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DEVELOPMENT OF COPPER SULFIDE/CADMIUM SULFIDE
THIN-FILM SOLAR CELLS

Thirteenth Technical Progress Report for July 1–September 30, 1982

By
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June 16, 1983

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Westinghouse R&D Center
Pittsburgh, Pennsylvania

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Solar Energy

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DEVELOPMENT OF COPPER SULFIDE/CADMIUM SULFIDE THIN-FILM SOLAR CELLS

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ABSTRACT

During this period we modified the characteristics of a completed cell by laser treatment in order to alter the sensitivity of the heterojunction behavior to the aging effects of oxygen and moisture. Previously we associated the changes in opposing current which affect the open-circuit voltage of the cells during aging with an increased value of the electric field in the space charge region. The present work demonstrates a strong correlation between the short-circuit current behavior and the density of deep donor states which control open-circuit voltage behavior. Practically speaking, the general degradation trends in the short-circuit current and the opposing current behavior, which we observed in control cells earlier, occur after substantial delay in the laser-treated cell. The laser treatment reduced the rate of the degradation effects in question by at least one order of magnitude. Furthermore, during the early stages of aging in wet oxygen, the laser-treated cell performance was enhanced in terms of both short-circuit current and opposing current.

1. SUMMARY

During this period we modified the characteristics of a completed cell by laser treatment in order to alter the sensitivity of the heterojunction behavior to the aging effects of oxygen and moisture. Previously we associated the changes in opposing current which affect the open-circuit voltage of the cells during aging with an increased value of the electric field in the space charge region.

In the previous period we found that argon laser treatment, in nitrogen, of a cell having more conventional tunneling-controlled behavior produced regular effects on the cell characteristics. In particular, the open-circuit voltage at constant short-circuit current increased as a result of the treatment. On the basis of the encouraging initial results, we continued to pursue laser treatment studies.

After the initial treatments in nitrogen, the cell was stored in flowing hydrogen for 15 days. It was then annealed in flowing hydrogen overnight at 150°C and laser treated in flowing hydrogen. The behavior of the cell exhibited several distinct features. The short-circuit current at fixed irradiance fell as a result of the first two laser treatments, with little change on subsequent treatment. Similar behavior was noted for the earlier laser treatment of this cell in nitrogen. The saturated value of the short-circuit current depended on the irradiance value, which is reflected in the pretreatment value of short-circuit current.

In analyzing the opposing current behavior of the cell, we used the tunneling model of Haines and Bube to treat the experimental curves of the logarithm of short-circuit current versus open-circuit voltage. These curves can be complex, generally having two branches. As a result of various treatments, the slopes and intercepts (saturation current

values) of both branches change. Systematic changes in these parameters due to annealing treatments can be discerned more easily than can changes in the original data. The slope parameter is of special physical interest, since it is a measure of the electric field at the heterojunction.

For our cells, a plot of the data in terms of the logarithm of saturation current versus values of the slope fall along a universal curve. The tunneling model associates the slope of the universal curve (or of a similar straight line) with the difference between the energy of the deep donor centers (below the CdS conduction band) and the barrier height of the heterojunction at zero temperature. The laser treatments had a relatively simple influence on the behavior of the tunneling model parameters: decreasing the values of slope and increasing the value of the current intercept.

The laser treatment in hydrogen had beneficial effects on both the short-circuit current capability and the opposing current behavior of the cell during room-temperature aging in flowing oxygen at 95% R.H. For decreasing irradiance levels, the aging time at which the short-circuit current achieved its maximum value decreased from 150 to about 6 hrs. In the time following the peak, the loss of short-circuit current was 10 to 40% with the larger losses being associated with lower irradiance values. Previously during aging we have seen substantial losses for control cells.

During the course of aging, the detailed photovoltaic behavior of the cell also underwent significant change. Under these conditions, the only source of physical variation in this parameter is a change in the effective density of the donors in the space charge region at the heterojunction. Just as for the short-circuit current behavior during aging, the time variation in effective density of donors for the laser-treated cell suggests the action of several opposing mechanisms. There was a decrease of 20 and 10% for the donor density values associated with the upper and lower branches, respectively, during the first 75 to

125 hrs of aging. After 267 hrs of aging, the respective donor densities increased and were 0 and 15% larger than initially. For the control cell the donor density increased throughout 400 hrs of aging, with more than a 40% increase during the first 50 hrs.

