SOLSTICE	Name of the PhD: **Paul OUBLON** Title of the PhD thesis: **Physics of solar cells operating under thermal stress** Dates (start/end): 10.2019 – 11.2022
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Context and objectives

Under concentration, solar cells are heating and thus may reach temperatures higher than 80 °C. Usually this heating must be mitigated as much as possible since photovoltaic conversion efficiency decreases with temperature [1]. For example, assuming a typical temperature coefficient for efficiency of -0.3%/°C, the 20% efficiency of a solar module in the Standard Test Conditions (25 °C) will get down to 16.7% at 80 °C. The complementary power fraction (83.3%) is almost fully heat that has no use whatsoever. Alternatively, in parellel to solar photovoltaic conversion, hybrid systems can take benefit of the solar energy which is converted into heat, either for heating a fluid for domestic use (PV-T), or for an indirect conversion into electricity via a turbine (PV-CSP), or for a direct conversion into electricity using a thermoelectric element (PV-TE). A thermodynamic analysis [2] shows that the limiting efficiency of such hybrid systems is strictly equivalent to that of solar photovoltaic and solar thermal converters taken separately (86.8%). Interestingly, even with a single-junction cell, the limiting efficiency of a hybrid solar-photovoltaic / solar-thermal converter is much higher (86.7%) than that of a solar photovoltaic converter only (40.7%) [2]. Nevertheless, specific challenges need to be overcome for such hybrid systems to reach the previously mentioned ideal performances. The photovoltaic cells will have to operate optimally at temperatures much larger than usual. Indeed, the temperature range targeted in the thesis, 150 to 200 °C, is that of high-temperature PV-T [3] and optimal PV-TE [4] systems. The objective of the thesis is then to analyze the physics of solar cells operating at such temperatures so as to be able to suggest suitable materials and structures for optimal operation in hybrid systems. It is worth having in mind that contrary to conventional cells, absorption of solar radiation will have to be maximized, even for photon energies below the bandgap. This unusual criterion is likely to have a strong impact on the optimal design.

Approach

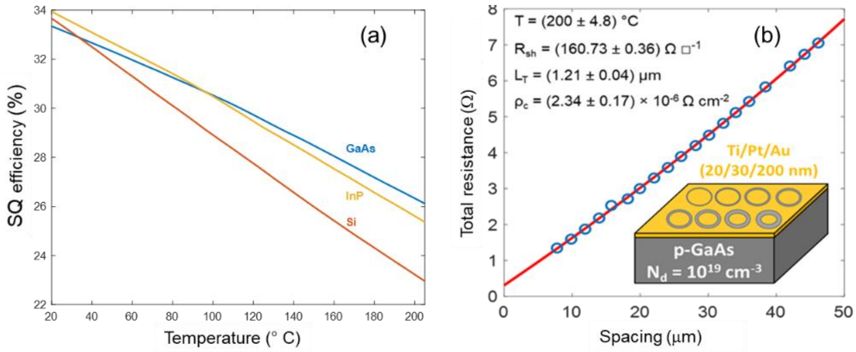
An examination of the state-of-the-art of solar cells operating under thermal stress [5] indicates that it is useless to analyze the temperature derivative (temperature coefficients) of figures of merit (conversion efficiency, short-circuit current, open-circuit voltage, fill factor) from 25 °C to 200 °C. The ultimate objective is to design solar cells operating optimally at high temperature instead of designing a cell operating optimally in the STC with minimal degradation of performances when temperature rises. Nevertheless, it makes sense starting from a well-known configuration (solar cell designed in the STC) in order to analyze the physics that will rule the conversion performances at higher temperature. Thus, the work program is as follows: 1/ fabrication of a solar cell designed for operating in the STC, using a wealth of published material; 2/ characterization of the cell when it operates at 150 to 200 °C, and analysis of the physics ruling its behavior at such temperatures (including a variety of physical parameters); 3/ proposal of rules for designing a cell operating optimally in a hybrid system at such high temperatures.
Calculations of the Shockley-Queisser (SQ) limit show that if crystalline silicon and gallium arsenide (GaAs) are equally optimal in the STC, GaAs is a much better and optimum choice at 150-200 °C. Moreover, GaAs-based photovoltaic cells are extremely mature and thus it is expected that the literature on the optical and electrical properties is abundant, even for temperatures much higher than 25 °C. TCAD 1D-simulations and pseudo-3D modeling [6] are used for designing a standard GaAs cell operating optimally in the STC. The stack of III-V material layers is fabricated using solid-source MBE (at LAAS, Toulouse). Conventional clean room processes are then used at IES for layer deposition (metallic contacts, anti-reflection coating) and etching (cap layer removal). Performances of the fabricated cells are characterized by measuring the I-V curves in the dark and under illumination, the spectral response, and the reflectance of the cells as a function of temperature, from 25 to 200 °C (mostly from 150 to 200 °C). An in-house heater and temperature controller were specially designed for these measurements. The physics explaining the differences in performances at 25 °C and in the range 150-200 °C are

