Numerical Modelling of Non-ideal Current-Voltage Characteristics of High-Efficiency Silicon Solar Cells

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Abstract

Under one-sun illumination, the highest energy conversion efficiencies of silicon solar cells are presently obtained with bifacially contacted n^+p cells, where contact to the p-type substrate is made via small openings in the rear passivating oxide. Experimentally, it has been found that the dark and illuminated current-voltage (I-V) characteristics of these devices deviate strongly from ideal diode theory. In this work the experimental I-V curves are compared with results obtained from 2- and 3-dimensional (2D, 3D) device simulation based on experimental cell parameters. Excellent agreement between theory and experiment is obtained. The paper shows why these solar cells cannot accurately be modelled by 1D simulators and reveals the physical reasons underlying the observed non-idealities.

1 Introduction

The *"passivated emitter and rear locally diffused"* (PERL) silicon solar cell of Fig. 1 has recently been developed at the University of New South Wales (UNSW) and produces record-high efficiencies of 23.1 % under one-sun (AM1.5) illumination [1, 2].

Owing to the large surface-to-volume ratio (the cell area is several cm^2, while the cell thickness is only about 0.3 mm), surface recombination losses are important in these cells. Much of the progress obtained in recent years is due to the reduction of surface recombination by means of a high-quality passivating SiO_2 layer on the non-metallised regions of both surfaces. Metal contact recombination is reduced by limiting the metallised fraction of both surfaces to the relatively small percentage imposed by metal contact resistance losses. This strategy led to the incorporation of point-contact metallisation schemes at the rear surface, where contact to the substrate is made via small openings in the rear passivating oxide (see Fig. 1). Below the rear metal contacts, a local p^+ diffusion is added in order to minimise contact resistance losses and metal contact recombination.

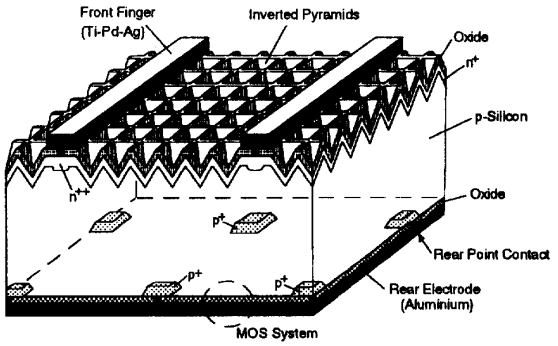

Figure 1: The UNSW PERL silicon solar cell.

2 Results

The squares in Fig. 2 show the measured *dark* I-V curve of a 280 μm thick 2 Ωcm n^+p PERL cell with planar front surface recently processed at UNSW. Below 400 mV, the semi-logarithmic I-V curve is a straight line with unity ideality factor (i.e. n = 1.0). This is exactly what would be expected for a n^+p diode which operates under low-injection condi-

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tions and which is dominated by Shockley-Read-Hall (SRH) recombination in the base and/or at the rear surface. This ideal behaviour shows that "parasitic" effects in these devices (such as edge effects, depletion region recombination, shunt resistance problems, pin holes etc.) are negligible. Interestingly, at about 400 mV, the I-V curve starts to bend to the right, until a second straight-line segment (with considerably higher ideality factor) is approached. This bending of the curve produces a clearly visible "hump" at about 450 mV.

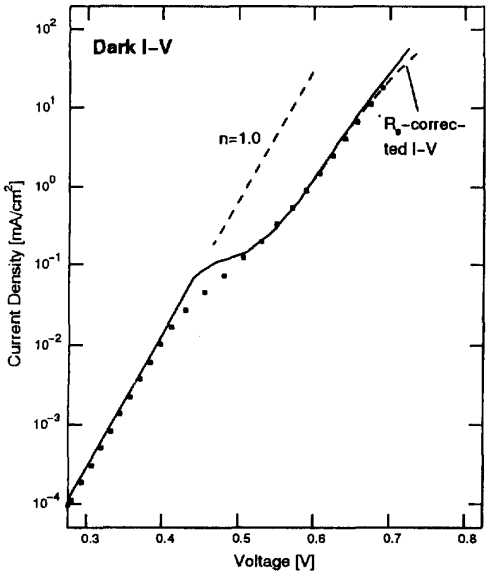

Figure 2: Measured (squares) and theoretical dark I-V curve (solid lines) of a 280 μm thick 2 Ωcm PERL cell.

