899418

# THERMAL ANNEALING OF GaAs CONCENTRATOR SOLAR CELLS

H. B. Curtis D. J. Brinker
NASA Lewis Research Center
Cleveland, Ohio

## ABSTRACT

Gallium arsenide solar cells have been considered for concentrator use in space power systems for some time. Previous work has resulted in GaAs concentrator cells being irradiated with various energy electrons and their performance measured. In this paper, we discuss the thermal annealing of GaAs concentrator cells after electron irradiation. Results are given for cells annealed at 150C, 200C, and 250C. Isochronal annealing was done for 20 minute intervals up to 350C. The cells had been irradiated with electrons with energies between 0.7 and 2.3 MeV.

## INTRODUCTION

The use of concentrators for space photovoltaic power generation has been under consideration for several years. There are several reasons for the use of concentrator cells. Among them are a higher operating efficiency; a more efficient utilization of higher cost advanced solar cells i.e. multi-junction cells; and a built in shielding for hostile environments, both natural and man-made. Along with the advantages of concentrators there are some drawbacks such as a higher operating cell temperature and the optical losses of the concentrator itself. These are obviously very dependent on the concentrator design and they usually can be minimized.

There are several solar cell types which can be used for concentrators with GaAs being the general first choice. The GaAs bandgap of 1.43 eV is very near the optimum bandgap for solar cells in AMO sunlight. GaAs also exhibits a fairly low decrease in power with increasing temperature. There is some data on the radiation resistance of GaAs concentrator cells under both electron and proton irradiations [1-4]. Results include measurements at concentrated sunlight levels and typical operating temperatures (100X AMO-80C), as well as temperature coefficients for current and voltage of irradiated cells.

Since cells have a tendency to run hotter in a concentrator, the possibility of annealing the damage caused by particle irradiation becomes appealing. Thermal annealing of GaAs planar cells has been shown to be effective at temperatures as low as 150C [5]. Earlier work has suggested that continuous annealing, such as continuously operating GaAs cells at temperatures around 150C, could greatly reduce radiation degradation [6]. Recent work at Wright Aeronautical Labs [7] involved annealing GaAs cells at 250C and 300C for one hour periods after successive 1 MeV irradiations of $1x10^{16}$ e/cm$^2$. Roughly half the output was still available after $1x10^{17}$ e/cm$^2$ and 10 annealing periods. This piecemeal annealing, although not continuous, gives some experimental backing to continuous annealing. In other work at JPL, a set of 30 minute isochronal anneals on GaAs cells indicated that proton damage is annealed less than electron damage [8].

All the previous work on annealing of GaAs has been done on cells designed for one sun operation, with all performance data taken at AMO. Concentrator cells have somewhat different designs and are usually much smaller. Our earlier work [1-4] indicated there are some moderate (10%) differences in measured degradation between data at AMO and at 100X. Since we had several GaAs concentrator cells which had been irradiated with various energy electrons, we decided to initiate an annealing program with with GaAs concentrator cells at Lewis. For this paper, cells which had been irradiated with electrons with energies from 0.7 to 2.3 MeV were annealed with 20 minute isochronal anneals to 350C, and isothermally annealed at 150C, 200C, and 250C. The isothermal anneals were carried out until recovery ceased. In the case of the 150C annealing, this amounted to months of time. Future work will include radiation with protons of various energies and subsequent annealing studies.

## CELL DESCRIPTION

The GaAs concentrator cells used in this work were obtained from three suppliers, ASEC, Hughes, and Varian. The cells are all small (5x5 mm with a 4 mm dia. active area) and designed to operate near 100X AMO. They all have AlGaAs windows and junction depths of near 0.5 microns. Some of the Varian cells are n/p while all the others are p/n. The Varian and Hughes cells were supplied to NASA/Lewis as part of research contracts, while the ASEC cells were directly purchased. The Varian and ASEC cells are OM-CVD grown while the Hughes cells are LPE grown. There were a total of 24 cells which were annealed in this work. Table I shows their average electrical performance values before electron irradiation. The average efficiency of over 21% at 25C and 100X AMO indicates a quality group of GaAs cells.

