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17.05.2025
SATURDAY / 10:30-12:30

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MODERATOR: Assoc. Prof. Dr. Onur ÇAVUŞOĞLU

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Sudegul KARATAS Emine KALIN Assoc. Prof. Dr. Gökhan SURUCU	Gazi University TÜRKİYE	Simulation-Based Performance Analysis Of Cigs Thin Film Solar Cells Using Scaps-1d
Emine KALIN Sudegul KARATAS Assoc. Prof. Dr. Gokhan SURUCU	Gazi University TÜRKİYE	Effect Of Layer Thicknesses On The Efficiency Of Cigs / In_2S_3 Solar Cells: A Scaps-1d Supported Study
Oğuz Kaan KOÇAN Assist. Prof. Dr. Oğulcan EREN	Gazi University TÜRKİYE	Development Of An Artificial Intelligence Model To Optimize Model Rotation In 3d Printer Slicer Applications Using User Feedback And Human-Centered Design
Esra KEÇECI Assoc. Prof. Dr. Gökhan SURUCU	Gazi University TÜRKİYE	Analysis Of A City's Energy Production And Consumption Balance Using Monte Carlo Simulation: Developing Energy Efficiency Scenarios
Gözde Yeşiltaş İMAMOĞLU Lect. Dr. Ayşegül TIRYAKI	Gebze Teknik University TÜRKİYE Yildiz Technical University TÜRKİYE	Molecular Docking Analysis Of Some Fda-Approved Small Molecules Agaixnst Hdac6
Assoc. Prof. Dr. Onur ÇAVUŞOĞLU Mahmut Tolga KARAKAŞ	Gazi Universitesi TÜRKİYE	Experimental Investigation Of The Ballistic Properties Of Hybrid Sandwich Composite Structures

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SCAPS-1D KULLANILARAK CIGS İNCE FİLM GÜNEŞ PİLLERİNİN SİMÜLASYON TABANLI PERFORMANS ANALİZİ

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ÖZET

Bu çalışma, CIGS (bakır-indiyum-galyum selenit) esaslı ince film güneş pillerinin optoelektronik performansını sayısal simülasyonlar aracılığıyla kapsamlı bir biçimde incelemektedir. Yüksek optik soğurma katsayısı ve bant aralığının ayarlanabilirliği ile dikkat çeken CIGS malzemesi, yeni nesil fotovoltaik cihazlarda öne çıkan bir aday olarak değerlendirilmektedir. Çalışmada, CIGS, OVC, CdS ve FTO katmanlarından oluşan çok katmanlı aygıt mimarisi SCAPS-1D simülasyon programı kullanılarak modellenmiştir. Bu katmanların aygıt üzerindeki etkileri detaylı olarak analiz edilmiştir.

Simülasyon sonuçlarına göre, geliştirilen güneş pili yapısı 0,4295 V açık devre gerilimi (Voc), 36,55 mA/cm² kısa devre akım yoğunluğu (Jsc), %62,45 doluluk faktörü (FF) ve %9,80 güç dönüşüm verimi (PCE) sergilemiştir. Bu olumlu performans özellikle, CIGS absorban tabakasının güneş spektrumu içerisinde geniş bir dalga boyu aralığında gösterdiği yüksek ışık soğurma kabiliyetinden kaynaklanmaktadır. Ayrıca, CdS tampon tabakasının arayüz kalitesine katkısı ve FTO'nun şeffaf iletken özelliği sayesinde taşıyıcı toplama verimliliği artırılmıştır.

Elde edilen sonuçlar, optimize edilmemiş bir CIGS tabanlı ince film güneş pili yapısının dahi dikkate değer fotovoltaik özellikler sergileyebileceğini göstermektedir. Bu bulgular, CIGS tabanlı ince film güneş pillerinin ticari uygulamalar ve yüksek verimli yeni nesil güneş hücresi tasarımları için önemli bir potansiyele sahip olduğunu ortaya koymaktadır.
Anahtar Kelimeler: CIGS, ince film güneş hücresi, SCAPS-1D, CdS tampon katmanı, fotovoltaik simülasyon, güç dönüşüm verimliliği

