



MODELING AND SIMULATION OF TEMPERATURE EFFECTS ON INGaP/InGaAs/Ge TRIPLE-JUNCTION SOLAR CELLS WITH PYAMS

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ABSTRACT

Multi-junction solar cells, particularly those based on *III-V* semiconductor materials; achieve high conversion efficiencies by employing multiple *P-N* junctions with different band gap energies to absorb distinct portions of the solar spectrum. Among them, the *InGaP/InGaAs/Ge* triple-junction photovoltaic cell stands out as a benchmark for efficiency. However, temperature variations strongly influence the electrical and thermal behavior of these subcells, often leading to performance degradation. In this work, we employ PyAMS to model and simulate the thermal response of *InGaP/InGaAs/Ge* solar subcells under varying temperature conditions. The developed model is validated against experimental data, ensuring accurate representation of the current-voltage (*I-V*) and power-voltage (*P-V*) characteristics. Key performance indicators—including short-circuit current density (*J_{sc}*), open-circuit voltage (*V_{oc}*), fill factor (*FF*), and overall efficiency (η) are analyzed as functions of temperature. Our results demonstrate that while *J_{sc}* remains almost unaffected by temperature, *V_{oc}* decreases significantly beyond 60°C under concentrated illumination (10 Suns). This drop in *V_{oc}* strongly impacts both *FF* and η , highlighting the critical role of thermal management. The findings of this study provide useful guidelines for the design of cooling strategies in triple-junction solar cells, thereby improving their long-term performance, reliability, and integration into high-efficiency photovoltaic systems.



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I. INTRODUCTION

III-V multi-junction solar cells are photovoltaic devices composed of multiple *P-N* junctions fabricated from different semiconductor materials with distinct band gap energies. Each junction absorbs and converts a specific portion of the solar spectrum into electrical energy, thereby enabling high conversion efficiency [1], [2]. The triple-junction photovoltaic (*TJ*) cell, consisting of Indium Gallium Phosphide (*InGaP*, top cell), Indium Gallium Arsenide (*InGaAs*, middle cell), and Germanium (*Ge*, bottom cell), is widely recognized as one of the most efficient architectures. However, like all electronic devices, the performance of these subcells is strongly influenced by temperature variations. Understanding their thermal behavior is thus crucial for optimizing performance and ensuring long-term reliability [3-6].

Realistic modeling of photovoltaic (*PV*) devices and accurate extraction of equivalent circuit parameters are of great importance for both design and operation, as they provide the foundation for future optimization strategies [7-14]. Thermal modeling, in particular, facilitates the development of efficient cooling systems for solar panels, helping to maintain high efficiency under concentrated illumination [15-18]. Among available simulation tools, PyAMS (Python for Analog and Mixed Signals) [19-22] has emerged as a powerful framework for studying the behavior of solar cells once their analytical equivalent circuits are established. PyAMS allows accurate representation of multi-junction devices while incorporating temperature dependence, making it possible to analyze critical performance parameters such as short-circuit current density (*J_{sc}*), open-circuit voltage (*V_{oc}*), fill factor (*FF*), and overall efficiency (η) [9].

This study focuses on investigating the performance of InGaP/InGaAs/Ge subcells under varying temperature conditions, with the objective of identifying the maximum allowable operating temperature that ensures optimal performance without degradation. To achieve this, the PyAMS software [22] is employed to develop a detailed model, which is then validated against experimental data. Subsequently, we analyze J_{sc} , V_{oc} , FF , and η as functions of temperature to determine the cooling requirements for stable operation.

The main contributions of this work can be summarized as follows:

1. Development of a PyAMS-based electrical and thermal model for InGaP/InGaAs/Ge triple-junction solar cells, incorporating temperature-dependent parameters such as saturation current, thermal voltage, and bandgap energy.
2. Validation against experimental data, confirming the accuracy of the model in reproducing I - V and P - V characteristics under different thermal and illumination conditions.
3. A comprehensive thermal performance analysis, showing that J_{sc} remains nearly stable with temperature, whereas V_{oc} decreases sharply above 60 °C under concentrated illumination.
4. Identification of the thermal operating limit of the Ge subcell (~60 °C at 10 Suns), which determines the overall system stability and directly affects fill factor and efficiency.
5. Providing practical design insights, offering guidelines for the integration of effective cooling strategies to enhance the long-term reliability of high-efficiency photovoltaic systems.

