

Absorber layer improvement and performance analysis of CIGS thin-film solar cell

A. Khamis^{a,*}, N. I. M. Rodzi^a, N. Z. A. Naharuddin^b

^a*Faculty of Electrical Technology and Engineering, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia*

^b*Fakulti Kejuruteraan Teknologi Elektrik dan Elektronik, Universiti Malaysia Pahang Al-Sultan Abdullah, 26600 Pekan, Pahang, Malaysia*

CIGS has shown significant potential for cost-effective and efficient photovoltaic applications, with efficiency often exceeding 20%. However, further improvements in cell performance are needed to reduce production costs. Thus, this study proposes an ultra-thin structure for CIGS solar cells by modifying the absorber layer thickness and composition. SCAPS software was used to evaluate the performance of the proposed design, such as open-circuit voltage (V_{oc}), short-circuit current (J_{sc}), fill factor (FF%), and conversion efficiency ($\eta\%$). Results showed that ultra-thin solar cells with the proposed GnP and CGS absorber layers are ideal due to their greater $\eta\%$, 25.33%.

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Keywords: Solar cell, Ultra-thin CIGS solar cell, CGS, GnP, Thickness of absorber layer, SCAPS.

1. Introduction

Solar cells are essential for the transition to cleaner, more sustainable energy sources. As the globe struggles with issues of climate change and environmental degradation, solar cells provide a way to generate electricity without spewing greenhouse gases or depleting precious resources [1]. Renewable energy is a potential solution that might be the future of the global supply of electricity in order to meet the necessary demand, which has been gradually increasing every year. Solar power is converted to electrical energy using photovoltaic technology. Common semiconductors used in solar systems include cadmium telluride, copper indium diselenide, microcrystalline silicon, monocrystalline silicon, and polycrystalline silicon [2]. For instance, Copper Indium Gallium Selenide (CIGS) is a semiconductor material that holds significant importance in the field of solar cell technology. CIGS demonstrated high conversion efficiencies, allowing a significant conversion of sunlight into electricity. Ongoing research and development efforts focus on enhancing the efficiency of CIGS solar cells by improving material properties, device architectures, and manufacturing processes. These advancements have the potential to make CIGS technology even more attractive for large-scale adoption.

The absorber layer is a crucial component of a CIGS solar cell. It's the layer that directly absorbs sunlight and generates the electrical charges (electrons and holes) that contribute to the generation of electricity. The properties and characteristics of the absorber layer play a significant role in determining the overall performance and efficiency of the CIGS solar cell.

The buffer and front contact in CIGS solar cells are frequently made of cadmium sulfide and zinc oxide, respectively [4]. The band gap, which determines whether an oxide is transparent to light, is more important than the photon energy of light since it contains energies required to generate electricity. The oxide shouldn't be able to absorb that light, according to this implication. The following layer, known as the absorber layer, consists of a semiconductor material often likened to the 'control center' of solar cells. This layer's capability to capture photons and stimulate electrons causes an overcurrent in the conduction band, confirming this effect [4].

Therefore, the choice of semiconductor material for the absorber layer aligns with the photon range present in the solar cell's section of the sunlight spectrum. At the same time, back-

* Corresponding author: aziah83@gmail.com

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contact solar cells work efficiently to eliminate losses due to shading. In thin solar cells, high-quality material is employed, allowing the rear of the cell to capture the electron-hole pairs generated by light absorption at the front layer. This necessitates the use of a transparent substrate to enable both reflection and absorption within and on the substrate. Thus, thin solar cells can effectively capture electron-hole pairs through a well-performing back contact.

According to the research, performance that consists of open-circuit voltage (V_{oc}), Short Circuit Current Density (J_{sc}), Fill Factor (FF%) and Efficiency ($\eta\%$) were altered by the absorber layer's thickness as more photons were absorbed with an efficiency of 21.3% as opposed to 16.39% for the older structure [4]. The absorber layer band gap thickness is important since it has a bearing on the cell's operation. The thickness of the band gap in the absorber layer is significant because it affects how the cell functions. As a result, it is necessary to reduce the thickness of the absorber layer while maintaining conventional solar cell performance. In addition, temperatures between 288 K and 323 K have an adverse effect on solar cell performance and reduce cell efficiencies[5]. This is brought on by a decrease in bandgap energy. As the temperature rises, the V_{oc} decreases. The cell of the solar itself also needs to be at the right temperature for CIGS solar cells. Conforming to the research, solar cells with a series resistance of 0 to 5 Ω had efficiency levels of 16.39% and 11.88%, respectively [6]. The impact is caused by the connectors' series resistance as well as the metallic contacts' front and back surfaces. Therefore, for optimal performance, series resistance must be in the low range.

