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Annealing Characteristics of Irradiated Hydrogenated Amorphous Silicon Solar Cells

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Introduction

Hydrogenated amorphous silicon (a-Si:H) solar cells have recently been proposed as candidates for future advanced space solar cell arrays based primarily on its high specific power density and radiation tolerance [ref. 1]. The purpose of this work is to report on our investigations of the radiation resistance properties of a-Si:H solar cells.

Past work shows that the effect of 1.00 MeV proton irradiation on a-Si thin film alloy solar cells is to degrade the efficiency mainly through degradation of the short-circuit current and the fill-factor [ref. 2]. Changes in the short-circuit current become noticeable at a fluence of about 1E12 cm^{-2} and decrease to about zero at 1E15 cm^{-2}. The initial efficiency can be restored by annealing the device at about 160°C for various times depending on the fluence, i.e., the higher fluences require longer times to completely restore the efficiency of the solar cell. No room temperature annealing of irradiated solar cells has been reported.

We have recently irradiated a-Si:H thin films in order to elucidate the effect of proton irradiation on the intrinsic layer of the solar cell [ref. 3]. Thin films of 1.0 and 1.5 micrometer thicknesses were irradiated with 1.00 MeV proton fluences in the range of 1E11 to 1E15 cm^{-2}. The optical and electrical properties of the films were measured. Photothermal Deflection Spectroscopy (PDS) was used to measure the sub-band-gap optical absorption; the dependence of the steady-state photoconductivity on photon flux was measured. 1.00 MeV proton irradiation produced an increase in the sub-band-gap absorption. The sub-band-gap optical absorption was modelled using a convolution method with a density of states function with a peak at about 1.35 eV below the conduction band edge and a full-width at half-maximum of about 0.1 eV. Large decreases in the photoconductivity were also observed. The slope of the photoconductivity versus intensity did not change with irradiation, suggesting that the form of the density of states above the Fermi level was not drastically changing. Room temperature annealing of the sub-band-gap absorption was observed; large changes were observed over a period of nineteen days at room temperature. Following the room temperature anneals, the samples were annealed for one hour at 175°C and the sub-band-gap absorption was restored to its original level for most of the samples. The sub-band-gap absorption of one sample, however, was below its initial level even though the sample had been annealed prior to irradiation. This effect was also observed in our earlier 2.00 MeV helium ion irradiation studies of a-Si:H thin films [ref. 4].

The purpose of this study is to determine whether state-of-the-art solar cells have different radiation resistance properties than cells used in past studies. The reason for raising the question is thin films which exhibited room temperature annealing [ref. 3] were fabricated using state-of-the-art technology. No room temperature annealing of the cells fabricated and studied in 1985 [ref. 3] was reported. Hence, there is a question of the role of the changing solar cell fabrication technology on radiation resistance and annealing characteristics. Additionally, we wish to determine if thin film properties can be correlated with solar cell behavior.

Experimental

Two sets of solar cells were used in this study. One set, referred to as "old cells", consists of four solar cells which were used in a previous study of the radiation resistance of a-Si:H alloy solar cells [ref. 2]. The second set of three cells was recently fabricated and is referred to as "new" cells. The old cells were fabricated in 1985 using the Plasma Enhanced Chemical Vapor Deposition (PECVD) method which was characteristic of the prototype manufacturing technology at that time. The new cells employ current research level PECVD solar cell fabrication technology; this technology was also used in our recent studies of degradation and annealing effects of proton irradiated thin films [ref. 3]. The structure of both sets of cells is ITO/mircrocrystalline $p^+/i/n^+$/stainless steel and the active areas are in the range of 0.8 to 1.0 cm^{-2}; ITO serves as the top electrical contact and anti-reflection coating. The old cells have a grid of screen-printed silver paint, whereas, one of the new cells has a 1000 Angstrom thick Au grid while the other two new cells do not have grids. The efficiencies of the cells were 6-8% under AM1.5 global illumination. One major difference between the old and new cells is the thickness of the intrinsic layers. The new cells were fabricated to produce about the same short-circuit current as the old cells; improvements in material quality result in an intrinsic layer thickness in the new cells which is about one-half the old cells. The intrinsic layer thickness of the old and new cells were 500 and 250 nm, respectively The new cell open-circuit voltage is also about ten percent greater than the old cells. Using an optimum intrinsic layer thickness the state-of-the-art technology may be used to produce single junction solar cells with about 10% efficiency under global AM1.5 illumination.

