Accelerated Stability Testing of Amorphous Silicon Solar Cells

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We present a comparison between four techniques proposed for fast aging of amorphous silicon p-i-n solar cells, and the viability of these techniques for testing of large area a-Si:H cells. The kinetics of creation of metastable defects for these four techniques (electron bombardment, forward current injection, high intensity illumination and light pulses) are discussed. It is pointed out that high intensity illumination as well as light pulses create defects in a way comparable to sun light illumination, and thus are better suited as accelerated tests. In particular, degradation by light pulses allows accelerated testing of cells under spectral and thermal conditions identical to AM 1.5 irradiation.

I. Introduction

The conversion efficiency of thin-film amorphous silicon solar cells is at present limited by the creation of light-induced defects in the absorbing layer. This causes an increase of the defect density from typically 3×10^{15} cm^{-3} to more than 10^{17} cm^{-3}, and correspondingly a decrease of the solar cell conversion efficiency by several percent during the first days or weeks of operation. In order to solve or at least minimize this fundamental problem, an optimization of material properties and cell design is necessary, which mainly occurs by systematic variation of deposition parameters, new deposition methods, new material combinations, etc. To see whether any of these alterations on the material side eventually could lead to an improved stability of the resulting solar cell, it is of course necessary to prepare an otherwise optimized cell and to check its degradation behavior under realistic conditions. This is usually done by exposing the cell to simulated AM1.5 irradiation for long times (typically 100 to 1000 hours). Such long exposure times are on the one hand necessary to allow a reasonable estimaie of "end-of-life" efficiencies, but on the other hand present a severe bottleneck for fast improvement by trial and error. Thus, there is a clear need for accelerated aging procedures, which allow one to produce metastable defects under conditions

as close to real operating conditions as possible, but at least 10 to 100 times faster than simulated AM1.5 aging tests. The purpose of this paper is to review different accelerated aging techniques proposed in the literature and to discuss their viability, especially in view of industrial production and testing of large-area solar cells.

Currently, four different methods have been considered for fast stability testing:

(i) irradiation by high-energy electrons[1,2]

(ii) degradation by current injection under forward bias[3-5]

(iii) irradiation by high-intensity light (10 - $100 \times$ AM1.5)[6-10]

(iv) illumination with short light-pulses[11-14]

In the following sections, we will present advantages and disadvantages of these various methods, with special emphasis on the last two which, in our opinion, are the most suitable ones for realistic solar cell aging.

II. Electron Bombardment

The principle of this technique is the observation that electrons with kinetic energies in the keV range

create inetastable dangling bonds in a-Si:H witli properties very similar to those of light-induced defects. This has beea described in detail by Schneider and Schröder[1]. KeV electrons interact witli amorphous silicon by creation of electron-hole pairs and plasmon-modes ratlier tlian by direct displacenient of atoms. Nevertlieless, tlie defect creation kinetics is quite different from tliat obtained for liglit-soaking. As reported in ref. [1], tlie defect creation during electron bombardment follows tlie relation

$$N(t) = N_{sat}(1 - exp[-c_e D]),\qquad(1)$$

where $N_{sat} = 5 \times 10^{17}$ cm^{-3} is a saturated defect density reached at long times, D is tlie electron irradiation dose (current x time), and c, is a material and electron energy dependent kinetic constant. Equation (1) is the solution of tlie differential equation for tlie defect creation rate

$$\frac{dN}{dt} = c_e(N_{sat} - N)j,\qquad(2)$$

where j is the keV electron current density. Equatioii (2) can t e easily derived by assumiiig tliat eacli keV electron impinging on tlie sample locally creates tlie saturated defect density, N_{sat}, in a very small volume ($\ll 1\mu m^3$) around its trajectory. Alteriiatively, one may assume tliat a second electron following tlie same trajectory as the first one produces only much less additional defects than the first electron. Then, tlie probability of clefect creation per incoming electron is simply proportional to tlie electron current times the volume fraction of tlie sainple not yet transversed by an electron. The latter fraction is given by tlie term $(N_{sat} - N)$ i eq. (2). Note that eq. (1) should hold for any type of particle-like irradiation as long as a direct dis placement of lattice atoms is not occuring. Indeed, a similar kinetic equation has been proposed for metastable defect creation in a-Si:H by syn-clirotron radial ion ($\hbar\omega = 100 - 1000$ eV)[15] or by ^{60}Co γ-rays[16], which could also serve as potential sources for fast metastsble defect creation in a-Si:H.