SIMULATION-BASED PERFORMANCE ANALYSIS OF CIGS THIN FILM SOLAR CELLS USING SCAPS-1D

ABSTRACT

This study provides a comprehensive numerical investigation of the optoelectronic performance of copper indium gallium selenide (CIGS)-based thin-film solar cells. Distinguished by its high optical absorption coefficient and tunable bandgap, CIGS has emerged as a promising candidate for next-generation photovoltaic devices. In this work, a multilayer device architecture comprising CIGS, OVC, CdS, and FTO layers was modeled using the SCAPS-1D simulation program, allowing for a detailed analysis of the impact of each constituent layer on overall device performance.

The simulation results revealed that the designed solar cell structure exhibited an open-circuit voltage (Voc) of 0.4295 V, a short-circuit current density (Jsc) of 36.55 mA/cm², a fill factor (FF) of 62.45%, and a power conversion efficiency (PCE) of 9.80%. This favorable performance is primarily attributed to the superior light absorption capability of the CIGS absorber layer across a wide wavelength range of the solar spectrum. Additionally, the inclusion of a CdS buffer layer improved the interface quality, while the transparent conducting properties of FTO contributed to enhanced carrier collection efficiency.

The findings demonstrate that even a non-optimized CIGS-based thin-film solar cell structure can deliver notable photovoltaic characteristics. These results underscore the significant potential of CIGS thin-film solar cells for commercial applications and the development of high-efficiency next-generation solar devices. In conclusion, this study provides a solid scientific foundation for future experimental and theoretical research in the field.
Keywords: CIGS, thin film solar cell, SCAPS-1D, CdS buffer layer, photovoltaic simulation, power conversion efficiency

INTRODUCTION

The escalating imperative to confront global climate change and diminish reliance on fossil fuels has catalyzed considerable interest in renewable energy alternatives. Among these alternatives, solar energy is distinguished as a clean, sustainable, and inexhaustible resource, presenting substantial potential to fulfill the increasing energy requirements of the global population while mitigating adverse environmental consequences [1,2]. Solar cells, which facilitate the direct conversion of sunlight into electrical energy, are pivotal to this paradigm shift, fostering the advancement of decentralized energy generation and endorsing the transition toward more sustainable energy systems [3,4]. Within the landscape of photovoltaic technologies, thin-film solar cells have emerged as an attractive alternative to traditional silicon-based devices. Thin-film solar cells offer several advantages, including reduced material usage, lower production costs, mechanical flexibility, and lightweight characteristics. These features make them suitable for a wide range of applications, from building-integrated photovoltaics to portable power systems [5,6]. Furthermore, their compatibility with large-area deposition techniques allows for scalable manufacturing, potentially lowering the cost of solar electricity even further.

Among the various thin-film technologies, Copper Indium Gallium Selenide (CIGS) based solar cells have gained substantial attention due to their high absorption coefficient, tunable bandgap, and impressive power conversion efficiencies [7]. The CIGS/CdS heterojunction structure, in particular, has demonstrated excellent photovoltaic performance and long-term stability, positioning it as a promising candidate for next-generation solar modules [8,9]. The use of a CdS buffer layer enables efficient charge separation and collection, further enhancing device performance [10].

To enhance the design and efficacy of CIGS/CdS solar cells, numerical simulation methodologies have become crucial in both the realms of research and development. A commonly utilized software tool is SCAPS-1D (Solar Cell Capacitance Simulator in One Dimension), which was developed by the University of Ghent [11]. SCAPS-1D facilitates comprehensive modeling of the electrical and optical characteristics of multilayered solar cells, thereby enabling researchers to examine the impact of various physical parameters—such as layer thickness, defect densities, and doping concentrations—on the overall efficiency of the device. With its intuitive user interface and an extensive array of functionalities, SCAPS-1D offers significant insights that inform experimental endeavors, expedite the development process, and assist in identifying optimal device configurations [12].

In this study, the optoelectronic properties of CIGS/CdS thin-film solar cells are systematically investigated using SCAPS-1D, with a focus on understanding the effects of key structural parameters on device performance.

