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# ANNEALING OF IRRADIATED n+p InP BURIED HOMOJUNCTIONS

R.J. Walters and G.P. Summers
U.S. Naval Research Laboratory
Washington, DC

and

M.L. Timmons, R. Venkatasubramanian, J.A. Hancock, and J.S. Hills
Research Triangle Institute
Research Triangle Park, North Carolina

## INTRODUCTION

At the last SPRAT conference, the Naval Research Laboratory (NRL) presented results from two experiments. One studied $n^+p$ diffused junction (DJ) InP solar cells (ref. 1), and the other studied $n^+p$ shallow homojunction (SHJ) InP mesa diodes grown by metalorganic chemical vapor deposition (MOCVD) (ref. 2). The former work showed that a DJ solar cell in which the maximum power ($P_{max}$) had been degraded by nearly 80% under irradiation recovered completely under short circuit illumination at 450K (fig. 1). The recovery was accompanied by the removal of all but one of the radiation-induced defect levels (fig. 2). The latter work, on the other hand, showed that the radiation-induced defects in the SHJ diodes did not anneal until the temperature reached 650K (fig 3). These results suggest that an irradiated DJ solar cell, under illumination, will anneal at a temperature 200K lower than an irradiated SHJ cell. This is an unexpected result considering the similarity of the devices. The goal of the present research is to explain this different behavior.

This paper investigates two points which arose from the previous studies. The first point is that the DJ cells were annealed under illumination while the SHJ diodes were annealed without bias. Given the known sensitivity of radiation-induced defects in InP to minority carrier injection-annealing (ref. 3), it is possible that the illumination is the cause of the lower annealing temperature. To test this, irradiated SHJ InP solar cells of the same structure as the diodes of ref. 2 have been annealed under illumination at temperatures ranging from 300-500K. The results of these experiments are presented here. The conclusion is that the illumination had no effect on the annealing, and the annealing follows that which was expected from the diode study of ref. 2 - i.e. the recovery is limited by a lack of defect annealing in this temperature range.

The second point investigated here is that the emitters of the DJ and SHJ devices were significantly different. The emitter of the DJ cells of ref. 1 were thick (0.3$\mu$m) and grown by diffusion which forms a graded carrier concentration profile. However, the emitter of the SHJ diodes of ref. 2 and cells studied here were thin (0.03$\mu$m) with a uniform carrier concentration profile. The thicker emitter means the DJ emitter current is much larger than that of the SHJ cells. Also, the different concentration profiles results in different spacial distributions of the junction electric field. These differences may impact the solar cell annealing characteristics. To investigate this, the Research Triangle Institute (RTI), under contract to NRL, used MOCVD to grow epitaxial cells with the structure of the DJ cells. The cells have a 0.25$\mu$m thick emitter with a graded dopant profile (fig. 4). The cells are referred to as deep homojunctions (DHJ). The growth of these cells is the subject of a companion paper given by RTI at this conference. The present paper reports the annealing characteristics of the DHJ cells following irradiation. Results of annealing both in the dark and under illumination in the temperature range of 175K-450K are presented. In general, the annealing characteristics of the DHJ cells was similar to that of the SHJ cells especially in terms of the defect spectrum. However, significantly more recovery of the short circuit current ($I_{sc}$) was seen in the DHJ cells than in the SHJ cells. Therefore, the thicker, graded emitter seems to enhance the recovery of $I_{sc}$, but the overall cell recovery is incomplete due to a lack of defect annealing just as in the case of the SHJ cells.

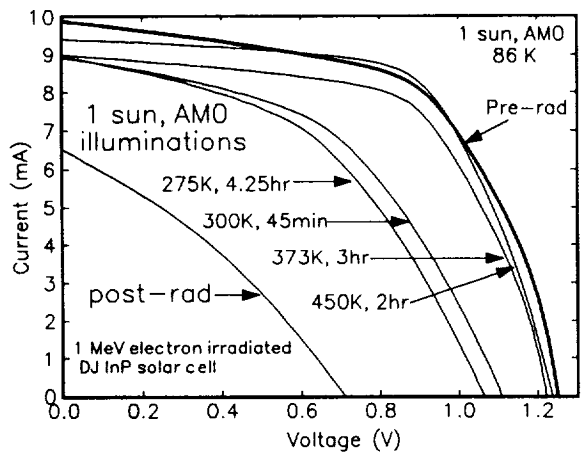



Figure 1: Photo-injection annealing of an irradiated DJ solar cell. Illumination at 275K causes substantial recovery, and full recovery is seen at 450K.

