Study of thin-film silicon solar cells at irradiances above ten thousand suns

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Abstract. We used a tightly focused Gaussian beam of a HeNe laser to study accelerated light-induced degradation (Staebler-Wronski effect) and high photocarrier generation rates in amorphous and microcrystalline silicon thin-film solar cells, at up to 13 MW/m² irradiance. For the experiments, the spot radius was varied from a minimum of 8.6 μm in the focus to around 1 mm away from the focus. According to COMSOL® simulations, even at these high power densities heat diffusion into a glass substrate aided by spreading conduction via the Ag back-contact restricts the temperature rise to less than 14 K. Short-circuit current can be measured directly over a range of irradiances, and the J-V characteristic may be estimated by taking into account shunting by the inactive part of the cell.

1. Introduction
Degradation in performance of solar modules over their operational lifetime is an important factor shaping the commercial future for large-area photovoltaics (PV). In amorphous silicon solar cells, light-induced mid-gap defects generated over the first few months of operation may reduce PV conversion efficiency by up to 20%. This is termed the Staebler-Wronski Effect (SWE) [1]. These defects are metastable silicon dangling bonds, which may be largely eliminated by annealing in the dark for a few hours at > 160°C. The two most widely-quoted models of SWE are the weak bond-dangling bond conversion model of Stutzmann, Jackson and Tsai [2] and the hydrogen collision model of Branz [3], although neither is entirely satisfactory, and after more than 30 years this important topic remains the subject of intensive research.

Typical light-soaking laboratory test conditions comprise 1000 hours exposure to AM1.5 radiation at 50 °C, in keeping with those met in service. However, there are reasons for wishing to study solar cell properties at elevated irradiance. Degradation is more rapid, opening up the possibility of faster initial screening of materials and devices prior to formal longer-term test. It is also useful to test theories of PV operation or degradation over a range of generation rates. However, the temperature rise accompanying higher irradiances usually requires the substrate to be cooled to control it. In the case of amorphous silicon, studies on 1 cm² cells at up to 140 suns [4] have been conducted under simultaneous forced cooling with nitrogen gas pre-cooled by liquid nitrogen. Another similar study [5] employed an air-cooled Al heat sink.

We believe it is possible to gain useful information at much higher irradiances, without the need for special cooling measures, simply by using a tightly-focused beam of laser light incident on a small area of the cell. Consider the case of a semi-infinite slab (the substrate) of thermal conductivity $k$...
coated with a thin optically-absorbing film (such as amorphous silicon). If a circular beam of radius \(a\) and uniform irradiance \(H\) is fully absorbed by the film, giving a disc-shaped heat source, the steady-state temperature rise at the centre of the disc (the hottest point) is [6]:

\[
\Delta T = \frac{Ha}{k}
\]  

(1)

Taking \(H = 10\) kWm\(^{-2}\) (10 suns), \(k = 1\) Wm\(^{-1}\)K\(^{-1}\) (typical for glass and silicon films) and \(a = 1\) cm yields \(\Delta T = 100\) °C. The need for cooling even at quite modest irradiances is apparent. However, if the disc is 10\(\mu\)m in radius, \(\Delta T\) is only 0.1 K. We demonstrate by means of a COMSOL\textsuperscript{®} [7] numerical thermal model that equation (1) is a good approximation for a film subjected to a beam whose radius is less than the thickness of the glass substrate. The model is extended to a solar cell structure by including an Ag film back-contact, which greatly reduces the peak temperature by spreading heat into the substrate. While the short-circuit current may be measured directly, the complete \(I-V\) characteristic requires any current flowing through the dark part of the cell to be accurately subtracted. To test this novel approach we used focused light from a HeNe laser to investigate both amorphous (aSi:H) and microcrystalline (μcSi:H) \(pin\) solar cells, which behave quite differently in respect of both PV properties and degradation behavior.

