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Original Paper

Open source software verification of performance and efficiency of quantum well and quantum dot solar cells

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Abstract

The characterization of photovoltaic cells is important for verifying and improving their efficiency because this determines their electrical power generation capacity. This highly available secondary source depends on certain geographic factors such as solar irradiance and temperature. In this work, the authors present a performance characterization of quantum well and quantum dot photovoltaic cells using own developments in open-source software and open standards, with an accuracy of around 99.99%. This is possible based on the proposed physical model and associated equations, along with the parameters determined for each of the cells under study. The results obtained using open-source software is compared with those obtained using commercial software tools. The results obtained in the laboratory made it possible to characterize the performance and efficiency of various photovoltaic cells based on quantum well and quantum dot technology under different temperature and solar irradiance conditions.

Keywords: photovoltaic cell, quantum well solar cell, quantum dot solar cell, efficiency, fill factor

1. Introduction

The evolution of photovoltaic cell manufacturing technologies allows improving the efficiency in the generation of electrical energy, since among the advantages compared to other alternative energy sources, is because they are generally fixed systems, they do not require inputs or fuels to operate, only sunlight, which geographically is available in most cases a fraction of the day. This work shows the adaptation of computational tools in free software and under open standards developed by Núñez (2018) and Núñez (2019) but for quantum technology cells. Most of the tools used today for characterization require payment of the license or the source code cannot be modified, such as those used in France (2022), Tin (2024) and Xutao (2023). However, this work shows the results from developments in Scilab, considering the three-diode physical model proposed in Quai (2022), to determine the performance and efficiency of quantum well and quantum dot cells under specific operating conditions.

The physical model used allows determining the carrier current under the photovoltaic phenomenon by means of non-linear equations, which are solved using the methodology described in the next section. The coefficients of the equations have been determined through the most important parameters of any photovoltaic cell: short circuit current density (J_{sc}) or short circuit current (I_{sc}), open circuit voltage (V_{oc}), maximum current (I_{max}) and voltage (V_{max}), based on the specifications of the prototyping laboratories and the data analyzed in the Photonics Laboratory of the Cendit.

Once the equations are solved, the current-voltage (I-V) and power-voltage (P-V) curves of the photovoltaic cell under study are obtained and compared with the results obtained with Matlab and with the data from the manufacturer of the cell under study. The developed software system not only shows the curves indicated above, but also shows the conversion efficiency, quantum efficiency and the form factor (Fill Factor or FF) of the photovoltaic cells consulted in this research.

2. Method

For reach the goal of this work, the physical and mathematical modeling of quantum photovoltaic cell are defined in order to solve the equations using own scripts on Scilab.

2.1 Physical and mathematical model

Photovoltaic cells are manufactured from intrinsic and/or extrinsic semiconductor materials. The diode model represents the currents associated with the cell, which is generally made up of a junction of n-type material (with excess negative carriers) and p-type material (with excess positive carriers).

These currents are:

– The current due to the absorption of photons in the material, which generates electron-hole pairs, which are primarily responsible for the electric current they generate. In the physical model, this is represented by a current source.

– The currents associated with the depletion region and the quasi-neutral region that form part of the junction. In the physical model, these are represented by one or more diodes.

Although the use of the two-diode circuit in parallel continues to prevail in recent studies to model the behavior of photovoltaic cells, the three-diode model as in Quai (2022), shown in figure 1, allows to contemplate additional phenomena, due to the modification of the structure of the material such as the case of cells with quantum wells, in which between the junction of n and p material, thin layers called quantum wells are introduced, allowing the carriers to be confined and reducing the energy levels of the material, specifically the energy gap, thus facilitating the absorption of photons as shown in figure 2. Since the absorption depends on that energy level, and this in turn depends on the wavelength of the photons, by reducing the energy gap, photons of shorter wavelength can generate electron-hole pairs, which increases efficiency due to the increase in the electric current produced in the process.

