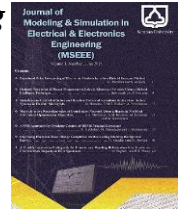




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Dual-Mechanism Enhancement in Ultrathin CIGS Solar Cells via Secondary Absorber and Passivated Layer Integration

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Abstract-- This study investigates the combined influence of a rear passivation layer and a secondary absorber on the performance of ultrathin CIGS solar cells through numerical simulations. Three potential secondary absorber materials—CIS, GaAs, and CGS—were systematically examined to assess their impact on device behavior. The results show that the incorporation of CIS leads to performance degradation, mainly due to enhanced rear-interface recombination. In contrast, both GaAs and CGS noticeably improve the device efficiency. The optimal configuration was achieved using a 0.2 μm CGS layer beneath a 0.8 μm CIGS absorber, which increased the power conversion efficiency from 19.77% to 25.5%. This improvement is primarily attributed to favorable band alignment, the formation of an effective back-surface field, and a strong reduction in rear-interface recombination losses. Although electric-field analysis revealed that GaAs generates a higher field peak at the rear interface, CGS offers superior band matching and interface quality, ultimately resulting in better overall device performance. These findings highlight that the combination of rear passivation with CGS as a secondary absorber is a promising strategy for suppressing recombination and enhancing the efficiency of ultrathin CIGS solar cells.

Index Terms- CIGS solar cell, solar cell efficiency, rear passivation, Cd-free CIGS solar cell

1. INTRODUCTION

Photovoltaic energy is a viable and efficient resource that can address energy concerns. Numerous research efforts focus on developing and fabricating CIGS solar cells[1]. CIGS solar cells possess a larger absorption coefficient compared to

silicon-based solar cells, which have achieved the highest efficiency of 23.8% at the laboratory level to date[2].

Thin-film solar cells have attracted considerable attention due to their potential for high efficiency, reduced material consumption, and compatibility with flexible and low-cost photovoltaic technologies. In particular, CIGS, CdTe, and CGS-based devices have been extensively investigated through numerical simulations to optimize device architecture, absorber thickness, buffer layers, and tandem configurations. Previous studies have demonstrated the significant influence of these structural and material parameters on the photovoltaic performance of thin-film solar cells [3-5].

Various techniques are being developed to improve the efficiency and performance of CIGS solar cells [6-11]. Efficient CIGS solar cells have traditionally employed a chemically bath-deposited cadmium sulfide (CdS) buffer layer. However, the 2.45 eV band gap of CdS restricts the cell's ability to collect short-wavelength photons and consequently reduces the short-circuit current [12]. CdS is also associated with environmental and safety concerns and, therefore, needs to be replaced. Current research is mainly focused on two general approaches to overcome these limitations: first, discovering and developing new buffer layer materials with wider band gaps; and second, carefully designing the electronic band structures at the critical interfaces between the window layer and buffer layer, as well as between the buffer layer and the CIGS absorber layer [13-22].

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Over the past decade, ZnMgO films have attracted increasing interest in the photovoltaic community. ZnMgO films have been investigated as potential alternatives to cadmium-based buffer layers in CIGS solar cells. The flexibility of ZnMgO films originates from the tunability of their band gap, which enables design optimization through controlled modification of the magnesium content [23–28]. The wider band gap allows the CIGS absorber to harvest more high-energy photons in the short-wavelength region, where CdS films exhibit limited transparency. In this work, we focus on the ZnMgO/ZnSO double buffer layer structure and its properties. The band gap is one of the most important parameters determining solar cell performance, as it governs both optical absorption and electrical transport properties.

One approach to improving charge collection is the introduction of additional electric fields within the solar cell. These fields are beneficial because they reduce carrier losses through recombination and enhance charge separation efficiency [29, 30].

The high production cost of CIGS solar cells is significantly affected by the limited availability of indium. Reducing the CIGS absorber thickness to conserve indium can result in performance degradation because CIGS layers thinner than 1 μm exhibit reduced light absorption and increased recombination at the back contact. Therefore, current research aims to minimize material consumption while maintaining high efficiency through strategies such as nanostructured light trapping and band gap grading within the CIGS absorber layer. Although thinner photovoltaic cells can reduce material costs and potentially increase manufacturing throughput, they also introduce challenges that can degrade efficiency, mainly due to increased recombination losses and reduced optical path lengths, which limit photon absorption [31–36].

Rear passivation has become an essential strategy for mitigating recombination losses in thin CIGS solar cells. As the absorber thickness decreases, photogenerated carriers are more likely to reach the back contact, where interface defects can induce severe non-radiative recombination, leading to reductions in Voc and overall efficiency [37–40]. Introducing a passivation layer at the rear interface can suppress these defects and create a back-surface field (BSF) that repels minority carriers away from the back contact [41–43]. Common materials such as Al_2O_3 , SiO_2 , HfO_2 , and MgF_2 have demonstrated promising results, not only by reducing electronic losses but also by reflecting unabsorbed photons back into the absorber layer, thereby enhancing optical confinement [44]. This dual functionality makes rear passivation a critical design strategy for achieving high-efficiency ultrathin CIGS devices.

The introduction of a secondary absorber layer has emerged as a promising strategy to address recombination losses at the rear contact of CIGS solar cells. Positioned between the bulk CIGS absorber and the back electrode, this layer is typically designed with a wider band gap, creating an energy barrier that repels minority carriers from defect-rich rear interfaces. As a result, non-radiative recombination is suppressed, while the majority carriers can efficiently transport toward the back contact. Furthermore, the secondary absorber can enhance the

built-in electric field, thereby promoting charge separation and improving carrier collection. Materials investigated for this purpose include wide-band-gap chalcopyrites, transition metal oxides, and highly doped p-type semiconductors, which have demonstrated significant improvements in open-circuit voltage (Voc) and fill factor (FF) in both simulation and experimental studies.