Graphene (GnP) a two-dimensional substance that is just one atom thick, is versatile in optoelectronics and photonics, common fields that use ultra-wideband technology. The unique properties of graphene, such as its excellent flexibility, remarkable conductivity, optical transparency, and high stability, are primarily responsible for its widespread utilisation [7]. Every approach has a varied bandgap composition for graphene; for example, compound semiconductors have a direct bandgap of 1.42 eV and good electron mobility at 300 K [8].

In addition, GnP has a broad absorption spectrum in the UV and IR areas, which is useful for photovoltaic systems. Due to its poor visible spectrum absorption coefficient, graphene cannot be used directly as a light absorber in solar cells [7]. However, numerous strategies to increase its ability to absorb light have been investigated by researchers. To change graphene's absorbency properties, one tactic is to manipulate or functionalize it. Another is to combine graphene with other materials to produce hybrid structures [9].

Due to the delocalized electrons' ability to flow freely inside the carbon lattice, graphene has a high electrical conductivity in its purest form. In fact, pure graphene has a conductivity that is higher than that of the majority of metals [8], making it is a good choice to be used as a conductive electrode material in solar cells. Lowering series resistance in earlier GnP sheets with a thickness of 4 nm contributed to improvements in electrical conductivity and carrier movement efficiency in the GnP sheet [9].

Due to their stoichiometry-dependent characteristics, copper gallium selenide (CGS) semiconductor thin films are useful for a variety of optoelectronic devices. According to a number of studies, CGS shows p-type region regardless of fluctuations in its stoichiometry that are explained by the doping-pinning rule [10]. CGS generally has a bandgap that ranges from around 1.0 eV to 1.7 eV. The bandgap value is influenced by the material's composition, stoichiometry, and any intentional doping or alloying. It is possible to adjust the bandgap to maximise sunlight absorption by adjusting the copper, gallium, and selenium ratio [11]. Copper gallium selenide ($CuGaSe_2$, CGS), one of these compounds, has an energy gap of 1.68 eV at ambient temperature and is anticipated to be a potential component for red-light emitting devices [10].

The high absorption coefficient of CGS is advantageous for solar cell applications because it enables efficient light absorption even in relatively thin layers of the material. This feature makes CGS an excellent fit for thin-film solar cell topologies, where a thin layer of absorber material is sufficient to capture a significant amount of sunlight [12][13]. Additionally, CGS's composition and stoichiometry may be changed to enhance its absorption qualities. The bandgap may be adjusted to increase light absorption efficiency by varying the proportions of copper, gallium, indium, and selenium [12][13].

The anion/cation ratio (Se/(Cu Ga)), which is maintained between 0.7 and 1.44, was used to categorise the CGS samples and determine their electrical conductivity at room temperature (300 K). In its pure form, CGS is a p-type semiconductor, meaning that positive charge carriers (holes) dominate and permit electrical conduction [12]. The electrical conductivity of CGS is greatly influenced by the concentration of these holes and their mobility inside the material [11]. Copper vacancies and selenide anti-site defects can both affect the carrier concentration and electrical conductivity.

Both of the solar cell's materials need to be stabilised, particularly in terms of their bandgaps and absorption coefficients. The two-dimensional carbon substance graphene may be included in a number of solar cell parts, such as an electrode or an interface layer. Improved electrical conductivity, improved charge transfer, lower resistance, and higher light absorption are just a few advantages that can come from combining graphene with CGS in solar cells. To ensure compatibility and achieve the necessary performance improvements, it is crucial to keep in mind that the integration of graphene with CGS may require optimisation of manufacturing methods, interface engineering, and device topologies. In order to improve the performance and efficiency of solar cells, ongoing research and development activities are examining several strategies for efficiently combining graphene with CGS.

Thus, this paper proposes a new Ultra-thin CIGS solar cell by improving the absorber layer using the SCAPs simulation and evaluate the proposed solar cell with existing CIGS solar cell structure. More specifically, the proposed CIGS involves two major steps. First, the proposed solar cell's performance is evaluated with respect to its electrical properties based on a few parameters, including operating temperature, absorber thickness, and series resistance, using the SCAPS simulation. Next, data analysis for CIGS solar cell performance is done to investigate efficiency ($\eta\%$), Fill Factor (FF), Open Circuit Voltage (Voc), Short Circuit Current Density (Jsc), and solar cell structure performance. The SCAPs simulation programme is then verified using the study paper's Quantum Efficiency finding. Note that this project's scope includes researching various solar cell structures that are currently in use and comprehending the factors that can affect solar cell performance. The behaviour of charge carriers within the absorber layer is better understood by researchers using computational models and simulations, which can assist them forecast how performance will vary as material properties or device architecture change.

