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Manufacturing of Ultra-High Efficiency Thin-Film Concentrator Cells

Final Subcontract Report
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On September 16, 1991 the Solar Energy Institute was designated a national laboratory, and its name was changed to the National Renewable Energy Laboratory.

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1.0 INTRODUCTION

This document is the final report for SERI Contract RC-0-10057 for Photovoltaic Manufacturing Technology, Phase I. The purpose of the multi-phase project is to advance photovoltaic (PV) manufacturing technologies, reduce module production costs, increase module performance, and expand U.S. production capability. Accordingly, we have investigated the application of advanced concentrator cell and module technology for these purposes. This report presents the results of a three-month effort to identify:

- current manufacturing and process development capability,
- manufacturing potential for increased capacity and reduced cost,
- challenges impeding achievement of these potentials, and
- costs and other market requirements.

In this introduction, we will briefly review the technical and business opportunity addressed, and will summarize the planned approach. The details will be provided in the sections to follow.

1.1 Definition of the Business Opportunity

The development of PV systems that can achieve levelized energy costs of about $0.12/kWh is one of the current goals of the DOE Five Year Research Plan: 1987-1991 for PV[1]. If met, this levelized energy cost goal is expected to result in significant installation of PV by utilities and others for electrical power generation, and the formation of a total installed PV module capacity exceeding 1 GW in the near-term, with a related module market on the order of $500M to $1B. Thus, if the technical requirements can be met, the market potential for PV energy technology is large and compelling. The benefits to the Nation include expansion of a distributed power network, reduced pollution, enhanced reliability -- all with no recurrent fuel cost and hence immunity to fluctuations in the price of fossil fuel.

Although PV is a technically proven power source with numerous successful technical demonstrations, substantial technical hurdles must be overcome to realize the above energy price goals from the high cost of present-day PV modules. For the case of either silicon flat-plate modules or concentrator systems, the price must be reduced by at least a factor of five to realize a $0.12/kWh levelized cost. It is generally agreed that combination of technical advances and large scale module production could lead to the attainment of this goal; nevertheless, few U.S. organizations are able to risk the capital required to attain this goal.

The business opportunity investigated during Phase I comprises a combined industry/government approach to the above problem. We will show that several technical advances can lead to a concentrator manufacturing technology that will satisfy the above levelized energy cost goal. Attainment of these advances requires substantial government investment, as will be described in the followup proposal.

1.2 Technical Challenges

The use of a concentrator approach has the potential to satisfy the above cost requirements, provided that the module is highly efficient and that the cost of the solar cell is low. By highly efficient, we mean $\eta_{CELL}>35\%$ (and we will describe an approach that will lead to $\eta>40\%$), leading to peak module output of about 16 watts at 1000 suns (depending on cell size). By low in cost, we mean solar cell assemblies (receivers) that cost about \$3.00 per unit, leading to a module price of about \$1.30/W_P. We will show that these aggressive goals can be met, provided the following improvements and advances are made:

- use of CLEFT III-V multi-junction cells for lowest cost and highest possible efficiency,
- use of low-loss optics for up to 1000 sun concentration,
- simplified module design for automated assembly,
- superior environmental endurance for 30 year lifetime,
- multi-megawatt manufacturing capacity for necessary economies of scale.

The use of CLEFT[2] permits the formation of III-V cells without a large substrate cost component. Low-loss optics are necessary to obtain the very highest module efficiency; the challenge is to obtain a lens efficiency of 85%. The module design will be based on a Varian passively-cooled point-focus approach, which has already yielded 22% module efficiency[3]. The Varian module will be redesigned however for better environmental endurance and less susceptibility to temperature variations. Finally, these modules must be manufactured in a large multi-megawatt production line to obtain the lowest possible cost.

1.3 Acquisition of Varian Technology

Recently, VS Corporation (a wholly-owned subsidiary of Kopin Corporation) acquired all of the solar cell technology and related equipment developed over the last 15 years by Varian Corporation. Six former Varian employees joined VS Corporation to continue the development of advanced III-V solar cells, modules, and production processes. The combined III-V solar cell expertise of the Kopin and VS teams and their complementary technologies make possible new highly advanced solar cells, and most particularly, highly efficient concentrator solar cells. It is the intent of Kopin Corporation to commercialize these new solar cell technologies.

An examination of the combined Kopin/VS capability has shown that proper development of tandem solar cells and high concentration modules can satisfy the energy price goals noted in the previous section. The III-V cell fabrication process is simple relative to that of high-efficiency Si cells. Kopin's CLEFT process makes possible the fabrication of III-V cells without high substrate cost. These CLEFT cells can be thermally managed and stacked for multijunction cells. VS concentrator expertise can be combined with CLEFT to form AlGaAs, GaAs, or InGaAs cells with bandgaps in the desired range to permit a multijunction concentrator with >35% efficiency (two-junction) or >40% (three-junction). The passively cooled VS 1000 sun module is the ideal baseline module for this effort, since it has been proven to work well with highly efficient cells.

1.4 Summary of Planned Approach

Phase I consisted of an examination of the development required to expedite the commercialization of the above technology. In summary, the findings of the Phase I work follow.

We baseline the GaAs concentrator cell and 1000X module design into pilot operation at Kopin. In order to attain the above improvements, we will use Kopin's existing pilot line for production of CLEFT GaAs solar cells; these cells already exhibit efficiency of about 24% AM1.5. We will modify the CLEFT cell to form concentrators that perform well at 500 to 1000 suns. The know-how for this modification will derive from an integration of Kopin and VS technologies. The pilot line will be broadened to include cell receiver and module assembly, using VS technology obtained from Varian as a baseline. A second generation design will be formulated to address improvements in the module and these will be incorporated into the pilot line, along with the CLEFT concentrator cell. In parallel, we integrate Kopin's CLEFT GaAs cell technology with the advanced AlGaAs and InGaAs material technology obtained by VS from Varian to develop a near-term two-junction mechanical stack with an efficiency of 35%. The receiver thus developed will be compatible with a three-junction approach that has been proposed elsewhere by Kopin. The use of a three-junction stack can yield efficiency of over 40%, and when such cells become available, the pilot line process will have been designed to utilize them.

2.0 MANUFACTURE OF CELLS AND MODULES

This section provides a review of the design of the baseline cell, receiver, and module. The baseline process for complete module formation is described. This module has served as the baseline for Phase I analysis. Areas for improvement have been identified and are be reported on.

2.1 Baseline Design Approach

The complete photovoltaic concentrator module comprises the concentrator solar cell, the receiver, and the module housing. A diagram of the baseline cell is provided in Fig. 2-1; the diagram shows that the cell is formed from conventional epitaxial GaAs. It has a light-receiving area of 0.196 cm^2 (the cell diameter is 0.5 cm), and is formed on a square die with outside dimensions of 0.6 cm by 0.6 cm. The receiver is shown in Fig. 2-2, and consists of a Cu heat-spreading base, a solar cell, a secondary lens, interconnect tabs, and a layer of thermally-conductive RTV to join the receiver to the module backplane. The module itself, also shown in Fig. 2-2, comprises multiple receivers, Fresnel lens panel, trough housing, bypass diodes, interconnects, and terminals. The baseline module and component parts will be described in greater detail in the sections to follow.