Recent studies have highlighted the dual role of secondary absorber layers in enhancing both electronic and optical properties. It has been demonstrated that introducing a vanadium oxide (V_2O_5) back-surface field (BSF) layer beneath the CIGS absorber, combined with a ZnSe buffer layer, can effectively suppress rear-surface recombination and improve the overall efficiency of ultrathin devices. Other studies have reported that the incorporation of a highly doped p-type silicon BSF layer, acting as a secondary absorber, provides significant performance improvements in solar cells with sub-micron absorber thicknesses [38, 39, 43].

In this study, we employ SiO_2 as a rear passivation layer in CIGS solar cells. SiO_2 has been widely recognized for its excellent passivation properties due to its high chemical stability, wide bandgap, and ability to effectively reduce interface defect states.[45, 46]. Furthermore, its dielectric nature allows it to act as a reflector for unabsorbed photons, thereby improving optical confinement and compensating for reduced absorber thickness. The choice of SiO_2 is also motivated by its abundance, low cost, and compatibility with large-scale thin-film deposition processes, which make it a practical candidate for industrial implementation.

In addition to rear passivation, this work investigates the incorporation of a secondary absorber at the rear side of an ultrathin Cd-free CIGS solar cell. Although rear passivation, BSF structures, and secondary absorber layers have been investigated in previous studies, the combined influence of these elements strongly depends on the band alignment, interface properties, and thickness of the secondary material. Therefore, the mere addition of a secondary absorber does not necessarily lead to improved device performance.

In this work, CIS, GaAs, and CGS are systematically evaluated as secondary absorbers within the same CIGS device architecture incorporating a SiO_2 rear-passivation structure. Particular attention is given to the relationship between band alignment, rear-interface electric-field distribution, recombination, and carrier collection. This approach makes it possible to distinguish whether the performance improvement originates primarily from enhanced optical absorption or from electronic effects associated with rear-interface engineering. The results further show that a stronger electric-field peak alone is insufficient to achieve the best performance, as demonstrated by the comparison between GaAs and CGS. The main contribution of this work is therefore the identification and physical interpretation of an investigated SiO_2 -passivated CIGS/CGS rear structure for ultrathin Cd-free CIGS solar cells, rather than the simple combination of rear passivation and a secondary absorber.

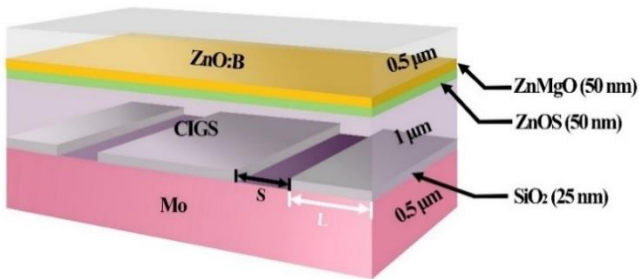
The selection of CIS, GaAs, and CGS as secondary absorbers was based on their distinct electronic properties and

their potential influence on the rear-interface behavior of CIGS solar cells. CIS and CGS were selected due to their chalcopyrite structure and greater compatibility with CIGS-based photovoltaic technology, allowing investigation of secondary absorber materials with similar structural characteristics. CGS, in particular, offers a suitable bandgap and favorable band alignment with CIGS, making it a promising candidate for rear-interface engineering. GaAs was included as a reference III–V semiconductor because of its excellent optoelectronic properties and high absorption capability, enabling evaluation of the impact of a high-quality semiconductor with different material characteristics. It should be noted that the inclusion of GaAs in this comparative study does not imply a direct industrial fabrication pathway with CIGS, considering differences in cost, crystal structure, and processing requirements. Instead, it provides insight into how secondary absorber properties affect carrier transport, band alignment, and recombination behavior. Among these materials, chalcopyrite-based absorbers such as CIS and CGS are considered more compatible with existing CIGS fabrication approaches, while further experimental studies are required to evaluate practical integration challenges.

II. DESIGN ARCHITECTURE

A three-dimensional representation of the structural configurations for both conventional and proposed CIGS solar cells is provided in Fig. 1. The conventional device comprises five sequential layers: ZnO:B/ZnMgO, ZnSO, CIGS, and a Molybdenum back contact. Device modeling incorporates Shockley-Read-Hall recombination under both low and high-injection regimes, along with mobility parameters that vary with carrier concentration and electric field. All simulations were performed using the Silvaco TCAD platform to ensure high-fidelity results.

a)



b)

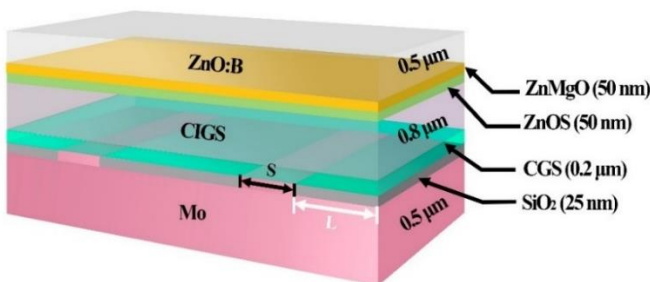


Fig. 1. (a) conventional CIGS solar cell with rear passivation, (b) proposed CIGS solar cell with rear passivation and secondary absorber.

For the numerical simulations, the physical models implemented in the Silvaco TCAD environment were consistently applied to all device configurations. The carrier transport, carrier statistics, bandgap narrowing, optical absorption/generation, and interface recombination models were enabled according to the simulation conditions used in this study. Shockley–Read–Hall recombination was considered for both low- and high-injection conditions, while the carrier mobility was modeled as a function of carrier concentration and electric field. The optical generation was calculated under AM1.5G illumination with an incident power density of 1000 W/m². The same physical models and boundary conditions were maintained for the reference and proposed structures to ensure a consistent comparison. These settings were used throughout the simulations reported in this work.

