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Vertical-tunnel-junction (VTJ) solar cell for ultra-high light concentrations (>2000 suns)

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***Abstract*— A novel architecture of cell structure tailored to ultra-high (>2000 suns) concentration ratios is proposed. The basic solar cell consists of two pn junctions connected in series by a highly doped tunnel diode with the metallic contacts located laterally. The tunneling connection allow using direct band-gap semiconductor compounds aiming to optimize the absorption of the spectrum. The performance of the novel architecture is investigated up to ultra-high concentration factors by using TCAD software. Results show its viability for developing a new generation of solar cells to increase the potential in terms of efficiency and cost reduction of ultra-high concentrator systems. The solar cell does not show any degradation with concentration and a value as high as 28.4% at 15000 suns has been obtained for a preliminary design.**

***Index Terms*— vertical solar cells, concentrator photovoltaics, gallium arsenide (GaAs), tunnel diode, series resistance.**

I. Introduction

Ultra-high concentrator photovoltaics (UHCPV), commonly referred to systems with fluxes exceeding 1000-2000 suns, poses a direct way to obtain high-efficiency and low-cost new generation solar systems [1], i.e. the theoretical efficiency of solar cells (η) grows with concentration (C_{ratio}), and the amount of semiconductor material is strongly reduced. In this sense, important efforts are being conducted to propose novel optical configurations [2 - 3], thermal management strategies [4 - 6] and architectures of solar cells [7 - 9] to develop suitable systems operating at such elevated concentration factors. Nowadays, concentrator solar devices are dominated by multi-junction (MJ) horizontal solar cells (HSC) made up of III-V compound semiconductors with different band-gaps. HSCs incorporate only two electrical terminals, located on the top and the back of the device, to extract the generated current. The trade-off between the shadowing of the front metal-grid pattern and the series resistance (R_s) seems to limit the peak of the η at C_{ratio} ≈< 1000-2000 suns [9]. Indeed, to the date, the developing of concentrator HSCs with η peaking at C_{ratio} > 1000 suns still remains pending [10].

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Vertical-multi-junction (VMJ) cells consist of a series connection of multiple solar cells with the metal electrodes located laterally [11]. With this strategy, it is possible to develop solar cells with a low R_s, due to the large cross section of the carriers, and therefore, to develop cells optimized for UHCPV applications, i.e. the feasibility of a silicon (Si) cell with a peak η ≈ 19% at a C_{ratio} ≈ 2500 suns has been experimentally proven [12]. However, to the date, only Si-based VMJ solar cells have been developed due their large minority carrier diffusion lengths (L), typically within 100-300 µm [13 - 14]. On the other hand, it would be beneficial to employ also direct band-gap III-V materials to develop multi-band-gap structures with the optimal absorption of the spectrum [15]. However, the feasibility of using these materials is limited due to their low L, typically 1-5 µm. This would imply the series connection of up to 10^3 vertical cells per mm by using lateral metallic contacts. So, although the low R_s of VMJ cells do not limit the peak of η with C_{ratio}, the lower exploitation of the spectrum prevents the development of high-efficiency VMJ solar cells for UHCPV applications.

In this letter, we propose a novel vertical architecture of solar cell that replaces the metal electrode connections by tunnel junctions. This allow the efficient usage of direct band-gap semiconductor materials. For the first time, we have demonstrated, using a GaAs VMJ solar cell, increasing efficiency values with the concentration up to 15000 suns.

II. Device Structure and Simulation

Fig. 1 shows the fundamental structure and dimensions of the vertical tunnel junction (1-VTJ) GaAs solar cell proposed in this work. This material has been selected due to its ability for achieving high conversion efficiencies. The proposed structure consists of two identical subcells connected via a tunnel junction (TJ). Each subcell is composed of two consecutive p-layers, the first one highly doped to 5 x 10^{19} cm^{-3} and the second one to 2 x 10^{17} cm^{-3}, followed by two n-layers, doped to 4 x 10^{16} cm^{-3} and to 5 x 10^{19} cm^{-3}, respectively. The TJ is a n+/p+ junction, with both layers 25 nm wide and doped to 7 x 10^{19} cm^{-3}. The total width (W) of the structure is 9.73 µm. Note that the 1-VTJ solar cell is oriented perpendicular to the sunlight (see how the current flows in the figure) and that it only needs two electrical terminals to extract the generated current (indicated in dark grey color in Fig. 1).

In this work, we have used Silvaco ATLAS software [16] to analyze the main properties of the GaAs 1-VTJ solar cell. It has been illuminated considering concentrator standard reference conditions (AM1.5d, 1 sun = 1000 W/m^2 and 25 °C). It also important to note that this structure has been optimized for these particular conditions and serves as a preliminary design used as a proof of concept for this new VTJ.

