THE INFLUENCE OF EDGE RECOMBINATION ON A SOLAR CELL'S I–V CURVE

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ABSTRACT: This paper presents an investigation into the influence of edge recombination on the I–V curve of a solar cell, for the situation where the p–n junction extends to the edge of that solar cell. With experiment and simulation, it is found that the edges can be considered as an exponential shunt across the p–n junction that is resistively isolated from the main body of the solar cell. An equivalent circuit that describes this situation is used to determine how the edge-recombination current decreases the efficiency of a laboratory-grade buried-contact solar cell. It is concluded that unless the edge-recombination current is below $\sim 10^{-8}$ A/cm, it significantly reduces the efficiency, even for medium-to-large area solar cells.
Keywords: Recombination - 1; Modelling - 2; Shunts - 3.

1. INTRODUCTION

The recombination rate at the edges of a solar cell is often much greater than elsewhere in the solar cell. At an edge, there is a complete disrupture of the crystal lattice, but unlike the front and rear surface, the edges are rarely passivated; the disrupture therefore increases the density of traps inside the "forbidden gap", and hence, increases the recombination rate. The edge recombination rate is further enhanced when a p–n junction extends to the edge, and when the process of edge-isolation damages the crystal lattice—both of which occur in many solar cells.

Edge recombination has been found to have a significant influence on the efficiency of small-area, high-efficiency solar cells [1][2]. In these structures, the p–n junction does not extend to the edge, and therefore, any edge recombination requires that minority carriers diffuse through the base to the edge. This type of edge recombination is insignificant in low-efficiency solar cells (which have a short diffusion length), and large-area solar cells (which have a more significant contribution from non-edge sources).

In many solar cells, however, the p–n junction does extend to the edge of the solar cell. This paper uses experiment and an equivalent-circuit model to investigate this situation.

2. EXPERIMENT

An experiment was conducted to investigate the influence of edge recombination on the I–V curve of a solar cell, for the situation where the p–n junction extends to the edge of that solar cell. The experiment was performed on a buried-contact solar cell, which is a commercially relevant solar cell that has this feature. The solar cell was fabricated following the conventional buried-contact procedure [3], except for the final fabrication step: the edge-isolation. In this experiment, the edges were first made a distance of d = 11 mm from the peripheral fingers (Fig. 1), and d was then reduced in 2 mm steps until the edges were 1 mm from the peripheral fingers (as is typically the case). The dark I–V curve was measured at each interval.

The solar cell was designed to ensure that the edge-recombination current was relatively large and hence, easily quantifiable: its area was small, with the finger pattern optimised for a 2 cm^2 solar cell; it was fabricated with the conventional buried-contact procedure, which is capable of attaining a relatively high efficiency (> 19%) [3]; and the edges were formed with a particularly damaging process. The last of these features relates to the edge-isolation fabrication step, in which a laser is used to scribe grooves into the rear of the solar cell and the outer parts of the wafer are "snapped off". In this experiment, these grooves were almost as deep as the thickness of the wafer, rather than half the thickness as is conventional, and thus, the laser damage at the edges was greater than usual.

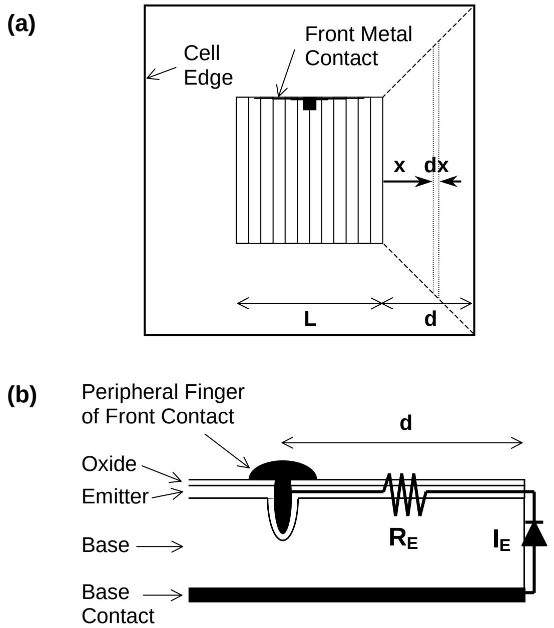

Figure 1: **(a)** Plan **(b)** cross section of the buried-contact solar cell of the experiment (not to scale).