2. Experimental

2.1. Solar cell deposition

Amorphous silicon cells were deposited in \(pin\) sequence by RF PECVD: Substrate temperature of 180 °C, power of 3 W, pressure of 5 mbar and silane:hydrogen process gas flow rate of 6.25:60 sccm. Microcrystalline silicon cells were deposited in \(pin\) sequence by hot-wire CVD: Substrate temperature of 220 °C, wire temperature of 1650 °C, pressure of 3 Pa, silane concentration 6% in hydrogen. In both cases the \(i\)-layer thickness was nominally 1 \(\mu\)m. Raman spectroscopy determined that the crystalline volume fraction of the microcrystalline absorber layer in the cell was 40%.

2.2. Optical system

To produce a spot of light of the requisite size, the beam from a Uniphase 1101 1.5 mW HeNe laser was firstly expanded using a reverse telescope, and then focussed by a converging lens to a Gaussian beam of waist radius \(w_0 = 8.6\) \(\mu\)m (at the 1/e\(^2\) points) and Rayleigh range \(z_R = 0.37\) mm. The solar cell was mounted on a translation stage, enabling it to be positioned orthogonal to the beam and moved along the beam axis \(z\) to vary the spot size [8]:

\[
w(z) = w_0(1 + (z/z_R)^2)^{1/2}
\]  

(2)

\(z = 0\) is the position of the beam waist. The peak irradiance varies as \(H(z) = 2P_0/\pi w^2(z)\) [8], where \(P_0\) is the beam power. A micrometer screw adjustment enabled the solar cell to be positioned accurately along the \(z\)-axis and for the irradiance to be tuned from 13,000 kWm\(^{-2}\) at the beam waist to 1 kWm\(^{-2}\) at \(z = 42\) mm. Solar cell current falls to a minimum value in the vicinity of the calculated position of the beam waist (\(z = 0\)) and increases symmetrically on either side. The current minimum was taken to signify that the cell was aligned precisely at \(z = 0\). The device physics has not yet been investigated, but bearing in mind the very high generation rates (> 10\(^{25}\) cm\(^{-3}\)s\(^{-1}\)) at the focus this behaviour may be associated with reduced carrier collection due to a high density of trapped space-charge [9]. Since spot size is normally much smaller than the cell contact area, new un-degraded regions can readily be found by moving the beam elsewhere on the cell.
2.3. **COMSOL® simulations**

The COMSOL® 3.3 heat transfer module (2-d axisymmetric geometry) was used for steady-state and transient simulations [7]. As temperature changes here are generally quite small, no temperature-dependence of material constants was included. The basic model substrate consists of a 10 mm radius glass disc 1 mm thick, coated on one side with a 1 μm silicon film. Heat was generated uniformly within the ‘illuminated’ part of the film to facilitate direct comparison with equation (1). It is possible within COMSOL® to model a generation depth profile, and also to include a Gaussian radial distribution, but this would significantly increase run times and would not change the key outcomes of this work. Two additional scenarios were investigated; a 1 μm film of Ag was added on top of the silicon film to give a structure resembling a solar cell with back contact, and the glass slide was exchanged for a sapphire one, with thermal conductivity some 30 times higher than glass. The mesh was refined to provide sufficient spatial resolution close to the generation volume.

3. **Results and discussion**

3.1. **Thermal modelling**

Figure 1(a) shows the simulated temperature profile produced by a 10 μm radius beam of irradiance $10^6$ Wm$^{-2}$ (1000 suns equivalent), fully absorbed by a 1 μm thick silicon film deposited on a 1 mm thick glass disc of radius 10 mm. Only one half-plane is shown, since the system is axially symmetric. For simplicity, both film and substrate have the same thermal conductivity of 1 Wm$^{-1}$K$^{-1}$. As this system is finite, boundary conditions must be imposed at all free surfaces. This has been done in two different ways, to investigate the sensitivity of the model. These are as follows: (i) Free film surface perfectly insulated, free substrate surfaces maintained at $T_0$ (set at 273.15 K here); (ii) All free surfaces subject to heat loss $h\Delta T$ per unit area to the surroundings, where $h = 4$ Wm$^{-2}$K$^{-1}$, typical for free convection in air. Case (ii) represents a minimum (worst-case) thermal coupling to the surroundings under normal laboratory test conditions. It is found that the maximum temperature rise above $T_0$ is 9.5 K in case (i) and 9.6 K in case (ii); both are in excellent agreement with the value of 10.0 K obtained from equation (1). In case (ii) the surfaces of the substrate are slightly above ambient, as required to maintain convective heat flow into the surroundings.

