

In Situ Irradiation and Measurement of Triple Junction Solar Cells at Low Intensity, Low Temperature (LILT) Conditions

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Abstract—The performance of triple junction InGaP/(In)GaAs/Ge space solar cells was studied following high energy electron irradiation at low temperature. Cell characterization was carried out *in situ* at the irradiation temperature while using low intensity illumination, and, as such, these conditions reflect those found for deep space, solar powered missions that are far from the sun. Cell characterization consisted of I-V measurements and quantum efficiency measurements. The low temperature irradiations caused substantial degradation that differs in some ways from that seen after room temperature irradiations. The short circuit current degrades more at low temperature while the open circuit voltage degrades more at room temperature. A room temperature anneal after the low temperature irradiation produced a substantial recovery in the degradation. Following irradiation at both temperatures and an extended room temperature anneal, quantum efficiency measurement suggests that the bulk of the remaining damage is in the (In)GaAs sub-cell.

Index Terms—LILT, Quantum Efficiency, Radiation Damage, Space Solar Cells, Triple Junction Solar Cells

I. INTRODUCTION

A number of space missions have been, or are being, designed to be powered by space solar cells but are farther away from the Sun than the Earth/Mars region where most of the previous use of these cells has taken place. These greater distances from the sun will result in the cells operating at low intensity and low temperature (LILT) conditions. A question that arises is one of whether the extensive data

Manuscript received July 11, 2008.) This work was supported in part by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration (NASA).

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previously taken following room temperature irradiation adequately describes the LILT irradiation response. Several studies have been published that subject state-of-the-art space solar cells to one or more of the aspects of these conditions, but none covers the conditions completely.

One group of previous LILT studies has consisted of high energy electron irradiations at room temperature followed by LILT measurements [1,2] which provide some insight to LILT performance following irradiation, but do not address the question of degradation during a low temperature irradiation. Another group of LILT studies has performed electron irradiations at low temperature [3], but included a room temperature warming step between irradiation and measurement and, as such, does not address the question of possible recovery during the warming step. The work by Ohshima *et al.* [4] compared *in situ* irradiation and measurement with 10 MeV protons at $\sim 140\text{K}$ with those at room temperature with 1 sun illumination. Those results showed the low temperature and room temperature behavior to be equivalent. However, that paper did not address low intensity effects nor were any annealing steps included.

The motivation for the present study is to perform high energy electron irradiations at low temperature and then perform cell characterizations at low light intensity without changing temperature. In this way, the irradiation and characterization temperature will properly reflect the conditions that solar cells on a deep space mission will experience. The LILT results will also be compared to normal intensity (~ 1 sun), room temperature (NIRT) irradiations to explore any differences that result. The LILT condition for this study was chosen to approximately match the conditions at Jupiter where cells will be $\sim 140^\circ\text{C}$ and see ~ 0.03 sun illumination. A room temperature anneal will also be included. The comparison of LILT and NIRT results, along with the effects of a room temperature anneal, is an important consideration for facilities that are unable to perform *in situ* measurements in the irradiation chamber.

II. EXPERIMENTAL PROCEDURE

The samples used in this study were bare (i.e. no cover glass) $2\text{ cm} \times 2\text{ cm}$ InGaP/(In)GaAs/Ge triple junction (3J) space grade solar cells. The results described herein are

focused on Emcore BTJ cells, which are the second generation advanced triple junction solar cell design from Emcore.

1 MeV electron irradiations were performed at the electron irradiation facility at JAEA. The cells were mounted within a custom built cryostat equipped with a thin Ti aperture to allow *in situ* electron irradiation and a quartz window to allow *in situ* light illumination. The sample stage within the cryostat is arranged so that it can be tilted to place the samples either normal to the electron beam or to the illumination source. Four 2 cm \times 2 cm solar cells were mounted within the cryostat at one time. The irradiations were performed in the dark and with the samples at open circuit.