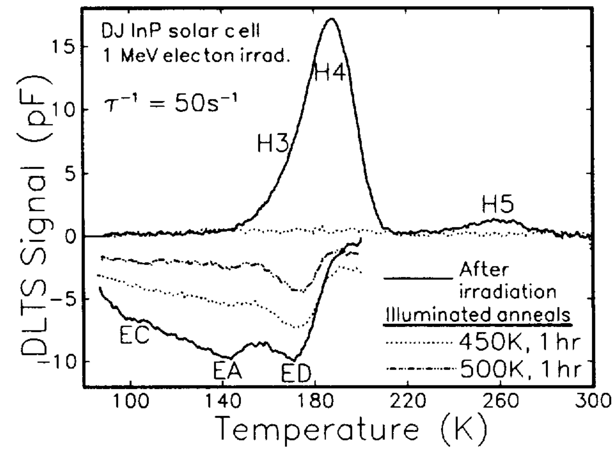



Figure 2: The defect annealing measured in the DJ cell of fig. 1. The illumination at 450K removed all but the ED defect.

## EXPERIMENTAL DETAILS

Data measured on two $n^+p$ SHJ solar cells are presented. One cell was annealed in the dark, and the other was annealed under illumination. The data for the cell annealed in the dark has already been published in ref. 4, but the data is reproduced here to allow for direct comparisons. This cell was grown using MOCVD by Spire Corporation under contract to NRL and has the structure of fig. 5. The cell was part of run number 5414-7-1. Si was the emitter dopant, and Zn was the base dopant. The total cell area was $0.25cm^2$ and BOL PV parameters were: $I_{sc}$=8.78mA, $V_{oc}$=0.883V, $P_{max}$=6.48mW, FF=0.836, Eff=18.95% (total area). The cell was 10 MeV proton irradiated up to a fluence of $10^{12}$ $cm^{-2}$. Dosimetry was achieved through a faraday cup and current integrator circuit, and the fluence is known to within about 15%. Capacitance vs voltage (CV) measurements on a diode grown on the same wafer as the solar cell and irradiated simultaneously

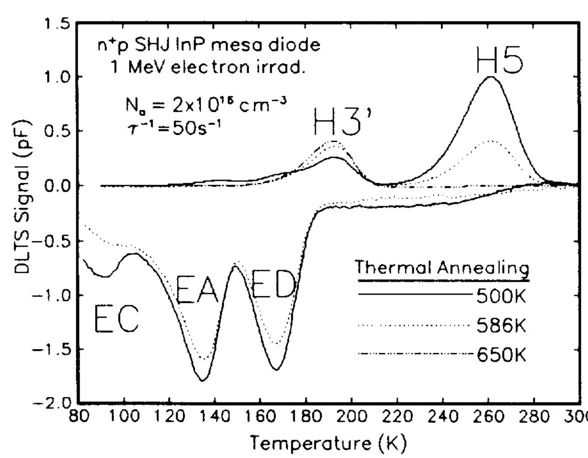



Figure 3: Annealing of an irradiated $n^+p$ SHJ diode. Only the H3 and H4 defects anneal below 500K. Not until 650K do the remaining defects anneal which is 200K higher than in the DJ cells (ref. 2).

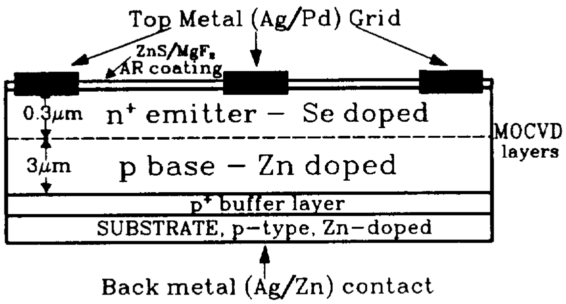



**Figure 4:** A schematic drawing of the DHJ cells grown by RTI. These are epitaxial cells grown to simulate the DJ cell structure, so the emitter is thick with a linearly graded dopant profile.

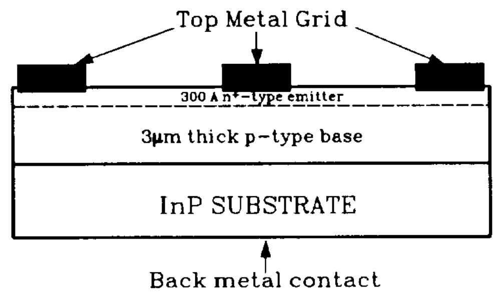
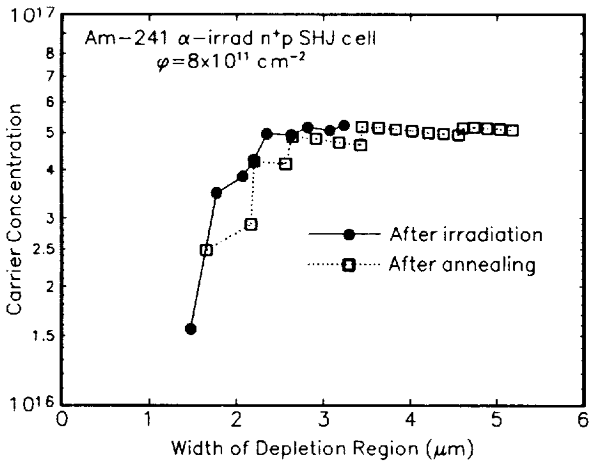