MATERIAL AND METHODS

All simulations conducted in the present investigation were executed utilizing SCAPS-1D, a sophisticated one-dimensional solar cell simulation application created at Ghent University. SCAPS-1D is extensively utilized for the modeling and examination of thin-film photovoltaic devices, enabling the user to specify multi-layer device configurations, electronic and optical parameters, defect characteristics, and contact conditions. Its intuitive interface facilitates graphical representation and data exportation, rendering it an instrumental tool for the design and enhancement of solar cells. A representation of the SCAPS-1D action panel interface employed in this research is illustrated in Figure 1.

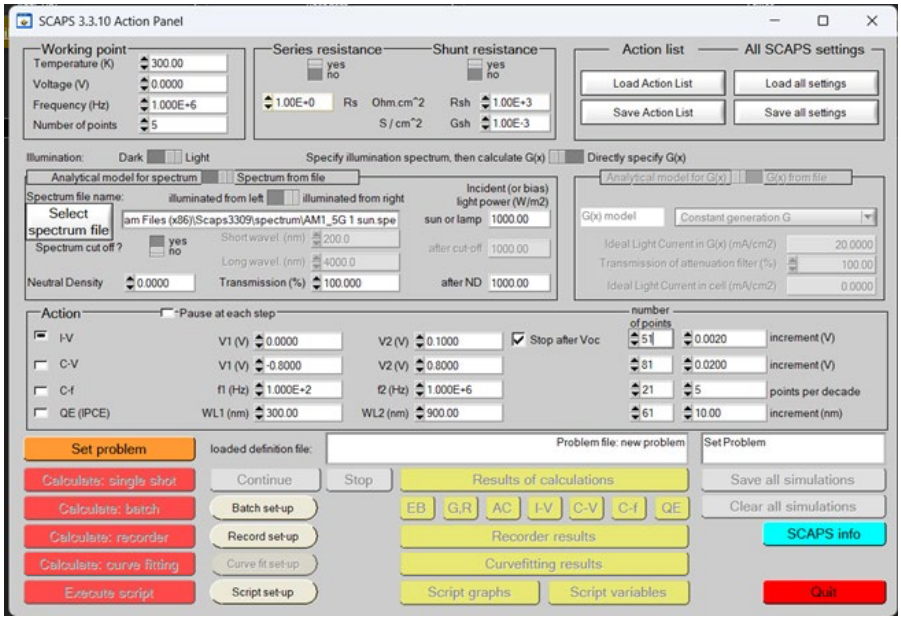
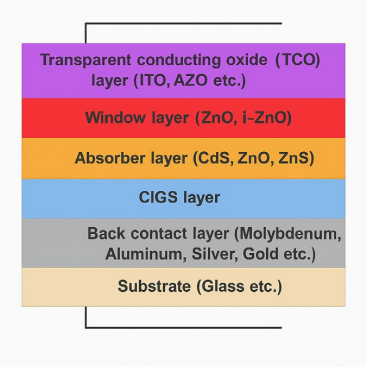


Figure 1. SCAPS-1D action panel interface used for device simulations.

The designed device architecture features a glass base, a fluorine-doped tin oxide (FTO) layer that is transparent and conductive, a cadmium sulfide (CdS) buffer layer, an optically visible carrier (OVC) transport layer, and a copper indium gallium selenide (CIGS) layer that acts as the absorber, topped off with a metallic back contact. A diagram illustrating the FTO/CdS/OVC/CIGS solar cell configuration is shown in Figure 2. In this design, CIGS is

utilized as the p-type absorber due to its superior absorption coefficient and ideal bandgap suited for photovoltaic use. CdS is used as the n-type buffer layer, which improves the p-n junction and the overall efficiency of the device. FTO serves as the transparent window layer, providing both high electrical conductivity and outstanding optical transmittance, while the OVC layer



facilitates effective carrier transport without obstructing light entry.

Figure 2. Schematic illustration of the FTO/CdS/OVC/CIGS thin-film solar cell architecture.

