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BURST ANNEALING OF ELECTRON DAMAGE IN SILICON SOLAR CELLS

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A study has been performed of burst annealing of electron damage in silicon solar cells. Three groups of cells consisting of 3 and 0.3 ohm-cm silicon were exposed to fluences of 2 x 10^{14}, 4 x 10^{14}, and 8 x 10^{14} 1-MeV electrons/cm^2 respectively. They were subsequently subjected to 1-minute bursts of annealing at 500°C. The 3 ohm-cm cells showed complete recovery from each fluence level. The 0.3 ohm-cm cells showed complete recovery from the 2 x 10^{14} e/cm^2 fluence; however, some of the 0.3 ohm-cm cells did not recover completely from the higher fluences. From an analysis of the results it is concluded that burst annealing of moderate to high resistivity silicon cell arrays in space is feasible and that with more complete understanding, even the potentially higher efficiency low resistivity cells may be usable in annealable arrays in space.

INTRODUCTION

Electron and proton damage presents a problem to space power system designers. Generally, in order to meet the requirements of a given mission, heavy shielding in the form of cover glasses and over sizing of the array have been the approaches taken to ensure adequate end-of-life performance. Depending on the mission, the radiation damage penalty can be 25 to 50 percent. Since the early 1960's researchers have investigated various techniques for reducing the extent of radiation damage in photovoltaic cells in order to minimize the need for shielding and over design. Early attempts included a study of thermal annealing of arrays in space by periodically covering the array with a special cover so that it heated up by a "greenhouse" effect to anneal the radiation damage. However, certain components of the damage in silicon cells would not anneal completely at temperatures compatible with the cell structures and array materials available at that time. Considerable effort was also expended on the development of lithium doped silicon cells which tended to spontaneously anneal at relatively low temperatures. However, there were problems with inherent instabilities in the lithium cells and certain components of the radiation damage would not readily anneal. These problems limited the application of the lithium cells.

Due to the factors mentioned above, the use of annealing of radiation damage has been limited to that of a research tool for better understanding the nature of radiation damage. In the course of these research studies, two methods of annealing have been employed, isochronal and isothermal. In the isochronal studies, irradiated samples are soaked for specific intervals of time, usually 15 or 20 minutes at a series of increasing temperatures. The number and types of defects remaining are measured between each interval. For both electron and proton damage certain "parent-daughter" relationships have been observed in which some defects break up or anneal at a relatively low temperature; one or more of the constituents of that defect then combine with another site or impurity to form a new, more stable defect which can be annealed only at much higher temperatures. In isothermal studies the irradiated samples are soaked at a single temperature and their annealing progress monitored. The results of both types of experiments have indicated certain anomalies. For example, cells annealed isothermally at high temperatures tend to anneal more rapidly and completely than would be expected based on the results of lower temperature anneals and on isochronal annealing studies (ref. 1).

The inference from these observations is that the soak at relatively low temperatures may create an environment that induces the formation of stable, annealing-resistant defects. This observation is substantiated by the data in figure 1 which shows a comparison between isochronally annealed cells at different soak times. The shorter soak times result in more rapid and complete recovery. Based on this hypothesis and the recent development of high-temperature silicon cells at Boeing (ref. 2), the concept of "burst annealing" was developed. In burst annealing, the irradiated cells are ramped very rapidly to high temperatures (500°C or more in < 10 seconds) and allowed to soak for times on the order of one minute.

An earlier study of burst annealing on proton irradiated silicon cells (ref. 1) showed that a 25 percent degradation in short circuit current could be recovered completely by a burst anneal at 500°C for one minute or less. Therefore this paper reports the results of a recent burst annealing study on 1-MeV electron damaged cells. Data in the literature indicates that electron damage can require higher annealing temperatures than proton damage silicon cells (ref. 3).

EXPERIMENTAL

The samples were crucible-grown boron doped, 3 Ω-cm or .3 Ω-cm silicon cells with special high-temperature metallizations developed at Boeing. A detailed description of the fabrication techniques and performance characteristics of the cells has been presented in an earlier publication. In this earlier work the cells were found to be stable in their electrical output after thermal soaks of up to 20 minutes at 700°C in vacuum. Therefore, the short burst anneals of one minute at 500°C present no stability problems for the cells.