The squares in Fig. 3 show the measured *illuminated* (one sun) I-V curve of the same cell. For this plot the curve was shifted by the measured short-circuit current (J_{sc} = 34.38 mA/cm^2) from the fourth quadrant into the first quadrant. This procedure is well suited to reveal non-idealities in illuminated I-V curves. Owing to fluctuations in the solar simulator light intensity, the plot is limited to currents larger than 10^{-2} mA/cm^2. Interestingly, as can be seen from Fig. 3, the illuminated I-V curve does not show any humps.

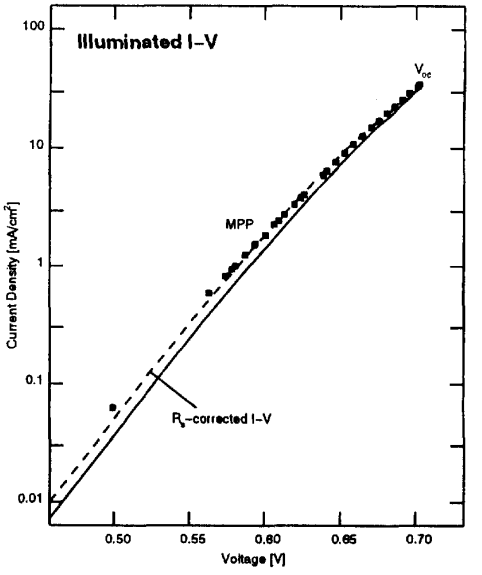

Figure 3: Measured (squares) and simulated one-sun I-V curves (lines) of the PERL cell of Fig. 2. The approximate bias point yielding maximum power output is indicated by "MPP".

The non-ideal I-V curves were analysed with the 2D/3D numerical device simulator Simul, which has recently been developed at ETH Zurich [3]. The solid lines in Fig. 2 and 3 were calculated with Simul on the basis of measured cell parameters (i.e. no parameter fitting was involved). Relatively good agreement between experiment and simulations is obtained. It has to be mentioned that these 2D simulations do not include resistive losses associated with the contact resistance of both electrodes nor resistive losses along the front metal fingers, and naturally also underestimate the resistive losses in the base arising from the "current crowding effect" towards the rear point contacts (see Fig. 1). The impact of resistive losses on the dark and illuminated I-V curve of PERL cells is well understood [4]. As a result of different current flow patterns, the series resistance R_s of these devices strongly depends on the operating condition of the cell (i.e. dark or illuminated I-V measurements) [4]. R_s of this particular cell was measured to be 0.35 cm^2 in the dark and 0.44 Ωcm^2 under 1-sun illumination.

In contrast, in the 2D simulations, R_s is only 0.04 and $0.20\,\Omega\text{cm}^2$, respectively. If the effects of the extra resistive losses are included (dashed lines in Fig. 2 and 3), excellent agreement is obtained over the whole voltage range.

The 2D simulations reveal that the hump visible in dark I-V curves arises from an effective surface recombination velocity at the rear oxidised surface which strongly improves when the cell voltage (or, correspondingly, the minority carrier concentration in the base) is increased [5]. This is due to the band bending (induced by positive oxide charges) and the strong asymmetry of the electron and hole capture cross sections ($\sigma_n \gg \sigma_p$) at the rear Si-SiO_2 interface [6]. Under illumination, the hump occurs at much smaller voltages than in the dark, so that it is not visible in the experimentally accessible current range. The less-than-ideal agreement near the hump in the dark I-V curve is attributed to a quasi-continuum of surface states. This results in a smoother transition for the real device, compared to the theoretical curve which is based on a single trap level at midgap. The simulations show that the surface recombination velocity at the rear oxidised surface depends crucially on the bulk electron and hole concentrations. These carrier concentrations are strongly affected by the multi-dimensional current flow arising from the rear point contacts. Consequently, since recombination losses at the rear oxidised surface are an important loss mechanism in rear locally-contacted silicon solar cells, the modelling of these devices has to be performed in at least 2 dimensions.