The measured dark ln(I)–V curves are plotted with symbols in Fig. 2. For clarity, three of the six curves have been omitted; these omitted curves exhibit the same trends as those shown in the figure. All of the ln(I)–V curves contain a prominent kink ($\sim$ 0.3–0.55 V), a feature that has also been observed in the ln(I)–V curves of other small-area solar cells in which the p–n junction extends to the edge [4][5]. The figure indicates that as the edge is brought closer to the main body of the solar cell (i.e., as d decreases), the ln(I)–V

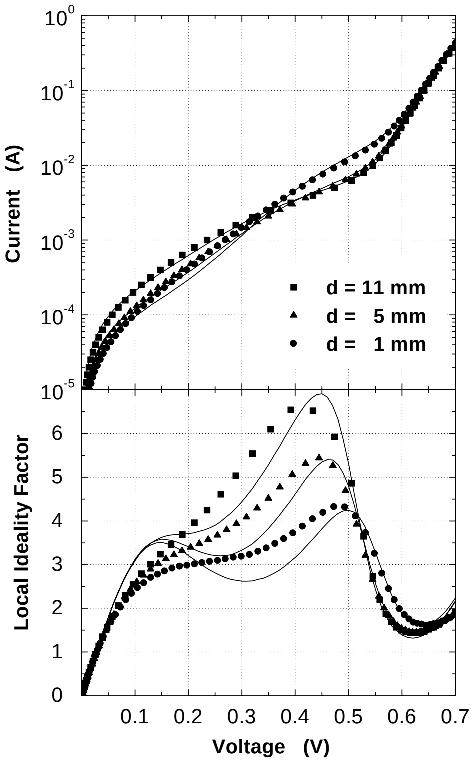

Figure 2: $\ln(I)$–V and m–V curves for $d = 11$, 5 and 1 mm; symbols show measured data and lines show simulated data.

curve shifts to a smaller current at low voltages, and the kink extends to a higher voltage.

The dependence on d can be better observed in the m–V curves that are also plotted in Fig. 2. The parameter m, the local ideality factor, is defined as $m = \frac{q}{kT}\left(\frac{dV}{d\ln(I)}\right)$, and is therefore inversely proportional to the differential of the $\ln(I)$–V curve. The m–V curve provides a way to observe structure in the $\ln(I)$–V curve that might otherwise go unnoticed. In this case, the $\ln(I)$–V kink corresponds to a broad hump, and as d decreases, the hump becomes smaller and shifts to a larger voltage. (Ref. [6] describes the m–V curves of ideal solar cells.)

3. EQUIVALENT CIRCUIT

The experiment indicates that the hump in the m–V curve is related to the edges. The reason for this behaviour and its relationshp to the cell edges can be understood with the equivalent circuit shown in Fig. 3. The circuit is divided into two parallel parts: one part to represent the main body of the solar cell, and the second part to represent the edges. The main body of the solar cell is comprised of the familiar one-diode model, with a series resistance R_s, an ohmic shunt resistance R_{sh}, an $I_1 = I_{01}[\exp(qV/kT) - 1]$ diode to represent the recombination current from sources other than the edges, and a current-generation component I_L to represent the light-generated current. The second part of the circuit contains a resistor R_E to represent the resistance that separates the edges from the main body of the solar cell, and an $I_E = I_{0E}[\exp(qV/m_EkT) - 1]$ diode to represent the recombination current at the edges.

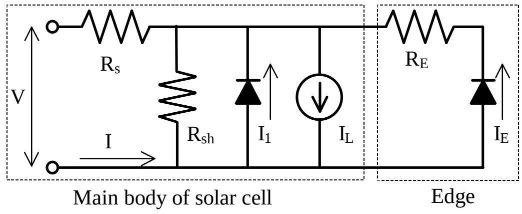

Figure 3: The equivalent circuit of a solar cell with a resistively isolated region of high recombination.

The circuit of Fig. 3 essentially describes a solar cell with a resistively isolated shunt across its p–n junction—a shunt that has an *exponential* relationship with voltage. In this study, the "exponential shunt" is a result of the high recombination current that occurs at the cell edges. In other studies, the circuit has been used to describe solar cells with damage at the peaks of their textured pyramids [7], and with localised Schottky-contact shunts [8].