**Figure 5:** A schematic diagram of the $n^+p$ SHJ cells. The emitter of these cells is thin with a uniform carrier concentration profile. This is the same structure as the mesa diodes of ref. 2.

with the cell showed the base dopant concentration to be a uniform $10^{16}$ $cm^{-3}$ before and after irradiation.

The second $n^+p$ SHJ solar cell studied here (the cell which was annealed under illumination) was also grown using MOCVD by Spire Corporation. This cell came from run number 2353-1-1. The cell structure was also that of fig. 5. Se was the emitter dopant, and Zn was the base dopant. The total cell area was $0.25cm^2$ and BOL PV parameters were: $I_{sc}$=7.32mA, $V_{oc}$=0.850V, $P_{max}$=4.927mW, FF=0.792, Eff=14.4% (total area). The cell was irradiated with alpha ($\alpha$) particles from an Am-241 source. A special acknowledgement goes to Dr. Pascale Gouker of Spire for performing the irradiations and supplying NRL with this cell. The cell was irradiated up to a fluence of $8\times10^{11}$ $\alpha$-particles/$cm^2$ which is equivalent to $5\times10^{16}$ 1 MeV electrons/$cm^2$ (the calculation of the 1 MeV electron equivalent fluence was done by E.A. Burke formerly of Spire). No pre-irradiation CV measurements of this cell were possible, but the target base carrier concentration was a uniform $5\times10^{16}$ $cm^{-3}$. CV measurements were performed on the cell after irradiation. The irradiation caused carrier removal near the junction (fig. 6).

Two of the RTI DHJ cells were studied. These cells came from RTI MOCVD run numbers 1955-a1 and 1955-a4. The total cell area was $0.25cm^2$. Due to metal contact shadowing on top of the cells, the active area was $0.16cm^2$. BOL PV parameters were: cell 1955-a1 - $I_{sc}$=4.82mA, $V_{oc}$=0.833V, $P_{max}$=3.32mW, FF=0.828, Eff=15.2% (active area) and cell 1955-a4 - $I_{sc}$=4.85mA, $V_{oc}$=0.841V, $P_{max}$=3.40mW, FF=0.834, Eff=15.6% (active area) . The cells were irradiated with 3 MeV protons at the Naval Surface Warfare Center (NSWC) in White Oak, MD using a Pelletron Accelerator. The samples were mounted on a grounded plate, and the fluence was determined by measuring the target plate current. Unfortunately, due to incomplete charge collection and an obscuring aperture in the beam line which was not accounted for, the dosimetry was poor. The best guess at the fluence is $6.12\times10^{11}$ $cm^{-2}$, but this could be off by as much as 40%. The cells were mounted and irradiated separately. The beam



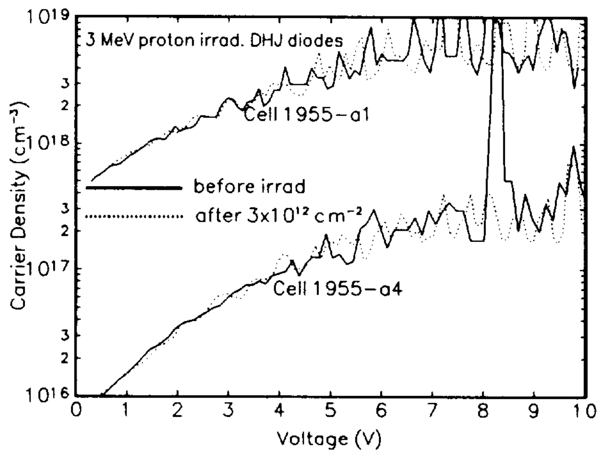




**Figure 6:** The carrier concentration profile of Spire cell 2353-1-1 after irradiation and after annealing. Carrier removal occurred near the junction, and the annealing had no effect.