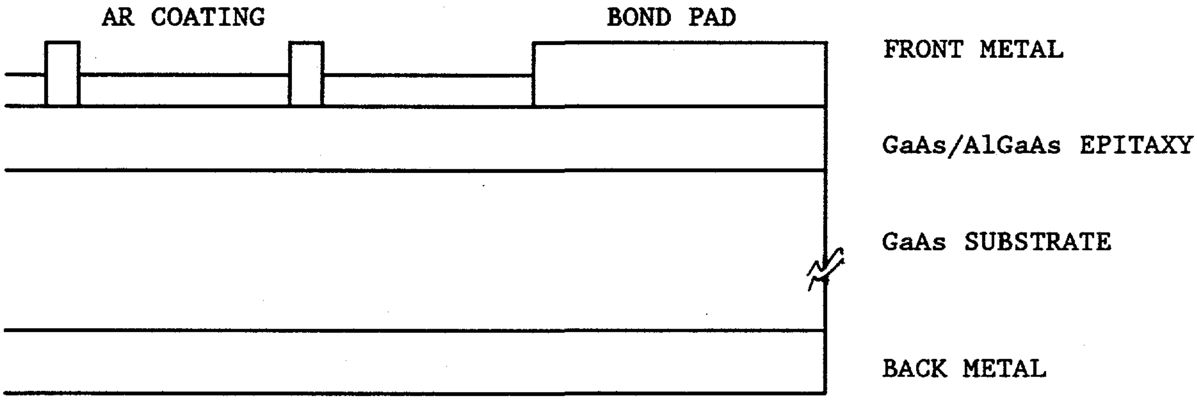


FIGURE 2-1. BASELINE GaAs CONCENTRATOR SOLAR CELL.

2.1.1 Concentrator Cells

The baseline concentrator cell is a GaAs/AlGaAs heterostructure deposited on a GaAs substrate. The dimensions of the cell are 0.6 cm by 0.6 cm by 0.03 cm thick. The active area is 0.196 cm2, corresponding to a light-receiving diameter of 0.5 cm. The front grid is a radial pattern, carrying current out toward a circumferential bus. Outside of the active area, the front surface is completely metallized to allow for four large contact areas for bonding. The back of the cell is completely metallized for bonding the cell down to a heat spreader.

The epitaxial structure is p-on-n GaAs layers with an AlGaAs window and heavily doped GaAs contact layer on top, shown in Figure 2-3. The layers are all deposited by organometallic chemical vapor deposition (OMCVD) in one deposition run on multiple wafers of GaAs. Cells with such a structure were provided to Sandia National Laboratory by Varian (now VS Corporation), and showed AM1.5 direct efficiencies over 28% at 400 to 600 suns concentration, and 27% efficiency at 1000X[4-5]. Similar cells were used in 942X concentrator modules which exhibited 22% module efficiency at real operating conditions in the baseline modules[3]. A specification sheet for these cells is shown in Figure 2-4.

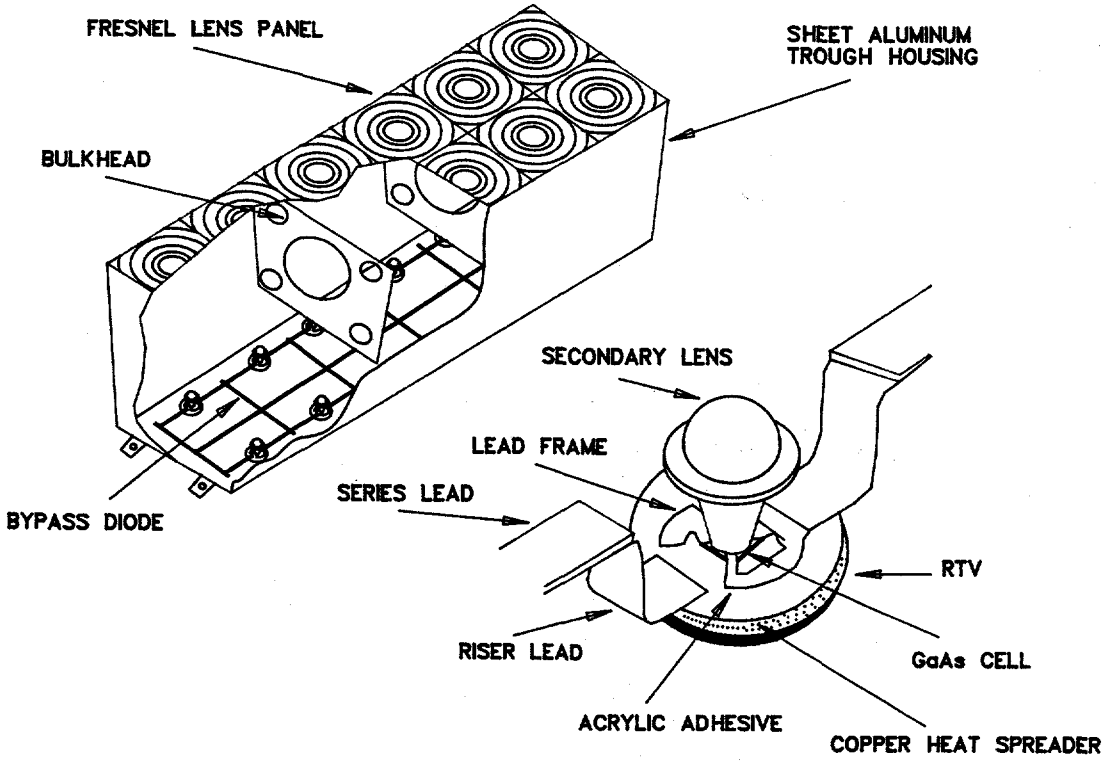


FIGURE 2-2. BASELINE RECEIVER/CELL ASSEMBLY AND 12 CELL MODULE WITH EXPLODED VIEW OF THE SOLAR CELL RECEIVER ASSEMBLY

Two important improvements have been identified for the cell for Phase 2: the cost needs to be reduced, and the performance needs to be improved. Our approach to cost reduction is to reuse the substrate, thus saving up to 40% of the total cost of the cell. Improved performance will be achieved with better heat sinking due to the absence of the GaAs substrate, and the later insertion of multi-junction solar cells into receivers. Both of these approaches are discussed in Section 3, Process Improvements.

2.1.2 Receivers

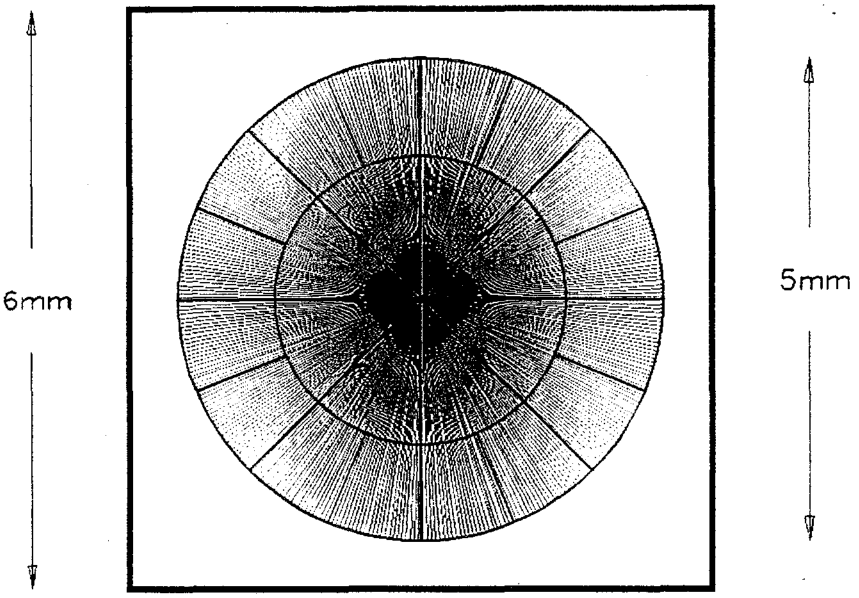
An exploded view of the receiver is also shown in Figure 2-2. Light is incident on the secondary refractive optical element, which is joined to the solar cell using low-loss DC 93-500 adhesive. In the baseline design, the adhesive is used to form both the physical joint between the secondary element and the cell, and the index-matching optical joint between the cell and optics. During Phase I, we identified the mechanical strength of this joint as a weak point in the design, and will describe a simple design improvement later.