Prior to irradiation each solar cell was annealed at 190°C for 90 minutes, and the current-voltage characteristics, I-V, measured at room temperature in the dark and under illumination. The illumination source was an ELH lamp filtered through a heat-absorbing filter. The intensity was set using a crystal silicon standard which was calibrated in the AM0 simulator at the NASA Lewis Research Center; the illumination was adjusted to produce the same crystal silicon short-circuit as produced in the AM0 simulator. Due to the spectral mismatch between AM0 and the ELH lamp, the currents observed in the amorphous silicon solar cells were about 70% of what would be obtained under true AM0 illumination. For this reason, we will only discuss changes in the normalized short-circuit current, I_{sc}, open-circuit voltage, V_{oc}, and fill-factor, FF.

The samples were uniformly irradiated with 1.00 MeV protons under a vacuum of 1E-6 Torr to fluences of 1.25E14 and 1.25E15 cm^{-2} using currents of about 50 nanoamperes. The irradiations were carried out with the cells in the dark at room temperature which was approximately 25°C. Half of the cells were irradiated under open-circuit conditions and the other half under short-circuit conditions. Following irradiation the cells were stored in the dark at room temperature and the I-V characteristics measured at various time intervals in order to assess the effect of room temperature annealing. Isochronal anneals, of one hour duration, were also performed at temperatures of 50, 100 and 150°C; the anneals were performed in a vacuum of 1E-7 Torr. The annealing apparatus was well characterized to insure that the sample temperature was the same as the measured temperature and that the ramp times were much less than the annealing times. Upon completion of the isochronal anneals the cells were annealed at either 190 or 200°C for an hour in an attempt to restore the original I-V characteristics.

Results

The effect of 1.00 MeV protons on the I-V characteristics of old and new solar cells is show in figures 1 and 2 . The uncertainty in the I-V measurements corresponds to the symbol sizes used in the figures. Figure 1 shows the effect of a 1.25E14 cm^{-2} fluence on old cell, O-5, and new cell N-3. Notice that the original I_{sc} and FF of cell O-5 and cell N-3 are quite similar. However, cell N-3 has a larger V_{oc} than cell O-5. The effect of the irradiation is to markedly decrease the I_{sc} and FF. Figure 1 shows that cell O-5 degrades much more than cell N-3. Figure 2 shows the effect of a 1.25E15 cm^{-2} fluence of 1.00 MeV protons on old cell, O-6, and new cell, N-6. Again, note that the I_{sc} of both the old and new cells are about the same before irradiation. The FF of cell N-6 appears to be lower than cells O-5, O-6 and N-3. The reason for this apparent discrepancy is cell N-6 does not have a top grid; the ohmic loss in the ITO layer for the collected current results in a low FF for cell N-6. However, the initial V_{oc} of cell N-6 in figure 2 is about the same as the V_{oc} for cell N-3 shown in figure 1. Figure 2 shows the serious irradiation induced degradation of the I_{sc} and FF for cells O-6 and N-6. There is also a marked decrease in the V_{oc} for both cells O-6 and N-6 following irradiation, with the V_{oc} of cell O-6 decreasing more than cell N-6. As with cells O-5 and N-3, the I-V characteristics of cell O-6 degrade more than cell N-6. Figures 1 and 2 show that 1.00 MeV protons with fluences of 1.25E14 and

1.25E15 cm^{-2} produce greater degradation in the I-V characteristics of old cells as compared to new cells.

The effect of annealing on the normalized I_{sc} was investigated at annealing temperatures, T_a=25, 50, 100, 150 and 190°C. The normalized short-circuit current, $I_{sc}(t)/I_{sc}(0)$, is defined as the short-circuit current, $I_{sc}(t)$, at various times, t, following irradiation divided by the short-circuit current before irradiation, $I_{sc}(0)$. We were concerned about the effect of light induced instabilities and annealing on the I-V characteristics of the cells. The effect of the I-V measurements on the cells was explored by carrying out several measurements of the I-V characteristics at one time; in every case the I-V measurements were within the uncertainty of the measurements showing that the normalized I_{sc} was not affected by the I-V measurements.