The sample stage within the cryostat consisted of a three-layer arrangement, with each layer made from copper. The bottom base layer was connected to outside the chamber by tubes through which liquid nitrogen could be introduced to cool the stage. The middle layer contained cartridge heaters with electrical connections to outside the cryostat. The combination of cooling and heating allowed the temperature to be controlled. The samples were attached to the top layer with silver paint. The top layer also contained a thermocouple to monitor sample temperature. The thermocouple was mounted into the copper adjacent to the cells.

Illumination was provided by a WACOM WXS-55S-5 solar simulator. The light intensity within the cryostat at the sample stage was measured with previously calibrated 3J cells to be 0.8 sun. The combination of solar simulator-to-sample spacing, dictated by the cryostat, plus attenuation from the quartz window prevented full 1 sun intensity from being achieved. Low intensity conditions were achieved by placing a set of metal screens between the solar simulator and the quartz window of the cryostat. The screen consisted of several individual layers of screen material mounted on top of each other and pulled tight within a metal frame. The frame stabilized the screen and allowed it to be reproducibly removed and replaced with no change in the intensity at the sample. The screen permitted 3% light transmission; approximating the light reduction between the earth and

Jupiter. The resultant light intensity at the samples was 0.024 sun.

One set of samples was irradiated while the samples were held at $\sim -140^\circ\text{C}$. During the irradiation, the temperature did not rise more than 20°C . At several steps throughout the irradiation, the beam was stopped and measurements were made at -140°C . The electron flux during irradiation ranged from 4×10^{11} to 9×10^{11} e/cm²/s. Another set of samples was irradiated at $\sim -90^\circ\text{C}$ using the same chamber with the same flux range. During the irradiation, the temperature did not rise more than 25°C . Measurements were made at -90°C . A third set of samples was irradiated at room temperature while mounted in the same chamber with the same flux range. There was no noticeable temperature change during the room temperature irradiations and measurements.

The I-V characteristics of the solar cells were measured with an ADC R6243 source-measure unit controlled from a computer running Sunrise W32-R6244SOL-N software through long cables extending outside the irradiation chamber; and in all cases were 4 terminal measurements. Measurements were made at specific accumulated fluences after first interrupting the electron beam and allowing the temperature to stabilize. Since the cryostat allows for *in situ* measurement, the cells remained at the irradiation temperature during the measurement period.

Quantum efficiency (QE) measurements were made following the irradiation and transport of the samples back to NRL. As a result, the cells experienced a long room temperature anneal prior to QE characterization. Unfortunately, due to the complicated experimental set-up needed for QE measurements, *in situ* measurements were not possible. The QE measurement technique and equipment are described in a recent publication [5].

III. EXPERIMENTAL RESULTS

A. I-V Characterization

Representative results of the low intensity, low temperature

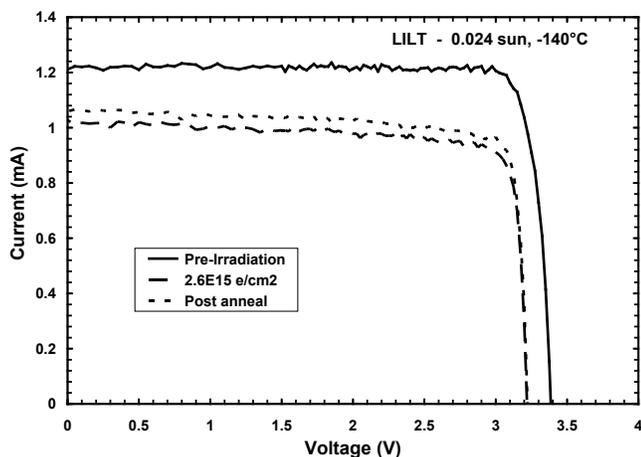


Figure 1. Comparison of I-V curves before irradiation, immediately after irradiation, and after an overnight room temperature anneal under LILT conditions. Irradiation was carried out at -140°C .

