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Research

Impact of Light-induced Recombination Centres on the Current–Voltage Characteristic of Czochralski Silicon Solar Cells

Jan Schmidt[1,*,†], Andrés Cuevas,[2,3], Stefan Rein[2] and Stefan W. Glunz[2]
[1]*Institut für Physikalische Elektronik, Universität Stuttgart, Pfaffenwaldring 47, D-70569 Stuttgart, Germany*
[2]*Fraunhofer Institut für Solare Energiesysteme, Oltmannsstr. 5, D-79100 Freiburg, Germany*
[3]*Department of Engineering, FEIT, Australian National University, Canberra ACT 0200, Australia*

We have investigated the effect of the light-induced deep-level recombination centre specific to boron-doped, oxygen-contaminated Czochralski (Cz) silicon on the current–voltage characteristic of Cz silicon solar cells by means of numerical simulation and experiment. The device simulation predicts the occurrence of a shoulder in the current–voltage curve after activating the characteristic recombination centre. The physical reason for the non-ideal diode behaviour, characterised by a local ideality factor greater unity, is the strongly injection-level-dependent bulk lifetime produced by the deep-level centre. The increased ideality factor causes a degradation in fill factor with the magnitude of degradation depending on the doping concentration of the Cz silicon base. In order to verify the theoretical predictions experimentally, we have performed measurements on high-efficiency Cz silicon solar cells. Current–voltage curves recorded before and after light degradation clearly show the theoretically predicted change in shape and the reduction in fill factor. An excellent quantitative agreement between calculation and experiment is obtained for the subtracted current–voltage curves measured after and before illumination.

INTRODUCTION

Although the light-induced degradation of Czochralski (Cz) silicon solar cells was discovered in the early 1970s,[1] only in recent years has there been considerable progress in the understanding of the fundamental mechanism causing the degradation.[2–5] The present understanding of the phenomenon attributes the degradation during illumination (or, alternatively, minority-carrier injection in the dark) to an excess-carrier-activated metastable defect complex correlated with the boron and the oxygen concentration of the Cz silicon material. As the defect complex – in its active state – exhibits an energy level close to the

* Correspondence to: Jan Schmidt, ISFH, Am Ohrberg 1, D-31860 Emmerthal, Germany.
†E-mail: j.schmidt@isfh.de

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middle of the silicon bandgap,[4] it acts as a very effective recombination centre and reduces the bulk carrier lifetime considerably, causing a degradation in cell efficiency. The light-induced deep-level centre can be deactivated by applying an annealing treatment at a temperature of 200°C and above. However, after illuminating the cell with a halogen lamp for approximately 12 h at an intensity of $\sim$100 mW/cm^2, the metastable defect is fully reactivated.

In the past, research was mainly focused on two aspects: (i) investigating the fundamental mechanism of the light degradation/thermal recovery cycle; and (ii) reducing the light degradation of Cz silicon solar cells.[2–6] The effect of the specific light-induced deep-level centre on the shape of the current–voltage (*I–V*) characteristic of Cz silicon solar cells has not been analysed so far. In the present publication, we compare *I–V* curves of Cz silicon solar cells before and after light degradation and analyse the changes due to the activation of the specific boron- and oxygen-correlated metastable defect.

NUMERICAL SIMULATION

As has been shown recently by means of a new lifetime spectroscopy method,[4] the fundamental light-induced recombination centre in boron-doped, oxygen-contaminated Cz silicon exhibits an energy level close to midgap, and the ratio of the electron and hole capture time constant τ_n/τ_p lies between 0·1 and 0·2. Using the common definition of the bulk lifetime τ_b as the quotient of the excess carrier concentration Δn and the net recombination rate U, $\tau_b \equiv \Delta n / U$, the above defect properties result in a bulk lifetime with a very strong injection level dependence $\tau_b(\Delta n)$. As injection-level-dependent recombination parameters are known to be one important cause of non-idealities in the *I–V* curves of silicon solar cells,[7–10] the activation of the characteristic defect centre in Cz silicon can also be expected to have an impact on the shape of the *I–V* curve of Cz silicon solar cells. In order to analyse this effect, we have performed numerical simulations, using the device modelling program PC1D V5.3 (P.A. Basore and D. A. Clugston, University of New South Wales, Sydney, Australia, 1998).