Three groups of four cells [illegible] were selected for the study. Each group contained cells from three different process batches. Two of the process batches used 0.3 ohm-cm silicon and one used 3.0 ohm-cm silicon. Three groups of cells were exposed to fluences of approximately 2×10^{14}, 4×10^{14}, and 8×10^{14} 1-MeV electrons/cm^2 respectively. The irradiations were performed in vacuum at room temperature using the Boeing Dynamitron. Dosimetry was performed using a shielded Faraday cup. I-V characteristics were taken at 25°C under simulated AMO sunlight (Spectrolab X25L) at one-sun intensity.

The burst annealing was performed in vacuum using a thermally isolated mount for the cells and a shuttered concentrated incandescent light beam directed through a quartz window onto the front of the cell in the vacuum chamber for heating. This arrangement allowed the cells to be raised to temperatures as high as 700°C in time intervals on the order of a few seconds. Figure 2 shows a typical thermal cycle characteristic as a function of time. This fast ramp to high temperature gives rise to the term burst annealing. The cells were removed from the vacuum chamber following each burst anneal and their I-V curves measured as described earlier.

DISCUSSION OF DAMAGE AND ANNEALING

Protons and electrons are the major components of the space radiation environment. Cover glasses can partially shield the cells from proton damage; however, electrons of 1-MeV energy and higher penetrate throughout the cell/array stack. The result is a nearly homogeneous production of isolated point defects throughout the cell base. The point defects, vacancies and interstitial atoms in the crystalline lattice, are highly mobile and tend to pair with other vacancies or with other impurity atoms within the crystal. The resulting defects are very stable and isochronal annealing studies have shown that temperatures in excess of 500°C are sometimes required in order to anneal them as illustrated in figure 3. Thus, the burst annealing approach is being studied in order to determine if it can successfully inhibit the formation of such high-temperature stable defects.

The number of initial defects formed in the silicon is generally treated as being directly proportional to the electron fluence.

Immediately following electron bombardment with energetic particles, the newly formed defects discussed above will consist almost entirely of single interstitials and single or multiple vacancies with single vacancies predominating. The vacancies and interstitials are highly mobile at room temperature in silicon, resulting in interaction of the vacancies and interstitials with each other or with impurities within the silicon. These interactions with impurities usually result in more stable defects that persist at higher temperatures.

As discussed earlier, it appears that the formation of more stable defect-impurity complexes can be minimized by rapidly ramping the cells to high temperature. However, even in the burst annealing situation if either the defect density or the impurity density is high enough, then there is increased probability of some of the defects encountering and pairing with impurities. In order to study this effect the three groups of cells were exposed to three fluences or defect densities and within each group there were cells made from 0.3 ohm-cm (high dopant impurity content) and 3.0 ohm-cm silicon material.

Figures 4, 5, and 6 shows the degradation and recovery curves typical of the 3-ohm-cm silicon cells after burst annealing from the three different damage levels. Within the accuracy of the measurements the recovery in these cells is complete at all three fluence levels. At the impurity density level of 3 ohm-cm silicon the burst annealing is successful at inhibiting the formation of secondary, more stable defects. This observation is supported by the results in the 0.3 ohm-cm cells. Figure 7 shows the worst case for one of these cells. As can be seen the cell shows considerably more electrical degradation for the same initial fluence than the 3 ohm-cm cells indicating that significant pairing of defects with dopant impurities has already occurred. As can be seen from the recovery curve the high temperature stable defects are already formed and no significant recovery is achieved until after the third anneal attempt of five minutes at 500°C. However, there was considerable scatter in the recovery characteristics of the low resistivity cells as indicated by figures 8 and 9. The almost complete recovery of the low-resistivity cell #207 shown in figure 9 suggests that if the annealing phenomena were better understood then the recovery of burst annealing could possibly be achieved for low resistivity cells also. The extent of recovery in the low resistivity cells was also a function of defect density as illustrated by the curves in figures 10 and 11. At the lower fluences or defect densities the low resistivity cells could be burst annealed effectively.

