CONTRACTOR REPORT

SAND82—7214
Unlimited Release
UC—63c

Development and Fabrication of Advanced Cover Glass for a GaAs Solar Cell

P. G. Borden, N. R. Kaminar, M Grounner
Varian Associates, Inc.
Solid State Laboratory
611 Hansen Way
Palo Alto, CA 94303

Prepared by Sandia National Laboratories Albuquerque, New Mexico 87185
and Livermore, California 94550 for the United States Department of Energy
under Contract DE-AC04-76DP00789

Printed January 1984

***When printing a copy of any digitized SAND
Report, you are required to update the
markings to current standards.***

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

NOTICE: This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government, any agency thereof or any of their contractors or subcontractors. The views and opinions expressed herein do not necessarily state or reflect those of the United States Government, any agency thereof or any of their contractors or subcontractors.

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

NTIS price codes
Printed copy: A05
Microfiche copy: A01

Development and Fabrication of Advanced Cover Glass for a GaAs Solar Cell

P. G. Borden, N. R. Kaminar, M. Grounner
Varian Associates, Inc.
Solid State Laboratory
611 Hansen Way
Palo Alto, CA 94303

Under Sandia Contract No. 74-6832

Abstract

This report summarizes work on improving solar cell conversion efficiencies by modifying the cell cover glass. Two approaches were investigated during the course of this work: grooved cover glasses to reduce the effect of top contact obscuration and secondary concentrators to improve concentrator solar cell performances in tracking modules. The grooved cover glass work used an array of metallized V shaped grooves in a thin cover glass (plastic) window to deflect incident light rays away from solar cell front surface regions covered by the solar cell electrical contact metallization onto unobstructed, optically active regions of the solar cell. Secondary concentrators are being considered for use on concentrator solar cells to improve overall system conversion efficiency and reduce receiver module cost. Secondary concentrators designed and fabricated during this project consist of small glass cones to attach directly to the top of the receiver solar cell. When appropriately designed, these secondary concentrator glass cones increase sunlight concentration on the solar cell, improve solar flux uniformity on the cell, improve system tolerance to tracking error, and allow for concentration ratios greater than can be ordinarily achieved with acrylic Fresnel lenses.

TABLE OF CONTENTS

<u>Section</u>	<u>Page</u>
I. INTRODUCTION	1
II. SECONDARY CONCENTRATOR COVER GLASSES	8
A. Design Concepts	8
1. Multiple-Angle Cones	14
2. Ray Trace Models & Design Tradeoffs	18
3. Thermal Considerations	24
B. Dispersion Effects	27
C. Fabrication/Prototyping Considerations	32
1. Bonding to the Cell	35
2. Cone Performance Tests	37
3. Single-Element Cones	40
4. Dimensions of Single Cone	40
5. Double-Element Cone Tests	44
III. GROOVED COVER GLASS	63
A. Groove Design	64
B. Comments on Cell Grid-Line Design	68
C. Process Development	70
1. Cutting Tool	71
2. Ruling Machine	74
3. Master Replication Techniques	77
4. Bonding to Cell	77
D. Performance Results	80
IV. CONCLUSION	83
V. REFERENCES	85

I. INTRODUCTION

The solar cell cover glass is a rather plain, but important component. Usually, a flat sheet of glass with an antireflection (AR) coating on the front and cement bonded to the front of the cell, it provides environmental protection for the solar cell. With any cell, silicon or GaAs, this is an important function. The front of the cells can be cleaned without fear of damaging the grid lines or the AR coating. In GaAs cells, which have an AlGaAs window layer on the front surface that readily oxidizes in air, the cover glass is even more important to ensure long-term environmental stability.

So, it can be argued that cover glasses are worth using, even if they add a bit to the cost of the solar cell, and add an additional optical interface. Of course, there is no rule that says the cover glass need be a simple, flat piece of glass. It can, for instance, be shaped as a secondary concentrator to provide efficient collection of concentrated light and increases in allowable tracking error (ATE). Or, it can be shaped with grooves over the grid lines to deflect light into the cell active area and cut down obscuration. This is precisely the purpose of the program described here. Simply stated, cover glasses can provide not only environmental protection, but can also significantly improve cell and optical system performance.

This program has focused on two approaches. The first is the dielectric secondary concentrator cone. The second is the grooved cover glass. Let us briefly see what each of these is, and why they are of value. Figure 1 shows various dielectric secondaries. These include the ideal compound parabolic concentrator,¹ or Winston collector, the single-angle cone, and the double-angle cone. In this program, for reasons described later, we have worked on the development of single- and multiple-angle cones.

a) CPC

b) Single-Angle Cone

c) Double-Angle Cone

Fig. 1 Various dielectric secondaries.

The cone acts like a light funnel. It collects most or all of the light rays incident within the acceptance angle and directs them into the cell active area. The effect is to significantly increase the cell aperture area without use of a guard band. The reasons for doing this are as follows:

1. **Cell Cost Reduction.** The highest efficiency cells, such as GaAs and monolithic cascade cells, are relatively expensive. Use of high concentration minimizes this problem, especially when the concentration is so high that the cell die size drops to the point where its cost is less than or equal to the cost of the package itself. At this point, die cost starts to become irrelevant, since all cells must be packaged. For GaAs, and probably for monolithic cascade cells, this requires a concentration of about 1000 suns, a level too high to reach with low-cost planar Fresnel lenses if flux uniformity is to be maintained. The secondary allows concentrations greater than 1000 suns to be reached with planar Fresnel lenses, while actually increasing efficiency, flux uniformity, and ATE.
2. **Improved Optical System Efficiency.** In any concentrator, a certain fraction of the rays land slightly outside the cell active area, a phenomenon known as spillover. In low-concentration systems, the way around this is to use a guard band. This, in effect, increases the size of the cell. A guard band is not practical in high-concentration, high-efficiency systems because of the increased size of already expensive cells, and because the added path length through the guard band to the bus reduces fill factor by adding series resistance. Use of a secondary cone provides a guard band to increase the effective cell size, without requiring larger cells. This collects the spillover and increases the optical system efficiency.

3. Improved Flux Uniformity at the Cell. As will be shown later, proper design of the cone provides good control of the flux uniformity at the cell. In fact, the light distribution can be tailored to throw more toward the edge of the cell. This provides a shorter current path to the bus and increases the fill factor.
4. Improved ATE. The large aperture of the cone allows the light spot to wander off center without a loss in collection efficiency. This provides increased ATE, translating into lower tracker structure costs via decreased tracking accuracy requirements.
5. Use of Planar Fresnel Lenses in High-Concentration Systems. Because of dispersion, planar Fresnel lenses are limited to concentrations of about 400 suns. It is desirable to use these lenses because they are relatively low cost, easy to make, either singly or in parquet form, and because the lens parquet presents a flat, smooth surface to the outside world. Secondaries allow use of these lenses in 1000-sun systems.
6. Ease of Module Assembly. The secondary makes cell placement noncritical, simplifying manufacture.

The second cover glass modification developed in this program is the grooved cover glass. This appears in Fig. 2. It consists of steep grooves formed in the bottom of the cover glass, so as to lie directly over the grid lines. Light striking the groove wall reflects into the cell active area. In this manner, obscuration is reduced and thicker grid lines can be used. This is a means of circumventing the traditional design tradeoff in high-concentration cells; namely, that high grid coverage is needed to reduce internal resistance, but high grid coverage blocks incident light, reducing efficiency.

Fig. 2 The grooved cover glass.

This program has led to the successful demonstration of both the secondary concentrator and the grooved cover glass. To summarize the key results:

1. A double-angle glass cone bonded to a GaAs concentrator cell has allowed operation at 1000 suns concentration with a planar Fresnel lens. The lens transmission corresponds to an ideal Fresnel lens, meaning that most spillover has been collected. The ATE is ± 0.7 degrees, a number equivalent to that obtained with low-concentration guard-band systems.
2. Computer models have been developed to design lens-cone systems. These models indicate the potential for further improvement in performance.
3. A number of bonding agents have been looked at, and it has been shown that secondary optics can be stably bonded to the front of the cell, in spite of the high concentration.
4. A process has been developed for the production of grooved cover glasses with grooves spaced 100 microns apart and with groove-tip radii of less than one micron.
5. Grooved cover glasses have been placed on a concentrator cell with 10% grid coverage, resulting in a 5.5% improvement in short circuit current.