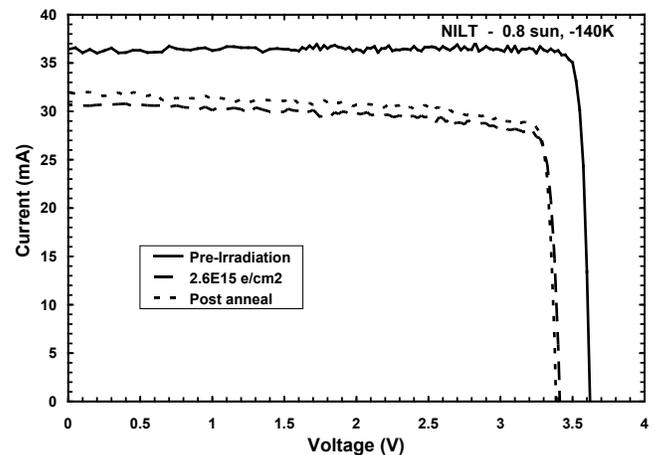


Figure 2. Comparison of I-V curves before irradiation, immediately after irradiation, and after an overnight room temperature anneal under NILT conditions. Irradiation was carried out at -140°C .

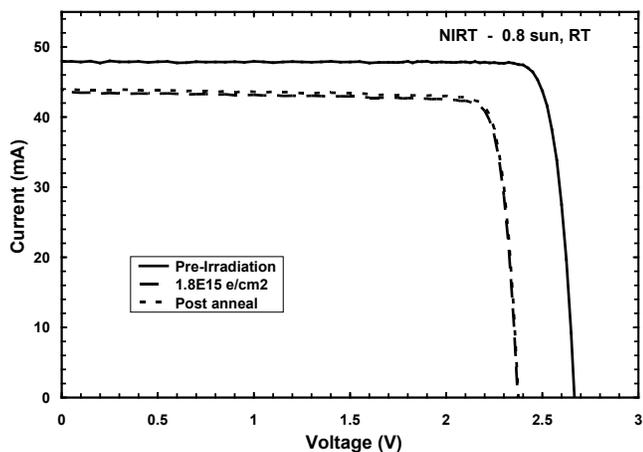


Figure 3. Comparison of I-V curves before irradiation, immediately after irradiation, and after an overnight room temperature anneal under NIRT conditions. Irradiation was carried out at room temperature. (Note: The fluence at RT is $\sim 30\%$ lower than that in Figs. 1 and 2.)

1 MeV electron irradiation are summarized in Fig. 1 by plotting the LILT measured I-V characteristics for 1) pre-irradiation, 2) immediately post irradiation to a level of 2.6×10^{15} e/cm², and 3) after an overnight room temperature (RT) anneal. Substantial degradation is readily apparent in the short circuit current, I_{SC} , and the open circuit voltage, V_{OC} , due to the irradiation. Following the room temperature anneal, there is recovery observed in the I-V characteristics that is primarily found in I_{SC} .

Figure 2 shows I-V data taken on the same cell at the same time and temperature as that in Fig. 1 but with the intensity reducing screen removed. In this normal intensity, low temperature (NILT) data, the same characteristics are observed. This result indicates that the light intensity is not influencing the results; i.e., the degradation during the irradiation and the recovery during the room temperature anneal is observed regardless of the light intensity used.

Similar results were observed when the irradiation was carried out at -90°C . Substantial degradation throughout the I-V characteristics was observed and recovery was observed in the short circuit current following an overnight room temperature anneal.

For comparison, a room temperature irradiation was also performed. The normal intensity, room temperature (NIRT) results are shown in Fig. 3. (Note: The final fluence at RT is $\sim 30\%$ lower than that in Figs. 1 and 2.) This is the condition under which radiation studies are performed for space applications near the Earth or Mars. It is also the condition generally used for previous testing that is reported on supplier's datasheets.

Substantial degradation is readily apparent in the short circuit current, I_{SC} , and the open circuit voltage, V_{OC} , due to the irradiation. Following an overnight room temperature anneal, no recovery is observed.