The physical and electronic characteristics for each layer were meticulously chosen based on published data and are presented in Table 1. The thickness of the CIGS absorber was adjusted within the range of 500 nm to 4000 nm, whereas the CdS buffer layer was examined over a span of 50–125 nm. The FTO window layer and OVC transport layer were kept constant at 200 nm and 15 nm, respectively. Bandgap values, electron affinities, dielectric constants, carrier mobilities, and doping concentrations were allocated to each layer in accordance with recognized device models.

Table 1. Physical and electronic parameters of the device layers used in simulations.

Parameter	CdS (Buffer)	CIGS (Absorber)	FTO (Window)	OVC
Thickness (nm)	50–125	500–4000	200	15
Bandgap (eV)	2.42	1.10	3.20	1.45
Electron affinity (eV)	4.10	4.50	4.46	4.50
Dielectric constant	9.00	13.60	9.00	10.00
CB effective DOS (1/cm^3)	3.0×10^{18}	2.2×10^{18}	2.2×10^{18}	2.0×10^{18}
VB effective DOS (1/cm^3)	1.8×10^{19}	1.8×10^{19}	1.8×10^{19}	2.0×10^{18}

Parameter	CdS (Buffer)	CIGS (Absorber)	FTO (Window)	OVC
Electron mobility ($cm^2/V \cdot s$)	100	100	20	1
Hole mobility ($cm^2/V \cdot s$)	25	25	10	1
Donor density ND ($1/cm^3$)	1.0×10^{17}	1.0×10^{1}	1.0×10^{18}	1.0×10^{13}
Acceptor density NA ($1/cm^3$)	1.0×10^{5}	2.0×10^{16}	—	0

The simulation setup in SCAPS-1D allows for direct parameter entry and visualization of the defined layers, as shown in **Figure 3** for the CIGS absorber layer, **Figure 4** for the OVC layer, **Figure 5** for the CdS buffer layer, and **Figure 6** for the FTO window layer.

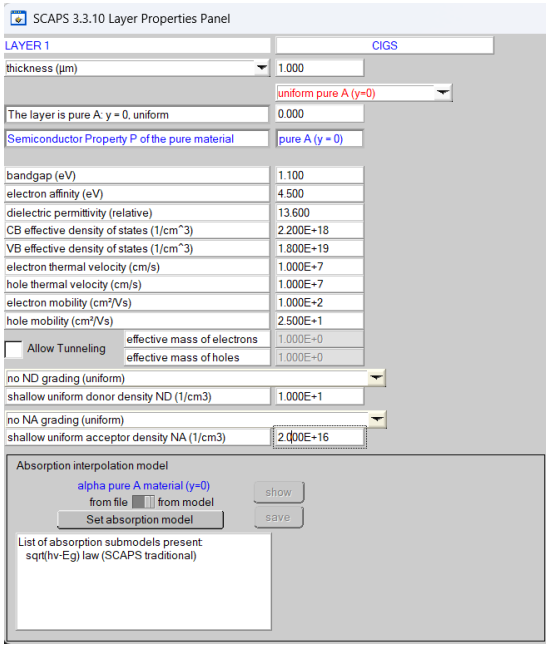


Figure 3. SCAPS-1D parameter entry window for the CIGS absorber layer.

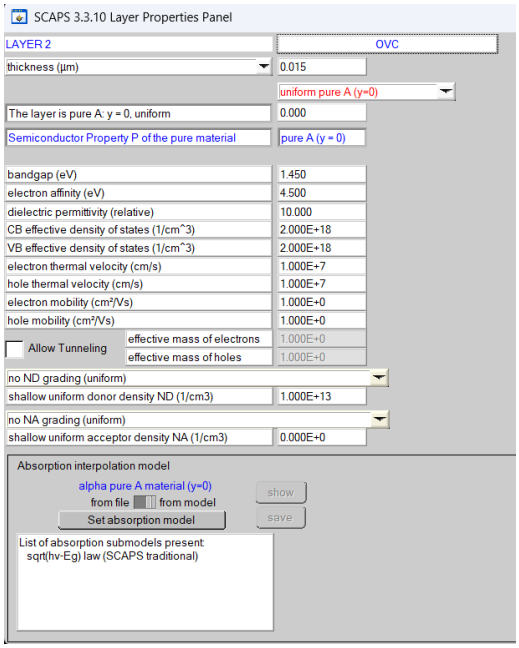


Figure 4. SCAPS-1D parameter entry window for the OVC carrier transport layer.