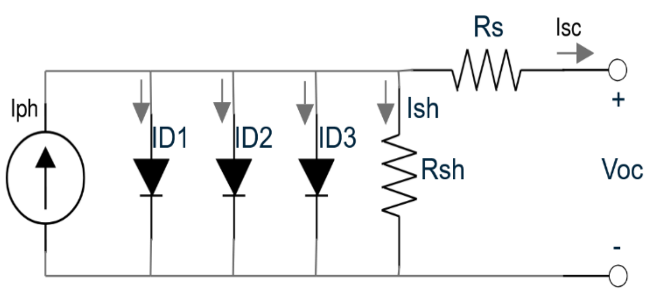

Figure 1. Physical model of a three-diode

Quantum-well photovoltaic cells are nanometric semiconductor structures that confine electrons in two dimensions, thus improving photovoltaic conversion efficiency compared to conventional cells. However, quantum dot technology cells are nanometric semiconductor structures that confine electrons in three dimensions, allowing for improved absorption, thereby increasing photovoltaic conversion efficiency compared to conventional cells, and even greater than that of quantum-well technology cells (see figures 2 and 3).

The equation that follows from circuit in figure 1 is shown in expression (1):

$$I_{sc} = I_{ph} - I_{D1} \left(e^{\frac{I_{sc} R_s}{n_1 V_t}} - 1 \right) - I_{D2} \left(e^{\frac{I_{sc} R_s}{n_2 V_t}} - 1 \right) - I_{D3} \left(e^{\frac{I_{sc} R_s}{n_1 V_t}} - 1 \right) - \frac{I_{sc} R_s}{R_{sh}} \quad (1)$$

Where: I_{sc} is the short-circuit current; I_{ph} is the photogeneration current; I_{D1}, I_{D2}, I_{D3}, are the diode currents (representing the currents in the depletion zone and in the quasi-neutral zones); R_s represents the ohmic losses at the ends due to the metal contacts of the cell and R_{sh} represents the ohmic losses due to the junction of the materials that make up the cell. Additionally, n_1, n_2, n_3, represent the ideality factors between the diodes. To solve this equation, the procedure described in Núñez (2018) and Núñez (2019) has been followed.

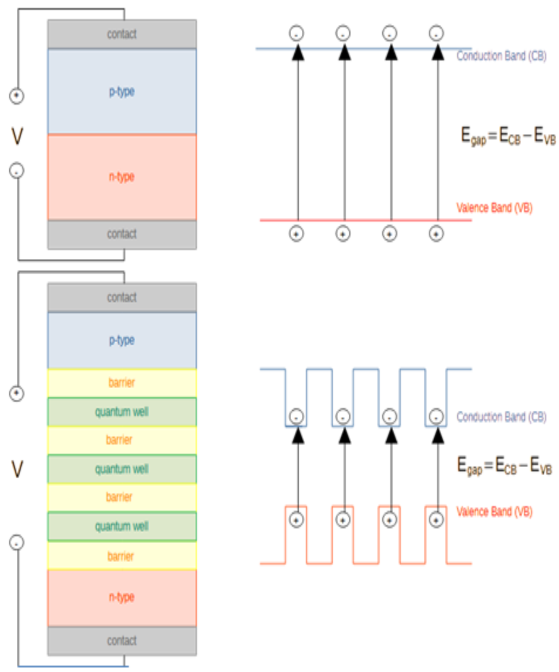

Figure 2. Difference between conventional cell and quantum well cell.