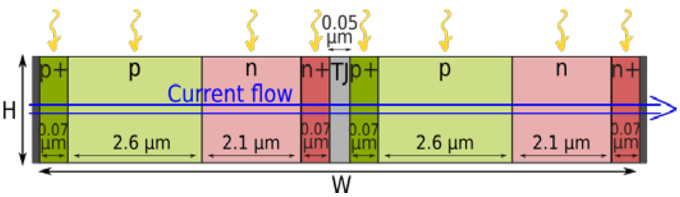

Fig. 1. 2D schematic of the VTJ solar cell (H = height and W = width).

III. RESULTS AND DISCUSSION

The IV characteristics of the 1-VTJ described in the previous section are shown in Fig. 2. The cell presents a low current and high voltage compared with single-band-gap HSCs. The high open-circuit voltage (V_{oc}) is the result of the series connection of two pn junctions of GaAs by using a tunnel diode. The value of the short-circuit current density (J_{sc}) is lower than that of GaAs HSC (≈ 20 mA/cm^2 [17]), which contributes to diminish the R_s power losses with concentration, as they are given by $\approx J^2 \cdot R_s$. In this sense, the R_s has been extracted from the simulated IV curve using the methods previously discussed in [18, 19], and a value ≈ 5 x 10^{-4} $\Omega \cdot cm^2$ has been found, around two orders of magnitude lower than that of concentrator HSCs [20, 21, 22]. The negligible impact of R_s is verified with the high fill factor (FF) obtained, a value ≈ 5% higher than that of concentrator HSCs at one sun [23, 24]. Overall, the VTJ presents a relative high value of η considering the simplicity of the structure investigated, i.e. the record η of a non-concentrating GaAs single-crystal HSC operating at one sun is 27.8% [10].

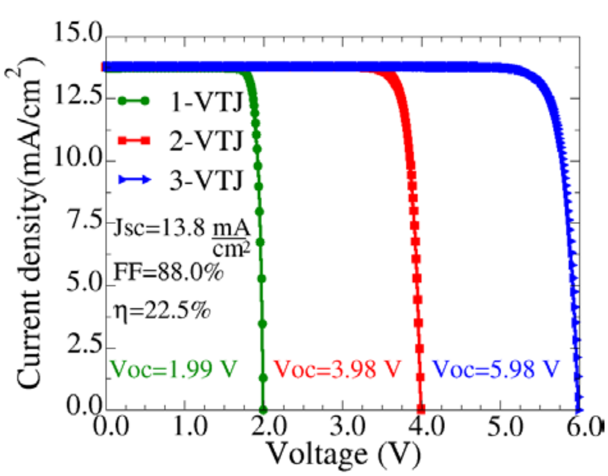

Fig. 2. IV characteristics of various solar cells made up of one (1-VTJ), two (2-VTJ) and three (3-VTJ) solar cells.

An interesting feature of the 1-VTJ is that is possible to increase the area of the cell exposed to the light (A_{cell}) by connecting multiple VTJ (m-VTJ) solar cells in series using tunnel diodes. The advantage, compared with HSCs, is that A_{cell} increases proportionally with the number of m units, but the current remains constant due to the connections in series. Hence, it is possible to develop cells with larger areas without increasing the R_s power losses. This is graphically shown in Fig. 2 through the IV characteristics of an 1-VTJ, 2-VTJ and 3-VTJ solar cell. As can be seen, the J_{sc} is kept constant and the V_{oc} grows linearly as m is increased. In addition, no degradation in the FF has been found. As a consequence, the power delivered increases linearly with the number of m-VTJ solar cells, and the η keeps constant and independent of the area.

The proposed structure is intended to be used at C_{ratio} > 2000 suns. At such elevated levels, A_{cell} values lower than 1 mm x 1 mm are recommended in order to decrease the heat waste produced by the cells, and therefore, to facilitate the thermal management [25]. In addition, micro-concentrator modules with A_{cell} ≈ 0.5 mm x 0.5 mm have shown the best performance since the conversion losses are reduced with the micro-scaling [26]. To achieve these areas, it is going to be necessary to monolithically grow around 50 VTJ solar cells connected by TJs. This is feasible considering the high accuracy of the manufacturing techniques nowadays and the low R_s of TJs, typically ranging from 10^{-5} to 10^{-7} $\Omega \cdot cm^2$ [27]. Indeed, the viability of monochromatic photovoltaic power converters with 20 pn junctions made up of GaAs have been already proven [28]. It is worth to mention that the fact that only one material is used in the VTJ solar cell is intended to facilitate the fabrication process. In addition, the final W of the 50-VTJ cell is similar to the thickness of current MJ HSCs, which is around ≈ 0.2 mm [29]. As consequence, the metallic contacts can be placed on the laterals of the m-VTJ structure using well-known techniques. This gives evidences regarding the manufacturing feasibility of the architecture here proposed.

