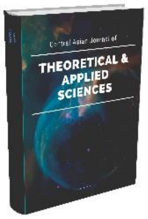

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Performance Analysis of Kesterite Solar Cells Under Varying Radiation and Ambient Temperature Conditions

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Abstract: *The demand for efficient and reliable solar energy conversion technologies has driven extensive research on novel photovoltaic materials, including kesterite solar cells. However, their performance is inherently affected by external environmental factors, such as solar radiation and ambient temperature. This research paper presents a comprehensive performance analysis of kesterite solar cells under varying radiation and ambient temperature conditions. SCAPS-1D is employed to model the electrical behavior of kesterite solar cells under different levels of solar radiation. The simulation results demonstrate a direct correlation between incident light intensity and key performance metrics, such as short-circuit current, open-circuit voltage, and fill factor. The influence of spectral variations in solar radiation on the device response is also studied, offering insights into the spectral sensitivity of kesterite solar cells. Furthermore, the impact of varying ambient temperature on the performance of kesterite solar cells is investigated using SCAPS-1D. The simulation analysis reveals temperature-dependent changes in the electrical characteristics of the solar cells. The insights gained from this study provide valuable guidance for the design and optimization of kesterite solar cells, supporting their integration into the renewable energy landscape as a viable and sustainable photovoltaic technology.*

Keywords: *Kesterite, CZTSe, Ambient temperature, solar radiation, SCAPS-1D.*

1. INTRODUCTION

The ever-increasing global demand for sustainable and renewable energy sources has led to extensive research and development in the field of photovoltaic technology. Among the emerging photovoltaic materials, kesterite solar cells have garnered significant attention due to their abundant and non-toxic constituent elements, making them environmentally friendly and cost-effective alternatives to conventional solar cell technologies. Kesterite solar cells, with the general formula $Cu_2ZnSn(S,Se)_4$ (CZTSSe), possess desirable optoelectronic properties, including tunable bandgaps and high absorption coefficients, enabling efficient solar energy conversion [1,2].

Despite their promising characteristics, the practical deployment of kesterite solar cells is still hindered by several challenges related to their performance under varying environmental conditions. There have been many factors leading to low efficiency such as panel tilt angle, shading, dust, solar radiation level, temperature and the other losses [3,4]. Among these factors, solar radiation level and the temperature have been more prominent. Two crucial external factors that significantly influence the performance of solar cells are solar radiation intensity and ambient temperature. Solar radiation, comprising the incident light intensity and spectral distribution, varies with geographic location, time of day, and atmospheric conditions, affecting the amount of light absorbed by the solar cell and thus its electrical output. Similarly, ambient temperature fluctuations can impact the electrical properties of the solar cell, leading to changes in the current-voltage characteristics and overall efficiency.

To understand and optimize the performance of kesterite solar cells under varying radiation and ambient temperature conditions, accurate and reliable simulation tools are indispensable. In this regard, SCAPS-1D (Solar Cell Capacitance Simulator-1D) has proven to be a valuable tool for modeling and analyzing the electrical behavior of solar cells. SCAPS-1D is a one-dimensional device simulator that provides insights into the complex physics and optoelectronic processes within the solar cell structure. It allows for the investigation of the impact of different factors on the device's performance, enabling the identification of potential limitations and guiding the design of optimized solar cell configurations.

In this research paper, we present a comprehensive performance analysis of kesterite solar cells under varying radiation and ambient temperature conditions using the SCAPS-1D simulation tool. By combining experimental measurements with SCAPS-1D simulations, we aim to gain deeper insights into the behavior of kesterite solar cells and assess their suitability for real-world applications.

2. SIMULATION METHODOLOGY AND MATERIAL PARAMETERS

Figure 1 illustrates the structure of the solar cell device analyzed in this study. The device comprises a p-type absorber layer of CZTSe, an n-type wide band gap buffer layer of CdS, a ZnO layer serving both as the window layer and passivation layer, and an Al-doped ZnO (Al:ZnO) transparent conducting oxide (TCO) layer. The material properties of the various components utilized in our simulations are summarized in Table 1, sourced from previous studies [5-9]. With these material properties, we conducted simulations to analyze the photovoltaic response of the proposed device structure.

For the simulation of the proposed solar cell device structures, we utilized SCAPS software, a powerful one-dimensional numerical simulator [10]. This software allowed us to effectively solve the coupled Poisson and electron-hole continuity equations, while incorporating appropriate boundary conditions defined at the contacts and interfaces [11-14]. SCAPS has been widely employed in previous studies to simulate diverse types of solar cells [15-20], making it a well-established and reliable tool for our research.