The time-dependent behavior during aging of both the short-circuit current and the effective donor density are strongly correlated. The enhancement of short-circuit current during the first 100 hours of aging could be explained by a decrease, because of the laser treatment, in the density of recombination centers in the space charge region adjacent to the copper sulfide. Since the percentage changes in both the short-circuit current enhancement and the decrease in effective donor density were 10 to 20%, the donor density must be dominated by the deep donors. These must also act as the recombination centers which reduce the collection of photocurrent. The irradiance sensitivity of the short-circuit behavior during aging suggests that photomodulation of these centers occurs under the conditions of the laser treatment and aging which we have used.

Finally, we note that during the course of aging, the covariation of the tunneling parameters did not follow exactly the universal curve behavior. In the context of the tunneling model, the deviation requires that the difference between the deep donor level and the zero-temperature barrier height energy be about 10% more positive than in an untreated aged cell. A 50 mV increase in the energy depth (below the conduction band) of the deep donor sites through which tunneling occurs would be needed for this change.

The origin of the deep donor sites has not been established. Haines suggests that they may be associated with the second level of a sulfur vacancy. The density would be reduced if adsorbed oxygen at the interface were to occupy sulfur sites. Since the interfacial region is expected to be highly disordered, the existence of energetically sharp states is unlikely. Changes in the chemical bonding details and the solid state chemistry of sulfur, oxygen, and other species affecting the

deep donors could be produced by local heating and photo-activation during the laser treatment, in conjunction with subsequent annealing in hydrogen. Such changes could perturb the donor state energy by the amount we infer from our studies.

Practically speaking, the general degradation trends in the short-circuit current and the opposing current behavior, which we observed in control cells earlier, occur after substantial delay in the laser-treated cell. The aging time required to develop 50% of the degradation in either short-circuit current or in the increase of effective donor density was about 35 hrs for the case of control cells. For the laser-treated cell, assuming that the same net degradation would be observed with sufficient aging, the time for 50% degradation exceeds 267 hrs. We conclude that the laser treatment reduced the rate of the degradation effects in question by at least one order of magnitude. Furthermore, during the early stages of aging in wet oxygen, the laser-treated cell performance was enhanced in terms of both short-circuit current and opposing current.

The results presented here show promise for improving the degradation behavior of thin-film, copper sulfide/cadmium sulfide solar cells. More effort would be required to understand and optimize the action of laser radiation on the chemical, structural, and defect properties of these cells.

2. INTRODUCTION

2.1 Objective

The objective of this program is to characterize and improve the stability of $\text{Cu}_2\text{S}/\text{CdS}$ thin-film solar cells having conversion efficiency values of at least 9%. Specifically, the current phase of the program is concerned with: 1) identifying mechanisms which degrade cell performance, 2) improving the stability of cells by encapsulation, and 3) improving the intrinsic stability of cells by modifying the cell structure during or after fabrication.

2.2 Background

This is the third phase of the present contract. In the other two phases we defined and characterized a reproducible process for fabricating high-efficiency cells⁽¹⁾ and we identified several major degradation effects in these cells which involve the combined influences of oxygen and moisture.⁽²⁾ During this phase we have associated the changes in opposing current which affect the open-circuit voltage of the cells during aging with an increased value of the electric field in the space charge region.⁽³⁾ In the context of a tunneling model proposed by Haines and Bube, the electric field is determined by the combined density of shallow and deep donors and of copper-related acceptors in the CdS adjoining the heterojunction.⁽⁴⁾

During the preceding quarter we attempted to modify the characteristics of completed cells by ion implantation and by laser treatment in order to alter the sensitivity of the heterojunction behavior to the aging effects of oxygen and moisture.⁽⁵⁾ Results with ion implantation were not encouraging. For a cell implanted with Mg^+ , the changes in open-circuit voltage and short-circuit current were

similar to those in control cells which were aged at the same time. We noted, however, that prior to implantation, the cells in question exhibited a typical tunneling-controlled behavior which is usually associated with very poor or degraded cells. The findings do not rule out the possibility of beneficial effects of ion implantation on cells selected for more typical behavior.

Also during the preceding quarter, we noted that argon laser treatment of a cell with more conventional tunneling-controlled behavior produced regular effects on the cell characteristics. In particular, tunneling-controlled opposing current appeared to be reduced by the laser treatments.⁽³⁾ On the basis of this encouraging indication, we have continued studies of laser-annealed, copper sulfide/cadmium sulfide thin-film solar cells.