The effect of annealing on the normalized I_{sc} of old cells, O-5, O-6, and O-9, and new cells, N-5 and N-6, is shown at the top of figure 3 for 1.00 MeV proton fluences of 1.25E14 and 1.25E15 cm^{-2}. Cells O-6, N-5 and N-6 were stored at room temperature in the dark following irradiation for 242, 235 and 260 hours, respectively. The I-V characteristics of the cells were measured at the times shown in figure 3 in order to determine the effect of annealing at T_a=25°C on the normalized I_{sc}. Figure 3 shows the normalized I_{sc} of cell O-6 did not change during 242 hours at T_a=25°C. However, there is considerable annealing of the normalized I_{sc} of cells N-5 and N-6 during the 235 and 260 hour periods, respectively, at T_a=25°C. The normalized I_{sc} increased between 0.1 and 0.15 during the T_a=25°C anneals. It is clear that for a 1.00 MeV fluence of 1.25E15 cm^{-2}, the two new cells anneal more readily at T_a=25°C than the old cell .

Following the T_a=25°C anneals, cells O-6, N-5 and N-6 were isochronally annealed at T_a=100°C for one-hour intervals; the I-V characteristics were measured after each one-hour anneal. Figure 3 shows the time and temperature of the anneals, and the changes in the normalized I_{sc}. The normalized I_{sc} of all three cells increased between 0.2 and 0.4 during the five 100°C isochronal anneals. At the end of the 100°C anneals, the normalized I_{sc} of cell O-6 was about 0.25 while the normalized I_{sc} of cells N-5 and N-6 were about 0.75. Improvements in the FF were also noted for the new cells. Following T_a=100°C anneals, the cells were stored in the dark at room temperature. A final one-hour anneal at T_a=190°C restored the normalized I_{sc} of cells N-5 and N-6 to within 5% of the pre-irradiation values However, a one-hour anneal at T_a=190°C restored the normalized I_{sc} of cell O-6 to within 10% of the pre-irradiation value; an additional one-hour anneal at 200°C restored the normalized I_{sc} of cell to the original value.

The role of 1.00 MeV proton fluence on the annealing of the normalized I_{sc} of two old cells is shown at the bottom in figure 3. Old cells, O-5 and O-9, were irradiated to fluences of 1.25E14 and 1.25E15 cm^{-2}, respectively, and annealed at T_a=25, 150 and 190°C. Annealing for about 330 hours following irradiation at T_a=25°C produced an increase of about 0.1 in the normalized I_{sc} of cell O-5. The change is less than the new cells which were irradiated with an order of magnitude higher fluence. The recovery in the normalized I_{sc} of cell O-9 is less than 0.02 during a 308 hour T_a=25°C anneal. The results of cell O-9 agree with those of cell O-6 also shown at the top of figure 3; cell O-6 was also irradiated to a fluence of 1.25E15 cm^{-2}. Room temperature annealing effects for the old cells which were irradiated to 1.25E15 cm^{-2} with 1.00 MeV protons may be considered to be negligible. Both of the old cells, O-5 and O-9, were annealed at T_a=150°C for one- hour intervals beginning 308 and 332 hours after irradiation, respectively; their annealing behavior is different and suggests that the higher level fluence introduces different defect structures. The first one-hour T_a=150°C anneal of cell O-5 produced a change of about 0.6 in the normalized I_{sc}; the second one-hour anneal does not produce a change in the normalized I_{sc}. The T_a=150°C anneals of cell O-9 produce a continuing increase in the normalized I_{sc}. The first T_a=150°C one-hour anneal of cell O-9 produced an increase of about 0.5 in the normalized I_{sc}; the second one-hour anneal increased I_{sc} about 0.15 and the third one-hour anneal produced an increase of about 0.05. Following the T_a=150°C anneals, the cells were stored at room temperature in the dark except for the time during which the I-V measurements were carried out; the measurements show there is no further room temperature annealing of the normalized I_{sc}. At about 350 hours following irradiation, cells O-5 and O-9 were annealed at T_a=190°C for one hour. The T_a=190°C anneals resulted in slight improvements the normalized I_{sc} but did not restore the original I-V characteristics. A final one-hour T_a= 200°C anneal restored the original I-V characteristics to within about 5%. Additional observations on another old cell showed that T_a=50°C anneals of a cell irradiated to 1.25E14 cm^{-2} produced negligible changes in the normalized I_{sc} following about 280 hours of T_a=25°C annealing.