Thus, from these data it is concluded that burst annealing can be an effective tool for annealing cells in space. The degree of recovery is a function of initial defect density with respect to the existing impurity density, however, for cells of 3 ohm-cm or higher material (typical of most current space cells) the recovery from even heavy degradation is complete for practical purposes. Thus, it is concluded that burst annealing of electron damage in silicon cells is feasible for moderate resistivity cells and that a better understanding of the phenomena might make it feasible to use very low resistivity cells in space which would yield higher beginning of life efficiencies.

ANNEALING OF ARRAYS IN SPACE

From the above data, certain observations can be made about the optimum conditions for annealing radiation damage in space. First, a temperature range for annealing of about 500°C $\pm$ 50°C has been found to be adequate. Second, the best way to accomplish the anneal is a single burst to high temperature, stepping the cell to the annealing temperature (500°C) in as short a time as is practical. The present data indicate that a burst of 60 seconds at 500°C with a ramp time of 0 to 10 seconds is sufficient to anneal greater than 99 percent of the electrical degradation out of the cells. After the damage is annealed the slower return to normal temperature necessitated by thermal radiation to space does not matter.

A suggested approach for accomplishing the burst anneal cycles is the use of thin film resistors deposited on the substrate of each cell string in the array. The cells strings could then be periodically switched onto the array bus line by an autonomous power management system. The subsequent joule heating would accomplish the anneal consuming negligible power from the array during the one minute anneal. When the cell string has cooled and returned to power production another string would be annealed.

Such an annealable array could reduce the size of array required for a particular mission by as much as 50 percent.

CONCLUSIONS

Based on the results discussed in this paper and in references 1 and 2, it is concluded that:

1. Silicon cells can be produced which are stable under multiple cycles to 500°C temperatures required for burst annealing.

2. Burst annealing can yield essentially complete recovery of 3 ohm-cm n/p silicon solar cells in very short times; hence, with less energy than previously thought possible.

3. High efficiency low resistivity cells also show promise of being fully annealable.

The questions remaining regarding the feasibility of burst annealing is the repeatability of the recovery cycle after multiple anneals and the effectiveness of the annealing in cells exposed to simultaneously combined environments of protons and electrons.

REFERENCES

1. Lowe, V., and Day, A. C., "High Temperature Metallization Technology for Solar Cells," IEEE Trans. on Electron Devices, Nov. 1983.

2. Horne, W. E., Day, A. C., Thompson, M. A., "Burst Annealing of Proton Damage in Silicon Solar Cells," Proc. 17th IEEE Photovoltaics Specialists Conf., Orlando, Florida, 1984.

3. Carter, J. R., Jr., "Defect-Impurity Relationships in Electron-Damaged Silicon," IEEE Trans. on Nucl. Sci., Vol. NS-13, No. 6, December, 1966.

