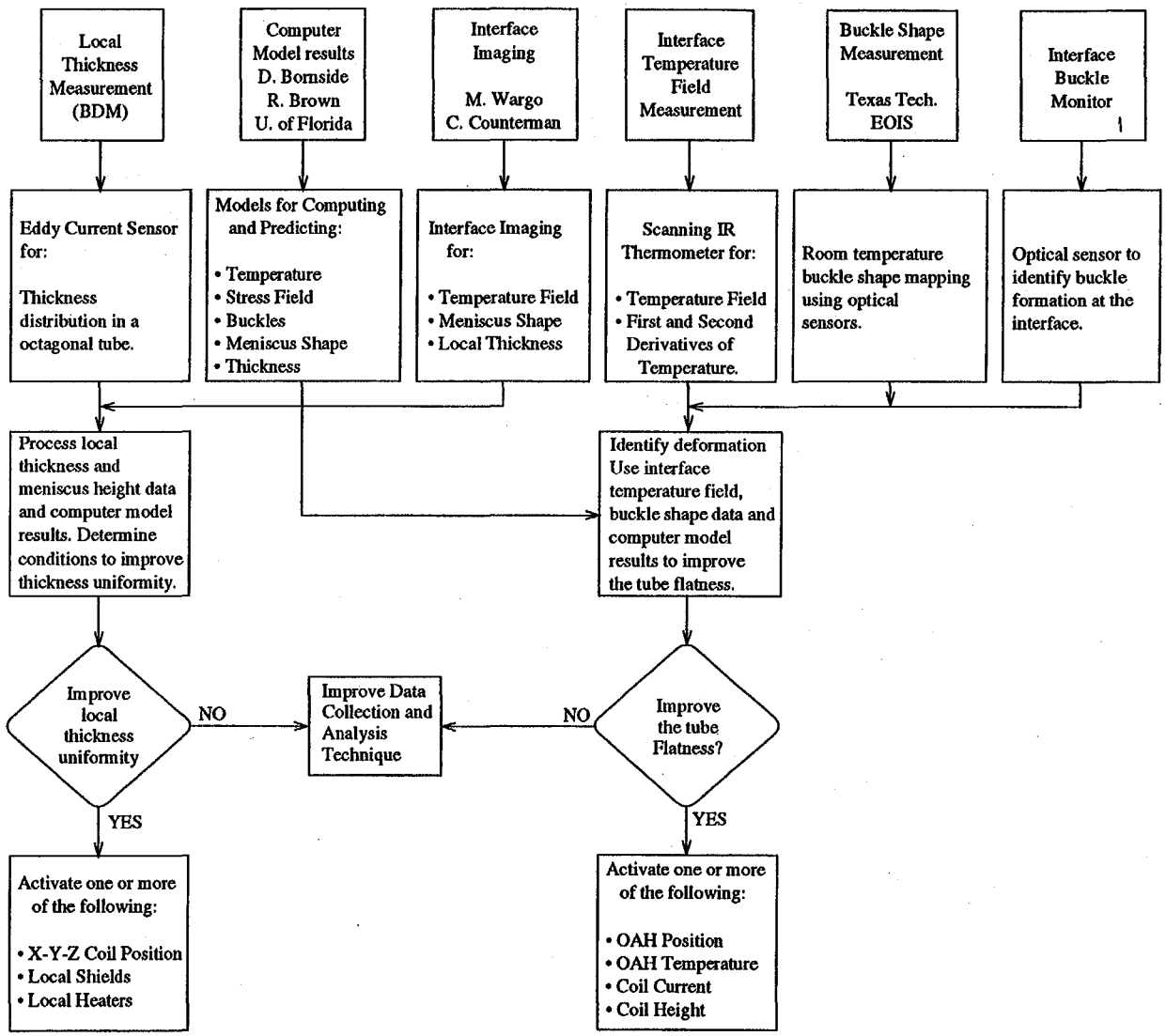


Figure 5. IPM implementation flow diagram.