Figure 4 shows I-V data taken on the same cell at the same time and temperature as that in Fig. 3 but with the intensity reducing screen in place. In this low intensity, room

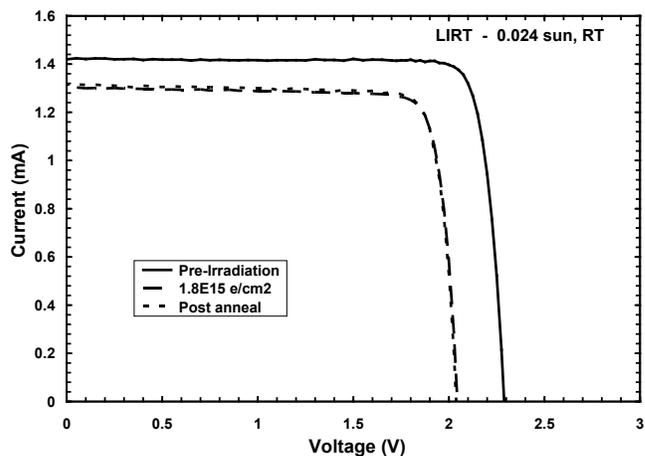


Figure 4. Comparison of I-V curves before irradiation, immediately after irradiation, and after an overnight room temperature anneal under LIRT conditions. Irradiation was carried out at room temperature. (Note: The fluence at RT is $\sim 30\%$ lower than that in Figs. 1 and 2.)

temperature (LIRT) data, the same characteristics are observed, again indicating that the light intensity is not influencing the results.

Comparison of the pre-irradiation data of Figs. 1 – 4, reveals differences in I_{SC} and V_{OC} that are related to both the light intensity (primarily in I_{SC}) and the temperature (both I_{SC} and V_{OC} although primarily in V_{OC}) [6]. The temperature coefficients are generally given in manufacturer's data sheets.

B. Quantum Efficiency Measurements

Quantum Efficiency was measured vs. wavelength following irradiation and an extended room temperature anneal. (The extended RT anneal was due to the shipment time necessary to transport the cells back to NRL for measurement.) Results comparing the QE for cells irradiated at room temperature and at -140°C are shown in Fig. 5. The QE measurements were performed at RT. The RT irradiated cell is the same as that shown in Figs. 3 and 4, while the LT irradiated cell is the same as that shown in Figs. 1 and 2.

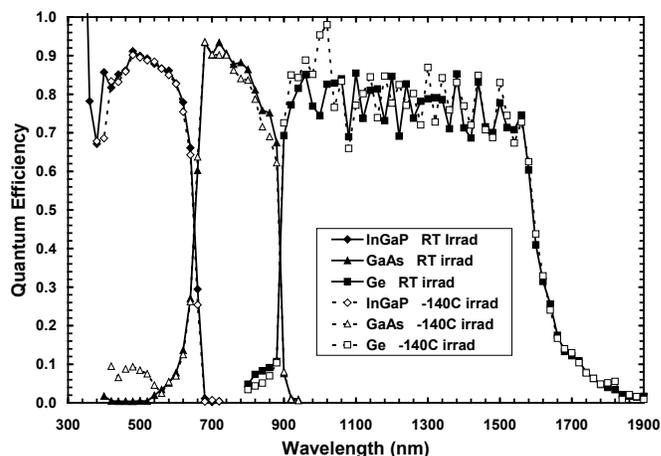


Figure 5. Comparison of Quantum Efficiency (QE) vs. wavelength for cells irradiated at RT and at -140°C . QE measurements were made at RT. Similar measurements made following irradiation at -90°C showed very similar results.

