Three-terminal tandem solar cells combining bottom interdigitated back contact and top heterojunction subcells: a new architecture for high power conversion efficiency

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TOPIC 1: New Materials and Concepts for Photovoltaic Devices

SUBTOPIC 1.2: New Materials and Concepts for Cells and Modules

Three-terminal tandem solar cells combining bottom interdigitated back contact and top heterojunction subcells: a new architecture for high power conversion efficiency

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ABSTRACT:

We present the design of a new architecture of three-terminal photovoltaic tandem solar cells. It combines an interdigitated back contacted bottom lateral subcell with a heterojunction vertical top cell. In this concept, the two subcells can work independently and there is no need for tunnel junctions. It is particularly well suited to silicon back contact subcells and to various types of top cell materials from III-V compounds or perovskites. The working principle is detailed here using as an example a p-i III-V front stack onto n-type silicon bottom cell. We perform 2D modeling using realistic material input parameters and show how interface bandgap engineering can improve the tandem cell efficiency up to a realistic 35% value. The proposed cell concept named BESTT (Bandgap Engineered Smart Silicon Three-Terminal) cell can be realized with less technological steps and at a lower cost compared to the conventional four-terminal process.

KEYWORDS:

Photovoltaics, three-terminal tandem cell, silicon, 2D modelling, high efficiency

REMARKS:

We chose TOPIC 1.2 because we present here a **new concept for photovoltaic cell**. The work of this submission concerns a new three-terminal architecture of tandem cell on silicon.

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AIM AND APPROACH USED

The laboratory record efficiencies of single junction solar cells are getting closer and closer to the theoretical limit. This is especially true for silicon solar cells where the theoretical limit at one sun illumination taking into account the intrinsic Auger recombination is of 29%, while achievements of 26.7% have been reported [1,2]. Multijunction solar cells are being actively studied since they can overcome the limit of single junction cells, with one-sun theoretical efficiencies of 42% and 49% for dual (tandem) or triple junction cells, respectively [3]. While the history of multijunction solar cells relies on the development of III-V compounds, with, for instance, the GaInP/GaAs/Ge triple cells that have been widely used in space applications, the scarcity of some elements or cost of substrates (in this example, Ge) together with costly processing technologies are serious limitations for their use for a large-scale terrestrial energy production. This is why strong research efforts are currently devoted to the development of multijunction solar cells based on silicon, especially for tandem cells. Interesting results have been obtained recently combining silicon with III-V compounds like GaInP [4] or with perovskites [5, 6], with efficiencies above 30% and around 25%, respectively. Two-terminal (2-T) and various four-terminal (4-T) tandem cell architectures have been proposed [7], the most common ones being the monolithically integrated 2-T and the mechanically stacked 4-T (Fig. 1).

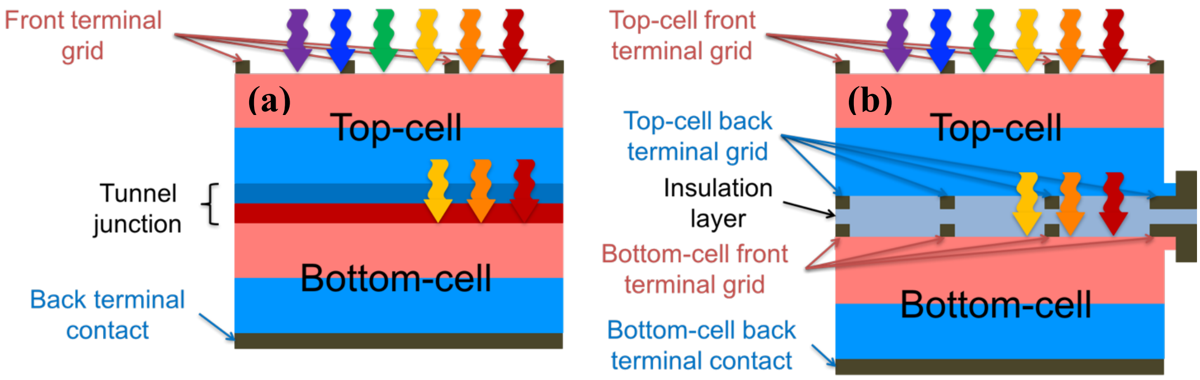

Fig. 1: *Schematic architectures of monolithically integrated 2-terminal (a), and mechanically stacked 4-terminal (b) tandem cells.*

Our aim is to propose a route for tandem solar cells based on a three-terminal (3-T) concept that can offer several advantages: 1) to suppress the constraint of photo-current matching and of tunnel junctions required in the 2-T design; 2) to facilitate the access to the different contacts of the top and bottom cells without the need for etching and without having to align buried contact grids; 3) to be adapted to the well mastered silicon technology for the bottom cell..

