PERIODIC ANNEALING OF RADIATION DAMAGE IN GaAs SOLAR CELLS

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INTRODUCTION

A leading motiviation for our study of radiation damage in GaAs solar cells is their capability to offer better resistance to radiation damage in space than Si cells. Key parameters known to affect the nature and the severity of such radiation damage are:

1. Type and energy of damaging particles (electrons, protons or neutrons).
2. Particle fluence.
3. Cell temperature during irradiation.

It is also known that GaAs solar cells can recover substantially from electron damage at temperatures as low as 200°C, with some evidence that even lower temperatures may be effective (ref. 1). We have, however, found that in some cases, conventional annealing of proton radiation damage is much less effective than the annealing of electron radiation damage. We have therefore studied in more detail the annealing of proton radiation damage in our GaAs solar cells. We wished to determine if and how proton radiation damage can effectively be annealed at relatively low temperatures ($\leq$200°C). The first results of this study are reported in this paper.

ANNEALING PROCESS

Radiation damage can be annealed by a number of different ways. The specific ones which we consider here are:

1. Post-annealing.
2. Periodic annealing.
3. Continuous annealing.

Post-annealing means annealing the solar cells by keeping them at a given temperature, after irradiation at room temperature. By continuous annealing we refer to the process of continuous recovery from radiation damage while irradiation proceeds; this is achieved by maintaining the solar cells at the desired annealing temperature (above room temperature) while irradiation takes place. The concept of continuous annealing has been proposed some time ago (ref. 2) and attractive extrapolations have already been made on the basis of existing electron radiation damage data. These extrapolations indicate that continuous annealing could in fact prevent electron radiation damage (ref. 2) at surprisingly low annealing temperatures ($<150^{\circ}C$). The data which we have recently obtained shows that continuous annealing can also be remarkably effective in preventing proton radiation damage. This data is given and discussed in the next section.

In periodic annealing, we irradiate the solar cells at room temperature up to a given fluence, anneal them thereafter for a limited time at the selected annealing temperature, and repeat this sequence a number of times. In space applications, this process could be attractive if the annealing time can be kept a small fraction of the irradiation time. Furthermore, this is a compromise between continuous annealing and a single post-annealing sequence. Periodic annealing is attractive because it leads to recovery from radiation damage before radiation damage has accumulated to a point where excessive loss of solar cell power output does occur. It will be interesting to determine if an adequate frequency of periodic annealing can provide results as favorable as these obtained with continuous annealing. Since the radiation flux rates in space are relatively low, this seems possible.

EXPERIMENTAL RESULTS

The measurements reported below were performed on 2 cm x 2 cm (AlGa)As-GaAs solar cells made at the Hughes Research Laboratories (HRL) with the parameters shown in Fig. 1. Both the (AlGa)As window thickness D and the junction depth x_j were equal to 0.5 μm. Irradiation was provided by 200 keV protons, in an ion implantation machine at HRL. The proton energy of 200 keV was selected because damage caused by this radiation had been found to be especially severe (ref. 3) in the GaAs solar cells with the structure given in Fig. 1. We performed two sets of experiments. In the first set, we compared periodic annealing to post-annealing. In the second set of experiments, we performed continuous annealing.

The flow chart of the measurements performed in the first set of experiments is shown in Fig. 2. Our original plan had been to perform all annealing steps at the same temperature of $200^{\circ}C$, for the periodic as well as for the post-annealing. We found, however, that the amount of radiation damage recovery observable after 200 keV proton irradiation and annealing at $200^{\circ}C$ is quite small, in contrast to the recovery observed at the same temperature after 1 MeV electron irradiation. We proceeded, therefore, with higher annealing temperatures, even though this led to a less systematic set of data. The results of these measurements are given on Tables 1 and 2. The key observations which result from inspection of these two tables are that:

1. The proton radiation damage caused by 200 keV protons is not effectively annealed at $200^{\circ}C$, neither by post-annealing nor by periodic annealing.

2. After annealing at an elevated temperature of 500°C, the amount of recovery attained in periodic annealing after these irradiation and annealing periods is approximately the same ($P/P_o = 77.4\%$) as that observed after a single post-annealing sequence ($P/P_o - 79\%$).* Similarly, periodic annealing can be compared to post-annealing at 300°C, where the solar cell power is seen to recover in both cases** to the same value of approximately 65%. In all comparisons considered above, the cumulative fluence was 3×10^{11} pcm^{-2}.