This report is divided into two sections. The first discusses the secondary concentrators. We begin with a discussion of design concepts and modeling methods. This is followed with a description of how prototype cones are made and bonded to the cell, followed by performance results. Finally, improved designs are discussed.

The second section discusses the grooved cover glass. First, the design procedure is discussed. The process, which is adapted from techniques used in the recording industry, is described in detail. Finally, performance results are given.

II. SECONDARY CONCENTRATOR COVER GLASSES

The secondary concentrator cover glass is shaped in the form of a cone, for the purpose of funneling light onto the active area of the cell. This section describes the development work carried out on these, including design concepts, fabrication and bonding, and performance results.

A. Design Concepts

Secondary concentrators are not new, and have been well described in the literature.¹⁻³ In this work, we have done two things that are new. First, we have adapted secondaries for use with solar cells at very high concentrations. Second, we have shown that the "ideal" concentrator usually discussed in the literature may not be the best design for use with a concentrator solar cell, and that certain "nonideal" designs may be preferred.

Let us first review some basic concepts of ideal concentrators. An example of an ideal concentrator is the compound parabolic concentrator, or CPC. The CPC has the property that all rays incident within its acceptance angle, θ_a , eventually reach the cell. This may be directly or through one or more reflections. Such a concentrator has a maximum concentration ratio of

$$C_{\max} = \frac{n^2}{\sin^2 \theta_a} ,$$

where n is the index of refraction of the CPC material and θ_a is the acceptance angle. For a short focal length system, typical of high-concentration photovoltaics, the acceptance angle is on the order of 23° ($f/1.2$). For a reflective CPC, the maximum concentration ratio is 6.6. For a glass CPC, with $n = 1.5$, the $C_{\max}$ is 14.7.

The advantages of a secondary become clear through these simple calculations. First, because of chromatic aberration, it is hard to exceed 400 suns with a planar resnel lens. Using a secondary allows some of the concentration to be taken up at the cell, reducing requirements on the lens. Use of a solid secondary allows more design freedom. Rays refract to the normal at the front of the secondary, resulting in higher concentration. This further reduces requirements on the lens and increases design freedom.

In practice, CPCs have a number of drawbacks that limit their use. These include

1. The CPC shape is difficult to prototype and cannot easily be formed by simple polishing. This means optical elements are expensive in small quantities.* This is a serious limitation in an R&D program.
2. Because of the single and multiple reflections, rays tend to be incident at oblique angles at the cell. In the solar thermal system, this is not a problem; in photovoltaics, however, the acceptance angle of the antireflection (AR) coating on the cell will limit optical efficiency.
3. In coupling the secondary to the cell, we seek a design that addresses several problems. First, the acceptance area of the cell must be increased to collect spillover and enhance ATE. Second, flux distribution at the cell must be made uniform, or even torroidal, to increase cell efficiency by reducing series resistance losses caused by current traveling too far in the front contact grid. Third, optical efficiency, including the AR coating at the cell, must be maximized. These three design criteria cannot be traded off if one sticks with a pure CPC design.

*We have found that plastic elements will melt and disfigure; the cone must be glass.

For all of these reasons, we have used single- and multiple-segment cone designs. Some of these are shown in Fig. 3. The idea here is to use cones made of straight walled segments. The larger the number of segments, the closer the approximation to a CPC. Such cones are relatively easy to fabricate. Furthermore, by adjusting wall angles, it is possible to make tradeoffs between acceptance angle, flux uniformity, aperture size, cone size, and transmission.

To understand these tradeoffs, consider the design of first a single-angle cone, and then a multiple-angle cone. Figure 4a shows the design problem for a single-angle cone. For simplicity, it is expressed in two dimensions. The wall angle is θ_w . The acceptance angle is θ_a , which is the maximum input angle given by $\theta_a = \tan^{-1}(1/2f)$, with f the system f number. The cone diameter at top and bottom is D_T and D_B , respectively. The design condition to capture all rays within a range of $\pm \theta_a$ is that the most extreme ray (as shown in Fig. 4a) must reflect to the far edge of the cell. The concentration ratio, given by the ratio of the aperture to cell area, is

$$C = \left[1 + \frac{2 \tan \theta_w}{\tan (2\theta_w + \theta_c) - \tan \theta_w} \right]^2 \quad (1)$$

θ_c is the angle of the ray in the cone, given by

$$\theta_c = \sin^{-1} \left(\frac{\sin \theta_a}{n} \right),$$

where n is the cone index of refraction.

Figure 5 is a plot of concentration as a function of wall angle for several system f numbers. Note that the peak concentration is relatively insensitive to f number, and occurs at a wall angle of about 12 degrees.

SINGLE CONE:

DOUBLE CONE:

- WIDER APERTURE THAN WITH SINGLE CONE
- ADJUST ANGLES FOR BETTER FLUX UNIFORMITY
- EASY TO PROTOTYPE

Fig. 3 Single-, multiple-segment cone designs.

Fig. 4a Single-element cone design problem.

Fig. 4b Double-element cone design problem.

Fig. 5

CONC. VS. WALL ANGLE

* f/number 1

f/number 1.5

o f/number 2

+ f/number 3

X f/number 4

The peaked shape of the curve can be explained as follows. From the design condition, as shown in Fig. 4a, it can be seen that as the wall angle becomes larger, the cone height must diminish so that the most extreme ray hits the cell. Eventually, the cone height is zero, and the concentration is unity. In the other extreme, as the cone wall becomes steeper, the cone becomes higher, but its aperture area drops. Eventually, the wall is vertical and the concentration is again unity. In between these two extremes, the concentration reaches a peak.

The peak concentration as a function of lens f number is seen in Fig. 6. This increases with f , because the incidence angle range for high f systems is smaller. For practical systems, in the range of $f/.8$ to $f/2$, the peak concentration lies in the range of about 2.5 to 4. A good Fresnel lens provides peak concentrations of 400-500 suns. The limitation arises from chromatic aberration. Even with a single-element cone, concentrations above 1000 suns are realizable from such a lens.

An important consideration is use of total internal reflection (TIR), since this is a more efficient reflection mechanism than reflection off a metallized wall. Figure 7 plots the maximum wall angle allowing TIR as a function of system f /number. In all cases of practical interest, the angle beyond which TIR does not hold for all rays is much larger than the peak concentration angle. This is particularly fortuitous, as it implies that a practical single-angle cone can use TIR.

1. Multiple-Angle Cones

The single-angle cone is the most straightforward approach to a secondary, but it is limited in performance and design flexibility. An improved approach is the multiple-angle cone, shown in Fig. 4b. Here, the cone consists of multiple angles, with segments having continually steeper angles as the height increases. The advantages of such a design are

Fig 6

PEAK CONC. VS. F/NUMBER

Fig. 7 MAX. TIR ANGLE VS. F/NUMBER

- 1) The design flexibility increases because the angle of each segment can be adjusted independently. This allows optimization to improve flux distribution and aperture simultaneously.
- 2) As the number of segments increases, the design approaches that of a CPC. This provides better concentration, or aperture size.
- 3) A multiple-segment cone is easy to prototype, because flat sections are easy to grind and polish.

The design algorithm for a multiple-angle cone is based on the same principles as for a single cone. This is seen in Fig. 4b for a 2-segment cone. The rule now is that for each segment, the most extreme ray striking at the top of that segment must hit the far edge of the cell. This ensures all rays must hit the cell. The angles are then chosen to maximize aperture in the simplest design. In more sophisticated designs, where it is desired to improve ATE, aperture and flux distribution, these design rules may be relaxed.

A straightforward method to calculate a multi-segment cone design, based purely on an optimized aperture, is to use a computer optimization in which all combinations of cone angles are tried. Figure 5 represents this algorithm for a single cone, by calculating the concentration for each possible wall angle, thereby converging on the peak concentration. For a double cone, a range of wall angles for the upper segment is tried for each choice of bottom segment angle.

This procedure becomes cumbersome as the number of segments increases. A method to speed convergence is to plot trends in the angle of each segment as a function of the number of segments. This provides a narrow search range for the next highest number of segments.

