

Simulation of Temperature Effect on the Photovoltaic Performance of a Perovskite/Silicon Tandem Solar Cell Using SCAPS-1D

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محاكاة تأثير درجة الحرارة على الأداء الكهروضوئي لخلاية شمسية ترادفية من البيروفسكايت/السيليكون باستخدام SCAPS-1D

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Abstract:

Temperature is a major environmental factor affecting solar cell performance. Therefore, evaluating solar cell behavior under varying temperatures is crucial for understanding their performance under real-world operating conditions. This is especially important for tandem solar cells, where the interaction between different semiconductor layers can influence the overall thermal response of the device. In this study, a two-terminal tandem solar cell with an FTO/TiO₂/n-MASnI₃/C-SiOx(n)/c-Si(p)/c-Si(p⁺) architecture was simulated using SCAPS-1D software. Before investigating the effect of temperature, the layer thickness and doping concentrations were numerically optimized to achieve a high-performance reference configuration. The optimized device achieved a power conversion efficiency of 27.60% at 300 K, with an open-circuit voltage of 0.7788 V, a short-circuit current density of 41.84 mA/cm², and a fill factor of 84.69%. Subsequently, the optimized configuration was simulated at temperatures ranging from 300 to 360 K in 10 K increments. The changes in current-voltage and recombination characteristics were analyzed, and linear regression was used to process the temperature-dependent photovoltaic parameters and calculate the temperature coefficients. This provided a quantitative measurement of the rate and direction of performance change with temperature, as well as an assessment of the linearity of these changes. The results showed that J_{sc} increased slightly, while V_{oc} and FF gradually decreased, resulting in a PCE of 23.47% at 360 K. The temperature coefficients for J_{sc}, V_{oc}, FF, and PCE were +0.0038% °C⁻¹, -1.47 mV °C⁻¹, -0.07055% °C⁻¹, and -0.2488% °C⁻¹, respectively. These results identify voltage-related parameters as the primary contributor to the simulated device's low performance.

Long-term stability and performance measurements, is recommended to assess the reliability of the simulated thermal response and the device's long-term performance sustainability.

Keywords: Tin-based perovskite; tandem solar cell; Performance optimization; Temperature coefficients; Linear regression

المخلص:

تعد درجة الحرارة من العوامل البيئية الرئيسية التي تؤثر في أداء الخلايا الشمسية، ولذلك فإن تقييم سلوك الخلايا الشمسية عند تغير درجات الحرارة يعد مهما لفهم طبيعة أدائها في ظروف التشغيل الفعلية. وتزداد أهمية ذلك في الخلايا الشمسية

الترادفية، حيث يمكن للتفاعل بين طبقات أشباه الموصلات المختلفة أن يؤثر في الاستجابة الحرارية للجهاز ككل. وفي هذه الدراسة، تمت محاكاة خلية شمسية ترادفية ذات البنية $\text{FTO}/\text{TiO}_2/\text{n-MASnI}_3/\text{C-SiOx(n)}/\text{c-Si(p)}/\text{c-Si(p}^+)\text{}$ باستخدام برنامج SCAPS-1D. وقبل دراسة تأثير درجة الحرارة، تم تحسين سمك الطبقات وتركيزات التطعيم عددياً للوصول إلى تكوين مرجعي ذي أداء مرتفع. وحقق الجهاز المحسن كفاءة تحويل قدرة بلغت 27.60% عند 300 كلفن، مع جهد دائرة مفتوحة قدره 0.7788 فولت، وكثافة تيار دائرة قصيرة بلغت 41.84 مللي أمبير/سم²، وعامل تعبئة قدره 84.69%. بعد ذلك، تمت محاكاة التكوين المحسن عند درجات حرارة تراوحت من 300 إلى 360 كلفن بزيادة قدرها 10 كلفن، مع تحليل التغيرات في خصائص التيار-الجهد وخصائص إعادة التركيب، واستخدام الانحدار الخطي لمعالجة المعلمات الكهروضوئية المعتمدة على درجة الحرارة وحساب معاملات درجة الحرارة، تم توفير قياسا كميا لمعدل واتجاه تغير الأداء مع درجة الحرارة. بالإضافة إلى تقييم مدى خطية هذه التغيرات. أظهرت النتائج أن J_{sc} ازداد بصورة طفيفة، في حين انخفض كل من V_{oc} و FF تدريجياً، مما أدى إلى انخفاض PCE إلى 23.47% عند 360 كلفن. وبلغت معاملات درجة الحرارة لكل من J_{sc} و V_{oc} و FF و PCE مقدار $+0.0038\% / ^\circ\text{C}^{-1}$ ، و -1.47% مللي فولت $^\circ\text{C}^{-1}$ ، و $-0.07055\% / ^\circ\text{C}^{-1}$ ، و $-0.2488\% / ^\circ\text{C}^{-1}$ ، على التوالي. وتحدد هذه النتائج المعلمات المرتبطة بالجهد باعتبارها المساهم الرئيسي في انخفاض الأداء للجهاز المحاكى. نوصي بإجراء قياسات للاستقرار والأداء على المدى الطويل، لتقييم موثوقية الاستجابة الحرارية للمحاكاة واستمرارية أداء الجهاز.

الكلمات المفتاحية: البيروفسكايت القائم على القصدير؛ الخلية الشمسية الترادفية؛ تحسين الأداء؛ معاملات درجة الحرارة؛ الانحدار الخطي.

Introduction

The efficiency of a single-junction solar cell is determined by the proportion of the solar spectrum that can be efficiently converted into electrical energy. Shockley-Queser analysis showed that an ideal single-junction solar cell has a theoretical efficiency limit of approximately 30%, with an ideal band gap of about 1.1 eV (Shockley & Queser, 1961). This limitation is primarily related to spectral losses, including the absorption of photons with energies higher than the band gap of the absorber material and the non-absorption of photons with energies lower than that. Tandem solar cells can reduce these losses by combining absorber materials with different band gaps, allowing for the utilization of a wider portion of the solar spectrum. Consequently, perovskite/silicon tandem cells have garnered significant attention, as the optical properties of the perovskite top absorber complement the spectral response of crystalline silicon.