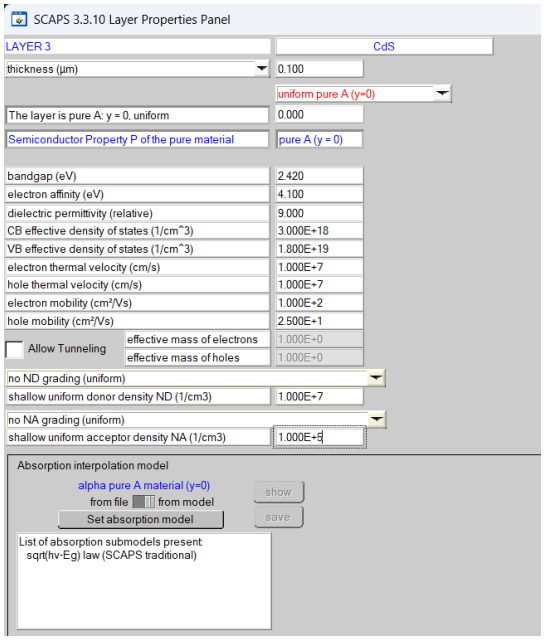


Figure 5. SCAPS-1D parameter entry window for the CdS buffer layer.

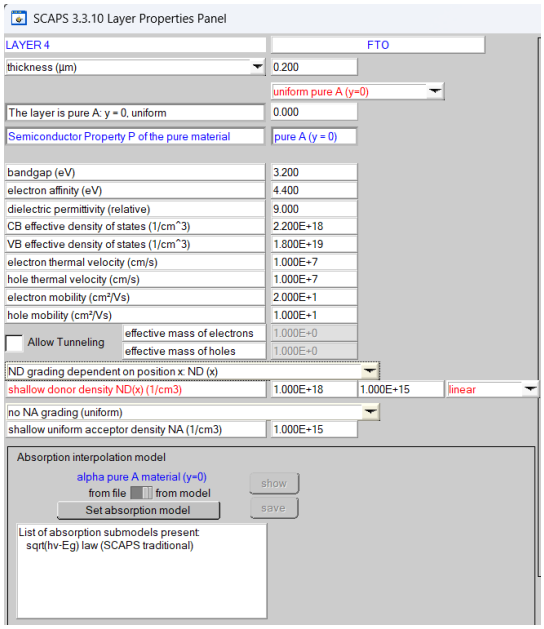


Figure 6. SCAPS-1D parameter entry window for the FTO window layer.

All simulations were performed at a temperature of 300 K under standard AM1.5G illumination, with an intensity of 1000 W/m². Series resistance was established at 1 Ω·cm² and shunt resistance at 1000 Ω·cm² to represent realistic operating conditions. The current-voltage (*I-V*) characteristics were assessed by varying the applied voltage from 0.000 V to 0.100 V with 51 data points, allowing for detailed analysis close to the open-circuit voltage (V_{oc}). The "Stop after V_{oc}" feature in SCAPS-1D was activated to conclude the simulation at V_{oc}, thus enhancing computational efficiency. All device parameters, simulation configurations, and boundary conditions were confirmed to guarantee physical consistency and precision. This methodology allowed for an in-depth analysis of how changes in the absorber and buffer layer thicknesses affect the photovoltaic performance of the CIGS/CdS thin-film solar cell structure. The outcomes of these simulations serve as the foundation for the discussion on device optimization and performance trends in the subsequent sections.

RESULTS AND DISCUSSION

The optoelectronic and electrical performance of the simulated CIGS/CdS/FTO thin-film solar cell structure was evaluated using SCAPS-1D, and the results are summarized below. Representative output graphs from the simulation, including the energy band diagram, carrier distributions, current densities, and trap occupancy probabilities, are shown in **Figure 7**.