Table I. Pre-irradiated electrical characteristics of the 24 GaAs concentrator cells at 25C and 100X AMO

| | Isc (mA) | Voc (V) | Fill | Eff. (%) |
|---|---|---|---|---|
| Maximum | 400 | 1.146 | .869 | 22.14 |
| Minimum | 348 | 1.085 | .774 | 19.48 |
| Average | 379 | 1.126 | .844 | 21.03 |

## EXPERIMENTAL DESCRIPTION

The GaAs concentrator cells had been irradiated with electrons in earlier work [1,4]. Varian cells, both n/p and p/n, were irradiated with electrons with energies of 0.4, 0.7, 1.0, and 2.3 MeV to $3x10^{15}$ e/cm$^2$. ASEC, Hughes, and other Varian cells, all p/n, were irradiated with 1 MeV electrons to $1x10^{16}$ e/cm$^2$. There were no cover glasses on the cells during electron irradiations. During cell performance measurements, the small area concentrator cells were individually mounted in separate cell holders. The holders consisted of a small metal base and a washer-like metal top with a beveled hole slightly larger than the illuminated area of the cell. These two pieces supply both a support for the cell and an area for the four wire electrical attachment. There was no soldering or welding of any contact to the cell.

There were two types of annealing done for this work, isochronal and isothermal. The isochronal annealing consisted of 20 minute anneals at temperatures starting at 100C and increasing to 350C in 50C intervals. Performance measurements were made at each temperature level. The isothermal annealing consisted of constant temperature anneals at temperature levels of 150C, 200C, and 250C. Performance measurements were made at increasingly longer time intervals. Total annealing time was in the thousands of hours for the 150C case.

During annealing the bare cells were in a quartz tube in a furnace with dry nitrogen flowing through the tube to prevent any oxidation of the cells. The temperature in the tube was monitored with a thermocouple and power to the furnace was adjusted for constant temperature. Performance measurements consisted of the following:

1. I-V data at 25C and one sun AMO using an X-25 xenon solar simulator and an appropriate standard cell.

2. I-V data at 25C and 100X AMO using a pulsed xenon lamp solar simulator and the linear assumption between irradiance and short-circuit current.

## RESULTS AND DISCUSSIONS

Isochronal Annealing.

Six different cells were used for the isochronal annealing study. Three n/p and three p/n Varian cells. In each polarity, one cell had been irradiated with 0.7 MeV, 1.0 MeV, and 2.3 MeV electrons respectively. The total fluence was $3x10^{15}$ e/cm$^2$ for all six cells. In the original irradiation work some cells were irradiated with 0.4 MeV electrons, but their degradation was so small they were not included in the annealing studies. Figures 1 and 2 show the results of the 20 minute isochronal annealing out to 350C for the n/p cells and the p/n cells respectively. There are several items to note in the two figures. First, the 20 minute annealing period does not produce any recovery until about 250C. Also, the recovery is fairly complete after the 300C anneal. Further annealing at 350C for 20 minutes has no effect. This may be as far as the cells can be annealed with 20 minute isochronal annealing, but it says nothing about longer annealing periods or continuous annealing.

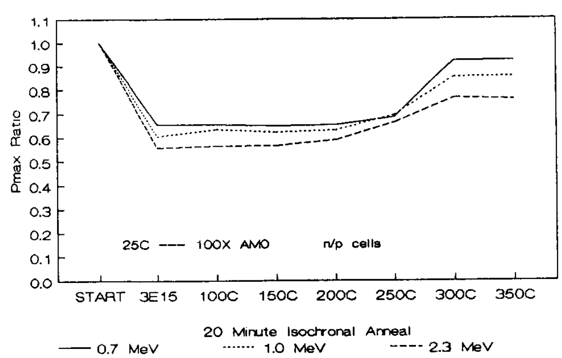


Fig. 1 Results of 20 minute isochronal annealing on Varian n/p cells irradiated with 0.7, 1.0, and 2.3 MeV electrons to 3E15.