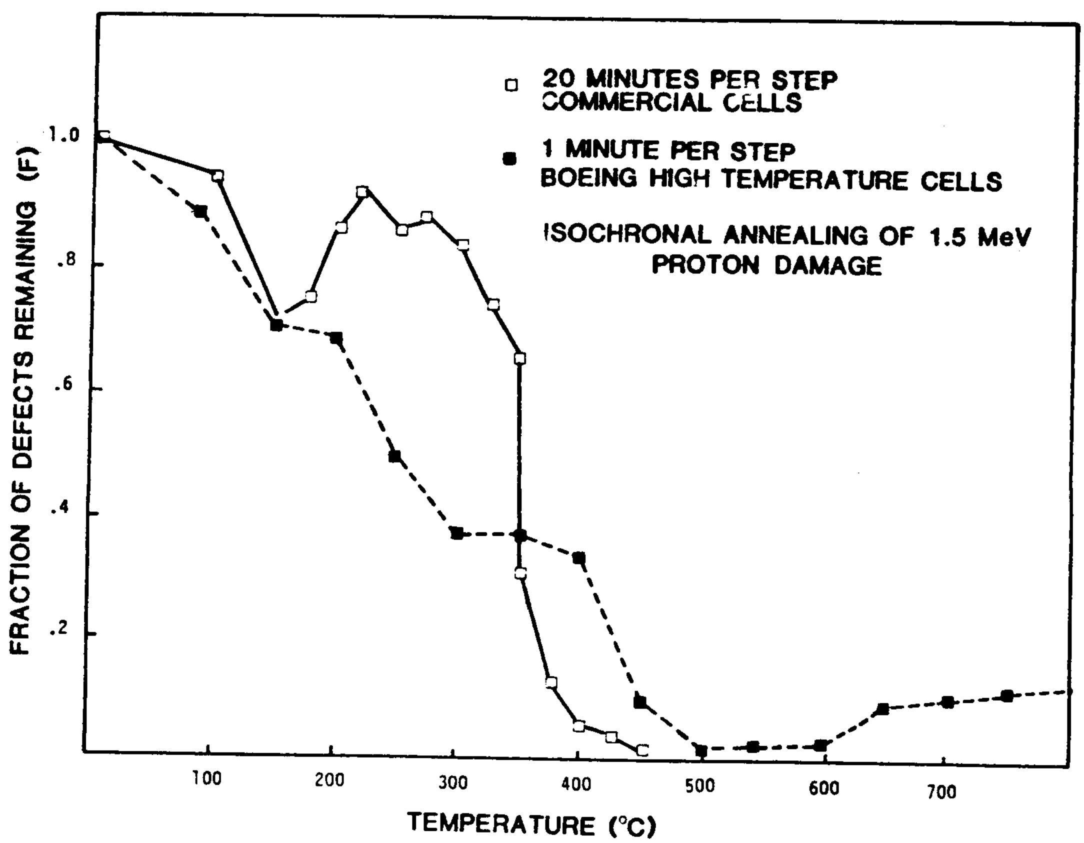

Figure 1. Comparison of Isochronal Annealing With Long and Short Annealing Times in Silicon Cells