**Figure 7:** Carrier concentration profiles of the two DHJ cells studied here. The irradiation had no affect on the concentration. The inset scale indicates the depth relative to the junction.

current was $\leq$ 22 nA/cm$^2$, and the irradiations were completed in a matter of seconds. The irradiations were done in vacuum, at open circuit, and in the dark. CV measurements on diodes grown adjacent to the cells before irradiation showed the base dopant concentration of cell 1955-a1 to be about $3\times10^{18}$ cm$^{-3}$ and of cell 1955-a4 to be about $10^{17}$ cm$^{-3}$, but both profiles were somewhat graded (fig. 7). These diodes were irradiated simultaneously with the cells with no effect on the carrier concentration.

The solar cells were mounted in a continuous flow liquid nitrogen cryostat which is equipped with a sapphire window to allow for illumination. The temperature range of the cryostat is 86 - 500K. All of the experiments were performed using the cryostat including the annealing experiments. The chamber was under constant vacuum. An Oriel 1000W Xe arc lamp solar simulator with AM0 filtering was used. The lamp intensity was adjusted to one sun using an InP reference cell calibrated by Keith Emery at NREL. Illuminated IV curves were measured using two Keithly 617 electrometers and a Kepco 50-2M bipolar amplifier. The radiation-induced defect spectrum was characterized through deep level transient spectroscopy (DLTS). A Bio-Rad DL4600 spectrometer with a Boonton 72-B capacitance meter was used. The reverse bias for every DLTS measurement was -2V. A saturation fill pulse was consistently used to ensure complete trap filling. The same capacitance meter was used for the CV measurements.

## EXPERIMENTAL RESULTS

### Thermal Annealing of a SHJ cell in the Dark

One of the goals of this report is to compare the annealing characteristics of SHJ InP solar cells which have been annealed in the dark with those which have been annealed under illumination. NRL and Spire have published thermal annealing in the dark data in ref. 4, and that data is now reproduced for comparison purposes. It should be noted that a similar experiment has been performed at NRL on a 1 MeV electron irradiated Spire MOCVD grown $n^+p$ SHJ InP solar cell which showed similar results.

Following irradiation with 10 MeV protons up to a fluence of $10^{12}$ $cm^{-2}$, cell 5414-7-1 was thermally annealed at 415 and then 500K. The cryostat was completely dark and no connections were made to the cell during the annealing. At 415K, the cell was annealed in incremental time steps beginning with 15 minutes and ending after 3 hours. After 3 hours at 415K, no further changes were observed, so the temperature was raised to 500K. The cell was again annealed in incremental time steps beginning with 15 minutes and ending after 1 hour and 15 minutes. After each time increment, the illuminated IV curve was measured at 298K (fig. 8). Also, both the majority and minority carrier trap DLTS spectra were measured after each time step (fig. 9). With the present DLTS system, a positive DLTS signal indicates majority carrier capture while a negative signal indicates minority carrier capture.

Considering the annealing at 415K, the only recovery of the PV parameters occurred after the first 15 minutes. The recovery consisted mainly of an increase in $I_{sc}$ (about a 3.5% increase). The recovery of $V_{oc}$ and the FF was 1% or less. The first 15 minutes at 415K also caused a small decrease in the concentration of all of the hole traps (fig. 9). The ED peak just become visible due to the decrease in the obscuring H3 peak. The continued annealing at 415K caused the complete removal of the H3 and H4 defects. Increasing the temperature to 500K caused another increase in $I_{sc}$, a very small one in $V_{oc}$, but none in FF. No changes in the DLTS spectra were seen. In total, the recovery was minimal - $P_{max}$, which was degraded by 25%, only recovered by 9.4%, and only the H3 and H4 defects showed annealing.

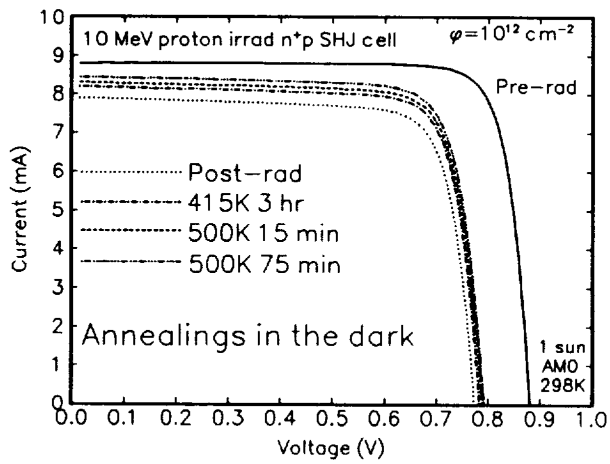
### Thermal Annealing of a SHJ cell Under Illumination

One of the missing pieces in the current discussion is a study of the annealing of an irradiated SHJ cell under illumination. This data is now presented. Following the $\alpha$-particle irradiation, Spire $n^+p$ SHJ InP solar cell number 2353-1-1 was illuminated short circuit at 350, then 400, and then 500K. As in the previous experiment, the annealing was carried out for progressively longer times at each temperature until no more changes were apparent. The temperature was then increased and the annealing repeated. After each time step, an illuminated IV curve was measured at 298K along with the full DLTS spectrum. The recovery of the IV curves is shown in fig. 10. The DLTS spectra are shown in fig. 11.