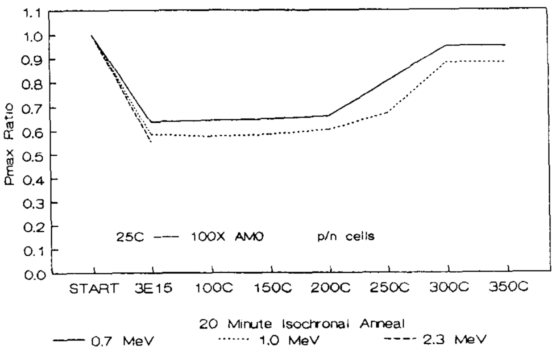


Fig. 2 Results of 20 minute isochronal annealing on Varian p/n cells irradiated with 0.7, 1.0, and 2.3 MeV electrons to 3E15.

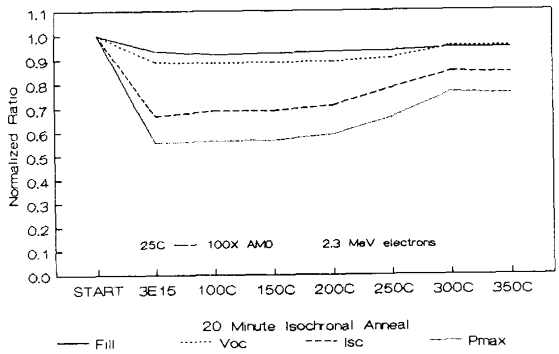


Fig. 3 Results of 20 minute isochronal annealing on one Varian n/p cell irradiated with 2.3 MeV electrons to 3E15.

The data for the p/n cell irradiated with 2.3 MeV electrons is not complete. This cell shunted during the test sequence and data was not available. Three of the 24 cells annealed during this work shunted somewhere during the test sequence. Four other cells had small partial shunts which lowered fillfactor (and hence Pmax) but left Isc and Voc unaffected. It appears clear that the source of the cell shunting is the numerous times the cell was mounted and de-mounted in its measurement holder. The top part of the holder is held down on the cell by a small pressure but GaAs cells are known to have some problems in being repeatedly handled. For the three cells which completely shunted, the data ceases, however for the four cells with small shunts, the Isc and Voc data is still available. Figure 3 shows the isochronal anneal data for Isc, Voc, Fill, and Pmax for the n/p cell irradiated with 2.3 MeV electrons. This is typical of all the cells during this work. Note that most of the degradation is in the current with a corresponding major portion of the annealed recovery is also in the current. This allows us to discuss annealing results using the current recovery on those cells which are partly shunted.

A tabular version of the results of the isochronal annealing is given in table II. (The three figures in each column are 1) I/Io or P/Po after irradiation; 2) the same data after isochronal annealing; and 3) the un-annealed fraction). The most notable feature of the data is the trend for less annealing as the electron energy increases. Most of the damage caused by the 0.7 MeV electrons can be annealed compared to about half for the 2.3 MeV electrons. There appears to be no major difference in the results of isochronal annealing between the n/p cells and the p/n cells. Future work is planned using DLTS to investigate the trap levels and help explain these trends.

Table II. Results of isochronal annealing on Varian n/p and p/n cells irradiated with 0.7, 1.0, and 2.3 MeV electrons to $3x10^{15}$ e/cm$^2$.

n/p cells

| 0.7 MeV | | 1.0 MeV | | 2.3 MeV | |
|---|---|---|---|---|---|
| Isc | Pmax | Isc | Pmax | Isc | Pmax |
| .762 | .656 | .725 | .605 | .669 | .557 |
| .981 | .921 | .925 | .853 | .848 | .764 |
| 8.0% | 23.0% | 27.1% | 37.2% | 45.8% | 53.3% |

p/n cells

| 0.7 MeV | | 1.0 MeV | | 2.3 MeV | |
|---|---|---|---|---|---|
| Isc | Pmax | Isc | Pmax | Isc | Pmax |
| .729 | .637 | .674 | .585 | .668 | .553 |
| .976 | .948 | .910 | .879 | --- | --- |
| 8.8% | 14.2% | 27.8% | 29.1% | --- | --- |

(in each column, the three data points are:
1) I/Io or P/Po after irradiation
2) The same data after annealing
3) The un-annealed fraction

Isothermal Annealing.

