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Research

Short Communication: Reduced Temperature Coefficients for Recent High-performance Silicon Solar Cells

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The PERC cell (passivated emitter and rear cell) and PERL (passivated emitter and rear locally-diffused) cell have recently demonstrated improved cell performance owing to the high quality of surface passivation and high bulk carrier lifetimes. The effect of temperature on the performance of these cells is reported. As anticipated, owing to higher open-circuit voltages these cells should have a lower temperature sensitivity of performance. The PERL cells demonstrated a normalized efficiency temperature variation of -2632 ppm $^\circ C^{-1}$, which is the lowest ever reported for a silicon cell. However, PERC cells with a similarly high open-circuit voltage showed a higher temperature sensitivity owing to the bulk resistance component, which limits the performance of PERC cells.

INTRODUCTION

The PERC cell (passivated emitter and rear cell) of Figure 1(a) and the PERL (passivated emitter and rear locally-diffused) cell of Figure 1(b) have been developed recently in the University of New South Wales. For silicon cells reported to date, not only do these devices display the highest energy conversion efficiencies[1,2] but it is shown that the temperature sensitivities of these devices are also the lowest ever.

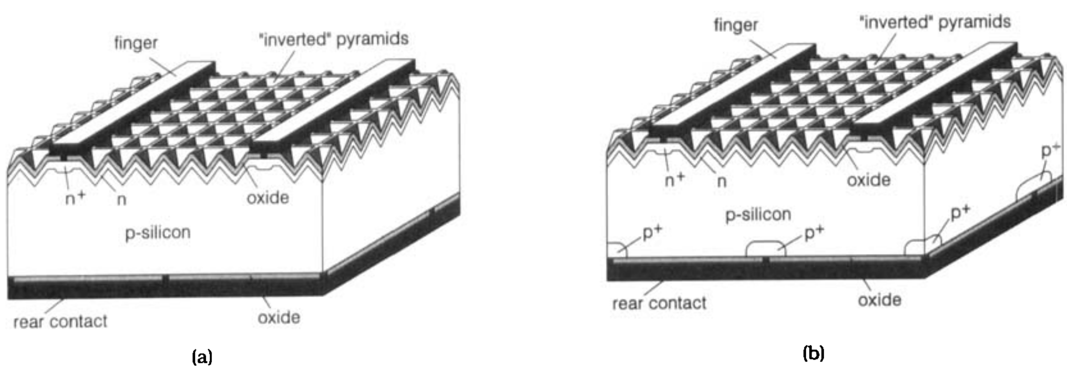

Figure 1. Schematic diagram of: (a) a PERC cell (passivated emitter and rear cell); (b) a PERL (passivated emitter and rear locally-diffused) cell

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CELL STRUCTURES

A distinctive feature of the PERC cell is the direct metal contact to the p-type substrate through a passivating rear oxide via contact holes separated by a few millimetres to reduce contact recombination.[1] On the front side, however, a heavy phosphorus diffusion in the areas immediately underlying the top metal contact improves open-circuit voltage (V_{oc}) and cell performance. Diffusion conditions for the remainder of the emitter can then be independently optimized.

An effective light-trapping scheme is formed by the 'inverted pyramids' on the top surface and the highly reflective 'dielectrically isolated' rear reflector. This scheme could be improved further by 'tilting' the pyramids[3] or possibly by structuring both front and rear surfaces.[4] An important feature is the use of trichloroethane-based processing.[1] This improves both surface passivation and post-processing bulk carrier lifetimes. With these improvements, PERC cells have demonstrated a 696-mV open-circuit voltage and 22.3% efficiency.[1,5]

The improvement of PERL cells over PERC cells arises from the boron diffusion under the rear metal contact areas. This boron-diffused area passivates the high recombination metal-contacted surface. Owing to the reduced recombination at the contact areas, the contact windows can be made closer and smaller. Hence, the series resistance of the cell is significantly reduced, considerably improving the fill factor. Some PERL cells have demonstrated 23.1% efficiency,[2,5,6] the highest ever for a silicon solar cell. Other PERL cells with a planar front surface have demonstrated a 717-mV open-circuit voltage, the highest on a silicon substrate.[7]

TEMPERATURE SENSITIVITY OF PERC CELLS

One advantage expected from the high V_{oc} is a reduced cell temperature sensitivity according to[8]

$$\frac{\mathrm{d}V_{oc}}{\mathrm{d}T} = \frac{-(V_{go} - V_{oc} + \gamma kT/q)}{T} \tag{1}$$

where V_{go} is the bandgap potential linearly extrapolated to 0°K from the temperature T of interest (V_{go} has the value of 1206 mV for T near to room temperature), kT/q is the thermal voltage and γ incorporates assorted temperature dependencies (typically lying between 1 and 4).[8] Hence, it was expected that PERC cells with their significantly improved V_{oc} would demonstrate considerably reduced temperature coefficients.