However, p:oblems arise wlien we attempt to quantitatively relate tlie degradation due to particle-like sources to tliat caused by visible photons. In tlie case of illurnination by visible light, the creation of metastable dangling bonds can be reasonably described by the rate equation[17]

$$\frac{dN}{dt} = c_{sw}\frac{G^2}{N^2},\qquad(3)$$

witli the solution

$$N^3(t) - N^3(0) = 3c_{sw}G^2t, N(t) \propto G^{2/3}t^{1/3}.\qquad(4)$$

In eqs. (3) and (4), G is the generation rate of photoexcited electron-liole pairs, which is proportional to the flux of absorbed photons with $\hbar\omega > 1.3$ eV, and c,, is

a material constant which can be quite different from tlie constant c_e in, eqs. (1) and (2). Obviously, eqs. (1) and (4) are quite different, so tliat there will be no simple relation between the defect density produced by a certain photon dose versus tliat produced by a given electron dose. This is shown in Fig. 1, where we compare the dependence of metastable clefect densities in undoped a-Si:H on tlie irradiation exposure for comparable doses of visible photons (2 eV, 300 mW/cm^2) and electrons (20 keV, 170 mW/cm^2). Altliough a degradation of a-Si:H from 10^{16} to 10^{17} defects per cm^{-3} can be acliieved by electron irradiation in a very short time (several ininutes), it is difficult to predict from tlie degradation upon electron bombardment tlie long term degradation, behavior due to exposure to sun light.

In addition, a couple of otlier experimental difficulties cast doubt on tlie usefulness of particle bombardinent for accelerated testing of a-Si:H solar cells:

- Irradiation can only be done through tlie back coiitact, ratlier than tlirough tlie glass substrate as in the case of liglit exposure;

- Vacuum is required for irradiation with keV electrons;

- The application for large area modules is questionable;

- Contact layers may also suffer noticable radiation damage;

- Tlie deptli distribution of metastable defects is determiiied by the energy loss function, dE/dx, of keV electrons, which is quite different froin tlie profile of carriers generated by illumination witli wliite light.

III. Current Degradation

The second possibility for fast metastable defect creation in amorphous silicon is tlie degradation by bipolar current injection. This effect lias already been used by Staebler and coworkers[3] early as 1981 in order to check whether metastable defects are created directly by photon absorption ratlier than by recombination of photogenerated electron-hole pairs. In tlie current degradatioii process, excess electrons and holes are injected into the intrinsic a-Si:H layer of a p-i-n solar cell structure by applying a sufficiently high forward bias. Injected electrons and lioles then recombine, causing metastable dangling bond creation as in the case of illumination. Because fairly high carrier deiisities can be reached with elevated injection currents, a fast degradation results, qualitatively similar to what is observed during high intensity light-soaking.
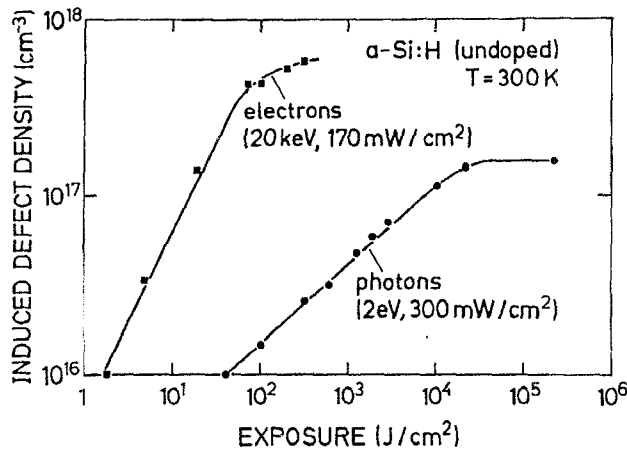
Figure 1: Induced defect density as a function of exposure for keV electrons (squares) an photons (circles).