GaAs CONCENTRATOR CELL
DATA SPECIFICATION SHEET

PHYSICAL DIMENSIONS

Active Area:	0.196 cm^2	(5-mm diameter)
Physical Area:	0.36 cm^2	(6-mm x 6-mm)
Thickness:	300 microns = 0.030 cm	

CELL GRID SCHEMATIC



TYPICAL ELECTRICAL CHARACTERISTICS (ASTM AM1.5 DN. 28°C)

Concentration	200X	400X	1000X
V_{oc} (open circuit voltage)	1.14V	1.18V	1.20V
ff (fill factor)	0.88	0.86	0.86
I_{sc} (short circuit current)	1.1 A	2.16 A	5.3 A
P_{max} (maximum power)	1.0 W	2.2 W	5.5 W
η (conversion efficiency)	28.1%	28.0%	27.9%

FIGURE 2-3. BASELINE GaAs CELL SPECIFICATION SHEET.

The secondary element is coated with a MgF_2 AR coating to reduce the reflectance to between one and three percent, with an average of about 1.5%. The reflection upon exit from the cone can be minimized by using an index-matched adhesive between the cone and the cell.

The cell is bonded to the Cu heat spreader using conventional solder techniques which are quite adequate for excellent thermal transfer and mechanical stability. The Cu spreader is bonded to the module backplane by Fe_2O_3-impregnated thermally conductive RTV. We have made an analysis of the temperature distribution in the cell, solder, Cu, and RTV, assuming a component stack with a uniform heat flux of 56 W/cm^2. The role of the heat spreader in enhancing lateral conduction of heat as not been taken into account. Table 2-1 summarizes the assumptions made in the calculation, as well as the resultant temperature drops in each layer. Note that even without the heat spreader, the total temperature drop is only 16 °C. Thus, the receiver yields exceptionally good thermal conductivity.

The heatspreader consists of a 3 cm (diameter) Cu disk, with a thickness of 1.6 mm. The spreader is bonded to the module backplane using thermally conductive Ecosil 4952 RTV. The leads form the receiver comprise Ni-plated Cu tabs. The tabs are insulated from the heatspreader with acrylic tape.

TABLE 2-1
TEMPERATURE DISTRIBUTION IN CONCENTRATOR RECEIVER

Input power at 1000 suns	88 W/cm^2
Nominal Cell Efficiency	25%
Input heat load:	56 W/cm^2
ΔT across 300 μm GaAs Cell:	4 °C
ΔT across 100 μm of solder:	2 °C
ΔT across 3 mm Cu heat spreader:	4 °C
ΔT across 100 μm of RTV:	6 °C
Total temperature drop	16 °C

2.1.3 Modules

The baseline module is the VS Corporation design, and has been described previously[6]. It consists of the Fresnel lens, aluminum housing, receiver, and positive and negative rear-mounted terminals. The lens is formed from CP-71 acrylic which yields excellent optical transmission. The combined optical efficiency of the Fresnel lens and refractive secondary optical element is approximately 85%.

2.2 Process Description

The fabrication processes for the cell, receiver, and module are distinct from one another, with the cell constituting a part for the receiver assembly and the receiver being inserted into the module assembly. The receiver has been designed to allow the later insertion of cells with advanced structures. Thus, upgrading of the cell from baseline to a CLEFT cell or higher efficiency tandem cell will not cause elaborate or costly redesign of either the receiver or module. Improvements in cell performance can therefore be passed on to future modules with minimum impact on the receiver or module production processes.

Details of the baseline cell, receiver, and module fabrication processes are given in the following sections.

2.2.1 Cell Processing

The baseline-cell fabrication process is shown below in Figure 2-X. Cell growth is carried out by OMCVD. The back metal is evaporated, followed by front-grid photolithography, front metallization, and metal liftoff. As part of the AR coating, the wafer is first selectively etched to remove the GaAs contact layer and expose the AlGaAs window (refer to figure 2-3). Wafers are diced into cells, which are then tested.

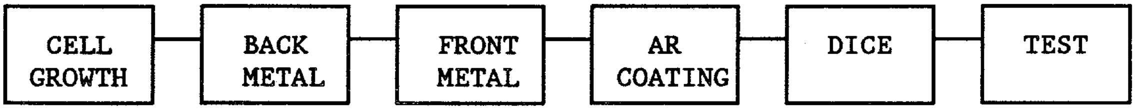


FIGURE 2-4 BASELINE CELL FABRICATION PROCESS FLOW.

2.2.2 Receiver Fabrication

Fixturing has been developed for the reliable and rapid alignment of the cell, interconnects, and secondary optics. Using one such fixture, the cell is centered and then soldered directly to the copper heat spreader, which serves as a backside contact. Pre-punched acrylic tape is placed on the heat spreader around the cell, providing electrical insulation for the interconnect leads. One leadframe is positioned over the cell and held in place with the tape, and the tabs are positioned on the leadframe and heat spreader. This assembly is placed in an oven to solder the leadframe to cell and tabs. The secondary optic is attached to the cell with an optical adhesive and the receiver is tested.

2.2.3 Module Assembly

The module comprises the housing with endplates and bulkheads, twelve receivers, bypass diode, and the wiring. The aluminum housing is formed and anodized, as are the end plates and bulkheads. Twelve receivers are positioned on and epoxied to the housing with a fixture. The electrical feedthroughs are bolted on and the interconnects are soldered to the receiver tabs. The housing bulkheads and sides, and wiring and bypass diode are installed. The lenses are assembled last, and the module is tested.

2.3 Baseline Cost

The baseline design emphasizes low cost, manufacturability, and high reliability. The primary optical element is 3M Fresnel lens film, available today at reasonable cost. The glass secondaries are made by a molding technique applicable to mass production. Inexpensive RTB adhesive is used as the electrical insulator, and the cells are passively cooled. The high cost of semiconductor material for the cells is mediated by the high concentration ratio and high efficiency of the system.

With a module cost of \$360/m2, an array cost of \$50/m2, and a balance of systems cost of \$120/m2, the annual energy cost for the baseline design is equal to \$0.12/kW-hr with a 28% cell efficiency. These are summarized in Table 2-2. Breakdown of the costs are given below.

TABLE 2-2

BASELINE MODULE COSTS

	Cost/m2
Cell	\$97
Receiver	\$160
Module	\$360
Array	\$50
Balance of Systems	\$120
Total System	\$530

Assuming a 71% cell yield and processing on 3"-diameter wafers, we project a baseline concentrator cell cost of \$1.90 per cell, or \$97 per m2 in large-scale production. This cell cost is dominated by material costs, and material costs are dominated by the GaAs substrate cost. Our calculations indicate that about 45% of the cell cost is due to the cost of the substrate, 30% is due to epitaxy, and 25% is due to processing. Clearly, the largest impact to the reduction in cell cost would be to reuse the substrate. Another reduction would occur with the scale up of the wafer size processed; almost all of the processing costs are per piece costs, which would not significantly change if the wafer size was increased from 3" to 4". This scale up would also benefit the epitaxy costs, as the labor and equipment costs would not rise proportionally to the area. These approaches are discussed in Section 3.1.

Cost of the receiver, without cell, is estimated to be $1.20 per or $60/m2 in large quantities. With the baseline cell, the total receiver cost would be about $3.10, or $160 per m2. Enhancements to the receiver are not expected to produce a noticeable cost increase in Phase 2.

The module cost dominates the cell and receiver cost components. Due primarily to the cost of the metal parts, the module cost is about $200/m2, subtracting the cost of the receivers. These parts will be under evaluation, as the reliability of the module sheet metal in maintaining the optical axis is an issue in Phase 2. The impact on cost and fabrication is discussed in Section 3.3.

3.0 PROCESS IMPROVEMENTS

We have identified potential cell, receiver, and module manufacturing processes that will lead to improved performance and reduced costs. These modifications and their long-range benefits are described below.