By addressing these aspects, this work advances beyond previous studies [3], [8], [9], [11], [13] by providing a validated PyAMS-based framework that simultaneously captures electrical and thermal behavior, while explicitly identifying practical cooling requirements for InGaP/InGaAs/Ge triple-junction solar cells.

II. SOLAR CELL MODELING

Modeling is a crucial step in understanding the electrical and thermal behavior of photovoltaic (PV) devices. In this section, we first discuss the equivalent circuit representation of a single-junction solar cell, which serves as the foundation for many studies in the literature. Then, we extend this representation into the PyAMS environment, highlighting its advantages in incorporating temperature-dependent relations and preparing the ground for triple-junction modeling [9], [23].

II.1 CLASSICAL EQUIVALENT CIRCUIT

As shown in Figure 1(a), the conventional single-diode equivalent circuit has been widely employed in the literature [9],[23],[24]. It consists of:

- A photocurrent source (I_{ph}), representing the current generated by photon absorption,
- A diode (D), describing the nonlinear behavior of the P-N junction according to the Shockley equation,
- A shunt resistance (R_{sh}), modeling leakage and parasitic currents across the junction, and
- A series resistance (R_s), accounting for ohmic losses in the semiconductor and electrical contacts.

This representation has proven effective in reproducing the current–voltage (I - V) behavior of solar cells. However, its classical formulation does not easily allow the integration of temperature-dependent effects, which are crucial for accurately modeling InGaP, InGaAs, and Ge subcells.

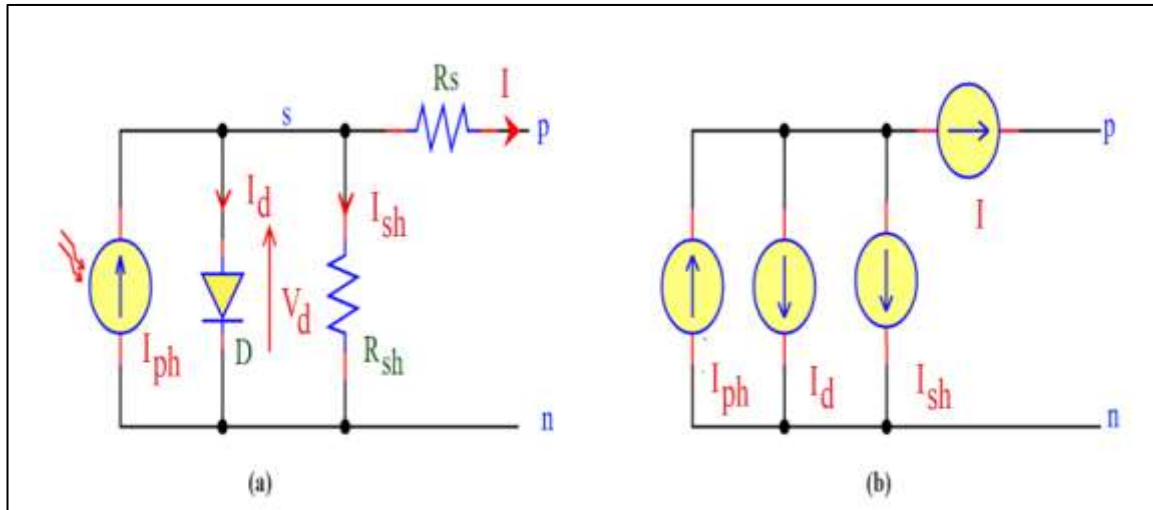


Figure 1: Equivalent electrical circuit of the solar cellM: (a) using discrete electronic components (b) using an independent current source as a function of voltage and parameters.

Source: Authors, (2026).