SCIENTIFIC INNOVATION AND RELEVANCE

In 2015, Marti and Luque [8] proposed theoretical calculations on a three-terminal double heterojunction bipolar transistor solar cell, showing that the theoretical limit efficiency was the same as for conventional tandem cells. However, neither concrete architecture nor material combination was proposed for this type of cell. We here propose a 3-T architecture that we recently patented [9]. It is built on an interdigitated back-contact (IBC) silicon bottom cell combined with a heterojunction front cell. Using ATLAS module of SILVACO TCAD, we illustrate the operation principle and show how a suitable management of the hetero-interface can improve the performance of this 3-T cell. Using realistic calculations that takes into account transport and recombination mechanisms, we demonstrate that efficiencies beyond 35% could be reasonably attained.

RESULTS

An example of the proposed 3-T solar cell concept is shown in Fig. 2a. It combines an n-type crystalline silicon absorber IBC bottom-cell and a top p-i-n heterojunction cell made of a 20 nm thick p-type GaP window cap layer, a 50 nm thick intrinsic $Ga_xIn_{1-x}P$ layer with graded bandgap (between 2.35 eV down to 1.78 eV), and a 1 µm thick intrinsic $Ga_{0.35}In_{0.65}P$ absorber, the bandgap of which is 1.78 eV. The graded bandgap layer has been chosen in order to smooth the band offsets between the window layer and the absorber.

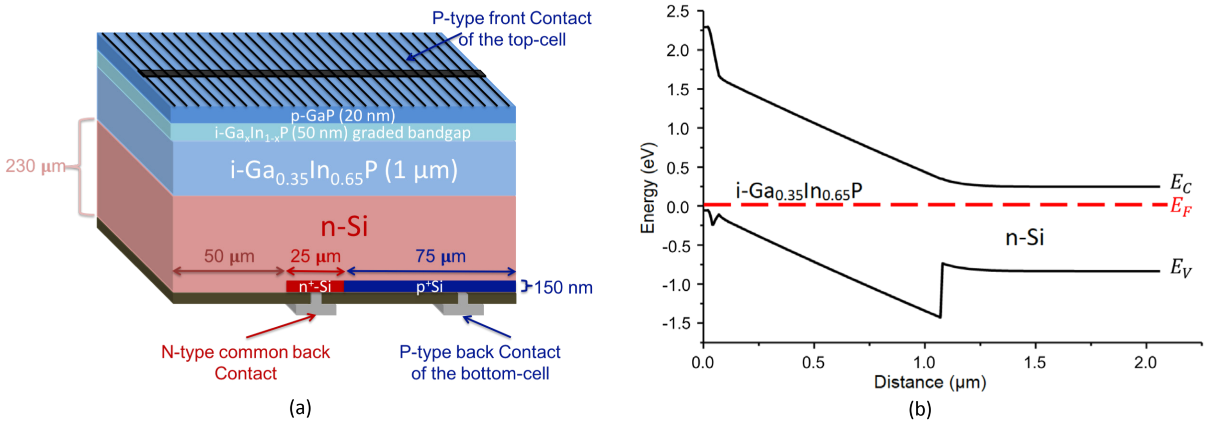

Fig. 2: *(a) Sketch of the structure chosen to illustrate the working principle and performance of the 3-T architecture on an n-type silicon wafer. The top subcell is made of a p(GaP)-i($Ga_{0.35}In_{0.65}P$)-n(Si) heterojunction. (b) The corresponding energy band diagram at equilibrium across the p-i-n heterojunction.*

1. Transport of electrons and holes

In this architecture, the back n^+-Si electrode works as a common electrode for both subcells. Therefore the top semiconductor must be chosen so that there is no barrier for electrons at the heterojunction to pass from the top larger bandgap layer into the silicon. On the other hand, the conduction band offset at the hetero-interface, $\Delta E_C = E_{C,top} - E_{C,bottom}$, should not have a too large positive value in order to avoid thermalization losses for the electrons photogenerated in the large bandgap layer. In Fig. 2b we show the preferred band alignment at the heterojunction where GaInP has almost the same electron affinity as silicon. The map of electrons current at short circuit conditions (Fig. 3) confirms that all photogenerated electrons are collected at the common back n+-Si electrode. Our 3-T architecture can be viewed as a vertical/lateral cell, e.g. a combination of a sub cell working mainly laterally (the bottom IBC cell) and a sub cell working mainly vertically (the top heterojunction cell).

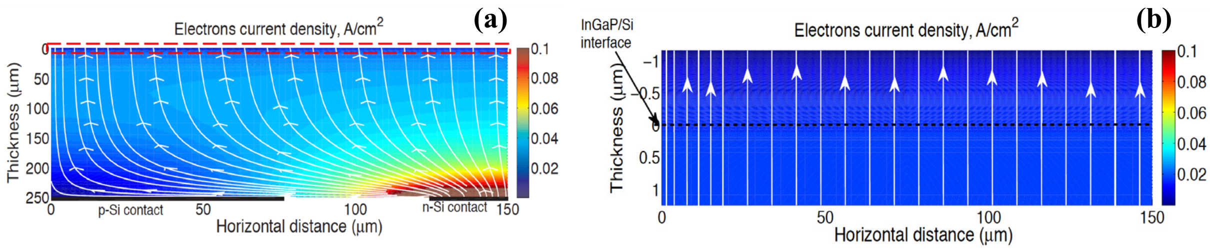

Fig. 3*: Electrons current mapping in the whole tandem solar cell under AM1.5G in the short-circuit configuration (for both subcells) (a), and its zoom-in close to the InGaP/Si heterointerface (b). Arrows indicate the conventional sense of current, the flow of electrons being in the opposite direction.*

