Operation of the three terminal heterojunction bipolar transistor solar cell

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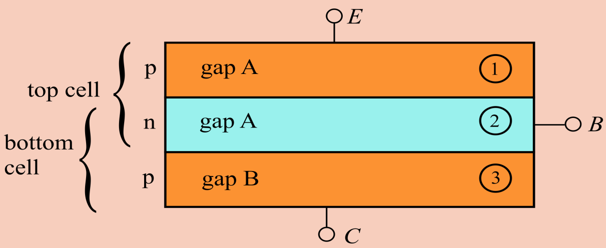
The three terminal heterojunction bipolar transistor solar cell (3T-HBTSC) is characterized by a muti-junction solar cell structure that resembles that of a (npn or pnp) bipolar transistor. The top cell consists of the top np (pn) layers which are made of a high bandgap semiconductor. The bottom n(p) layer is made of a low bandgap semiconductor and, together with the middle p(n) layer, forms the bottom solar cell. The transistor structure allows some simplifications in the layer structure with respect to that of conventional multi-junction solar cells since, for example, tunnel junctions are not necessary. In spite of the name, in the 3T-HBTSC the transistor effect has to be avoided since, in the limit, this would result in the voltage of the top cell being limited by the voltage of the bottom cell.



Simplified layer structure of the three terminal heterojunction bipolar transistor solar cell (3T-HBTSC).

1 Introduction Multi-junction solar cells reveal the strategy for approaching the limits of photovoltaic energy conversion [1]. The cells in the stack can be independently connected (IC) or connected in series (SC). Although for a fixed solar spectrum and optimized gaps, both approaches exhibit the same limiting efficiency [2,3], the efficiency of the IC approach is more robust to changes in the solar spectrum as, for example, those that take place along the day and year [4]. This constitutes the main motivation for exploring new IC solar cell architectures that easy the path towards their practical implementation. In this respect, the ”three terminal heterojuntion bipolar transistor solar cell” (3T-HBTSC) [5] constitutes, in our view, the maximum possible simplification for implementing a three terminal multi-junction solar cell .

2 The three terminal heterojunction bipolar transistor solar cell Fig. 1 shows the basic layer structure of a 3T-HBTSC. The structure resembles that of bipolar transistor and, in this respect, it can be either *npn* or *pnp*. In this work, we will base our description assuming a *pnp* structure, being the *npn* case conceptually identical with the role of electrons and holes interchanged.

The top cell is made of high bandgap semiconductors A and A’. The bottom cell is made of semiconductors A’ and B being semiconductor A’ of high bandgap and semi-

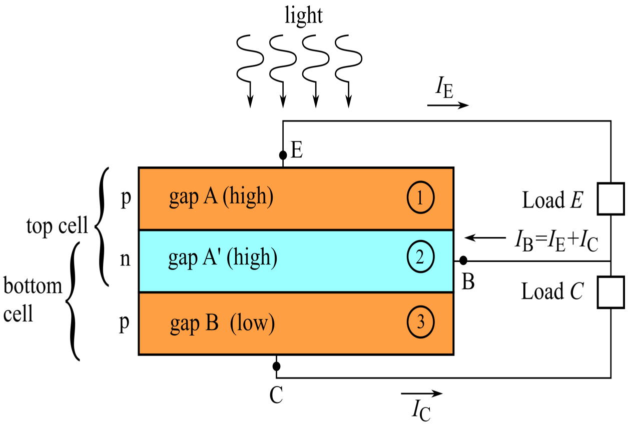


Figure 1 Structure of a three terminal heterojunction bipolar transistor solar cell.

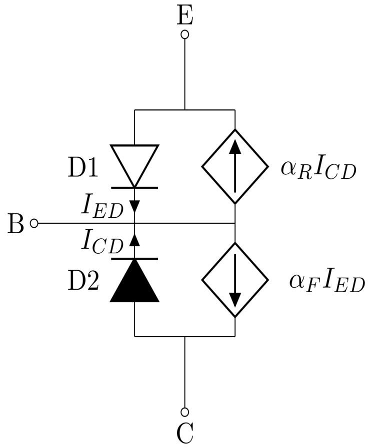


Figure 2 Ebers-Moll model for the solar cell in dark conditions. Notice I_{ED} is the total current through the diode that forms the base-emitter junction and I_{CD} is the total current through the diode that forms the base-collector junction. α_F and α_R are the common-base current gains for the transistor operating in active-forward and active-reverse respectively.

conductor B of low bandgap. The emitter terminal collects the current generated by the top cell, I_E. The collector terminal collects the current generated by the bottom cell, I_C. Both currents add-up at the base terminal, re-enter the solar cell and close the electrical circuit. The power generated by the top cell is collected at load E and the power generated by the bottom cell is collected at load C.