Figure 4 shows the detailed I-V characteristics under illumination for new cell, N-3, prior to irradiation, and at various times following irradiation during the T_a=25°C anneals; the I-V characteristics following a final one-hour T_a=190°C is also shown. The first I-V measurement on cell N-3 following the 1.00 MeV proton irradiation was at 48 hours and shows that the effect of a fluence of 1.25E 14 cm^{-2} is to cause a decrease of about 30% in the normalized I_{sc}. There are significant increases in I_{sc} for T_a=25°C at 163 and 212 hours following irradiation. The I_{sc} is within a few percent of the pre-irradiated value after 212 hours of T_a=25°C annealing. The open-circuit voltage and fill factor are however not restored. The effect of a one-hour T_a=190°C anneal is to restore the FF and V_{oc} to the original values; the annealing increased I_{sc} to a value approximately 20% greater than the value prior to irradiation.

Discussion

One of the purposes of this work is to evaluate the radiation resistance of cells fabricated using current research technology, referred to as new cells, with cells fabricated in 1985, referred to as old cells. The results shown in figures 1 and 2 show that the new cells have radiation resistances that are far superior to the old cells. The new cells degrade less than the old cells for 1.00 MeV proton fluences even when the fluences are an order of magnitude greater. There are two major known differences between the new and old cells which are believed to be due to the materials used in the fabrication of the solar cells.

The first device material difference between the new and old cells is the improvements make it possible to fabricate thinner single junction solar cells with the same efficiencies as the older thicker cells. This is believed to be due to the fact that the new materials result in increased collection efficiencies of the new cells. Increased collection efficiencies are inferred from the relationship between cell current and thickness. The new and old cell currents are about the same under AM1.5 global illumination while the cell thicknesses differ by about a factor of two. The new cells are between 250 to 300 nanometers thick, whereas the old cells are between 500 to 600 nanometers thick. However, figures 1 and 2 show that the I_{sc} are about the same. The increased radiation resistance of the new cells suggests that thickness may be an important parameter. Earlier work by Woodyard and Hanak [ref. 6] showed that tandem junction solar cells are more radiation resistant than single junction devices. Since the individual intrinsic layers of tandem junction solar cells are thinner than those of single junction cells, they suggested that the improved radiation resistance of the tandem cells was due to the fact that the intrinsic layers were thinner. We also suggest that one of the reasons for the improved radiation resistance of the new cells is due to the fact that the cells are thinner than the old cells.

The second material dependent difference between the new and old cells is the current fabrication technology results in solar cells with increased V_{oc}. The V_{oc} increase is about 0.1 V as shown in figure 1. The improved V_{oc} is a result of improved materials. These improved materials may result in better solar cells for many reasons including, among other things, better junction interfaces, wider band-gap p^+ and n^+ layers, and fewer electrically active defect centers in the cell layers. The reasons for these improvements are not well understood but are probably related to the structure of the material and the role of hydrogen. We have studies in progress with the objective of separating the role of material structure and hydrogen by fabricating cells under different conditions and controlling the hydrogen concentration through annealing and hydrogenation schedules.

The work reported in this paper does not support the point of view that the only reason for the good radiation resistance of solar cells fabricated from a-Si:H based alloys is the poor initial efficiency and quality of the device material. The point of view suggests that the reason for the good radiation resistance is the virgin material has a high level of intrinsic defects and the cell parameters do not decrease until the radiation induced defects exceed the intrinsic defects. Those with this point of view suggest that this will occur at a higher fluence than for cells fabricated with good material. This work shows that as the quality of the a-Si:H material increases, both the cell parameters and radiation resistance improve. We conclude that it is possible the improved radiation resistance of the new solar cells is due to the improved material quality. In order to understand the role of cell thickness and material quality, device simulation studies must be carried out using numerical models which include fundamental device parameters, such as the density of electronic states and device structure. This is a subject of intense interest in this and other laboratories. We believe that a definitive and quantitative relationship between cell thickness, material properties and radiation resistance can be developed by solar cell modelling studies. To this end, we have solar cell modelling work in progress and will report on these studies in the future. A combination of material properties and thickness are probably important in determining the radiation resistance of a-Si:H alloy based solar cells.

