Polymer tandem solar cells
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Chapter 5

Current-Voltage Characteristics of Organic Tandem Cells

Abstract

In order to understand the electrical properties of a tandem organic solar cell, we consider in this Chapter a tandem cell that is based on two sub cells with totally different electrical properties. In this general case, the bottom cell generates higher current but lower voltage compared to the top cell. It is important to understand the physics behind the tandem devices for a given performance of the sub cells, since theoretical predictions can strongly reduce the experimental work needed to reach the optimum device structure. The experiments on tandem organic solar cells were already mentioned in the Chapters 3 and 4 in which the sub cells were connected electrically in series (Chapter 3) or in parallel (Chapter 4). In this chapter we demonstrate how the electrical characteristics of tandem cells that are either connected in series or parallel can be predicted from the characteristics of the sub cells. In order to compare the calculated results with experiment, the 4-electrode tandem cell is used that was demonstrated in Chapter 4. The use of such a device has two advantages; First, because of the presence of 4 electrodes the J-V characteristics of the individual bottom- and top cell as well as the tandem cell can be measured in one single device. Second, since the sub cells are electrically separated, both the series and parallel configuration can be measured within the same device. In this way the test conditions (STC) are exactly the same for all cells.
5.1 Series configuration

Suppose that we have two arbitrary sub cells (bottom and top cell) with different current and voltage characteristic under illumination, as shown in Figure 5.1.

![Figure 5.1. The current-voltage characteristic of two arbitrary sub cells. The bottom cell generates more photocurrent while the top cell has higher generated voltage but lower photocurrent.](image)

The question now is how the $J$-$V$ characteristic of a tandem cell based on those two sub cells will look like when they are electrically connected in series or in parallel. As a first step we consider the series configuration and later the parallel tandem cell is also discussed. When the two sub cells are connected in series, the total generated photocurrent will be constant throughout the device (conservation of charge) in steady state. Furthermore, the voltages generated by the sub cells will add up. As a result for each point of the $J$-$V$ characteristic of the tandem device the following relations are valid,

$$J_{Tandem} = J_{Bottom} = J_{Top}$$  \hspace{1cm} (5.1)

$$V_{Tandem} = V_{Bottom} + V_{Top}$$  \hspace{1cm} (5.2)
Graphically, equation 5.1 means that we can draw an arbitrary horizontal line through Figure 5.1, indicating a chosen constant current density that flows through the cells. This horizontal line crosses the $J-V$ curves under illumination of the individual bottom and the top cell at a specific voltage for each cell. Those cross-points are the values of the voltages with which the sub cells are effectively biased in order to generate the chosen constant current density. Equation 2 then shows that we have to add those two voltage values in order to determine the bias voltage of the tandem cell in series at that constant current density. To do so, we replot Figure 5.1 between zero and $-10 \text{ A/m}^2$ in order to enlarge the vertical axis and choose three arbitrary current densities as shown in Figure 5.2. The horizontal line 1 is the open-circuit condition for both sub cells in which the current densities in both of them are zero (cross-points A and B). Line 2 shows the short-circuit condition of the top cell (cross-point C) whereas the bottom sub cell is biased by a positive voltage (cross-point D). Line 3 is the condition in which the bottom cell is biased by a positive voltage (cross-point F), whereas the top is biased by a negative voltage (cross-point E).
Following equations 5.1 and 5.2 we can say that,

At line 1:

\[
J_{\text{Tandem}} = J_{\text{Bottom}} = J_{\text{Top}} = J_1 = 0 \text{ [A/m}^2\text{]} \tag{5.3}
\]

\[
V_{\text{Tandem}}^{\text{OC}} = V_{\text{Bottom}}^{\text{OC}} + V_{\text{Top}}^{\text{OC}} = V_A + V_B = (0.57) + (0.7) = 1.27 \text{ [Volt]} \tag{5.4}
\]

At line 2:

\[
J_{\text{Tandem}} = J_{\text{Bottom}} = J_{\text{Top}}^{\text{SC}} = J_2 = -6.68 \text{ [A/m}^2\text{]} \tag{5.5}
\]

\[
V_{\text{Tandem}} = V_{\text{Bottom}} + V_{\text{Top}} = V_C + V_D = (0) + (0.56) = 0.56 \text{ [Volt]} \tag{5.6}
\]