TABLE I
Simulation Parameter Values for Both Devices[37]

Parameters	GaAs	CIS	CGS	CIGS
Thickness (μm)	variable	variable	0.2	0.8
Bandgap (eV)	1.42	1.02	1.68	1.38
Electron affinity (eV)	4.07	4.35	3.68	4
Relative permittivity (F/cm)	13.2	13.5	13.6	13.6
Conduction band effective density of states (cm ⁻³)	4.35×10^{17}	2.2×10^{18}	2.2×10^{18}	2.2×10^{18}
Valence band effective density of states (cm ⁻³)	1.29×10^{19}	1.8×10^{19}	1.8×10^{19}	1.8×10^{19}
Electron mobility (cm ² /V.s)	8500	100	100	100
Hole mobility (cm ² /V.s)	400	25	25	25
Acceptor (cm ⁻³)	10^{20}	3×10^{17}	3×10^{17}	3×10^{17}
Donor (cm ⁻³)	0	0	0	0
Trap density	5×10^{15}	8.4×10^{13}	8.4×10^{13}	8.4×10^{13}

To analyze the solar cell performance, we utilized AM 1.5G spectrum illumination at a power density of 1000 W/m². Material parameters for simulation are provided in Table I. To ensure the accuracy of the simulation, the results were compared with two reference devices. The first was a CIGS solar cell without any rear passivation layer, as shown in Fig. 2, and its corresponding energy band diagram is illustrated in Fig. 3. Also, the experimental and simulation results are presented in Table II.

Rear passivation in the target solar cell is achieved by using three SiO₂ elements underneath the CIGS layer, as indicated in Fig. 1-b. The investigated size for the passivation boxes is used in our previous work ($L=0.1\mu\text{m}$, $s=0.1\mu\text{m}$)[37].

It should be noted that interface defects were considered in the TCAD simulations through the interface defect density parameter. The photovoltaic performance is sensitive to the quality of the semiconductor interfaces, since an increase in interface defect density introduces additional recombination centers and consequently reduces carrier collection and device efficiency. Therefore, the reported efficiency of 25.5% corresponds to the specified interface conditions considered in the present simulations and should not be interpreted as an unconditional practical efficiency. In an experimental device,

additional effects such as interdiffusion, lattice mismatch, and process-induced interface defects may further influence the recombination behavior and photovoltaic performance. These factors should be carefully controlled during fabrication and will require further experimental investigation.

III. RESULT AND DISCUSSION

As discussed earlier, minimizing carrier recombination is one of the most effective approaches to enhance solar cell efficiency. A clearer understanding of this issue can be achieved by considering the carrier collection probability in solar cells. This parameter represents the chance that a photogenerated charge carrier can travel to the p-n junction and be successfully collected as part of the photocurrent. The collection probability is mainly influenced by two factors: the distance a carrier must travel relative to its diffusion length, and the extent of recombination occurring at the device surfaces and interfaces.

In the depletion region, this probability is nearly unity because the internal electric field rapidly separates electrons and holes and directs them toward their respective contacts. In contrast, as the generation point moves farther from the junction, the likelihood of collection gradually decreases. Carriers generated at distances exceeding their diffusion length have a significantly reduced probability of reaching the junction. Likewise, carriers formed near surfaces or interfaces with high recombination rates are more prone to recombine before they can contribute to the photocurrent [48].

TABLE II

Comparison of the Simulation and Experimental Results of the CIGS Solar Cell [47]

	J_{sc} (mA/cm ²)	V_{oc} (V)	FF (%)	η (%)
Simulation Results	39.8	0.736	80.5	23.37
Experimental Results	39.6	0.734	80.4	23.35

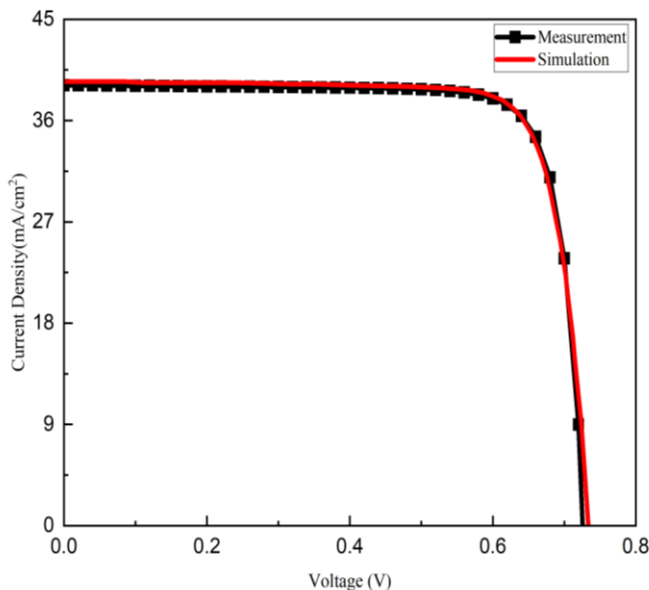


Fig. 2. Measured and simulated J-V characteristics of the conventional CIGS solar cell[47]