Figure 8 plots the peak concentration for multi-segment cones as a function of the number of segments. Also shown is the ideal concentration for a CPC, calculated from

$$C_{\text{CPC}} = \left(\frac{n}{\sin \theta_a} \right)^2 ,$$

with n the cone index of refraction and θ_a the acceptance angle. The plot is for an index of $n = 1.5$ and a θ_a of 24.4° , corresponding to $f/1.1$ optics.

It should be noted that the above formula is for three dimensions, and the simple cone calculations are for two. Thus, they are not strictly comparable. In practice, a two-dimensional calculation may tend to under-estimate the concentration. This is seen upon inspection. Figure 9 shows a single cone bonded to a cell, as viewed from a shallow angle. Note two crescent-shaped regions, one on the cell and one at the top. These regions are where light reflects out without hitting the cell. They are widest directly along the plane of view. Thus, concentration is lowest in this plane. A two-dimensional calculation finds the concentration for this plane.

2. Ray Trace Models and Design Tradeoffs

The preceeding discussion is based on two-dimensional models of the cone. In reality, a three-dimensional analysis is required. To this end, a ray trace program has been developed to find performance of real cones. This determines optical system transmission and illumination distribution at the cell.

This is an extension of a Monte Carlo ray trace (MCRT) Fresnel lens design program. Once it designs a lens, it traces rays randomly from the sun to points on the lens and onto the cell itself. This

Fig. 9 A single cone bonded to the front of a 1/3" diameter GaAs solar cell. The background grid is 1 cm x 1 cm.

program uses two-dimensional cone design algorithms, which are adjustable as described below. It finds transmission through the lens, front of the cone, and into the cell. Included are quarter-wave coatings on the front of the secondary and the cell.

In the above discussion of two-dimensional design, the sole criterion was maximum aperture under the constraint that all rays within the acceptance angle are collected. To ensure meeting of this criterion, the calculation forced the most extreme ray to hit the far edge of the cell. In practice, we wish to optimize ATE and flux distribution; to this end, it is profitable to relax the absolute collection constraint.

The relaxation method is shown in Fig. 10. The idea is to make the intersection of the extreme ray with the cell plane adjustable, rather than fixed at the cell edge. Thus, in the nonadjustable model, the ray intersect point is as shown in Fig. 4. In the variable model, this point is specified separately.

This idea has been applied to a two-segment cone. For this case, the bottom segment is used to adjust the flux distribution, as this segment lies close to the cell and can be used to fold rays back onto the cell. Since we are trying to smooth an otherwise peaked distribution, the intersection point is brought inward, as shown in Fig. 10. A typical value is $0.55 d_c$, where d_c is the cell diameter.

The top segment comes into play to increase ATE. It only sees rays when the system is off track. To increase ATE, it is desirable to increase the aperture. Choosing an intersection point greater than the cell radius, as seen in Fig. 10, accomplishes this. A typical value is $1.35 d_c$ for an $f/1.2$ system.

Figure 11 shows the effect of this design on ATE. The ideal cone has perfect collection until rays start to miss the front aperture.

Fig. 10 Relaxation of design constraints to improve flux distribution and ATE.

Fig. 11 The effect of relaxed design on ATE.

At this point, losses rise rapidly. The larger aperture gives a significant increase in ATE over the cell alone. The nonideal design has a still larger aperture, so that ATE is improved. The tradeoff is the loss of some extreme rays at smaller tracking error angles. Thus, the loss curve rises earlier, but less steeply than for the ideal design.

Figures 12 and 13 show the effect of such a design on flux distribution and ATE. This is for a 2-segment cone mounted on a .25" diameter cell. The lens is square, 7" on a side, with a focal length of 11.9" ($f/1.2$). The cone bottom and top angles and heights are, respectively, 23.7° , 12.75° , .084" and .538". The aperture diameter is .567". Note the peak-to-average (PA) flux ratio is 1.1, transmission through the cell AR coating is .79, ATE is 0.85° at the $\pm 90\%$ points, and geometric concentration is 1000 suns. These are compared to typical parameters for other lens technologies in Table I.

TABLE I: A COMPARISON OF VARIOUS CONCENTRATORS

<u>System</u>	<u>Flat Fresnel + Sec.</u>	<u>Flat Fres.</u>	<u>Domed Fres.</u>	<u>Mirror</u>
f	1.2	1.2	1.2	1.2
Max. Concentration (suns)	>1000	400-500	800-1000	>1000
ATE (degrees)	0.85	.25	.35	.25
P/A flux	1.1	2.0	2.0	≥ 2
Transmission (%) (through cell AR)	.79	.75	.75	.8

3. Thermal Considerations

There is some concern that the higher temperature environment of the epoxy bond between the cone and the cell might damage the bond. A simple calculation shows this not to be a problem. The glue bond is

AVERAGE OPTICS TRANSMISSION	= 0.7936 +/- 0.0008
AVERAGE TRANSMISSION THRU SECONDARY	= 0.9615 +/- 0.0009
FRACTION OF RAYS LOST BY TIP IN LENS	= 0.0000 +/- 0.0000
FRACTION OF RAYS HITTING DRAFT SURFACES	= 0.0158 +/- 0.0006
FRACTION OF RAYS MISSING SECONDARY	= 0.0000 +/- 0.0000
FRACTION OF RAYS REFLECTED BACK UP SECONDARY	= 0.0000 +/- 0.0000
FRACTION OF RAYS LOST BY NO SECONDARY TIR	= 0.0002 +/- 0.0001
GEOMETRIC CONCENTRATION RATIO	= 998.2 SUNS
AVERAGE TRANSMISSION THROUGH AR COATING	= 0.9316
PEAK FLUX CONC RATIO =	997 +/- 43 SUNS

Fig. 12 Flux distribution at the cell for a 2-segment nonideal cone mounted on a 1/4" diameter cell

TRACKING ERROR TOLERANCE FOR OPTIMIZED DOUBLE CONE

Fig. 13 ATE for a 2-segment nonideal cone design.

typically about 25 microns thick and the glue has thermal conductivity of about 7×10^{-3} W/cm-°K. The maximum service temperature is 150°C.

We will do what is by far a worst-case calculation. Suppose the concentration is 1000 suns and 10% of this flows through the epoxy as heat. This corresponds to a heat flow of 10 W/cm^2 . Needless to say, this is a gross overestimate; absorption in the cone is at most 1-2% and much of this radiates or convects to the air without flowing through the epoxy.

In this case, the temperature drop is

$$\Delta T = \frac{P}{K} \Delta X \quad ,$$

with P the power flux, K the thermal conductivity, and ΔX the thickness. For the above number, the temperature drop is $\Delta T = 1.4^\circ\text{C}$. Since the epoxy is bonded to the cell with a junction temperature typically 80°C, the epoxy operates well below its service temperature.

B. Dispersion Effects

The Fresnel lens-secondary system is fairly dispersive because of the variation in index of refraction of the lens with photon energy. As a result, the light distribution at the cell is flat only when the full solar spectrum is considered. For monochromatic light, this distribution is not necessarily flat.

Figures 14 through 17 show the flux distribution for photon energies of 1.5, 2.0, 2.5 and 3.0 eV, respectively. The first two correspond to the bandgaps of silicon and GaAs. Note the sharp spike at 3.0 eV. Unless the bond agent is carefully chosen, such a spike can lead to UV degradation of the bond at the center.

Fig. 14 Flux distribution for optimized optical system at:
a) all frequencies
b) 1.5-eV photons.

HV=2.0 eV

Fig. 15 Flux distribution for optimized optical system, 2.0-eV photons.

HV=2.5 EV

Fig. 16 Flux distribution for optimized optical system, 2.5-eV photons.

Fig. 17 Flux distribution for optimized optical system, 3.0-eV photons.

C. Fabrication/Prototyping Considerations

In large quantities, cones would be made using molding techniques. In the small quantities required for this program, cones have been made by grinding and polishing, thereby avoiding the high tooling and setup costs for molding. The choice of grinding and polishing has somewhat dictated both the choice of glass and the choice of shape. For example, fused quartz is easier to polish than some lower-cost or higher-index but softer glasses. Flat surfaces have been used, again for simplicity of fabrication.