At line 3:

\[
J_{\text{Tandem}}^{\text{SC}} = J_{\text{Bottom}} = J_{\text{Top}} = J_3 = -7.46 \text{ [A/m}^2\text{]} \tag{5.7}
\]

and because for this current the distance from E and F to the y-axis are equal,

\[
V_{\text{Tandem}} = V_{\text{Bottom}} + V_{\text{Top}} = V_E + V_F = (-0.55) + (0.55) = 0 \text{ [Volt]} \tag{5.8}
\]

In this way the open-circuit voltage (equation 5.4), short-circuit current (equation 5.7) and an additional arbitrary point (at short-circuit condition of the top cell) of the series tandem cell are predicted. In Fig. 5.2 also the energy-band diagrams are schematically depicted for these three cases. We now discuss the biasing conditions of this series tandem cell in more detail: In a series configuration the cathode of the bottom cell is electrically connected with the anode of the top cell. In the tandem cell studied here the bottom cell generates much more photocurrent than the top cell (Figure 5.1) under for example short-circuit condition. This means that there are not enough holes arriving from the top cell to recombine with the large amount of electrons arriving from the bottom cell. As a result, in steady-state the excess of electrons negatively charges the connected electrodes of the sub-cell.
cells. This charging reduces the effective voltage across the bottom cell, and thus also the extracted current from the bottom cell. On the other hand, the additional electrons in the middle electrode provide a stronger voltage-drop across the top cell (the top cell is more reversed biased) and therefore a higher current flows through the top cell. Steady-state is reached when the lowered current in the bottom cell is equal to the enhanced current of the top cell. This situation is schematically demonstrated in Figure 5.3.

**Figure 5.3.** Schematic picture of the series tandem cell. In steady-state, the middle electrodes are negative charged with electrons since the bottom cell generates more photocurrent than the top cell. The charging of the electrodes changes the effective voltage across both sub cells in an opposite way. The voltage across the top cell is enhanced, whereas the voltage across the bottom cell is decreased.

At the open-circuit voltage (line 1 in Figure 5.2) both the sub cells are biased in such a way that the effective electric field across them is close to zero (the bias neutralizes the built-in electric field). Current matching is then achieved since both cells do not generate any current, they only act as two voltage sources of which the generated voltages add up. Line 2 in Figure 5.2 shows the situation where the effective bias across the top cell is zero (C), meaning that the field across the top cell is now equal to its built-in electric field. Due to the negative charging of the middle electrode the effective voltage across the bottom cell is strongly reduced (D) in order to balance the current with the top cell. For line 3 in Figure 5.2 the electric field across the top cell is even further enhanced by the increasing amount of charge on the middle electrode, such that it is now reverse (negative) biased. In
this case, the electric field across the top cell is larger than its built-in electric field (E). Finally, line 3 in Figure 5.2 is chosen in such a way that the negative bias across the top cell (E) is equal to the positive bias of the bottom cell (F). As a result the total voltage across the tandem equals zero, such that line 3 in Figure 5.2 represents the short-circuit current of the tandem cell. By choosing sufficient horizontal lines (current levels) and extracting the voltages as mentioned above, the whole illuminated J-V curve of the series tandem cell can be constructed. In Figure 5.4, the given J-V characteristic of the bottom, top and constructed series tandem cell under illumination (STC) are demonstrated.

![Figure 5.4](image.png)

**Figure 5.4.** The current-voltage characteristic of two sub cells (bottom and top) and calculated series tandem.

Qualitatively, the constructed J-V characteristic of the tandem device is in agreement with the experimental series tandem cells that are shown in the Chapters 3 and 4. For these cells the extracted current in the tandem cell was very close to, but slightly larger than, the lower current of the top cell. A quantitative comparison will be made in the next section.
5.2 Parallel configuration

When the two sub cells are electrically connected in parallel, in steady-state for each point of the $J$-$V$ characteristic of the tandem device the following relations are valid,

\[ V_{\text{Tandem}} = V_{\text{Bottom}} = V_{\text{Top}} \]  \hspace{1cm} (5.11)

\[ J_{\text{Tandem}} = J_{\text{Bottom}} + J_{\text{Top}} \]  \hspace{1cm} (5.12)