Several points are to be emphasized concerning the annealing results shown in figures 3 and 4. The first is that both new and old solar cells show room-temperature annealing effects. The rate of annealing appears to be dependent upon the total number of radiation induced defects as evidenced by the decrease in the normalized I_{sc}. That is, if the light I-V characteristics are about the same following irradiation, then the rate of annealing appears to be similar. A comparison of N-5 and O-5 in figure 3 illustrates this point. This hypothesis must however be tested over a very much larger range of fluences. The annealing rate is temperature dependent; the rate for T_a=100°C is greater than the T_a=25°C rate. An analysis of the figure 3 data suggests there are at least two types of defects and/or annealing mechanisms. One type appears to operative at T_a <150°C and the other at T_a >190°C. This effect has been reported earlier [ref. 6] and was suggested as being due to different defect structures. We are no closer to understanding this effect except that room temperature annealing also raises the possibility that the T_a <150°C annealing may be due to defects resulting from electronic stopping effects. Electronic stopping was excluded in the earlier work because the degradation in cell efficiency followed the changes in nuclear stopping power.

These investigations were also carried out to determine if our earlier PDS studies with thin films of a-Si:H could be used to predict solar cell characteristics [ref. 4]. In the earlier work, we observed room-temperature annealing of the sub-band-gap optical absorption; we also observed that irradiation and annealing produced lower sub-band-gap optical absorption than a virgin film. As discussed above, the room temperature annealing of solar cells was observed, suggesting the usefulness of the PDS observations. This work shows that irradiation with subsequent annealing results in a higher cell efficiency than the virgin cell. The convincing evidence is figure 4 which shows a 20% improvement in the normalized I_{sc} following irradiation and annealing. This observation is also in agreement with our PDS predictions. Based on our PDS investigations and density of states model [ref. 4], we suggest the increase in the normalized I_{sc} results from a decrease in the density of states within the mobility gap of the intrinsic layer; the decrease reduces the number of recombination centers. The reduction in the number of recombination centers increases the carrier collecting efficiency and normalized I_{sc}.

Conclusions

We have shown that 1 MeV proton irradiation with fluences of 1.25E14 and 1.25E15 cm^{-2} reduces the normalized I_{sc} of a-Si:H solar cell. Solar cells recently fabricated showed superior radiation tolerance compared with cells fabricated four year ago; the improvement is probably due to the fact that the new cells are thinner and fabricated from improved materials. Room-temperature annealing was observed for the first time in both new and old cells. New cells anneal at a faster rate than old cells for the same fluence. From the annealing work it is apparent that there are at least two types of defects and/or annealing mechanisms. One cell had improved I-V characteristics following irradiation as compared to the virgin cell. The work shows that the PDS and annealing measurements may be used to predict the qualitative behavior of a-Si:H solar cells. We anticipate that our modelling work will quantitatively link thin film measurements with solar cell properties.

Quantitative predictions of the operation of a-Si:H solar cells in a space environment will require a knowledge of the defect creation mechanisms, defect structures, role of defects on degradation, and defect passivation and annealing mechanisms. We have work in progress to develop the engineering data and knowledge base for justifying space flight testing of a-Si:H alloy based solar cells.