Based on the results of the isochronal annealing, we decided to do isothermal annealing at three temperatures, 150C, 200C, and 250C. At each temperature, a set of six cells was annealed. Each set consisted of three Varian cells, either p/n or n/p, irradiated to $3x10^{15}$ e/cm$^2$ with 0.7, 1.0, or 2.3 MeV electrons, similar to those used in the isochronal annealing. Each set also contained three other cells, irradiated with 1.0 MeV electrons to a fluence of $1x10^{16}$ e/cm$^2$. These three were made by Varian, ASEC, and Hughes. This gave us some additional annealing data on cells irradiated to a higher fluence. At each temperature, the cells would be removed for performance measurements at increasing time intervals. Measurements were made after total annealing times of: 20 min, 80 min, 3 hr, 9 hr, 27 hr, 81 hr, 243 hr, 729 hr, and 1326 hr. For the 250C case, annealing was finished at 81 hours, and no further annealing was done. At 200C, the cells are essentially finished after 1326 hours. We are continuing the 200C anneal out to 2187 hours for final data. At 150C, annealing has just started after 729 hours and the experiment is continuing.

The results of the isothermal annealing are summarized in tables III and IV. Table III has data for the Varian cells irradiated with 0.7, 1.0, or 2.3 MeV electrons out to $3x10^{15}$ e/cm$^2$, while table IV is for the cells irradiated with just the 1.0 MeV electrons out to $1x10^{16}$ e/cm$^2$. (As in table II the three figures in each column are 1) I/Io or P/Po after irradiation; 2) the same data after isothermal annealing; and 3) the un-annealed fraction).

By comparing the un-annealed fractions for the cells annealed at 250C or 200C with the isochronal anneal data, we note that the cells have about the same amount of recovery. For example, consider the cells irradiated with 0.7 MeV electrons. For the isochronal annealing, the un-annealed fractions for Pmax were about 14% and 23% (table II), while for the isothermal annealing, they were 15% and 25% (table III). Similar comparisons can be made for the cells irradiated with 1.0 and 2.3 MeV electrons. This implies that there may be a limit to how much recovery can be obtained with post-irradiation annealing.

For the data in table IV, all the cells were irradiated with 1 MeV electrons to a larger fluence of $1x10^{16}$ e/cm$^2$. However, even though they started recovery at a deeper degradation than the isochronal annealed cells ($3x10^{15}$ e/cm$^2$), the un-annealed fractions, both for Isc and Pmax, are very similar. For example the Isc un-annealed fractions for the isochronal annealed 1 MeV (3E15) cells are approximately 27% and 28%, while for the isothermal annealed 1 MeV cells (1E16) they are 17%, 25%, 26%, 26%, 27% and 30%. This implies that any limit to post-irradiation annealing recovery may be independent of fluence level.

Isothermal annealing was done at three temperatures, 250C, 200C, and 150C. It is reasonable to assume that annealing at higher temperatures will bring on recovery quicker. This is indeed the case. Figure 4 shows Pmax recovery for three cells annealed at 250C. Since some of the cells in the 250C portion of the experiment had shunting problems, the data in figure 4 is for cells irradiated to different fluences. The lower two curves are for cells irradiated with 1 MeV electrons to $1x10^{16}$ while the upper curve is for a cell irradiated with 0.7 MeV electrons to $3x10^{15}$ e/cm$^2$. Note that the annealing is essentially complete after the 27 hour point, and further annealing to 81 hours has little effect.

Table III. Results of isothermal annealing at 250C, 200C, and 150C on Varian n/p and p/n cells irradiated with 0.7, 1.0, and 2.3 MeV electrons to $3x10^{15}$ e/cm$^2$.