To clarify the reason for the m–V hump, the operation of the equivalent circuit is now explained for dark conditions (when $I_L = 0$). Fig. 4 presents dark I–V and m–V curves produced by the equivalent circuit. The dashed line shows the $\ln(I)$–V characteristic of the main body of the solar cell; this line depicts a diode with a "slope" of $m = 1$. The thin solid line shows the $\ln(I)$–V characteristic of the edge region, in which the diode with a "slope" of $m = m_E$ is evident ($m_E = 2$ in this example), as well as the flattening of the $\ln(I)$–V curve caused by R_E. Since these two parts are connected in parallel, the total current that flows through the circuit is equal to the sum of the current flowing through each part, shown as the thick solid line. (For simplicity, the effects of R_{sh} and R_s are omitted from this discussion.)

The cause of the m–V hump is now apparent. At low voltages, the dominant current flow is that through I_E and R_E, but because the $\ln(I)$–V curve flattens, there comes a voltage at which dominant current flow is that through I_1. It is the flattening of the $\ln(I)$–V curve due to R_E and the subsequent steepening of the $\ln(I)$–V curve due to I_1 that corresponds to a broad hump in the m–V curve.

4. SIMULATION

The equivalent circuit of Fig. 3 was used to simulate the solar cell of the experiment. The circuit parameters that describe the edge region (R_E, m_E and I_{0E}) were chosen as follows. Since the dominant source of R_E was the resistance of the emitter that separates the edge from the peripheral fingers (Fig. 1(b)), R_E depended on the sheet resistance of the emitter $\rho_\square$ and the geometry of the solar cell (Fig. 1(a)), as

$$R_E = \frac{\rho_\square}{4}\int_0^d \frac{dx}{L+2x} = \frac{\rho_\square}{8}\ln\left(\frac{L+2d}{L}\right), \qquad (1)$$

where L and $\rho_\square$ were experimentally measured to be $L = 1.2$ cm and $\rho_\square = 250 \pm 30\ \Omega/\square$. A value of $m_E = 2$ was used since in many studies, a large $\exp(qV/2kT)$

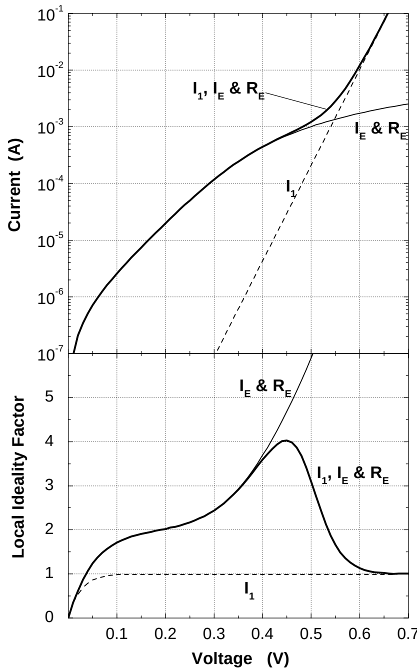

Figure 4: $\ln(I)$–V and m–V curves for the equivalent circuit of Fig. 3 with the parameters, $I_{01} = 10^{-12}$ A, $I_{0E} = 5 \times 10^{-6}$ A, $m_E = 2$ and $R_E = 100\ \Omega$.

recombination current is observed when a p–n junction is intercepted by the surface of a semiconductor [9][10]; note that this mechanism is different to depletion-region recombination [9]. The value of I_{0E} (the saturation current of the edges) was maintained as a free parameter.

The circuit parameters that describe the main body of the solar cell were $R_s = 0.07\ \Omega$, as measured with the method of Aberle *et al.* [11]; $R_{sh} = 1.3$ kΩ as was measured at 10 mV; and $I_{01} = 2.5$ pA, which gave a close fit to the experimental curves for all values of d.

With the afore-mentioned values of R_E, m_E, R_s, R_{sh} and I_{01}, the value of I_{0E} was adjusted so that the I–V curve of the equivalent circuit fit best with the experimental I–V curve, for each value of d. The simulated curves (lines) are compared to the experimental curves (symbols) in Fig. 2. The figure indicates that there is reasonable match between the I–V curves, especially in the region where the I–V curve flattens due to R_E. The simulated curves are also included in the m–V plot, which, being the differential of the I–V curve, emphasizes any differences between the curves. Both the height and the voltage location of the m–V hump are well matched, supporting the use of the equivalent circuit.