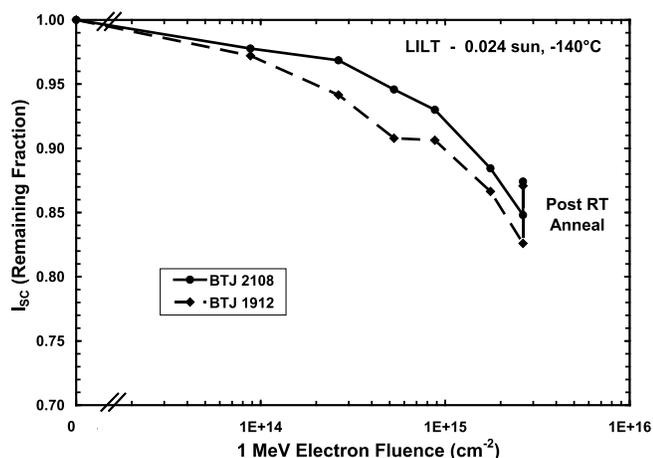


Figure 6. Change in the short circuit current (I_{sc}) vs. fluence at -140°C and RT anneal.

The QE results following the irradiations at the two different temperatures are nearly the same. The spectral dependence is essentially the same for both cases. The only apparent difference is the magnitude of the quantum efficiency in the (In)GaAs sub-cell. The QE is slightly higher in the cell irradiated at RT than in the cell irradiated at -140°C . This difference is expected to translate into a higher I_{sc} for the cells irradiated at RT.

An additional cell that was irradiated at -90°C , and subjected to the same extended room temperature anneal, also showed the same spectral dependence. The QE intensity was approximately the same as for the cell irradiated at -140°C .

IV. DISCUSSION AND ANALYSIS

The change in the short circuit current (I_{sc}) with irradiation fluence and anneal is shown in Fig. 6 for the parts irradiated at -140°C , where the plot is normalized to the initial value. I_{sc} shows a degradation of $\sim 16\%$ at the final fluence. Following the RT anneal, the cells show a recovery of $\sim 21\%$ of this degraded amount.

A similar plot is shown in Fig. 7 for the maximum power (P_M). The irradiation causes a degradation of $\sim 24\%$ in P_M . The RT anneal produces a recovery of $\sim 20\%$ of this degradation.

Fig. 8 shows the behavior for both I_{sc} and P_M for a cell irradiated at an intermediate temperature of -90°C with illumination at 0.024 sun. Under these conditions, I_{sc} was observed to degrade 11% during the irradiation and showed a recovery of 20% of this degradation during the room temp anneal. Similarly, P_M degraded 21% during the irradiation and the RT anneal produced a recovery of 15% of this degradation. The slightly smaller degradation in these parameters at -90°C is due to the slightly lower fluence (1.8×10^{15} vs. 2.6×10^{15} e/cm^2) that the cells received during the irradiation at this temperature (see Figs. 9 and 11).

The heating for the room temperature anneal began immediately after the last low temperature measurement for all cells. As such, no information was obtained regarding potential

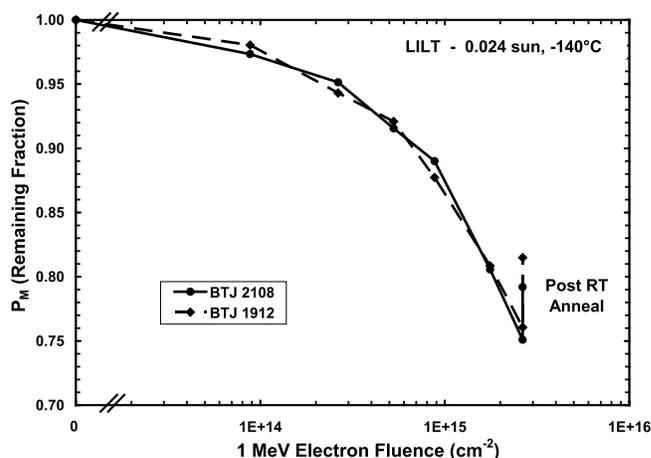


Figure 7. Change in the maximum power (P_M) vs. fluence -140°C and RT anneal.

short term annealing. This will be included in future experiments.

During the room temperature anneal procedure; the parts were warmed from the irradiation temperature to room temperature with the aid of the internal heater. It took approximately 45 minutes to get to room temperature. Once room temperature was reached the I-V characteristics of the cells were measured. Prior to cooling down after the overnight RT anneal, the cells were re-measured.