The current phase of the program has three tasks:

Task 1. Identify major degradation mechanisms. This task is to be addressed by subjecting cells to selected conditions of temperature and moisture content of the gas ambient, then characterizing relevant performance as a function of aging time.

Task 2. Improve environmental stability of cells by encapsulation. Except for work already completed in terms of characterizing and selecting cells suitable for encapsulation, this task has been reduced in scope to permit the remaining program effort to be applied to Task 3.

Task 3. Improve the intrinsic stability of $\text{Cu}_2\text{S}/\text{CdS}$ solar cells. Modification of the copper sulfide layer will be attempted by several means, including ion implantation. Evaluations of the effects of these changes will be made in terms of cell behavior during aging, with comparisons being drawn using results for baseline and encapsulated cells.

2.3 Approach

There are three aspects to the technical approach being taken during this phase of the program: 1) determining the kinetics of the short-circuit current loss and of the opposing current changes for baseline cells aged under various conditions, 2) evaluating the efficiency of encapsulation in retarding these degradation effects, and 3) investigating whether chemical or physical modifications of the cell structure can suppress the degradation effects.

During the current period, we continued characterization of the cell which had been previously laser annealed in a nitrogen ambient. The cell was first given a standard overnight anneal in hydrogen at 150°C and then examined in terms of its J_{SC} versus V_{OC} behavior. Subsequently, the cell was laser annealed in flowing hydrogen to make comparisons with the effects of similar treatment in flowing nitrogen, reported earlier in Reference 5. Finally, we aged this treated cell in a room-temperature ambient of flowing oxygen at about 95% relative humidity in order to determine if the laser treatment was beneficial in reducing degradation of cell performance during such aging.

3. PROGRESS

3.1 Laser Annealing in Hydrogen

The cell used for this study had been previously laser treated in flowing nitrogen and characterized in terms of its photovoltaic performance, as described in Reference 5. After that investigation, the cell was stored for approximately 15 days at room temperature in flowing hydrogen at 150°C. The effects of the overnight anneal were to increase the short-circuit current of the cell for fixed irradiance and to increase its open-circuit voltage at either fixed irradiance or at fixed short-circuit current.

As we have noted previously, the details of the experimental curves showing $\ln J_{SC}$ versus V_{OC} behavior can be complex. Generally, the curves have two branches, as shown by the solid and broken lines in Figure 1. (The discontinuity in the upper branch behavior at zero on the ordinate reflects some slight spectral sensitivity arising from the rise of gelatine filters in obtaining data at low irradiance values.) As a result of various treatments, the slopes and intercepts of both branches change. From the experimental data, we have evaluated the tunneling model parameters (qa_1) and $\ln J_0$ which were used by Hainès and Rube,⁽⁴⁾ This allows us to discern systematic changes due to annealing treatments more easily than can be done by considering the raw data.

The parameter qa_1 is a measure of the electric field at the heterojunction. For our cells, pairs of qa_1 and $\ln J_0$ values usually fall along a universal curve, which is shown as the solid line in Figure 2. In the tunneling model, the slope of the universal curve (or of a similar straight line) is equal to the difference between the energy

Figure 1... Example of photovoltaic performance, showing upper (solid) and lower (dashed) branches of the $\ln J_{sc}$ versus V_{oc} curves.

Figure 2. Tunneling parameter behavior for a laser-treated cell.

below the CdS conduction band of the deep donor centers and the barrier height of the heterojunction at zero temperature (ϕ_{T0}).

In the current study before annealing, the cell behavior was slightly above the universal curve which appears to describe the behavior of our cells. After annealing, the behavior of the upper branch of the $\ln J_{SC}$ versus V_{OC} curve was nearly on the universal curve.

With laser treatments in flowing hydrogen, the behavior of the cell exhibited several features. As we also have noted in Reference 5 for the case of laser treatment in nitrogen, the short-circuit current at fixed irradiance fell as a result of the first two laser treatments, with little change on subsequent treatment (Figure 3a). The saturated value of the short-circuit current depended on the irradiance value,

Figure 3. Effects of laser treatment on short-circuit current performance of a cell at various irradiance levels.

which is reflected in the pretreatment value of short-circuit current, as shown in Figure 3b.