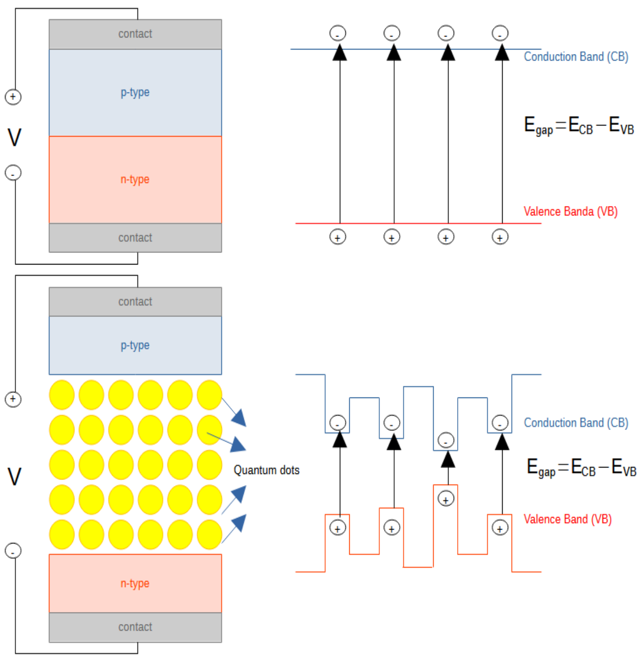

Figure 3. Difference between conventional cell and cell with quantum dots

Additionally, in order to obtain the quantum efficiency (η_{QE}) of the photovoltaic cells, the expression (2) was used:

$$\eta_{QE} = \frac{I_{ph}}{q} \frac{h\frac{c}{\lambda}}{P_{inc}} \quad (2)$$

Where: I_{ph} is the photogeneration current; q is the electron charge, h is the Planck constant, λ is the photon wavelength, P_{inc} is the incident photon power.

2.2 Software development

Scripts were developed in Scilab to solve the system of nonlinear equations constituted from the transcendental expression (1) and the parameters obtained for the photovoltaic cells under study. The I-V, P-V and FF curves generated in Scilab, under Standard Operating Conditions (STC), in this case 1,000 W/m2 and 25 °C, from the three-diode mathematical model and solved for each quantum photovoltaic cell under study, are shown in figures 4, 5, 6, 7, 8 and 9.

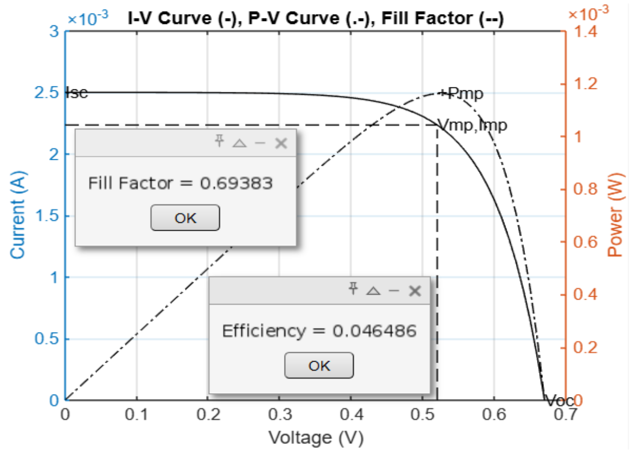

Figure 4. I-V and P-V curves of a quantum well cell developed in Thin (2024) under characterization using free software. Parameters: Voc = 0.67 V; Jsc = 10 mA/cm², Area = 0.25 cm², FF=69.35%.

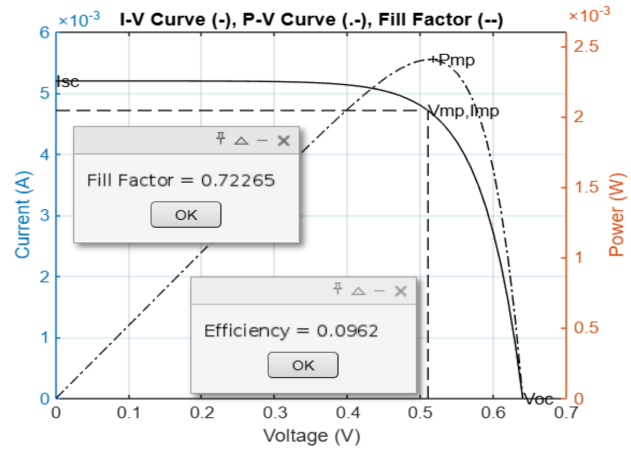

Figure 5. I-V and P-V curves of a quantum well cell developed by Xutao (2023) under characterization using free software. Parameters: Voc = 0.64 V; Jsc = 20.80 mA/cm², Area = 0.25 cm², FF=72.25%.