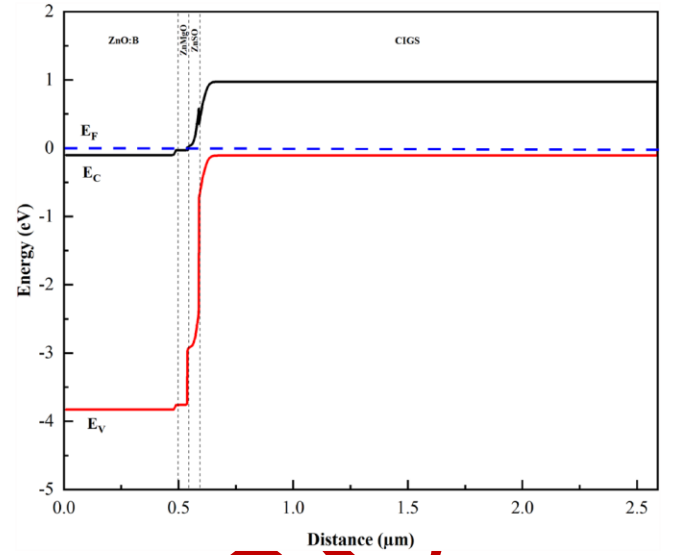


Fig. 3. Energy band diagram of the conventional cell under equilibrium conditions

As mentioned earlier, the carrier collection probability decreases significantly near the solar cell surface [49]. This reduction is strongly influenced by the surface recombination velocity, such that higher values of recombination velocity result in increased carrier losses and, consequently, a lower collection probability. As a result, reducing the surface recombination velocity is a crucial factor in improving the light-generated current density.

As noted previously, electron-hole pairs generated close to the back surface of the solar cell are particularly susceptible to recombination because of the short lifetime of minority carriers in this region. One effective approach to mitigate this loss mechanism is the formation of an electric field at the rear interface, which can be realized by introducing a passivation layer. As shown in Fig. 4, the electric field profile across the device exhibits a pronounced peak at the back surface in the presence of this passivation layer. This localized electric field acts as a barrier, preventing minority carriers from diffusing toward the defect-rich rear contact.

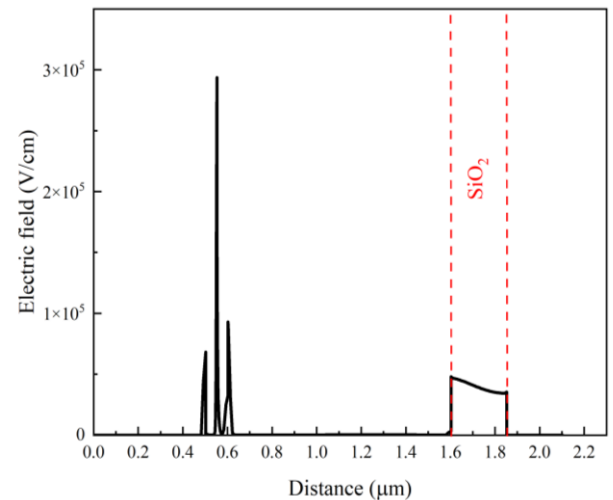


Fig. 4. Electric field distributions of the passivated CIGS solar cells

Instead, the field drives these carriers toward the depletion region, where they can be efficiently separated and collected. In this way, the passivation layer not only reduces carrier losses but also actively enhances charge collection. Building upon this concept, the introduction of a secondary absorber layer can further reinforce this effect by generating additional field peaks within the device structure. These extra field regions help guide carriers more effectively, minimizing the chances of recombination and ultimately increasing the photocurrent. This dual strategy—combining rear passivation with secondary absorbers—offers a promising pathway for sustaining high efficiency in ultrathin CIGS solar cells, where carrier losses at the back contact are otherwise a critical limiting factor.

It should be noted that the electric field observed within the SiO_2 rear-passivation layer does not originate from free carrier transport, as SiO_2 is an insulating dielectric with negligible carrier concentration. Instead, this field results from the electrostatic potential distribution established by fixed oxide charges at the SiO_2/CIGS interface. These charges modify the local electric potential and induce band bending near the rear semiconductor interface. Therefore, the role of the SiO_2 layer is not to provide a transport path for carriers, but rather to electrostatically influence the adjacent CIGS region by reducing unfavorable carrier accumulation and suppressing rear-interface recombination. Consequently, the electric-field distribution should be interpreted as an interface-engineering effect rather than direct carrier transport through the dielectric layer.

A. CIS as secondary absorber

We first investigated the use of CIS (CuInSe_2) as a secondary absorber layer positioned beneath the main CIGS absorber and directly above the back contact. Since CIS has a smaller bandgap compared to CIGS, one might initially expect it to absorb longer-wavelength photons that are not captured in the CIGS layer, thereby contributing positively to the photocurrent. However, the simulation results indicate the opposite behavior: introducing CIS reduces device efficiency, and this negative impact becomes more pronounced as CIS thickness increases while the CIGS thickness reduces (Fig. 5).

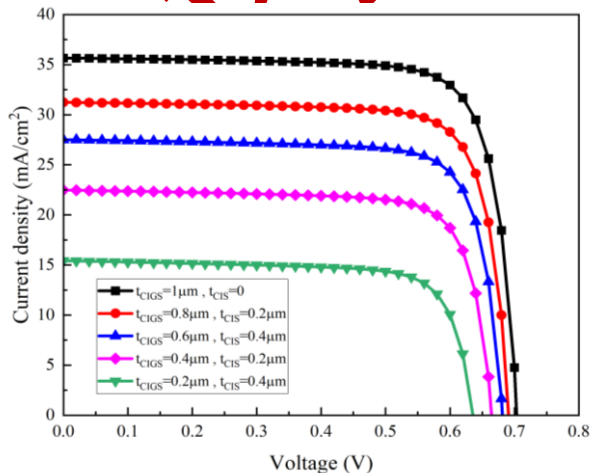


Fig. 5. Effect of the CIS layer as a secondary absorber and its thickness variation

This outcome can be explained by several physical mechanisms. First, inserting a narrower-bandgap CIS layer at the rear interface disrupts the beneficial band alignment that typically acts as a back-surface field (BSF) in ultrathin CIGS devices. Instead of repelling minority carriers away from the rear, the CIS region forms a bandgap notch that attracts electrons toward the back contact, thereby increasing the likelihood of recombination. Second, photons absorbed in the CIS layer generate carriers farther away from the p-n junction. Due to the limited diffusion length and carrier lifetime, many of these carriers recombine before reaching the junction, which means the additional optical absorption in CIS does not translate into useful current. Third, reducing the thickness of the main CIGS absorber to accommodate CIS further compromises device performance, since CIGS generally supports better carrier collection than the rear CIS region. Finally, the CIS/back-contact interface itself remains recombination-active, and without a true passivation barrier, the overall rear recombination velocity remains high.

