

The Use of Injection-Level Dependent Lifetime Measurements for Determining Solar Cell Parameters

D. Macdonald and A. Cuevas

Centre for Sustainable Energy Systems, Dept. of Engineering, FEIT
Australian National University, Canberra ACT 0200
AUSTRALIA

E-mail: daniel@faceng.anu.edu.au

Abstract

The open-circuit voltage of a silicon solar cell is well known to be directly related to the effective recombination lifetime of the substrate as measured under 1-sun illumination. However, an important feature of the recombination lifetime is that it is dependent on the concentration of excess carriers present, often very strongly. This can result in a significantly lower recombination lifetime at maximum-power as compared to open-circuit conditions, and consequently cause a reduction in the cell fill factor. In high efficiency multicrystalline silicon cells, such a varying lifetime is often the result of impurities and defects residing in the bulk of the material. Injection-level dependent lifetime measurements on such wafers are shown to provide a good explanation of low fill factors observed in finished cells. The impact of these bulk recombination centres on fill factors in commercially produced multicrystalline silicon cells is modelled and discussed.

1. Introduction

In this paper we examine the injection-level dependence of the effective recombination lifetime of high efficiency multicrystalline silicon (mc-Si) solar cells. The measured lifetime curves are accurately modelled using Shockley-Read-Hall (SRH) statistics and an emitter recombination term, as well as a correction that accounts for the presence of trapping centres. It is shown that a good correlation exists between the measured open-circuit voltage and the *magnitude* of the recombination lifetime measured under 1-sun illumination. Also, for the cells examined here which had little series and shunt resistance effects, the measured fill factor was well correlated to the *dependence* of the recombination lifetime over the range of carrier densities from below maximum-power up to open-circuit conditions.

The cells studied have excellent emitter and rear surface passivation, and we are able to show that the strong injection-level dependence of the recombination lifetime is caused by recombination in the base of the cells. The implications of these findings for commercial mc-Si cells, which are generally not as well passivated and contain more heavily doped emitters, are discussed. By using the saturation current densities typical of industrial emitters and Aluminium back-surface-fields, and superimposing the injection-level dependence of the SRH centres observed above, the effect of the injection-level dependence on the fill factor is shown to be somewhat ‘dampened’, but nevertheless still significant. To completely explain the low fill factors in industrial cells, however, the presence of a shunt resistance is also required.

2. Experimental Methods

Solar cells were fabricated on 1.5 Ω .cm boron-doped cast mc-Si wafers grown by directional solidification at Eurosolare, Italy. High-efficiency cell structures were used to ensure good sensitivity to

bulk lifetime dependence in the cells. Photolithographically defined contacts on lightly-doped ($>100\Omega/\text{square}$), oxide-passivated emitters ensured low emitter recombination losses. Point-contacts through an aluminium-annealed (annealed) oxide on the rear of the cells similarly afforded very low rear-surface recombination losses (surface recombination velocity $<10\text{cm/s}$ for the oxidised regions). In fact, measurements on control float-zone wafers revealed that surface recombination losses are negligible in comparison to base and emitter losses in the mc-Si cells (Macdonald and Cuevas, 2000, Cuevas et al., 1999). Edge effects were avoided through the use of planar diffusions through a 4cm^2 window in a thermal oxide extending well beyond the cell boundaries.

Lifetime measurements were performed using the quasi-steady-state photoconductance (QSSPC) technique (Sinton and Cuevas, 1996). Such a technique is well suited to predicting wafer-averaged cell parameters from lifetimes on highly inhomogeneous materials like mc-Si, since the steady-state nature of the method ensures that both high and low lifetime regions contribute with appropriate weight to the total result. Recently, an improved, more general method for analysing QSSPC data has been developed (Nagel et al., 1999), which enables reliable measurement of lifetimes ranging from $1\mu\text{s}$ to above 1ms , over an injection-level range from around 1×10^{12} to about $5\times 10^{16}\text{cm}^{-3}$, depending on the magnitude of the lifetime.

After metallisation, the one-sun I-V curves of the cells were measured, as were their illumination- V_{OC} profiles. The latter was achieved by monitoring the open-circuit voltage on an oscilloscope while simultaneously monitoring the intensity of an exponentially decaying flash-lamp (Sinton and Cuevas, 2000).

3. Modelling Techniques

In the cells analysed here, the important recombination channels are SRH recombination in the bulk and recombination in the emitter. Auger recombination was negligible due to the relatively low defect-related lifetimes ($<100\mu\text{s}$), and also because the cells operate at relatively low carrier densities. Surface recombination is also negligible, as explained above. Therefore, the total recombination lifetime τ_r resulting from these simultaneously occurring mechanisms can be conveniently expressed as

$$\frac{1}{\tau_r} = \frac{1}{\tau_{\text{SRH}}} + \frac{1}{\tau_{\text{emit}}} \quad (1)$$

Where τ_{SRH} is the SRH bulk recombination lifetime and τ_{emit} an effective emitter recombination lifetime.