Most high-performance perovskite solar cells contain lead, raising environmental concerns regarding toxicity during long-term use (Li et al, 2023). Consequently, research has focused on developing lead-free perovskite materials capable of delivering competitive performance. In this context, methylammonium tin iodide ($\text{CH}_3\text{NH}_3\text{SnI}_3$ or MASnI_3) has attracted significant interest; experimental measurements indicate a bandgap of approximately 1.33 eV, making it suitable for absorbing high-energy photons while allowing crystalline silicon to absorb the lower-energy portion of the spectrum (Huang et al., 2019). Experimental studies have demonstrated the photovoltaic potential of MASnI_3 , although factors such as tin ion (Sn^{2+}) oxidation, defect formation, and non-radiative recombination remain critical influences on its electrical performance (Hao et al., 2014; Noel et al., 2014).

The performance of tandem solar cells depends on a range of factors and electrical properties; layer thickness influences light absorption and charge carrier accumulation, while doping concentrations affect carrier density, electric fields, and charge transport. Additionally, defect density and recombination characteristics impact the extraction of photo-generated charge carriers and the achievable voltage. Consequently, numerical simulation serves as a valuable tool for investigating these parameters and selecting an optimal device configuration prior to analyzing performance under various operating conditions. Previous numerical studies have indicated that efficiencies exceeding 27% can be achieved with MASnI_3/Si -based structures. In this context, Yadav and Kumar (2024) investigated the effects of various structural and physical parameters on the MASnI_3/Si heterojunction, achieving a simulated efficiency of 27.2%. Similarly, Abuafyiah and AbuZriba (2025) reported a simulated efficiency of 27.35% for a structure comprising the following layers: $\text{ITO}/\text{ZnO}/\text{MASnI}_3/\text{C-SiOx(n)}/\text{P-Si}/\text{P}^+-\text{Si}$. These studies highlight the promising potential of MASnI_3/Si configurations and underscore the importance of controlling the device's structural and electrical parameters.

However, performance recorded at a reference temperature does not fully describe the operational behavior of a photovoltaic device, as temperature fluctuations affect semiconductor properties and internal electrical processes. These changes impact key photovoltaic parameters in distinct ways: short-circuit current (J_{sc}) is primarily linked to the generation and collection of photo-generated charge carriers, whereas open-circuit voltage (V_{oc}) is strongly influenced by carrier concentration and recombination processes. The fill factor depends on the shape of the current-voltage (J - V) curve and is thus affected by the combined influence of transport and recombination mechanisms. Consequently, the temperature dependence of overall efficiency is determined by the simultaneous

variation of these parameters rather than by a single physical process. Temperature effects are particularly significant in tandem structures, as different semiconductor regions respond to temperature in varying ways; changes in the properties of the light-absorbing material can affect the generated current, while temperature-dependent recombination processes can alter the voltage and the shape of the J-V curve. Experimental and numerical studies have demonstrated that the temperature coefficients of photovoltaic (PV) cells depend on material properties, device architecture, interfaces, illumination conditions, and the temperature range (Paudyal & Imenes, 2021; Babics et al., 2023).

Consequently, separately evaluating short-circuit current density (J_{sc}), open-circuit voltage (V_{oc}), fill factor (FF), and power conversion efficiency (PCE) provides more precise information regarding temperature-induced performance changes than evaluating efficiency alone. These changes are quantified using temperature coefficients, which can be derived from the slope of the relationship between the photovoltaic parameter and temperature; linear regression offers a direct method to determine this slope within a specific temperature range. The resulting coefficient describes the magnitude and direction of the temperature dependence, while the coefficient of determination (R^2) indicates how accurately the linear model represents the simulated data. This approach has been employed in studies examining the impact of temperature on photovoltaic systems to determine the temperature sensitivity of electrical parameters (Paudyal & Imenes, 2021). Applying this same analysis to key photovoltaic parameters in a simulated tandem device allows for a standardized comparison of their temperature sensitivities.

Furthermore, recombination current characteristics provide insights into the electrical processes underlying temperature-induced changes in device performance. Examining recombination current as a function of voltage can reveal the voltage range where recombination processes become most pronounced. This is particularly useful for interpreting changes in open-circuit voltage (V_{oc}) and fill factor (FF), given the close link between these parameters and the recombination and charge-transport processes occurring within the device.

This study aims to investigate the photovoltaic performance of a tandem solar cell with an FTO/ TiO_2 /n-MASnI₃/C-SiOx(n)/c-Si(p)/c-Si(p⁺) architecture using SCAPS-1D software, focusing on the effect of temperature. The study specifically examines the impact of temperature on J_{sc} , V_{oc} , FF, and PCE characteristics. Furthermore, the study aims to determine the temperature coefficients for the main photovoltaic parameters using linear regression and to investigate their linearity and temperature dependence using the coefficient of determination (R^2), in order to provide a quantitative assessment of the thermal sensitivity of the proposed device and to understand the effect of temperature on its performance.

Material and methods

Device Structure and Numerical Optimization

A two-terminal (2T) tandem solar cell was designed and simulated using SCAPS-1D software. The selected device structure is: FTO/ TiO_2 /n-MASnI₃/C-SiOx(n)/c-Si(p)/c-Si(p⁺). The structure was defined as a single device within SCAPS-1D, enabling the evaluation of the photovoltaic response of the complete tandem configuration based on simulated current density-voltage characteristics. Figure 1 illustrates the device structure and the sequence of the simulated layers.

Fluorine-doped tin oxide (FTO) was used as the transparent conductive oxide (TCO), chosen for its high optical transparency and excellent electrical conductivity. Titanium dioxide (TiO_2) was selected as the electron-transport layer (ETL) to facilitate electron transport from the perovskite absorber material to the front contact; it allows only electrons to pass toward the electrode while blocking holes, thereby limiting recombination and enhancing cell efficiency. An n-MASnI₃ layer was selected as the absorber for the top section of the tandem solar cell. A crystalline silicon oxide C-SiOx(n) layer was inserted between the MASnI₃ and crystalline silicon regions to minimize recombination, while the c-Si(p) and c-Si(p⁺) layers constituted the p-type silicon region and the heavily doped back region, respectively. The layer sequence remained constant throughout the optimization process.