3. While the final power was the same in both the periodic and in the post-annealing sequences, periodic annealing did provide the anticipated advantage that the maximum power loss experienced in the course of periodic annealing ($P/P_o = 58\%$) was less severe than that experienced with a single post-annealing sequence ($P/P_o = 50.6\%$).

In the first set of periodic annealing experiments reported above, we note that the first annealing sequence was applied after the radiation fluence had already reached a relative high value of 1×10^{11} pcm^{-2}, leading to correspondingly severe radiation damage ($P/P_o = 61\%$). In our second set of experiments reported below, we shall show that more favorable results are obtained with continuous annealing. This leads to the prospect that more favorable results may also be attained if periodic annealing is initiated at lower fluences than those used in our first experiments.

The results of our continuous annealing experiment at 150°, 200° and 250° C are shown in Fig. 3. For reference, we show in the same figure the effect of post-annealing one of our GaAs solar cells for 50 h at 200°C, after exposure to a 200 keV proton fluence of 10^{10} pcm^{-2}. Consistent with our previous observations, post-annealing at 200°C is seen to provide very little recovery, in contrast to the substantial improvement obtained with simultaneous annealing at the same fluence. The key observations to be made as a result of inspecting Fig. 3 are that:

1. Continuous annealing is much more effective than post-annealing in limiting proton irradiation damage or in providing recovery from it.

2. A continuous annealing temperature as low as 150°C is effective in limiting proton radiation damage.

3. In the continuous annealing experiment of Fig. 3., because of the high flux rate, the total time was very short (1 h) compared to the time in space to reach the same proton fluence. It is therefore plausible that at the lower flux rates prevalent in space, temperatures even lower than 150°C may be effective in providing continuous annealing.

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*We have to qualify this observation by noting that, in the periodic annealing sequence, the first annealing sequence went only up to a temperature of 300°C, while the other annealing steps and post-annealing went up to 500°C.

**Note that a temperature of 500°C was reached in the course of the second periodic annealing step.

Since continuous annealing at 150°C or lower seems a distinct possibility to minimize proton radiation damage, methods of achieving such a goal have to be seriously considered. A simple method of realizing such an objective is to use solar concentrations of the order of 5 to 10 suns and design the solar panel to achieve an equilibrium temperature of approximately 150°C. The loss in solar cell efficiency due to the higher operating temperature should be compared to the benefits obtainable from improvement in end-of-life efficiency for the specific mission. While our observations relate to proton radiation damage, electron radiation damage has been found to anneal even more readily. This approach appears, therefore, even more attractive for missions where electron radiation damage is present or is predominant.

SUMMARY AND CONCLUSION

In our two sets of experiments, we have compared continuous annealing of GaAs solar cells with periodic annealing to determine their relative effectiveness in minimizing proton radiation damage. The main conclusions are:

1. Continuous annealing of the cells in space at 150°C can effectively reduce the proton radiation damage to the GaAs solar cells.

2. Periodic annealing is most effective if it can be initiated at relatively low fluences (approximating continuous annealing), especially if low temperatures of less than 200°C are to be used.

3. If annealing is started only after the fluence of the damaging protons has accumulated to a high value ($\geq 10^{11}$ pcm^{-2} in our experiments), effective annealing is still possible at relatively high temperatures. However, the practicality of such annealing in most space panels remains to be determined.

Finally, since electron radiation damage anneals even more easily than proton radiation damage, we can expect that substantial improvements in GaAs solar cell life can be achieved by incorporating the proper annealing capabilities in solar panels for practical space missions where both electron and proton radiation damage have to be minimized.

REFERENCES

1. Walker, G. H. and Consay, E. J.: "Annealing Kinetics of Electron-Irradiated GaAs Heteroface Solar Cells in the Range 175 to 200°C," Appl. Phys. Lett. 35, p 459 (15 Sept. 1979).

2. Heinbockel, J. H.; Conway, E. J.; and Walker, G. H.: "Simutaneous Radiation Damage and Annealing of GaAs Solar Cells," Conference Records of the Fourteenth IEEE Photovoltaic Specialists Conference (IEEE, New York, 1980, p 1085).

3. Knechtli, R. C.; Kamath, G. S.: Ewan, J.; and Loo, R. Y.: "Development of Space-Qualified GaAs Solar Cells," Proceedings of Second European Symposium on Photovoltaic Generators in Space, ESA publication SP-147, p 124, Fig. 8 (Heidelberg, Germany, 1980).