Having confirmed agreement with the analytic solution, a solar cell structure with a 1 μm Ag ‘back-contact’ on top of the silicon film was then modelled. The result under the same conditions as case (ii) above is shown in figure 1(b). It is seen that the maximum temperature rise in the silicon film is dramatically reduced, by a factor of 10, to 1 K. The temperature distribution is considerably

![Figure 1.](image-url)
modified in comparison to figure 1(a); the region of highest temperature now lies at the generation volume - substrate interface, heat is conducted along the Ag film to more distant regions of the substrate, increasing its temperature. This ‘spreading’ effect afforded by the Ag film is clearly beneficial in reducing the temperature of the generation volume. The TCO top-contact behaves similarly, but as its thermal conductivity is around one tenth that of Ag the effect is less pronounced.

We have also simulated a sapphire substrate in place of glass. This has a similarly dramatic effect on the maximum temperature rise, and a combination of Ag film and sapphire substrate gives a reduction in $\Delta T$ of a factor of around 20. The thermal time-constant with regard to achieving steady-state conditions in the generation volume is less than one millisecond in all cases. Substrate geometry is found to have little bearing on the temperature profile in the generation volume, provided the spot size is less than the minimum dimension of the substrate.

The solar cells studied here were deposited on borosilicate glass substrates ($k = 0.9$ Wm$^{-1}$K$^{-1}$), and the Ag layer is nominally 0.7 $\mu$m thick. These parameters, and a value of $k = 1.3$ Wm$^{-1}$K$^{-1}$ for the silicon layer, were used to simulate the maximum temperature rise likely to be encountered in this work, i.e. with the beam most tightly focussed ($a = 8.6$ $\mu$m). This was found to be some 14 K above ambient. It follows that in this work thermal effects should have negligible impact in comparison to optically-driven phenomena such as SWE and the influence of space-charge [9] on carrier transport.

3.2. Effects of light-soaking
The results of light-soaking on amorphous and microcrystalline silicon solar cells up to a maximum irradiance of 13 MWm$^{-2}$ are shown in figure 2. This was carried out under short-circuit conditions, and the currents shown are those measured under full irradiance. Each trace is normalised to the initial current prior to degradation. As expected, in the case of amorphous silicon higher irradiance results in more rapid degradation. At maximum irradiance, short-circuit current falls by 10% in just one second. The results at lower irradiance are broadly in keeping with Yang et al [4], who monitored reduction in efficiency with time at up to 140 suns. However it is not possible to make a direct comparison with their data, as we have not yet measured fill-factor, which is a better indication of degradation, and open-circuit voltage (see section 3.3 below), and so cannot calculate efficiency.

The quality of the data at higher irradiance is somewhat poorer, with oscillations and less well-defined fluctuations being apparent. As these greatly exceed the variations in laser amplitude after warm-up, the most likely explanation is mode instability, which causes changes in the shape of the irradiance curve, particularly for a tightly-focussed beam. The microcrystalline silicon cell is far more resilient to degradation than the amorphous cell. At maximum irradiance, it takes approximately one day for the current to degrade by 10%. Previous reports [10] indicate that exposure for 1000 hours (40 days) is normally needed to obtain a similar reduction under AM1.5.

