$GaInP_2$/GaAs TANDEM CELLS: PROBLEMS AND SOLUTIONS

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ABSTRACT

The various factors that affect the open-circuit voltage (V_{OC}) of a two-terminal $GaInP_2$/GaAs tandem cell are examined. These include a) an anomalous problem associated with the GaAs bottom cell and b) back surface passivation of the thin $GaInP_2$ top cell. Solutions to these problems are presented and yield tandem V_{OC}s close to the practical theoretical limits.

INTRODUCTION

The tandem combination of an optically thin $Ga_{0.51}In_{0.49}P$ (hereafter $GaInP_2$) top cell and a GaAs bottom cell has achieved a one-sun, air mass 1.5 (AM1.5) efficiency of 27.3%[1]. A schematic of the original or prototype device is shown in Fig. 1. The parameters for this device are shown in Table I along with projected values based on theoretical calculations.[2] The short-circuit current density (J_{SC}) and V_{OC} of this prototype device are within 2-3% of their projected values. However, the major factor affecting the efficiency loss is primarily a decrease in V_{OC} of about 120 mV. In a two-terminal, series-connected tandem cell, it is difficult, if not impossible, to separately measure in a tandem stack the V_{OC}s of the individual subcells or any other stray or parasitic light-induced voltages.

	Thickness [μm]
n^{++}-GaAs	0.1
n-AlInP	0.03
n^{+}-$GaInP_2$	0.1
p-$GaInP_2$	0.7
p^{++}-GaAs	0.02
n^{++}-GaAs	0.02
n-$GaInP_2$	0.03
n^{+}-GaAs	0.1
p-GaAs	2.5
p^{+}-GaAs substrate	

Figure 1. Standard $GaInP_2$/GaAs tandem cell with AlInP window layer.

Therefore, one is forced to study the subcells in a stand-alone configuration. The V_{OC}s for the $GaInP_2$ and GaAs subcells are shown in Table II. The standard subcells are identical to those in the prototype tandem cell and include a simulated companion subcell. For example, the standard GaAs subcell is covered with a tunnel junction and 1-μm-thick *p*-type layer of $GaInP_2$. Also included in Table II are the theoretical or predicted values for the V_{oc}s of each subcell. The sum of the V_{oc}s is equal to the V_{oc} in Table I. In the following we discuss the causes and "solutions" for the various losses.

EXPERIMENTAL DETAILS

All of the cells were grown by atmospheric-pressure metal-organic chemical vapor deposition. All are of the *n*-on-*p* configuration, with an n^{++}-GaAs contacting layer to provide an ohmic contact to the n^+ emitter. The contact metallization is unannealed, electroplated gold and the cell area of 0.25 cm^2 is defined by photolithography and wet chemical etching.[1] A range of characterization techniques was applied to these cells. The techniques include dark and light current-voltage (I-V) electrical measurements and secondary ion mass spectroscopy (SIMS) profiling.

GaAs BOTTOM CELL OPEN-CIRCUIT VOLTAGE

The V_{oc} of a typical single-junction GaAs cell is 1.05 V. In a tandem configuration, the photocurrent in the GaAs bottom cell is attenuated by a factor of two by absorption of light in the top cell. The change in the V_{oc} can be calculated from the equation

$$\Delta V_{oc} = \left(\frac{nkT}{e}\right) \ln(J_{sc}^T / J_{sc}^S) \qquad (1)$$

where J_{sc}^T and J_{sc}^S are the GaAs short-circuit currents in the tandem- and single-junction configurations, respectively. For a good GaAs bottom cell, *n* (the ideality factor) is close to 1 and ΔV_{oc}=0.02 V. Therefore, we expect the GaAs bottom cell to contribute 1.03 V to the V_{oc} of the tandem cell.

The V_{oc}s of several GaAs solar cells are compared in Table III. The first device, which is identical to that listed in Table II, is a single-junction GaAs cell covered with a thin GaAs tunnel junction and a simulated $GaInP_2$ top cell. The total thickness of the *p*-type $GaInP_2$ is equal to the thickness of the $GaInP_2$ top cell in the standard $GaInP_2$/GaAs tandem cell. The V_{oc} is 0.98 V, or about 50

Table I. Present and projected device parameters for the $GaInP_2$/GaAs tandem solar cell.

Tandem Cell Parameters	Present	Predicted
V_{oc} [V]	2.29	2.41
J_{sc} [mA/cm^2]	13.6	14.0
Fill Factor	0.87	0.89
Efficiency	27.3%	30.0%
@1000X		35%

Table II. Present and projected top and bottom cell V_{oc}.