Regarding the holes, due to the large valence band offset at the hetero-interface (Fig. 2b), photogenerated holes in silicon cannot pass into GaInP, and are collected at the back p-electrode, just as in the case of the traditional IBC cell. As for the holes photogenerated in the GaInP layer, they are collected primarily by the front electrode due to the built-in field of the p-i-n heterojunction. However, when this junction is forward biased, the intensity of the electric field decreases so that diffusion begins playing a role. Since holes have no barrier to pass from the large bandgap layer into the silicon, some holes will diffuse into silicon. Interestingly, these holes are not lost and can then be extracted by the back p-electrode, thus increasing the photocurrent in the IBC cell. However, due to the valence band offset when going from GaInP to silicon they thermalize, causing some power loss and limiting the open circuit voltage of the top cell to a value of 1.13 V, which is much less than the value obtained in single record GaInP cells (> 1.4 V) [10].

2. Optimization and performance outlook

We have shown that, in order to limit this thermalization loss, one can adapt the heterojunction by inserting a thin layer of a larger bandgap semiconductor that can provide a barrier for holes in both directions, while assuring a small conduction band offset. A good candidate here can be GaN, as can be shown in Fig. 4.

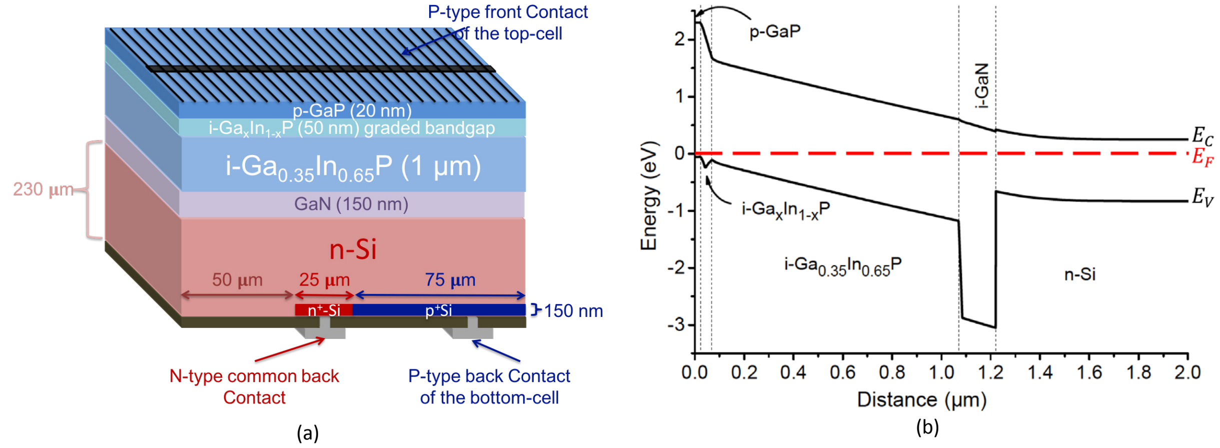

Fig. 4: Sketch of the improved 3-T structure integrating a thin GaN layer (a), and energy band diagram at equilibrium across the top layers and the heterointerface with n-Si (b).

With insertion of this selective band offset GaN buffer layer, the open circuit voltage of the top cell is increased to 1.49V and the two sub cells are now operating fully independently from each other. The output I-V characteristics for both subcells are shown in Fig. 5. The total power conversion efficiency amounts to 35%.

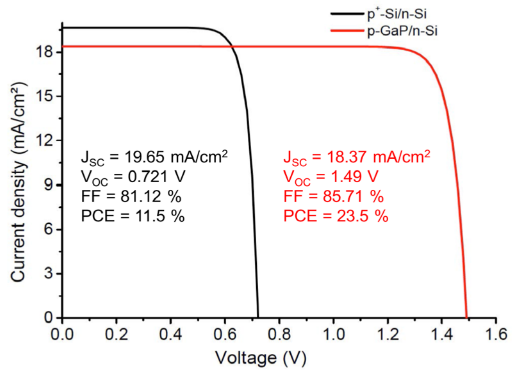

Fig. 5: Output current-voltage characteristics of the two sub cells of the 3-T architecture.

CONCLUSION AND OUTLOOKS

We have proposed a 3-T architecture using an IBC silicon bottom cell combined with a heterojunction top cell that opens new possibilities for high efficiencies. Realistic calculations for a combination of GaInP on silicon have shown that efficiencies of 35% can be attained. Other calculations using perovskites as the top cell are being performed and will be presented.

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