Figure 1(a,b) shows the calculated dark *I–V* curves of a 400-µm-thick n^+p high-efficiency silicon solar cell structure with two different base doping concentrations ($N_{dop} = 10^{16}$ cm^{-3} and $N_{dop} = 10^{15}$ cm^{-3}, respectively) before and after activation of the characteristic deep-level centre. In order to highlight the impact of the bulk recombination, both cell surfaces are assumed to be perfectly passivated, i.e., the surface recombination velocities at the front and the rear are set at zero. The n^+-emitter has a Gaussian profile with a 1-µm-deep junction and a surface dopant concentration of 10^{19} cm^{-3}. To avoid any additional possible causes of non-idealities in the *I–V* curves, no series resistance and no shunt are implemented. For the calculations under one-sun AM1·5G illumination, we assume a textured front with optimal anti-reflection properties and perfect light trapping.

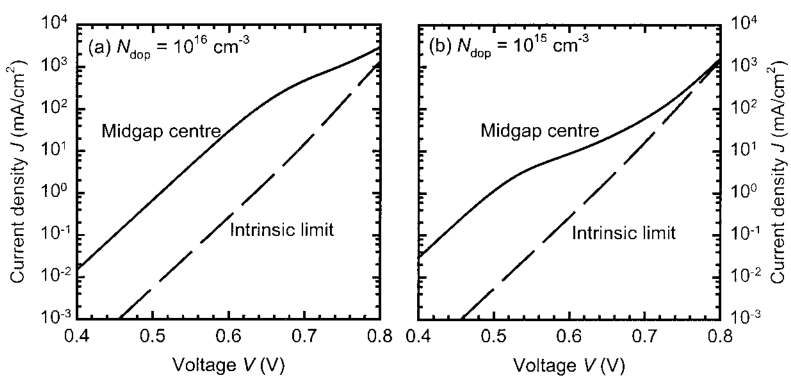

Figure 1. Calculated dark *I–V* curves of a high-efficiency silicon solar cell structure with a base doping concentration of (a) $N_{dop} = 10^{16}$ cm^{-3}, (b) $N_{dop} = 10^{15}$ cm^{-3} before (dashed lines) and after (solid lines) introducing the midgap recombination centre specific to light-degraded Cz silicon (see text for simulation parameters)

The dashed lines in Figure 1 show the dark *I–V* curves for a perfect, defect-free silicon crystal, where recombination takes place exclusively via the intrinsic recombination channels of band-to-band Auger and, to a minor degree, radiative recombination. The solid lines show the *I–V* curves after introducing a recombination centre possessing the characteristic properties of the fundamental light-induced defect centre in Cz silicon. The energy of the recombination centre is positioned in the middle of the silicon bandgap, and the ratio of the capture time constants is kept constant at $\tau_n/\tau_p = 0 \cdot 1$ throughout all following calculations. A τ_n value of 10 µs, as is typical[4] for Cz silicon with a doping concentration of 10^{16} cm^{-3}, is assumed in Figure 1(a). As the concentration of the metastable defect in Cz silicon is known to increase proportionally with the boron doping concentration,[3,4] τ_n is set at 100 µs for the cell with the 10^{15} cm^{-3} doping concentration in Figure 1(b). This argument implicitly assumes that both cells have the same oxygen concentration. Comparing the solid and the dashed lines in Figure 1(a) and (b), the introduction of the recombination centre produces a pronounced shoulder in the semi-logarithmic *I–V* curves. The position of this shoulder depends on the doping concentration of the silicon, shifting to higher voltages with increasing doping concentration. The physical cause of the shoulder is the injection-level-dependent bulk lifetime produced by the characteristic deep-level centre with the strongly asymmetric capture time constant ratio. On increasing the voltage, the injection level within the bulk increases and with it the bulk lifetime, leading to a relative reduction in recombination current. Very similar behaviour has been reported for high-efficiency silicon solar cells with injection-level-dependent rear surface recombination velocity[7–9] and for multicrystalline silicon solar cells with injection-level-dependent bulk lifetime.[10]