	Present	Predicted
Top Cell V_{oc}	1.31	1.38
Bottom Cell V_{oc}	0.98	1.03

mV less than the expected value. The next two devices in Table III indicate that the problem is not caused directly by either a photoactive tunnel junction or some parasitic junction in the $GaInP_2$. In the second device, we eliminated the p^{++}-GaAs part of the tunnel junction and lightly doped the $GaInP_2$ layer *n*-type; in the third device, we eliminated the $GaInP_2$ layer and replaced it with an anneal time at growth temperature equal to the $GaInP_2$ growth time used in the first two devices. These first three experiments suggest that the cause of the problem may be related to a diffusion effect. In the last device, a thin (30 nm) layer of AlInP is inserted between the $GaInP_2$ window layer of the bottom cell and the remaining parts the tandem device. Invariably, this leads to the expected V_{OC} of 1.03 V. Ostensibly, the AlInP layer inhibits the diffusion of some species into or out of the GaAs device, and this species has a pronounced effect on the dark current of this device. Experiments to confirm this model are in progress.

$GaInP_2$ TOP CELL OPEN-CIRCUIT VOLTAGE

The $GaInP_2$ top cell, with a band gap of 1.85 eV, must be less than 1 μm thick to achieve current matching.[2] At this thickness, the surface recombination velocity at the back of the cell will significantly affect the V_{OC}.[2] Hence, the V_{OC} of the 27.3% device, which contained no intentional back surface field (BSF), was about 100 mV less than the expected value. To remedy this situation, we studied the efficacy of two BSF structures. The first was an $Al_{0.06}Ga_{0.45}In_{0.49}P$ (hereafter AlGaInP) alloy with a band gap of ~1.95 eV. The second was $GaInP_2$ grown under conditions that yield a band gap of 1.88 eV. (The band gap of $GaInP_2$, at constant composition, is a function of numerous growth conditions and can be varied from 1.8 to 1.9 eV).[3, 4] In this section, we examine the differences between the two candidate materials for passivating the back surface of the $GaInP_2$ top cell.

Figure 2 shows dark I-V curves for two typical cells, one with a $GaInP_2$ BSF and one with a quaternary BSF. For these cells, the behavior of the dark current can be divided into two regimes. Above about 1.1 V, the cells exhibit n=1 dark currents, i.e., $I \propto \exp(-eV/nkT)$ with n ≈ 1, while below 1.1 V, there is a transition to n=2 behavior. While n=2 behavior is most frequently attributed to generation/recombination in the junction, in practice, this current can be dominated by perimeter currents.[5] For our cells under one-sun AM1.5

Table III. V_{OC}s of several GaAs solar cells.

GaAs overlayer(s) or procedure	V_{OC} (V)
Simulated top cell (*p*-type) with tunnel junction (Zn/Se)	0.98
Simulated top cell (*n*-type) with half tunnel junction (Si or Se)	0.98
Half tunnel junction (Si or Se) with 10 min anneal	0.98
Insert AlInP between bottom cell and the GaAs tunnel junction	1.03

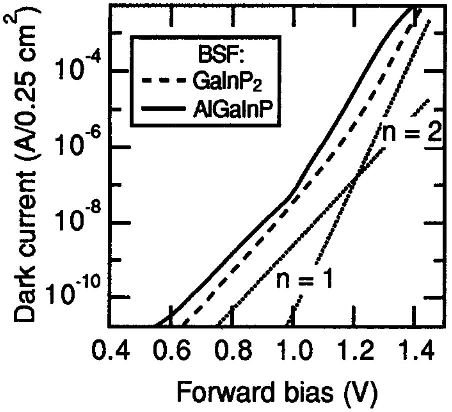

Figure 2. Dark current J_1 as a function of forward bias voltage for selected top cells.

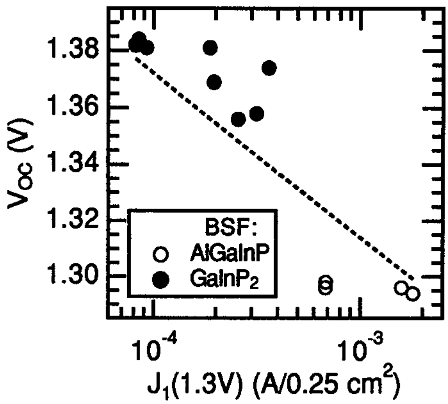

Figure 3. Dark current J_1(1.3V) vs. V_{OC} for various cells. The type of BSF used in the cells is indicated.

illumination, the maximum power-point voltage was typically 1.25 V or greater; thus, Figure 2 shows that perimeter and junction recombination currents are not significant for these cells.

The n=1 dark currents J_1 for a number of cells are summarized in Figure 3, where for each cell J_1(1.3V) is plotted against the corresponding V_{OC} for that cell. The BSF used for each cell is indicated in the figure. The cells with the high-band-gap $GaInP_2$ BSF have a lower dark current (and hence a higher V_{OC}) than that of the cells with the quaternary BSF. Note, however, that V_{OC} increases with the cell band gap, and that there is some variation in the latter, due mostly to variations in the composition x of the $Ga_{1-x}In_xP$. To confirm that the improved V_{OC} is due to the superiority of the $GaInP_2$ BSF and not merely to variations in the band gap of the emitter/base, Figure 4 displays V_{OC} against band gap for the cells of Figure 3, as well as for other cells that did not have a clearly defined n=1 region. The figure confirms that, for any given band gap, the cells with the $GaInP_2$ BSF have higher V_{OC} values than the cells with the quaternary BSF. The expected variation of V_{OC} with band gap is easily seen for the $GaInP_2$ BSF cells; for the quaternary BSF cells, the scatter in V_{OC} masks this dependence.