The photocurrent (I_{ph}) of the PV cell (Figure 1) depends on both the incident radiation and the temperature, as described by equation (1) [5], [23], [25], [26].

$$I_{ph} = [I_{sc} + K_i (T - 298)] \frac{Sun}{1000} \quad (1)$$

Where I_{sc} represents the short-circuit current, K_i is a coefficient ($0.0017A/^{\circ}C$), T denotes the temperature, and Sun stands for solar irradiance (W/m^2). The I_d in Figure 1 is the current flowing through the diode D . The current is expressed by the following equation:

$$I_d = I_s \left(\exp\left(\frac{V_d}{V_t}\right) - 1 \right) \quad (2)$$

For I_s [24], [27], [28], [29]:

$$I_s(T) = I_{so} \left(\frac{T}{300} \right)^3 \exp\left(\left(\frac{T}{300} - 1\right) \frac{E_g}{V_t}\right) \quad (3)$$

The saturation current in the diodes of types InGaP, InGaAs, and Ge is expressed by the following formula [9], [23], [30]:

$$I_s(T) = I_{so} \left(\frac{T}{300} \right)^{\frac{3+\gamma}{2}} \exp\left(\left(\frac{T}{300} - 1\right) \frac{E_g}{V_t}\right) \quad (4)$$

For V_t :

$$V_t = n \frac{KT}{q}. \quad (5)$$

In equations (2), (3), and (4), V_d represents the voltage applied across the diode, I_s is the reverse saturation current of the diode, q is the charge of an electron, V_t is the thermal voltage, K is Boltzmann's constant, T is the junction temperature, n is the ideality factor of the diode, I_{so} is the initial reverse saturation current of the diode, γ is a constant and E_g is the band gap energy of the semiconductor. The relationship between band gap energy and temperature is described by equation (6) below [8], [9], [10], [31]:

$$E_g(T) = E_g(0) - \frac{\alpha T^2}{T + \beta} \quad (6)$$

where α and β are a constant. The current in the resistor R_s or R_{sh} (Figure 1) is expressed by ohm's law:

$$I_{sh} = \frac{V_d}{R_{sh}} \quad (7)$$

and:

$$I = \frac{V_s}{R_s} \quad (8)$$

For V_s is the voltage applied across the resistor R_s . The open circuit voltage, V_{oc} , is the maximum voltage available from a solar cell, and this occurs at zero current. An equation for V_{oc} is found by setting the net current equal to zero in the solar cell equation to give [3]:

$$V_{oc} = \frac{nKT}{q} \ln\left(\frac{I_{sc}}{I_s} + 1\right) \quad (9)$$

II.2 PYAMS-BASED CURRENT-SOURCE MODEL

To overcome these limitations, we reformulate the equivalent circuit into a PyAMS-based current-source model, illustrated in Figure. 1(b). In this representation, each element of the solar cell is implemented as an independent current source defined as a function of voltage and physical parameters. This novel reformulation enables seamless integration of temperature-dependent relations into the model equations. The implementation in PyAMS is shown in Figure 2, where:

- The photocurrent (I_{ph}) is calculated as a function of irradiance, short-circuit current (I_{sc}), and temperature,
- The diode current (I_d) follows the Shockley relation with a temperature-dependent reverse saturation current $I_s(T)$,
- The shunt current (I_{sh}) is derived from the voltage across R_{sh} , and
- The series resistance contribution is expressed as an additional current component (I).

These currents are combined according to Kirchhoff's Current Law (KCL) within the `analog(self)` function in PyAMS. Temperature-dependent parameters such as the thermal voltage (V_t), the bandgap energy $E_g(T)$ (Varshni equation), and the reverse saturation current $I_s(T)$ are precomputed in the `start(self)` function before the simulation. Figure 3 presents the symbolic representation (symbol) of the single-junction solar cell in PyAMS. This symbol provides a reusable and modular block that can be directly inserted into larger circuit simulations, such as those involving triple-junction configurations.

```

# The single-junction solar cell solar cell model
class JunctionSolarCell(model):
    .....
    .....

    def start(self):
        # Thermal voltage at T (Eq. 3)
        self.Vt=vth(self.T)
        # Bandgap energy (eq.6)
        self.Eg=self.Ego-(self.α*self.T*self.T/(self.β+self.T))
        # Saturation current (Eq. 4)
        self.Is=self.Iso*pow(self.T, (self.γ+3)/2)*exp(-self.Eg/self.Vt)

    def analog(self):
        # Photocurrent equation (Eq. 1)
        self.Iph+= (self.Isc+self.Ki*(self.T-300))*self.Sun/self.Si
        # Diode equation (Eq. 2)
        self.Id+=self.Is*(explim(self.Vd/(self.n*self.Vt))-1)
        # Shunt resistor equation-high hom (Rsh) (Eq. 7)
        self.Ish+=self.Vd/self.Rsh
        # Series resistor equation-low hom (Rs) (Eq. 8)
        self.I+=self.Vs/self.Rs

```

Figure 2: The PyAMS model of a single-junction solar cell.
Source: Authors, (2026).