The illuminations at 350K had no effect on the IV curve or the DLTS spectrum. At 400K, all of PV parameters recovered a small amount except the FF which showed no change. Raising the temperature of illumination to 500K caused another moderate rise in $V_{oc}$, but $I_{sc}$ and the FF did not show an increase. Overall, the IV curves showed only minimal recovery. In particular, the complete lack of increase in the FF significantly suppresses $P_{max}$. These results are similar in nature to the DLTS results. Illumination at 350K had no effect on the defect spectrum. At 400K, the H3 and H4 defects were completely removed, and at 500K, the H3' defect emerged (ref. 2). No other defect reactions were observed. The recovery of the IV curves is minimal and only two of the 6 radiation-induced defects show annealing stages.

### Annealing of a DHJ Under Illumination

The second part of this study investigated the effect of the emitter structure on the annealing properties of irradiated InP solar cells. The first data set to be presented is the annealing of the RTI grown DHJ cell #1955-a4 under short circuit illumination. Since irradiated DJ cells showed substantial recovery due to short circuit illuminations below room temperature (ref. 1 and figs. 1 and 2), the first experiments were below room temperature illuminations. Initially, it was established through DLTS



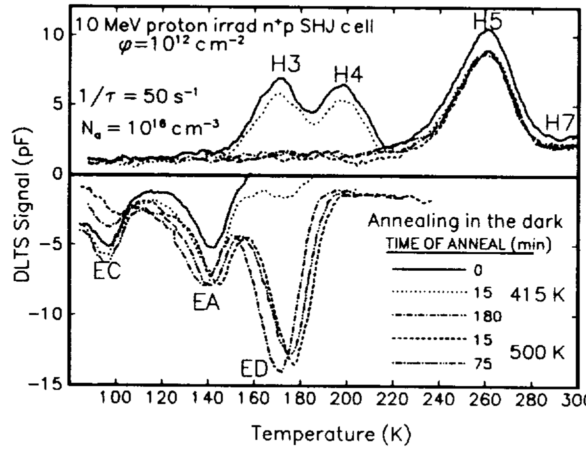
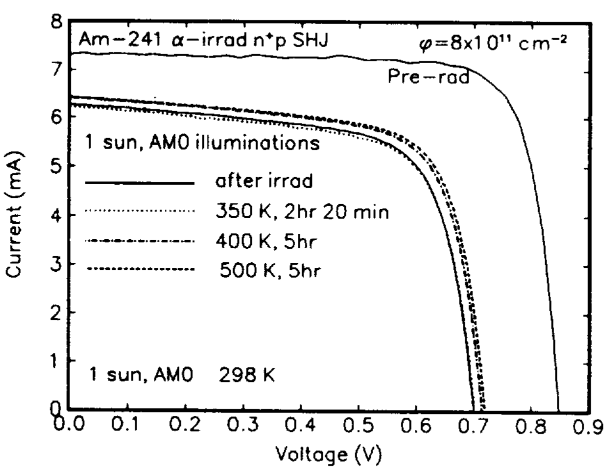




**Figure 8:** Thermal annealing in the dark of Spire cell 5414-1-7. Even at 500K, only limited recovery is seen especially in $V_{oc}$ and the FF.

**Figure 9:** Defect annealing in the SHJ cell of fig. 8. Only the H3 and H4 defects anneal. Increase in negative signal is due to the removal of the positive signal and not an increase in defect concentration.



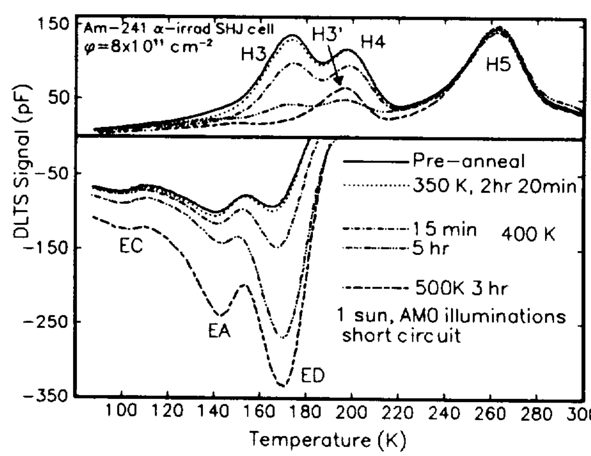




**Figure 10:** Illuminated thermal annealing of the α-irradiated SHJ cell. Only moderate annealing occurs even after 5 hrs at 500K. The lack of recovery in FF suppresses $P_{max}$.

