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Series resistance caused by the localized rear contact in high efficiency silicon solar cells

Jianhua Zhao, Aihua Wang and M.A. Green

Centre for Photovoltaic Devices and Systems, University of New South Wales,
Kensington 2033, Australia

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High efficiency PERL (passivated emitter and rear locally-diffused) cells have demonstrated over 700 mV open-circuit voltage and 23% efficiency under standard test conditions. However, the relatively low fill factor is the main parameter limiting performance. This paper analyses the series resistance caused by the localized rear contact design. This resistance is found not to limit the performance of one-sun PERL cells, even though it does become significant for concentrator PERL cells.

1. Introduction

The PERL (passivated emitter and rear locally-diffused) cell structure of Fig. 1 has been recently developed at the University of New South Wales. These cells have demonstrated efficiency above 23% under the air mass 1.5 global spectrum at 25°C [1,2], and 25% efficiency under about 10 suns concentration [3]. Both the front and the rear surfaces of the cells are passivated by a layer of TCA (1,1,1,trichloroethane) grown oxide. To reduce the recombination at the rear metal contact areas, the contacts are made through small openings in the oxide. The metal contact areas are also passivated by locally diffused boron regions to further reduce recombination. However, the PERL cell structure has shown relatively low fill factors of about 80% on 1 Ω cm substrates, even though the space between the contacts has been as small as 250 microns. This paper analyses the series resistance generated by such contact design to clarify contributions to the relatively low fill factors observed.

2. Computer model

A three-dimensional analysis is used to analyse the series resistance from the closely spaced rear contacts. The unit current collecting area for a rear contact

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Correspondence to: J. Zhao, Centre for Photovoltaic Devices and Systems, University of New South Wales, Kensington 2033, Australia.

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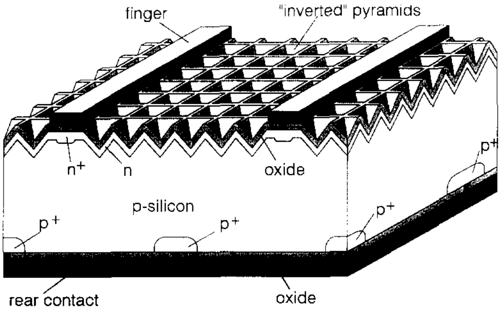

Fig. 1. Structure of the PERL (passivated emitter and rear locally-diffused) cell.

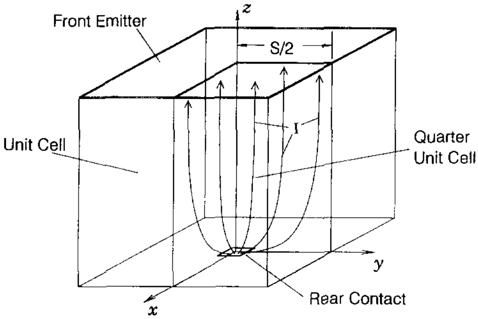

Fig. 2. The unit current collecting cell for a rear contact window. Only a quarter of the unit cell is used for the computer modelling. The current flow in the quarter unit cell is three dimensional.

window is shown in Fig. 2. Only a quarter of the unit cell is needed for the analysis due to the symmetrical geometry of the rear contact arrangement.

The analyzed volume is divided three-dimensionally into several thousand mesh points. A simplified case is analyzed where the effect of illumination is restricted to the cell emitter and all carrier flow in the base is assumed to be due to majority carriers. A mesh point and its neighbours are shown in Fig. 3. Due to the current

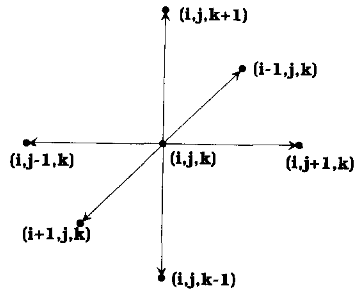

Fig. 3. Mesh point and neighbouring points.

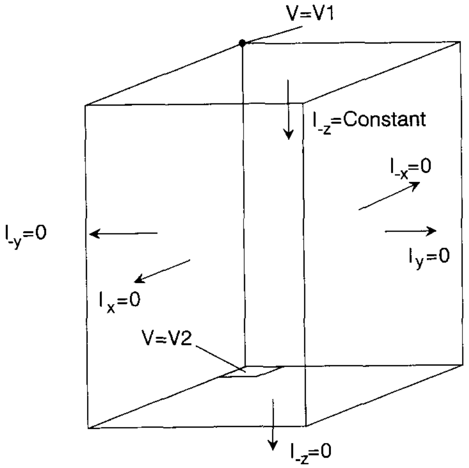

Fig. 4. Boundary conditions for the computer modelling.

continuity relation, the sum of the current from one mesh point to neighbouring points is zero in the base under these conditions.

The boundary condition for the calculation is shown in Fig. 4. The voltage has a value of V_1 at the centre of the emitter and a value of V_2 at the rear contact. A constant current density is assumed over the entire top surface. This situation corresponds most closely to the case where the cell is illuminated by strongly absorbed blue light, but is a reasonable approximation for sunlight illumination. Due to the geometrical symmetry of the quarter unit cell, there is no current across its four side walls. There is also no current across the rear surface of the cell except in the metal contact areas. The voltage distribution and the current flows through the quarter unit cell are then iteratively calculated from these boundary conditions. A uniform distribution of voltage across the cell is used as the initial iteration condition.