A recent kinetic study of defect creation in p-i-n diodes by current injection has been published by Street[4]. For sufficiently large injection currents, Street reported an accelerated defect creation following a $t^{1/2}$-time dependence, which is again different from the $t^{1/3}$ dependence expected from eq. (4) and shown in Fig. 1. Also, a pronounced dependence of the steady-state defect density reached for long current-stressing times on the actual current level was reported. The high steady-state defect density reached after several hours of strong current injection decreased again and eventually reached a new steady state with a lower metastable defect density, when the injection current was decreased during the experiment. This demonstrates clearly that the steady state is determined by a balance between defect creation due to electron-hole recombination on one side, and defect annealing by Joule heating and/or other carrier-related processes on the other side.

Current injection is certainly the most convenient accelerated degradation method as far as experimental requirements are concerned. Problems exist, however, for the predictive powers in respect to actual light-soaking experiments. Similar to the case of electron-bombardment, a first difficulty is the relation between the observed kinetic behaviors, which are not systematically understood at present. Thus, it is not clear whether there is a unique relation between the steady-state defect density reached after long current-injection and the steady state efficiency of an a-Si:H p-i-n cell exposed to sun light. An additional problem is related to the influence of the field and excess carrier distribution in a given cell structure for current injection versus illumination. Light-soaking studies of a-Si:H solar cells are usually performed under open- circuit or optimal load conditions, with a bias voltage close to U_{oc}, and either zero or relatively small current levels. Accelerated current-degradation, on the other hand, usually occurs in the dark with comparatively high foward bias voltages and currents. Therefore, local fields and

carrier densities are significantly different for the two degradation methods throughout the solar cell. This will cause difficulties in two ways. First, for a given cell structure, the depth profile of metastable defects can be expected to be quite different for current-stressing versus light-soaking. In the case of light-soaking, the defect profile is essentially given by the absorption profile of the incoming light, suitably broadened by carrier diffusion lengths in the i-layer under the influence of the electric-field distribution present there. In contrast, for current-stressing the defect distribution will be dominated by the average Schubweg, $s = E\mu\tau$, of injected carriers. Current-induced defects will mainly occur in the region where injected electrons and holes overlap, i.e. close to the p-contact, since the mobility μ of holes at room temperature is much less than that of electrons. Moreover, the region of overlap can be expected to change a as function of time because of changes in the carrier lifetime, τ. Secondly, quite different effects of the variation of cell design parameters such as layer thicknesses, doping levels, band gaps, etc. will be expected for current-versus light soaking. A reasonable comparison of both degradation methods is only possible on the basis of reliable quantitative computer models for fields, charge distributions, and recombination processes in a-Si:H solar cells. This, however, destroys much of the advantage given by the ease of experimental implementation of current-degradation studies.

When we think about accelerated stability testing of a-Si:H solar cells on the module or submodule level, the current stressing method has a further significant disadvantage, namely the effect of lateral inhomogeneity. Typical problems which one might encounter are, for example, current filament formation, inhomogeneous field distributions, etc. At present, no systematic survey of these effects in modules exists to our knowledge, but a detailed understanding of lateral inhomogeneities will certainly be necessary if one wants to adopt current-stressing for accelerated module testing.

IV. High Intensity Illumination

The third method of accelerated stability testing is degradation by high intensity illumination (typically 1 - 20 W/cm^2). The light sources normally used for this purpose are Xe arc lamps, and lasers (Kr$^+$, Ar$^+$). High-intensity light-soaking has been widely used in the literature, and has proved to be a convenient accelerated stability test. We would like to point out however that, for a quantitative analysis of this method, care has to be taken to correctly include both thermal and light-induced annealing of metastable defects[6,17,19,20]. These two effects and their influence on the kinetics of high-intensity degradation will now be discussed in detail.

Thermal annealing of metastable defects cannot be neglected, even at room temperature[6,19]. The anneal-

ing rate lias a strong exponential dependeiice on temperature that has to be taken into account when comparing defect creation different conditions. In tlie case of high intensity illumination, the actual teinperature of tlie thin film sainple and of tlie heat sink, where tlie temperature is measured, can differ by many degrees. One can easily estimate this temperature difference by using tlie thermal conduction equatioii