analyzed using TCAD simulations with appropriate input physical properties. In particular, ellipsometry measurements are made (at Institut Pprime, Poitiers) with specifically fabricated samples for determining the optical properties of GaAs and AlGaAs at high temperature. Similarly, Hall mobility measurements and contact resistance (CTLM) measurements are made. In order to make a fair assessment, cell performances are rated with respect to the SQ limit values, which already include certain temperature effects. Changes in the different current and voltage losses from 25 to [150-200] °C are examined in detail so as to be able to propose modifications of the materials and cell structure in order to mitigate the losses.

Main results

After trial – error – correction iterations (two for MBE, more for processing), the latest fabricated cell has an efficiency of 14.9% at room temperature with a single layer (SiO_2) anti-reflection coating. This result is below the expectations (21%) for reasons that were anticipated and confirmed by EQE measurements, exhibiting low values at the smallest wavelengths due to recombinations taking place close to the surface, probably due to oxidation of the AlGaAs window layer. However, it is worth noting that the cell is used in the thesis as a testing sample for analyzing the physics, not for breaking records. The front contact grid design using a pseudo-3D model and processing techniques are validated since the series resistance is as low as 3 mΩ. While AuGeNi compound is used for the back-contact layer, CTLM measurements show that it is not appropriate for the top contact grid. Performances are improved with a stack of Ni, Pt and Au. A decrease of the specific contact resistance with temperature is experimentally observed. An in-depth analysis indicates that the reliability of the methodology for characterizing the contacts is strongly dependent on the number and quality of the samples. Therefore, a novel approach is proposed, which eliminates some usual simplifying assumptions and considers the propagation of measurement errors by using a Monte Carlo technique. Measurements of cell performances with appropriate physical properties (measurements for the complex refractive indices and mobilities) and corresponding simulations at higher temperatures are in progress. The multiple ongoing tasks will then converge and allow providing a clear view of the physics explaining changes in losses from 25 to 150-200 °C.

Illustration



(a) Shockley-Queisser efficiency for various semiconductors as a function of temperature.
(b) CTLM measurements at 200 °C for Ti/Pt/Au on p-GaAs.

Publications in scientific journals and international conferences

- Oublon P. et al. (2020, March). Physics of GaAs solar cells operating under thermal stress. In Les Houches School of Physics-Physics of Solar Cells: from basic principles to advanced characterization. Poster presentation.
- Oublon P. et al. (2021, January). Analysis of the performances of a conventional GaAs solar cell operating at up to 200° C. In Journées Nationales du Photovoltaïque 2020. Poster presentation (online).

References

[1] Dupré O. et al. (2017). Thermal behavior of photovoltaic devices. Physics and engineering, Springer.
[2] Luque A. & Martí A. (1999), Solar Energy Materials and Solar Cells, 58(2), 147-165.
[3] Lamnatou C. et al. (2021). Renewable and Sustainable Energy Reviews, 137, 110625.
[4] Huen P. & Daoud W. A. (2017). Renewable and Sustainable Energy Reviews, 72, 1295-1302.
[5] Vaillon R. et al. (2020). Cell Reports Physical Science, 1, 100267.
[6] Parola S. et al. (2019). Solar Energy Materials and Solar Cells, 200, 110042.