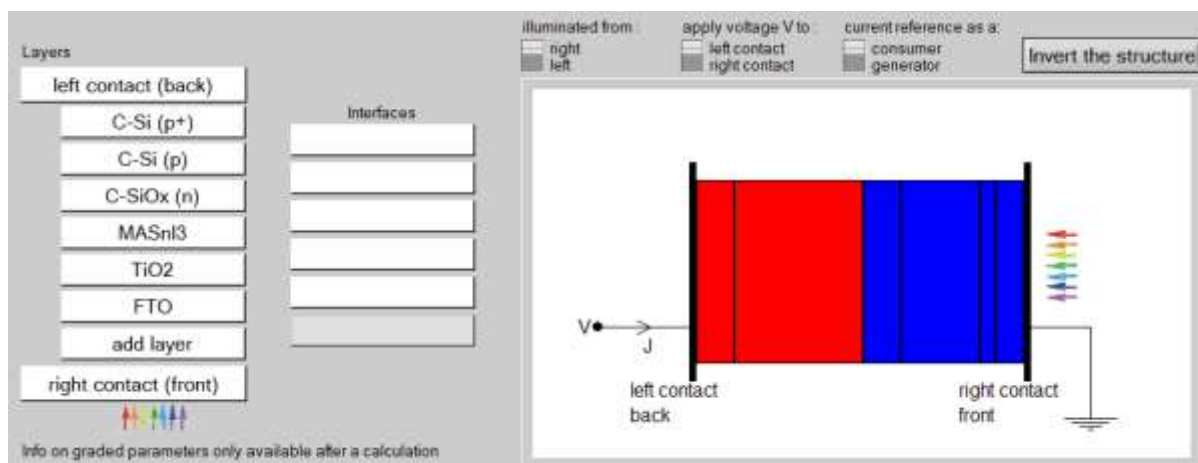


Figure 1: Structure of the proposed MASnI₃/Si tandem solar cell using SCAPS-1D

The electrical and material properties of the individual layers were defined in SCAPS-1D. The parameters included the layer thickness, band-gap energy, electron affinity, relative permittivity, effective density of states in the conduction and valence bands, electron and hole mobilities, doping concentration, and defect density. The initial values of the material parameters were selected from previously reported studies and used as the starting parameters for the simulations. The corresponding literature sources are given in Table 1.

The device parameters were then adjusted numerically while maintaining the selected device architecture. The thicknesses of the individual layers were varied to determine suitable values for the final configuration. Selected donor and acceptor concentrations were also adjusted during the optimization. In the final model, MASnI₃ and C-SiOx were treated as n-type layers, whereas the crystalline-silicon layers were defined as c-Si(p) and c-Si(p⁺).

The defect densities were also included in the simulations to account for bulk recombination within the individual layers. The photovoltaic performance obtained from each selected parameter set was evaluated from the simulated J–V characteristics. The optimization was continued by adjusting the selected thicknesses and doping concentrations while keeping the layer sequence unchanged. The complete set of parameters used for the optimized device at 300 K is presented in Table 1. The listed values include both literature-based material properties and parameters that were adjusted numerically during the optimization process. The optimized layer thicknesses are therefore model-derived values rather than values directly taken from the cited studies.

Table 1. Input parameters of the optimized device structure used in the SCAPS-1D simulations at 300 K.

	FTO	TiO ₂	MASnI ₃	C-SiOx (n)	C-Si (p)	C-Si (p ⁺)
Thickness (μm)/ optimized	0.150	0.080	0.420	0.200	0.680	0.200
Band gap (ev)	3.50	3.26	1.33	1.124	1.124	1.124
Electron Affinity (ev)	4.00	4.00	4.17	3.90	4.05	3.90
Relative permittivity	9.00	10.0	10.0	11.9	11.9	11.9
CB effective density (cm ⁻³)	2.2×10^{18}	2.0×10^{17}	1.0×10^{19}	2.8×10^{19}	2.8×10^{19}	2.84×10^{19}
VB effective density (cm ⁻³)	1.8×10^{19}	6.0×10^{17}	1.0×10^{18}	2.6×10^{19}	2.6×10^{19}	2.68×10^{19}

Electron mobility (cm^2/vs)	20.0	100	1.6	1.215×10^3	1.041×10^3	1.215×10^3
Hole mobility (cm^2/vs)	10.0	25.0	1.6	4.43×10^2	4.21×10^2	4.43×10^2
Donor Density (cm^{-3})	2.0×10^{19}	1.0×10^{18}	1.0×10^{19}	1.0×10^{18}	0	0
Acceptor Density (cm^{-3})	0	0	0	0	1.0×10^{18}	9.0×10^{20}
Defect Density (cm^{-3})	1.0×10^{15}	1.0×10^{15}	1.0×10^{14}	1.0×10^{14}	1.0×10^{14}	1.0×10^{14}
References	Basyoni et al. (2021), Moinuddin et al. (2024)	Islam et al. (2021)	Huang et al. (2019), Moinuddin et al. (2024)	Ramli et al. (2017), Moinuddin et al. (2024)	Ramli et al. (2017)	Ramli et al. (2017)

Temperature-dependent photovoltaic simulation

The optimized device was used as the reference configuration for the temperature-dependent simulations. The device structure and the input parameters listed in Table 1 were kept unchanged, while the operating temperature was varied from 300 to 360 K in steps of 10 K. The same illumination and simulation conditions were maintained throughout the temperature analysis.

At each temperature, the SCAPS-1D calculation was repeated to obtain the current density–voltage (J–V) characteristics of the device. The short-circuit current density (J_{sc}), open-circuit voltage (V_{oc}), fill factor (FF), and power conversion efficiency (PCE) were extracted from each calculated J–V characteristic. The recombination current density curve was examined at each temperature to follow its variation with increasing temperature. The values obtained directly from the simulations are summarized in Table 2.

Table 2: Simulated photovoltaic parameters of the optimized tandem cell at different temperatures.