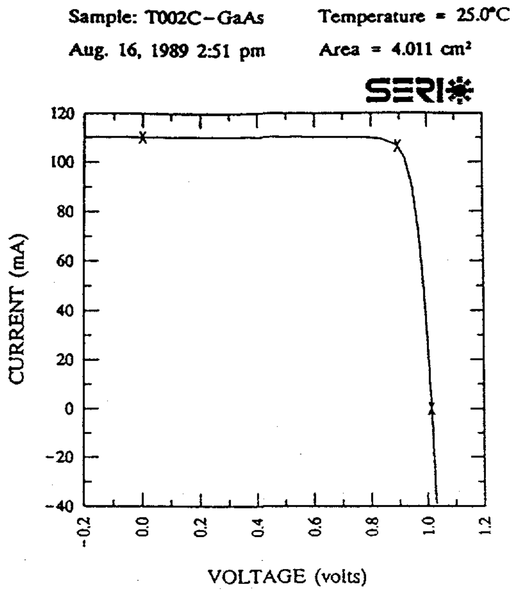
3.1 Cell Performance Improvement

Cell efficiency is the single most important parameter for the energy cost of this concentrator system. All other costs staying constant, an improvement in cell efficiency to 35% would reduce the baseline system annual energy cost to less than $0.10/kW-hr, and a cell efficiency of 40% translates to energy costs of less than $0.085/kW-hr. Conversely, the higher efficiency cells would allow the system to meet the $0.12/kW-hr energy cost goal with higher overall system and cell costs. The higher efficiency cells would therefore allow the low-cost objectives to be met sooner and with lower production levels than needed for the 28% cell.

With all other things being equal, it is likely that a higher efficiency cell will actually cost more than the baseline cell. Therefore, one aspect of our approach is to address a lower-cost method of fabricating the cell. Since the largest single cost component of the cell is the substrate, we propose to use our CLEFT process to produce a thin-film cell of GaAs and reuse the GaAs substrate. The CLEFT cell would later become one component of a tandem cell, allowing higher performance while keeping the tandem cell cost close to the baseline cell cost.

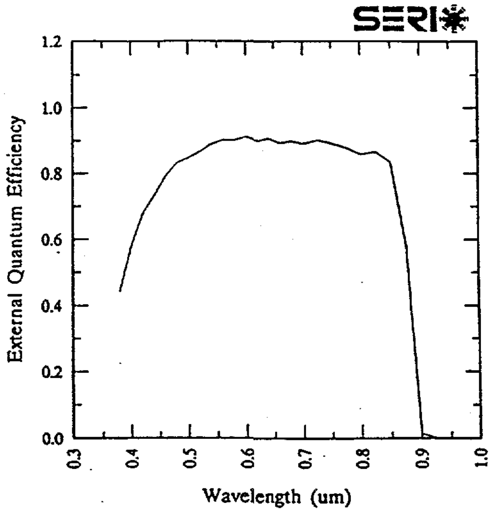
Figure 3-1 shows the efficiency of a 4 cm^2 cell measured independently by SERI. The very high efficiency obtained from this cell is indicative of extremely high quality in the layers, as well as low losses in the metallization system. The external quantum efficiency of the cell is shown in Figure 3-2. We note that the anti-reflection coating comprises a single layer of Si_3N_4 designed for use with a glass cover, and that further gains in efficiency would be obtained by utilizing either a cover, or a multi-layer anti-reflection coating (as would be used for a concentrator). Other information on the cell is shown in Table 3-2.

Thin-film cells are characterized by a layer of semiconductor material supported by a substrate with different structure. The layer of semiconductor is typically on the order of microns in thickness, allowing optimal use of the semiconductor for the active device layers. Bulk cells, on the other hand, typically use several hundreds of microns of semiconductor material as either the active device or the supporting substrate for the active device. The presence of this thick layer may lead to problems, as in the case of GaAs or Ge substrates, in the conduction of heat away from the active layers or in parasitic absorption of light in a tandem cell structure. The thin-film cell can be designed to avoid these problems with the suitable choice for its substrate. Thin-film cells have been used as upper cells in tandem structures, and have exhibited excellent sub-bandgap transmission characteristics. With proper heat sinking, thin-film cells should be capable of better performance than bulk cells. In


Sample: T002C-GaAs
Aug. 16, 1989 2:51 pm
Temperature = 25.0°C
Area = 4.011 cm^2

V_{oc} = 1.015 volts
J_{sc} = 27.51 mA/cm^2
Fill factor = 85.11 %
Efficiency = 23.8 %
I_{sc} = 110.3 mA
P_{max} = 95.3 mW
I_{max} = 106.5 mA
V_{max} = 0.8949 V

FIGURE 3-1. **CURRENT-VOLTAGE CHARACTERISTIC OF A KOPIN PLANAR GaAs CELL.** The cell area is 4 cm^2. The test temperature is 25°C. The insolation is AM1.5. Courtesy of K. Emery (SERI).



Sample: 5097R
Jan. 10, 1989 10:31 am

Temperature = 25.0°C
Area used = 4.000 cm²

Light bias = 107 mA
Zero voltage bias

FIGURE 3-2. EXTERNAL QUANTUM EFFICIENCY OF A KOPIN PLANAR CELL.

TABLE 3-2: CLEFT CELL DESIGN AND CHARACTERIZATION DATA

Cell Structure	AlGaAs/GaAs heteroface cell
Polarity	n-type emitter on p-type base
Sheet Resistance	250 ohms per square
Front Grid Metal	electro-plated Au
Contact Resistance	10^{-4} ohm-cm^2 (unsintered)
Shadow Loss	5%
Plating Height	4 microns
AR Coating Type	Single layer, Si_3N_4
Base Thickness	4 microns
Base Diffusion Length	approx. 10 microns
Base Doping	10^{17} cm^{-3}
Base Minority Carrier Mirror	$Al_{.2}Ga_{.8}As$
Substrate	Removed
Back Surface Metal	Electro-plated Au grid

addition, thin-film cells are inherently lower cost than bulk cells, as they avoid the high substrate costs of the bulk cells.

At the start of Phase 1, almost all of the component parts of the fabrication process to produce thin-film concentrator cells were known and demonstrated. The one aspect requiring evaluation was the cell separation from the reuseable substrate. We had two techniques which essentially accomplish the same end, which is to separate the thin-film cell from the substrate. One technique, named the Cleavage of Lateral Epitaxy For Transfer (CLEFT) technique[2,7-9], uses mechanical separation of the cell from the substrate. The other technique uses a chemical removal process called chemical epitaxial liftoff to obtain the same result. In both techniques, this separation step releases the thin-film cell from the substrate, which is reused many more times. Based upon manufacturing readiness, we selected the CLEFT technique for use in Phase 2 of this manufacturing technology program.

The steps for the proposed concentrator-cell process are listed in Table 3-1. With the exception of the separation step, the process uses standard semiconductor processing equipment and procedures. Currently, the CLEFT process is running on three-inch diameter wafers, with the use of standard wafer cassettes and some cassette-to-cassette automated equipment.

TABLE 3-1: THIN-FILM CONCENTRATOR CELL FABRICATION PROCESSES

Wafer Preparation	
Cell Deposition	
Back Metallization	
Cell Separation	Substrate Reuse
Front Metallization	
Front AR Coating	
Cell Cut	
Test	
Dice	

Although the Wafer Preparation and Cell Separation steps (and Substrate Reuse step) are unique to the CLEFT process, most of the steps are self explanatory. Wafer preparation entails the generation of the CLEFT layer on the substrate; this has been described in detail previously. The cell structure is deposited by organometallic chemical vapor deposition (OMCVD); in this process the structure would be deposited top-side first. The as-grown epitaxial structure is shown in Figure 3-3. The back metal is then evaporated onto the wafer's top surface.