Figure 18 shows how the 2-segment cone is made. A cylinder is cored from flat glass and glued to a tool (Fig. 18a). This is ground to the angle of the upper cone (Fig. 18b). The end is ground to the lower cone angle (Fig. 18c). Finally, the cone is cut from the tool at the correct length, and the piece is polished.

The cone requires both dielectric and metal coatings. Specifically, an AR coating is applied to the front. In this work, MgF vacuum deposited at 300°C is used. The index is 1.35, and a quarter wave at 2 eV is used for a thickness of $1150 \text{ \AA}$. In addition, a thin metal band near the base is required. When the cone is bonded to the cell, the glue forms a fillet around the base. This fillet will frustrate total internal reflection (TIR) near the cell; this would critically degrade performance. The reflective metal band prevents this problem. The metal is sputtered aluminum. Evaporated silver has been tried, but its adherence to quartz is poor. Sputtered or chemically-deposited silver may be usable, but results with these were inferior to those obtained with aluminum.

Finally, careful consideration has been given to choice of the glass. Table II lists relevant properties of various glasses.

Fig. 18 2-segment cone prototyping technique.

a) cored cylinder

b) angle of upper segment is ground.

Fig. 18 2-segment cone prototyping technique.

c) bottom segment is ground.

d) cone cut from tool and polished.

TABLE II: GLASSES

Glass:	Fused Quartz	SF8	SF9	Borosilicate
Index:	1.46	1.68	1.65	~1.5
Thermal Exp ($\times 10^{-6}$, /A):	.5	9.1	9.2	3.25
Transmission through 1 cm:				
- 1.1 eV:	.99	.999	.999	.97
- 2 eV:	.99	.999	.999	.97
- 3 eV:	.99	.98	.98	.97
Density (g/cm ³):	2.2	4.22	3.91	2.23

The advantage of the two Schott glasses -- SF8 and SF9 -- is the high index of refraction. The disadvantages are relative softness, weight, and tendency to crack during thermal cycling. Fused quartz is easy to polish; its sole drawback is high cost. Borosilicate would probably be the choice for molded cones, principally because of its low thermal expansion coefficient. Borosilicate is not as easy to polish, and it has not been used here.

1. Bonding to the Cell

In the course of this program, we have examined a number of bonding agents. The properties considered important include:

- 1) transparency
- 2) flexibility, to take up mismatches between the cell and cone, or between the glue and the cell and/or cone,
- 3) ease of application,
- 4) index of refraction match to the cone.

While extensive life tests were not performed, a qualification test was devised to evaluate several possible bonding agents. These were all optical cements, designed for the joining of glass elements. Table III lists the cements. Each cement was used to join two flat sheets of quartz, about one inch on a side. Their spectral transmission was measured, followed by immersion in boiling water for up to 48 hours. After immersion, the samples were inspected for spectral transmission and any mechanical degradation.

III. COVER GLASS ADHESIVES

3M 3520 B/A	Passed 15 hours in boiling water, followed by 15 hours at 250°C, followed by 24 hours in boiling water.
DEVCON 2-TON	Passed 24 hours in boiling water.
HYSOL 608	Delaminated in boiling water.
ROLYN OCELITH	Fast failure in boiling water.
NORLAND 61 (UV)	Some delamination after 24 hours in boiling water, with some recovery.

Table III lists the results of some of these tests. The 3M-3520B/A and Devcon 2-Ton showed no effects, either in transmission or in degradation. These must be considered best and good candidates for more extensive life testing. The Norland-61, while not quite as durable as the two mentioned above, is particularly easy to use. It sets under UV exposure, as produced for example, in a solar simulator.

Long-term, intense UV exposure may degrade epoxy adhesives. In this event, silicone or RTV may be preferred. Sylgard, for example, has been found to work well, have good transmission, and be insensitive to UV exposure. Its sole drawback may be permeability to water. While this UV sensitivity may prove to be a long-term problem, the utility of a single-component, UV-curing adhesive is valuable for experimental work. The Norland-61 can also be removed in A40 photoresist stripper. These features have led to the use of Norland-61 for most experiments reported here.

Of special note is the test of the 3M-3520B/A. The samples were boiled in a Teflon beaker. The wafer accidentally boiled away, leaving the sample dry in the beaker overnight. As the beaker melted, the temperature reached about 260°C, the melting point of Teflon. Following this, the sample was reboiled in water for 48 hours. While the fillet of adhesive exposed to air darkened, there was no visible change in the bond. Transmission before and after also show insignificant change, as seen in Figs. 19 and 20.

2. Cone Performance Tests

Experiments have been performed with both single- and double-segment cones bonded to GaAs concentrator solar cells. These have demonstrated significant improvements in both lens-cell efficiency and ATE over cells without cones. This section summarizes these experiments and results.

3M 3520 ADHESIVE, BETWEEN TWO QUARTZ SLIDES
MEASURED 11/12/81

Fig. 19 Transmission of 3M-3520 between two quartz slides before life test.

Fig. 20 Transmission of 3M-3520 between two quartz slides
after life test.

3. Single-Element Cones

Figure 21 shows a single-element cone bonded to a 1/3-inch diameter AlGaAs/GaAs solar cell mounted in a standard Varian Mo base-plate package. This package has been described elsewhere. As described above, the cone has a quarter-wave MgF AR coating and is bonded to the cell with Norland-61 optical cement. Instead of a metallization band near the base, this cone had its walls entirely metallized with aluminum. The cone itself is fused quartz, with top and bottom diameters of .55 and .333 inches. A front bevel, required for polishing, gives an effective aperture of 0.5 inches. The wall metal is 1 micron of sputtered Al.

This cone was tested with an F/3.8 hexagonal-shaped curved-groove fresnel lens with an active area of 268 cm^2 and a diagonal measure of 8 inches. The geometric concentration ratio is 476 suns.

The test procedure was to first characterize the cell alone, and to then repeat the characterization with the cone bonded to the same cell. The characterization procedure comprised first a measurement of lens-cell efficiency as a function of lens-cell spacing. This, in effect, is a sweep of the cell through the focus of the lens. A second test determined lens-cell efficiency as a function of tracking error. The cell was set at the point of highest lens-cell efficiency and the tracker was progressively sent off track along the lens diagonal.

In these tests, the cell was actively cooled with 50°C water. Insolation was monitored using an Eppley normal incidence pyrheliometer.

4. Dimensions of Single Cone

Figure 22 shows the lens-cell efficiency as a function of lens-cell spacing with and without the single cone. Figure 23 plots the tracking error. We see two major gains -- in efficiency and in

Fig. 21 Single-element cone bonded to a packaged GaAs cell.

Fig. 22 Lens-cell efficiency as a function of lens-cell spacing for an $f/3.8$ lens, single-segment cone, and GaAs cell.

Fig. 23 ATE at peak efficiency lens-cell spacing for an
f/3.8 lens, GaAs cell, single-element cone.

sensitivity to lens-cell spacing. Without the cone, the peak efficiency is 17.6%. With the cone, this rises to 19.2%, a 9% improvement. This is entirely accounted for by the improvement in lens transmission from 79% to 86%, a 9% increase $((86-79)/79)$. From this, we can surmise that the cone adds very little optical loss, and its larger area collects most light that would normally spill off the cell active area. The measured 86% lens transmission is in fact close to ideal for an acrylic curved-groove, flat, fresnel lens.

The larger aperture also reduces the sensitivity to lens-cell spacing. This is because the cell can move further through the focus before light falls off the periphery of the cone. This is of obvious benefit in reducing module assembly tolerances.

The ATE is also improved significantly. The measured values are low because this is a long focal length system. However, significant improvement is seen over the configuration with no secondary.

5. Double-Element Cone Tests

Three sets of double cone tests have been conducted. These have been with the following lens-cone-cell configurations:

- 1) An f/1.1, 11.7" diagonal-measure, curved-groove Fresnel lens illuminating a two-segment cone optimized for maximum aperture bonded to a 1/3" diameter GaAs cell. This lens had been designed to provide uniform illumination on a 1/2" diameter cell at the focal point. The lens shape is hexagonal.
- 2) The same cone and cell configuration as above, but with an f/1.5 lens designed to form a tightly-focused spot. The lens size and shape is the same as above.