The simulation and experiment differ most at low voltages. A very close match could be attained if a value of $m_E \sim 3$ were chosen for the simulations, but to the authors' knowledge, no physical mechanism gives rise to this value. The difference is perhaps better explained as a consequence of two-dimensional non-uniformities in the sheet resistance (which varied by $\pm 30\ \Omega/\Box$) and in the damage at the edges (due to their formation with a pulsed laser). Two-dimensional non-uniformities tend to smoothen the I–V curve, which reduces the detail in the m–V curve. The difference between the simulation and the experiment might also be a consequence of surface charges in the native oxide at the edges, which introduce a voltage-dependent I_{0E} [5].

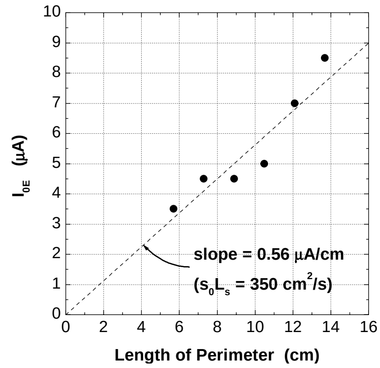

Figure 5: I_{0E} versus cell perimeter, where I_{0E} was determined by attaining the best fit between simulated and experimental I–V curves.

The value of I_{0E} that gave the best fit is plotted against the cell perimeter in Fig. 5. The figure indicates that there is an approximately linear relationship with a slope of 0.56 μA/cm. Following the notation of Henry *et al.*, this amounts to $s_0 L_s \sim 350$ cm^2/s.

The consistency between simulation and experiment indicates that a solar cell in which the p–n junction extends to the edge can, to a first approximation, be modelled by the equivalent circuit of Fig. 3.

5. THE ILLUMINATED I–V CURVE

Fig. 6 plots the illuminated I–V curve of the finished solar cell ($d = 1$ mm); the symbols show experimental data and the line shows a simulated curve. The simulated curve was determined with the same parameters as those used for the dark conditions above (when $d = 1$), except that $I_L = 67$ mA, which is equal to the measured short-circuit current, and $R_s = 0.65$ Ω, which was equal to R_s measured at the maximum-power point. The consistency between the simulated and experimental curves further supports the use of the equivalent-circuit for this solar cell, and indicates that, except for R_s, the physical mechanisms of the solar cell obey the principle of superposition.

6. EFFICIENCY VS EDGE RECOMBINATION

The illuminated I–V curve whon in Fig. 6 is noticably rounded about the maximum-power point. This rounding is manifested as a hump in the m–V curve and is therefore a consequence of the resistively isolated edge recombination. In this instance, the edge recombination acts to reduce the fill factor from 0.77 to 0.63, the equivalent of a 17% decrease in the relative efficiency. This detrimental influence is substantial but not surprising when one considers that the solar cell was designed to have a large edge-recombination current.

Having established the equivalent circuit of Fig. 3

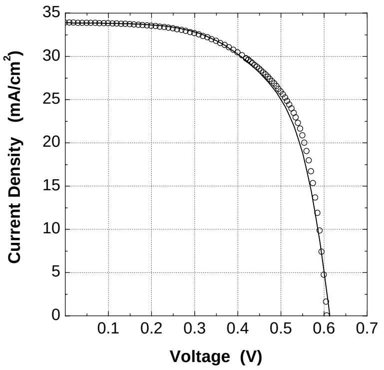

Figure 6: The measured (symbols) and simulated (line) I–V curve of the experimental solar cell under one-sun illumination.

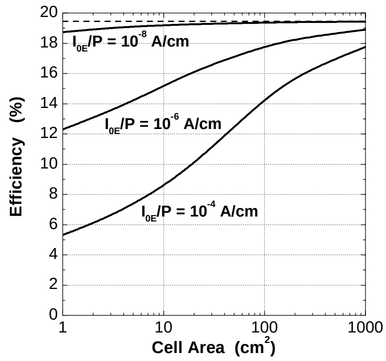

Figure 7: Dependence of efficiency on cell area and I_{0E}/P for a laboratory-grade buried-contact solar cell.