The Shockley-Read-Hall bulk lifetime for p-type silicon is calculated via (Smith, 1959):

$$\frac{1}{\tau_{\text{SRH}}} = \frac{N_A + \Delta n}{\tau_{p0}(n_1 + \Delta n) + \tau_{n0}(N_A + p_1 + \Delta n)} \quad (2)$$

Here, Δn is the excess carrier density, N_A the dopant density, n_1 and p_1 the equilibrium densities of electrons and holes, respectively, when the Fermi energy coincides with the recombination centre energy, and τ_{n0} and τ_{p0} the capture time-constants for electrons and holes of the particular SRH centre.

Emitter recombination is determined by (Cuevas, 1999):

$$\frac{1}{\tau_{\text{emit}}} = \frac{J_{0e}(N_A + \Delta n)}{qn_i^2 W} \quad (3)$$

Where J_{0e} is the emitter saturation current density, W the cell thickness and $n_i=8.7\times 10^9\text{cm}^{-3}$ the intrinsic carrier concentration in silicon at 25°C .

The values of W , N_A and J_{0e} are known by measurement. By adjusting the remaining unknown parameters, namely τ_{n0} and τ_{p0} , a good fit can be obtained for the mid- to high-injection levels. A further complicating issue that is important for the mc-Si samples is the presence of trapping centres. These states cause an abnormally large photoconductance at injection levels equal to and less than the trap density, in turn causing the lifetime to increase dramatically with decreasing injection level (Macdonald and Cuevas, 1999). These effects can be dealt with by applying a trapping model (Hornbeck and Haynes, 1955) to the measured data and then effectively turning the traps 'off'. This procedure is explained in detail elsewhere (Macdonald and Cuevas, 2000, Macdonald et al., 1999).

With an expression for the injection-level dependence of the recombination lifetime, we can then proceed to predict the open-circuit voltage of a substrate upon metallisation, through the expression:

$$V_{OC} = \frac{kT}{q} \ln \left(\frac{\Delta n(N_A + \Delta n)}{n_i^2} \right) \quad (4)$$

Following the method suggested by Sinton (Sinton and Cuevas, 2000, Sinton, 1999), and noting that the current is linear (confirmed by measurement), the implied illumination- V_{OC} curve, as calculated from the lifetime expression, can be converted into an implied 1-sun I-V curve by invoking the superposition principle, and neglecting the effects of series resistance. It is then possible to calculate an implied fill factor for each cell. The result will only correlate well with the measured fill factor if the series resistance of the finished cell is negligible at 1-sun operation. Such a condition is satisfied for these cells due to the low resistance ($<0.3\Omega\text{cm}^2$) of the photolithographically-defined and electroplated front fingers.

4. Results and Discussion

Figure 1 shows the constituent parts as well as the total lifetime model as fitted to experimental data from a $1.5\Omega\text{cm}$ cell precursor. The data is plotted in the form of inverse lifetimes in order to make apparent the additive nature of these various components, as expressed by equation 1. To obtain a good fit, it was necessary to use two independent SRH centres, an emitter term, and the effect of trapping centres. Note that the recombination lifetime is also shown as extrapolated from regions above the onset of trapping (at about $5\times 10^{13}\text{cm}^{-3}$) to well below it by 'turning off' the traps in the model.

The important curve in figure 1 is the recombination lifetime curve, i.e. the sum of the SRH and emitter terms, but with the traps turned off. It is this curve which is used to calculate the implied illumination- V_{OC} and I-V curves. Two deep SRH centres (0.35eV below the conduction band) were required to obtain a good fit. The measured parameters for this cell are $W=0.028\text{cm}$, $J_{0e}=8\times 10^{-13}\text{Acm}^{-2}$ and $N_A=1.0\times 10^{16}\text{cm}^{-3}$. The values of the fit parameters are $\tau_{n0}=3.33\times 10^{-5}\text{s}$ and $\tau_{p0}=1.11\times 10^{-2}\text{s}$ for the first deep SRH centre and $\tau_{n0}=1.09\times 10^{-4}\text{s}$ and $\tau_{p0}=1.09\times 10^{-3}\text{s}$ for the second deep SRH centre (Macdonald and Cuevas, 2000).