$$J = \kappa \nabla T \, , \qquad (5)$$

where $\mathbf{J}$ is tlie energy flux density, κ tlie thermal conductivity and ∇T tlie temperature gradient. Let us suppose tliat tlie liglit incident on a solar cell is completely converted into lieat, and that tlie cell is grown on a 0.1 cm thick glass substrate ($\kappa \approx 8$ mW/cmK [19]) in thermal contact with a copper block at constant ternperature. In this case tlie teinperature rise will be $\nabla T \approx 13 \mathrm{Kcm}^2/\mathrm{W}$. As an example, for an illumination intensity of $2 \mathrm{W/cm}^2$, tlie ternperature of tlie sainple is around 30 °C above tlie copper block temperature!
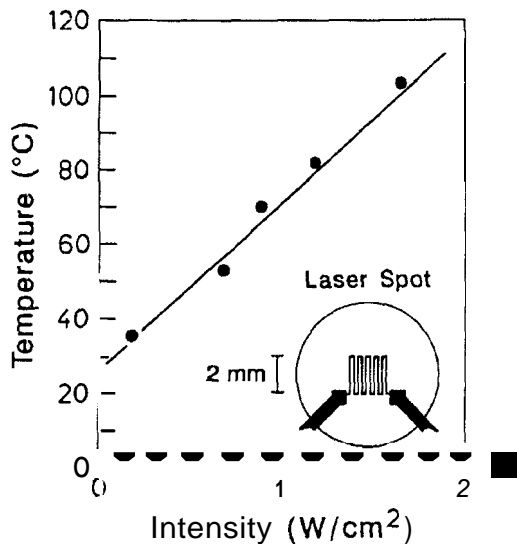

Figure 2: Temperature of tlie sample as a function of illumination intensity, for a laser spot mucli larger than the Ni-meander tlie:mometer. Tlie structure of tliis thermometer is shown in the inset.

In order to test this simple estimate experimentally, we used an a-Si:H tliin film grown over a Ni-meander therniometer, as shown by the inset in Fig. 2. In this figure, we plot the temperature of the a-Si:H film, T, as a function of liglit intensity for illumination with defocused, homogeneously absorbed laser light ($\lambda = 647$ lnm). Tlie results indicate a linear relation $\nabla T / I =: 40 K cm^2/W$. Tliis experimentally determined temperature rise is a factor of **3** larger tlian our simple estimate based on eq. *(5)*. Tliis discrepancy can be explained by the fact that in tlie real system, the film/substrate itnd substrate/copper block interfaces do

not represent a perfect thermal contact, but give rise to an additional teinperature drop. As a consequeiice, for any given sample/substrate system, it is necessary to ineasure tlie temperature difference between film and tlie lieat sink, since tlie result can depend critically on tlie thermal quality of tlie interfaces.

A second important precaution for liigli-intensity degradation of large-area devices concerns tlie inclusion of lateral heat transport. In order to illustrate this point, we have nieasured the temperature rise in our a-Si:H/Ni-meander tliermometer as a function of illuminated area for a constant and homogeneous illumination intensity ($2 \mathrm{Wcm}^{-2}$ over a total beam radius of 5 mm). Tlie illuminated area was determined by a circular iris placed into the beam. The effective temperature rise in tlie therniometer is shown in Fig. **3** as a function of spot size. For illumiiiation areas much larger tlian tlie Ni-meander nrea, tlie temperature rise approaches a value of 70 K, in accordance with Fig. 2. For smaller illumination areas liowever, ∇T is strongly dependent on tlie actual spot size. When the laser spot is comparable to tlie meander size (2 x 2 mm^2), a teinperature rise of only 20 K is observed, due to a considerable lieat flow into tlie surrounding a-Si:H film. This emphasizes tlie iinportance of liomogeneous illumination conditions for liigli-intensity liglit soaking.
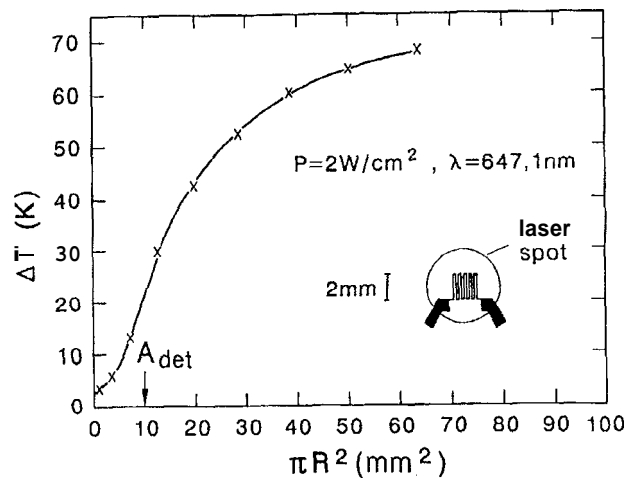

Figure **3**: Temperature rise of tlie sample due to irradiation heating, as a function of tlie area of tlie laser spot. A schematic drawing of the experimental set-up is also shown. Tlie area of the detector is indicated by tlie vertical arrow.