**Figure 11:** The defect annealing in the cell of fig. 10. As seen during thermal annealing in the dark, only the H3 and H4 defects show any annealing stages.

measurements that illuminated IV measurements at 86K did not cause annealing. Then the cell was held at 175K and illuminated short circuit for 1 hour. A subsequent illuminated IV measurement at 86K showed no change (fig. 12). A subsequent DLTS measurement also showed no change (fig. 13) which is a very unexpected result because independent of PV recovery, the H4 defect has always shown annealing at temperatures of 175K and above (1-5).

Following the 175K experiment, cell 1955-a4 was illuminated short circuit at 300K and above. As shown in fig. 13, illumination at 300K did cause the familiar reduction of the H4 peak height. The H5 peak is seen to grow concurrently which is characteristic of the SHJ cells, but not the DJ cells (refs. 1,2, and 5). A very small recovery stage of the PV parameters may be apparent (fig 14 -note that since the annealing temperature is 300K or larger, the IV measurements were taken at 298K). Illumination at 375K caused significant recovery in the IV curves, and illumination at 450K caused even more recovery which lead to complete recovery of $I_{sc}$. However, the recovery of $V_{oc}$ is quite limited. The changes in the DLTS spectra are shown in fig. 13. The illuminations only affected the H3 and H4 defects which is very similar to the SHJ cell results.

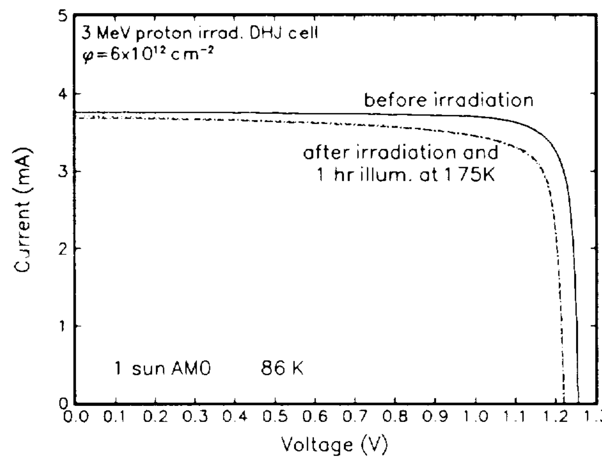
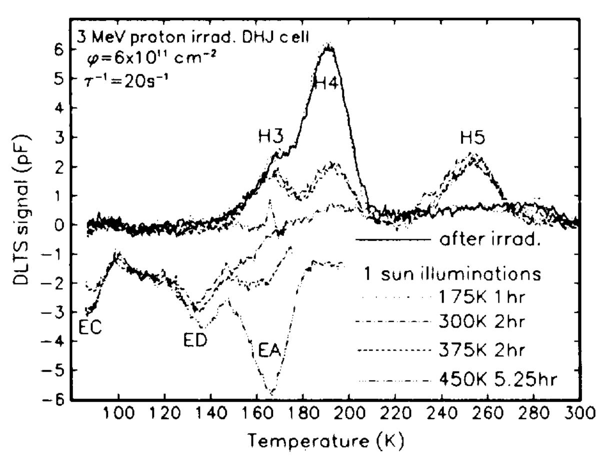



**Figure 12:** Low temperature illumination of RTI DHJ cell 1955-a4. One hour of short circuit illumination at 175K causes no recovery. IV curves measured at 86K to avoid annealing during the measurement.



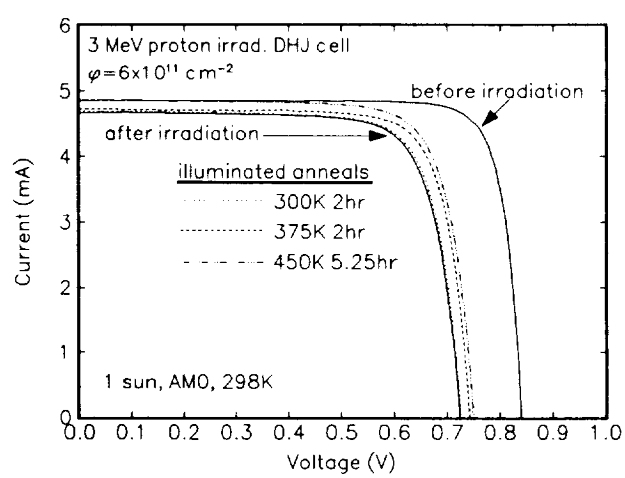




**Figure 13:** Illumination of RTI DHJ cell 1955-a4. At 175K, annealing of the H4 defect was expected but not seen. Above 300K, only the H3 and H4 defects anneal while the H5 peak grows.