In all cases, the I-V characteristics measured at RT at the beginning of the anneal were the same as those immediately after the anneal. This result indicates that the recovery shown in Figs. 6 to 8 occurs prior to the extended RT anneal step. It must occur during the process of warming to room temperature. As a result, it is not known at what temperature, or temperatures, the recovery actually takes place, only that it occurs below room temperature.

A comparison of parameter degradation at the three different irradiation temperatures is shown in Figs. 9-11. The data in all of these figures was taken with a low light intensity of ~ 0.024 sun, and is plotted as remaining factor.

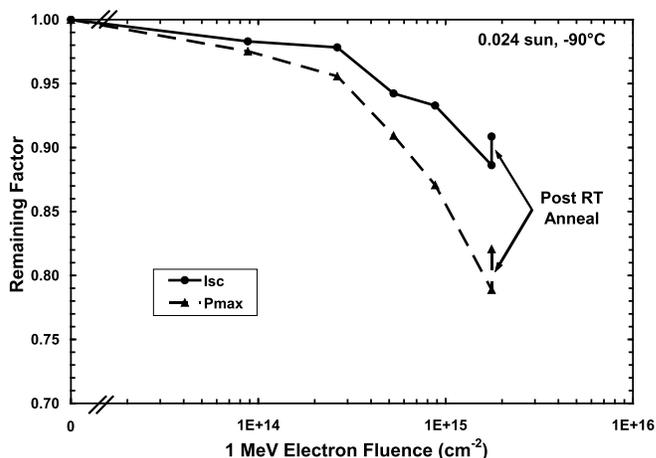


Figure 8. Change in the short circuit current (I_{sc}) and maximum power (P_M) vs. fluence at -90°C and RT anneal.

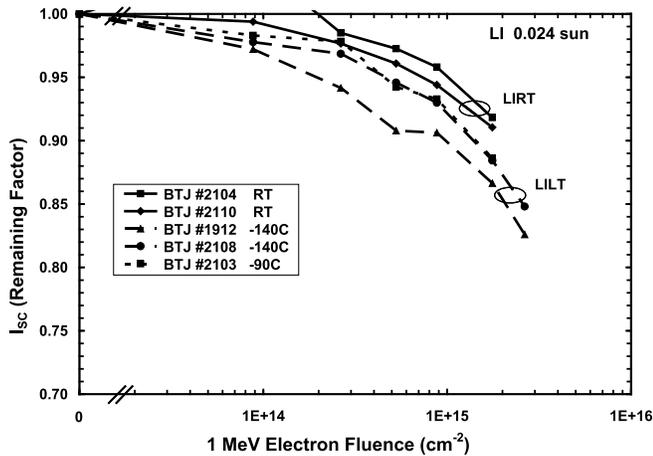


Figure 9. Comparison of I_{sc} measured *in situ* at low intensity following irradiation at RT, -140°C, and -90°C.

The amount of degradation in I_{sc} is greater at the lower temperatures than it is at room temperature while the amount of degradation in V_{oc} is less at the lower temperatures. It is not clear at this time why the behavior of the two parameters is opposite at the different temperatures. What is especially interesting is that the different behavior in I_{sc} and V_{oc} balances when P_M is determined as shown in Fig. 11. The behavior of the P_M degradation appears to be independent of temperature. Of course, Figs. 9 to 11 ignore the recovery that takes place following a room temperature anneal. However, a cell on a deep space mission would not see such an anneal step.

Even though the P_M degradation is independent of temperature, the fact that I_{sc} and V_{oc} are different should be taken into account when optimizing solar cell design for these conditions that reflect those far from the sun. This is also true for the design of space solar cell modules.