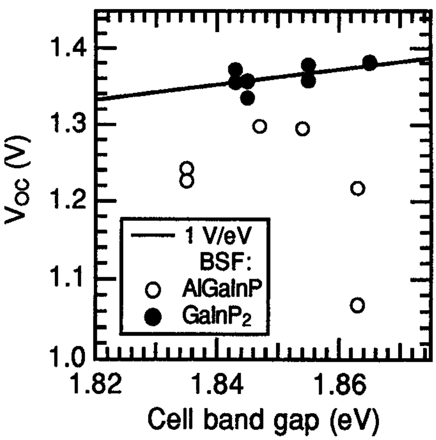

Figure 4. V_{OC} vs. band gap for various cells. The type of BSF used in the cells is indicated. The solid line shows the expected slope of V_{OC} vs. band gap when all other factors are held constant.

To estimate the back surface

recombination velocity provided by the $GaInP_2$ BSF, we compared two top cells with $GaInP_2$ BSFs, identical except for the thickness of the base, which was 0.6 μm for the thin cell and 6 μm for the thick cell. The J_1 currents for the two cells were related by $J_1(\text{thick})/J_1(\text{thin})=4.1$. Figure 5 shows a calculation[6] of J_1 as a function of base thickness for a model cell simulating the thick/thin pair, for various values of the back surface recombination velocity. For the thick cell to have a J_1 current four times that of the thin cell, the back surface recombination velocity had to be about 5×10^3 cm/sec, a low value consistent with the conclusion that the $GaInP_2$ BSF is effective in reducing recombination at the back of the cell.

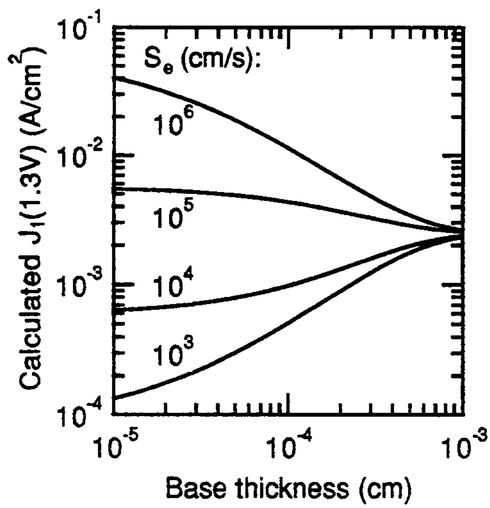

Figure 5. Calculation of J_1 as a function of base thickness for a model cell simulating the thick/thin pair discussed in the text, for various values of the back surface recombination velocity.

To provide some insight into the nature of the problem with the quaternary BSF, Figure 6 shows a SIMS scan through a top cell with a quaternary BSF. The level of oxygen contamination peaks at the location of the BSF, as might be expected from the known oxygen-gettering properties of aluminum. It seems reasonable to guess that the oxygen content of the quaternary layer is responsible for its poor performance as a BSF, and that reducing the oxygen content might lead to a more effective quaternary BSF.

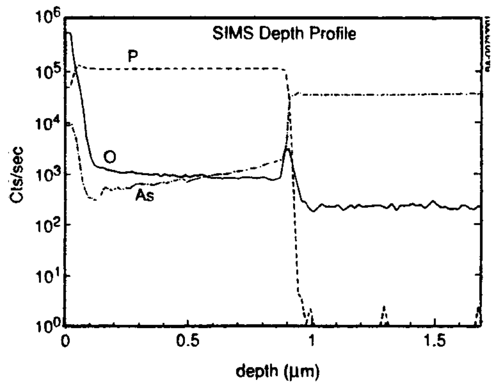

Figure 6. SIMS depth profile of a top cell with a quaternary BSF. Note the peak in the oxygen level at the location of the BSF.

SUMMARY

In summary, we have shown that the V_{OC} loss in the original, prototype $GaInP_2$/GaAs tandem cell is caused by a high BSF recombination velocity in the optically thin top cell, and an anomalous problem with the GaAs bottom.

The problem with the bottom cell is not well understood, but the insertion of an AlInP diffusion barrier between the emitter layer of the bottom cell and tunnel junction interconnect increases the V_{OC} by 50 mV. For the top cell, an AlGaInP BSF proved to less effective than a high-band-gap $GaInP_2$ BSF. This may be related to recombination through oxygen-related deep traps in the AlGaInP.[7]

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