Table 1. Periodic Thermal Annealing Result on Cell #4416 Bombarded by 200 keV Proton

Proton Irradiation Temp ^oC	Proton Irradiation Fluences p cm^{-2}	Thermal Annealing Temp ^oC	Thermal Annealing Time hr	Total Annealing Time hr	I_{sc} ma	V_{oc} v	FF	P_m mW	η %	Power Ratio* P/P_o %
					114	0.99	0.76	86.1	15.9	
25	$1x10^{11}$				84	0:84	0.74	52.5	9.7	61
		200	21		85	0.86	0.75	54.8	10.1	63.5
		300	4.5		89	0.89	0.75	59.3	11.0	69.2
25	$1x10^{11}$				82	0.84	0.73	50.4	9.3	58.5
		300	4.0		88	0.88	0.74	57.3	10.6	67
		500	2		108	0.93	0.75	75.1	13.9	87.4
25	$1x10^{11}$				80	0.84	0.74	49.7	9.2	58
		200	1		82	0.85	0.73	51.1	9.4	59.3
		"	3	4	82	0.85	0.73	51.1	9.4	59
		"	18	22	83	0.85	0.74	52.5	9.7	61
		"	72.5	94.5	84	0.86	0.74	53.3	9.8	61.6
		"	51	145.5	84	0.86	0.74	53.3	9.8	61.6
		300	4		87	0.85	0.74	56.2	10.4	65.4
		"	74	78	88	0.87	0.73	55.7	10.3	64.8
		350	2.5		89	0.87	0.73	56.9	10.5	66
		400	1	1	93	0.89	0.72	59.8	11	69.2
		"	3.5	4.5	94	0.89	0.73	61.2	11.3	71.0
		500	1		101	0.90	0.73	66.4	12.3	77.4
		550	1		105	0.90	0.69	64.8	12	75.5

* P = power after annealing

P_o = power before irradiation

Table 2. Thermal Annealing Result on Cell #4440 Bombarded by 200 keV Proton

Proton Irradiation Temp ^oC	Proton Irradiation Fluences p cm^{-2}	Thermal Annealing Temp ^oC	Thermal Annealing Time hr	Total Annealing Time hr	I_{sc} ma	V_{oc} v	FF	P_m mW	η %	Power Ratio P/P_o %
					113	0.99	0.76	85.5	15.8	
25	$1x10^{11}$				85	0.84	0.74	52.5	9.7	61.4
25	$1x10^{11}$				81	0.82	0.73	48.3	8.9	56.3
25	$1x10^{11}$				76	0.80	0.71	43.2	8.0	50.6
		200	1		79	0.81	0.72	46.2	8.54	54
		"	3	4	79	0.81	0.72	46.2	8.54	54
		"	18	22	81	0.82	0.73	48.4	8.95	56.6
		"	72.5	94.5	83	0.82	0.72	49.6	9.2	58.2
		"	51	145	83	0.82	0.72	49.6	9.2	58.2
		300	4		87	0.85	0.73	53.9	10.0	63.2
		"	74	78	89	0.87	0.73	56.1	10.4	65.8
		350	2.5		88	0.86	0.73	55.4	10.2	64.5
		400	1		91	0.87	0.72	56.8	10.5	66.4
		"	3.5	4.5	92	0.87	0.70	56.1	10.4	66
		500	1		106	0.90	0.71	67.7	12.5	79
		550	1		106	0.91	0.72	69.4	12.8	81