At this point the cell layer is bonded with a thermal epoxy to a thermally conductive substrate, and the layer is separated from the substrate. The front of the cell layer is now exposed for processing while the substrate is put back into the reuse process loop. The cell is now oriented as shown in Figure 3-4, a cross section of the completed cell. Front metallization

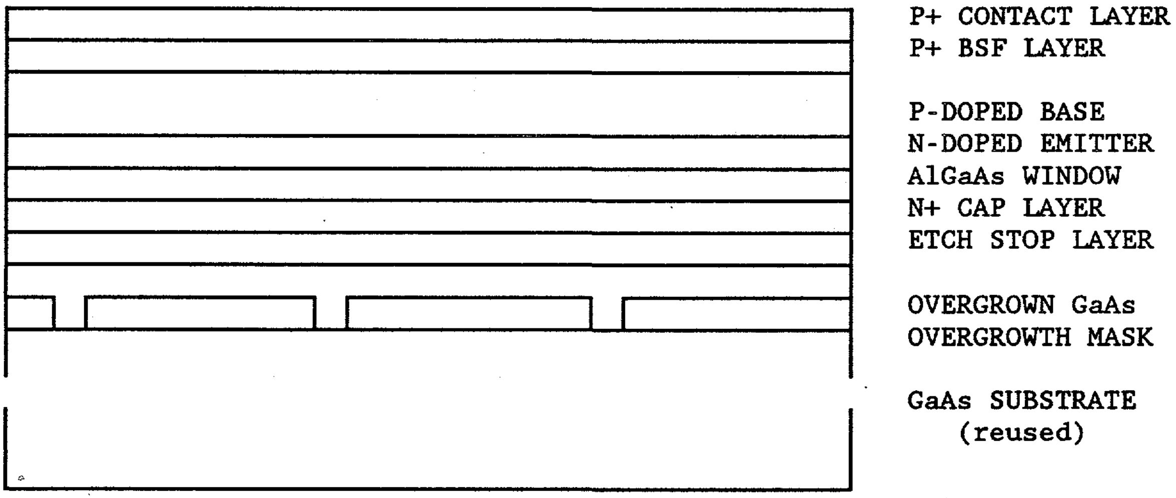


FIGURE 3-3. THE AS-GROWN EPITAXIAL STRUCTURE FOR THE CLEFT CELL.

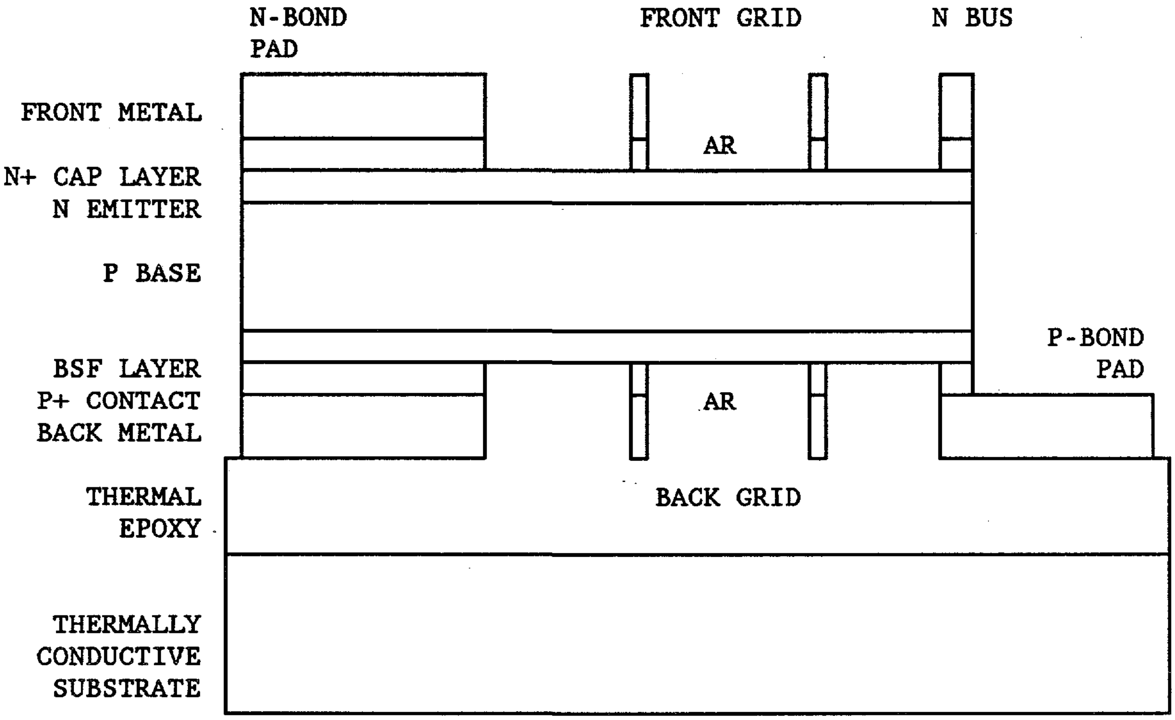


FIGURE 3-4. SCHEMATIC CROSS SECTION OF THE CLEFT CELL.

is similar to back metallization, and currently uses the same equipment. After a selective etch to remove the GaAs cap, the front of the cells on the wafer are antireflection (AR) coated in a plasma-enhanced CVD system.

The cells are now defined on the substrate in the cell cut step by patterning resist, then by etching through the 5 microns of GaAs layer, which also exposes the back metallization for bonding. Thus, coplanar front contacts have been formed, and the cells are ready for testing. We have set up both one-sun and concentration testing on an commercial prober with automatic indexing and testing of cells over an entire three-inch wafer. Individual cells could be inked for binning after dicing. Then, the dicing step physically separates the dies from one another. The dicing saw cuts through only the substrate, the cells having been previously isolated in the cell cut step. This sequence allows the automatic testing of cells on the wafer, since the dicing step which follows does not affect the cells' electrical performance.

As stated earlier, the module design accepts cell upgrades as they became available. The approach to improved efficiency is through the use of multibandgap cells with two or more junctions. VS Corporation has been working on several tandem and three-junction cells to use with this module design, and Kopin has developed mechanically stacked two-junction cells for the space power market with its CLEFT process. Our approach for the tandem cell upgrade is described in Section 5.2.

The impact of these cell improvements is both immediate and important: higher electrical output without proportionally higher costs. The system becomes more competitive as the user benefits from lower cost electricity.

3.2 Receiver Enhancements

The baseline receiver design incorporates several features intended to yield high humidity resistance. These include: encapsulation of the solar cell surface by the secondary optical element, and use of refractive optics to obviate oxidation of the secondary. Nevertheless, the humidity resistance can be further improved by potting the receiver in RTV, acrylic, or epoxy; this potting requires modification to the secondary optical element.

The secondary optics comprise a refractive light-collecting cone. Owing to the requirement for total internal reflection in the cone, the surrounding material must have an index of refraction close to unity. For this reason, we propose to modify the design so as to incorporate a glass cylinder that will join the handling ring to the heat spreader, as shown in Figure 3-5. This cylinder will serve two functions. First, it will prevent the potting material from contacting the optical surface of the secondary concentrator. Second, it will provide mechanical support to the secondary optic, making it more resistant to vibration and mechanical stress. The net result of this improvement in the design of the secondary optical element will be improved humidity resistance and improved mechanical strength leading to longer module lifetime. The potted receiver is shown in Figure 3-6.