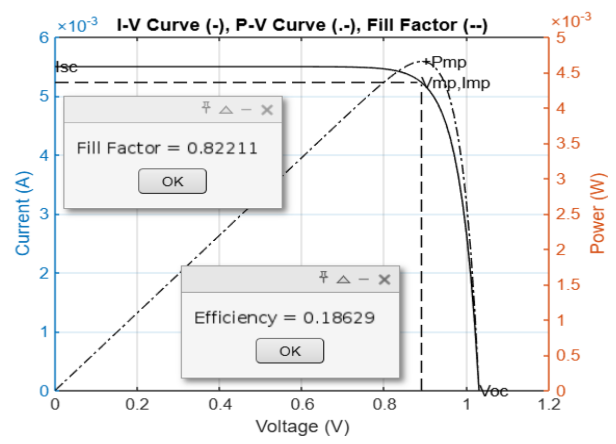

Figure 6. I-V and P-V curves of a quantum well cell developed in France (2023) under characterization using free software. Parameters: Voc = 1.03 V; Jsc = 22 mA/cm², Area = 0.25 cm², FF= 82%.

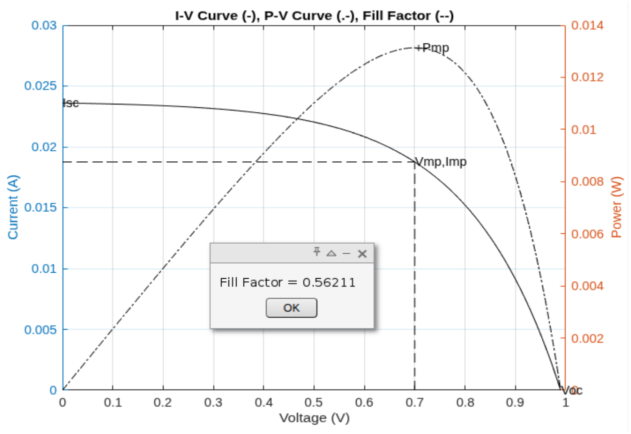

Figure 7. I-V and P-V curves of a quantum dot cell developed at Sawires (2025).

Parameters: Voc = 0.99 V; Isc = 23.6 mA, Area = 25.5 mm², FF = 56%.

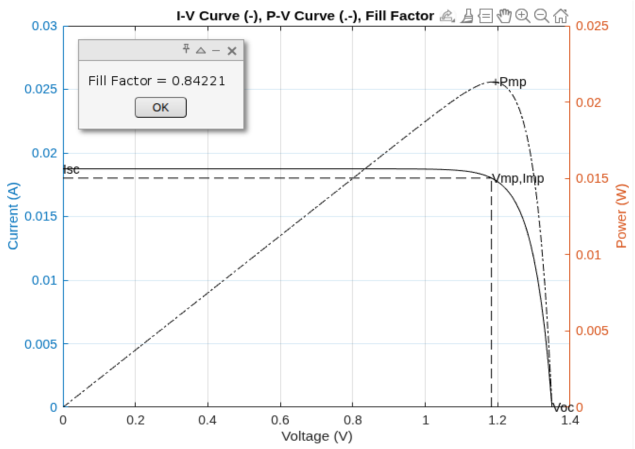

Figure 8. I-V and P-V curves of the quantum dot cell developed by Liu (2024).

Parameters: Voc = 1.35 V; Isc = 18.75 mA, Area = 0.049 cm², FF = 84%

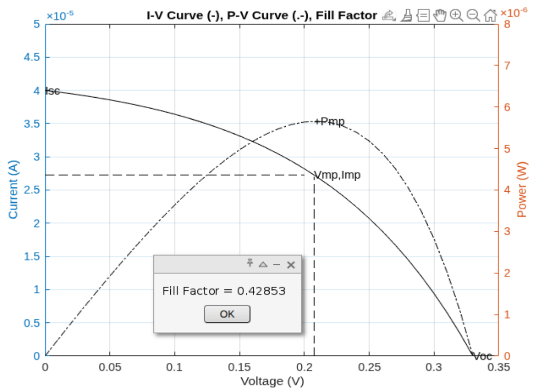

Figure 9. I-V and P-V curves of the quantum dot cell developed by Prasatsap (2020).

Parameters: Voc = 0.33 V; Isc = 0.04 mA/cm², Area = 0.25 cm², FF = 82%.

