Modeling of three-terminal heterojunction bipolar transistor solar cells

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***Abstract*—Three-terminal solar cells exploiting the heterojunction bipolar transistor structure combine the advantages of independently connected tandem cell architectures – suboptimal gaps, high resilence to spectral variations and to radiation damage – with a simple monolithic structure, since they do not need tunnel junctions. In this work, we study this novel device concept by means of optoelectronic simulations based on realistic material parameters, and discuss the solar cell operation and its design optimization.**

I. Introduction

III/V semiconductor multijunction (MJ) solar cells are the workhorse for space and concentrator photovoltaics due to their high efficiency, stable performance, and consolidated technology. The most common implementation relies on series connected subcells, resulting in a two-terminal device whose achievable efficiency is limited by the constraint of matched subcell currents. This restricts the set of suitable materials, with the right energy bandgap combination. Moreover, it makes the solar cell prone to the unavoidable sun spectrum variations, limiting the annual energy yield [1], and to radiation damage in space [2]. Aiming at increasing the power-to-cost ratio of high efficiency photovoltaic technologies, research efforts focus today on developing MJ cells with cheaper materials, and on devising alternative architectures that can relax the current matching constraint. In this context, multi-terminal configurations – where the subcells are independently connected – are extensively investigated [3].

Among these, an attractive concept is the three terminal heterojunction bipolar transistor solar cell (3T-HBTSC) [4] illustrated in Fig. 1. With respect to the series/connected double junction (DJ) solar cell, the bipolar transistor structure allows to realize two subcells (emitter/base and base/collector) electrically connected through the common base layer, thus avoiding the use of tunnel junctions. The generated electrical power is extracted through two independent loads, connected at the emitter, base and collector contacts, therefore realizing a three terminal device with the above mentioned advantages of material flexibility and performance. Moreover, the absence of tunnel junctions makes the 3T-HBTSC a promising building block for solar cells with a higher number of junctions, since it allows for a remarkably simpler epitaxial structure.

It has been proven that the detailed balance efficiency of the 3T-HBTSC is equal to that one of a double junction

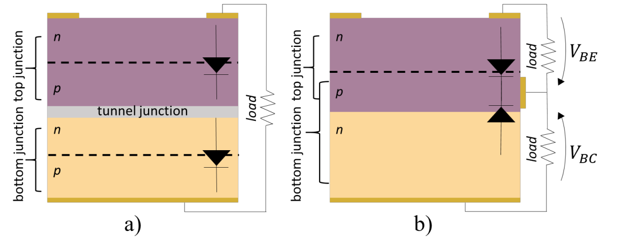


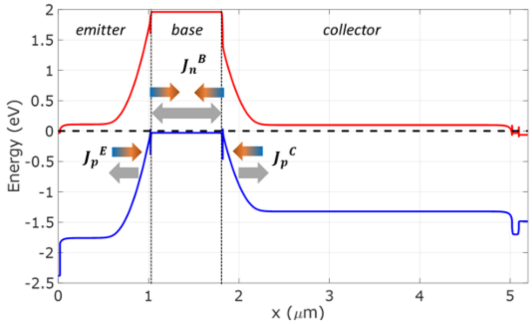
Fig. 1. Sketch of a conventional series connected DJ solar cell (a) and of the 3-terminal HBTSC (b).

solar cell, provided that minority carrier injection from the emitter to the base is suppressed, effectively quenching the transistor action [4]. As concrete device proposals emerge [5], [6], the availability of modeling and simulation tools able to link the device behavior to its material and geometrical parameters is essential. In this direction, [7] analyzed the cell dark characteristics based on the classical bipolar junction transistor model, developing guidelines for the base design.

In this work, we present for the first time full optoelectronic simulations of 3T-HBTSC solar cells. A case study for the AlGaAs/GaAs material system is discussed, demonstrating an efficiency higher than 36% with realistic material parameters.

II. Results

We consider a 3T-HBTSC realized with $Al_{0.33}Ga_{0.67}As$ emitter, $Al_{0.5}Ga_{0.5}As$ base, and GaAs collector. The energy band diagram at thermodynamic equilibrium is shown in Fig. 2. The device was optimized in terms of material gap, doping, and layer thickness, based on an extended Shockley model accounting for photogeneration. Under the assumption of quasi-neutrality and by calculating the photogeneration term from the Lambert-Beer law, the drift-diffusion equations admit for a closed form analytical solution of the minority carriers current components. The depletion region photocurrents are computed integrating the photogeneration rate assuming unitary collection efficiency. The complete model formulation will be reported elsewhere. For the sake of this discussion, it is sufficient to highlight that the interplay between the junctions occurs through the base dark current component of $J_n^B(V_{\rm BE}, V_{\rm BC})$, and that under photovoltaic action both cells develop a forward bias. As shown from the current flows in