To illustrate tlie consequences of the above results, let us suppose tliat a cell with similar thermal conditions than the sample in Fig. 2 is honiogeneously exposed to a 2 W/cm^2 light source. In order to obtain results comparable to sun light illumination (at least in what concerns the thermal annealing of defects), tlie temperature of tlie cell should be kept around 40 to 50 °C. In this case, tlie temperature of the heat sink should be approximately -20 °C, wliich is undesirably

low for standard testing. Alternatively, one lias to ensure that tlie thermal contact between tlie cell or a-Si:H thin films and tlie lieat sink is sufficiently good, so tliat significant tliermal gradients cannot occur. IIowever, tliis will not always be easy to achieve, in particular for encapsulated cells.

The second effect mentioned above is tlie light induced annealing of metastable defects[19,20]. This effect is difficult to observe directly, but cannot be negleted when different degradation methods have to be compared quantitatively. Light-induced annealing is particularly important for high-intensity light-soaking. Tlie kinetics of liglit-induced defect creation and annealing can be reasonably described by adding an annealing term to eq. (3), leading to:

$$\frac{dN}{dt} = Ac_{sw}\frac{G^2}{N^2} - BN_{met}\frac{G}{N}, \qquad (6)$$

where N is tlie total density of defects, and N_{met} is the metastable defect density[19]. From tlie steady-state condition $dN/dt = 0$, one finds $N(\infty) = (Ac_{sw}\ G/B)^{1/2}$. Tlie solutions of eq. (6) and eq. (3) are plotted in Fig. 4 for different illumination intensities. A clear shift of tlie clefect density versus time to smaller times (by about a factor of 100) is observed for tlie case of high intensity illumination. However, at tlie same time tlie defect density in tlie "end-of-life"
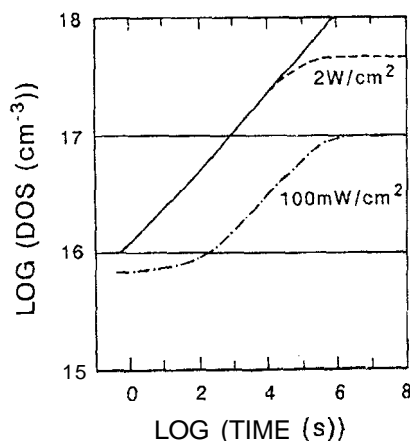

Figure 4: Logaritlim of the density of states (DOS) as a function of the logarithm of illumination time, calculated from, eq. (3) for an illumination intensity of 2 W/cm² (solid line). Tlie solution of eq. (6) for an illumination intensity of 2 W/cm² (dashed line) and for an illumination intensity of 100 mW/cm² (point-dash line). Note tliat different intensities lead to different "end-of-life" defect densities.

state is increased by about a factor of four. Tlius, a major problem with high intensity illumination is tliat, although the creation of defects becomes faster, the "end-of-life" efficiency may be quite different from the case of AM1.5 illumination. In order to obtain reliable estimates for the "end-of-life" efficiency, a quantitative

knowledge of the creation rate and tliermal as well as liglit-induced annealing rates is necessary.