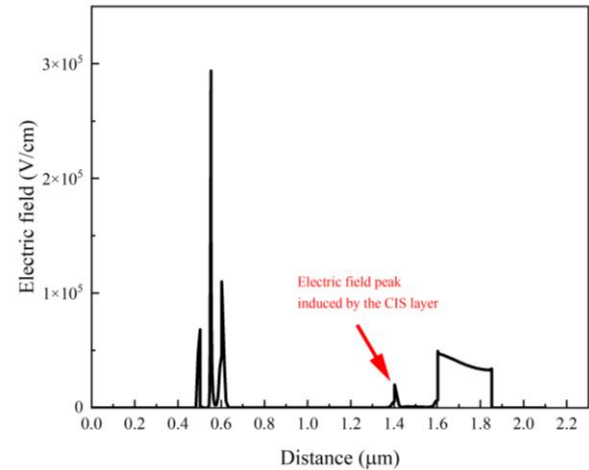


Fig. 6. Electric field distributions of the passivated CIGS solar cells with CIS as secondary absorber

The electric-field distribution provides further insight into this behavior. As shown in Fig. 6, the introduction of CIS creates a small local field peak at the CIGS/CIS interface. This peak arises from the discontinuity in bandgap and doping at the heterointerface, which causes limited charge accumulation. However, the magnitude of this peak is weak, and its spatial extent is too narrow to function as an effective passivation field. As a result, it does not significantly suppress recombination at the rear contact nor provide meaningful protection for minority carriers.

In summary, including CIS as a secondary absorber beneath CIGS is counterproductive. Instead of enhancing the current generation, it increases rear recombination, diminishes the effectiveness of the back-surface field, and reduces overall efficiency. These findings emphasize that successful rear-side engineering in ultrathin CIGS devices requires strategies focused primarily on recombination reduction rather than on extending optical absorption, such as employing wider-bandgap

secondary absorbers and robust dielectric passivation layers.

B. GaAs as a secondary absorber

In the next stage, GaAs was introduced as a secondary absorber layer positioned beneath the CIGS absorber. Unlike CIS, the inclusion of GaAs leads to a clear improvement in device performance. Simulation results show that the optimal configuration occurs when the GaAs thickness is $0.2\ \mu\text{m}$, and the CIGS thickness is $0.8\ \mu\text{m}$, yielding a significant increase in efficiency from 19.77% to 25.2% (Fig. 7).

The underlying reasons for this improvement can be explained through both optical and electrical effects. First, GaAs possesses a wider bandgap than CIS, which prevents the formation of a bandgap notch at the rear interface. Instead, the GaAs layer contributes to the creation of a back-surface field (BSF) that effectively repels minority carriers away from the defect-prone back contact. This reduces rear-surface recombination and enhances open-circuit voltage and fill factor. Second, photons absorbed within GaAs are generated closer to the depletion region compared to CIS, which increases the probability of successful carrier collection and translates into useful photocurrent. Additionally, the combination of GaAs and CIGS with adjusted thicknesses ensures that the main optical absorption still occurs in CIGS, while GaAs contributes constructively without sacrificing the primary absorber's performance.

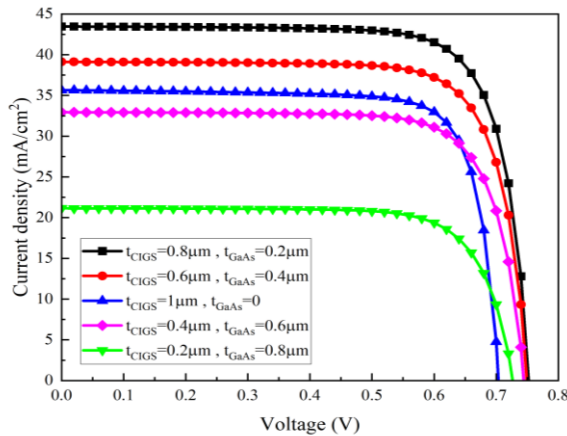


Fig. 7. Effect of the GaAs layer as a secondary absorber and its thickness variation

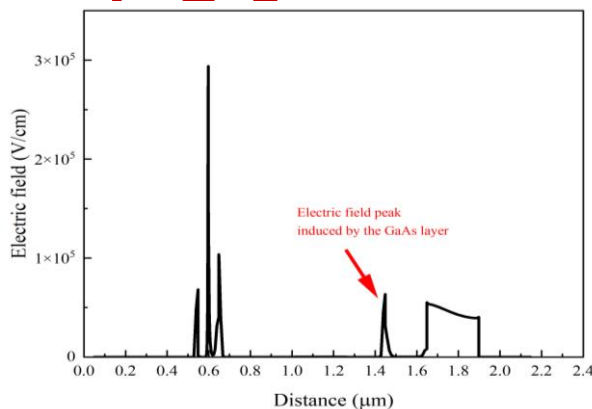


Fig. 8. Electric field distributions of the passivated CIGS solar cells with GaAs as secondary absorber

Further evidence is provided by the electric-field distribution. As shown in Fig. 8, the peak electric field generated by GaAs is nearly four times stronger than the peak produced by CIS. This strong local field significantly helps drive minority carriers toward the junction before they recombine, thereby improving charge collection. Unlike the weak and spatially limited peak induced by CIS, the GaAs-induced field is both stronger and more effective, making it a meaningful contributor to device passivation.