- 3) A system in which all components had been computer optimized to match one another. This used a flat-grooved Fresnel lens 7" on a side square, a two-element cone, and a .25" diameter GaAs cell. The cone was optimized on the computer using the wall angle adjustment algorithm described earlier, to provide both good flux uniformity on track and high ATE. The cell had a grid pattern optimized both for the flux distribution as presented on track, and the off-track distribution. This was accomplished by increasing the metal line width near the cell periphery, so as to minimize series resistance as rays bunched up at the cell edge under off-track conditions.

Before describing the above tests, let us summarize some of the key results. These are:

1. It is very important to match the lens to the cone. Not doing so provides only marginal results. Doing so provides near theoretical results.
2. A properly designed system provides impressive results: 18.8% lens-cell efficiency at 1000 suns geometric concentration, with lens transmission close to 90% and an ATE half-angle of 0.8° measured at the 90% point. The range in lens-cell spacing over which lens-cell efficiency is better than 90% of the peak value is better than 10% of the focal length.
3. A good lens design rule is to simply design the lens for a tight spot, and then design the cone to optimize system performance. The tight spot optimizes ATE; the cone can then smooth the distribution at the cell to provide flux uniformity.

4. While a small metallization band is necessary near the base of the cone to allow glue fillet to form without frustrating the total internal reflection, metallization of the cone reduces transmission to the cell significantly.
5. The cone stays bonded to the cell, and does not fall off due to glue degradation at high levels of concentration.

Let us now consider each of the experiments in more detail. The first of these used an 11.7" diagonal-measure hexagonal curved-groove Fresnel lens, with an active area of 573.6 cm^2 . Its focal length was about 13"; thus, it was an f/1.1 lens. This lens had originally been designed to illuminate a 1/2"-diameter solar cell with a reasonably uniform pattern. As such, it was not really optimum for use with a secondary. However, with the short focal length, it was possible to move a short distance beyond the design point to obtain a tight spot. It was also desirable to evaluate a short focal length system, since this is a more practical case. Use of a 1/3"-diameter cell provided a geometric concentration of 1019 suns.

The cone was designed to maximize the aperture, with no consideration given to flux uniformity or to matching of the cone to the lens. The wall angles were chosen using design methods described earlier. The cone itself was made with fused quartz. This material was chosen because it can handle large gradients of temperature without cracking, has a low thermal expansion coefficient, and is relatively easy to work and polish. A glass borosilicate-like Pyrex and Kimax would probably be used in large volumes with molded pieces. However, these glasses are hard to polish. The final cone dimensions are given in Table IV.

The cone had a single-layer MgF AR coating applied to the front, evaporated in an e-beam system with the cone heated to a temperature of 300°C. An aluminum band, 50-mils wide, was evaporated onto the bottom

TABLE IV: CONE DIMENSIONS

	<u>1/3" Cell Cone</u>	<u>1/4" Cell Cone</u>
Bottom Diameter	.33"	.25"
Bottom Segment Height	.15	.084
Diameter at Transition	.462	.324
Top Diameter	.695	.567
Net Cone Height	.716	.622
Bottom Angle	23.43°	23.70°
Top Angle	11.63	12.75

of the lower segment. The cone was bonded to the cell using Norland-61 UV-curing adhesive. First, a single drop of the adhesive was applied to the cell. The cone was then carefully set on the cell so as to avoid any voids. After positioning, the assembly was placed in a solar simulator to set the glue. The glue takes about 30 minutes to completely set at one sun.

The cell was a standard Varian 1/3"-diameter AlGaAs/GaAs cell, packaged in the standard Varian molybdenum baseplate package. The cone was applied to an otherwise completely assembled cell.

Testing was carried out with water cooling, with a nominal coolant temperature of 50°C. The cell mount was affixed to a lead screw, so that the lens-cell position could be varied while holding the cell on the lens axis and parallel to the lens. The insolation was measured with an Epley NIP pyrhelimeter. The efficiency was measured using a computer-controlled load, with each point measured in about 20 seconds.

Figures 24 through 27 show the lens-cell efficiency as functions of lens-cell spacing and tracking error, and the fill factor and transmission as functions of lens-cell spacing. The test procedure was to first measure these with the cell alone, then to bond the cone to the cell and remeasure these parameters. In this manner, the effect of the cone could be determined. It will be noted that in the lens-cell spacing plot, the curves are shifted in position by the thickness of the cone. This is because we plot lens-cell spacing in both cases, rather than lens-aperture spacing when the cone is in place.

The cone improves the lens-cell efficiency and provides a broad peak over which the lens-cell efficiency is relatively constant. This is simply because the cone, with its increased aperture, captures light that would otherwise miss the cell. This larger aperture is also responsible for the increase in ATE. In fact, the increase in efficiency can be accounted for by assuming a lens transmission of about 80% without the cone, and about 85% with the cone. The latter is the transmission for an ideal curved-groove Fresnel lens. It will be noted, however, that the lens-cell efficiency dips near the point where it should peak. This is because of a loss in fill factor, brought about by nonuniform illumination of the cell. This, in turn, is due to the fact that we have not properly matched the cone to the cell.

Also seen are measurements with the cone completely metallized. The curves for this case track the total internal reflection results, but with reduced efficiency. This is because the cone reflectivity is about 90% in the former case, and nearly 100% in the latter. This shows the advantage of minimizing the metallized area.

The measurements were repeated using an $f/1.5$, 18" focal-length Fresnel lens. The lens dimensions were the same, so that the geometric concentration was still 1019 suns. This lens, however, was designed to

Fig. 24 Lens-cell efficiency versus lens-cell spacing.

Fig. 25 Lens-cell efficiency versus tracking error.

Fig. 26 Transmission versus lens-cell spacing.

CELL 30M 24948

- * -- NO CONE
- + -- DOUBLE CONE, NOT ALUMINIZED
- O -- DOUBLE CONE, ALUMINIZED

Fig. 27 Fill factor versus lens-cell spacing.

have a smaller spot, without consideration of flux uniformity at the focus. Such a lens is preferable for use with a secondary, since the tighter spot provides greater ATE. Figures 29 through 31 give the results of this test. We see about the same results as with the other lens in the lens-cell spacing tests. However, the ATE is improved to a half angle of 0.7° at the 90% point. This is comparable to the ATE of low-concentration silicon systems.

The final measurement was with the system in which the lens, cone and cell have been jointly optimized. Here we see the real advantages offered by the flat Fresnel lens and secondary cone optics, as shown in Figs. 32 through 35. The lens is 7 inches on a side and the cell circular with a diameter of .25 inches, for a geometric concentration ratio of 998 suns. This configuration provides uniform illumination at the point of peak transmission, resulting in a high lens-cell efficiency of 18.8%. This is one of the highest module efficiencies ever measured. Note that the efficiency remains high over a wide range of lens-cell spacing, about 1.2 inches with a peak at 12 inches. This means that a module or array made with this optical system does not need critical manufacturing tolerances to achieve peak performance.

The ATE is also high -- a half angle of 0.8° . This is measured parallel to the flat edge of the lens. Figure 36 shows both the measured and theoretical performance, indicating that the model is accurate. This has been obtained both by using a small spot at the front of the aperture to provide maximum transmission off track, and by adjusting the angle of the upper cone to provide the best possible off-track illumination distribution.

Fig. 28 Test results for an $f/1.5$ hex lens and two-segment cone bonded to a $1/3$ " diameter GaAs cell. Lens-cell efficiency versus lens-cell spacing.

Fig. 29 Lens-cell efficiency versus tracking error.

Fig. 30 Fill factor versus lens-cell spacing.

Fig. 31 Transmission to cell versus tracking error.

SINGLE CELL TEST RESULTS

Fig. 32 Test results for an optimized lens-cell system. $f/1.2$ square lens, 2-segment cone, $1/4$ " GaAs cell. lens-cell efficiency versus lens-cell spacing.

SINGLE CELL OFF TRACK OPTICAL TRANSMISSION WITH CONE

RELATIVE TRANS

* THEORETICAL

OFF TRACK deg
TEST RESULTS

Fig. 33 Test results for an optimized lens-cell system. $f/1.2$ square lens, 2-segment cone, $1/4$ " GaAs cell. Relative transmission versus tracking error.

RELATIVE TRANS & FF

Fig. 34 Test results for an optimized lens-cell system. $f/1.2$ square lens, 2-segment cone, $1/4$ " GaAs cell. Fill factor versus lens-cell spacing.