250C -- p/n cells

| 0.7 MeV | | 1.0 MeV | | 2.3 MeV | |
|---|---|---|---|---|---|
| Isc | Pmax | Isc | Pmax | Isc | Pmax |
| .806 | .690 | .755 | .632 | .539 | .448 |
| .987 | .922 | --- | --- | --- | --- |
| 6.8% | 25.2% | --- | --- | --- | --- |

(Annealing complete at 81 hours)

200C -- n/p cells

| 0.7 MeV | | 1.0 MeV | | 2.3 MeV | |
|---|---|---|---|---|---|
| Isc | Pmax | Isc | Pmax | Isc | Pmax |
| .782 | .659 | .735 | .598 | .661 | .523 |
| .997 | .949 | .958 | .864 | .840 | .738 |
| 1.2% | 14.9% | 16.0% | 33.8% | 47.2% | 55.0% |

(Annealing nearly complete after 1326 hours)

150C -- n/p cells

| 0.7 MeV | | 1.0 MeV | | 2.3 MeV | |
|---|---|---|---|---|---|
| Isc | Pmax | Isc | Pmax | Isc | Pmax |
| .778 | .661 | .706 | .601 | .666 | .536 |
| .810 | --- | .733 | .617 | .762 | .623 |
| 85.7% | --- | 91.0% | 96.0% | 71.1% | 81.4% |

(Annealing just starting after 729 hours)

(in each column, the three data points are:
1) I/Io or P/Po after irradiation
2) The same data after annealing
3) The un-annealed fraction

Table IV. Results of isothermal annealing at 250C, 200C, and 150C on Varian, ASEC, and Hughes p/n cells irradiated with 1.0 MeV electrons to $1x10^{16}$ e/cm$^2$.

250C

| Varian | | ASEC | | Hughes | |
|---|---|---|---|---|---|
| Isc | Pmax | Isc | Pmax | Isc | Pmax |
| .525 | .427 | .288 | .224 | .414 | .305 |
| .883 | .836 | .814 | --- | .823 | .706 |
| 24.7% | 28.7% | 26.1% | --- | 30.3% | 42.3% |

(Annealing complete at 81 hours)

200C

| Varian | | ASEC | | Hughes | |
|---|---|---|---|---|---|
| Isc | Pmax | Isc | Pmax | Isc | Pmax |
| .483 | .381 | .268 | .209 | .411 | .307 |
| .913 | .833 | .810 | --- | .841 | --- |
| 16.9% | 27.0% | 26.0% | --- | 26.9% | --- |

(Annealing nearly complete after 1326 hours)

150C

| Varian | | ASEC | | Hughes | |
|---|---|---|---|---|---|
| Isc | Pmax | Isc | Pmax | Isc | Pmax |
| .514 | .415 | .385 | .307 | .440 | .320 |
| .674 | .548 | .427 | .351 | .500 | .383 |
| 67.0% | 77.2% | 93.1% | 93.7% | 89.2% | 90.7% |

(Annealing just starting after 729 hours)

(in each column, the three data points are:
1) I/Io or P/Po after irradiation
2) The same data after annealing
3) The un-annealed fraction

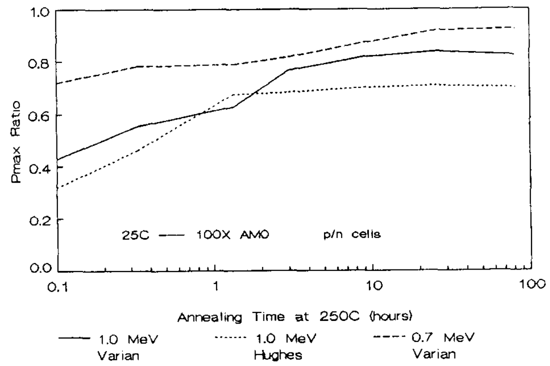


Fig. 4 Results of 250C isothermal annealing on two cells irradiated with 1 MeV electrons to 1E16 and one cell irradiated with 0.7 MeV electrons to 3E15.