Graphically, equation 5.11 means that we can now draw an arbitrary vertical line through Figure 5.1, which indicates the chosen operating voltage for the sub cells. This vertical line crosses the $J$-$V$ characteristics under illumination of the bottom and the top cell at a specific current for each cell. Those cross-points are the values of the current density generated by the sub cells at the chosen operating voltage. These two values of the current densities of the bottom and top cell then have to be added (Equation 5.12) to calculate the current of the parallel tandem cell for the chosen operating voltage. We now enlarge the horizontal axis of Figure 5.1 and again draw three vertical lines, as shown in Figure 5.5. The vertical line 1 is the open-circuit condition for the top cell and positive current density for the bottom cell (cross-points K and L). Line 2 shows the condition in which the sub cells have opposite current densities. At line 2, the bottom cell generates positive current due to dark injection (cross-point M), whereas the top cell generates a negative photocurrent (cross-point N). Line 3 is the short-circuit condition for all cells in which both the bottom cell (cross-point O) and the top cell (cross-point P) generate negative photocurrents.
From equations 5.11 and 5.12 we obtain that

At line 1:

\[ V_{\text{Tandem}} = V_{\text{Bottom}} = V_{\text{Top}} = V_1 = 0.69 \text{ Volt} \]  \hspace{1cm} (5.13)

\[ J_{\text{Tandem}} = J_{\text{Bottom}} + J_{\text{Top}} = J_K + J_L = (87.5) + (0) = 87.5 \text{ A/m}^2 \]  \hspace{1cm} (5.13)

At line 2:

\[ V_{\text{OC}} = V_{\text{Bottom}} = V_{\text{Top}} = V_2 = 0.58 \text{ Volt} \]  \hspace{1cm} (5.14)

since M and N have equal distance to the x-axis,
\[ J_{\text{Tandem}} = J_{\text{Bottom}} + J_{\text{Top}} = J_M + J_N = (4) + (-4) = 0 \text{ [A/m}^2\text{]} \] (5.16)

At line 3:

\[ V_{\text{Tandem}} = V_{\text{Bottom}} = V_{\text{Top}} = V_3 = 0 \text{ [Volt]} \] (5.17)

\[ J_{\text{Tandem}}^{\text{SC}} = J_{\text{Bottom}}^{\text{SC}} + J_{\text{Top}}^{\text{SC}} = J_O + J_P = (-83.65) + (-7.1) = -90.75 \text{ [A/m}^2\text{]} \] (5.18)

With this method, the short-circuit current, open-circuit voltage and an additional point of the tandem \( J-V \) characteristic are determined for a parallel tandem cell based on the sub cells mentioned before. By drawing sufficient vertical lines through the \( J-V \) curves of the sub cells and extracting the operation points the complete \( J-V \) characteristic of the parallel tandem device can be constructed. The constructed \( J-V \) curve of the parallel tandem cell is shown in Figure 5.6, together with the characteristics of the individual sub cells.

![Figure 5.6 Current-voltage characteristic of the sub cells and calculated parallel tandem device.](image)

Also shown in Fig. 5.5 are the corresponding energy band diagrams for the three lines. In the parallel configuration the two outer electrodes are connected and show up on an equal level in these diagrams. For line 1 in Figure 5.5 the top cell is biased such that the electric field across the cell is close to zero (L). However, because of the lower built-in field in the bottom cell the electric field in the bottom cell changes sign (K) under this bias. As a result the dark injection in the bottom
cell is switched on and electrons now flow to the PEDOT:PSS in stead of to the LiF/Al electrode, leading to a positive current. For the voltage corresponding to line 2 in Figure 5.5 the bottom cell is still dominated by (positive) dark current, but its current is now of equal magnitude as the (negative) photocurrent generated by the top cell. This voltage therefore represents the open-circuit voltage of the tandem cell and is located in between the $V_{OC}$ ‘s of the individual cells. Finally, line 3 in Figure 5.5 shows the situation when there is no bias applied across the parallel tandem. In that case both sub cells are effectively biased by their built-in electrical fields.

Using the procedures described in this section the current-voltage curve of any parallel- and series connected tandem solar cell can be derived from the electrical performance of the individual sub cells. It should be noted that this method can also be used for the prediction of the $J$-$V$ curves of multi-junction organic solar cells with three or more active layers.