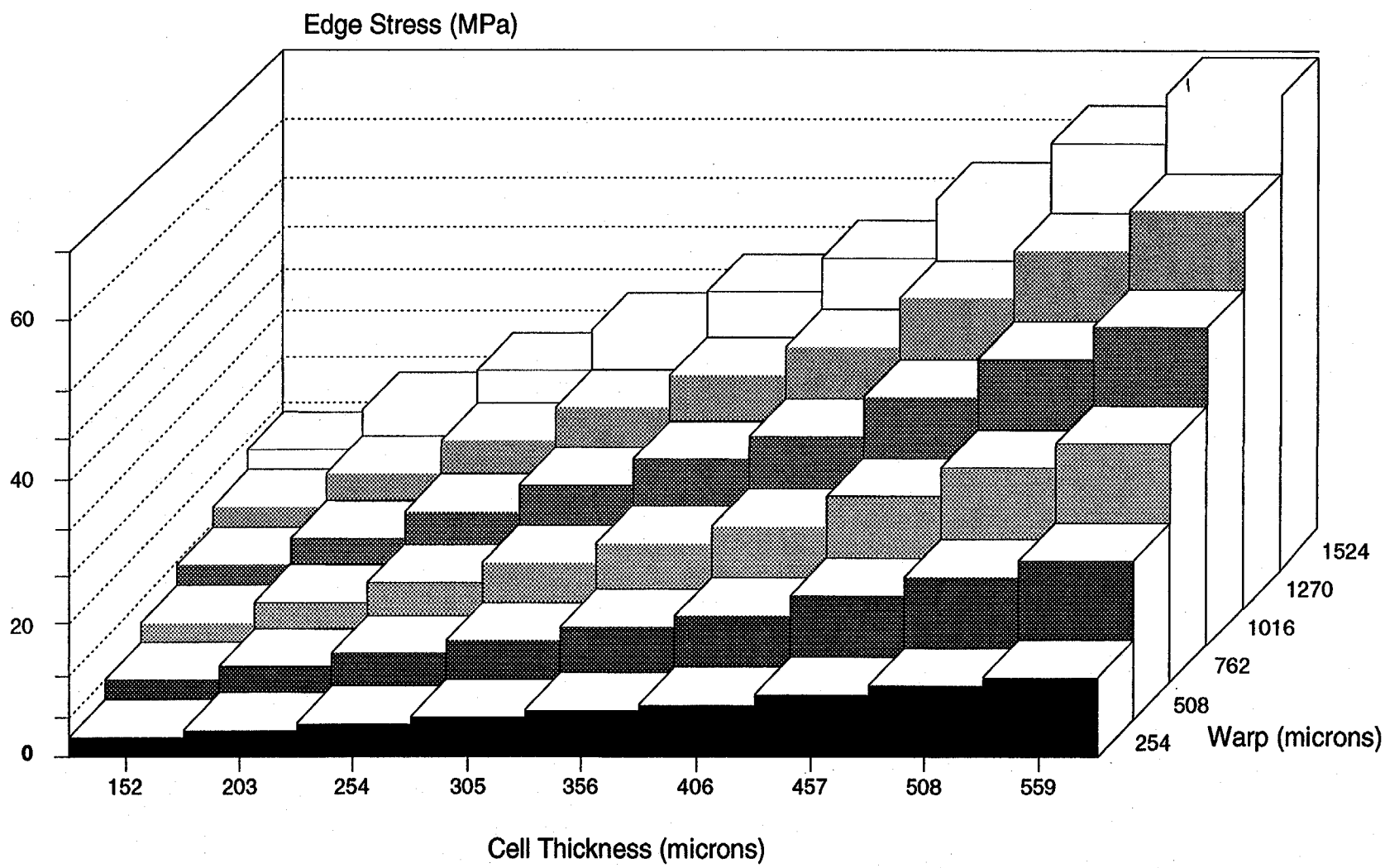


Figure 6. Edge stress in flattened cylindrical profile for various thickness and warp.

A second approach on measuring residual stress in uncut octagon tubes is being investigated by Professor T. Gross at the University of New Hampshire. This will attempt to use a conventional hole-drilling method combined with monitoring the resultant strain changes using holography. The residual stress in an uncut tube would be useful to monitor improvements in the crystal growth process.