It should be noted that the magnitude of the electric-field peak alone does not determine the photovoltaic performance of the device. The rear electric field primarily influences minority-carrier transport by establishing an electrostatic barrier that reduces minority-carrier accumulation and recombination near the rear contact. However, the effectiveness of this barrier also depends on the band alignment and electronic properties of the heterointerface.

Although the GaAs structure produces a stronger electric-field peak than the CGS structure, the CGS/CIGS interface provides more favorable band alignment and more effective suppression of rear-interface recombination. Therefore, the slightly lower electric-field peak in the CGS structure does not imply inferior carrier collection. Instead, the combined effect of the electric field, band alignment, and interface recombination determines the final device performance. This explains why CGS achieves a slightly higher efficiency (25.5%) than GaAs (25.2%) despite its lower electric-field peak.

C. CGS as secondary absorber

Finally, CGS (CuGaSe_2) was examined as a secondary absorber layer below the primary CIGS absorber. Among all the investigated materials, CGS provided the best overall performance. As shown in Fig. 9, adding a $0.2\ \mu\text{m}$ CGS layer beneath $0.8\ \mu\text{m}$ of CIGS improved the device efficiency from 19.77% to 25.5%. To further validate this configuration, different thickness combinations of CGS and CIGS were simulated. The optimum CGS thickness of $0.2\ \mu\text{m}$ can be attributed to the balance between the electronic benefits of the secondary absorber and the optical and electrical contribution of the primary CIGS absorber. At a relatively small CGS thickness, the layer is sufficient to modify the rear-interface band alignment and establish an effective barrier against minority-carrier recombination. Increasing the CGS thickness further requires reducing the CIGS thickness because the total absorber thickness is maintained at approximately $1\ \mu\text{m}$. This reduction in CIGS thickness limits the effective absorption and collection of photogenerated carriers in the primary absorber. Consequently, beyond $0.2\ \mu\text{m}$, the additional improvement in rear-interface carrier suppression is outweighed by the reduced contribution of the CIGS absorber, leading to a decrease in overall photovoltaic performance. Thus, the $0.2\ \mu\text{m}$ CGS/ $0.8\ \mu\text{m}$ CIGS configuration provides the most favorable balance between rear-interface passivation and effective photon absorption and carrier collection.

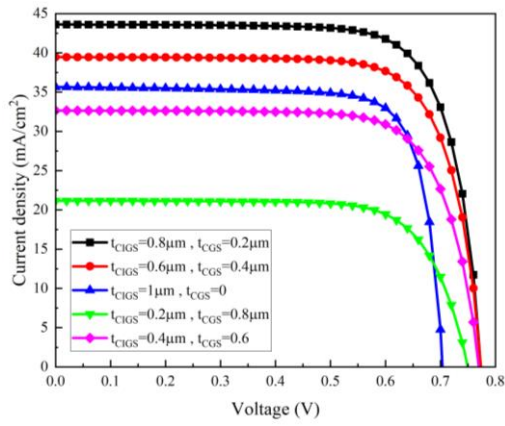


Fig. 9. Effect of the CGS layer as a secondary absorber and its thickness variation

The superior performance of CGS stems from a few key factors. First, CGS has a wider bandgap than CIGS, so it avoids inefficient absorption of long-wavelength photons like CIS and instead creates a favorable band alignment at the rear. This alignment forms a back-surface field that pushes minority carriers away from the back contact, reducing recombination. Second, because most light is still absorbed in the CIGS layer near the depletion region, CGS mainly acts as an electronic barrier without competing for absorption. This minimizes carrier losses and boosts open-circuit voltage, fill factor, and overall efficiency. Electric-field analysis supports this view: CGS produces a clear field peak at the rear interface. While slightly smaller than GaAs, it provides effective carrier repulsion and, importantly, better band alignment and material compatibility with CIGS. This ensures smoother carrier transport and fewer recombination-prone defects, explaining why CGS delivers the highest efficiency improvement among the secondary absorbers tested.