5.3 Comparison with experiment

In order to compare the calculated $J$-$V$ characteristics of the tandem cells with experimental data we can use the measurements on the tandem device as shown in Figure 4.1B in Chapter 4. The tandem cell we now consider is based on a 250 nm P3HT:PCBM blend for the bottom cell and a 80 nm MDMO-PPV:PCBM blend for the top cell. An optical spacer with a thickness of 190 nm was used to separate the sub cells. For this thickness the optical spacer maximizes the transmitted light for the wavelengths that correspond to the absorption spectrum of the MDMO-PPV. The experimental $J$-$V$ characteristics of the individual bottom- and top cell of this structure were already shown in Figure 5.1. The complete structure of this tandem test device is given in Figure 5.7. The two sub cells can be connected electrically in series or in parallel using external wiring.
Figure 5.7. Structure of the tandem test device. The electrical performance of this device is given in Figure 5.1. The electrodes of the device can be electrically connected in parallel or in series by adjusting the external wires.

First, the electrodes of the device under illumination were connected in series. In Figure 5.8 both the experimental and calculated $J-V$ characteristic of the series tandem cell are shown under illumination (STC). It is clear that the experiment is in very good agreement with the characteristic that is extracted from the two individual sub-cells, as described in the previous section.
Polymer Tandem Solar Cells

Figure 5.8. The current-voltage measurements of the experimental series tandem device under illumination (STC) and the calculated series tandem cell.

Subsequently, the electrodes of the sub cells of the above-mentioned 4-electrode tandem device in Figure 5.7 were connected in a parallel configuration. The J-V characteristics under illumination (STC) of both the calculated- and experimental parallel tandem cell are shown in Figure 5.9.
Again, a very good agreement between the calculated and experimental J-V characteristics is obtained. In order to make a more quantitative comparison we determine for the calculated- and experimental J-V curves of Figure 5.8 (series connection) and Figure 5.9 (parallel connection) the exact values for $V_{OC}$ and $J_{SC}$, the voltage $V_{max}$ and the current density $J_{max}$ at the maximum power point, and the corresponding fill factor (FF) and efficiency $\eta$. For the series connection, the FF and $\eta$ are given by

$$
FF \equiv \frac{J_{max} \times V_{max}}{J_{SC} \times V_{OC}} = \frac{A}{B} = \frac{(-5.67) \times (0.91)}{(-7.34) \times (1.27)} = 55\%
$$

(5.19)

$$
\eta \equiv FF \frac{J_{SC} \times V_{OC}}{P_{light}} \cong 0.5\%.
$$

(5.20)

For the parallel configuration we find that,

$$
FF \equiv \frac{J_{max} \times V_{max}}{J_{SC} \times V_{OC}} = \frac{(-66.31) \times (0.39)}{(-90.93) \times (0.58)} = 48\%
$$

(5.20)

$$
\eta \equiv FF \frac{J_{SC} \times V_{OC}}{P_{light}} \cong 2.53\%.
$$

(5.21)

The results are summarized in Table 5.1
Polymer Tandem Solar Cells

<table>
<thead>
<tr>
<th>Cell</th>
<th>$J_{max}$ [A/m²]</th>
<th>$V_{max}$ [Volt]</th>
<th>$J_{SC}$ [A/m²]</th>
<th>$V_{OC}$ [Volt]</th>
<th>$FF$ [%]</th>
<th>$\eta$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculated series</td>
<td>-5.64</td>
<td>0.91</td>
<td>-7.34</td>
<td>1.27</td>
<td>55</td>
<td>0.50</td>
</tr>
<tr>
<td>Experimental series</td>
<td>-6</td>
<td>0.89</td>
<td>-7.60</td>
<td>1.28</td>
<td>54</td>
<td>0.48</td>
</tr>
<tr>
<td>Calculated parallel</td>
<td>-66.31</td>
<td>0.39</td>
<td>-91.15</td>
<td>0.58</td>
<td>48</td>
<td>2.53</td>
</tr>
<tr>
<td>Experimental parallel</td>
<td>-64.80</td>
<td>0.40</td>
<td>-89.94</td>
<td>0.58</td>
<td>49</td>
<td>2.56</td>
</tr>
</tbody>
</table>

Table 5.1. Comparison between calculated and experimental parameters of the series and parallel tandem solar cell shown in Figure 5.8 and 5.9.

It is clear from table 5.1 that all relevant solar cell parameters for the series- and parallel connected tandem cells can be accurately predicted from the electrical characteristics of the individual sub cells. Verification of the predicted characteristics with experimental data now allows us to further investigate the effects other parameters, as the fill factor of the bottom- and top cell, on the fill factor and performance of series- and parallel connected tandem cells.