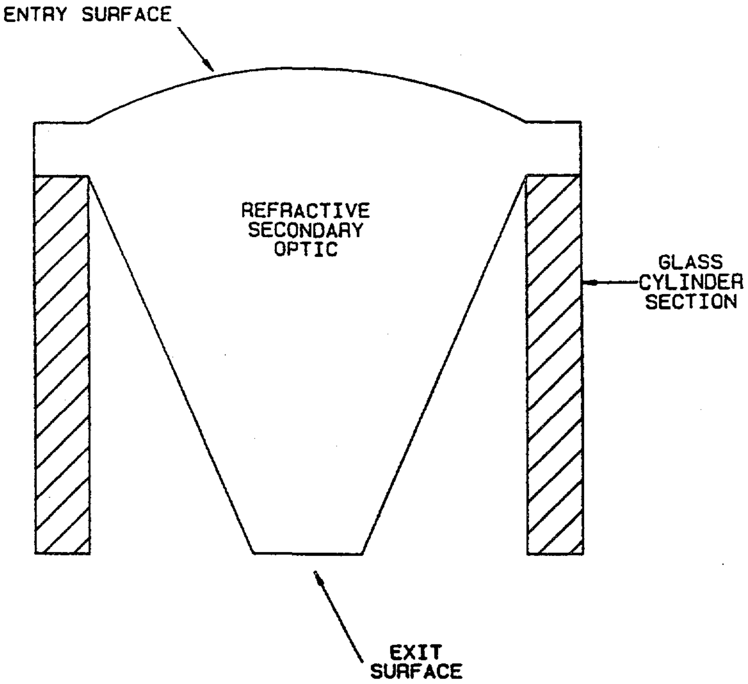


FIGURE 3-5. SECONDARY REFRACTIVE OPTICAL ELEMENT WITH STABILIZING SECTION.

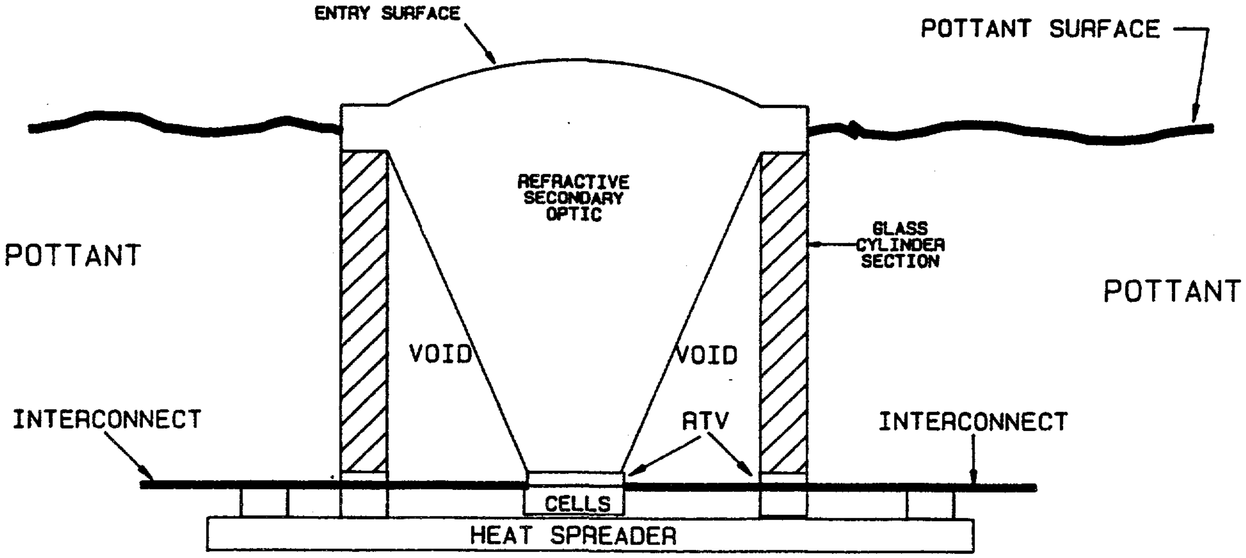


FIGURE 3-6. POTTED RECEIVER WITH STABILIZING SECTION.

The secondary optic element comprises a solid glass refractive cone used to obtain better off-axis tracking and more uniform flux distribution on the solar cell. The glass is molded from B-270 crown glass to the shape of a cone with a domed top surface. A circular flange is provided for handling. This flange can be used to increase the mechanical stability of the cone, as shown in Fig. 2-4, by providing a glass sleeve that mounts between the flange and the Cu heat spreader. If the sleeve is used, the receiver may be potted in acrylic (or other material) without changing the refractive properties of the secondary element.

With the above improvement to the secondary optical element, the receiver will provide the functionality and reliability required for a high performance long-life module. We add that glass secondary cracking has never been a problem in the VS concentrator, and we are confident that it will not occur in this design.

The efficiency of the receiver can be enhanced by employing a tandem cell, which will introduce new thermal and interconnect requirements. We propose a monolithic two junction tandem that will be compatible with mechanical stacking onto a third low bandgap (E_G) cell. The top two-E_G cell will comprise AlGaAs/GaAs (top cell $E_G = 1.9$ eV, middle cell $E_G = 1.43$ eV) and since it is monolithic, will introduce no new requirements on the interconnect or heat spreader. However, to expand the two junction cell to three, the top cells will be stacked mechanically on a bottom cell made from a low bandgap material such as Si. This mechanical stacking will require careful attention to thermal transfer as well as to the four terminal interconnect that will be required.

In order to keep the interconnect and thermal transfer approach simple, in the full three-junction structure, we propose to use two key approaches:

(1) AlGaAs/GaAs monolithic cells. These two terminal cells will require no interconnect redesign and can be substituted for GaAs cells easily. The cells have already been developed and can be converted to concentrator cells by simple changes in doping and grid design.

(2) Point-contact Si bottom cells. These bottom cells will be commercially available in the next year or two; if so they will be easily incorporated in the proposed approach. The point contact bottom cells are ideal for the because they have no top grid, are made from semi-insulating Si, and are coated with dielectric layers. Thus, top cells can be mechanically stacked onto the Si point contact cell with relative ease.

The above approach is the simplest possible route to a three junction stack. The conversion from a GaAs cell to a monolithic two-junction AlGaAs/GaAs cell requires no change in the receiver design. The Si point contact bottom cell provides a mounting surface that is equivalent to the surface to which the GaAs cell is joined, thus no change in the top cell design is required. The only change in receiver design is the use of a point-contact-compatible heat spreader.

3.3 Module Enhancement

The baseline module requires several improvements to insure longevity and reliability. We have already discussed how we will improve the humidity resistance of the receiver. We will further improve the back plane of the module by using a cast acrylic to pot the entire back surface. The material will be chosen to have a coefficient of thermal expansion that is matched to the expansion of the lens. In this way, thermal cycling of the module will not affect the optical alignment between the primary lens and the secondary.

The use of an acrylic potting compound requires a redesign of the thermal management at the module back plane, since the acrylic will replace the Al housing on the back plane. We believe that the thickness of the pottant can be increased to accomodate the lower thermal conductivity.

3.4 Cost Benefits

The motivation for the above enhancements are both economics and reliability, but it is the cost impact which is most easily quantified. Table 3-6 below gives the cost breakdown for the baseline system and three enhancements. As previously stated, use of the CLEFT process brings the cell cost down for both the single- and tandem-junction cells. Addition of a third junction in a mechanical stack increases cell and receiver costs, but provides savings on the system level due to the higher efficiency. These costs are assuming an annual production approaching one hundred megawatts.

TABLE 3-6

COST IMPACT OF ENHANCEMENTS

	Baseline	CLEFT	Tandem	3-Junction
Cell Efficiency	28%	28%	35%	40%
Cell Cost	\$ 97/m2	\$ 68/m2	\$ 75/m2	\$100/m2
Receiver Cost	\$160/m2	\$130/m2	\$137/m2	\$170/m2
Module Cost	\$360/m2	\$330/m2	\$337/m2	\$400/m2
Module Cost/W_p	\$1.63/W_p	\$1.50/W_p	\$1.23/W_p	1.27/W_p

4.0 RISK AREAS

Problems have been identified that may impede the achievement of the potential benefits described in the previous section. These are listed below along with an assessment of their importance or probability. We have divided these problems into categories of the CLEFT cell, the tandem cell, the receiver, the module, and safety. The section on safety addresses the risks associated with fabricating the cells.