V. Pulsed Illumination

Tlie fourtli approach for accelerated aging consists in replacing continuous illumination by pulsed light. Suitable pulsed liglit sources are flash lamps or pulsed lasers. In order to illustrate tlie potential of pulsed illumination for fast testing of a-Si:H solar cells, we compare in Fig. 5 tlie normalized efficiency of a cell as a functioii of illumination time for continuous versus pulsed illumination[12]. Tlie most important advantage of pulsed light-soaking compared to all otlier techniques above is tliat the same average illumination intensity (100mW/cm²) gives rise to degradation which is a factor of 100 times faster than for continuous illumination. Tlius, special precautions for temperature control are not necessary in tliis case, provided tliat tlie individual pulse energics remain within tlie limits discussed below.
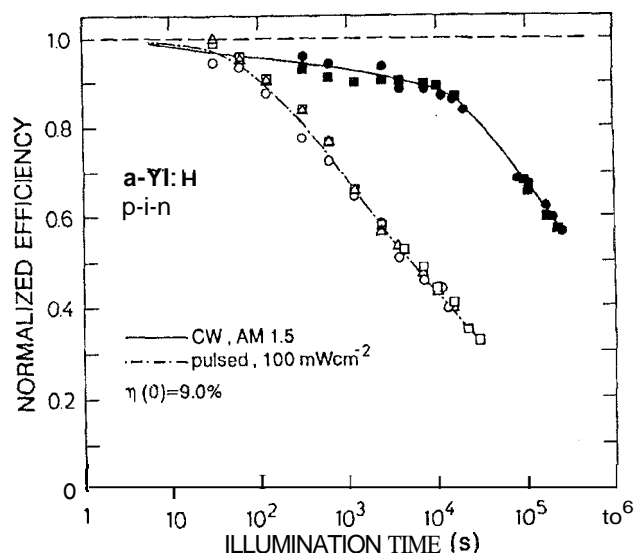

Figure 5: Normalized conversion efficiency as a function of exposure time with simulate AM 1.5 light (solid circles) and for pulsed illumination (open symbols).

During and following a liglit pulse, optically excited carriers thermalize and recombine, transforming all electronic energy eventually into lieat. Since tlie electronic relaxation times ($\leq 10^{-6}$s) are much shorter tlian tliermal relaxation times for a-Si:H on an insulating substrate (N 10^{-3}s), a given pulse energy causes a temperature rise in the amorphous silicon film which can be estimated to:

$$\Delta T \approx \frac{E_p A}{c_p V} = \frac{E_p}{c_p d}. \qquad (7)$$

Here V, A, and d, are the volume, area, and thickness of the a-Si:H sample, respectively, and c_i is tlie heat capacity of a-Si:H per unit volume (c_p N 2J

$cm^{-3}K^{-1}$). Thus for a typical sample with tlie diinensions of 1 cm x 1 cm x 1 μm, a pulse energy density of E, $= 10^{-3}$ J/cm^2 should cause a temperature rise of $AT \approx 5K$. Therefore, in order to avoid thermal effects which miglit influence the observed metastable defect creation, single pulse energy densities should not exceed significantly 10 mJ/cm^2, a limit which obviously depends to some extent on the actual pulse duration employed and on tlie absorption deptli of tlie photons.

We have actually measured tlie temperature rise due to single light pulses in an a-Ge:H sample using a Xenon flash lamp with a pulse widtli t, $\approx 2 \mu$s and a peak intensity $I_p \approx 150$ W/cm^2, $(E_p = I_p \, t_p = 0.3$ mJ/cm^2). With tliese pulse conditions, tlie repetition rate ν_{rep} necessary to achieve an average illumination intensity of 100 mW/cm^2 is 300 Hz. The teinperature rise expected from eq. (7) is 1.5 K. We measured tlie sample temperature following a liglit pulse indirectly by clianges in tlie dark conductivity. a-Ge:H was used instead of a-Si:H because it has a very poor pliotoconductivity, but similar thermal properties [c, $(a-Ge:H) = 2$ J cm^{-3} K^{-1}]. Tlie experimentally observed temperature rise is shown in the lower part of Fig. 6. Also shown are the
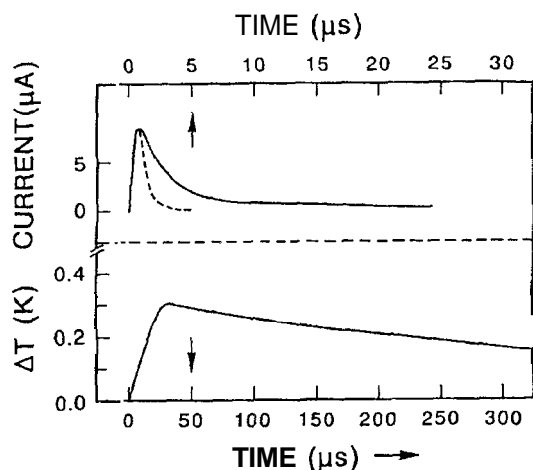

Figure 6: Current and temperature rise as a function of time, during and after a liglit pulse. Tlie dashed line in tlie upper part is tlie measured light pulse and tlie solid line represents the current measured on the sample. Note tlie different time scales.