5.4 The fill factor and efficiency of tandem solar cells

Another important question is how the fill factor of a tandem cell is affected when one of the sub cells has a very poor $FF$. Will it be closer to the highest or the lowest $FF$ when connected in series or parallel? In order to investigate this we consider a range of $J-V$ characteristics as shown in Figure 5.10. These artificial $J-V$ curves are
constructed in such a way that they all have the same $V_{OC}$ and $J_{SC}$, but a large variation in FF (from 25 to 66%). Each (artificial) solar cell has a different maximum power point ($MMP$), which arises from the different maximum current ($J_{max}$) and maximum voltage ($V_{max}$) for each cell, as demonstrated in Figure 5.10.

![Figure 5.10](image)

Figure 5.10. Current-voltage characteristic of 6 artificial solar cells with different fill factor. The area’s B/A = 0.66, C/A = 0.54, D/A = 0.44, E/A = 0.39, F/A = 0.31 and G/A = 0.25 demonstrates the fill factor of the cell 1 until the cell 6, respectively.

The relevant solar cell parameters as extracted from Figure 5.10 are given in Table 5.2.

<table>
<thead>
<tr>
<th>Cell number</th>
<th>$V_{OC}$ [Volt]</th>
<th>$J_{SC}$ [A/m²]</th>
<th>FF [%]</th>
<th>η [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.59</td>
<td>95.3</td>
<td>66</td>
<td>3.71</td>
</tr>
<tr>
<td>2</td>
<td>0.59</td>
<td>95.3</td>
<td>55</td>
<td>3.09</td>
</tr>
<tr>
<td>3</td>
<td>0.59</td>
<td>95.3</td>
<td>46</td>
<td>2.58</td>
</tr>
<tr>
<td>4</td>
<td>0.59</td>
<td>95.3</td>
<td>39</td>
<td>2.19</td>
</tr>
<tr>
<td>5</td>
<td>0.59</td>
<td>95.3</td>
<td>34</td>
<td>1.91</td>
</tr>
<tr>
<td>6</td>
<td>0.59</td>
<td>95.3</td>
<td>25</td>
<td>1.40</td>
</tr>
</tbody>
</table>
Table 5.2. Electrical performance of the 6 artificial solar cells as extracted from Figure 5.10.

With these 6 cells as input we can now construct on paper a series of tandem cells: we choose the characteristic of cell 1 ($FF=66\%$) as bottom cell and then add all curves 1 to 6 subsequently as top cell. For each combination of 2 curves we then apply the method as explained in section 5.2, and construct the resulting electrical tandem characteristics when the cells are connected either in series or parallel. In this way, we can investigate the effect of a variation of the $FF$ in one of the sub cells on the $FF$ and performance of the tandem cells. For the series connection the resulting $J$-$V$ characteristics of the various tandem cells are shown in Figure 5.11.

![Figure 5.11. Calculated current-voltage characteristics for tandem solar cells in series configuration. The bottom cell (cell 1) is combined with itself as top cell as well as with the other cells that have different fill factors.](image)

It is clear that the lower fill factor of the top cell also strongly decreases the fill factor of the series tandem device. Furthermore, the fill factors of the series
tandem devices are higher than the fill factors of the top cells. Only when the bottom cell (cell 1) is combined in a tandem cell with itself, the fill factor of the tandem device equals to the fill factor of the bottom cell (cell 1, 66%). The values extracted from Figure 5.11 are given in the table 5.3. Combining the highest (66%) and lowest (25%) FF as sub cells in a series tandem device leads to a FF of 38%, which is below the average value (45.5%).

<table>
<thead>
<tr>
<th>Series tandem cell number</th>
<th>$V_{OC}$ [Volt]</th>
<th>$J_{SC}$ [A/m²]</th>
<th>FF [%]</th>
<th>η [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.18</td>
<td>95.3</td>
<td>66</td>
<td>7.42</td>
</tr>
<tr>
<td>2</td>
<td>1.18</td>
<td>95.3</td>
<td>59</td>
<td>6.63</td>
</tr>
<tr>
<td>3</td>
<td>1.18</td>
<td>95.3</td>
<td>54</td>
<td>6.07</td>
</tr>
<tr>
<td>4</td>
<td>1.18</td>
<td>95.3</td>
<td>48</td>
<td>5.39</td>
</tr>
<tr>
<td>5</td>
<td>1.18</td>
<td>95.3</td>
<td>45</td>
<td>5.06</td>
</tr>
<tr>
<td>6</td>
<td>1.18</td>
<td>95.3</td>
<td>38</td>
<td>4.27</td>
</tr>
</tbody>
</table>

Table 5.3. Electrical performance of the various series tandem cells with cell 1 as bottom and cell 1 to 6 as top cell. The data are extracted from Figure 5.14.