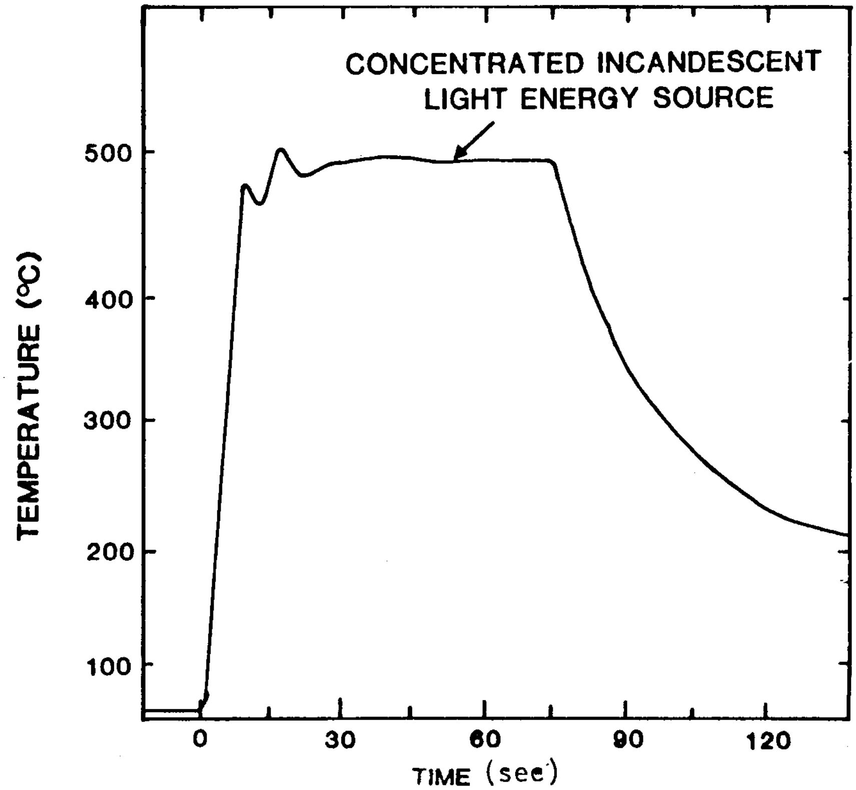

Figure 2. Typical Thermal Cycle for Burst Annealing

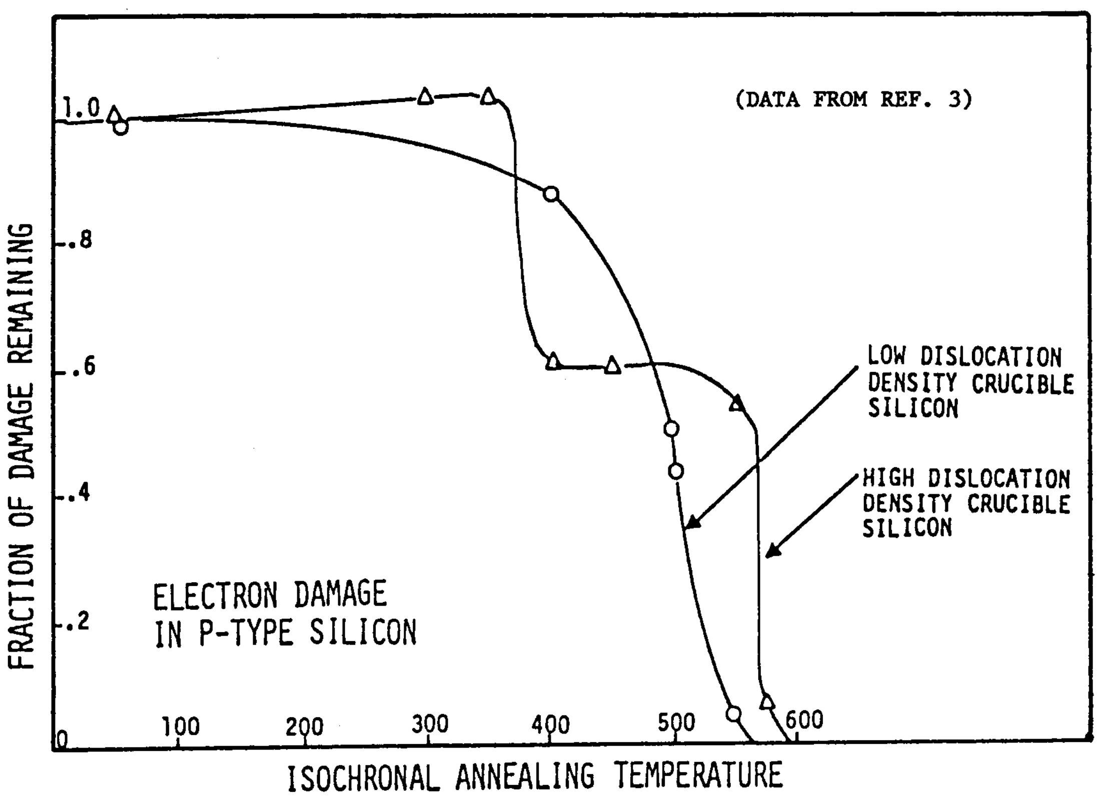

Figure 3. Electron Damage Recovery in Two Types of P-Type Silicon Material

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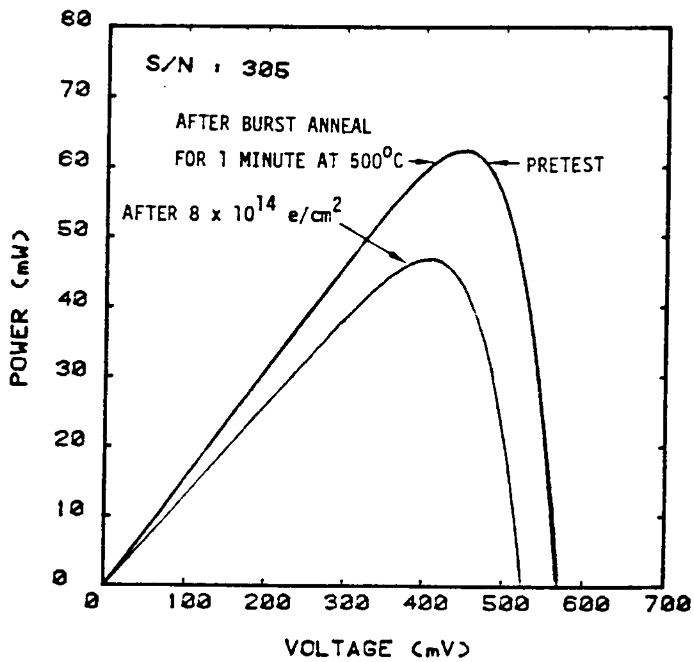