The temperature performance of a PERC cell (Z141R) was measured between 15 and 50°C at nominally 5°C intervals. Linear regression analysis showed that the key cell parameters all varied virtually linearly with temperature over this range (Table I). In particular, the V_{oc} variation was well described by Equation (1) with $\gamma = 1.6$. The normalized efficiency variation of -3190 ppm °C^{-1} was comparable to the best previously reported for silicon under these test conditions (-3202 ppm °C^{-1})[9] and substantially lower than values for standard silicon space cells (-4070 to -5350) ppm °C^{-1}).[8]

The fill factor (FF) coefficient of -1234 ppm °C^{-1} differed appreciably from that of -898 ppm °C^{-1} expected from an earlier expression[8]

$$\frac{1}{FF}\frac{\mathrm{d}FF}{\mathrm{d}T} = (1 - 1.02FF_0)\left(\frac{1}{V_{oc}}\frac{\mathrm{d}V_{oc}}{\mathrm{d}T} - \frac{1}{T}\right) \tag{2}$$

However, that expression neglected the temperature dependence of the cell series resistance R_s. Corresponding modifications give

$$\frac{1}{FF}\frac{\mathrm{d}FF}{\mathrm{d}T} = (1 - 1.02FF_0)\left(\frac{1}{V_{oc}}\frac{\mathrm{d}V_{oc}}{\mathrm{d}T} - \frac{1}{T}\right) - \frac{R_s}{(V_{oc}/I_{sc} - R_s)}\left(\frac{1}{R_s}\frac{\mathrm{d}R_s}{\mathrm{d}T}\right) \tag{3}$$

where FF_0 is the idealized fill factor without series resistance (83.5% at 25°C for the present cell with an

Table I. Linear regression analysis of temperature sensitivity of PERCs and PERL cells

Parameter	PERC (Z141R)	Planar PERL cell (Wm1-R)	Inverted pyramid PERL cell (Wt043-L)
V_{oc} (25°C)	693 mV	711 mV	696 mV
V_{oc} (0 K intercept)	1245.9 mV	1225.7 mV	1216.5 mV
dV_{oc}/dT	−1.855 mV °C^{-1}	−1.725 mV °C^{-1}	−1.730 mV °C^{-1}
$(1/V_{oc})\, dV_{oc}/dT$ (25°C)	−2678 ppm °C^{-1}	−2424 ppm °C^{-1}	−2468 ppm °C^{-1}
J_{sc} (25°C)	39.2 mA cm^{-2}	34.5 mA cm^{-2}	40.0 mA cm^{-2}
dJ_{sc}/dT	0.0291 mA cm^{-2} °C^{-1}	0.0149 mA cm^{-2} °C^{-1}	0.0190 mA cm^{-2} °C^{-1}
$(1/J_{sc})\, dJ_{sc}/dT$ (25°C)	703 ppm °C^{-1}	438 ppm °C^{-1}	480 ppm °C^{-1}
FF (25°C)	79.8%	80.9%	77.7%
dFF/dT	−0.098 % °C^{-1}	−0.050 % °C^{-1}	−0.071 % °C^{-1}
$(1/FF)\, dFF/dT$ (25°C)	−1234 ppm °C^{-1}	−618 ppm °C^{-1}	−913 ppm °C^{-1}
Efficiency (25°C)	21.9%	19.8%	21.6%
dE_{ff}/dT	−0.0734 % °C^{-1}	−0.05167 % °C^{-1}	−0.0623 % °C^{-1}
$(1/E_{ff})\, dE_{ff}/dT$ (25°C)	−3193 ppm °C^{-1}	−2632 ppm °C^{-1}	−2912 ppm °C^{-1}

ideality factor of 1.09) and I_{sc} is the short-circuit current. As the cell's series resistance of about 0.75 $\Omega \cdot cm^2$ came mainly from the bulk regions, the temperature coefficient of R_s was approximately that of 0.5 $\Omega \cdot$cm silicon (6450 ppm °C^{-1}).[10] Equation (3) then gives a fill factor coefficient of −1201 ppm °C^{-1} in close agreement with experiment.