A very useful figure of merit to describe non-idealities of *I–V* characteristics is the local ideality factor. Figure 2 shows the local ideality factor *n* (solid line), as determined from the solid *I–V* curve shown in Figure 1(b), together with the bulk lifetime τ_b (dashed line) as a function of voltage. The local ideality factor was determined by fitting the simple diode equation $J(V) = J_0\,[\exp(V/nV_T) - 1]$, where V_T is the thermal voltage, to the measured current–voltage curve in a small voltage range around *V*. Free fit parameters were the saturation current density J_0 and the local ideality factor *n*. As can be seen from comparison of Figure 1(b) with Figure 2, the shoulder in the *I–V* characteristic corresponds to an ideality factor larger unity, with the maximum in *n* lying at the flex point of the semi-logarithmic *I–V* curve. The physical origin of the increased ideality factor is the strong increase of τ_b with voltage (dashed line in Figure 2). As the position of this increase on the voltage scale depends on the doping concentration, the position of the maximum in *n* also depends on N_{dop}. This is why the shoulder of the cell with 10^{16} cm^{-3} doping concentration (Figure 1a) occurs at a higher voltage compared with the cell with doping concentration of 10^{15} cm^{-3} (Figure 1b).

Table I summarises the calculated one-sun solar cell parameters, together with the local ideality factors at maximum power point n_{MPP} and under open-circuit conditions n_{Voc}. For the solar cell with 10^{15} cm^{-3} doping concentration, n_{MPP} increases from 0·95 (intrinsic limit) to 1·86 after introducing the recombination centre.

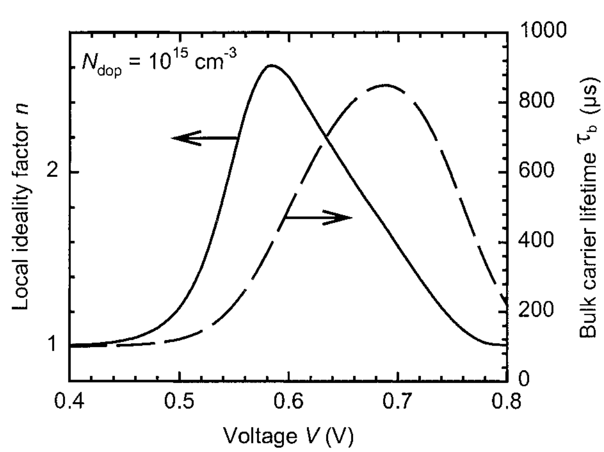

Figure 2. Local ideality factor *n* (solid line) as a function of the applied voltage *V* calculated from the solid *I–V* curve with midgap centre in Figure 1(b). Also shown is the bulk carrier lifetime τ_b as a function of the applied voltage *V* (dashed line)

Table I. Calculated cell parameters (V_{oc} open-circuit voltage, V_{MPP} voltage at maximum power point, J_{sc} short-circuit density, FF fill factor, η efficiency, $n_{Voc/MPP}$ local ideality factors at V_{oc} and maximum power point) of two silicon solar cells with different base doping concentrations N_{dop} (10^{15} and 10^{16} cm^{-3}). The cells have a perfect surface passivation and neither shunt nor series resistance. Two different cases are assumed for the recombination in the bulk. Case A is the intrinsic limit, i.e., bulk recombination within the cell is dominated by the Auger recombination process in silicon. In case B, a midgap recombination centre is introduced which exhibits the characteristic properties of the boron- and oxygen-correlated light-induced recombination centre in Czochralski silicon

	$N_{dop}=10^{15}cm^{-3}$		$N_{dop}=10^{16}cm^{-3}$	
Cell parameter	A (intrinsic limit)	B (midgap centre, $\tau_n/\tau_p=0\cdot1, \tau_n=100$ µs)	A (intrinsic limit)	B (midgap centre, $\tau_n/\tau_p=0\cdot1$, $\tau_n=10$ µs)
V_{oc} (mV)	720·0	681·8	722·0	604·0
V_{MPP}(mV)	640·0	540·0	644·0	520·0
J_{sc} (mA/cm^2)	41·4	40·6	41·0	36·2
FF (%)	85·2	72·6	85·8	82·3
η (%)	25·4	20·1	25·4	18·0
n_{Voc}	0·87	1·76	0·86	1·09
n_{MPP}	0·95	1·86	0·98	1·01

The increased ideality factor has a direct impact on the fill factor FF of the cell, which degrades from 85·2% to only 72·6%. On the other side, in the case of the solar cell with $N_{dop}=10^{16}$ cm^{-3}, the shoulder in the I–V curve occurs at a voltage much larger than the voltage at maximum power point. Hence, n_{MPP} of this cell shows only a negligible increase from 0·98 to 1·01, owing to the introduction of the recombination centre. Consequently, the fill factor remains at a very high level. The slight reduction in FF from 85·8 to 82·3% is due only to the increased recombination within the bulk of the cell. However, the cell with 10^{16} cm^{-3} base doping concentration exhibits a much stronger reduction in V_{oc} and J_{sc} compared with the cell with 10^{15} cm^{-3} base doping concentration.

