Modeling and Design of 3-Terminal Perovskite/Silicon HBT Tandem Solar Cell

Author: Gemma Giliberti

Supervisor: Federica Cappelluti

Abstract

The *energy transition* aims to move the global energy sector from fossil-based sources towards a zero-carbon system. Among sustainable energies, Silicon-based photovoltaic devices, providing clean energy at a low cost, are a viable alternative to traditional non-renewable sources of energy. Substantial investments in solar technology are ongoing to minimize their manufacturing costs while increasing their efficiency.

In this ever-changing scenario, Perovskite has drawn significant attention in the photovoltaics research community owing to their optimal opto-electronic properties and the fast progress achieved in the last decade. Perovskite is emerging as an ideal candidate for the development of low-cost thin-film silicon-based tandems, able to overcome the efficiency bottleneck of single-gap Si cells.

To date, perovskite/silicon (PVS) tandem devices reported in the literature exploit mainly the 2-Terminal (2T) series connected structure, however 3-Terminal (3T) solutions, with interdigitated back contact (IBC) silicon bottom cell, have recently attracted great interest due to their potential for higher energy yield. Although the IBC cell is an ideal candidate for 3T tandems, according to the International Roadmap for Photovoltaics their commercialization will remain comparatively limited with respect to double-sided contact cells.

In this direction, this thesis investigates a novel 3T PVS tandem solar cell employing a well-known structure used in microelectronic applications and proposed in 2015 by Martí and Luque as elementary building block for multi-junction solar cells: the hetero-junction bipolar transistor (HBT) structure. The 3T-HBT architecture properly engineered, allows the independent operation of the top and bottom sub cells, achieving maximum efficiency as high as classical 2T and 3T approaches, but with a simpler device architecture, because it also avoids the need of any tunnel junction or intermediate recombination layer.

After reviewing the theoretical limit efficiency of the 3T-HBT grounded on detailed balance model, we introduce for the first time a compact closed-form analytical model of the 3T-HBT

solar cell, by extending the well-known analytical drift-diffusion Hovel model of single-junction solar cells. The generalized Hovel model provides an ideal means to analyze the basic operating principle of the 3T-HBT with a mindset already oriented to a realistic device (with realistic material properties and geometry), allowing to gain the preliminary knowledge needed to get insight from more advanced numerical models. It also naturally yields to the formulation of an equivalent circuit model of the HBT solar cell suitable for the assessment of parasitic loss.

In the second part of the dissertation, we present a thorough analysis of both planar and textured PVS 3T-HBT solar cells made on hetero-junction silicon bottom cell, based on coupled electromagnetic and transport numerical simulations. The numerical model is firstly validated against experimental data of a representative 2T series-connected tandem taken from the literature. Then, we use it to study the photovoltaic behavior of the 3T-HBT compared to the 2T one, devising possible bottlenecks and routes of optimization. The results show promising performance of the *intrinsic* device, i.e. when possible additional optical and electrical loss induced by the need of a third terminal are not considered.

However, to foster the development of this attractive concept, concrete design solutions shall deal not only with the optimization of the HBT-like multilayer stack, but also with the problem of conceiving appropriate layouts for the current collecting grid of the middle base terminal. In this direction, to address the additional optical and resistive losses associated to the current collecting grids of the HBT architecture, in the last part of the dissertation, we present a modeling framework that combines electro-optical simulations of *intrinsic* 3T-HBT tandem stack with circuit-level simulations. The impact of the optical and electrical loss due to the current collecting grids on the scalability of the cell size is analyzed to ultimately develop a holistic optimization of the device design. In this regard, several possible approaches are considered for the development of HBT perovskite/silicon cells with heterojunction and homojunction c-Si technologies. The results show that the HBT architecture is a promising candidate for developing high efficiency 3T perovskite/silicon tandem solar cells compatible with standard silicon photovoltaics industry.