The resistance of the quarter unit cell is calculated as

$$R = \frac{V_1' - V_2}{I}, \tag{1}$$

where V_1' is the average voltage along the top surface.

3. Results

One of the calculated voltage distributions over the y–z plane is plotted in Fig. 5. The unit cell is 250 μm wide and 280 μm thick for this calculation. The current is determined by the gradient of the voltage distribution and can be seen to be quite uniformly distributed under the emitter apart from the area close to the rear

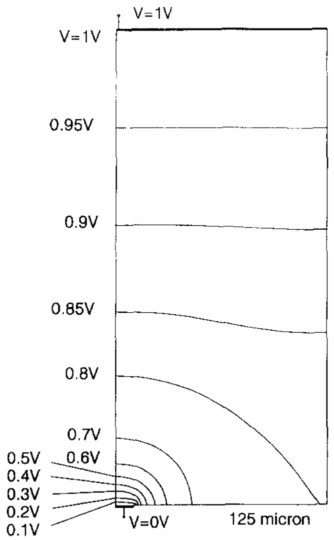

Fig. 5. The calculated voltage distribution on $y-z$ plane.

contact window. The current-crowding in this area causes a dramatic voltage drop, corresponding to the spreading resistance associated with this contact.

A standard expression for the spreading resistance from a hemispherical contact [4] is given by:

$$R_s = \frac{\rho_b}{\pi d_c}, \tag{2}$$

where ρ_b is the substrate resistivity, and d_c is the width of the rear contact window. While the spreading resistance of a circular planar contact is given by [5,6]:

$$R_s = \frac{\rho_b}{2 d_c}. \tag{3}$$

The spreading resistance of a square planar contact of side d_c would be expected to be larger than eq. (3) and closer to eq. (2). Use of this equation was found to give a very good approximation to the results of the numerical simulation. For small contact spacing, the series specific resistance for PERL cell, R_{series}, is approximately the sum of substrate resistance and spreading resistance:

$$R_{\text{series}} = R_b + R_s = \rho_b W_b + S_c^2 \frac{\rho_b}{\pi d_c}, \tag{4}$$

where R_b is the normal resistance from the substrate of a cell with contact over the entire rear surface, R_s are the spreading resistance, W_b is the substrate thickness and S_c is the rear contact spacing. $1/S_c^2$ is the number of rear contacts in a square centimetre.

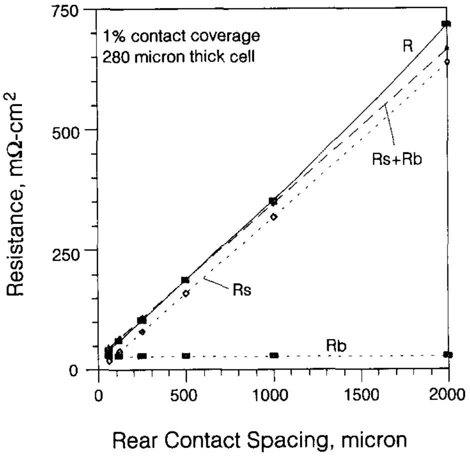

Fig. 6. Calculated effect of rear contact spacing on the series resistance (1% rear contact coverage is assumed for the calculation). R is the calculated resistance, R_b is the substrate resistance, and R_s is the contact spreading resistance.

If the rear contacts are far separated from each other much more than the cell thickness, the contribution from the lateral resistance of the substrate also becomes important [7].

The numerically calculated results for the effect of rear contact spacing on the series resistance is shown in Fig. 6. A rear metal contact coverage of 1% is assumed for this calculation. The substrate resistivity and wafer thickness are chosen as 1 Ω cm and 280 μm. The substrate resistance R_b is a constant while spreading resistance R_s linearly increased with contact spacing (since the rear contact coverage is held constant at 1%). Their sum is also shown in the figure.

With small contact spacings, the calculated resistance R is very close to the sum of the substrate resistance R_b and contact spreading resistance R_s from eq. (4). It only begins to separate from the sum of R_b and R_s when the contact spacing is larger than 1000 μm, since lateral resistance only becomes important for such large spacing conditions [7]. The increasing cell series resistance, R, causes considerable fill factor drop when the spacing, for 1% contact area, increases to above 500 μm. With 500 μm spacing, the cell series resistance is about 8 times higher than the substrate resistance.

From the above results, it is seen that the simple eq. (4) can be used as a good approximation for the calculation of series resistance for typical cell designs. For one-sun PERL cells, series resistance has to be kept below 500 mΩ cm^2 to obtain reasonable fill factors. Since most PERL cells are made on 1.0 Ω cm substrates, rear contact windows of 30 μm by 30 μm with 250 μm spacing appear to be a good choice. This design would cause about 1.5% loss in the cell fill factors corresponding to a drop from the theoretical value of 84.7% down to 83.4%. Other resistance such as lateral emitter resistance and metal finger resistance would further reduce it to 82.3%. This value is still higher than the typical 80% fill factors experimentally achieved on such cells. Hence, other factors such as recombination at the rear surface also must play an important role in reducing the cell fill factors [8,9].

4. Conclusion

A three-dimensional computer analysis shows that the series resistance of the rear point contact design in high efficiency PERL cells can be approximated by the sum of the normal substrate resistance and the spreading resistance associated with current crowding near the rear contact. The total resistance is not sufficiently large to explain the relatively low fill factors of experimental PERL cells. The low fill factor of PERL cells under one-sun illumination level is caused by other factors such as the recombination at the rear surface.

Acknowledgement

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