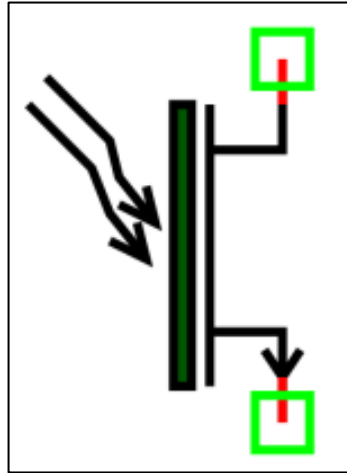


Figure 3: Single-junction solar cell symbol design by PyAMS.
Source: Authors, (2026).

II.3 CONTRIBUTION OF THE PYAMS REPRESENTATION

While Figure 1(a) reflects the standard baseline model used in most prior works, Figures 1(b), 2, and 3 illustrate the novelty of this study. By translating the conventional circuit into a PyAMS current-source framework, we enable:

- Direct integration of thermal effects, including $I_s(T)$ and $E_g(T)$,
- Modularity, as each current component is explicitly modeled and can be modified or extended, and
- Flexibility for multi-junction extension, since the single-junction block can be replicated and connected in series to form the InGaP/InGaAs/Ge triple-junction solar cell.

This approach bridges the gap between purely mathematical models and practical circuit-level simulations, offering a more accurate and flexible framework for analyzing both the electrical and thermal behaviors of high-efficiency photovoltaic devices.

II.4 MODELING OF TRIPL- JUNCTION SOLAR CELL

Building upon the single-junction framework, the structure of a triple-junction solar cell (TJSC) is illustrated in Figure 5(a). It consists of three subcells stacked in series:

- The top cell (InGaP) with a bandgap of approximately 1.9 eV,
- The middle cell (InGaAs) with a bandgap of 1.4 eV, and
- The bottom cell (Ge) with a bandgap of 0.6 eV [32-35].

This configuration is carefully designed so that each subcell absorbs a specific portion of the solar spectrum (Figure 4, right). The high bandgap top and middle subcells absorb shorter wavelengths, while the low bandgap Ge bottom cell absorbs longer wavelengths. This spectral division allows triple-junction devices to achieve significantly higher conversion efficiencies compared to single-junction solar cells [9]. The electrical model of the InGaP/InGaAs/Ge TJSC can be derived by connecting three single-junction submodels in series, each represented by its PyAMS-based equivalent circuit. This is shown in Figure 5(a), where the triple-junction equivalent circuit is constructed from three diode-based subcells. In the PyAMS implementation (Figure 5(b)), each subcell is replaced by its corresponding PyAMS model (developed in Section II.2). The series connection ensures that the same current flows through all three subcells, while the output voltage of the TJSC is the sum of the voltages of the individual cells. However, the lowest-performing subcell (typically the Ge bottom cell) determines the overall current, making it the limiting factor in device efficiency. By adopting this PyAMS-based modular approach, the TJSC model:

1. Accurately captures the spectral and electrical characteristics of each subcell,
2. Allows for the integration of temperature-dependent effects ($I_s(T)$, $E_g(T)$) for all three junctions, and
3. Provides a scalable framework that can be extended to simulate more advanced multi-junction architectures.

Thus, the novelty of our work lies in transforming the traditional equivalent circuit representation into a flexible PyAMS model, where each junction is explicitly defined and thermally coupled, enabling detailed analysis of the electrical–thermal behavior of the InGaP/InGaAs/Ge triple-junction solar cell.