	Emitter	Base	Collector
Material	$Al_{0.33}Ga_{0.67}As$ (E_g = 1.87 eV)	$Al_{0.5}Ga_{0.5}As$ (E_g = 1.99 eV)	GaAs (E_g = 1.42 eV)
Thickness [nm]	1000	800	3200
Doping [cm^{-3}]	10^{16}	4×10^{18}	10^{16}

Fig. 2. Energy band diagram at thermodynamic equilibrium of the device under study: $Al_{0.33}Ga_{0.67}As/Al_{0.5}Ga_{0.5}As/GaAs$ HBTSC with AlInP window and AlGaAs back-surface-field. The coloured and grey arrows indicate - out of equilibrium - the emitter, base, and collector current components due to optical and electrical injection, respectively.

Fig. 2, the component of J_n^B due to electron injection from the emitter (collector) adds up to the B/C (E/B) photocurrent. The same dark current component, however, degrades the open circuit voltage of the corresponding junction. In other words, a power transfer from one junction to the other takes place. The overall budget of this power transfer is negative and reduces the total electrical power delivered to the loads. The injection from the B/C to the E/B junction is inherently marginal, since the top E/B cell has larger bandgap than the bottom B/C one, so as to absorb short wavelength photons only and leave longer wavelength photons to the B/C subcell. On the other hand, the E/B to B/C injection might be relevant and must be minimized acting on E/B bandgaps and (base) doping, resulting in the optimized values reported in Fig. 2. The External Quantum Efficiency spectrum with the contributions from the quasi neutral and depleted regions is reported in Fig. 3. The contribution from the wide gap, strongly doped base layer is almost negligible. As shown in Fig. 4, there is no interplay between the two junctions biased at maximum power point (MPP). The effect of carrier injection from the E/B to the B/C junction is significant only for V_{BE} approaching the open circuit condition. Therefore, the MPP of the optimized 3T-HBTSC corresponds to the MPP of the individual junctions. On the other hand, the injection effect at high V_{BE} explains recent experimental results [5]. In conclusion, we find that the device achieves a remarkable 36.7% efficiency. We verified that such high efficiency withstands lower doping or thickness of the base. However, in practical devices, parasitic losses associated to the lateral current flow through the base layer must be taken into account, and this imposes far more stringent constraints on the design of the base to maintain high efficiency.

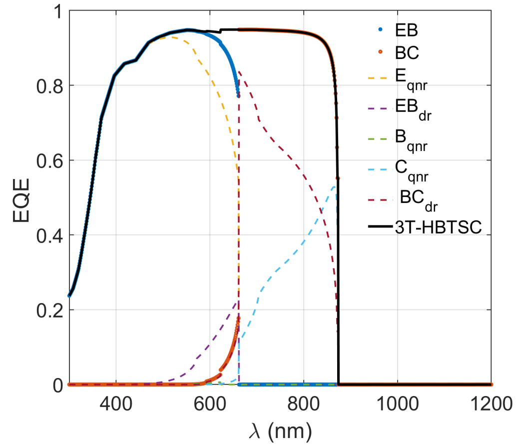


Fig. 3. EQE spectrum of the 3T-HBTSC and its components from the quasi neutral (qnr) and depleted (dr) regions.

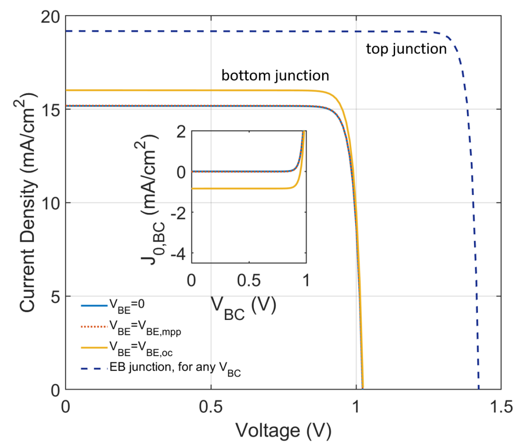


Fig. 4. Current voltage characteristics of the E/B (/BC) junction at different V_{BC} (V_{BE}). The E/B junction is insensitive to V_{BC} and therefore only one curve is shown. The B/C junction is analyzed with the E/B one at short circuit, maximum power point, and open circuit condition. In the inset, the B/C dark current component with the E/B junction biased at MPP and open circuit.

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