light pulse and the resulting current pulse in an a-Si:H sample. The light pulse has a width of approximately 2 μs, the current pulse has a duration of 20 μs, while the thermal heating decays with a characteristic time constant of abcut 600 μs. Tlie experimental results indicate a maximum temperature rise of 0.3K, coinpared to the predicted 1.5K. Tliis difference can be in part understood by coisidering in addition that (i) $\approx$ 50% of the light is reflected by tlie interface a-Ge:H /air, and (ii) the illumination was not homogeneous (the light spot size was comparable to the contact spacing, so that

according to Fig. 3 approximately 50% of tlie generated lieat is lost to tlie surrounding film). Including these two phenomena in our simple model, tlie predicted and tlie experimentally observed temperature rise agree reasonably well.

In addition to the negligible thermal effects, using a Xe flash lamp for rapid stability tests of a-Si:H solar cells has the advantage tliat tlie spectral coinposition of the flasli light is quite similar to that of sun light. This ensures that tlie spatial distribution of light induced defects in tlie cell is comparable in botli cases. As seen in Fig. 7, tlie Xenon flasli lamp filtered by a lieat loss filter (KG3) has basically tlie same spectral distribution as sun liglit (AM1.5) for photon energies higher than tlie a-Si:H band gap (M 1.7 eV).
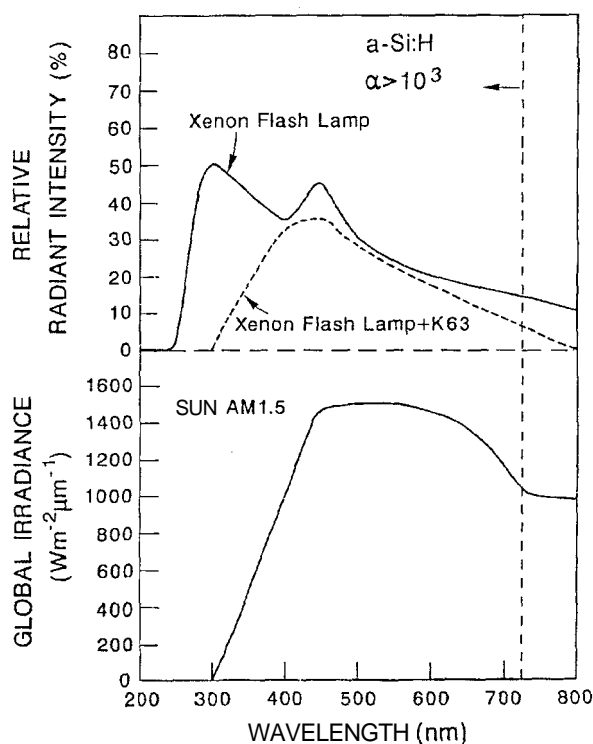

Figure 7: Relative radiant intensity of the Xenon flash lamp (upper part) and the global irradiance of tlie sun (AM1.5) as a function of wavelength. Tlie dashed line indicates tlie optical gap of a-Si:H (1.7 eV). The effect of putting a heat absorbing filter (KG3) on the relative radiant intensity of the flasli lamp is also shown.

Now let us turn to the kinetics of defect creation by pulsed light. Using again eq. (3), and integrating over eacli puise separately, we obtain for the number of metastable dangling bonds per pulse

$$\Delta N = \int_{t_{min}}^{1/\nu_{rep}} c_{sw} np d\tau \approx c_{sw} \int_{10^{-12}s}^{10^{-5}s} n^2(\tau) d\tau, \quad (8)$$

wliere t_{min} is a short time limit for defect creation aiid tlie long time limit is given by the inverse of tlie repetition rate or tlie excess carrier recombination rate $(1/t_{rec})$ whichever is shorter. The detailed analysis aiid solution of this equation is treated elsewhere[14]. Here, we will present only tlie solution ill tlie limit of loiig pulses $(t_p \gg t_{rec})$ aiid in tlie limit of monomolecular carrier recombiiiation (via stable and metastable defects). In this limit one can write

$$dN = c_{sw}\frac{G_p^2}{N^2}\nu_{rep}t_p dt = c\!\!-\!\!\frac{<G>^2}{N^2}\frac{1}{\eta}\& \qquad (9)$$