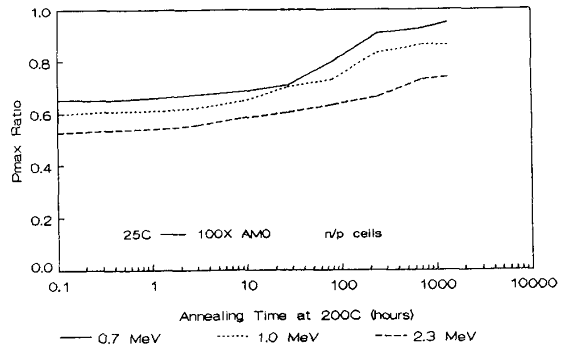


Figure 5 Results of 200C isothermal annealing on Varian n/p cells irradiated with 0.7, 1.0, and 2.3 MeV electrons to 3E15.

For the 200C annealing, more time is required to obtain recovery. Figure 5 shows normalized Pmax as a function of annealing time at 200C for the Varian cells irradiated with three different electron energies. Most of the recovery occurs between about 10 and 200 hours. However there is more annealing even out to 1326 hours (the last data point), and we are continuing to anneal at 200C.

At 150C, it appears that quite a bit of time is required for annealing to take place. Figures 6 and 7 both show annealing results at 150C. Figure 6 shows normalized Pmax vs. annealing time for the three cells irradiated to $1 \times 10^{16}$ with 1 MeV electrons. There is starting to be some recovery, especially in the Varian cell where the un-annealed fraction has been reduced to about 77%. The last data point is at 729 hours and annealing is in progress to 2187 hours (about 3 months). Figure 7 shows the normalized Isc ratio for three Varian cells irradiated to $3 \times 10^{15}$ with different energy electrons. Again, we are starting to see some annealing, especially in the cell irradiated with 2.3 MeV electrons. There is no apparent reason for this, especially since the isochronal data and the isothermal data at 250C and 200C seems to indicate less annealing for cells irradiated with higher energy electrons. A comparison of the annealing at each of the three temperatures is given in figure 8. The Pmax ratio is plotted for three similar Varian cells irradiated with 1 MeV electrons to $1 \times 10^{16}$. The annealing at longer times for lower temperatures is quite evident.

If we do get significant annealing at 150C, the annealing time will be too long to be practical. There are no spacecraft which can wait months to anneal their arrays. What could be very beneficial is real time continuous annealing as described in ref. 6. In this case, the cells are operated from the very beginning at their lowest annealing temperature such as 150C, and a continuous annealing occurs

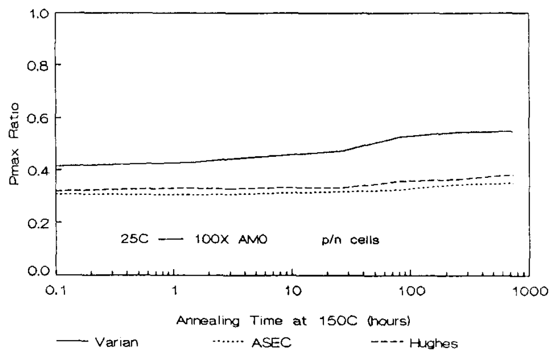


Figure 6 Results of 150C isothermal annealing on three p/n cells irradiated with 1 MeV electrons to 1E16.

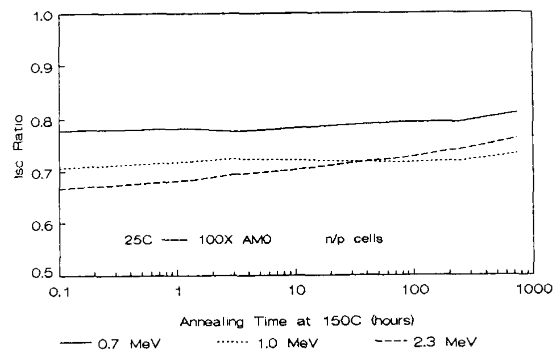


Figure 7 Isc ratios for Varian n/p cells irradiated with 0.7, 1.0, and 2.3 MeV electrons to 3E15 annealed at 150C.