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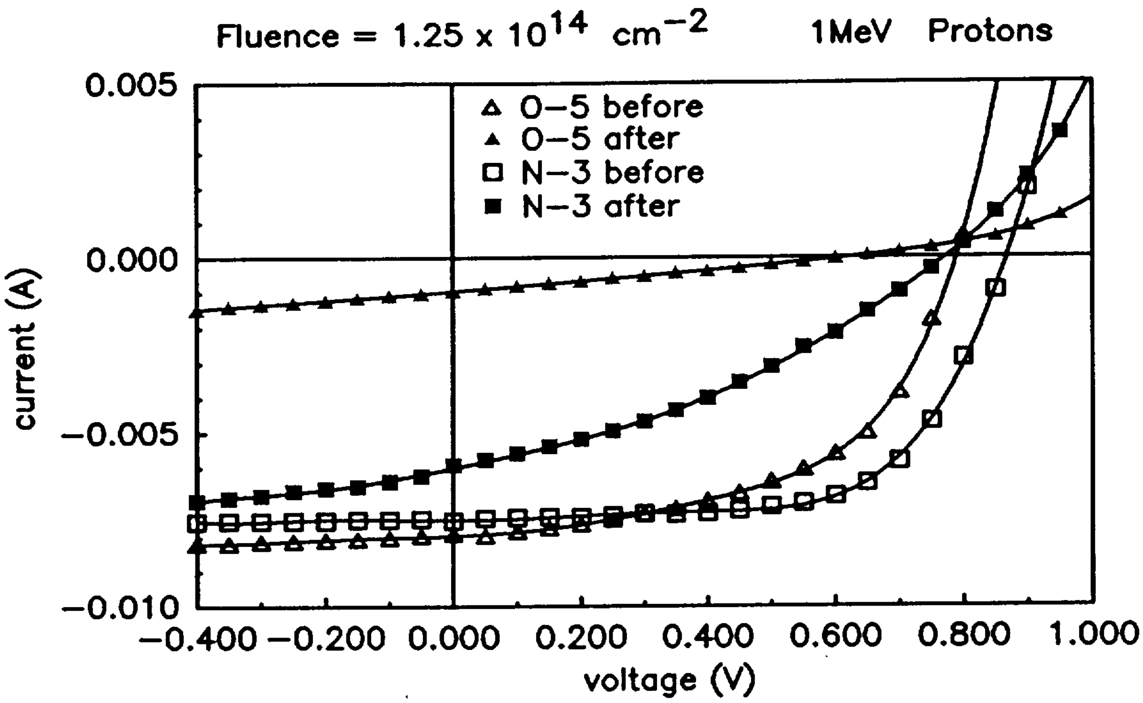

Figure 1. Light I-V characteristics of old cell, O-5, and new cell, N-3, before and after irradiation with a 1.00 MeV proton fluence of 1.25E14 cm-2