2. Numerical simulation

There are various numerical methods such as PC1D, ANSYS Semiconductor, Silvaco TCAD, and Matlab/Simulink, which can be utilized to observe the behavior of photovoltaic systems in order to find a suitable parameter and test a new parameter in a solar cell. One of the specialized forms of simulation used in the field of photovoltaics (solar cells) is known as solar cell capacitance simulation (sometimes referred to as SCAPs simulation). SCAPS is a 1-D simulation tool for solar cell architectures developed by researchers at the University of Gent, Belgium's Department of Electronics and Information Systems (ELIS).

The SCAP simulation was designed to assess and anticipate the electrical performance and behavior of solar cells based on their capacitance characteristics. The SCAP simulation assists scientists and engineers in grasping and optimizing a variety of solar cell capacitance-related elements, such as efficiency analysis and design enhancement. The SCAP simulation permitted a complete analysis of the efficiency of the solar cell by taking into account its capacitance features. As a result, this analysis assists in identifying potential improvement areas and improving the design for improved conversion efficiency. Thus, this analysis assists in identifying potential improvement areas and improving the design for improved conversion efficiency. Meanwhile, scientists and engineers may examine how different material selections, device designs, and manufacturing techniques impact overall performance by modeling solar cell capacitance. With this understanding, solar cell designs may be altered to obtain higher stability and efficiency.

2.1. Application SCAPs for CIGS solar cell

In this study, the Spectral-Correlation-Analysis Procedure (SCAP) was employed to assess the effectiveness of modifying layer parameters and other variables for both Ultra-thin CIGS solar cells with a GNP+CGS absorber layer and conventional CIGS solar cells. The process of creating the Ultra-thin CIGS solar cells with the GNP+CGS absorber layer, progressing from the front to the rear surface of the solar cell, is illustrated in Figure 1, while Figure 2 exhibit the structure of CIGS. Table 1 tabulates the parameter values for each layer that is being used in SCAP's simulation software.