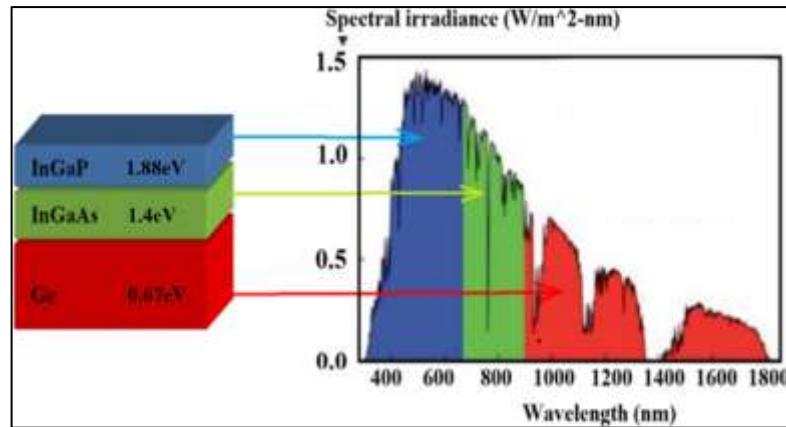


Figure 4: Triple junction solar cell: (a) Structure of a triple junction cell InGaP/InGaAs/Ge (b) The solar radiation spectrum versus wavelength and its useful spectrum portion.

Source: Authors, (2026).

This combination of materials was chosen because the P-N junction of each material would convert certain wavelengths of sunlight into electrical energy (Figure 5.b). Multi-junction solar cells with different band gap energies have high conversion efficiency [9]. The electrical modelling of the InGaP/InGaAs/Ge triple-junction photovoltaic cell can be implemented by the circuit shown in Figure 5(a) structure of circuit by triple circuit it presented in ref [8-11], where each sub-cell is represented by an independent single photovoltaic cell, in a way that gives the three cells the ability to be connected in series with decreasing gaps from top to bottom Figure 5(a) below shows the model for a triple junction solar cell, the PyAMS model of the triple-junction solar cell is developed based on this equivalent circuit, by replacing cell by equivalent Figure 5(b).

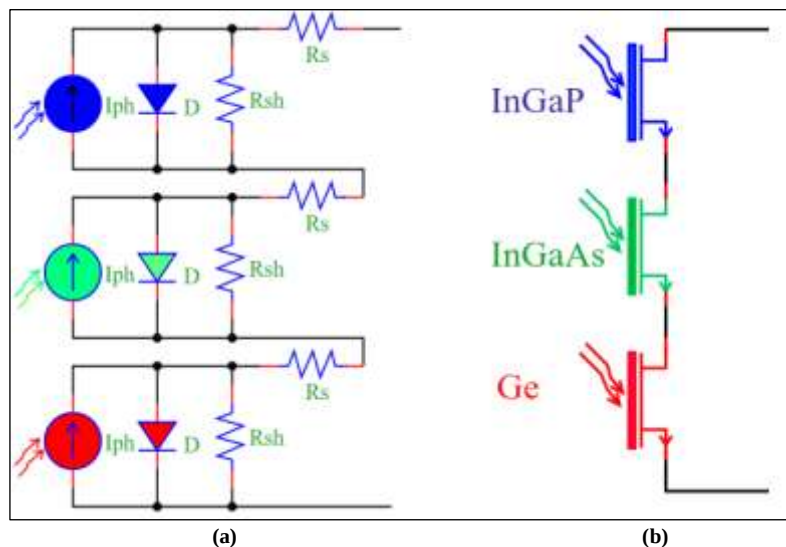


Figure 5: The model of triple-junction Solar Cell: (a) Equivalent circuits (b) The PyAMS circuit.

Source: Authors, (2026).

III. SIMULATION RESULTS AND DISCUSSION

To validate the proposed PyAMS-based model, simulations were performed for the InGaP/InGaAs/Ge triple-junction solar cell and compared with published experimental data. The equivalent circuit of the three-junction device (Figure 5(b)) was implemented in PyAMS using the parameter values listed in Table 1, which were extracted under standard test conditions (air temperature of 27 °C and irradiance of 1000 W/m²).

Table 1: The parameters of the three junctions.

Parameter	Junction (InGaP)	Junction (InGaAs)	Junction (Ge)
Short circuit current I_{SC}	18mA	15.5mA	34mA
Bandgap energy E_g	1.89eV	1.40eV	0.683eV
Series resistance R_s	0.2190 Ω	0.0219 Ω	0.0219 Ω
Shunt resistance R_{sh}	600k Ω	600k Ω	600k Ω
Alpha(α)	7.50 10 ⁻⁴	5.58 10 ⁻⁴	4.77 10 ⁻⁴
Beta(β)	372	204	235
Gamma(γ)	2	2	2
Ideality factor (n)	1.97	1.75	1.96
Saturation current I_o	2.44 10 ⁻¹⁵	3.39 10 ⁻¹¹	25 10 ⁻⁵

Source: Authors, (2026).