EXPERIMENTAL

In order to verify experimentally the theoretically predicted formation of a shoulder in the I–V characteristic of Cz silicon solar cells after illumination, we have investigated high-efficiency Cz silicon solar cells fabricated at the Fraunhofer ISE.[5] Processing details of these 'random-pyramid passivated emitter, rear locally diffused cells' (RP-PERL) have been reported elsewhere.[5] To avoid any effect of the series resistance on the measured current–voltage curves, we applied a new method recently suggested by Sinton.[11] This method measures the open-circuit voltage V_{oc} as a function of the light intensity while illuminating the cell with a flash lamp. At the same time, the light intensity is measured with a calibrated concentrator solar cell. As the short-circuit current density J_{sc} of the solar cell under test was found to depend linearly on the incident light intensity, the J_{sc}–V_{oc} curve of the solar cell can be easily calculated from the measured intensity–V_{oc} curve. The one-sun J_{sc} values of the cells were measured separately under standard testing conditions.[5]

Figure 3 (a,b) shows the measured J_{sc}–V_{oc} curves of a 0·77 Ω cm ($N_{dop}=2\cdot0\times10^{16}$ cm^{-3}) and a 5·4 Ω cm ($N_{dop}=2\cdot6\times10^{15}$ cm^{-3}) boron-doped Cz silicon solar cell, respectively, after annealing the cells for 30 min at 200°C (dashed lines) and after illuminating them for 30 h at one sun (solid lines). The illumination clearly produces a shoulder in the I–V curves of both cells, with the trend of occurring at lower voltages with decreasing doping concentration. This is in good qualitative agreement with the simulated I–V curves of the previous section. A direct quantitative comparison of the measured I–V curves with the simulation results is not reasonable because of the additional recombination paths within the RP-PERL cells, as there is recombination at the oxidised rear surface, the front surface and via residual defect centres in the bulk. In order to circumvent this problem, we analyse the *difference* of the short-circuit current densities measured after illumination and after

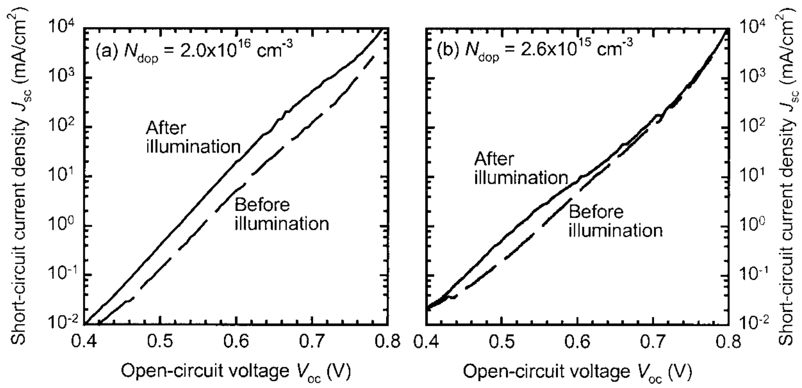

Figure 3. Measured J_{sc}–V_{oc} curves of: (a) a 0·77 Ω cm, (b) a 5·4 Ω cm boron-doped Cz silicon solar cell after annealing the cells for 30 min at 200°C (dashed lines) and after illuminating them for 30 h at one sun (solid lines)

annealing $J_{sc.i} - J_{sc.a}$. Assuming that no other recombination parameter is changed during illumination, this quantity shows solely the effect of the *additional* recombination centres activated by illumination.