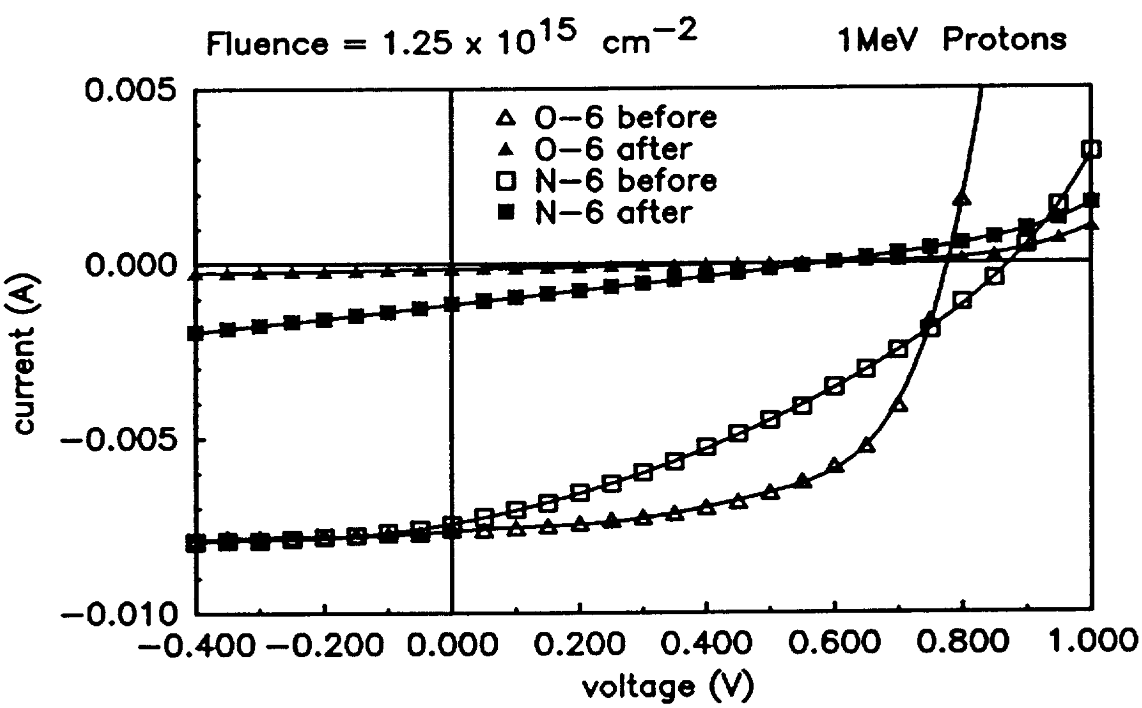

Figure 2. Light I-V characteristics of old cell, O-6, and new cell, N-6, before and after irradiation with a 1.00 MeV proton fluence of 1.25E15 cm-2