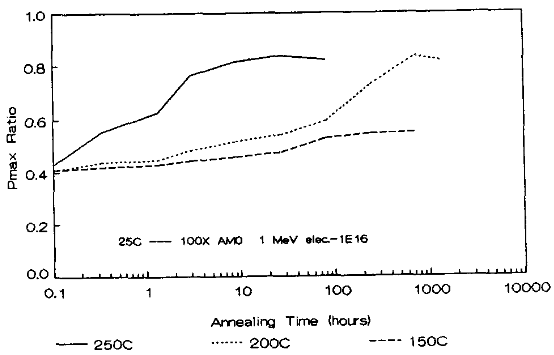


Figure 8 Comparison of Pmax annealing for three cells irradiated with 1 MeV electrons to 1E16 at 250C, 200C, and 150C.

side-by-side with the radiation induced degradation. What we have shown in this paper is the ability of GaAs concentrator cells to recover most of the electron induced degradation by a post-irradiation annealing at 200C and perhaps at 150CC in a time period of months. The time required to reach the degradation levels involved in this work in space is several years, depending on the orbit. This slow degradation rate of cells in space is at the heart of the argument for continuous annealing. Even though the annealing is slow, it happens as fast as the induced degradation, hence complete or near complete annealing occurs. Operating temperatures of near 150C can readily be achieved in concentrator arrays, and continuous annealing may be possible.

For continuous annealing to be proven successful, several questions must be answered. Among them are:

1) The annealing characteristics of proton induced damage.

2) The annealing effects of irradiating cells in the lab at the annealing temperature.

3) The annealing effects when the cells are irradiated at temperature with a flux similar to those encountered in space (typically several orders of magnitude slower than lab experiments).

We intend to look at the first two items in future work. Due to the long term nature of the third item, there are no practical experiments which can be performed using particle accelerators. A final answer to the feasibility of continuous annealing may require a flight test, probably in the radiation belts.

## SUMMARY

We have performed isochronal and isothermal annealing tests on GaAs concentrator cells which had been irradiated with electrons of various energies to fluences up to $1x10^{16}$ e/cm$^2$. The results include:

1) For cells irradiated with electrons from 0.7 to 2.3 MeV, recovery decreases with increasing electron energy.

2) As determined by the un-annealed fractions, isothermal and isochronal annealing produce the same recovery. Also, cells irradiated to $3x10^{15}$ or $1x10^{16}$ e/cm$^2$ recover to similar un-annealed fractions.

3) We are starting to see some significant annealing at 150C although very long times are required.

## REFERENCES

[1] H. B. Curtis and C. K. Swartz, "Performance of GaAs and Silicon Concentrator Cells Under 1 MeV Electron Irradiation", 18th PVSC, pp. 356-361: Oct. 1985.

[2] H. B. Curtis and C. K. Swartz, "Performance of GaAs and Silicon Concentrator Cells Under 37 MeV Proton Irradiation", 19th PVSC, pp. 664-668: May 1987.

[3] H. B. Curtis and R. E. Hart Jr., "Temperature Coefficients for Concentrator Cells at Various Electron and Proton Fluence Levels", 23rd IECEC, Vol. 3, pp 85-89: Aug. 1988.

[4] H. B. Curtis and R. E. Hart Jr., "Performance of GaAs Concentrator Cells Under Electron Irradiations from 0.4 to 2.3 MeV", 20th PVSC, Vol. 2, pp 1020-1023: Sept. 1988.

[5] R. Loo, R. C. Knechtli, and G. S. Kamath, "Enhanced Annealing of GaAs Solar Cell Radiation Damage", 15th PVSC, pp 33-37: May 1981

[6] J. H. Heinbockel, E. J. Conway, and G. H. Walker, "Simultaneous Radiation Damage and Annealing of GaAs Solar Cells", 14th PVSC, pp 1085-1089: Jan. 1980.

[7] M. A. Chung et al, "Electron Radiation and Annealing of MOCVD GaAs and GaAs/Ge Solar Cells", 20th PVSC, pp. 924-929: Sept. 1988.

[8] B. E. Anspaugh and R. G. Downing, "Damage Coefficients and Thermal Annealing of Irradiated Silicon and GaAs Solar Cells", 15th PVSC, pp 499-505: May 1981.