Temperature (K)	J_{sc} (mA/cm^2)	V_{oc} (v)	FF (%)	PCE (%)
300	41.841398	0.7788	84.69	27.60
310	41.859460	0.7634	84.14	26.89
320	41.876296	0.7479	83.58	26.17
330	41.892061	0.7325	82.99	25.46
340	41.906880	0.7172	82.36	24.75
350	41.924842	0.7056	81.74	24.18
360	41.937984	0.6900	81.12	23.47

The temperature coefficient was used to quantify the temperature dependence of the photovoltaic parameters. A temperature coefficient describes the change in a photovoltaic parameter with temperature and can be expressed in normalized form as:

$$TC_X = \frac{1}{X_{ref}} \frac{dX}{dT}$$

where (X) is the parameter under consideration, (X_{ref}) is its value at the reference temperature, and (dX/dT) represents the slope of the variation of (X) with temperature (Paudyal & Imenes, 2021). A reference temperature of 300 K was used in the present analysis. The values of J_{sc} , V_{oc} , FF, and PCE obtained at 300, 310, 320, 330, 340, 350, and 360 K were fitted using linear regression. The slope of each linear fit was used to determine dX/dT . For J_{sc} , FF, and PCE, the resulting coefficients were normalized to their respective values at 300 K and expressed in %/°C. For V_{oc} , the temperature coefficient was expressed directly as the change in voltage with temperature in mV/°C. The calculated temperature coefficients are presented and discussed in the Results and Discussion section.

Results and discussion

Device optimization and photovoltaic performance

The optimization process yielded observations consistent with the physics of photovoltaic cells; specifically, treating the $MASnI_3$ material as an n-type semiconductor resulted in a notable improvement in calculated efficiency. Simulating changes in the doping concentration which affects charge carrier concentration and modifies distribution near the interfaces led to enhanced performance, as these changes facilitate charge carrier transport and extraction, thereby reducing losses associated with carrier recombination and inefficient charge transport. Additionally, Simulations regarding the adjustment of device layer thicknesses also highlighted the necessity of striking an appropriate balance between light absorption and charge carrier accumulation. While increasing the absorber thickness can enhance photon absorption and carrier generation, excessive thickness extends the carrier transport distance, potentially increasing recombination losses. Consequently, the optimal thickness was determined through a numerical optimization process based on the simulated device response. The complete set of parameters used for the optimized device is listed in Table 1 within the "Materials and Methods" section. Subsequently, the performance of the optimized device was evaluated at 300 K; Figure 2 illustrates the resulting current-voltage characteristics, and the corresponding photovoltaic cell parameters are discussed below.

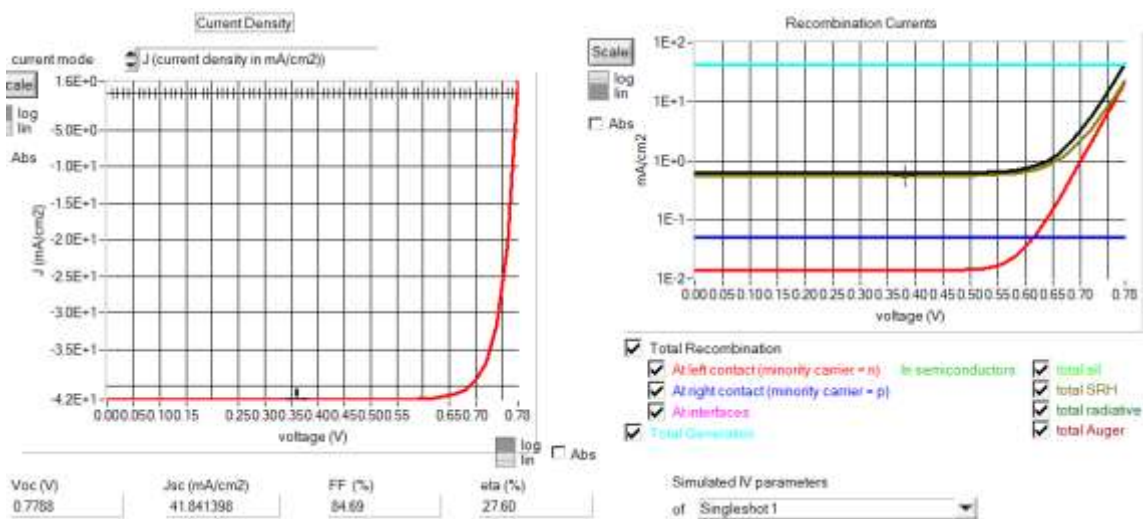


Figure 2: Simulated J-V characteristic and Recombination currents of the optimized cell at 300 K

The optimized device achieved a V_{oc} of 0.7788 V, a J_{sc} of 41.84 mA cm^{-2} , an FF of 84.69%, and a PCE of 27.60% at 300 K. The J-V and recombination current characteristics are shown in Figure 2, while the corresponding photovoltaic parameters are listed in Table 2. The J-V curve remains close to the short-circuit current over most of the voltage range and then decreases rapidly as the voltage approaches V_{oc} . The relatively square shape of the curve is consistent with the high FF obtained for the device.

The recombination-current plot shows that the total generation current remains nearly constant over most of the voltage range, whereas the recombination currents remain relatively low at lower voltages and increase at higher voltages, particularly near V_{oc} . Previous numerical studies have reported high efficiencies for $MASnI_3/\text{Si}$ -based solar cells, reaching 27.20% in the study by Yadav and Kumar (2024) and 27.35% in the study by Abuafyiah and AbuZriba (2025). Additionally, the study by Moinuddin et al. (2024) achieved a peak efficiency of 23.41% using

FTO as the TCO layer. These results confirm that the 27.60% efficiency achieved by the current model represents a high level of simulated performance for MASnI₃/Si solar cells.

Effect of temperature on the photovoltaic performance

The effect of temperature on the optimized device was studied, ranging from 300 to 360 K in 10 K increments. The current-voltage (J-V) characteristics and recombination currents at the studied temperatures are shown in Figures 3 to 7, respectively.