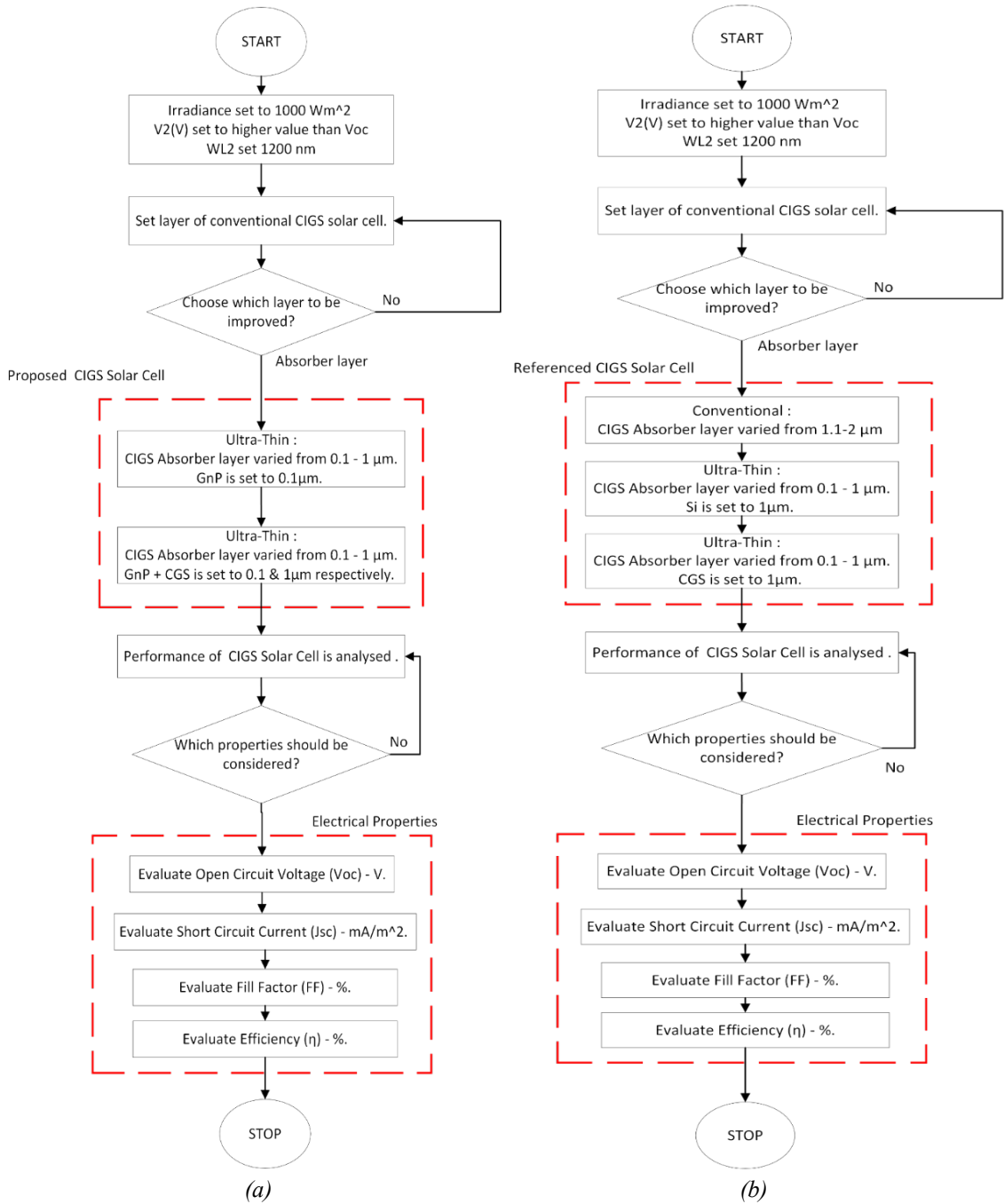


Fig. 1. Flowchart for CIGS solar cell (a) Proposed CIGS solar cell (b) Referenced CIGS solar cell.

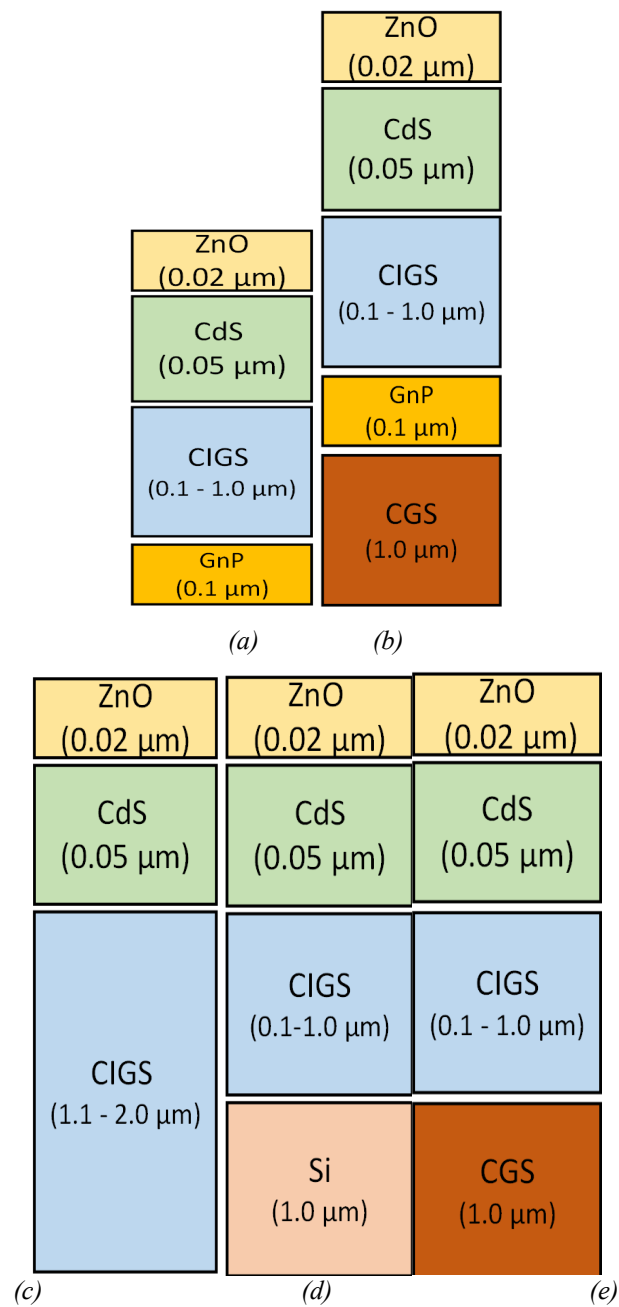


Fig. 2. (a) Solar cell structure for ultra-thin CIGS solar cell with proposed GnP absorber layer, (b) solar cell structure for ultra-thin CIGS solar cell with proposed GnP +CGS absorber layer, (c) solar cell structure for ultra-thin CIGS solar cell with CGS absorber layer, (d) solar cell structure for ultra-thin CIGS solar cell with Si absorber layer, (e) solar cell structure for conventional CIGS solar cell.