We also observed that the first laser treatment produced a distinct discontinuity in the $\ln J_{sc}$ versus V_{oc} curve at an ordinate value of about -0.68, as is shown in Figure 4. This effect appears to be associated with the gelatine filters used to extend the lower range of irradiance characterization.* In this case, the net result of the effect on the upper branch of the $\ln J_{sc}$ versus V_{oc} curve was to improve

* In characterizing the cell for the aging experiment, which is described in the next section, we also used an optical filter consisting of a metal film on glass (purchased from Melles Griot, Irvine, CA). With that filter, which is more constant in its transmission versus wavelength behavior than the gelatine filter, there was no discontinuity of the type noted when the gelatine filter was used.

Figure 4 Changes in photovoltaic performance resulting from the first laser treatment, using the behavior following a hydrogen anneal at $150^\circ C$ for 17 hrs as the reference.

the open-circuit voltage by approximately 30 mV in comparison with results obtained without the use of the filters. This effect was not influenced significantly by three more laser treatments like the first.

Finally, we note that the laser treatments had a relatively simple influence on the behavior of the tunneling model parameters -- $q a_i$ and $\ln J_0$ -- as shown in Figure 5. Considering the entire series of treatments, the general trend was for values of $q a_i$ to decrease and for values of $\ln J_0$ to increase as a result of the laser exposures. The only exception to this was an opposite sense of change for the behavior of the lower branch of the $\ln J_{SC}$ versus V_{OC} curve after the first laser exposure.

3.2 Aging of a Laser-Annealed Cell

We installed the laser-treated cell described above in the Stress/Evaluation tube described in the Tenth Technical Progress Report for this program.⁽⁶⁾ After equilibrating the cell in an ambient of flowing dry hydrogen at room temperature, we characterized its photovoltaic performance over a wide range of irradiance values to establish upper and lower branches for the $\ln J_{SC}$ versus V_{OC} curve. The gas in the tube was changed to flowing oxygen at 95% (or greater) relative humidity and the cell was aged in that ambient at room temperature. No control cells were used in this experiment since at least six had been aged under similar conditions in the past.

During an aging period of more than 250 hrs, the behavior of the laser-treated cell was distinctly different from anything which we had observed earlier on other cells. Short-circuit current at the highest irradiance levels which we used improved substantially within the first 100 hrs of aging. By way of contrast, for untreated cells we have always seen a significant loss in short-circuit current capability under such conditions.

Figure 6 shows a plot of short-circuit current behavior (for various irradiance values over a range of about one decade) during

Figure 5. Changes in tunneling parameters during the course of laser treatments.

aging. The curves are normalized with respect to the short-circuit current value at each level of irradiance prior to the start of aging. These results show a relatively complex influence of the irradiance. For decreasing irradiance levels, the aging time at which the short-circuit current achieved its maximum value decreased from 150 to about 6 hrs. In the time following the peak, the loss of short-circuit current was 10 to 40%, with the larger losses being associated with lower irradiance values.

Figure 6. Short-circuit current capability, for various levels of irradiance, of a laser-treated cell during aging in a flowing ambient of moist oxygen at room temperature.

During the course of aging, the detailed photovoltaic behavior of the cell underwent significant change as well. This can be best appreciated in terms of the changes in the tunneling model parameters -- qa_i and $\ln J_{SC}$ versus V_{OC} data. For the upper branch, the value of qa_i increased during the first 75 hrs of aging. This was accompanied by a decrease in the value of $\ln J_0$ in a manner consistent with, but not falling directly on, the universal curve of Figure 2. For the lower branch, during the first 6 hrs of aging, the value of qa_i dropped

slightly, recovered after 25 hrs, and increased slightly to follow the behavior of the upper branch thereafter. The value of $\ln J_0$ tracked the changes in qa_1 to follow the universal curve of Figure 2.

Aging produced no significant changes in the tunneling model parameters for the 75 to 120 hr periods. Data taken after 195 hrs of aging indicated some intermittent contact problems. For the next set of measurements, which were taken after 267 hrs of aging, there was a substantial change in the behavior of both branches, giving lower values of qa_1 .

The aging experiment was terminated after 267 hrs because of the contact problems. After cleaning of the contact and annealing the cell in flowing hydrogen at 150°C for about 100 hrs, the short-circuit current capability of the cell was restored. The opposing current behavior of the cell was not restored to its pre-aging state, however. In fact, for the upper branch, the final value of qa_1 was about 20.8/eV.