Another important feature on this graph is the solid circle representing the recombination lifetime and injection-level which occur under 1-sun illumination. This is the point which determines the open-circuit voltage at 1-sun, and using the appropriate values in equation (4) gives an implied V_{OC} of 642mV. This compares well with the final measured value on the finished cell of 644mV. In fact we find that these values generally correlate well, provided there are no major shunts in the cell, and that trapping does

not obscure the lifetime measurement. The behaviour of the lifetime below this 1-sun point will influence the fill factor. If the lifetime decreases below the 1-sun point, as it does in this case, a reduced fill factor will result. For this $1.5\Omega\text{.cm}$ substrate, the 1-sun point occurs quite near the maximum lifetime, with a strong SRH dependence below. Since there exists a significant injection-level range below the 1-sun point that is not affected by trapping, we can use this data to determine the implied illumination- V_{OC} and 1-sun I-V curves, and hence predict the fill factor for this cell with some accuracy. This is not always possible in mc-Si samples, since trapping often obscures too much of the recombination lifetime.

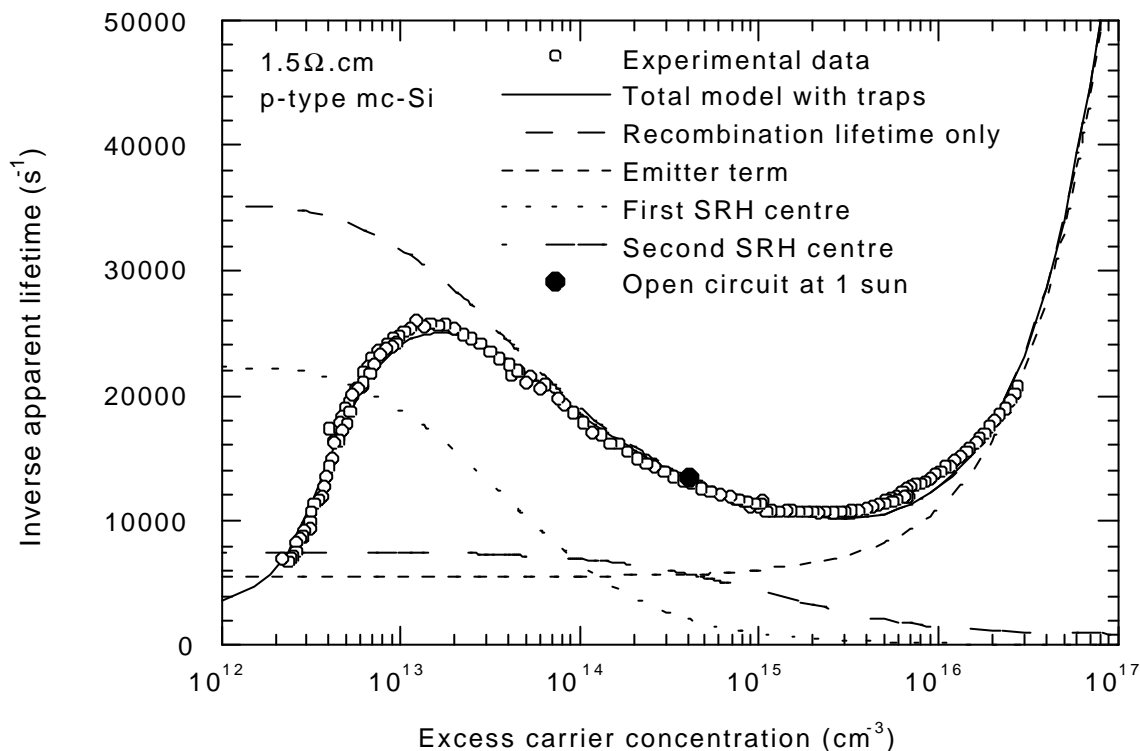


Figure 1. Injection-level dependent lifetime measurement on a $1.5\Omega\text{.cm}$ cell precursor. Also shown are two modelled SRH lifetimes and an emitter recombination term that add together inversely to model the measured recombination lifetime data.

Figure 2 shows the measured and implied I-V curves for the $1.5\Omega\text{.cm}$ cell. For the implied curve, the measured value of J_{SC} (34.4 mA/cm^2) is used to scale the current axis. Excellent agreement between the measured and implied fill factors can be seen in the values of 0.785 and 0.790 respectively. Also shown on the figure is the I-V curve expected for a similar cell, but with a constant recombination lifetime below open-circuit conditions. The effects of emitter recombination are retained for high injection, leading to an ideality of 1 for all injection levels in this case. This curve represents an ‘ideal’ cell, and yields a fill factor of 0.835. Thus the low measured fill factor can be attributed to the injection level dependence of the bulk-lifetime, essentially an intrinsic property of the material, and not to device design problems such as series or shunt resistance, or edge effects, nor to junction recombination.