**Figure 14:** Continued illumination of RTI DHJ cell 1955-a4 at T≥300K. Some recovery seems evident at 300K. $I_{sc}$ completely recovers at 450K. $V_{oc}$ limits the cell recovery.

### Thermal Annealing of a DHJ in the Dark

The final data sets to be presented are the thermal annealing of an irradiated DHJ cell in the dark. The DHJ cell #1955-a1 was annealed in the dark (and unbiased) at 375 and 450K. Initially, the cell was illuminated at 300K to ensure all room temperature annealing stages were complete. The recovery of the cell is shown in fig. 15. All of the PV parameters recovered with $I_{sc}$ recovering the most. The effect on the DLTS spectrum is shown in fig 16. The annealing removed H3 and H4 but did not affect the remaining defects. These results follow the same trends as the illuminated annealing data.

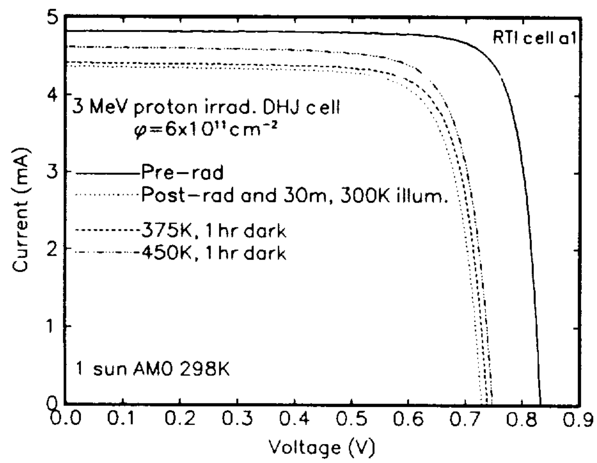



**Figure 15:** The effect of thermal annealing in the dark on RTI DHJ cell 1955-a1. The recovery stages are similar to those seen during the illuminated annealing of cell 1955-a4.

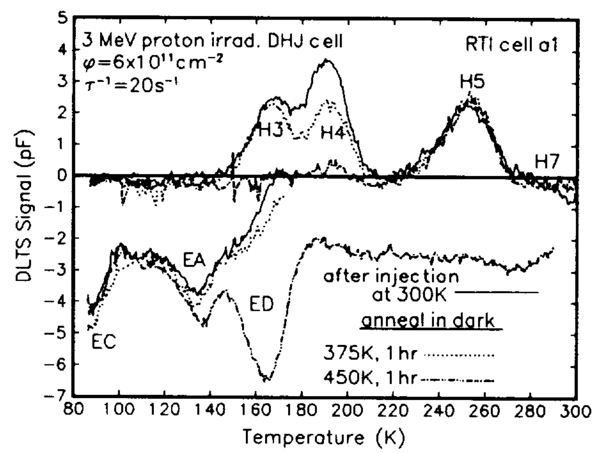



**Figure 16:** The effect thermal annealing in the dark on RTI DHJ cell 1955-a1. Basically the same defect reactions are seen as in the illuminated annealing of cell 1955-a4.

## DISCUSSION

The first question under investigation was - would illuminating an irradiated SHJ cell above room temperature enhance the cell annealing characteristics ? The answer is no. Essentially the same amount of annealing of the PV parameters was seen following annealing under illumination and in the dark, and the recovery is far from complete. Furthermore, the residual defect spectra measured at the end of both annealing experiments are essentially the same. As was predicted by the results of ref. 2, very little solar cell recovery is seen in the SHJ cells after annealing at temperatures below 500K, regardless of the illumination.

These results provide a better understanding of the cause of the different annealing behavior in DJ and SHJ solar cells. In a DJ cell, illumination at 450K removed all of the radiation-induced defects from the cell junction except for the electron trap, ED, which only partially annealed after 2 hours at 450K. In a SHJ cell, on the other hand, below 500K, none of the defects show annealing stages except the H3 and H4 defects. These two defects are removed in the range of 375-450K, but all others remain.