as a reasonable model to describe a solar cell in which the p–n junction extends to the edges, the circuit is now applied to determine how cell efficiency depends on the edge-recombination current. The parameters were chosen to represent a conventional, laboratory-grade buried-contact solar cell. The parameters that describe the main body of the solar cell varied linearly with cell area: $R_s = 0.5\ \Omega\cdot\text{cm}^2$, $R_{sh} = 1\ \text{M}\Omega\cdot\text{cm}^2$, and $J_{01} = 10^{-12}\ \text{A/cm}^2$. Of the parameters that describe the edges of the solar cell, m_E was set at 2; R_E was calculated with Eq. 1 for $\rho_\square = 100\ \Omega/\square$, $d = 1$ mm, and L dependent on the cell area; and three values of I_{0E}/P were used, where P is the perimeter of the solar cell. Thus, R_E decreases with cell area, and I_{0E} increases with the square of the cell area.

Fig. 7 plots the simulated cell efficiency as a function of cell area and of I_{0E}/P. The figure shows that as the cell area increases, the cell edges have less of an influence on the cell efficiency. This is a consequence of I_{01} increasing linearly with cell area but I_{0E} increasing linearly with the cell perimeter. The figure indicates that for an edge-recombination current of 10^{-8} A/cm, the cell efficiency is significantly reduced for cell areas less than 100 cm^2. For larger edge-recombination currents, there is a significant reduction in cell efficiency, even for large-area solar cells. The values of the plot were calculated for a buried-contact solar cell, but the trends are similar for other solar cells in which the p–n junction extends to its edges.

This study also reveals an important point with regards to cell characterisation. The I–V curve of experimental solar cells are often well approximated by a two-diode model, in which the second diode has an $\exp(qV/2kT)$ dependence. The mechanism behind this second diode is usually taken to be depletion-region recombination, yet depletion-region recombination exhibits this dependence on V only under very specific conditions [12]. It is possible, therefore, that for some solar cells, the mechanism behind the second diode is not depletion-region recombination but edge recombination. This conclusion would apply to medium-to-large area solar cells (when R_E is negligible) which have a p–n junction that extends to the edge.

7. CONCLUSION

This paper investigated the influence of edge recombination on the I–V curve of a solar cell, for the situation where the p–n junction extends to the edge of that solar cell. It was found through experiment, that the edges can be considered as an exponential shunt across the p–n junction that is resistively isolated from the main body of the solar cell. The cause of the exponential shunt is the large recombination rate at the cell edges. An equivalent circuit that describes this situation was used to determine the relationship between the edge-recombination current and cell efficiency for a laboratory-grade buried-contact solar cell. It was found that unless the edge-recombination current is below $\sim 10^{-8}$ A/cm, the edges act to reduce the cell efficiency, even for medium-to-large area solar cells. The study also indicates that the mechanism behind the $exp(qV/2kT)$ current observed in some solar cells might be due to edge recombination rather than depletion-region recombination.

REFERENCES

[1] R.A. Sinton *et al.*, *13th EC PVSEC* (1993) 1586.

[2] P.P. Altermatt *et al.*, *Progress in Photovoltics* **4** (1996) 355.

[3] C.B. Honsberg and S.R. Wenham, *Progress in Photovoltaics* **3** (1995) 79.

[4] M.A. Green *et al.*, *J. Appl. Physics* **58** (1985) 4402.

[5] O. Breitenstein and J. Heydenreich, *Solid-State Phenonema* **36–37** (1994) 139.

[6] S.J. Robinson *et al.*, *12th EC PVSEC* (1994) 1831.

[7] F. Hernando *et al.*, *15th EC PVSEC* (1998) 1321.

[8] J.E. Cotter *et al.*, "Combined emitter and groove diffusion in buried-contact solar cells", *16th EC PVSEC.*

[9] C.H. Henry *et al.*, *J. Appl. Physics* **49** (1978) 3530, and references therein.

[10] T.J. de Lyon *et al.*, *Appl. Phys. Lett.* **50** (1987) 1903; S.R.D. Kalingamudali *et al.*, *Solid-State Electronics* **37** (1994) 1977; R. Kühn *et al.*, *15th EC PVSEC* (1998) 1390.

[11] A.G. Aberle *et al.*, *23rd IEEE PVSC* (1993) 133.

[12] K.R. McIntosh *et al.*, "Depletion-region recombination in silicon solar cells: When does $m_{DR} = 2$?", *16th EC PVSEC* (2000).