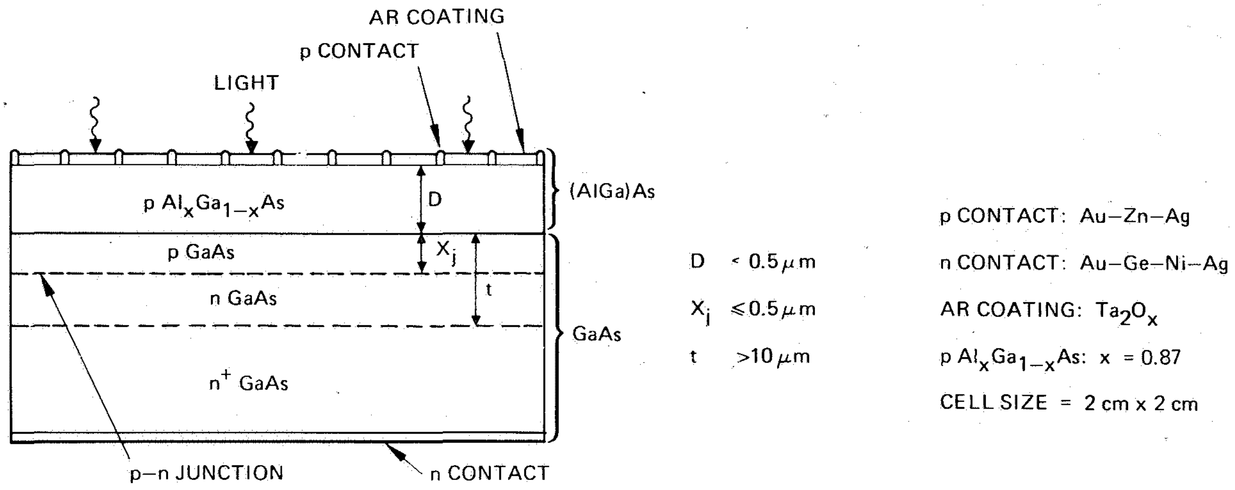

Figure 1. (AlGa)As-GaAs solar cell structure

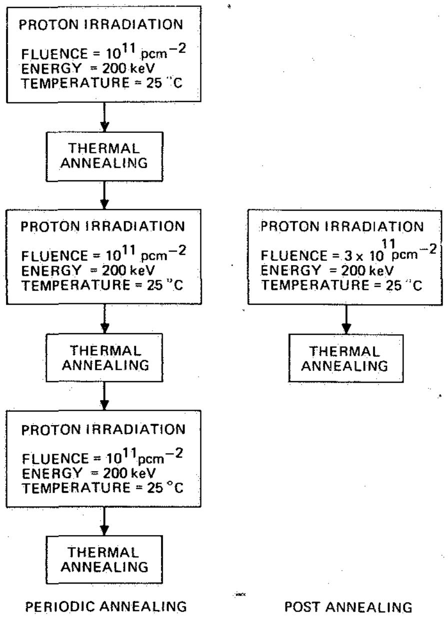

Figure 2. Flow chart for periodic annealing experiment

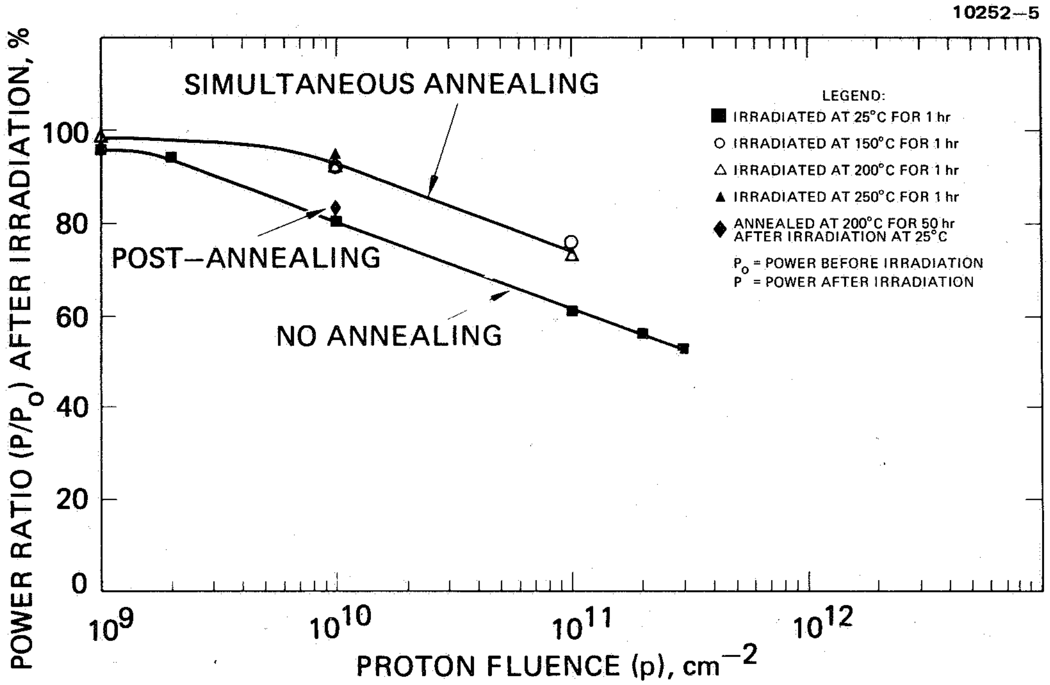

Figure 3. Continuous annealing during irradiation with 200 keV protons