Figure 4. Burst Annealing of 3 ohm-cm Silicon Cell #305 From High Fluence Level

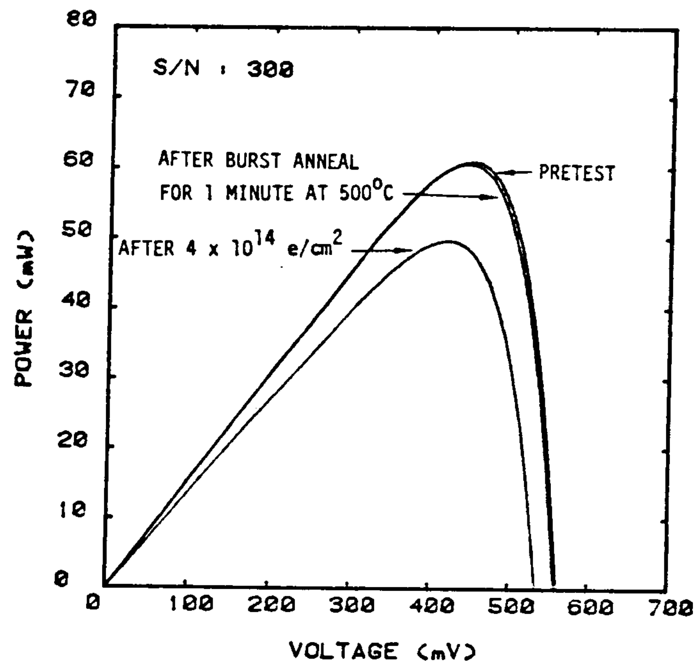

Figure 5. Burst Annealing of 3 ohm-cm Cell #300 From Intermediate Fluence Level

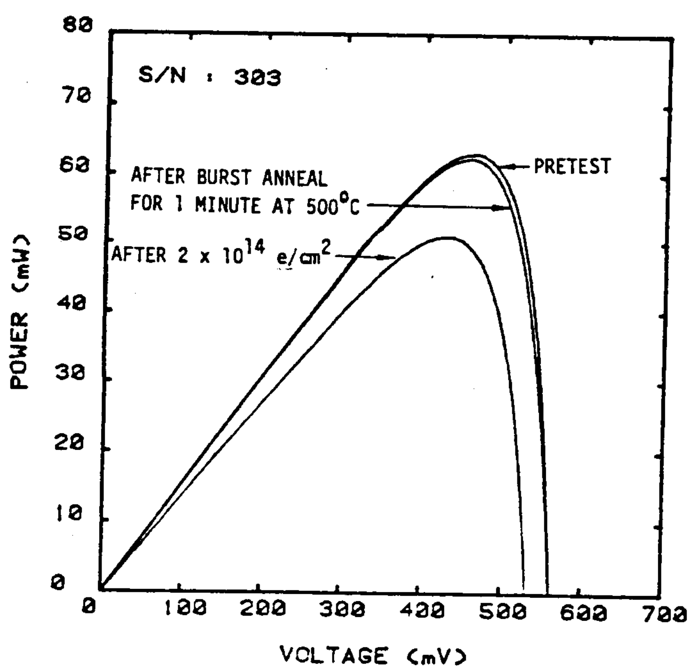

Figure 6. Burst Annealing of 3 ohm-cm Cell #303 From Low Fluence Level