Wafer Edge Strength. Laser-cut EFG wafers have been sampled on a monthly basis from EFG octagon experimental runs in order to build up baseline information on fracture behavior of nominal 10 cm × 10 cm area, 300 micron average thickness material. This baseline data will be used to monitor the progress in laser programs toward their objectives of increasing EFG wafer edge strength.

Initial Weibull fracture test data have been obtained for the Mobil Solar CO_2 laser and are shown in Fig. 7. These lasers are being used currently to cut octagons on this program until advanced concepts in Nd:YAG laser cutting become available from outside contractors. Representative fracture strength probability curves (see Ref. 10) are given for both 300 micron thick EFG wafers and 380 micron thick CZ single crystal wafers. Test sample dimensions are 9.6 cm × 9.6 cm and 5 cm × 5 cm, respectively. The CZ material will be used as a control. It provides a means to study the effects of laser parameters on fracture strength that is free of the nonideal factors such as polycrystallinity, nonuniform thickness, nonflatness and residual stress characteristic of EFG material. The Weibull relationship used to fit the data is given by defining a cumulative probability of fracture by P_f as follows:

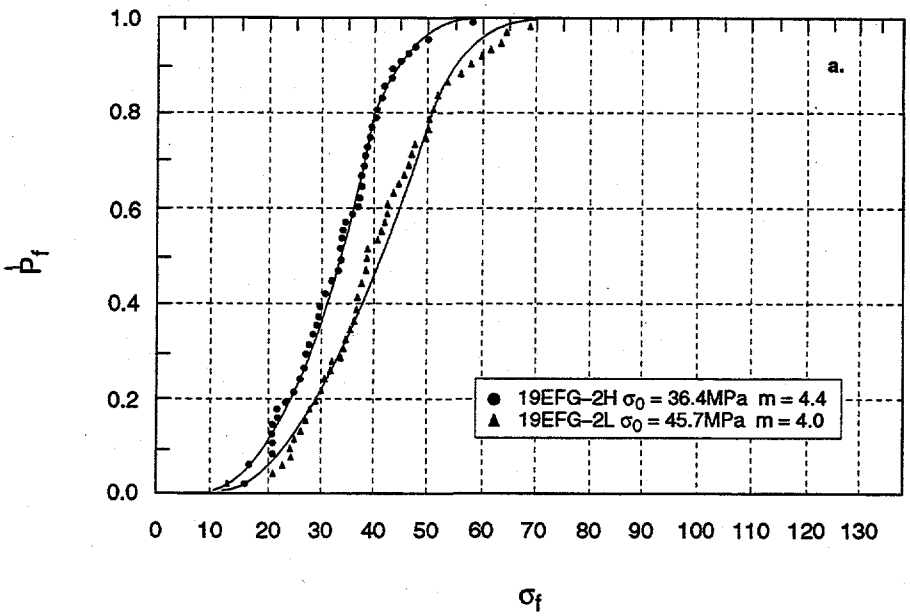
$$P_f = 1 - \exp[(-\sigma_f/\sigma_o)^m]$$

Here, σ_f is the fracture strength of the sample, and σ_o and m are two Weibull fitting parameters used to characterize the distribution. σ_o represents the fracture strength at the 63% point of the distribution and m is a parameter inversely proportional to the microcrack length variance.

In each case in Fig. 7, the CZ reference samples are cut under identical conditions to those for the EFG wafers in order to help establish trends in fracture behavior as a function of laser cutting conditions. From Figs. 7(a) and 7(b), it is clear that the same trends are seen in the CZ data as in the EFG data, and these are essentially independent of the material parameters. They are therefore attributed to the change in laser beam conditions. In the case shown, laser energy per pulse has been increased by a factor of two between the sample set labeled with an "L" or with "H".

The fracture probability curves depend on both sample size and thickness. For example, σ_o values must be scaled up by a factor of 1.3 in going from the larger to the smaller sample dimension in order to directly compare the data on the two sizes. Additional reference data are being obtained both for 5 cm × 5 cm EFG and CZ wafers. This will allow the smaller area CZ reference material to be used more extensively by reducing the need for more costly larger diameter CZ wafers. In addition, the smaller sample size reduces the deflections at fracture. This reduces the influence of nonlinear effects which make the model calculations of the fracture stress more difficult.