3. Results

I-V curves for the different photovoltaic cells studied are shown in Figures 10, 11 and 12. The comparison between the curve obtained in the manufacturer's laboratory (solar simulator) and the results in Matlab and Scilab under Standard Operating Conditions or STC (1000 W/m2, 25 °C) is shown. Since the three curves obtained for the cell studied are not distinguishable, it was necessary to include an enlargement in each case in order to estimate the deviation from the values obtained in the original laboratory.

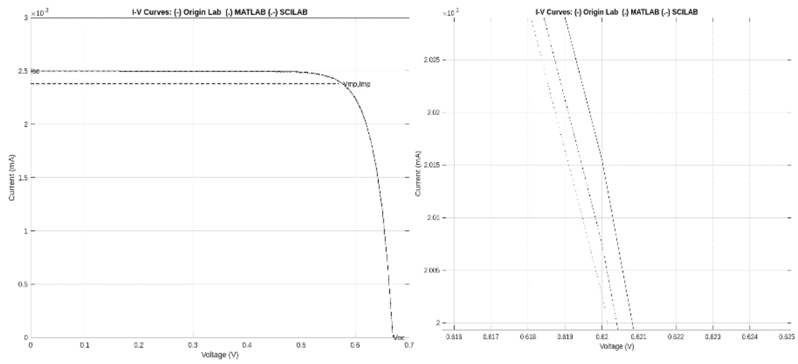

Figure 10. I-V curves of a quantum well cell developed in Thin (2024) and characterized using free software. Left figure shows the complete curve. Right figure is enlarged for detail.

Parameters: Voc = 0.67 V; Jsc = 10 mA/cm², Area = 0.25 cm², FF = 69.35%.

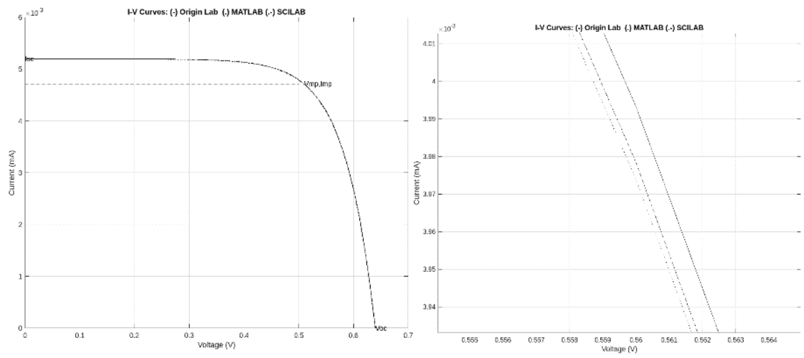

Figure 11. I-V curves of a quantum well cell developed in Xutao (2023) under characterization using open source software. Left figure shows the complete curve. Right figure is enlarged for detail.

Parameters: Voc = 0.64 V; Jsc = 20.80 mA/cm², Area = 0.25 cm², FF = 72.25%

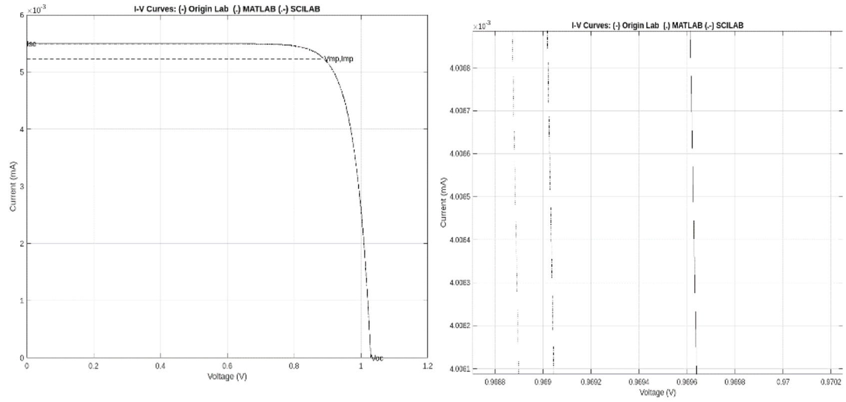

Figure 12. Quantum well cell curves developed in France (2022) under characterization using open source software. Left figure shows the complete curve. Right figure is enlarged for detail.