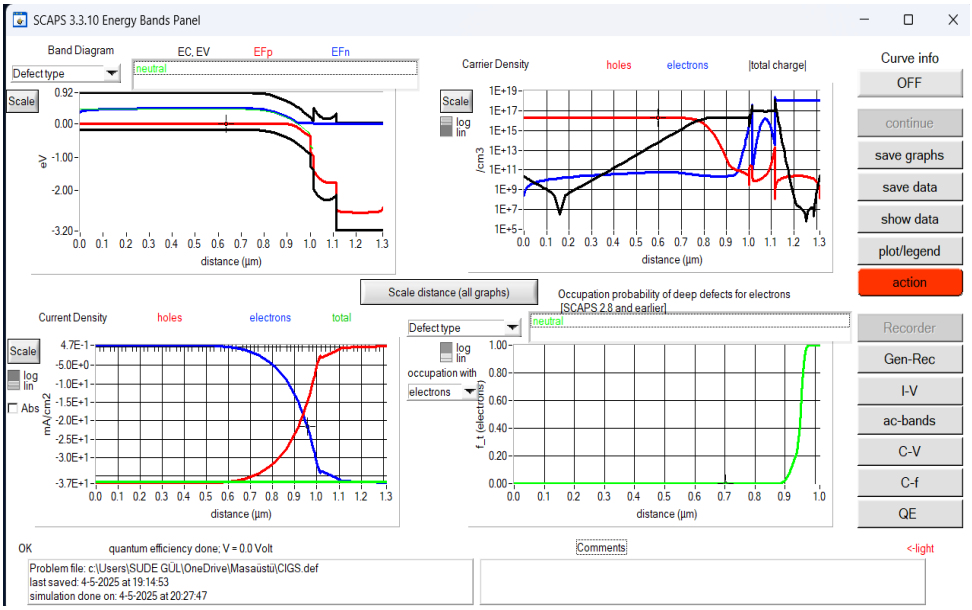


Figure 7. SCAPS-1D simulation output: (top left) energy band diagram, (top right) carrier densities, (bottom left) current densities, (bottom right) deep trap occupancy probability.

The energy band diagram distinctly illustrates the conduction band (E_C), valence band (E_V), and quasi-Fermi levels for both electrons (E_{Fn}) and holes (E_{Fp}). Discontinuities at the junctions, stemming from the heterojunction design, represent band offsets that impact carrier movement. The noticeable gap between the Fermi levels signifies effective charge separation—a crucial element driving the photovoltaic effect. The carrier density profiles exhibit a clear p-n junction, with variations in electron and hole densities at the boundary between the absorber and buffer layers. Interestingly, the logarithmic representation of carrier densities also shows variations, potentially indicating the existence of deep-level traps or interface states that may affect recombination processes [13].

The current density analysis indicates that electron and hole currents flow in opposite directions, consistent with efficient carrier separation in a well-formed junction. The total current (green curve) remains close to zero under dark conditions, confirming minimal leakage and recombination in the absence of illumination. The deep trap occupancy probability graph shows increased occupation in specific regions, suggesting the existence of surface or interface defects

acting as recombination centers [14]. These findings highlight the importance of minimizing defect densities and optimizing interface quality to enhance device performance.

The key photovoltaic parameters extracted from the simulated *I-V* curve under standard AM1.5G illumination are given in Table-2.

Table 2. Output parameters of the simulated CIGS/CdS/FTO solar cell under optimized conditions.

Parameter	**Value**
V_{oc} *(V)*	*0.4295*
J_{sc} *(mA/cm²)*	*36.55*
Fill Factor (%)	*62.45*
Efficiency (%)	*9.80*

The simulated efficiency, while moderate, is in line with typical values for early-stage or unoptimized CIGS devices. The high short-circuit current density underscores the strong absorption and carrier generation capability of the CIGS layer, yet the relatively low open-circuit voltage and fill factor suggest non-idealities such as interface recombination, band alignment issues, or resistive losses. These performance-limiting factors point toward opportunities for further improvement through material quality enhancement and interface engineering [15].