For simulating CZTSe single-junction solar cells, we adopted the following device structure: Al:ZnO / ZnO / CdS / absorber layer / back contact. The Al:ZnO layer served as both the front electrical contact and a transparent medium for incident solar radiation. ZnO acted as the window layer, while n-CdS was utilized as the buffer to form a p-n junction, creating a heterostructure with the p-type CZTSe light-absorbing layer. In the light-absorbing layer, defects were introduced at 0.6 eV above the valence band maximum (E_v) with a single energetic distribution, thereby representing mid-gap defects. The back contact was assumed to have a flat band, and surface recombination velocities of approximately 1×10^5 cm/s and 1×10^7 cm/s were assigned for electrons and holes, respectively.

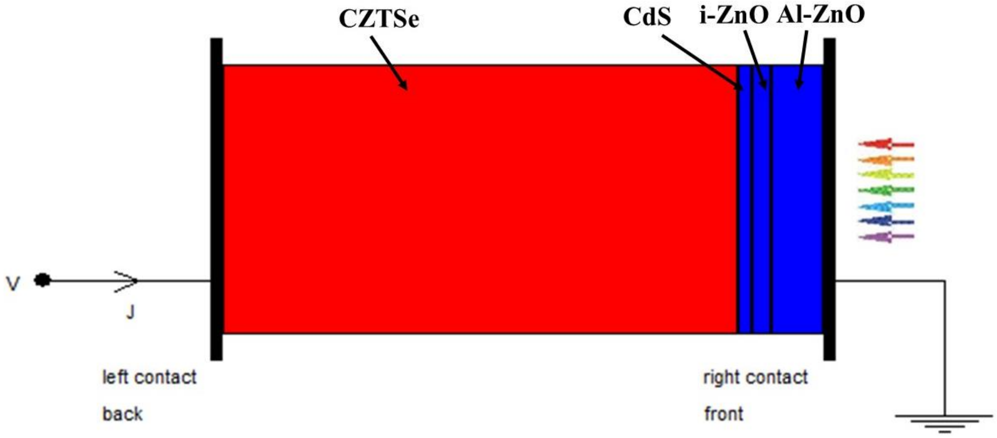

Figure 1: Schematic of *"Al-ZnO/i-ZnO/CdS/CZTSe/Back contact"* solar cell used in present simulation.

Table 1: Material parameters used for simulating solar cell structures [5-9]

	CZTSe	**CdS**	**i-ZnO**	**Al-ZnO**
Thickness (µm)	2	0.05	0.080	0.2
Electron Affinity (eV)	4.46	4.5	4.6	4.6
Bandgap (eV)	1	2.42	3.37	3.37
Dielectric Permittivity	9.1	9	9	9
CB Effective DOS (cm^{-3})	2.2×10^{18}	1.8×10^{19}	2.2×10^{18}	2.2×10^{18}
VB Effective DOS (cm^{-3})	1.8×10^{19}	2.4×10^{18}	1.8×10^{19}	1.8×10^{19}
Hole Thermal Velocity (m/s)	1×10^{7}	1×10^{7}	1×10^{7}	1×10^{7}
Electron Thermal Velocity (m/s)	1×10^{7}	1×10^{7}	1×10^{7}	1×10^{7}
Hole Mobility (cm^2/Vs)	40	50	25	25
Electron Mobility (cm^2/Vs)	145	160	150	150
Shallow Uniform Acceptor Density NA (cm^{-3})	5×10^{16}	0	0	0
Shallow Uniform Donor Density ND (cm^{-3})	0	1×10^{17}	1×10^{17}	1×10^{20}