For the parallel configuration the results of tandem cells based on the bottom cell (cell 1) with itself and the other 5 sub cells as top cells are given in Figure 5.12.
Again it is clear that the fill factor of the top cell limits the performance of the parallel tandem device by lowering its fill factor, equal to the series configuration. However, the fill factor of the parallel tandem cell is higher than the series configuration in all cases. The solar cell parameters extracted from Figure 5.15 are given in the table 5.4 see Table 5.4.
Table 5.4. Electrical performance of a series of parallel tandem cells with cell 1 as bottom cell and cells 1 to 6 as top cell. The data are extracted from Figure 5.12.

<table>
<thead>
<tr>
<th>Parallel tandem cell number</th>
<th>$J_{SC}$ [A/m²]</th>
<th>$V_{OC}$ [Volt]</th>
<th>$FF$ [%]</th>
<th>$\eta$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-190.6</td>
<td>0.59</td>
<td>66</td>
<td>7.42</td>
</tr>
<tr>
<td>2</td>
<td>-190.6</td>
<td>0.59</td>
<td>59</td>
<td>6.80</td>
</tr>
<tr>
<td>3</td>
<td>-190.6</td>
<td>0.59</td>
<td>58</td>
<td>6.28</td>
</tr>
<tr>
<td>4</td>
<td>-190.6</td>
<td>0.59</td>
<td>52</td>
<td>5.90</td>
</tr>
<tr>
<td>5</td>
<td>-190.6</td>
<td>0.59</td>
<td>49</td>
<td>5.62</td>
</tr>
<tr>
<td>6</td>
<td>-190.6</td>
<td>0.59</td>
<td>42</td>
<td>5.00</td>
</tr>
</tbody>
</table>

In order to demonstrate the different behavior of the series- and parallel configuration tandem device when the fill factor of one sub cell is varied, we plot the fill factor of the tandem devices as a function of the fill factor of the top cell, as shown in Figure 5.13. The mathematical average, which is the sum of the fill factors of the sub cells divided by two, is also plotted.
Polymer Tandem Solar Cells

Figure 5.13. Fill factor of the tandem devices, series and parallel, as a function of the fill factor of the top cell. The parallel configuration shows a higher fill factor as compared with the series configuration.

When the two sub cells have an equal fill factor both the series- and parallel configuration have that same fill factor. When the top cell has a significantly lower fill factor the parallel configuration follows the mathematical average and shows a higher fill factor as compared to the series one. This is also the same for the change in the power conversion efficiency of the tandem cells. The parallel tandem has higher efficiency than the series one. The performance of all tandem cells considered are compared with the sum of the efficiencies of the sub cells in Figure 5.14.

Figure 5.14. Efficiency of the series- and parallel tandem cells considered as well as the sum of the efficiency of the sub cells in each case as a function of the efficiency of the top cell. When both sub cells have similar electrical performance, both series and parallel configuration leads to nearly identical efficiencies. If one of the sub cells (top cell here) exhibits a lower fill factor, the parallel configuration is the better choice to fabricate.

It is demonstrated that the series tandem solar cell is affected to a larger extent by the unbalanced electrical performance of the sub cells as compared to the parallel configuration. The mathematical average of the fill factors of the sub cells is a good
approximation for the fill factor in the parallel configuration. The series configuration has significantly lower fill factor and therefore lower efficiency.

5.5 Summary

In this chapter it has been presented how the current-voltage characteristic of any arbitrary tandem device can be derived from the electrical performance of the sub cells. The calculated characteristics are in very good agreement with experimental data on both series- and parallel connected tandem devices. In general, when both sub cells have almost the same electrical properties, series and parallel configurations lead to tandem devices with the same performance. If there are large differences in the electrical performances of the sub cells, the parallel configuration is a better structure since its overall efficiency is higher than the series configuration.