Therefore, the enhanced annealing evident in the DJ solar cells can be attributed, at least in part, to the enhanced defect annealing in the cell junction. Considering these results with those of ref. 2, it is expected that the defects in the junction of a SHJ cell will anneal if the temperature is raised to 650K. Therefore, it may be concluded that a SHJ solar cell will show complete recovery after annealing at 650K. If this is the case, then it can also be concluded that, irradiated $n^+p$ InP solar cells grown by S diffusion will completely recover at a temperature which is 200K lower than an irradiated $n^+p$ InP SHJ cell grown by MOCVD. This is a strong possibility given the present results, but since data from an irradiated $n^+p$ SHJ cell annealed above 500K do not yet exist, no definite conclusions can be drawn.

The second question under investigation was if the difference in emitter structure between the SHJ and DJ cells was responsible for the different cell annealing behavior. The enhanced annealing of the DJ cells was above shown to be, in part, due to enhanced defect annealing. Since the radiation-induced defects in SHJ InP have been shown to be sensitive to an electric field (ref. 6), this enhancement may be an electric field related effect. The DHJ cells were grown to simulate the DJ cells, so the junction electric field is expected to be similar in both cell types. However, the residual defect spectrum measured in both DHJ cells (i.e. in both the cell annealed in the dark and the cell annealed under illumination) was essentially the same as that of the SHJ cells. Therefore, the difference in the junction electric field of the DJ and SHJ cells most likely is not the cause of the enhanced defect annealing. However, it should be noted that the exact structure of DHJ and the DJ cells has not yet been analyzed. Therefore, these conclusion can only be tentative. A more precise determination of the structure of these devices is the next step in the NRL/RTI research project.

The annealing of the DHJ cells is also similar to that of the SHJ cells in terms of the recovery of $V_{oc}$. $V_{oc}$ shows almost no recovery in both of these cell types. The DJ cells, on the other hand, have shown complete recovery in $V_{oc}$. This is almost certainly due to the fact that most of the radiation-induced defects in the base of the DHJ cells are not removed by the present annealing experiment while in the DJ cells, all but the ED defect are removed. The persistence of the radiation-induced defects in the epitaxial cells following these annealing experiments inhibits the recovery of $V_{oc}$ while the annealing of the defects in the diffused junctions induces full recovery of $V_{oc}$ in the DJ cells.

While the annealing of the defect spectrum in the DHJ cells is similar to that of the SHJ cells, the recovery of the PV parameters shows a significant difference. Annealing a DHJ cell for 5.25 hrs under illumination at 450K caused complete recovery of $I_{sc}$, and annealing a DHJ for 1 hour in the dark at 450K showed substantial $I_{sc}$ recovery. The SHJ cells did not show this much recovery, so it does seem that the emitter structure of the DHJ cells has enhanced the annealing characteristics of $I_{sc}$. The DLTS results suggest that this is not due to enhanced defect annealing in the base (DLTS samples only the base region), so the enhanced recovery it most likely due to an annealing mechanism in the n-type emitter. This result is consistent with work presented at this conference by Messenger et al. on irradiated $p^+n$ InP solar cells. Those results show recovery in $I_{sc}$ due to short circuit illumination at room temperature and below. It seems, now, that a possible explanation has emerged for why $I_{sc}$ in the DJ cells recovers under illumination at $T<300K$ and $I_{sc}$ in the SHJ cells does not. It may be that the $I_{sc}$ recovery is caused by an increased carrier collection efficiency in the n-type InP due to the illumination and only the DJ cells have enough n-type material for the effect to be seen.

## CONCLUSIONS

The present research has shown that illuminating an irradiated $n^+p$ SHJ InP solar cell during thermal annealing above 300K does not enhance the recovery of the PV parameters or the defect annealing rate. The results strongly suggest that irradiated $n^+p$ DJ solar cells will anneal at a temperature

200K lower than an irradiated $n^+p$ SHJ cell with or without illumination. The measured full recovery of $I_{sc}$ in an irradiated DHJ cell has indicated that illumination may be only affecting the current collection in the n-type InP material, so only $n^+p$ cells with thick emitters, i.e. the DJ and DHJ cells, show recovery of $I_{sc}$ under illumination. However, the fact that the $I_{sc}$ of the DHJ cells did not recover under illumination below room temperature shows that the present DHJ cell structure still lacks qualities of the DJ cell structure which are essential for optimizing this effect. Furthermore, the lack of recovery of $V_{oc}$ and the lack of defect annealing in the DHJ cells indicates that there is still a major difference between the epitaxial and diffused cell structures which inhibits the epitaxial cells from obtaining full recovery of radiation-induced damage.

These points clearly indicate that while the present investigation of the effects of the cell structure on the cell annealing characteristics has indicated the importance of the n-type emitter, more research into the device structure needs to be done to fully understand the mechanism for the enhanced annealing properties of the DJ solar cells.

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