3 Circuit model Fig. 2 shows the equivalent circuit of the three terminal solar cell without illumination. This equivalent circuit is nothing else than the Ebers-Moll model for the bipolar transistor [6] that constitutes the core of the cell. The question arising here is whether the current dependent generators $\alpha_R I_{CD}$ and $\alpha_F I_{ED}$, that count for the transistor effect, are beneficial for the solar cell performance or not. The answer, as we shall see, is they are not beneficial. This implies that, although the structure of the solar cell is the one of a bipolar transistor, the transistor effect must be avoided for photovoltaic operation.

The reasons why the transistor effect must be avoided were explained in [5] using detailed balance arguments. We will now explain the reasons using more conventional, and perhaps, intuitive arguments.

Hence, when exploring the limiting efficiency of solar cells, it is customary to assume carriers exhibit infinity mobility. By doing so, ohmic losses are expected to be reduced to zero. Furthermore, detailed balance models for calculating the limiting efficiency of single gap solar cells [7] become fully consistent since they demand constant quasi-Fermi level split, a characteristic that is achieved when infinite mobility is assumed [8,9].

However, the assumption of infinite mobility in the 3T-HBTSC would lead to operation conditions in which the bandgap of the collector could limit the output voltage of the top cell. This is illustrated by means of Fig. 3,a. In this respect, when carrier mobility approaches infinity, electron and hole quasi-Fermi levels (E_{Fe} and E_{Fh} respectively) have to be flat. If we recall that the output voltage of the cell is given by the split of quasi-Fermi levels, if we would assume that the output voltage of the top cell (multiplied by the electron charge) would exceed the gap of the collector, the collector would be under conditions of inverted population what would provoke stimulated emission in it [10] and, therefore, operation conditions of extremely high radiative recombination. On the contrary, if we assume finite mobility (Fig. 3,b) quasi-Fermi levels are allowed to bend and allow for operation conditions in which the voltage of the top cell is not limited by the gap of the collector.

The price to pay is that finite carrier mobility can lead to series resistance losses. In the case of the *pnp* cell illustrated, it is the hole quasi-Fermi level E_{Fh} the one that is allowed to bend to account for the voltage difference between top and bottom cells. In spite of finite mobility, series resistance associated to hole transport can still be minimized if hole current is minimized. To some extent, the situation is similar to having a resistor but preventing this resistor from dissipating power by forcing to zero the current through it. In transistor terminology, eliminating the hole current through the base is equivalent to making the transistor injection efficiency of the emitter-base (γ_F) and collector-base (γ_R) junctions equal to zero. The injection efficiency ($\gamma_{F(R)}$) is defined as the ratio between hole and total current that crosses the corresponding pn junction (F for the emitter-base junction and R for the collector-base junction. The forward and reverse current gains (α_F and α_R) appearing in the circuit model in Fig. 2 are related to the injection efficiency by $\alpha_{F(R)} = \gamma_{F(R)}\alpha_T$ where α_T is the base transport factor (we have assumed the transport factor to be the same for forward and reverse operation conditions). Therefore, when $\gamma \approx 0$, $\alpha_{F(R)} \approx 0$ and the current dependent generators in Fig. 2 can be re-