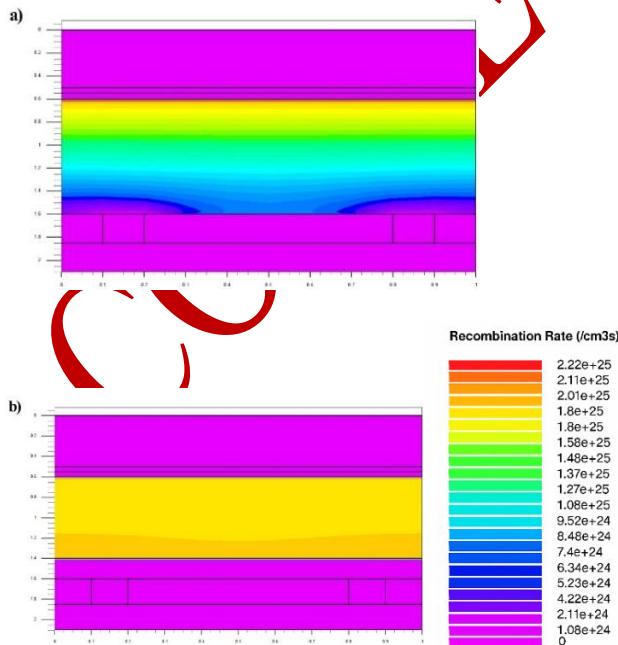


Fig. 10. Recombination rate in (a) the cell without CGS and (b) with CGS

To further investigate the effect of the CGS secondary absorber on carrier-loss mechanisms, the recombination-rate distributions of the reference CIGS structure without CGS and the proposed CGS/CIGS structure were analyzed, as shown in Fig. 10. In the structure without CGS (Fig. 10a), a higher recombination activity is observed near the rear interface, indicating increased carrier losses in this region. After introducing the CGS secondary absorber (Fig. 10b), the recombination rate near the rear side is reduced, demonstrating the beneficial effect of rear-interface engineering. This reduction can be attributed to the combined influence of improved band alignment and electrostatic field modulation provided by the CGS layer, which reduces minority-carrier accumulation near the rear interface and decreases the probability of recombination. These results provide additional evidence that the performance enhancement of the proposed structure is not solely related to electric-field redistribution, but also originates from effective suppression of recombination losses at the rear interface.

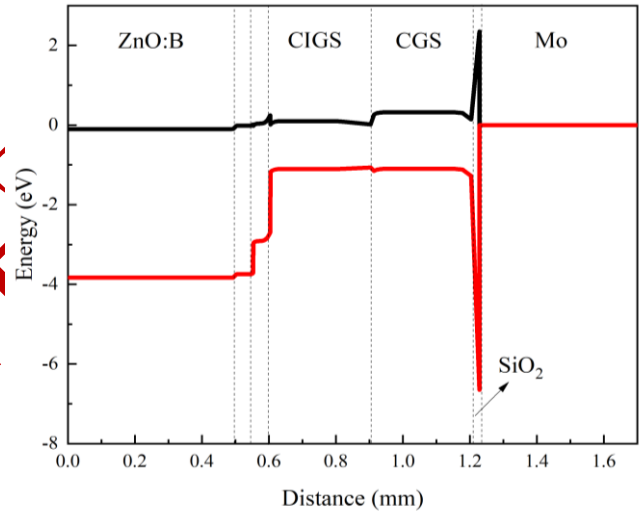


Fig. 11. Simulated energy band diagram of the proposed ZnO:B/CIGS/CGS/SiO₂/Mo structure showing the band alignment and rear-interface barrier formation induced by the CGS secondary absorber.

D. Investigated cell

As discussed earlier, the highest efficiency was achieved when CGS (CuGaSe₂) was employed as a secondary absorber layer beneath CIGS. This investigated configuration provided a significant improvement in device performance compared to other designs, confirming CGS as the most effective choice for suppressing rear recombination and enhancing carrier collection.

Although the proposed SiO₂/CGS/CIGS structure demonstrates promising photovoltaic performance through numerical simulations, its practical fabrication requires further investigation. The deposition of a rear SiO₂ passivation layer beneath an ultrathin CIGS absorber should be carefully controlled to maintain interface quality and minimize defect formation. In addition, integrating a CGS secondary absorber requires precise control of deposition conditions to achieve suitable band alignment while preventing undesirable elemental

diffusion across the CGS/CIGS interface. Possible approaches, such as controlled thin-film deposition techniques followed by appropriate thermal treatments, may provide a pathway for realizing the proposed structure. However, challenges related to interface contamination, adhesion between different layers, diffusion management, and compatibility with existing CIGS fabrication processes must be addressed experimentally. Therefore, further experimental studies are required to validate the proposed architecture and investigate the fabrication conditions for practical photovoltaic applications.

To further evaluate the stability of this proposed device, the effect of trap density (N_t) was investigated (Fig. 12). The results clearly demonstrate that increasing trap density leads to a reduction in efficiency, fill factor (FF), short-circuit current density (J_{sc}), and open-circuit voltage (V_{oc}). This degradation can be explained by the fact that higher defect density introduces additional recombination centers within the absorber. These defects act as traps for photogenerated carriers, shortening their lifetime and reducing the probability of successful collection.

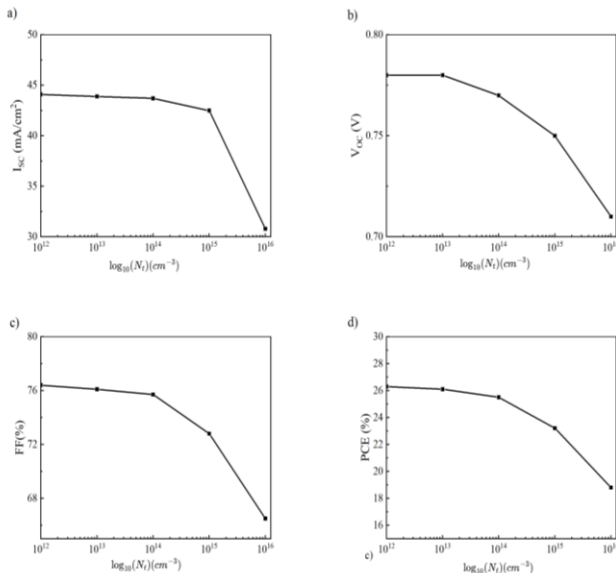


Fig. 12. Effect of absorber trap density on the photovoltaic performance of the CIGS solar cell: (a) short-circuit current density, (b) open-circuit voltage, (c) fill factor, and (d) power conversion efficiency (PCE).

In particular, V_{oc} is strongly affected because recombination lowers the quasi-Fermi level splitting, while FF decreases due to increased recombination losses that distort the ideal diode behavior. J_{sc} also declines as more carriers recombine before being collected at the junction. Consequently, the overall efficiency drops as trap density increases. This analysis highlights the importance of controlling material quality and minimizing trap density in order to preserve the benefits of the proposed CGS/CIGS device structure.