The differences in the behavior at the different irradiation temperatures are probably the result of different defects being stable at the different temperatures. The recovery that takes

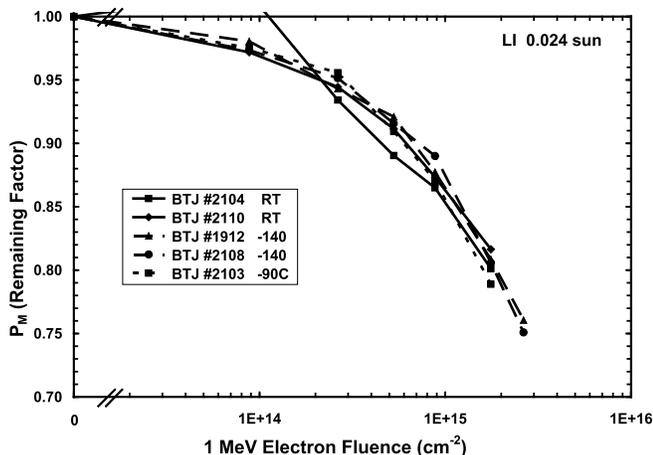


Figure 11. Comparison of P_M measured *in situ* at low intensity following irradiation at RT, -140°C, and -90°C.

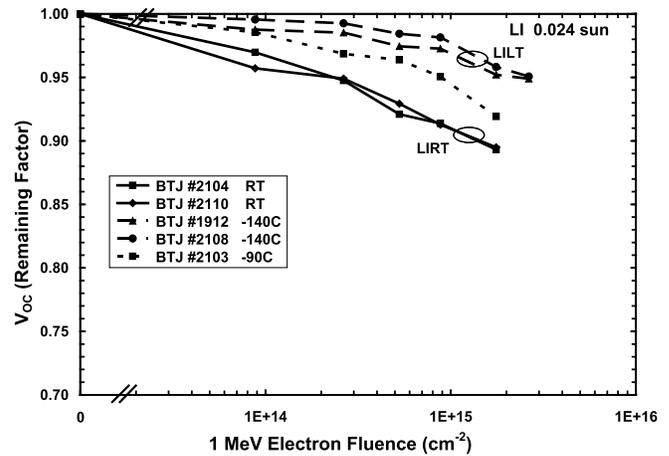


Figure 10. Comparison of V_{oc} measured *in situ* at low intensity following irradiation at RT, -140°C, and -90°C.

place after the room temperature anneal is probably due to changes in the stable defects resulting from defects with low activation energies disappearing. The present study does not provide any detailed information about the stable defects. Additional experiments are planned to address this issue.

The QE results of Fig. 5 indicate that the nature of the damage produced by irradiation at the different temperatures affects the individual sub-cells in substantially the same way, at least after an extended room temperature anneal. Unfortunately, the cells were not measured prior to irradiation, so it is not possible to identify, in detail, the changes produced by the irradiation. However, measurements on other similar structures, such as Emcore's ATJ line [5,7,8], that have not been irradiated, have similar spectra with the only difference being the intensity at the long wavelength side of the (In)GaAs sub-cell [5].

Generally, prior to irradiation, the QE throughout the (In)GaAs sub-cell is more constant *vs.* wavelength [5,7,8] than is seen in Fig. 5, rather than dropping in intensity at longer wavelengths. This difference in the intensity between similar unirradiated samples and these irradiated samples suggests that the bulk of the remaining damage is in the (In)GaAs sub-cell. A more detailed comparison of pre- and post-irradiation QE results is planned for the future.

V. CONCLUSION

The results presented in this paper emphasize the importance of making end-of-life predictions of solar cell performance using the conditions under which the cell will be used. The indication is that allowing the solar cells to warm to room temperature between irradiation and measurement will induce significant recovery that would not be seen on a deep space mission. In addition, the results indicate differences in the details of the parameter degradation between irradiations carried out at different temperatures. Both of these indicate that the wealth of existing data taken following room temperature irradiation and measured at room temperature need to be used carefully for evaluating missions that are far

from the sun. The effects seen in this study indicate that the different radiation induced degradation effects observed are related to temperature and not light intensity. Preliminary QE measurements suggest that the resultant damage following irradiation and extended room temperature anneal is primarily in the (In)GaAs sub-cell.

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