3.3 Discussion

3.3.1 Laser Treatment in Hydrogen

In our experiments with the laser treatment of copper sulfide/cadmium sulfide thin-film solar cells, we have not observed a substantial difference of photovoltaic performance associated with the gas ambient during the treatment. For either nitrogen (as treated in Reference 5) or hydrogen, the short-circuit current at constant irradiance falls with subsequent treatments at constant laser power, saturating after two or three treatments. The percentage lost at saturation is a function of the irradiance (Figure 3b), indicating that a simple mechanism such as the reduction of the minority-carrier diffusion length cannot explain the effect. There is a possibility that this effect involves photomodulation of traps which control heterojunction collection efficiency, as we noted in Reference 5. In the present case of treatment in hydrogen, there is co-variation of the loss of short-circuit current (Figure 3a) with changes in values of the

tunneling parameter qa_1 (Figure 5a). This suggests that the laser treatment in hydrogen affects the density of centers which control heterojunction collection efficiency as well as junction opposing current. Previously, for treatment in nitrogen, there was no discernible effect on the parameter qa_1 .

Another indication of defect-related spectral sensitivity associated with the laser treatment in hydrogen is the shift in upper branch behavior of the $\ln J_{SC}$ versus V_{OC} curve (Figure 4) associated with the use of a gelatine-type neutral density filter. With the use of a metal thin-film filter having an optical density of 1.00 ± 0.05 for the 330 to 700 nm range of wavelengths, there was no such effect.

From these observations a qualitative picture can be proposed of the effect of laser treatment on the cell in question. Based on the upper branch of the $\ln J_{SC}$ versus V_{OC} curve, the effective density of donors in the space charge region is increased slightly by laser treatment. For the lower branch there is a similar but stronger effect when the entire course of treatments is considered. For this branch the first laser treatment seems to have an opposite effect, namely to decrease somewhat the effective density of donors.

The vertical displacements of the curves for qa_1 and for $\ln J_0$ in Figure 5 indicate the degree to which those parameters fall along the universal curve of Figure 2. The ordinate scales in Figure 5 were chosen so that congruent points for $\ln J_0$ and for qa_1 would indicate behavior along the universal curve of Figure 2. From Figure 5 we note that the upper branch behavior tracks the universal curve during the series of laser treatments. For the lower branch, however, the $\ln J_0$ parameter is lower in value than that associated with the universal curve. In Section 3.3.2 we will consider a related effect which is associated with changes in the cell due to aging in wet oxygen.

3.3.2 Aging of Cells After Laser Treatment in Hydrogen

The laser treatment in hydrogen had several beneficial effects on the photovoltaic performance of the cell in question during room-temperature aging in flowing oxygen at 95% R.H. In the first place, the loss in the short-circuit current capability of the treated cell was much less than for untreated cells which were characterized earlier. In the second place, the treated cell exhibited much smaller changes in opposing current behavior than we have seen in untreated cells under similar aging conditions.

Considering short-circuit current behavior during aging, we have previously seen substantial losses for control cells. These losses could be viewed as being approximately exponential in time with moderate values of time constants (25 to 47 hrs). Examples of loss for those cases are shown by the broken curves of Figure 6. The curves are adapted from original results shown in Figure 1 of Reference 4 and in Figure 3 of Reference 7. In the present case of the laser-treated cell, the short-circuit current loss behavior for low irradiance levels (Curves E and F in Figure 6) may be approximately exponential. The data for the aging period we used are not sufficient to establish this. If exponential components of loss are assumed, their normalized values would be less than 0.5 instead of approximately 1.0 for the untreated cells.

For higher irradiance values, net loss did not occur until after an interval during which there was current enhancement of 10 to 25%, as shown in curves A through D in Figure 6. Such behavior suggests the operation of at least two competing mechanisms. We discuss below a phenomenological model for such behavior.

In order to compare aging effects on opposing current behavior for the treated cell with that for an untreated one considered earlier (Figure 2 and 3, Reference 3), we have used the values of the tunneling parameter qa_1 in Figure 7. For the aging experiment, the only source of physical variation in this parameter is a change in the effective

Figure 7. Changes in tunneling parameters of a laser-treated cell during the course of aging in moist oxygen.

density of the donors in the space charge region at the heterojunction. Specifically, $q a_i$ is inversely proportional to the square root of the effective density of donors.