Preliminary damage studies of samples cut with the different laser pulse energies have been carried out at a lower-tier subcontractor, New Hampshire Materials Laboratory. These indicate that the extent of the heat affected zone at the sample edge increases with laser pulse energy. This is to be expected when the excess pulse energy goes into widening the thermal energy diffusion zone around the beam. Since this zone has been postulated to control the length of the critical microcracks responsible for fracture,[11] this trend corresponds with the observed decrease in wafer edge strength found in the Weibull fracture distributions in Fig. 7.



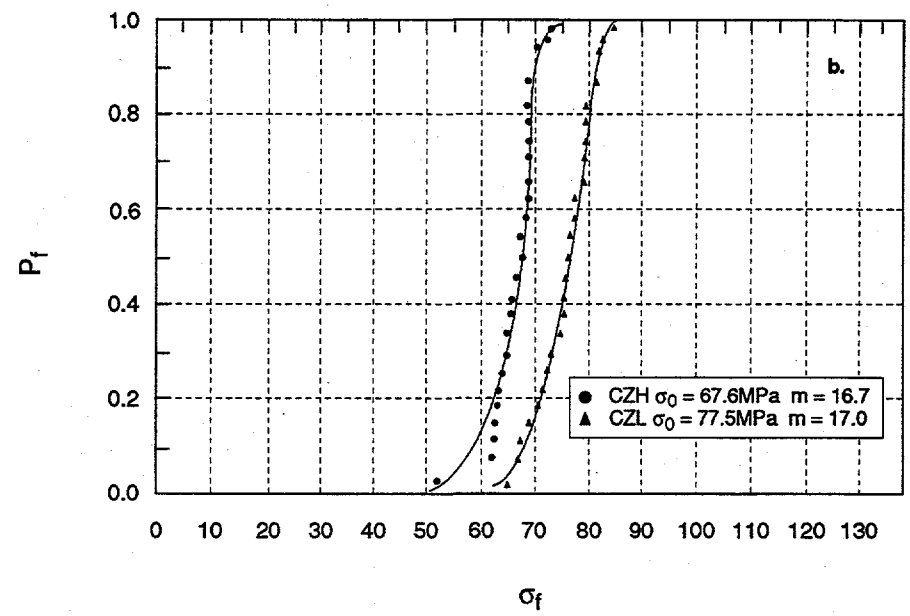


Figure 7. Fracture strength of EFG (a) and CZ (b) silicon wafers cut with a CO_2 laser. Sample size and thickness are, respectively, 9.6 cm × 9.6 cm and 300 μm for EFG, and 5.0 cm × 5.0 cm and 380 μm for CZ samples.

Studies on the effect of other laser parameters such as cutting speed, and comparison of different lasers, are continuing.

250 Micron Thick Octagons. The Phase 1 objectives have set targets for thickness uniformity, flatness, and residual stress improvements, and for laser cutting yields for 250 micron thick octagons (see Fig. 1). Preliminary data on laser cutting yields and flatness inspection results comparing experimentally grown tubes and cut wafers at 300 and 250 micron thicknesses are given in Table 2. The typical laser cutting yields are above 94% for both thickness tubes. However, it has been noticed that the experimental thinner tubes have a greater probability of getting an occasionally lower yield, viz., 85.3% in Table 2. This appears to occur because the current excessive buckling and stress lead to a higher probability that a longer crack, once introduced accidentally, propagates through a number of wafers to produce the reduction in yield.

Two flatness inspection levels have been chosen to monitor the progress in reducing buckling. A given level is defined by a "window" height, which represents the distance between a flat surface and a monitoring bar placed above it, between which the wafer will slide on the surface unimpeded. Again, although the best results for the two thickness tubes are in the same range, wider variations occur at 250 microns. The two low flatness inspection results, for tubes 3EFG-4-05 and 32EFG-2-04, were produced with growth configurations, discussed in the subtask on stress above, where deliberate experimental design changes led to known higher tube stress levels in growth.