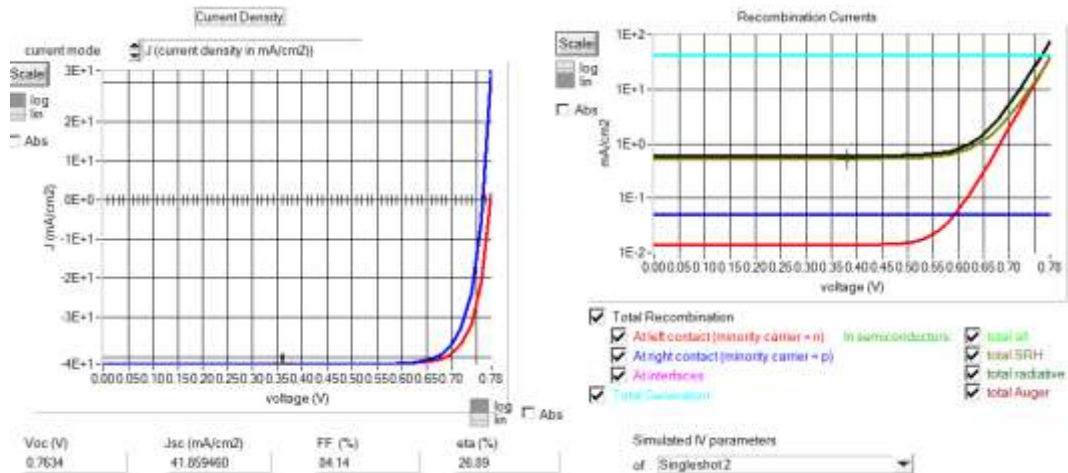


Figure 3: Simulated J-V characteristic and Recombination currents of the optimized cell at 310 K

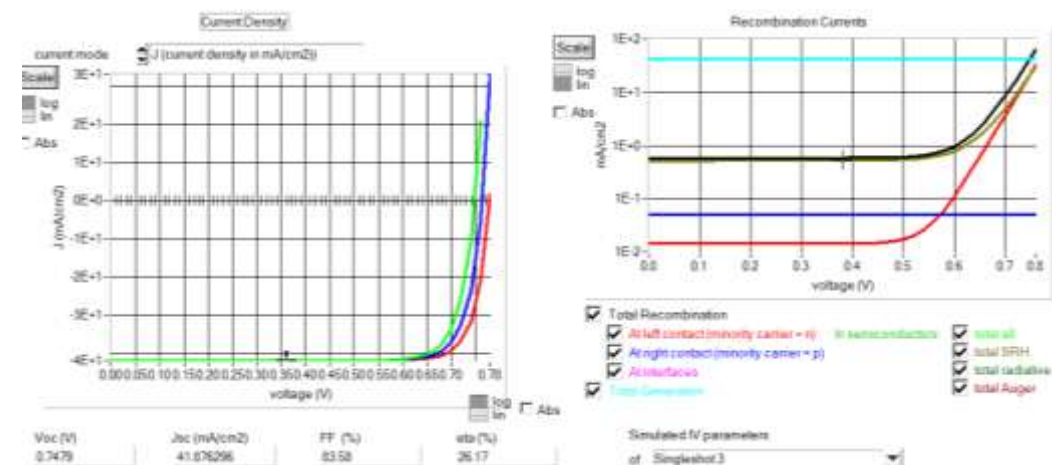


Figure 4: Simulated J-V characteristic and Recombination currents of the optimized cell at 320 K

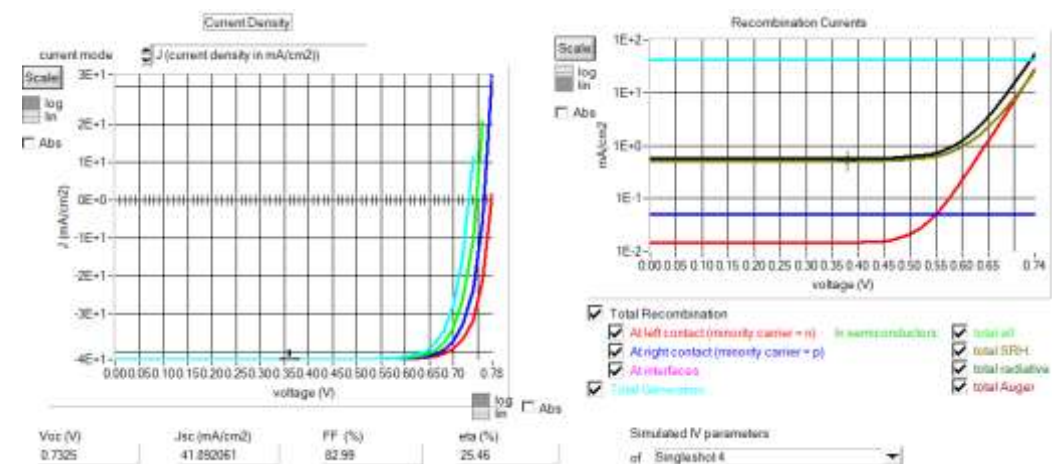


Figure 5: Simulated J-V characteristic and Recombination currents of the optimized cell at 330 K

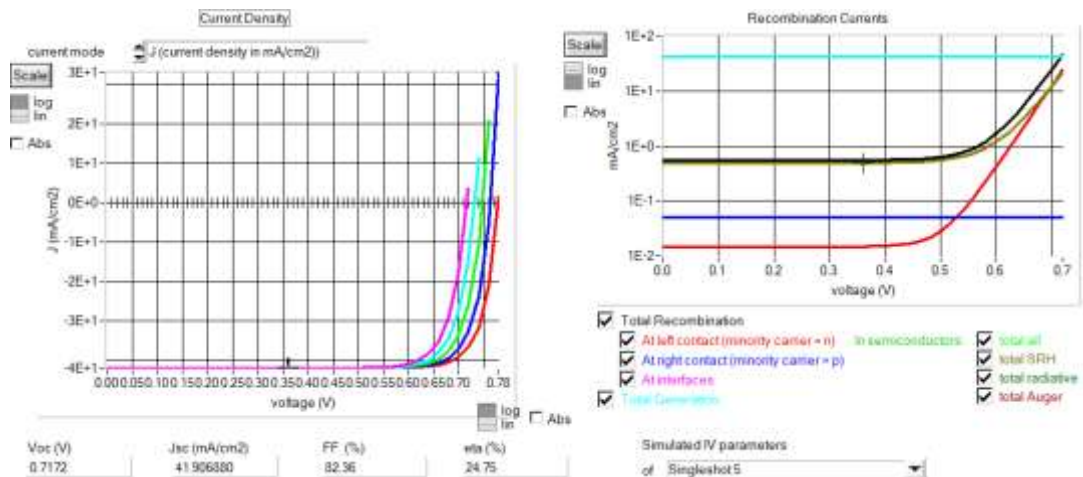


Figure 6: Simulated J-V characteristic and Recombination currents of the optimized cell at 340 K