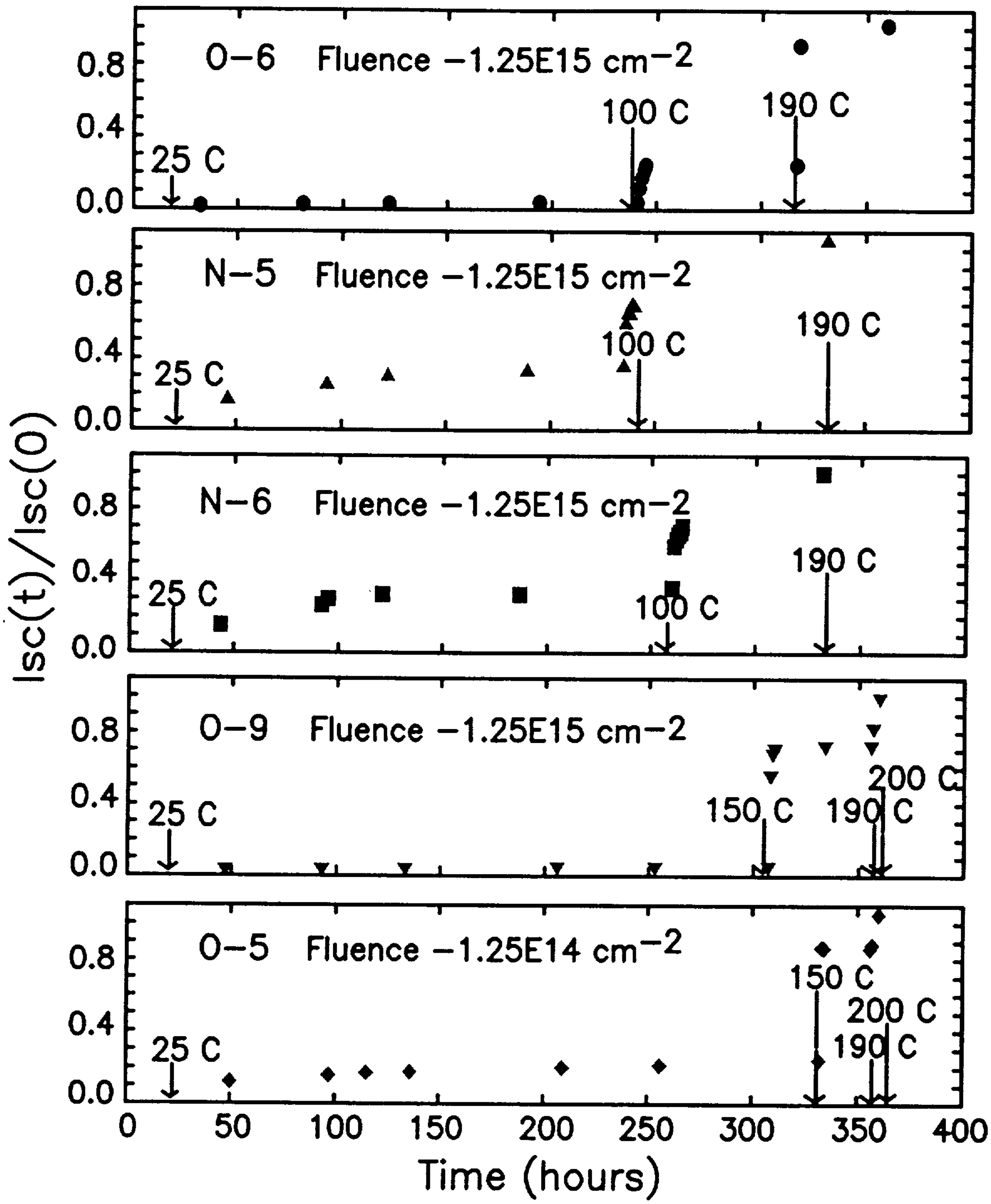

Figure 3. Annealing characteristics of the normalized Isc following irradiation with 1.00 MeV protons. The fluence was 1.25E14 cm-2 for cell O-5 and 1.25E15 cm-2 for cells O-6, O-9, N-5 and N-6. The annealing temperatures were 25 °C for the times shown. One-hour 100, 150, 190 and 200 °C anneals were carried out at the times shown by the arrows.

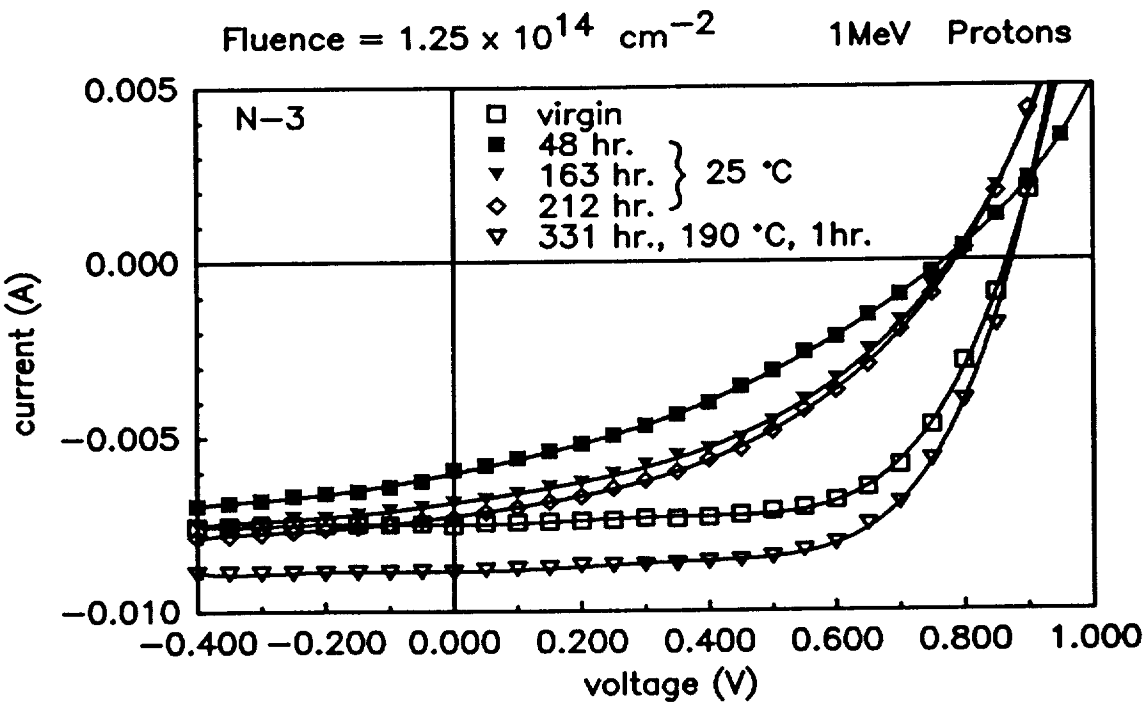

Figure 4. Light I-V characteristics of new cell, N-3, before and after irradiation with a 1.00 MeV proton fluence of 1.25E14 cm-2. The I-V characteristics were measured at various times during a 331 hour anneal at 25°C and then after a one-hour anneal at 190°C.