Figure 4 shows the measured values of the current difference $J_{sc.i} - J_{sc.a}$ as a function of V_{oc} (symbols) in comparison with the calculated curves (lines). For the PC1D calculations, we use the same set of device parameters as applied in Figure 1 with only the doping concentration being changed to $N_{dop} = 2 \cdot 0 \times 10^{16}$ and $2 \cdot 6 \times 10^{15}$ cm^{-3}, respectively, corresponding to the base resistivities of the measured cells of 0·77 and 5·4 Ω cm. The light-induced recombination centre is assumed to lie at midgap and $\tau_n/\tau_p = 0 \cdot 1$. Furthermore, we assume a typical τ_n value of 10 μs for the 0·77 Ω cm cell, while a τ_n value of 270 μs is applied in the case of the 5·4 Ω cm cell. This value is derived from the τ_n value of the 0·77 Ω cm cell, taking into account the different boron and oxygen concentrations of both materials (the interstitial oxygen concentration of the 0.77 Ω cm Cz material is 13·14 ppma, while that of the 5·4 Ω cm Cz silicon lies at 10·25 ppma).[5] Moreover, the concentration of the light-induced recombination centre is known to increase proportionally with the boron and super-linearly (to the power of five) with the interstitial oxygen concentration.[3,4] Because of these considerations, the simulations do not include any free parameter. However, despite the fact that we have no fit parameter involved in our calculations, an excellent agreement between measurement and calculation is obtained in Figure 4. Note that these results are rather tolerant towards variations in τ_n.

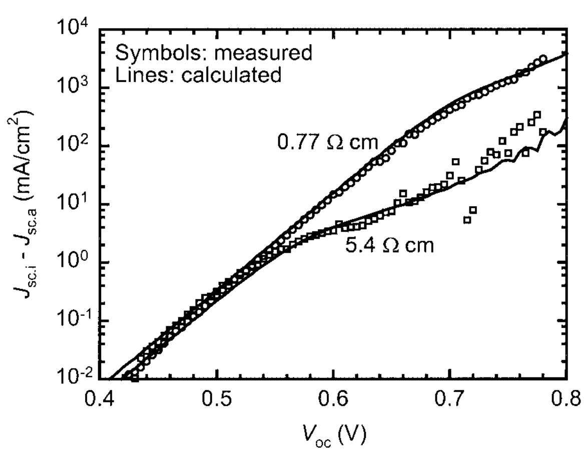

Figure 4. Difference of the short-circuit current densities measured after illumination and after annealing $J_{sc.i} - J_{sc.a}$ as a function of the open-circuit voltage V_{oc} (symbols) in comparison with the calculated curves (lines)

According to our theoretical analysis presented in the previous section, the prominent shoulder in the *I–V* curve of the 5·4 Ω cm cell, occurring in the vicinity of the one-sun operating voltage, should lead to a degradation in fill factor. In the case of the 0·77 Ω cm cell, the shoulder occurs in a voltage range outside the one-sun operating range of the solar cell. Hence, no effect on fill factor is expected for the latter cell. In fact, exactly this behaviour is observed experimentally under one-sun AM1·5 illumination (a detailed compilation of the cell parameters has been published[5]); for the 0·77 Ω cm solar cell, a fill factor of 80·2 and 79·9% is measured before and after degradation, respectively. This small reduction (−0.4% relative) in fill factor lies within the uncertainty range of the measurement. At the same time, the open-circuit voltage of the cell degrades from 656·7 to 626·2 mV (−4·6%), owing to the strong degradation of the bulk lifetime. For the 5·4 Ω cm cell, V_{oc} is still at a high level of 666·1 mV (−1.3%) after degradation (674·9 mV before degradation), because the bulk lifetime of the degraded high-resistivity material is still quite large. However, owing to the emerging shoulder, the fill factor of this cell degrades significantly (−3.8%) from 79·1 to 76·1%. These cell results confirm the theoretical predictions of the earlier section.

Finally, it is noteworthy that the results presented here are not only relevant to boron-doped Cz silicon solar cells, but also provide clear experimental evidence of ideality factors greater unity in silicon solar cells, caused by the injection level dependence of recombination parameters, an effect which is under discussion since many years.[7–10]

CONCLUSIONS

The light-induced activation of the deep-level recombination centre specific to boron-doped, oxygen-contaminated Cz silicon leads to a shoulder in the current–voltage curve of solar cells fabricated on this material. This effect has been demonstrated by means of numerical simulation using PC1D and measurements on high-efficiency Cz silicon solar cells. The physical reason for the non-ideal behaviour, characterised by a local ideality factor greater unity, is the strongly injection-level-dependent bulk lifetime produced by the characteristic light-induced defect centre. The increased ideality factor causes a degradation in fill factor, with the magnitude of degradation depending on the doping concentration of the Cz silicon. The comparison of current–voltage curves measured before and after degradation clearly shows that the reduction in fill factor is not due to device issues (i.e., series resistance, shunt, recombination in the space charge region), but is an *inherent property* of boron-doped, oxygen-contaminated Cz silicon as it is widely used in the fabrication of solar cells.

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