Table 2. Comparison of 250 and 300 micron thick wafers.

Run No.	Thickness (micron)	% Cutting Yield	% Flatness Yield 1000 micron Window	650 micron Window
1EFG-2-01	300	98	90.4	-
1EFG-2-02	300	99.4	89.9	77.2
1EFG-2-03	300	99.7	85.6	46.9
5EFG-2-07	300	100	90.2	60.1
7EFG-4-04	300	98.6	94.3	68.4
14EFG-4-05	300	95.7	91.7	50.0
19EFG-2-02	300	99.1	93.8	64.0
19EFG-2-05	300	99.1	98.5	61.0
20EFG-2-11	300	97.5	84.3	-
28EFG-2-02	300	94.4	89.7	-
28EFG-2-03	300	99.1	95.1	-
29EFG-4-03	300	95.5	87.5	58.3
31EFG-2-02	300	98.3	87.4	68.4
32EFG-2-03	300	99.4	87.7	65.2
2EFG-4-07	250	97.2	89.4	53.2
3EFG-4-05	250	85.3	52.6	13.2
4EFG-2-05	250	96.7	91.8	61.4
31EFG-2-04	250	97.8	88.8	59.0
32EFG-2-04	250	94.2	61.3	26.1

Explanation of run no.: xxEFG-y-zz
xx: Cumulative NREL experimental run number
y: Furnace identification
zz: Tube number

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Appendix 1
EFG Wafers Delivered to NREL

In fulfillment of milestones m-1.3 and m-1.9 and deliverable requirements D-1 for the current reporting period, the following representative samples of EFG octagon material have been sent to NREL:

Four samples each from experimental runs numbered:

May	4EFG-2, 5EFG-2, 7EFG-4
June	10EFG-2, 12EFG-4, 14EFG-4
July	18EFG-4, 19EFG-2, 20EFG-2
August	24EFG-2, 25EFG-6, 26EFG-4
September	28EFG-2, 30EFG-2, 32EFG-2

for a total of 60 samples.

In addition, 12 samples from runs 20EFG-2 (sample no. 20T21) and 22EFG-4 (sample no. 22T41) were delivered for defect characterization on 8/11/92.

Abstract

This report describes the PVMaT program at Mobil Solar for the period covering April 1, 1992 to September 30, 1992. Mobil Solar is developing advanced technology for growth and cutting of 200 micron thick Edge-defined Film-fed Growth (EFG) octagon tubes that will reduce the manufacturing costs of 10 cm × 10 cm polycrystalline EFG silicon wafers. Mobil Solar has made progress in identifying factors that impact on thickness nonuniformity, and means by which to reduce the deleterious impact of ambient-related effects that have caused reduction in crystal growth productivity and wafer yield. The current main obstacle to meeting material yield targets arises on account of the buckling produced by thermal stress. Studies of laser cutting of EFG silicon using Nd:YAG and dye lasers are under way to develop reduced damage cutting methods. Mobil Solar has carried out design reviews for crystal growth and laser cutting equipment. A task has been initiated to evaluate new on-line sensors for crystal growth process control and to study implementation of advanced control concepts for productivity and yield improvements.

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16. Abstract (Limit: 200 words)

This report describes work carried out for the PVMaT program at Mobil Solar for the period covering April 1, 1992, to September 30, 1992. Mobil Solar is developing advanced technology for growing and cutting 200-μm-thick edge-defined film-fed growth (EFG) octagon tubes that will reduce the manufacturing costs of 10-cm x 10-cm polycrystalline EFG silicon wafers. Mobil Solar has made progress in identifying factors that impact on thickness nonuniformity and means to reduce the deleterious impact of ambient-related effects that have caused reduction in cyrstal growth productivity and wafer yield. The current main obstacle to meeting material yield targets arises due to the buckling produced by thermal stress. Studies of laser cutting of EFG silicon using Nd:YAG and dye lasers are underway to develop reduced damage cutting methods. Mobil Solar has carried out design reviews for crystal growth and laser cutting equipment. A task has been initiated to evaluate new on-line sensors for crystal growth process control and to study implementation of advanced control concepts for productivity and yield improvements.

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