![Figure 2](image1.png)  
*Figure 2. Degradation of short-circuit current vs. time for a range of irradiance values (in kWm$^{-2}$).*  

![Figure 3](image2.png)  
*Figure 3. Short-circuit current measured prior to, and following, degradation, vs. irradiance.*
Figure 3 summarises the effect of increasing irradiance on solar cell current prior to degradation, and after one day exposure. The aSi:H cell is strongly affected by increased volume generation rate (up to $10^{25} \text{cm}^{-3} \text{s}^{-1}$) by a mixture of the above and additional recombination via light-induced defects. To separate these effects it is necessary to measure the degraded spot at a lower irradiance, which we are unable to do at present. The μcSi:H cell shows quite different behaviour. The current increases with increasing irradiance, reaching a maximum at 420 kWm$^{-2}$, 15% higher than at 1 kWm$^{-2}$. The reason for this is presently unclear. The laser output was calibrated against a standard Si detector, and the current corresponding to an external quantum efficiency of 1 is 0.84 mA ±10%.

Figure 4 shows the photocurrent decay in an aSi:H cell under high irradiance at short times, and the effect on the current of interrupting the beam. The initial decay is very rapid, and it is likely that the current reaches even higher values at shorter times. It then decays roughly according to a power law. When the beam is interrupted and then re-applied, the decay recommences from the same current level, and follows continuously in time – there is no spike. Thus the decay is not due to a reversible cycle such as heating/cooling or charging/discharging of traps. The behaviour is in keeping with SWE, but we have not yet determined if the current is restored to its original value by annealing. Until then, the possibility of crystallisation, hydrogen effusion, persistent photoconductivity or other processes cannot be completely ruled out. Viera et al [11] have studied laser-induced crystallisation of aSi:H using Raman spectroscopy, and report no effect on the structure at $10^4$ kWm$^{-2}$, which is close to the maximum irradiance used here. In their case, the irradiance reached $90 \times 10^4$ kWm$^{-2}$ before crystallisation occurred. However, from a thermal point of view these results cannot be properly compared without knowledge of spot size, as is clear from equation (1).

3.3. I-V characteristic

Figure 5 shows the I-V curve for a degraded aSi:H cell, in the dark, and under a 13 MWm$^{-2}$ spot. Also shown is the result of subtracting the dark trace to leave the I-V curve of the active volume. This is fairly successful until the forward current becomes large and device plus measurement noise exceeds the difference between the two traces. It seems unlikely that the entire fourth quadrant could be recovered in this way, but we are continuing to investigate this possibility.

4. Conclusions

COMSOL® thermal models of a thin-film silicon solar cell illuminated by a focused laser spot indicate that very high local irradiance can be delivered without incurring excessive temperature rise. The maximum temperature rise in the active volume of a typical solar cell under an 8.6 μm radius Gaussian...
spot focused down from a 1.5 mW HeNe laser (peak irradiance 13 MWm$^{-2}$) is predicted to be 14 K. The Ag back contact has a beneficial effect in spreading the heat by conduction. This is in contrast to standard uniformly-illuminated 1 cm$^2$ test structures, which require forced cooling to attain much more modest irradiances. By moving the cell along the beam axis, this set-up provides adjustable irradiance.

The Staebler-Wronski effect in amorphous silicon solar cells has been investigated as a function of irradiance, by monitoring short-circuit current vs. time. Degradation is shown to be more rapid with increasing irradiance, in keeping with previous studies although these do not extend to such high irradiance values. There is evidence of fluctuations in beam profile at smaller spot size, which may be caused by laser mode instability. A microcrystalline silicon cell was also investigated, and found to be far more resistant to degradation. This approach could be used for initial rapid screening of promising low-degradation materials prior to longer-term tests at one sun.

This method was also used to study the effect of very high generation rates (over $10^{25}$ cm$^3$s$^{-1}$) on solar cell operation. In the case of thick amorphous silicon cells, increased irradiance markedly reduces the quantum efficiency, even at 10 kWm$^{-2}$ (10 suns equivalent). Microcrystalline silicon cells however, show a 15% increase in quantum efficiency from the 1 sun value, at around 400 suns equivalent irradiance. It is possible to measure part of the $I-V$ curve of the active region of the cell by subtracting the dark $I-V$ curve, but unfortunately this is limited in its success by noise considerations.

Future work is planned, including more stable laser and optics to improve beam quality, faster and more accurate data-logging, and a temperature-controlled stage that will allow samples to be thermally annealed in situ, essential when working on a small spot on a much larger cell.

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