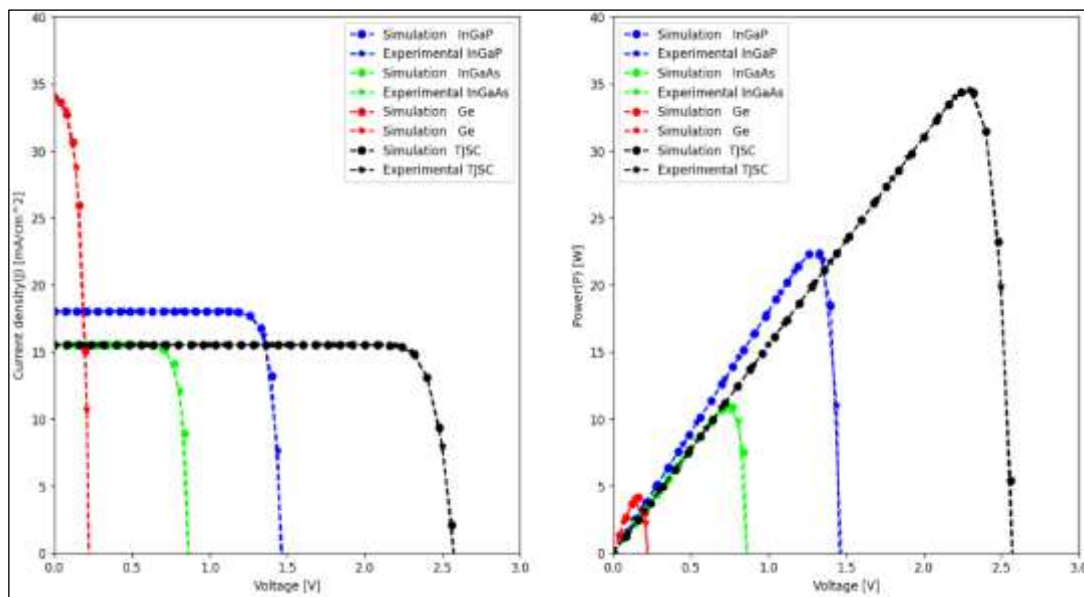


Figure 6: Validation of I - V (a) and P - V (b) characteristics of the individual bottom, middle and top subcells.

Source: Authors, (2026).

III.1 MODEL VALIDATION AGAINST EXPERIMENTAL DATA

The simulated current-voltage (I - V) and power-voltage (P - V) curves of the individual subcells (InGaP, InGaAs, Ge) and the full TJSC are shown in Figure 6. A close agreement is observed between simulated and experimental characteristics [32], confirming the accuracy of the PyAMS model. Quantitative performance metrics are summarized in Table 2, where the deviation between simulation and experiment is negligible (<1%). For example, the simulated short-circuit current density (J_{sc}) of the InGaP subcell (17.99 mA/cm²) is nearly identical to the experimental value (18.08 mA/cm²). Similar consistency is found for V_{oc} , FF , and η across all subcells and the complete TJSC.

Table 2: Performance parameters of simulated multijunction cell compared with experimental.

Junction	Result	$J_{sc}(\text{mA}/\text{cm}^2)$	$V_{oc}(\text{V})$	$P_{max}(\text{mW})$	$FF(\%)$	$\eta(\%)$
InGaP	Simulation	17.99	1.50	23.18	85.37	23.18
	Experimental	18.08	1.49	22.9	84.90	23.00
InGaAs	Simulation	15.50	0.89	11.19	80.66	11.19
	Experimental	15.63	0.88	11.14	80.50	11.14
Ge	Simulation	33.99	0.24	4.59	54.31	4.59
	Experimental	34.23	0.25	4.57	54.17	4.57
TJSC	Simulation	15.76	2.60	34.50	84.15	34.90
	Experimental	15.79	2.58	34.33	84.06	34.33

Source: Authors, (2026).

This validation demonstrates that the PyAMS-based approach is capable of reproducing the performance of III–V multi-junction devices with high accuracy, comparable to experimental measurements.

III.2 TEMPERATURE-DEPENDENT ANALYSIS

To determine the maximum temperature tolerance of the sub-cells and the operating temperature efficiency of the triple-junction solar cell, we conducted simulations across a temperature range of 0°C to 80°C under concentrated illumination of 1000 Suns. The performance of each subcell analyzed as a function of temperature using PyAMS. The temperature limit deduced by observing the point at which the open circuit voltage dropped to almost zero.