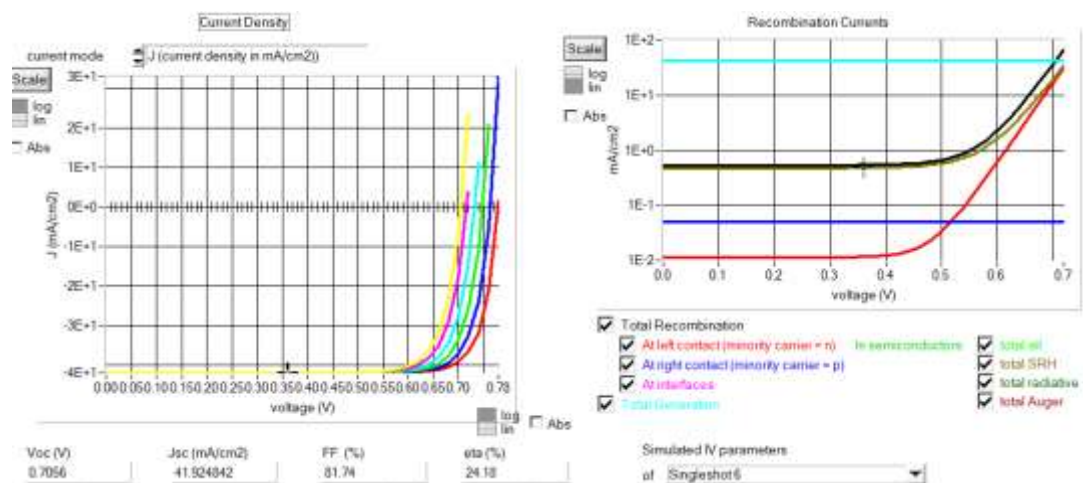


Figure 7: Simulated J-V characteristic and Recombination currents of the optimized cell at 350 K

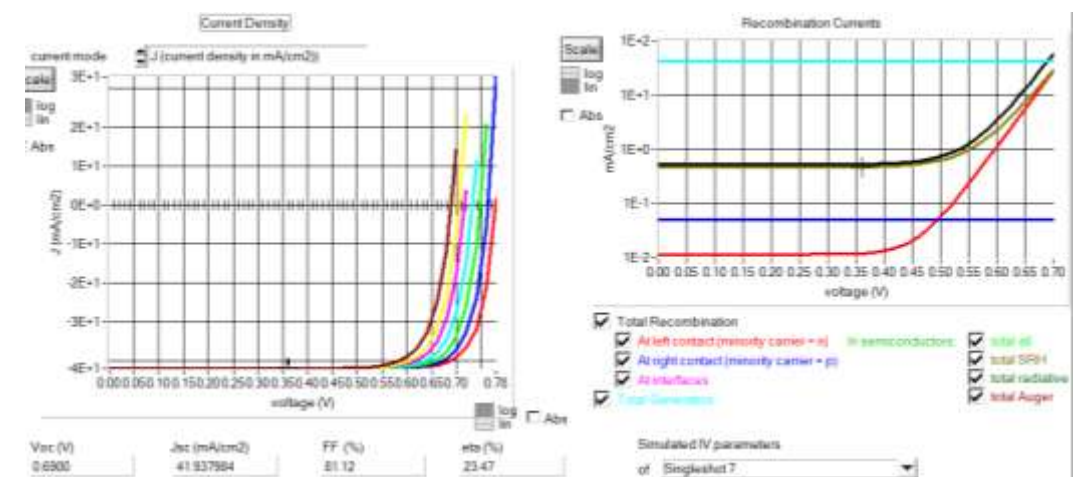


Figure 8: Simulated J-V characteristic and Recombination currents of the optimized cell at 360 K

The J-V curves show a clear decrease in voltage as the temperature increases. The curves retain a similar overall shape, but the voltage corresponding to the open-circuit condition shifts to lower values. This behavior is reflected by the decrease in Voc with increasing temperature. In contrast, the short-circuit current changes only slightly over the investigated temperature range.

The recombination-current curves remain nearly constant over most of the voltage range. A noticeable increase appears only at high voltages close to Voc. As the temperature increases, Voc decreases, and the rapid increase in recombination current therefore occurs at progressively lower voltages. The recombination curves consequently

show a faster rise in the high-voltage region at higher temperatures. This behavior is consistent with the change observed in the J–V characteristics and indicates that recombination becomes more significant as the device approaches the open-circuit condition. As shown in Figures 2 to 8, the total generation current remains constant at all temperatures, while the recombination current increases with increasing temperature. The photovoltaic parameters obtained from the simulations are summarized in Table 2. The V_{oc} decreased from 0.7788 V at 300 K to 0.6900 V at 360 K, while J_{sc} increased slightly from 41.84 to 41.94 mA cm^{-2} . Over the same temperature range, the FF decreased from 84.69% to 81.12%, resulting in a reduction in PCE from 27.60% to 23.47%.

Temperature coefficients and thermal response

The temperature dependence of the photovoltaic parameters was evaluated using the simulated results summarized in Table 2. The temperature coefficients of J_{sc} , V_{oc} , FF, and PCE were obtained from linear regression of the corresponding parameters over the temperature range of 300–360 K. The resulting regression plots are presented in Figures 9–12, while the calculated temperature coefficients are summarized in Table 3.