Parameters: Voc = 1.03 V; Jsc = 22 mA/cm², Area = 0.25 cm², FF = 82%.

The I-V curves for various levels of solar irradiation and temperature were obtained by programming the Scilab Xcos module (see figure 13) for the photovoltaic cells under study, with the results shown in figures 14, 15, 16 and 17.

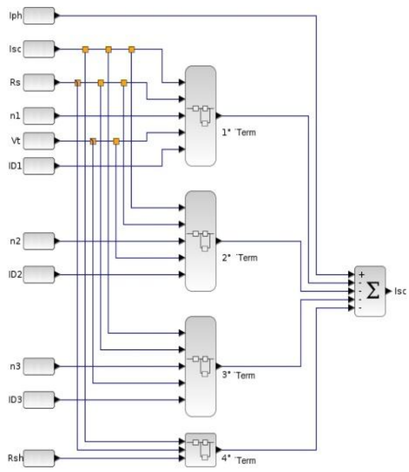

Figure 13. Block diagram to solve the transcendental equation (1) using Xcos of Scilab.

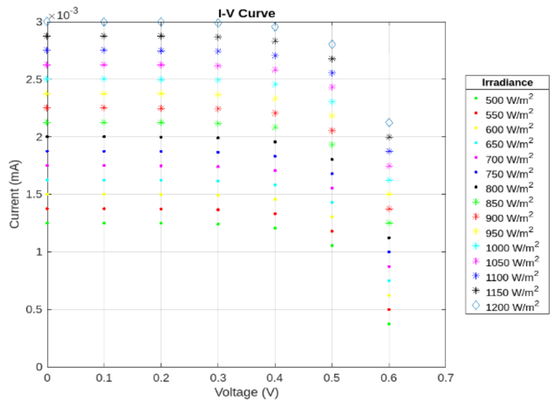

Figure 14. I-V curves for different irradiance conditions of cell developed in Tin (2024).

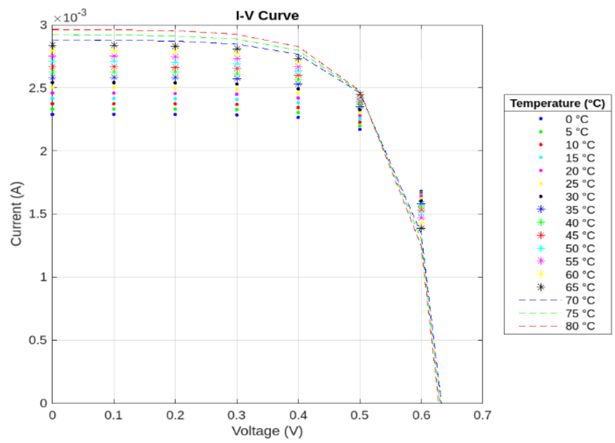

Figure 15. I-V curves for different temperature conditions of cell developed in Tin (2024).

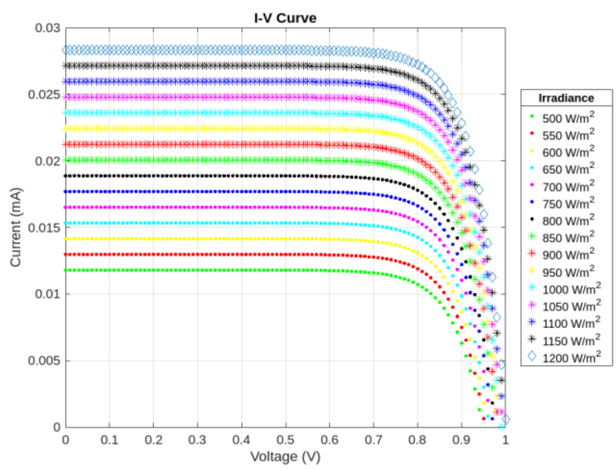

Figure 16. I-V curves of a quantum dot cell developed at Sawires (2025) with different levels of solar irradiance.