Capacitance–voltage (*C–V*) measurements at 1 MHz in dark conditions offer further understanding of the device physics (Figure 8). The capacitance rises with the increase in applied voltage before it starts to decline, which aligns with the anticipated behavior of a p-n heterojunction and the existence of a depletion region. Conductance shows an upward trend with voltage, featuring a noticeable increase around 0.4 V, signifying the beginning of considerable carrier injection and potential trap-assisted recombination. The Mott–Schottky graph ($1/C^2$ *vs. V*) displays a linear, downward-sloping segment, validating the p-type characteristics of the absorber along with a consistent doping profile [16]. Analyzing the doping profile indicates a higher carrier concentration closer to the surface, likely linked to interface states or carrier injection, before it stabilizes at greater depths within the absorber. These findings are in strong agreement with established models for CIGS thin-film solar cells.

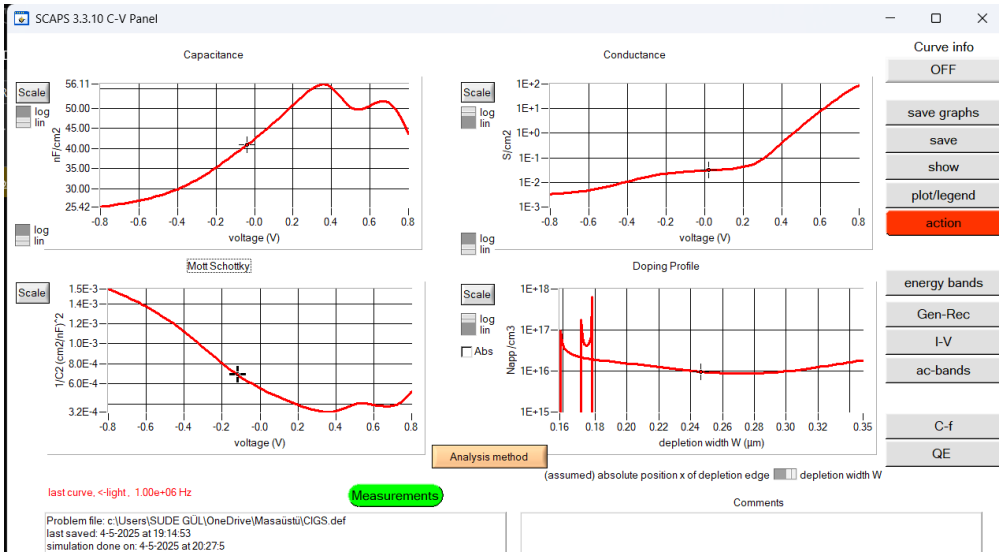


Figure 8. (a) Capacitance–voltage curve, (b) conductance–voltage curve, (c) Mott–Schottky analysis, and (d) doping profile extracted from the SCAPS-1D simulation.

Further insight into trap dynamics and interface quality is obtained from capacitance–frequency (*C–f)* and conductance–frequency measurements (**Figure 9**). Capacitance remains nearly constant at low frequencies, then rapidly drops at frequencies above 10^5 Hz, reflecting the inability of slower trap states to respond to high-frequency signals. Conductance rises with frequency, highlighting the activation of trap-related processes and the increasing contribution of interface states at higher frequencies.

The Nyquist plot presents a semicircular shape, characteristic of a single *RC* time constant, and the G/ω vs. frequency graph demonstrates a monotonic decrease, reaching a minimum at high frequencies. These features are indicative of trap state response times and can be used to estimate trap densities and time constants, which are critical parameters for further device optimization.