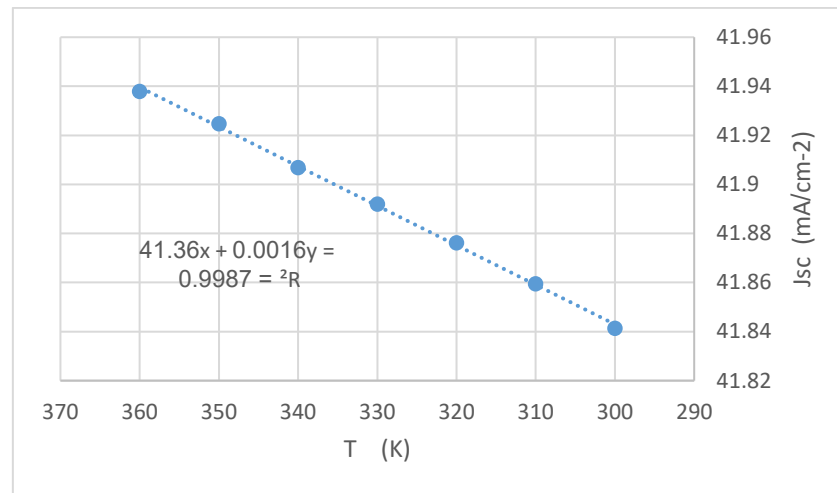


Figure 9: Linear regression of short-circuit current density (J_{sc}) as a function of temperature

The J_{sc} showed only a small variation with temperature. As listed in Table 2, J_{sc} increased from 41.84 mA cm^{-2} at 300 K to 41.94 mA cm^{-2} at 360 K. The linear regression in Figure 9 gave a slope of $+0.0016 \text{ mA cm}^{-2} \text{ }^{\circ}\text{C}^{-1}$, corresponding to a normalized temperature coefficient of $+0.0038\% \text{ }^{\circ}\text{C}^{-1}$. The high R^2 value of 0.9987 indicates that the small increase was approximately linear over the investigated temperature range. The limited change in J_{sc} indicates that the photocurrent generation of the simulated device was relatively insensitive to temperature compared with the voltage and power-related parameters.

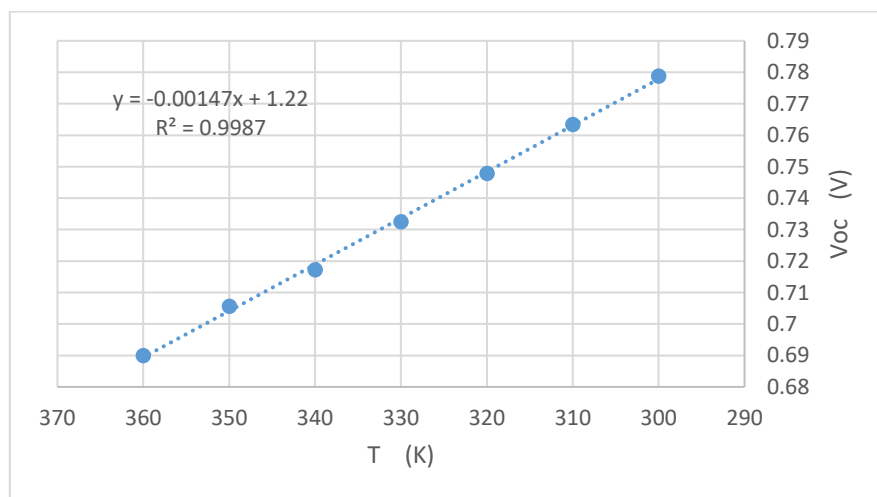


Figure 10: Linear regression of open-circuit voltage (V_{oc}) as a function of temperature.

In contrast to J_{sc} , V_{oc} showed a clear decrease with increasing temperature. According to Table 2, V_{oc} decreased from 0.7788 V at 300 K to 0.6900 V at 360 K. The regression shown in Figure 10 resulted in a slope of $-0.00147 \text{ V }^{\circ}\text{C}^{-1}$, or $-1.47 \text{ mV }^{\circ}\text{C}^{-1}$, with $R^2=0.9987$. Normalizing this slope to the V_{oc} value at 300 K yielded a relative temperature coefficient for the V_{oc} of $-0.1893\% \text{ }^{\circ}\text{C}^{-1}$. The negative temperature coefficient confirms the

pronounced temperature sensitivity of Voc over the investigated temperature range. This temperature dependence of Voc is consistent with the temperature sensitivity reported for perovskite solar cells by Wei et al. (2023).

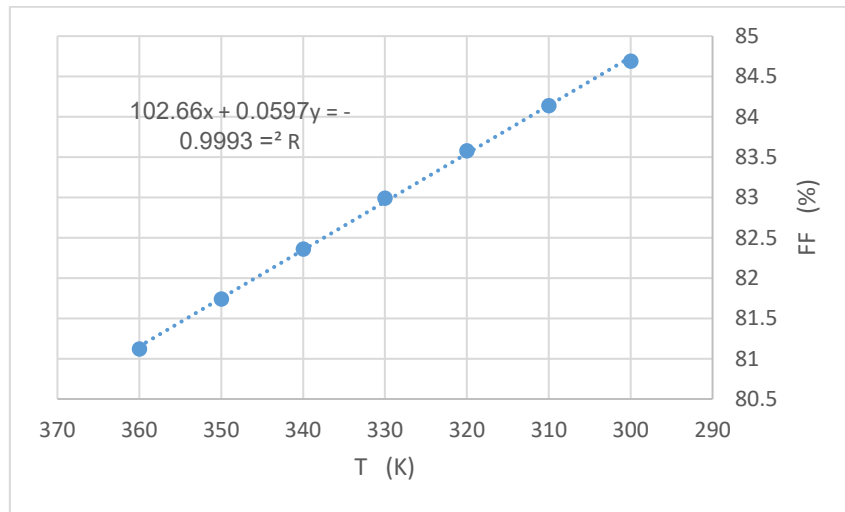


Figure 11: Linear regression of fill factor (FF) as a function of temperature.

The FF also decreased continuously with temperature, from 84.69% at 300 K to 81.12% at 360 K (Table 2). The linear fit in Figure 11 produced a slope of -0.0597 percentage point °C⁻¹, corresponding to a normalized temperature coefficient of -0.07055% °C⁻¹. The R² value of 0.9993 indicates a strong linear dependence over the investigated range. The magnitude of the relative temperature coefficient of the fill factor FF (-0.07055% °C⁻¹) is lower than that of the relative temperature coefficient of the open-circuit voltage Voc (-0.1893% °C⁻¹), indicating that the open-circuit voltage Voc is more sensitive to temperature than the fill factor within the studied range.