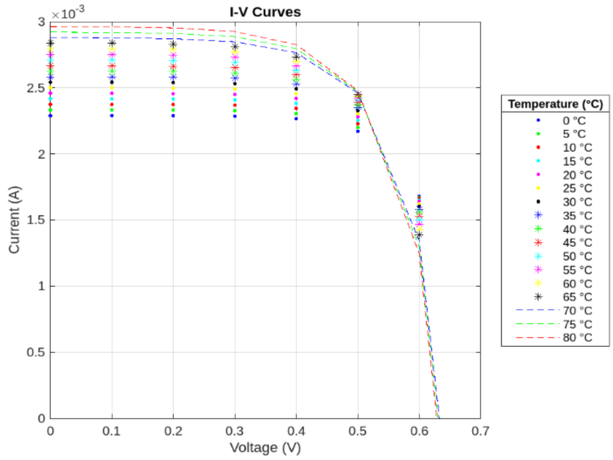

Figure 17. I-V curves of a quantum dot cell developed at Sawires (2025) with different levels of temperature.

4. Discussion

I-V and P-V curves were modeled using scripts developed by the authors in Scilab for quantum well and quantum dot photovoltaic cells manufactured in the laboratories indicated in the references, with a high accuracy. The fill factor and quantum efficiency were also calculated using proprietary Scilab developments. These computational tools allow for estimating the behavior of the photovoltaic cells studied under different solar irradiance and temperature conditions.

5. Conclusion

The computational tools presented in this work, based on free software and public license platforms, can model the behavior of quantum well and quantum dot photovoltaic cells with 99.99% accuracy, thus presenting it as an alternative to privative license software solutions.

Acknowledgements

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References

France, M. et al. (2022). *Triple-junction solar cells with 39.5% terrestrial and 34.2% space efficiency enabled by thick quantum well superlattices.* Joule 6, 1121–1135, 2022. https://doi.org/10.1016/j.joule.2022.04.024

Liu, Y. et al. (2024). *A three-dimensional quantum dot network stabilizes perovskite solids via hydrostatic strain*. Matter, vol. 7, 1° edition, 2024, pag. 107-122. https://doi.org/10.1016/j.matt.2023.10.015

Núñez-Ramírez, H. L. et al. (2018). *Highly Accurate and Inexpensive Computational Tool for Improving Photovoltaic Arrays Performance and Efficiency Measures.* Proceedings of the IEEE 2018 Open Innovations Conference (OI), Johannesburg 2018 https://doi.org/10.1109/OI.2018.8535899

Núñez-Ramírez, H. L. et al. (2019). *Low-Cost and Accurate Computational System for Efficiency Measures over Photovoltaic Arrays.* Adv. Sci. Technol. Eng. Syst. J. 4(5), 39-45 (2019). https://doi.org/10.25046/aj040505

Prasatsap, U. et al. (2020). *Equivalent Circuit Parameters of Hybrid Quantum-Dot Solar Cells*. Materials Today: Proceedings, vol. 23, part 4, 2020, pag. 767-776. https://doi.org/10.1016/j.matpr.2019.12.272.

Quai, M. et al. (2022). *"Accurate Three-Diode model estimation of Photovoltaic modules using a novel circle search algorithm.* Ain Shams Engineering Journal de Science Direct, 13, 2022. https://doi.org/10.1016/j.asej.2022.101824.

Sawires, E. et al. (2024). Exploring various Integration Methods of carbon quantum dots in CsPbCl3 perovskite solar cells for enhanced power conversion efficiency. J. Mater Sci: Mater Electron 35, 800 (2024) https://doi.org/10.1007/s10854-024-12464-0

Tin, H. et al. (2024). *Analysis of Third-Generation Solar Cell Design with Physics of Semiconductor.* Journal of Novel Engineering Science and Technology, vol. 3, No. 02 (2024). https://doi.org/10.56741/jnest.v3i02.525

Xutao, Y. et al. (2023). *High Efficient Solar Cell Based on Heterostructure Constructed by Graphene and GaAs Quantum Wells.* Advanced Science, 2023, 10, 2204058. https://advanced.onlinelibrary.wiley.com/doi/pdf/10.1002/advs.202204058