wliere $\eta = \nu_{rep}t_p$ is tlie illumination duty cycle, aiid G, is tlie generation rate of carriers cliiriiig the pulse. G_p aiid the average generation rate, are related via $< G >= G_p\nu_{rep}t_p$. From eq. (9) we find that for the same average light-intensity, $< G >$, pulsed-illumination mitli long liglit pulses enhances tlie defect creation rate by a factor 1/17 $\gg$ 1, biit does not change tlie analytical dependence of N on $<G>$ and t already derived iii eq. (4) for tlie case of continuous illumination:

$$N^3(t) - N^3(0) = 3c_{sw}\eta^{-1} <G>^2 t. \qquad (10)$$

Since in tlie derivation of eq. (10) we have assumed $t_p > t_{rec}$, tlie largest enhancement of the defect creation rate should be obtained in a-Si:H by pulses with a duration of several μs with a low repetition rate (low duty cycle). However, there are several constraints to tlie clioice of tlie repetition rate and tlie pulse eiiergy. First, in order to satisfy the requirement of a pulse duration long cornpared to the recombination time, we chose $t_p = 10\mu s$. Second, to avoid significant heating by a single pulse, tlie pulse energy $E_p = I_p t_p$ sliould be smaller tlian 10 mJ/cm^2. A reasonable clioice is $E_p = 1$ mJ/cm^2. In tliis case, we obtain a pulse power $I_p = 100$W/cm^2. Third, to simulate AM1.5 solar irradiation the average liglit intensity $< I >= \nu_{rep}t_p I_p$ should be 100mW/cm^2, giving $\nu_{rep} = 100$Hz. For tlie clioices made, η is found to be 10^{-3}, so that the degradation at long times sliould be accelerated by tliree orders of magnitude. Tliis large acceleration is indeed obtained experimentally[14].

Another interesting problem wliicli can be addressed better by pulsed illumination than by the other accelerated aging metliods is an accurate prediction of tlie long term ("end-of-life") efficiency. One of tlie basic problems for tlie determination of when exactly the "end-of-life" steady state has been attained is that under AM1.5 conditions ($I = 100$mW/cm^2) it takes at least 10^5s (1 day) to approach the steady state value (see Fig. 4). But to safely characterize the steady state condition, one should wait at least ten times longer. Tliis problem can be solved by creating defects above tlie expected steady-state value (using tlie Xenon flash lamp) and then change to continuous illumination. In this case, light-induced annealing will occur instead of

liglit-induced creation of defects, as predicted by eq. (6). This will give a reliable lower liinit for the long term efficiency in about 10^5s. Tliis lomer limit can be combined with the *upper* efficiency liinit obtained by standard continuous light-soaking also in about 10^5s, so that a good estimate of the real loiig terin efficiency sliould be possible after a total test time of about two days.

VI. Conclusions

We have analysed and compared four techniques proposed for accelerated aging of a-Si:H solar cells: electron bombardment, curreiit injection, high intensity illumination and light pulse soaking. Although keV electron bombardment creates defects very fast, tlie kinetic of defect creation is very different from AM1.5 sun liglit illumination, rendering a qiiantitative coinparison of both methods quite difficult. A similar objection holds for tlie case of curreiit injection. In addition, electron bombardment aiid current degradation are expected to give rise to different spatial distributions of inetastable defects, and a reliable predictioii of long term behavior appears unpractical.

For tlie case of high intensity illumination, tlie biggest drawback is tlie temperature rise due to illumination, and tlie liglit induced annealing of inetastable defects. Heating forces an active cooling of tlie solar panel to avoid thermal annealing of defects. Tliis can be ratlier inconvenient: for cxample for $I = 2$W/cm^2, tlie temperature of tlie heat sink on wliicli tlie sainple is mounted sliould stay at -20 °C. Light-induced annealing implies a differeiit "end-of-life" state for differeiit illumination intensities, again turning aiiy comparison between simulation aiid outdoor performance difficult.

Tlie pulsed liglit illumination thus appears to be tlie most recommendable fast agiiig test. Defects are created easily 100 times faster tlian with sun liglit (AM1.5, 100mW/cm^2), under identical thermal condition. We propose an easy aiid quick test for tlie "end-of-life" state, combining pulse degradation and tlie liglit-induced annealing of defects.

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