4.1 CLEFT cell

The introduction of the CLEFT cell is one means of achieving an effective cost reduction in the cell as well as taking one step towards the higher efficiency two- and three-junction multibandgap cells. Although CLEFT has not yet been used to make a 1000X CLEFT concentrator, we have successfully used CLEFT for space concentrators designed for the mini-Cassegrainian concentrator at 100X[10]. Cell performance was 23.5% AM0 efficiency at 100X and 28°C(courtesy of D. Brinker of NASA Lewis), and 26.0% AM1.5 direct at 100X and 25°C(courtesy of J. Gee of Sandia National Lab). The curve for AM1.5D efficiency versus concentration for a CLEFT concentrator is shown in Figure 4-1. We therefore believe that the risk to use the CLEFT process for the 1000X concentrator is low. However, the 1000X CLEFT concentrator needs to be demonstrated early in Phase 2 of this program, if only to provide test data and interfacing information for the receiver design.

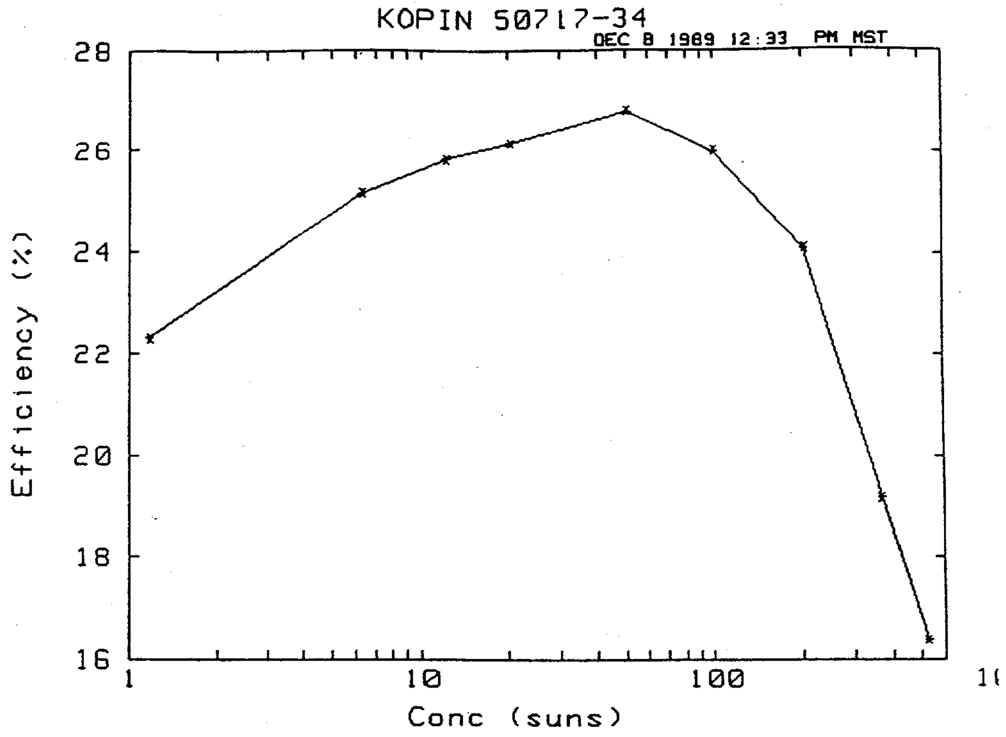


FIGURE 4-1: AM1.5D efficiency versus concentration for a CLEFT concentrator showing 26% efficiency at 100 suns (Data courtesy of J. Gee of Sandia National Lab).

The key advantage to the CLEFT process is substrate reuse, and as such the number of substrate reuses is of direct interest. We therefore need to look at concentrator performance as a function of substrate usage. We have previously demonstrated four layers from the same substrate, and we have observed that cells from reused substrates show the same performance as cells fabricated from new substrates.

The reuse, or recycling of the GaAs substrate not only removes a significant cost driver to the cell, but results in a cell consisting of only 5 microns of semiconductor. Processing, handling, and contacting these thin films have been developed at Kopin over the last six years. We have made over a thousand cells with CLEFT material, and have tested these cells exhaustively. Of particular interest, CLEFT cells have survived without change all of the space qualification tests, including humidity, vibration, and thermal cycling tests[11]. The latter test comprised almost 1000 temperature cycles from -120C to +85C. The reliability of the CLEFT cells has been established in these accelerated tests.

To fully realize the cost reductions of the CLEFT process, it is necessary to minimize the added costs of processing that allow substrate reuse. There are three additional steps: substrate preparation, layer separation, and cell cut. Cell cut is the etch step which defines the cells on the new substrate; this step effectively pays for itself in the ability to test all of the cells while still on the wafer. The substrate preparation step involves masking the GaAs substrate and overgrowing a GaAs layer; we are currently funded by SERI to investigate approaches which would allow over a hundred reuses of a single substrate, necessary for the use of CLEFT for terrestrial one-sun cell applications. Since the concentrator cost goals can be achieved with as few as five reuses, the existing substrate preparation and reuse processes are adequate. Lastly, the layer separation step has been previously developed to the point where it is ready for process automation. To achieve the required throughput and cost advantages, this step will need the fixturing and custom equipment to allow for the hands-off separation of the layer from the GaAs substrate. In discussions with a vendor of custom automated equipment, we have been told that it would be straightforward, and that dispensing and using adhesives was one of the first processes to use automation.

To summarize, the risks are low to use the CLEFT process for the fabrication of 1000X concentrators on reused GaAs substrate. Key elements of the development are the cell and reuse demonstrations, and the automation of the separation step.

4.2 Tandem cell

Insertion of a tandem cell for the CLEFT single-junction cell will depend on the status of the development of high-efficiency tandem cells. As in any developmental program, there are numerous problems and pitfalls to overcome, but we can minimize these by (1) choosing more than one material system to develop further, and (2) selecting material systems which have already been demonstrated to produce high efficiency multijunction cells. Using these criteria, one of the junctions used will be GaAs, and other materials, both with higher and lower bandgap, will be grown deposited along with the GaAs cell. Specific problems to overcome are tunnel junctions with any higher bandgap material, and the compatibility of GaAs with the other semiconductors. These risks can be managed with the appropriate choice of material systems.

4.3 Receiver

The proposed modifications to the receiver need to undergo environmental testing to ensure their effectiveness and reliability. Both the potential problems of humidity resistance and electrical insulation are generic, and there are probably many solutions from which to choose. The risk factor associated with these modifications is small.

4.4 Module

In order to improve the reliability of the optical alignment, the housing material can be changed or the secondary optical element could be redesigned. These two approaches to the module housing modification should result in successful modification and low risk. An added benefit may be that the former approach could result in a material cost reduction, the baseline housing being the most expensive component of the module without the receiver.

4.5 Safety

Some of the risks which we have investigated are associated with the safety of using hazardous materials to fabricate the solar cell. These can be divided into three categories: risk of accident, risk of regulation, and risk of supply shortages. Any of these problems could cause work stoppage on cell processing, and therefore each has been analyzed and its risks assessed.

When working with hazardous materials, the risk of accident is always present and is continually addressed. Having many years of experience and the benefit of expert consultants, we have built a facility at Kopin with multiple levels of protection against the exposure of our employees or the release to the environment of hazardous materials. Automated systems linked to many different sensors rapidly bring the facility into a benign state in any nonstandard situation. Our employees are trained and retrained in the use and handling of the materials and the protective gear and systems needed. We will maintain our tight controls over the safety aspects of this and other programs at Kopin to minimize any chance of an accident occurring.