Fig. 4 shows the dependence of the cell's maximum power output on the spacing of the rear point contacts as obtained from 2D and 3D simulations [7]. The 3D simulations (curve "3D-1%") used the rear metallisation fraction of 1% of actual PERL cells. The 2D simulations were performed using either the same metallisation fraction, resulting in very narrow fingers (curve "2D-1%"), or the same contact width as in 3D, resulting in a metallisation fraction of 10% (curve "2D-10%"). The latter geometry was handled in two ways: for case "2D-10%" a 2D simulation mesh was created in a way analogous to the "2D-1%" case, while in the "2Dex3D-10%" case the 2D grid was created by extracting the grid points

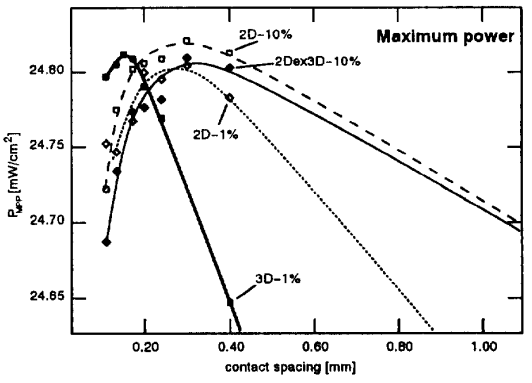

Figure 4: One-sun PERL cell efficiency as a function of rear contact spacing according to 2D and 3D simulations.

from one plane of the 3D grid (the front plane in Fig. 1). This resulted in two different grids for the same 2D simulation, which allows us to estimate the effect of discretisation errors. As the 3D simulations were at the limit of available computer capacity (grid sizes of 80k–120k points requiring about 0.5 Gbyte of primary memory and days of CPU time on a Sun SuperSPARC/40 processor or about 4-6 hours on a Fujitsu VP-2200 supercomputer), it was not possible to refine the grids to such a degree that discretisation errors were negligible.

The predicted maximum efficiencies are quite similar in 2D and 3D (the differences are below the error margin of the simulations). However, the steeper slope of the 3D curve shows that the cells are much more sensitive to the rear contact spacing than indicated by 2D simulations. While the 2D simulations predict an optimum contact spacing of about 0.25–0.30 mm, the value resulting from 3D simulations is considerably smaller ($\approx$ 0.15 mm). 2D simulations predict larger optimum spacings as they underestimate the "crowding" of the hole current occuring at the corners of the rear metal contacts, which increases ohmic losses. Experimental studies of PERL cells with various rear contact spacings (0.126, 0.25, 0.5, 1.0, and 2.0 mm) showed 0.25 mm to yield the highes efficiency. A possible reason for this larger value, compared to 3D simulations, is the degrada-

tion of carrier lifetimes arising from the p^+ (boron) diffusions [5], a phenomenon which is not included in our simulations. This effect becomes important for small contact spacings, shifting the optimum spacing towards larger values.

3 Conclusions

In this work, a 2D and 3D numerical device simulator is applied to rear locally-contacted high-efficiency silicon solar cells. For the first time the strongly non-ideal I-V curves of these devices have been accurately modelled. This is achieved by the proper inclusion of the complex recombination behaviour at the rear oxidised surface. The non-ideal I-V curves result from the unequal capture cross sections of electrons and holes at the rear Si-SiO_2 interface and the surface band bending induced by positive oxide charges. Owing to the strong dependence of rear surface recombination losses on the electron and hole concentrations, these devices cannot be accurately modelled in one dimension.

A comparison of 2D and 3D simulations results shows that while the predicted maximum efficiencies are very similar, optimum rear contact spacings predicted from 2D simulations (0.2–0.3 mm) are significantly larger than what results from a full 3D treatment (0.15mm). The difference is due to the current crowding effect towards the rear point contacts, which is underestimated in 2D simulations.

This paper considerably improves the understanding of the operating conditions present high-efficiency silicon solar cells. Our results reveal that in order to accurately model high-efficiency silicon solar cells, surface recombination effects must be properly included. We have also shown that 2D simulations are not sufficient for determining the optimum rear contact geometry of PERL-type silicon solar cells.

4 Acknowledgments

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