Figure 8 shows the effective density of donors during aging (normalized with respect to the density value at the beginning of the respective experiments) in a comparison of the present results for the laser-treated cell with those reported earlier (in Figure 5 of Reference 3) for an untreated cell. For the control cell (broken curve in Figure 8), the donor density increased throughout 400 hrs of aging, with more than a 40% increase during the first 50 hrs. For the laser-treated cell

Figure 8. Comparison of the effective density of donors in the CdS space charge region during aging for a laser-treated cell (solid curves) and for an untreated cell.

we have used the qa_i behavior of Figure 7 which was obtained by considering both the upper and the lower branches of the original $\ln J_{SC}$ versus V_{OC} curves. Just as for the short-circuit current behavior during aging, the time variation in effective density of donors suggests the action of several opposing mechanisms. There was a decrease of 20 and 10% for the upper and lower branches, respectively, during the first 75 to 125 hrs of aging. After 267 hrs of aging, the respective donor densities increased and were 0 and 15% larger than initially.

When considered together, the time-dependent effects during aging of short-circuit current enhancement or loss and the relative increase or decrease of effective donor density appear to be strongly correlated. The correlation could be explained by a simple phenomenological view of laser treatment effects on the cell.

We noted above that during the course of aging, the co-variation of the tunneling parameters -- $\ln J_0$ and qa_i -- did not follow exactly the universal curve of Figure 2. In the interval from 50 to about 125 hrs, as the value of qa_i increased (effective donor density decreasing), the values of $\ln J_0$ were higher than those along the universal curve. Thus, if one were to fit a single curve to the data of Figure 2, the slope would have a lower negative value than does the universal curve. In the context of the tunneling model, this requires that the quantity $(E_i - \phi_{T0})$ be about 10% more positive than in an untreated, aged cell. Since a change in ϕ_{T0} would imply a change in the net bulk doping of the CdS, it is unlikely to be the source of the effect.

The remaining alternative requires a 50 mV increase in the energy depth (below the conduction band) of the deep donor sites through which tunneling occurs. The nature of these sites has not been established. Haines (Reference 7, p. 112) suggests that they may be associated with the second level of a sulfur vacancy in which the density would be reduced if adsorbed oxygen at the interface occupied sulfur sites. Since the interfacial region is expected to be highly disordered, the existence of energetically sharp states is unlikely. Changes in the chemical bonding details and the solid state chemistry of sulfur, oxygen, and other species affecting the deep donors could perturb the donor state energy by the amount we infer from our studies. Such changes could be produced by local heating and photo-activation during the laser treatment in conjunction with subsequent annealing in hydrogen.

The enhancement of short-circuit current during the first 100 hrs of aging can be explained by a decrease in the density of

recombination centers in the space charge region adjacent to the copper sulfide. Since the percentage changes in both the short-circuit current enhancement and the decrease in effective donor density were 10 to 20%, the donor density must be dominated by the deep donors. These must also act as the recombination centers which reduce the collection of photocurrent. The irradiance sensitivity of the short-circuit current behavior during aging indicates that photomodulation of the population of these centers occurs under the conditions of the laser treatment and aging which we have used. It is likely that the details of the upper and lower branch opposing current behavior are affected in a related manner.

Finally, we consider the cell behavior after about 150 hrs of aging. From Figures 6 and 8 it appears that the general degradation trends in the short-circuit current and the opposing current behavior, which we observed in control cells earlier, occur after substantial delay in the laser-treated cell. The aging time required to develop 50% of the degradation in either short-circuit current or in the increase of effective donor density was about 35 hrs for the case of control cells. For the laser-treated cell, assuming that the same net degradation would be observed with sufficient aging, the time for 50% degradation exceeds 267 hrs. We estimate that aging times of more than 350 hrs would be needed to see such effects.

We conclude that the laser treatment reduced the rate of the degradation effects in question by at least one order of magnitude. Furthermore, during the early stages of aging in wet oxygen, the laser-treated cell performance was enhanced in terms of both short-circuit current and opposing current.

4. PLANS

We will continue with studies of laser treatment to improve the stability of cells aged in moist oxygen. New cells will be selected to use as controls and for laser treatment. In particular, we plan to extend the duration of the aging experiments and to consider a laser-treated cell aged under room-temperature conditions.

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