Fig. 35 Test results for an optimized lens-cell system. f/1.2 square lens, 2-segment cone, 1/4" GaAs cell. Fill factor versus tracking error.

SINGLE CELL OFF TRACK OPTICAL TRANSMISSION WITH CONE

Fig. 36 Measured and theoretical tracking error performance of the optimized system.

III. THE GROOVED COVER GLASS

The second major aspect of this program was the development of a grooved cover glass, called the GCG for convenience. In a typical concentrator cell, over 10% of the front surface is covered with grid lines. The idea behind the GCG is to deflect light that would normally hit these grid lines into the cell active area. This provides two advantages. First, heavier grid lines can be used, thereby increasing fill factor. Second, efficiency increases as more of the available light is collected.

The GCG is made by techniques analogous to those used to make phonograph records. A nickel master is tooled and replicated, to form a flat cover glass with the grooves embossed in the bottom. This replica is bonded to the cell with the grooves fitting over the grid lines. The grooves will reflect light if either they are metallized or the glue has a low enough index of refraction to provide total internal reflection at the groove surface.

Implementation of this idea for concentrator cells is not simple. Phonograph records are ruled with diamond tools at an angle of 45° . This is convenient because such tools can be made by cleaving a diamond. The criterion of reflection into the active area, especially with low f number systems, requires use of very steep groove walls with angles on the order of 15° to the normal. The groove walls must be ruled smoothly, with a very small-tip radius. Groove lines must be closely spaced, typically 100 microns, and must be accurately spaced so as to lie over the grid lines. The required tasks are, then,

1. design of the groove angles to match the cell grid-line spacing,
2. design of the cell grid lines to take advantage of the wider allowed line width, under the constraint that the grid lines must be parallel,

3. develop a tool capable of properly cutting the grooves,
4. develop a ruling machine to accurately step the grooves,
5. develop master replication techniques, and
6. develop a method of either bonding the cover to the cell with a low-index glue, or metallizing the inside of the grooves.

The following text will discuss each of these aspects of the development of the GCG. Performance results will then be presented, in which as much as a 5.5% improvement in short circuit current is observed in a cell with about 10% grid coverage.

A. Groove Design

The groove design proceeds on the basis of the following criteria.

1. The groove spacing is determined by the grid-line spacing, which follows from an optimization of the emitter sheet resistance of the solar cell.
2. The groove width at the base is determined by the grid-line width, which follows from a minimization of the grid-line series resistance.
3. The wall angle is determined by the constraint that the most extreme ray hitting the top of the groove does not hit the next groove.

Figure 37 shows the situation on which the design calculation is based. The first criterion depends on the solar cell design criteria that are essentially independent of the design of the grooved cover glass. On the basis of the grid line spacing and the third criterion, the groove wall angle is given by the transcendental expression

Fig. 37 THE GROOVED COVER GLASS

$$S = H(\tan \theta_g + \tan (\theta_{ic} + 2\theta_g)) \quad (1)$$

Here S is the grid line spacing, θ_g is the angle of the groove wall with respect to the cell normal, and θ_{ic} is the angle of incidence for the most extreme ray, given by

$$\theta_{ic} = \sin^{-1} \left(\frac{\sin \theta_i}{n} \right) \quad (2)$$

θ_i is the angle of incidence to the cover glass, given by

$$\theta_i = \tan^{-1} \left(\frac{1}{2f} \right) \quad (3)$$

with $f = F/d$ the lens f number, where F is the focal length and d the lens diameter. n is the cover glass index of refraction. The height of the groove, H , is also a function of the groove wall angle, and is partially determined by the size of the grid line. This is because the grid line must fit under the groove. If the grid line height is H_g and its width is W_g , then the groove height is given by

$$H = H_g + \frac{W_g}{2 \tan \theta_g} \quad (4)$$

Simultaneous solution of these equations gives the groove angle.

Figure 38 is a plot of minimum allowed grid-line spacing as a function of the groove angle with respect to the cell normal for a typical short focal length system, with an f number of 1.1. For this case, $\theta_i = 24.4^\circ$, and the incidence angle to the groove is 16° , assuming a cover glass index of 1.5. Two cases are shown. The lower curve is for grid lines typical of a concentrator cell 2-microns thick and 8-microns wide. Case 2 is for thicker, wider lines, as would be used with a grooved cover glass to take advantage of the fact that the grooves reduce obscuration.

Fig. 38 Minimum allowed groove spacing as a function of groove angle with respect to the cell normal. $f/1.1$ system.

B. Comments on Cell Grid-Line Design

Depending on the application, concentrator cells will have either parallel or radial grid-line designs. The parallel design is used in line focus systems and certain other types of cells, such as a high-voltage cell or metal-interconnected cascade cell. The radial design is used in point-focus systems. The GCG is completely compatible with parallel grid-line designs. However, point-focus cells must also employ a parallel grid-line design to be used with the grooved cover glass.

The only drawback to this is that typical radial grid designs include periodic lateral connections, to distribute current and to get around any breaks in grid lines. These lateral connections cannot be used with the GCG. These lateral connections allow the current to be spread among many grid lines. The center lines are longest and have the highest voltage drop along their length.

Consider Fig. 39, showing a parallel grid cell. The output voltage is measured at the contact bus as V_o . The lowest voltage point is V_c , at the center of the longest grid line. Shorter grid lines have voltages between V_c and V_o . The object is to minimize the power dissipated along the length of these grid lines.

While an exact calculation of the grid design is rather involved and is beyond the domain of this report, a simple, approximate calculation is appropriate to show that power losses in a linear grid design are not excessive.

Ignoring fractional grid coverage and assuming the voltage drop along the grid line is small, the ratio of the resistive power loss in a grid line to the collected power is

$$\frac{P}{P_o} = \frac{\rho S L^2 J_c^2}{24h w \eta P_i} \quad *$$

*This is derived by integrating the resistive power loss along a grid line.

Fig. 39 Parallel grid solar cell design.

where ρ is the grid-line resistivity, s the grid-line spacing, L the grid-line length, J_c the cell current density, h and w the grid-line thickness and width, η the cell efficiency, and P_i the incident power density. For a 1000-sun cell, 0.25 inches in diameter and 20% efficiency with a current density of $J_c = 30 \text{ A/cm}^2$, grid-line spacing, resistivity, and dimensions of $s = 100$ microns, $\rho = 3 \times 10^{-6} \Omega\text{-cm}$, $h = 3$ microns and $w = 15$ microns, and an incident power of $P_i = 100 \text{ W/cm}^2$, about 3.5% of the power is lost. This is the worst case for the longest grid line, so that the real power loss in the entire cell would be somewhat less.

C. Process Development

The process begins with a lacquer master identical to that used in the recording industry. The stock masters, which consist of black lacquer on aluminum, are cut into smaller 1"-diameter discs using a coring tool. Grooves are cut into this master using a heated diamond tool and a modified semiconductor dicing saw. The grooved master is then coated with aluminum in an evaporator and nickel plated. The lacquer can then be dissolved off in acetone to leave a nickel replica. The nickel replica forms the hard tool for successive replication.

The replication process involves first evaporating mannitol and then aluminum onto the master. The mannitol is a mold-release agent. The master is then removed from the evaporator and epoxy and a glass cover applied. The epoxy is the medium in which the grooves are formed. The glass cover provides a hard front surface with an antireflection coating. The process currently used to remove the metal from the flat area, leaving it only in the grooves, is to coat with photoresist, expose so as to leave photoresist in the grooves, and etch in buffered HF. The resist is then dissolved, leaving a finished cover glass with metallized grooves that can be bonded to a cell with optical cement.

Let us now review each of these process steps in greater detail.

1. The Cutting Tool

The cutting tool must meet a number of requirements.

- It must have the proper shape, including steep walls and a fine tip radius.
- It must have smooth edges to form smooth groove walls.
- It must be shaped to remove material, rather than displacing material.

During the course of the program, we have gone through several iterations in tool design before coming up with a shaped diamond tool that meets our needs. The original tool was a stainless steel scalpel blade. This meets the requirements of tip radius and wall steepness. Unfortunately, it is so soft that honing it into the proper shape is not possible without leaving the edges scratched.