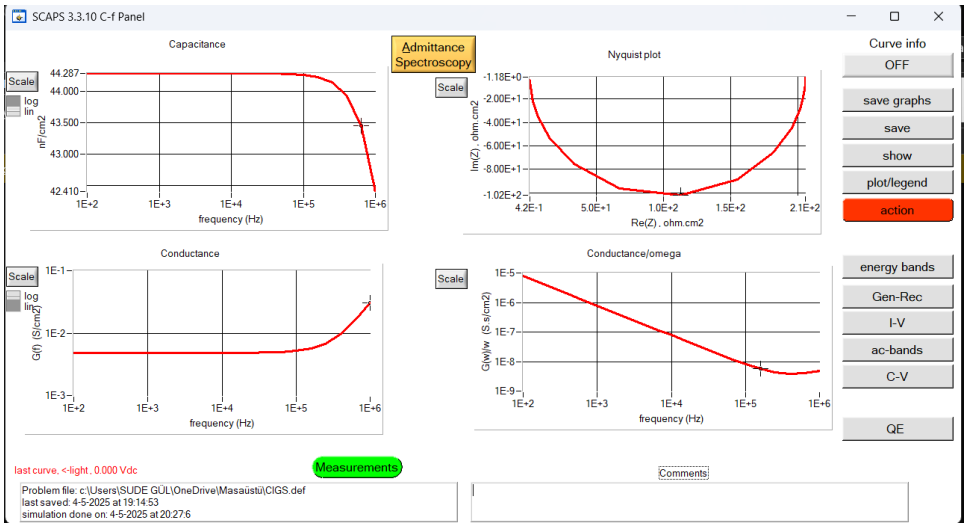


Figure 9. (a) Capacitance–frequency, (b) conductance–frequency, (c) Nyquist plot, and (d) G/ω vs. frequency for the simulated device.

The external quantum efficiency *(EQE or QE*) spectrum, shown in Figure 10, demonstrates the wavelength-dependent photon-to-electron conversion efficiency of the device. The QE is low in the 300–500 nm range, attributed to optical losses in the front layers, but reaches up to 80% between 500–900 nm, reflecting efficient absorption and carrier extraction in the CIGS absorber. QE drops rapidly above 900 nm as sub-bandgap photons are not absorbed.

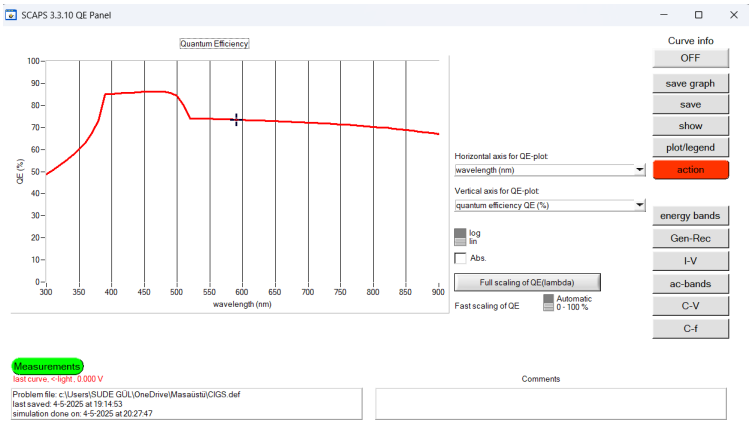


Figure 10. Simulated quantum efficiency (QE) spectrum of the CIGS/CdS/FTO device.

These results confirm that the device performs well in the mid-visible to near-infrared region, while improvements in short- and long-wavelength response could be achieved through antireflection coatings, optimized window layers, and absorber engineering.

CONCLUSIONS

In this study, the optoelectronic properties and performance of CIGS/CdS/FTO thin-film solar cells were systematically investigated using the SCAPS-1D simulation software. The simulation results demonstrated that the CIGS absorber layer provides strong light absorption and efficient charge generation, as evidenced by the high short-circuit current density (Jsc = 36.55 mA/cm²). However, the relatively moderate open-circuit voltage (Voc = 0.4295 V) and fill factor (FF = 62.45%) indicate that interface recombination and resistive losses remain significant limiting factors, resulting in an overall energy conversion efficiency of 9.80%.

Detailed analyses of band alignment, carrier distribution, capacitance-voltage characteristics, and quantum efficiency highlighted the critical influence of layer thicknesses, defect states, and interface properties on device performance. The observed quantum efficiency spectrum confirms effective operation in the visible to near-infrared range, while losses at short and long wavelengths suggest avenues for further structural optimization.

Overall, this work provides valuable insight into the physical mechanisms governing the performance of CIGS-based thin-film solar cells and underscores the importance of device engineering for future efficiency improvements. The simulation approach employed here offers a robust platform for the design and optimization of high-performance thin-film photovoltaic devices, and the findings serve as a useful reference for guiding experimental efforts and advancing CIGS solar cell technology.

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