Hence, even though PERC cells demonstrated a lower temperature dependence of their open-circuit voltage owing to their high voltage, the high bulk series resistance increased the temperature dependence of their fill factors. The overall temperature coefficient of cell efficiency was not improved much from the earlier generation PERC cells.[9] However, with further improvement of open-circuit voltage and fill factor, the temperature coefficient might be reduced further.

TEMPERATURE SENSITIVITY OF PERL CELLS

PERL cells with planar and inverted pyramid front surfaces on 1.0-$\Omega \cdot$cm substrates were measured between 15 and 40°C at nominally 5°C intervals. The results are also shown in Table I.

The V_{oc} variation was again well described by Equation (1), with $\gamma = 0.74$ for the planar cell and $\gamma = 0.21$ for the inverted pyramid cell. As the minority carrier lifetime has been improved significantly in these cells, recombination in doped surface regions becomes more important than in the bulk region. Hence, the γ value reduces below that normally observed, attributed to bandgap narrowing in these doped regions. The normalized efficiency variations of −2632 and −2912 ppm °C^1 were much lower than the lowest previously reported for silicon under these test conditions (3202 ppm °C^{-1}).[9] Most of the reduction of the temperature sensitivity of the PERL cells came from the reduced sensitivity of fill factors.

The effect of determining the fill factors has been discussed elsewhere.[7,11] The dark current–voltage (I–V) characteristics of a planar PERL cell as a function of measuring temperature are shown in Figure 2. To remove the effect of the cell series resistance on the I–V curve in the high current range, the illuminated I_{sc} versus V_{oc} is also plotted in this figure. It is seen that the I–V curves have three sections to their characteristics. In both the low and high current ranges, the cell had relatively low ideality factors (close to unity) but different saturation current densities in each range. There is another section in the middle current range with an ideality factor that is much higher than unity. As discussed elsewhere, electrostatic conditions at the rear cell surface combined with asymmetrical capture cross-sections of

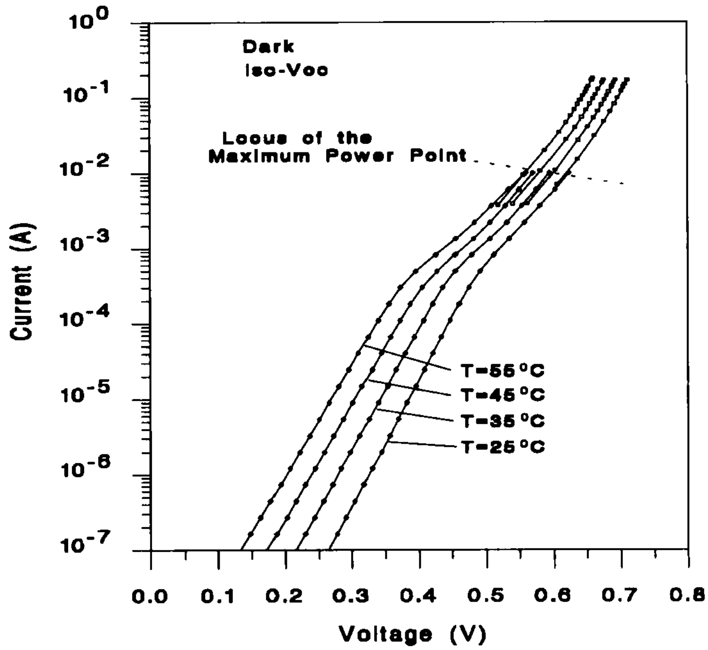

Figure 2. The current–voltage characteristics of a planar PERL cell as a function of measuring temperature. For currents up to 10 mA, the measurements were taken in the dark. For higher currents, J_{sc} was plotted against V_{oc} under different illumination levels to eliminate the effect of R_s

oxide/silicon interface states are thought to cause this effect.[7,11] However, this rear surface effect shifted the low ideality factor section at the high current range downwards at higher temperatures, as is apparent from Figure 2. This reduces the temperature sensitivity of the fill factor and the overall cell performance.

CONCLUSION

The increased open-circuit voltage of recent high-performance silicon solar cells reduces their temperature sensitivity. The rear surface depletion effect combined with the asymmetrical capture cross-sections of Si/SiO_2 interface states in PERL cells further reduces this sensitivity. The normalized efficiency temperature variation of -2632 ppm $°C^{-1}$ reported for a planar PERL cell is the lowest ever reported for a silicon solar cell and approaches values in the -1950 to -2640 ppm $°C^{-1}$ range reported for GaAs cells.[8]

Even though PERC cells demonstrate a similarly high open-circuit voltage (about 700 mV), substrate resistance contributions increased their temperature sensitivity.

Acknowledgements

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