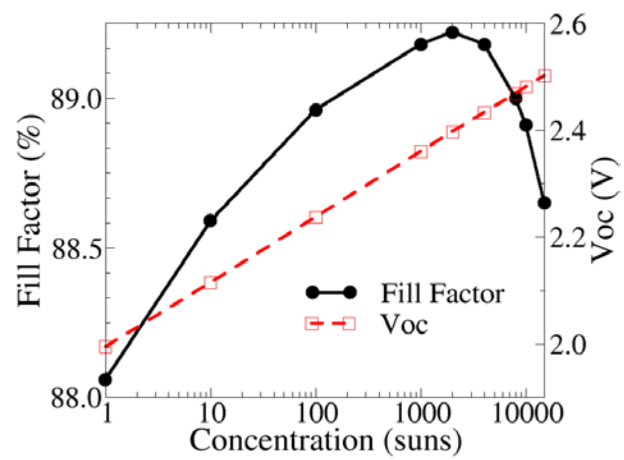

Fig. 3. Fill factor and open-circuit voltage vs sun concentration for the 1-VTJ.

Fig. 3 shows the dependence of V_{oc} and FF with C_{ratio} for the case of the 1-VTJ solar cell up to 15000 suns. As can be seen, V_{oc} increases logarithmically with C_{ratio} from ≈ 2.0 V at 1 sun to ≈ 2.5 V at 15000 suns, and no degradation by Auger recombination has been found. This is important since this recombination mechanism is expected to dominate and limit the efficiency of solar cells at UH C_{ratio} [30]. On the other hand, the FF also grows in a logarithmic manner with C_{ratio} ranging from ≈ 88.1% at 1 sun to ≈ 89.2% at 2000 suns. Above this C_{ratio}, slightly decreases due to R_s losses. Despite of this, FF shows a small range of variation for all the concentrations investigated (≈ 1%). The low reduction of FF for C_{ratio} > 2000 suns does not limit the increase of η as with light intensity. As shown in Fig. 4, the η of the proposed VTJ trends to grow due to the logarithmic increase of V_{oc} with C_{ratio}. Indeed, a value of η ≈ 28.4% at C_{ratio} ≈ 15000 suns have been found. This is a promising result considering that the record η of a concentrator GaAs HSC is 29.3% at a C_{ratio} ≈ 50 suns [10], far below the concentration levels reached by the VTJ structure. In order to highlight the importance of this result, Fig. 4 also shows the experimental data of various concentrator HSCs available in the literature [31]. In fact, the proposed VTJ structure is expected to deliver a higher η than concentrator HSCs cells made up of more than one band-gap at ultra-high concentrator fluxes.

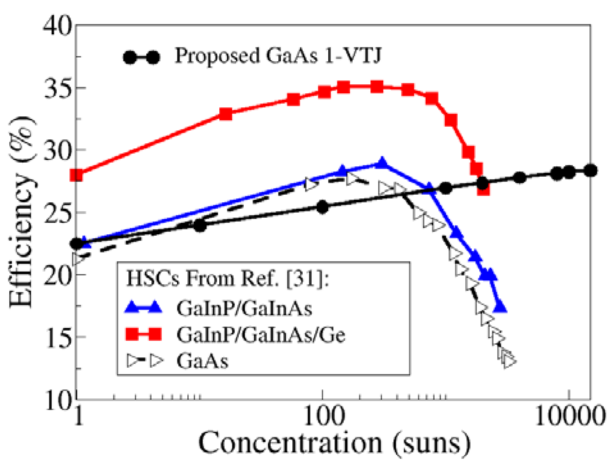

Fig. 4. Efficiency vs sun concentration for the 1-VTJ, along with experimental data available of three different types of concentrator HSCs [31].

IV. CONCLUSIONS

We have proposed a novel architecture of solar cell tailored to concentrations factors exceeding 2000 suns. Its fundamental structure is formed by two identical subcells connected via a tunnel junction (TJ). This vertical-tunnel-junction (VTJ) solar cell offers a unique way to use high-efficiency III-V direct band-gap semiconductor materials. As a first approach, we have studied the output of a VTJ cell made up of GaAs up to 15000 suns using TCAD software. The cell has no shown any limitation caused by series resistance losses or Auger recombination for the concentrations investigated. Indeed, the efficiency grows linearly with the logarithmic increase of concentration from 22.5% at 1 sun to 28.4% at an extreme concentration of 15000 suns.

The VTJ structure offers two main advantages compared with current concentrator solar cells. On one hand, the almost total elimination of the series resistance losses allows to exploit the theoretical increase of the efficiency with light intensity. On the other hand, the use of direct-band-gap materials permits to develop multi-band-gap structures with a better absorption of the spectrum. The cell introduced here serves as a proof of concept of the design. Further work will be focused in improving the architecture and studying other materials to enhance the final efficiency.

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