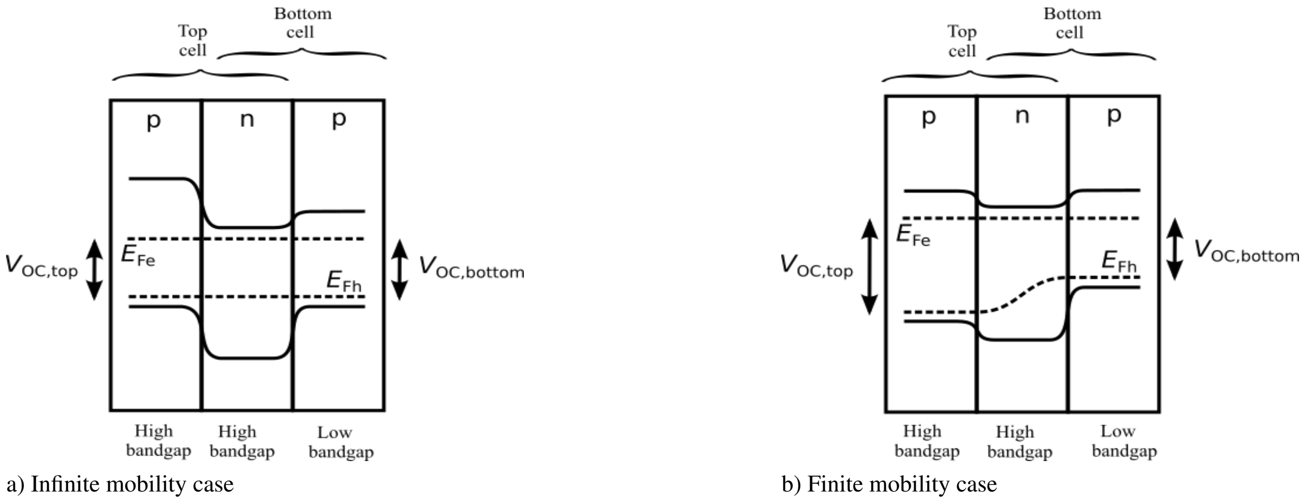


Figure 3 Qualitative plot of the shape of the quasi-Fermi levels when the top and bottom cell are illuminated and in open-circuit and when a) infinite mobility is assumed and b) finite mobility for the holes is assumed. $V_{OC,top}$ and $V_{OC,bottom}$ indicate the open-circuit voltage of top and bottom cell respectively.

moved from the transistor model leading to a circuit model with just two diodes in opposition. These two diodes represent now the top and bottom cells. To model them as solar cells, we finally add two current generators (I_{EL} and I_{CL}) to count for the photogenerated current in each of the cells leading to the equivalent circuit represented in Fig. 4. This circuit model could also have been obtained assuming $\alpha_T \approx 0$. However we have shown this is not necessary what give us an extra degree of freedom for the future design of a practical solar cell.

Contrarily to what is pursued in a transistor design, low injection efficiencies can be obtained, for example, by doping the base higher than the emitter and collector. Having the base with a high doping favors achieving a low base series resistance to what majority carrier transport concerns which can be a relevant issue since both the emitter and collector currents are collected laterally through the base.

Finally, it must be mentioned that, in spite of the requirement for a low injection efficiency, the limiting efficiency if the 3T-HBTSC seems to be quite tolerant to $\gamma \neq 0$. For example, in [5] it was shown that, under 6000 K black-body illumination and maximum light concentration, the limiting efficiency of a 3T-HBTSC only dropped from 54.7 % to 54.4 % when $\gamma = 0.90$.

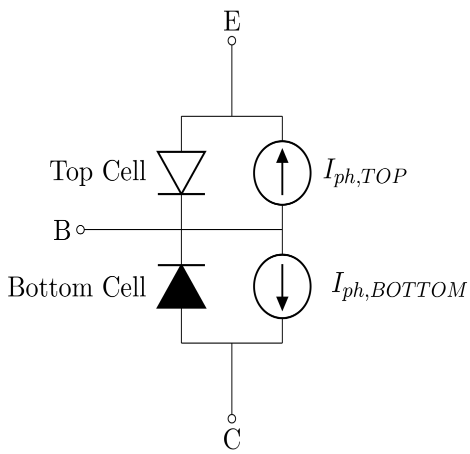


Figure 4 Circuit model for the solar cell when transistor effects are removed. I_{EL} and I_{CL} are now photo-generated currents whose value depends on the illumination conditions.

4 Implementation at module level Solar cells have to be interconnected at module level to increase the current and the output voltage to usable levels. When solar cells have two terminals, increasing the current is achieved by connecting several solar cells in parallel and increasing the voltage is achieved by connecting the cells in series. When cells exhibit several terminals, how to interconnect them at module level is a non-trivial problem. In particular, in the case of a three terminal solar cell, Gee [11] provided a solution for the cell interconnection which is illustrated in Fig. 5.

5 Conclusions The 3T-HBTSC model describes the minimum layer structure that is necessary to implement a three terminal solar cell based on a top and a bottom cell. Its structure resembles that of a bipolar transistor. However, in the case the structure is used to implement a solar cell the transistor effect should be avoided.

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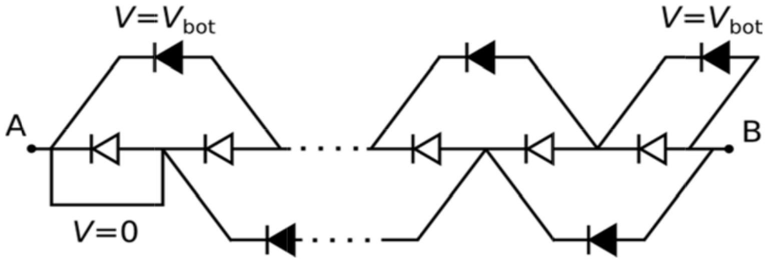

Figure 5 Layout showing a possible cell interconnection at module level. The filled diodes represent the bottom cell. The hollow diodes represent the top cell. V_{bot} indicates the voltage of the bottom cell. A and B represent the two terminals of the module (Adapted from Gee [11]).

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