This led us to try tungsten carbide, a considerably harder material. The problem here is that it is very brittle, and the tips readily crack. This led us to reject use of tungsten carbide.

We were finally able to obtain satisfactory diamond tools from Technodiamanat of Amsterdam. Figure 40 shows an electron micrograph of such a tool. The surface has been coated with metal to make it visible in the SEM; this is the surface coating seen. Note that the tip is so fine that its radius is not visible at a magnification of 2000x.

Figure 41 shows a detailed drawing of the tool shape. The tip is the lowest point, with relief behind the tip. The front cutting surface is tapered at the edges to push material out rather than dis-

Fig. 40 Electron micrograph of a diamond tool. Flaking on surface is a metal coating applied so that the tool can be seen in the electron microscope.

- DIMENSIONS IN INCHES (EXCEPT MARKED μm)

X.XX $\pm .010$

X.XXX $\pm .005$

- ANGLES $\pm 5^\circ$

- MIN. TIP EXPOSURE : $100 \mu\text{m}$

- MAX. OPERATING TEMP. : 200°C

Fig. 41 Diamond tool shape.

placing it. Figure 42 shows a groove cut with this tool. For comparison, Fig. 43 shows a groove cut with a tool that does not remove material. In the latter case, note the mounds of material to either side of the groove. The good groove has a flat transition to the surface, a fine tip radius, and smooth walls.

2. The Ruling Machine

The ruling machine is a modified Rucker and Kolls dicing saw. A number of changes have been made to this saw in order to make it suitable for this application. These include the following.

- A new stage has been added to ensure flatness over the length of the groove cut.
- The lead screw is not accurate enough to maintain the required 5-micron stepping accuracy over the width of the master. In other words, the cuts cannot wander or they will not fit over the grids. To overcome this, the microscope has been modified to give a very accurate view of the sample. In addition, photoresist lines are placed on the lacquer before ruling to act as markers for the cuts.
- A heater for the tip has been added.
- The saw has been mounted on a vibration-free table. Even small vibrations can misalign cuts.

As modified, this saw is suitable for cutting masters on 100-micron spacings. This is suitable for most concentrator solar cell grid designs.

Fig. 42 Grooves cut with the diamond tool.

Fig. 43 Groove cut with a scalpel blade which pushes aside rather than removes material.

3. Master Replication Techniques

Once the master has been ruled, it must be replicated. The replication proceeds in the following stages:

- a. metallization,
- b. nickel plating,
- c. separation, and
- d. replication.

The first three steps produce a hard nickel master. This master is then used to produce copies in epoxy. In the metallization stage, silver is evaporated on the master. This provides a conductive metal base. The metallized lacquer master is then plated with about 30 mils of nickel. The nickel is separated by dissolving the lacquer master in acetone. While this is destructive, it leaves a hard master which can be used repeatedly to form copies of the GCG.

The replication proceeds in the following manner. The master is placed in a small vacuum chamber. Using two filaments, mannitol and aluminum are evaporated on. Mannitol is a long chain alcohol with a relatively low melting point. This provides a mold-release agent. The aluminum is the base to which the epoxy sticks. The coated master is pulled from the vacuum and coated with a thin layer of epoxy. An aluminum retaining ring holds the epoxy in place. A thin glass cover, coated with a single layer of MgF, fits over the epoxy. After the epoxy sets, the assembly is peeled from the master. This results in a cover glass with a hard antireflection-coated front surface and an underside with grooves. The grooved surface is coated with aluminum.

4. Bonding to The Cell

The problem with bonding the cover directly to the cell is that if the bonding agent is index matched to the cover, then the

grooves will not reflect light. There are two solutions to this problem. The first is to metallize the insides of the grooves. The second is to use a bonding agent with an index lower than that of the cover glass, so that the grooves totally internally reflect light.

The first solution, metallization, presents the problem of how to remove the metal from the flat surface while leaving it in the grooves. Polishing has not proven a satisfactory method, because the cover is not perfectly flat. As a result, some of the grooves are removed. The only workable solution is to coat with photoresist, expose through a mask that covers the grooves, and etch the metal in HF.

An alternate solution is to use a bonding agent with a low index of refraction, so that the mismatch causes light to be reflected from the grooves. Unfortunately, this solution is not workable in all cases. For example, for a groove angle of 15° to the cell normal and an f/1 system with an extreme incidence angle of 26° to the cover glass normal, the bonding agent must have an index of refraction of 1.27, if the cover glass index of refraction is 1.5. Nevertheless, our first demonstrations of the GCG principle have been with a water interface in a solar simulator. Here, the water has an index of about 1.35 and the light is relatively collimated. The nice feature of the water is that the GCG can be removed to get a comparison of the relative advantage of using it.

Alignment of the cover glass to the cell, as it turns out, is not a problem. With large grid lines, as found on lower-concentration cells, the cover glass locks in place. In this case, alignment can be done by hand with the naked eye. With finer grid lines, as found on high-concentration cells, this locking does not take place. Here, alignment can still be done with the naked eye using Moirre patterns. These are shown in Fig. 44. When the cover is out of alignment, a set

Fig. 44 Use of Moirre patterns to align
the grooved cover glass.

of parallel bands appear across the cell. As alignment improves, these bands widen and finally disappear as the cells comes into alignment.

D. Performance Results

The grooved cover glass has been used on both a silicon cell with grid lines spaced at 1-mm intervals and a silicon cell with grid lines spaced at 100-micron intervals. In both cases, over 5% improvement in short circuit current has been obtained. To facilitate the measurement, it has been performed in a solar simulator using a water interface. This allowed easy replacement of the grooved cover glass with an identical cover glass without grooves, so that a relative measure of the benefit of the GCG could be found. Figure 45 shows the cover glass with some misalignment. The grid lines are clearly visible. As the cover glass moves into alignment, the grid lines disappear and the grid line areas take the color of the background. This is seen in Fig. 46. In this example, the grooves are 25-microns wide on 100-micron centers. The grid lines are 15-microns wide.

In both cases, about 5% improvement is found. With the 1-mm grid-line cell, the grid coverage was 10%, so we have recovered about half of the original obscuration. With the 100-micron grid-line cell, the grid coverage was 15%, and we have recovered about a third of the original obscuration. In the latter case, however, we have been able to use very wide grid lines; such a cell can be expected to have an improved fill factor as a result, providing an added benefit.

In addition, grooved cover glasses with metallized grooves have been bonded to the 100-micron grid-line cells. At the time of this writing, the metallized groove process has not been perfected sufficiently to yield a performance gain.

Fig. 45 Micrograph of the GCG on a cell
with some misalignment.

Fig. 46 Micrograph of the GCG on a cell
with alignment.

IV. CONCLUSION

This program has achieved a number of important results, proving that significant increases in cell performance can be obtained with simple modifications of the cover glass. With secondary elements, we have demonstrated the highest module efficiency (19.1%), highest ATE (0.8°), and highest concentration (1000 suns) ever obtained with flat Fresnel lenses. The performance of an optimized system (1000 suns, 18.8% module efficiency, 0.8° ATE) is the best ever obtained from any system, and that it was obtained with a flat fresnel lens and a glass element shows that high-performance, low-cost optical systems are practical. The grooved cover glass has been shown to be a workable method of reducing grid-line obscuration and allowing use of heavier grid lines, thereby buying one or two percentage points of efficiency at very little cost.

A number of significant improvements in these results are in the offing, with some additional work. For example:

- Putting a lens-shaped front surface on a cone can provide even better ATE, since off-track rays are refracted more to the normal.
- More complex shapes than the two-segment cone are possible, especially if molded rather than ground and polished elements are used.
- Lower-cost glasses, such as Pyrex or Kimax, could be used.
- The grooved cover glass provides a tool for the realization of a mechanically-stacked cascade cell. In such a cell, the top cell requires grid lines on both front and back. This increases obscuration dramatically. By using the GCG, both sets of grid lines can be put under the grooves, so that obscuration is minimized.

An inevitable question is whether a secondary cone can be coupled to a cell with a grooved cover glass. The only problem with this is that rays reflecting off the walls of the secondary enter the cell at oblique angles. Many of these rays, should they hit a groove over a grid line, would bounce out of the cell. This would tend to undo the effectiveness of the secondary cone in the off-track condition. In the on-track condition, it would also have an adverse effect if the cone was used to tailor the flux distribution at the cell.