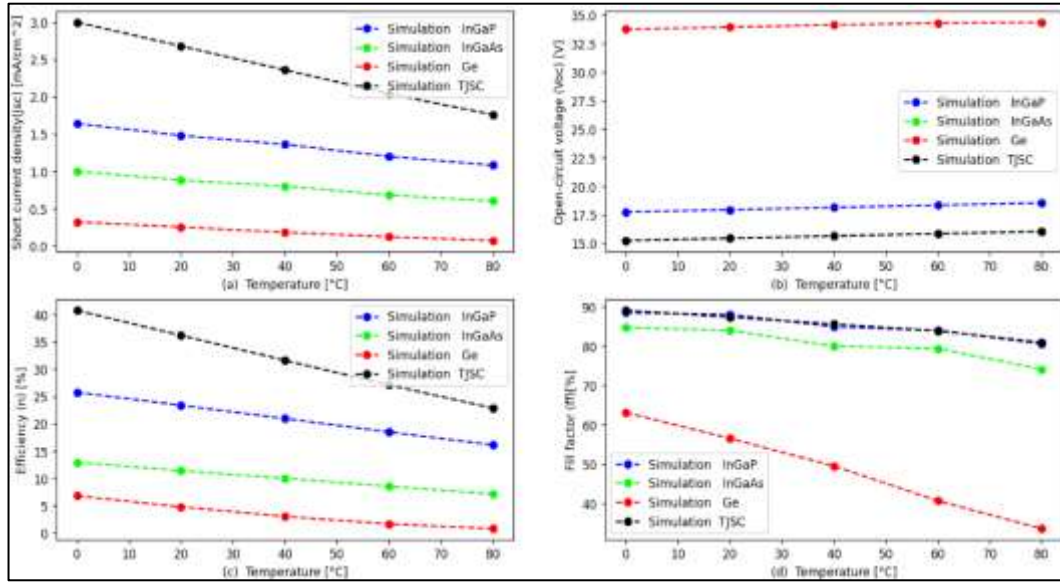


Figure 7: Effect of temperature on open-circuit voltage (a), current density (b), efficiency (c), and fill factor (d) for InGaP, InGaAs, Ge, and TJSC.

Source: Authors, (2026).

Figure 7(a) illustrates the short-circuit current density as a function of temperature of the three sub-cells and tandem cell. Interestingly, we observe no significant effect of temperature on the short-circuit current. In Figure 7(b), the open-circuit voltage plotted against temperature for the three sub-cells and the tandem cell. It is evident that the open-circuit voltage decreases significantly with increasing temperature. This decrease reflected in the slope, which diminishes across all concentration levels. Notably, for the Ge subcell, the open-circuit voltage approaches zero, resulting in a collapse of the current-voltage (I - V) curves for temperatures exceeding 60°C, whereas the upper and middle sub-cells can withstand temperatures exceeding 60°C. This decrease in open-circuit voltage significantly affects the fill factor and overall efficiency of the solar cell, as depicted in Fig. 7(c) and Figure 7(d). Consequently, the temperature tolerance range for this cell is limited to 0°C to 80°C. Figure 8 demonstrates this for the Ge subcell when exposed to various levels of solar radiation, showing that the open-circuit voltage completely disappears at a temperature of 60°C under concentrated illumination of 10 Suns.