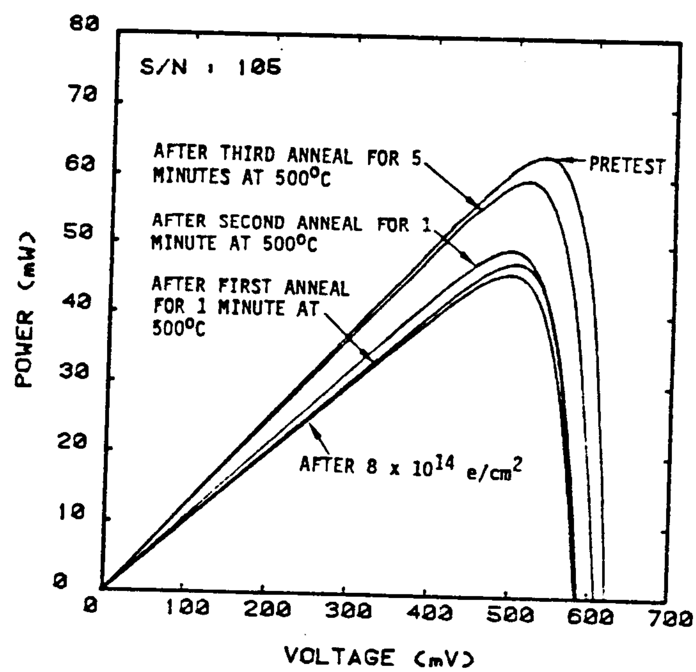

Figure 7. Burst Annealing 0.3 ohm-cm Cell #105 From High Fluence Level

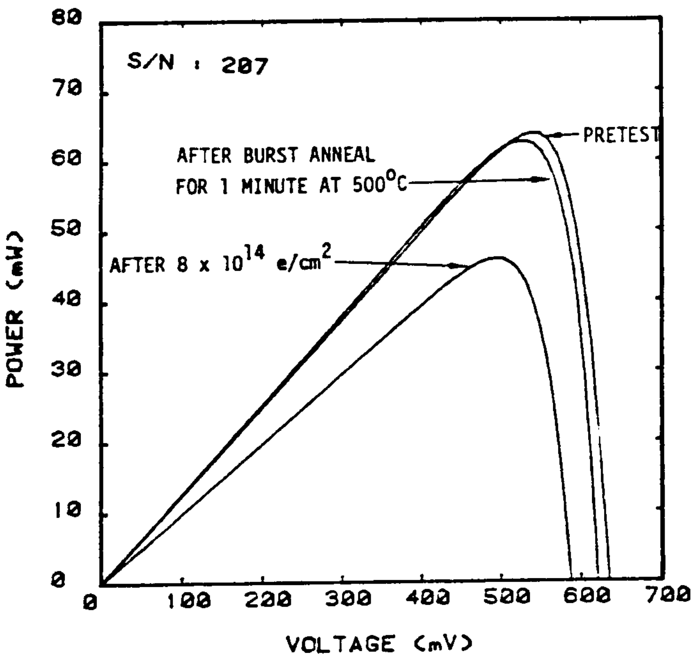

Figure 8. Burst Annealing of 0.3 ohm-cm Cell #207 From High Fluence Level

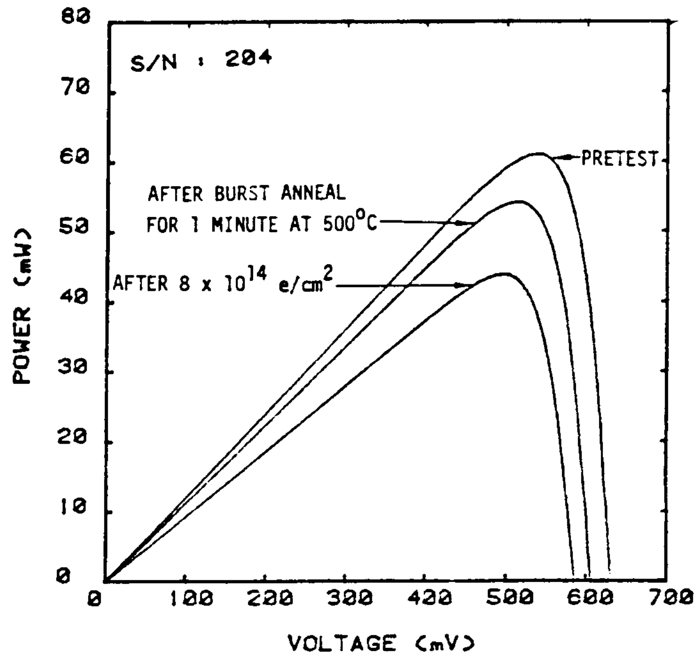