Government regulation of hazardous materials used in our solar cell production is extensive. We have maintained compliance and, since the production quantities of these materials anticipated for this effort are comparable to our existing usage, we do not need to change either our operation or our compliance program.

As we purchase the materials needed for cell fabrication, we are also sensitive to potential vendor problems which may interrupt our supply of materials. Our solution to this problem is to maintain at least two qualified suppliers.

5.0 PLANNED APPROACHES

The approaches to solutions for the above problems are described below, along with time and cost estimates for the solutions. The work has been divided into the areas of CLEFT Cell Insertion, Tandem Cell Insertion, Module Optimization, and Pilot Line Operation. Receiver modifications are included in the Cell Insertion sections and, where appropriate, in with Module Optimization. Safety approaches are included in Pilot Line Operation.

5.1 CLEFT Cell Insertion

Changing from the baseline cell to the CLEFT cell will entail cell design and optimization leading to the demonstration of 28% efficiency and cell reliability, modification if needed to the receiver for the CLEFT cell, the demonstration of at least 5 reuses of the GaAs substrate, and the development and implementation of the automated separation step in the CLEFT process.

The CLEFT process currently is used to form state of the art cells with efficiency nominally about 22 to 23% AM1.5, and can be adapted to the formation of 1000X concentrators with minor change. The only process variation that must be explored is the reduction in contact resistance. The contact resistance is presently about 10^{-4} ohm-cm^2, and should be reduced to below 10^{-5} ohm-cm^2 in order to avoid series resistance losses. The contact that we currently use for one-sun cells is formed by electroplating Au directly to the GaAs cap layer, without sinter. For the purposes of concentrator cell production, however, we will use a Au-Ge based contact which is directly compatible with our existing cell structure. This alloyed contact along with a heavily doped cap layer will yield the desired low resistance.

The CLEFT cell will be optimized via both grid design and epitaxial structure. An installed device model will be used to determine the optimized epitaxial structure, and based upon the improved contact resistance and the epitaxial material parameters, a grid will be designed using in-house codes. The cell design will in turn be used to ensure compatibility with the receiver, and at this point the receiver will be modified as needed. Wafers will be grown and fabricated, with empirical optimization.

Once CLEFT concentrator cells are fabricated, the substrate reuse program and the manufacturing development of the separation step will both begin. We will use our existing wafer tracking system to construct a file to maintain substrate history by lot, and to track concentrator cell performance for each lot. The development and implementation of the automated separation step in the CLEFT process will be based on the automated handling of the wafer and dispense/curing of the adhesive.

The CLEFT cell insertion task is a twenty-four man-month effort, which would need about one year to complete. Successful development of the CLEFT cell would mean substitution of this cell and its process for the baseline GaAs cell in the pilot operation.

5.2 Tandem Cell Insertion

Insertion of a tandem cell would occur after the CLEFT cell work was complete, and would mimic much of the CLEFT cell insertion task. Selecting a suitable tandem cell technology, the cell would go through a redesign for 1000X operation and receiver compatibility. Optimization and demonstration of cell operation would be followed by reliability testing and the process development necessary to lower the manufacturing costs of the higher-efficiency cell. Successful development again will result in the upgrading of the entire module pilot operation to tandem cells.

Significant progress has been made in recent years, as tandem cells have finally achieved higher levels of performance than single-junction cells. As previously mentioned, both VS and Kopin have extensive experience in making tandem cells, and we have several different candidate material systems from which to choose. As we are developing these material systems under separately funded programs, we need not select the particular tandem cell until about one year into Phase 2 of this program. Once selection is complete, the insertion work is expected to take one year and require twenty-four man-months of effort.

This tandem cell will be monolithic CLEFT, allowing direct insertion of the cell into the receiver with no modifications. It will also be possible to stack this tandem cell on a lower-bandgap cell such as Si, in order to achieve even higher efficiencies. This latter, three-junction cell, would require some receiver redesign.

5.3 Module Optimization

The improvement to the module is centered around the potential replacement of the aluminum housing with an alternative material. Constraints are the optical alignment of the lenses and the secondary, heat dissipation, electrical isolation, cost, and reliability. Different materials will be investigated, and prototypes made and tested from leading candidates. Should a suitable replacement material not be found, it may be necessary to redesign the secondary optical element to allow for more reliable optical alignment.

This work will take six months, at a level of effort of nine man-months.

5.4 Pilot Line Operation

The pilot line operation is a key element of this program, as it is within this task that all of the baseline manufacturing technology is developed. The pilot line will be used to maintain a steady throughput of cells, receivers, and modules, and to provide cost, yield, and throughput data on the baseline process. The output at each level of the process will be tested to determine performance and reliability of the components and modules during the course of the program. It will be through this data history that improvements in both product and process will be able to be measured.

Complete process documentation will be maintained and updated when changes to the baseline are made via work on the other tasks. Documentation will include quality control and safety procedures. We will use our installed Oracle database and computer-integrated manufacturing system to track both the process and the process data.

Equipment will be purchased, at Kopin's expense, to increase the annual production capacity from 20 to 80 MW at the end of three years. To the extent that increases occur in the usage and storage amount of hazardous materials, additional permits will be obtained. The line will be located in the existing Kopin facility in Taunton.

6.0 SUMMARY

Phase I consisted of an examination of the development required to expedite the commercialization of the GaAs concentrator technology. In summary, the approach derived from the Phase I work follows.

We baseline the GaAs concentrator cell and 1000X module design into pilot operation at Kopin. In order to attain the above improvements, we will use Kopin's existing pilot line for production of CLEFT GaAs solar cells; these cells are already exhibit efficiency of about 24% AM1.5. We will modify the CLEFT cell to form concentrators that perform well at 500 to 1000 suns. The know-how for this modification will derive from an integration of Kopin and VS technologies. The pilot line will be broadened to include cell receiver and module assembly, using VS technology obtained from Varian as a baseline. A second generation design will be formulated to address improvements in the module and these will be incorporated into the pilot line, along with the CLEFT concentrator cell. In parallel, we integrate Kopin's CLEFT GaAs cell technology with the advanced AlGaAs and InGaAs material technology obtained by VS from Varian to develop a near-term two-junction mechanical stack with an efficiency of 35%. The receiver thus developed will be compatible with a three-junction approach that has been proposed elsewhere by Kopin. The use of a three-junction stack can yield efficiency of over 40%, and when such cells become available, the pilot line process will have been designed to utilize them.

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16. Abstract (Limit: 200 words)

This report describes a research project to study developments required to expedite commercializing the GaAs solar cell concentrator technology. We baseline the GaAs concentrator cell and 1000X module design into pilot operation at Kopin Corporation. To attain these improvements, we will use Kopin's existing pilot line to produce cleavage of lateral epitaxial film for transfer (CLEFT) GaAs solar cells; these cells already exhibit efficiencies of about 24% at air mass 1.5. We will modify the CLEFT cell to form concentrators that perform well at 500-1000 suns. We will derive the know-how for this modification from an integration of Kopin and VS Corporation technologies. The pilot line will be broadened to include cell receiver and module assembly, using VS Corporation technology obtained from Varian as a baseline. A second-generation design will be formulated to address improvements in the module, and these will be incorporated into the pilot line along with the CLEFT concentrator cell. In parallel, we integrate Kopin's CLEFT GaAs cell technology with the advanced AlGaAs and InGaAs material technology obtained by VS Corporation from Varian to develop a near-term, two-junction mechanical stack with an efficiency of 35%. The receiver thus developed will be compatible with a three-junction approach that has been proposed elsewhere by Kopin. Using a three-junction stack can yield an efficiency of over 40%, and when such cells become available, the pilot line process will have been designed to use them.

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