3. RESULTS AND DISCUSSION

3.1. Effect of Different Solar Radiation Spectrum

AM0, AM1.5D1SUN, AM1.5D, AM1.5G1SUN, and AM1.5G refer to different solar spectral distributions that are used as standard reference spectra for solar cell testing and characterization. These reference spectra are defined based on the solar radiation intensity and spectral distribution at different terrestrial conditions. AM0 represents the solar spectrum outside the Earth's atmosphere, which means no atmospheric absorption or scattering is considered. It represents the full intensity of solar radiation from the Sun in space. AM1.5D1SUN (Air Mass 1.5 Direct 1 Sun) is a specific terrestrial solar spectrum that considers the solar radiation after it has traveled through the Earth's atmosphere with an air mass value of 1.5. The "Direct 1 Sun" indicates that the spectrum is scaled to simulate sunlight conditions when the Sun is at its highest point in the sky (solar noon) on a clear day at sea level. AM1.5D (Air Mass 1.5 Direct) is similar to AM1.5D1SUN but without the scaling to 1 Sun conditions. It represents the solar spectrum at an air mass value of 1.5 after traveling through the Earth's atmosphere. This spectrum is useful for testing and characterizing solar cells under standardized illumination conditions. AM1.5G1SUN (Air Mass 1.5 Global 1 Sun) is another terrestrial solar spectrum that takes into account both direct and indirect (diffuse) sunlight. It simulates sunlight conditions when the Sun is at its highest point in the sky on a clear day at sea level, similar to AM1.5D1SUN. AM1.5G (Air Mass 1.5 Global) is similar to AM1.5G1SUN but without the scaling to 1 Sun conditions. It represents the solar spectrum at an air mass value of 1.5, considering both direct and indirect sunlight after traveling through the Earth's atmosphere. These standardized solar spectra are used to ensure consistency and comparability in the performance evaluation of solar cells and other photovoltaic devices under different environmental conditions. AM1.5G is one of the most commonly used reference spectra for solar cell testing and efficiency measurement.

The effect of these different spectra on the photovoltaic performance of the simulated CZTSe Kesterite solar cells was investigated. The results have been presented in Table 2. It can be clearly observed that the efficiency is maximum for AM1.5G 1SUN radiation spectrum.

Table 2: Variation of PV parameters with different radiation spectrum.

PV Parameters	**Radiation Spectrum**				
	AM0	**AM1.5D1SUN**	**AM1.5D**	**AM1.5G1SUN**	**AM1.5G**
V_{oc}	0.5342	0.5276	0.5212	0.5282	0.5273
J_{sc}	32.71463	25.434723	19.51244	26.080488	25.10454
FF	80.09	80.03	79.56	80.06	80.05
Efficiency	10.29	10.74	10.55	11.03	11.01

3.2. Effect of ambient temperature

The effect of ambient temperature was studied on the PV performance parameters of the CZTS Kesterite Solar cells. The temperature was varied from 270 K to 380 K. The ambient temperature has a significant effect on the performance of solar cells. As the temperature increases, several factors come into play that can either positively or negatively impact the solar cell's efficiency and output. Solar cells have a temperature coefficient of efficiency, which indicates how much the cell's efficiency changes with temperature. Kesterite solar cells experience a decrease in efficiency with increasing temperature. This is due to the decrease in the open-circuit voltage (V_{oc}) and an increase in the saturation current (I_s) at higher temperatures. As a result, the overall power output decreases. This is primarily due to the increase in non-radiative recombination, leading to a reduction in the voltage across the solar cell terminals.

Table 3: Variation of PV parameters with different ambient temperature.

PV Parameters	**Ambient Temperature (K)**											
	270	**280**	**290**	**300**	**310**	**320**	**330**	**340**	**350**	**360**	**370**	**380**
V_{oc}	0.58	0.56	0.54	0.52	0.50	0.48	0.46	0.45	0.43	0.41	0.39	0.37
J_{sc}	24.94	25.93	26.00	26.08	26.15	26.22	26.29	26.36	26.43	26.50	26.58	26.65
FF	81.97	81.72	80.91	80.06	79.16	78.21	77.21	76.14	75.01	73.81	72.53	71.16
Efficiency	11.92	12.01	11.52	11.03	10.54	10.04	9.54	9.04	8.54	8.04	7.53	7.03

4. CONCLUSION

In conclusion, our research delved into the comprehensive performance analysis of Kesterite solar cells under varying radiation and ambient temperature conditions, employing SCAPS-1D as the numerical simulator. Through rigorous simulations and investigations, we gained valuable insights into the behavior of the proposed solar cell device structure. The research findings clearly indicate that the efficiency of the Kesterite solar cells is maximized when exposed to the AM1.5G 1SUN radiation spectrum. This result is in line with common expectations as the AM1.5G 1SUN spectrum represents solar radiation conditions at an air mass value of 1.5, considering both direct and indirect sunlight. It is widely recognized as the standard reference spectrum for solar cell testing and characterization under terrestrial conditions. Furthermore, the impact of ambient temperature on solar cell efficiency was thoroughly explored. As expected, higher temperatures led to a decrease in the solar cell's efficiency due to the temperature coefficient of efficiency, which primarily affected the open-circuit voltage and short-circuit current density. Overall, our study provided valuable insights into the performance characteristics of Kesterite solar cells and offered valuable guidelines for designing and optimizing solar energy systems to harness the most promising and naturally abundant thin-film PV absorber materials. The knowledge gained from this research can serve as a stepping stone for further advancements in the field of solar cell technology, aiding in the development of efficient and robust solar energy solutions for a sustainable future.

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