It is interesting to note that the highest efficiency mc-Si cells made to date (Zhao, et al., 1998), on similar $1.5\Omega\cdot\text{cm}$ material and with a similar cell structure, also achieved a fill factor of 0.795. We suggest that this cell may also have been affected by the injection-level dependence of the bulk lifetime. It is also worth noting that a similar reduced fill factor effect was reported in high efficiency single-crystal cells, but was shown in that case to be due to the injection-level dependence of the surface recombination velocity of the rear oxide (Aberle, et al., 1993, Robinson, et al., 1994).

Commercially produced mc-Si cells do not have the benefits of passivated, lightly-doped emitters and well passivated rear-surfaces. The recombination characteristics of an industrial emitter and Aluminium back-surface-field can be characterised by saturation current densities. Typical values of J_{0e} and J_{0BSF} for a commercial process are $8\times 10^{-13}\text{Acm}^{-2}$ and $5\times 10^{-13}\text{Acm}^{-2}$ respectively (Macdonald, et al., 2000). Using these values, in conjunction with the bulk SRH parameters determined above for the $1.5\Omega\cdot\text{cm}$ mc-Si cell, gives an indication of the impact of the injection-level dependence on commercial cell fill factors. The result is an implied V_{OC} of 606mV, and an implied fill factor of 0.815. The reduction in the fill factor is not as severe as for the high efficiency cell, since the relatively high saturation currents of the heavily doped regions in the commercial cell ‘dampen’ the injection-level dependence of the total effective lifetime. Most commercial mc-Si cells have fill factors around 0.75-0.76. The injection-level dependence of the bulk recombination centres may be partly responsible for these low values, but not entirely. The remaining performance reduction is usually due to some shunting at the cell edges.

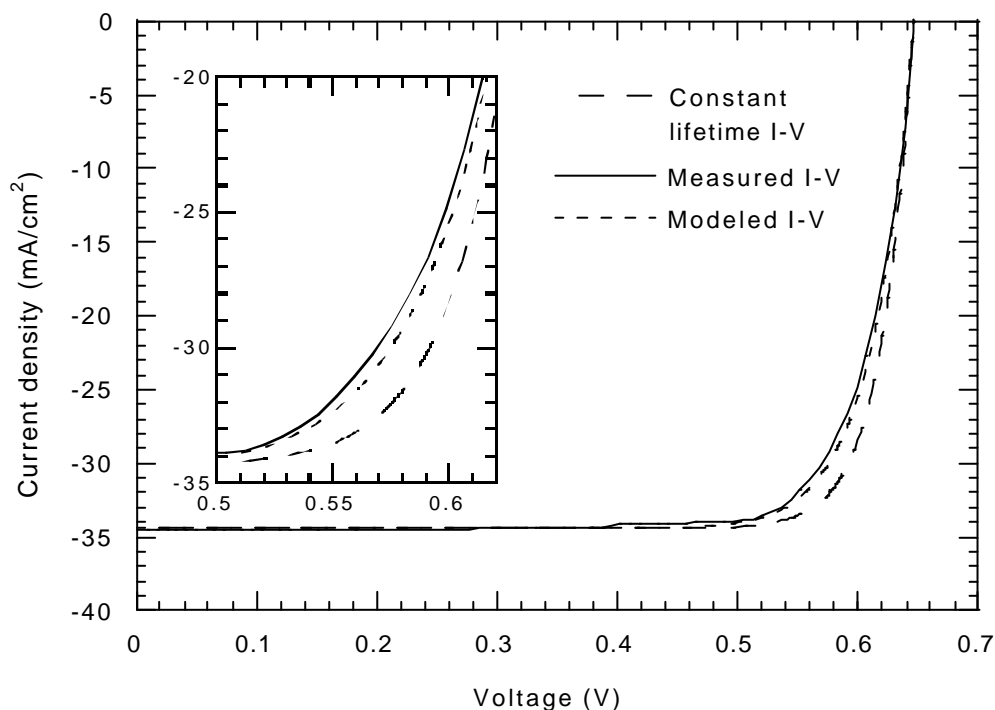


Figure 2. Modelled and measured I-V curves for the $1.5\Omega\cdot\text{cm}$ cell. Also shown is an ‘ideal’ I-V curve, modelled with a constant low-injection lifetime, which gives rise to a fill factor of 0.835.

5. Conclusions

The magnitude of the effective recombination lifetime at 1-sun illumination correlates well with the final open-circuit voltage of a cell, provided accurate measurement of the lifetime is not hampered by trapping effects. Furthermore, injection-level dependent recombination lifetimes below 1-sun illumination can cause low fill factors in mc-Si solar cells. In high efficiency cells, which are more sensitive to the behaviour of the bulk centres, the reduction in the fill factor is quite strong. In industrial cells, the presence of the heavily doped emitter and back-surface-field weaken the injection-level dependence of the effective lifetime, and hence these cells are less prone to fill factor degradation.

6. Acknowledgments

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7. References

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