Figure 9. Burst Annealing of 0.3 ohm-cm Cell #204 From High Fluence Level

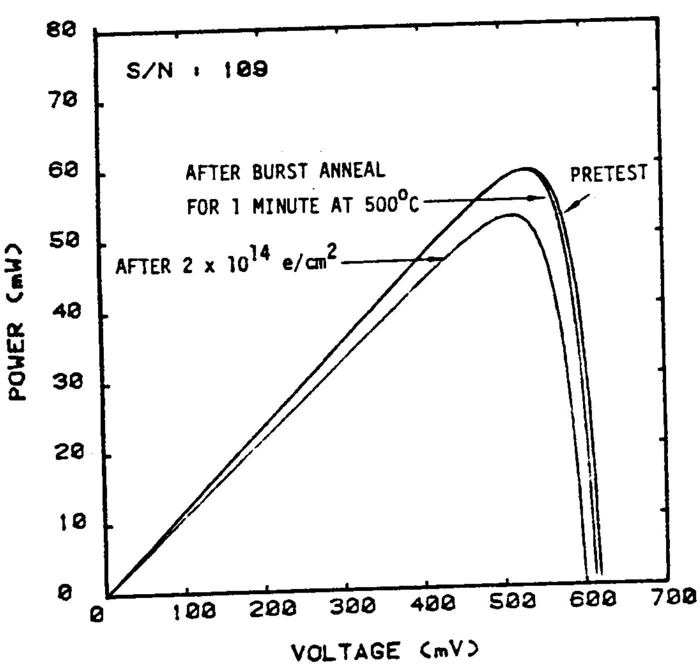

Figure 10. Burst Annealing of 0.3 ohm-cm Cell #109 After Low Electron Fluence

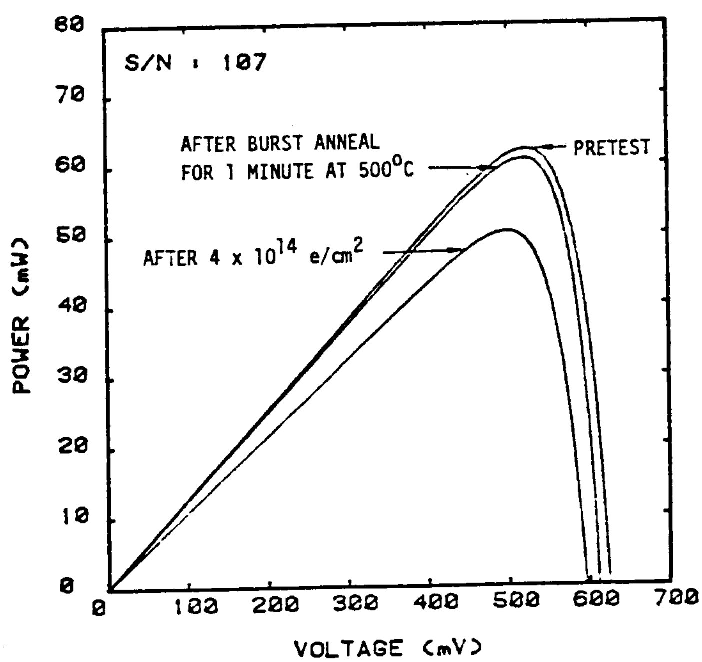

Figure 11. Burst Annealing of 0.3 ohm-cm Cell #107 After Intermediate Electron Fluence