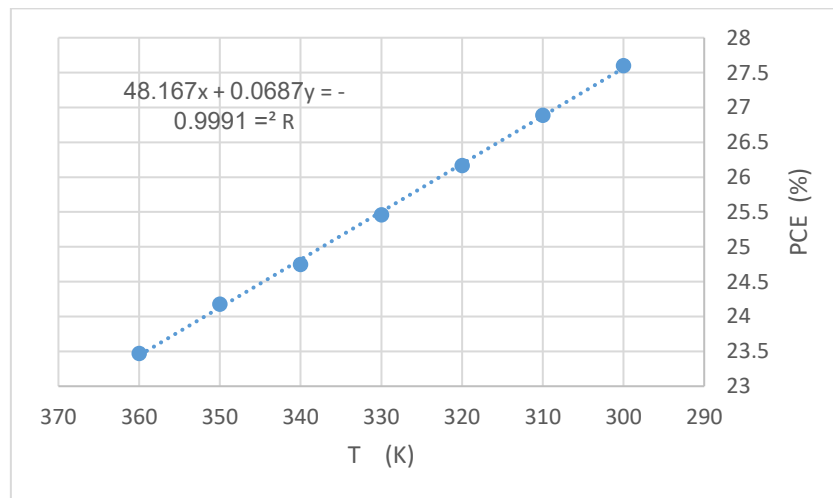


Figure 12: Linear regression of power conversion efficiency (PCE) as a function of temperature.

The combined effect of the changes in Voc, FF, and Jsc is reflected in the PCE. As shown in Table 2, PCE decreased from 27.60% at 300 K to 23.47% at 360 K. The regression in Figure 12 gave a slope of -0.0687 percentage point °C⁻¹, with R²=0.9991. After normalization to the PCE at 300 K, the temperature coefficient was -0.2488% °C⁻¹. This relatively low magnitude of the PCE temperature coefficient indicates a limited temperature-induced loss in the simulated device compared with the stronger performance degradation reported for some photovoltaic devices under elevated temperatures (Paudyal & Imenes, 2021).

Table 3: Temperature coefficients of the photovoltaic parameters of the optimized tandem cell

Parameter	Slope	Temperature coefficient
Jsc	+0.0016 mA cm ⁻² °C ⁻¹	+0.0038 % °C ⁻¹
Voc	-0.00147 V °C ⁻¹	-1.47 mV °C ⁻¹
FF	-0.0597 percentage point °C ⁻¹	-0.07055 % °C ⁻¹
PCE	-0.0687 percentage point °C ⁻¹	-0.2488 % °C ⁻¹

The results presented in Table 2 show that not all parameters characterizing the device's thermal response are affected to the same extent. The limited change in J_{sc} , compared to the more significant changes in V_{oc} and FF, indicates that the decline in photovoltaic performance with rising temperature is primarily associated with changes in voltage and fill factor, rather than a substantial change in photocurrent generation.

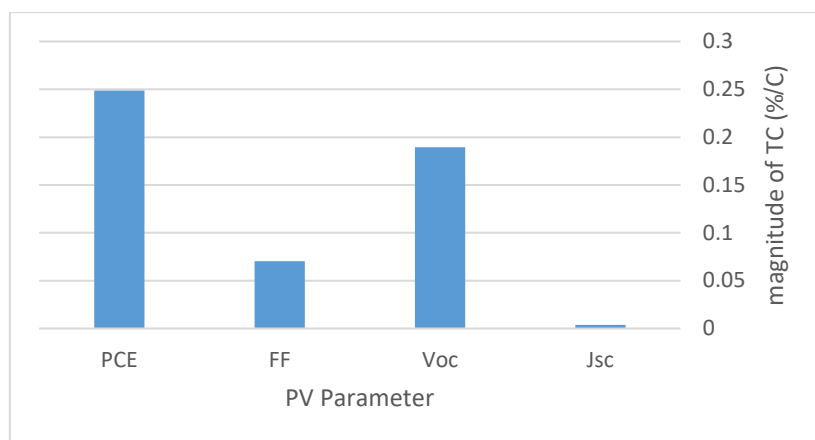


Figure 13: Magnitude of relative temperature coefficients of PV parameters

Figure 13 illustrates the magnitudes of the relative temperature coefficients for the photovoltaic parameters under study. It shows that J_{sc} exhibits the lowest thermal sensitivity, whereas V_{oc} and FF show greater sensitivity; PCE displays the highest temperature coefficient magnitude, as it is influenced by changes in the other PV parameters.

Conclusion

A two-terminal tandem solar cell with the structure FTO/TiO₂/n-MASnI₃/C-SiOx(n)/c-Si(p)/c-Si(p⁺) was simulated using SCAPS-1D software, focusing on the effect of temperature on photovoltaic performance. After numerically optimizing the layer thicknesses and doping concentrations, the device achieved a V_{oc} of 0.7788 V, a J_{sc} of 41.84 mA/cm², an FF of 84.69%, and a power conversion efficiency (PCE) of 27.60% at 300 K. The J–V characteristics exhibited a relatively square shape, while recombination currents increased more noticeably at high voltages near V_{oc} .

Thermal simulation results showed that raising the temperature from 300 K to 360 K caused a limited change in J_{sc} ; the value rose from 41.84 to 41.94 mA/cm², corresponding to a temperature coefficient of +0.00385% °C⁻¹. In contrast, V_{oc} dropped from 0.7788 V to 0.6900 V (temperature coefficient of -1.474 mV °C⁻¹), and FF decreased from 84.69% to 81.12% (relative temperature coefficient of -0.07055% °C⁻¹). Consequently, the PCE fell from 27.60% to 23.47%, with a (relative temperature coefficient of -0.2488% °C⁻¹). The R² values, ranging from 0.9987 to 0.9993, indicate that the variation in these parameters was nearly linear within the studied temperature range. Recombination characteristics also revealed that the region of significant increase in recombination current shifted to lower voltages as the temperature rose, coinciding with a decrease in V_{oc} . Overall, the impact of temperature was more pronounced on V_{oc} and FF than on J_{sc} , a trend primarily reflected in the decline of PCE with increasing temperature.

These results represent the simulated device response within the 300–360 K temperature range and do not constitute an assessment of long-term thermal or operational stability. Therefore, future studies would benefit from extending the temperature range and incorporating temperature-dependent material parameters—specifically charge carrier mobility, defect density, and recombination parameters. Furthermore, the structure and parameters employed in the model require experimental validation to assess how well the simulated thermal response aligns with actual device performance.

Compliance with ethical standards

Disclosure of conflict of interest

The author declare that they have no conflict of interest.

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