Fig. 13 compares the current–voltage (J–V) characteristics of the proposed cell with those of a device without a secondary absorber and a conventional CIGS cell without rear passivation. As can be observed, the proposed device exhibits superior J–V performance.

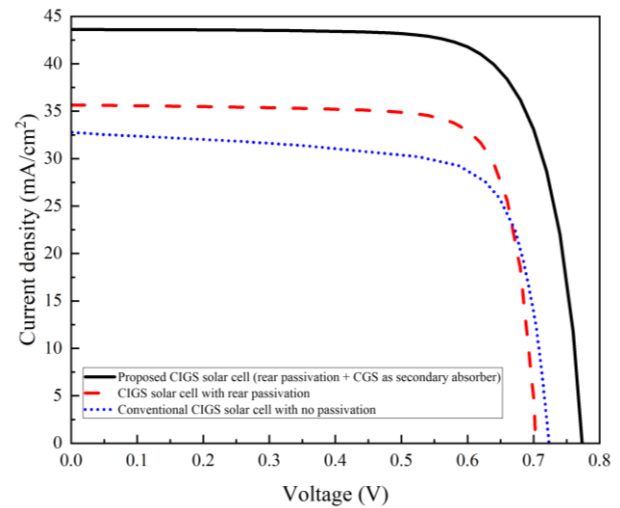


Fig. 13. Comparison of J–V characteristics between the proposed CIGS solar cell with CGS secondary absorber and rear passivation, a CIGS cell without the secondary absorber, and a conventional cell without passivation.

It should be noted that the conventional reference structure used in the comparative analysis of Fig. 10. The structure in Fig. 2 was designed only for model calibration by reproducing the experimentally reported performance of a conventional CIGS solar cell. Therefore, certain parameters, including layer thicknesses and device configuration, differ from those used in the reference structure of Fig. 10.

The improvement in the J–V curve is mainly due to the suppression of rear-surface recombination, which enhances the open-circuit voltage and fill factor. The incorporation of both the CGS secondary absorber and the rear passivation layer establishes favorable band alignment and strong electric-field peaks at the rear interface. These features repel minority carriers from the back contact, allowing more photogenerated carriers to be collected efficiently, thereby increasing the short-circuit current density.

To place the findings of this work in context, the results were compared with those of previously reported studies, as summarized in Table III.

As such, Table III shows that the proposed CGS/CIGS configuration achieves improved simulated photovoltaic performance compared with the investigated ultrathin CIGS structures, highlighting the potential of the dual-layer strategy for improving the performance of thin-film photovoltaic devices.

It should be noted that the values presented in Table III are collected from previously reported studies with different device architectures, material compositions, absorber and buffer layers, and simulation or experimental conditions. Therefore, this comparison is intended to provide a general assessment of the photovoltaic performance of the proposed structure rather than a direct performance ranking under identical evaluation conditions. The proposed CGS/CIGS configuration demonstrates competitive simulated performance within the assumptions and simulation conditions adopted in the present study. A rigorous quantitative comparison with previously reported devices would require identical material parameters, device architectures, and evaluation conditions.

TABLE III
Comparison of Different CIGS Solar Cell Performances

PV characteristic s	J_{sc} (mA/cm ²)	V_{oc} (V)	FF (%)	η (%)	Ref
CIGS solar cell with ZnMgO/ZnS O dual buffer	39.60	0.73	80.40	23.3	[44]
CdS buffer + Al ₂ O ₃ back layer & graded CIGS	35.97	0.71	74.56	19.1	[20]
ZnSO buffer & graded CIGS	35.12	0.87	78.27	24	[50]
ZnMgO/ZnIn S dual buffer & graded CIGS	38.67	0.80	81.20	25.1	[51]
ZnSe/In ₂ S ₂ dual buffer	32.21	0.97	77.14	24.1	[52]
ZnMgO/ZnS O dual buffer with dual rear passivation	35.2	0.86	82	25.5	[53]
ZnMgO/ZnS O dual buffer, SiO ₂ back layer & CGS as secondary absorber	43.7	0.77	75.7	25.5	This Work

In addition, the proposed CGS/CIGS structure could be considered as a potential candidate for future tandem photovoltaic studies involving perovskite solar cells; however, further investigations are required to assess its practical feasibility. In particular, perovskite solar cells based on mesoporous TiO₂ are highly compatible with this configuration [54], as the mesoporous TiO₂ scaffold provides efficient electron extraction and enhanced interfacial contact, which improves charge transport and reduces interfacial recombination at the perovskite/transport layer interface. This leads to improved current matching and overall performance in tandem devices.

IV. CONCLUSION

This study explored how combining a rear passivation layer with a secondary absorber affects ultrathin CIGS solar cells using numerical simulations. The results show that CIS, with its narrower bandgap, could not improve efficiency and even worsened performance due to increased rear recombination, whereas GaAs and CGS significantly enhanced efficiency. In particular, a thin CGS layer beneath the CIGS absorber raised efficiency from 19.77% to 25.5%, thanks to its wider bandgap, favorable band alignment, reduced rear-interface recombination, and effective back-surface field without interfering with light absorption in CIGS. Electric-field analysis confirmed that the rear passivation and secondary absorber work together to suppress carrier losses at the back contact. Although CGS produced a slightly smaller field peak than

GaAs, its better band alignment and interface quality with CIGS resulted in superior overall performance. Device optimization also highlighted the importance of low defect density for sustaining these gains.

Overall, the study demonstrates that integrating rear passivation with a well-chosen secondary absorber—especially CGS—effectively suppresses recombination, improves carrier collection, and significantly boosts the efficiency of ultrathin CIGS solar cells.

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CONFLICTS OF INTEREST

The author declares that there is no conflict of interest regarding the publication of this article.

DATA AVAILABILITY

All data generated or analyzed during this study are included in this published article.

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