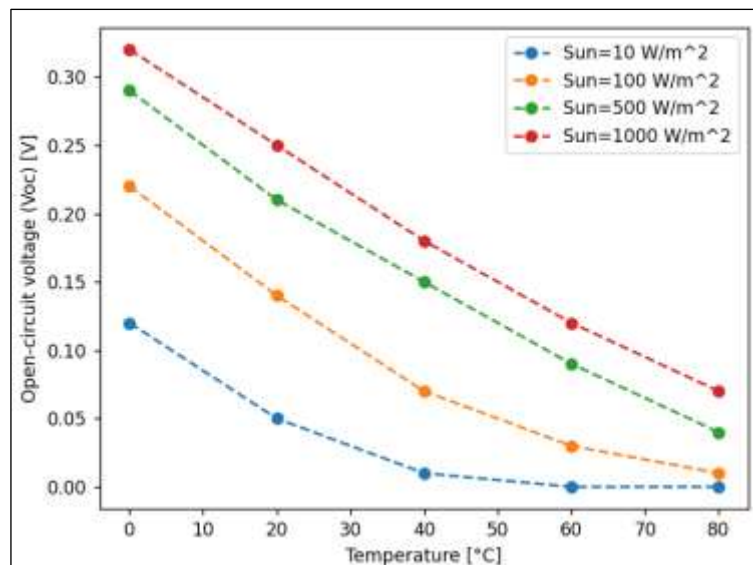


Figure 8: Effect of temperature and concentrated sunlight on open circuit voltage V_{oc} for bottom subcell.

Source: Authors, (2026).

After creating the InGaP/InGaAs/Ge equivalent model and comparing the experimental results in [32] with the same method of calculating the effect of temperature in [13], we obtained the same characteristics. Finally, we can conclude that the temperature limit is 60°C when exposed to concentrated illumination of 10 Suns, necessitating a cooling system to prevent the degradation of the InGaP/InGaAs/Ge MJSC.

III.3 DISCUSSION AND COMPARISON WITH PREVIOUS WORKS

The results highlight that while the upper InGaP and InGaAs subcells can tolerate elevated temperatures, the Ge subcell dictates the maximum operating limit of the TJSC. The identified threshold of ~60 °C under 10 Suns is consistent with experimental findings reported by Ota [9] and Djermane [13], but our model extends these works by providing a validated **PyAMS framework** that integrates both electrical and thermal effects. Unlike conventional SPICE-based or purely mathematical models, the PyAMS implementation offers two key advantages:

1. Explicit thermal coupling, by incorporating $I_s(T)$, V_t , and $E_g(T)$ directly into the circuit-level model.
2. Modularity and scalability, enabling straightforward extension to multi-junction configurations while maintaining consistency with experimental behavior.

III.4 KEY FINDINGS

From this analysis, the following points can be emphasized:

- The PyAMS model reproduces experimental I–V and P–V data with high accuracy.
- Temperature has negligible influence on J_{sc} but a strong negative impact on V_{oc} .
- The Ge bottom cell defines the thermal operating limit (~60 °C), beyond which FF and η rapidly degrade.
- Effective thermal management is essential to maintain stable performance of InGaP/InGaAs/Ge TJSCs under concentrated illumination.

IV. CONCLUSION

In this study, we developed and validated a PyAMS-based model for InGaP/InGaAs/Ge triple-junction solar cells. By reformulating the classical equivalent circuit into a modular current-source representation, the model successfully integrates temperature-dependent parameters such as saturation current, thermal voltage, and bandgap energy. Validation against experimental data confirmed that the PyAMS framework reproduces the I–V and P–V characteristics of individual subcells and the complete TJSC with high accuracy. Through systematic thermal analysis, we demonstrated that:

- The short-circuit current density (J_{sc}) remains nearly unaffected by temperature variations.
- The open-circuit voltage (V_{oc}) decreases significantly with increasing temperature, with the Ge subcell approaching zero V_{oc} at ~60 °C.
- This drop in V_{oc} strongly impacts the fill factor (FF) and overall efficiency (η), establishing the Ge subcell as the limiting factor in high-temperature operation.

These findings emphasize the critical role of thermal management in maintaining the stability and performance of multi-junction solar cells under concentrated illumination. The proposed PyAMS modeling framework not only provides accurate reproduction of experimental behavior but also offers a scalable and flexible tool for extending the analysis to advanced photovoltaic architectures. Future work will focus on integrating spectral effects, dynamic cooling strategies, and exploring the application of the PyAMS framework to other multi-junction material systems, thereby enhancing its potential as a versatile platform for photovoltaic device design and optimization.

V. AUTHOR'S CONTRIBUTION

Conceptualization: Fathi Dhiabi and Okba Benelmir.

Methodology: Fathi Dhiabi.

Investigation: Fathi Dhiabi and Okba Benelmir.

Discussion of results: Fathi Dhiabi and Okba Benelmir.

Writing – Original Draft: Fathi Dhiabi.

Writing – Review and Editing: Fathi Dhiabi.

Resources: Fathi Dhiabi.

Supervision: Fathi Dhiabi.

Approval of the final text: Fathi Dhiabi and Okba Benelmir.

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