V. REFERENCES

1. R. Winston, Solar Energy 16, 89 (1974).
2. A. Rabl, Solar Energy 18, 93 (1976).
3. See Solar Energy Handbook, Kreider and Kreith, ed., Chapters 3 & 8 (McGraw-Hill, 1981).

DISTRIBUTION LIST:

Acurex Corporation (3)
Attn: George Sutton
Bob Spencer
Dariush Rafinejad

Aerospace Corporation
Attn: Ed Simburger
2350 El Segundo Blvd.
El Segundo, CA 90266

Alliance Tool Corporation
Fresnel Optics Division
Attn: Helmut Walter
1300 Mt. Read Blvd.
Rochester, NY 14606

Applied Solar Energy Corp. (2)
Attn: Frank Ho
Ken Ling
15251 E. Don Julian Road
City of Industry, CA 91746

ARCO Power Systems
Attn: Floyd Blake
Suite 307
7061 S. University Blvd.
Littleton, CO 80122

Arizona State University (2)
Attn: Charles Backus
Robert Sanderson
College of Engineering
Tempe, AZ 85281

Ray Bahm & Associates
Attn: Ray Bahm
2513 Kimberly Court NW
Albuquerque, NM 87130

Battelle
Attn: Don Carmichael
505 King Avenue
Columbus, OH 43201

The BDM Corporation (3)
Attn: Tim Lambariski
Wayne Kauffman
Bill Schwinkendorf
1801 Randolph Road SE
Albuquerque, NM 87111

Black & Veatch
Attn: Sheldon L. Levy
P. O. Box 8405
Kansas City, MO 64114

Boeing Engineering & Const. Co.
Attn: Roger Gillette
P. O. Box 3707
Seattle, WA 98124

Burns & Roe, Inc.
Attn: G. A. Fontana
800 Kinderkamack Road
Oradell, NJ 07649

Carbone Investment
& Management Corp.
Attn: Robert C. Carbone
570 Dwight Place
Berkeley, CA 94704

Chevron Research (2)
Attn: John Cape
L. Fraas
P. O. Box 1627
Richmond, CA 94802

Cyro Industries
697 Route 476
Clifton, NJ 07015

U. S. Dept. of Energy
ALO
Attn: D. L. Krenz
P. O. Box 5400
Albuquerque, NM 87115

U. S. Dept. of Energy
Attn: John Hanson
Nuclear & Geosciences Div.
P. O. Box 5400
Albuquerque, NM 87115

U. S. Dept. of Energy (9)
Div. of PV Energy Technologies
Attn: R. Annan
A. Krantz
M. Prince
L. Herwig (5)
A. Scolaro
1000 Independence Ave. SW
Washington, DC 20585

EPRI (2)
Attn: Roger Taylor
Ed DeMeo
P. O. Box 10412
Palo Alto, CA 94303

E-Systems (3)
Attn: Mark O'Neill
A. J. McDanal
Skip Waller
P. O. Box 226118
Dallas, TX 75266

General Electric Co.
Attn: Ron Hodge
P. O. Box 527
King of Prussia, PA 19406

Graham Hatfield
8402 Magnolia, Suite H
Santee, CA 92071

Hirst Company
Attn: Carrol Cagle
P. O. Drawer 1926
Albuquerque, NM 87103

International Rectifier
Attn: Harold Weinstein
235 Kansas Street
El Segundo, CA 91214

Intersol Power Corporation (2)
Attn: John Sanders
Sid Broadbent
11901 West Cedar
Lakewood, CO 80228

Jacobs Engineering
Attn: Bob Martin
251 South Lake Ave.
Pasadena, CA 91101

Jet Propulsion Lab (3)
Attn: K. Shimada
R. Ferber
Solar Data Center
4800 Oak Grove Drive
Pasadena, CA 91109

Martin Marietta (3)
Attn: R. Hein
D. Hughes
J. Baumann
P. O. Box 179
Denver, CO 80201

McGraw Hill
607 Boylston St.
Boston, MA 02116

Microwave Associates
Attn: Joel Goodrich
South Avenue MS-116
Burlington, MA 01803

MIT/Lincoln Lab
Attn: John C.C. Fan
Box 73
Lexington, MA 02173

3M (2)
Attn: Sanford Cobb
Optical Technology Center
235 2D15
3M Center
St. Paul, MN 55144

Motorola
Attn: Keith Kingston
GED
8201 E. McDowell
Scottsdale, AZ 85252

NASA, HQ
Attn: John Loria
Code RET-1
Washington, DC 20546

New Shelter Home Magazine
9317 Shoshone
Albuquerque, NM 87111

Oak Ridge National Lab
Attn: Steve Kaplan
P. O. Box X
Oak Ridge, TN 37830

Photowatt (2)
Attn: William Taylor
Mike Keeling
2414 W. 14th Street
Tempe, AZ 85281

Power Hybrids
Attn: Jeff Meyer
1742 Crenshaw Blvd.
Torrance, CA 90501

PRC
Attn: E. Stirewalt
5201 Leesburg Pike
Suite 400
Falls Church, VA 22070

Purdue University (2)
Attn: Richard Schwartz
Mark Lundstrom
Electrical Engineering Dept.
West Lafayette, IN 47907

Quantum PV Concentrator Systems
Attn: James E. Molle
163 Verde Circle
Rohnert Park, CA 94928

Research Triangle Institute
Attn: Mayrant Simons
Box 12194
Research Triangle Park, NC 27709

SERI (3)
Attn: Gene Blakeslee
Lee Cole
John Benner
1617 Cole Blvd.
Golden, CO 80401

SERI, Library (2)
1536 Cole Blvd., Bldg. #4
Golden, CO 80401

Solar Works
Attn: Paul Wilkins
Route 2, Box 274
Santa Fe, NM 87501

Southern Cal Edison
Attn: Spencer Carlisle
2244 Walnut Grove Ave.
Rosemead, CA 91770

Spectrolab (2)
Attn: Brian Elm
Steve Olah
12500 Gladstone Avenue
Sylmar, CA 91342

Spire (4)
Attn: S. Tobin
M. Nowlan
R. Little
S. Rechteris
Patriots Park
Bedford, MA 01730

Springborn Laboratories, Inc.
Attn: Bernard Baum
Enfield, CT 06082

Star Light Energy
Attn: J. Furber
4505 Dresden St.
Kensington, MD 20895

Strategies Unlimited
201 San Antonio Circle
Suite 205
Mountain View, CA 94040

Thermo Electron
Attn: Abbot Moffat
45 First Avenue
Waltham, MA 02154

United Energy Technologies
Attn: John Mackay
420 Lincoln Center Dr.
Foster City, CA 94404

University of Wisconsin
Attn: Prof. J. D. Wiley
Dept. of Electrical Engineering
Madison, WI 53706

UNM/NMERI
Attn: G. Leigh
Campus Box 25
Albuquerque, NM 87131

Varian & Associates (2)
Attn: R. Bell
N. Kaminar
611 Hansen Way K-219
Palo Alto, CA 94303

Wright Patterson AFB
Attn: Jack Geis
AFWAL/POOC
Wright Patterson AFB, OH

Wyle Labs (2)
Attn: Dave Christenson
George Meares
7800 Governors Drive West
Huntsville, AL 35807

1133 R. Chaffin
1133 J. Wiczer
1141 R. Dawson
1142 J. Gee
1811 R. Assink
1822 J. Sweet
Attn: M. Moss, R. Pettit
1823 M. Chamberlain
1845 R. Eagan
2146 R. Nasby
2146 J. Rodriguez
2146 H. Weaver
6200 E. Beckner, Actg.
6220 D. Schueler
6221 J. Banas
6221 H. Gerwin
6223 E. Burgess
6224 E. Boes
6224 D. Arvizu
6224 L. Beavis
6224 C. Chiang
6224 M. Edenburn
6224 B. Hansen
6224 D. King
6224 A. Maish (20)
6224 M. Rios
6224 B. Rose
6224 R. Siegel
6224 C. Stillwell
3141 L. J. Erickson (5)
3151 W. L. Garner (3)
3154-3 C. H. Dalin (25)
For DOE/TIC
(Unlimited Release)
8214 M. A. Pound