Table 1. Parameter value for each layer in SCAPs simulation software.

Parameter	n-ZnO	n-CdS	p-CIGS	p-Si	p-GnP	p-CGS
Thickness (μm)	0.02	0.05	conventional (1.1- 2) Ultra-thin (0.1 -1)	1.00	0.10	1.00
Bandgap, E_g (eV)	3.30	2.45	1.10	1.12	1.80	1.66
Electron affinity, X_e (eV)	4.60	4.40	4.50	4.05	3.92	3.67
Dielectric constant, ϵ_r	9.00	10.00	13.60	11.90	10.00	8.15
Density of states at conduction band, N_c (cm^{-3})	2.20×10^{18}	2.20×10^{18}	2.20×10^{18}	2.80×10^{19}	2.80×10^{19}	2.20×10^{17}
Density of states at valence band, N_v (cm^{-3})	1.80×10^{19}	1.80×10^{19}	1.80×10^{19}	2.65×10^{19}	2.65×10^{19}	1.80×10^{18}
Electron mobility, μ_n (cm^2/Vs)	100.00	100.00	100.00	1450.00	1.00×10^9	100.00
Hole mobility, μ_p (cm^2/Vs)	25	25	25	500	10	25
Electron and hole concentration, n, p (cm^{-3})	1.00×10^{20}	1.00×10^{20}	2.00×10^6	1.00×10^{20}	1.00×10^{20}	1.00×10^{20}
Defect density (cm^{-3})	1.00×10^{14}	1.00×10^{14}	1.00×10^{14}	1.00×10^{14}	1.00×10^{14}	1.00×10^{14}

3. Result and discussion

Efficiency is one of the four primary characteristics that will be evaluated since it has demonstrated better performance in the conversion of solar energy to electrical energy than the other parameters. The efficiency of a solar cell determines how it converts sunlight into electricity. A higher efficiency, usually expressed as a percentage, indicates that the cell can convert sunlight more successfully into electricity [14]. The efficiency can be calculated:

$$\eta = Voc Jsc \frac{FF}{Pin} \quad (1)$$

where Voc is open circuit voltage (V), Jsc is short circuit current density (A), FF is fill factor (%), and Pin is intensity of radiation incident (W). Fill Factor for Solar Cell defined as a relationship between a cell's maximal power output and the sum of Voc and Jsc values[15]. The fill factor can be written mathematically as:

$$FF = \frac{Pmax}{(Voc \times Jsc)} \quad (2)$$

Additionally, it is employed to determine the efficiency, which is a measurement of how successfully the cell converts sunlight into energy [16] and stated as:

$$Voc = \left(\frac{kT}{q}\right) \ln\left(\left(\frac{Jsc}{Jo}\right) + 1\right) \quad (3)$$

where k is identity factor, T is temperature (K), q is electronic charge (C), Jsc is light generated current (A), and Jo is dark generated current (A). The Jsc of a CIGS solar cell is typically from 15-20 A/cm², but this can vary depending on the specific design and manufacturing method used[17], which can be evaluated as:

$$Jsc = q \int_{hv=Eg}^{\infty} \left(\frac{dNph}{dhv}\right) d(hv) \quad (4)$$

where ph is photogenerated current density (A), q is elementary charge (C), and hv is hole generated current density (A).

Due to their distinct qualities and advantages, the heterojunction CIGS solar cell is selected as the model to verify the SCAPs simulation program. One of these is a complex heterojunction structure, which refers to the heterojunctions between several semiconductor materials that make up CIGS solar cells' many layers and interfaces [18]. The behaviour of these intricate heterojunction contacts must be taken into account while simulating the capacitance properties of CIGS solar cells. SCAPs simulation may be made to more properly represent the capacitance effects at these interfaces by validating it using CIGS solar cells[19]. Because of this validation procedure, the simulation model may be utilized confidently for future analysis, optimization, and design of solar cell devices. Figure 3 depicts data from the referenced and simulated.

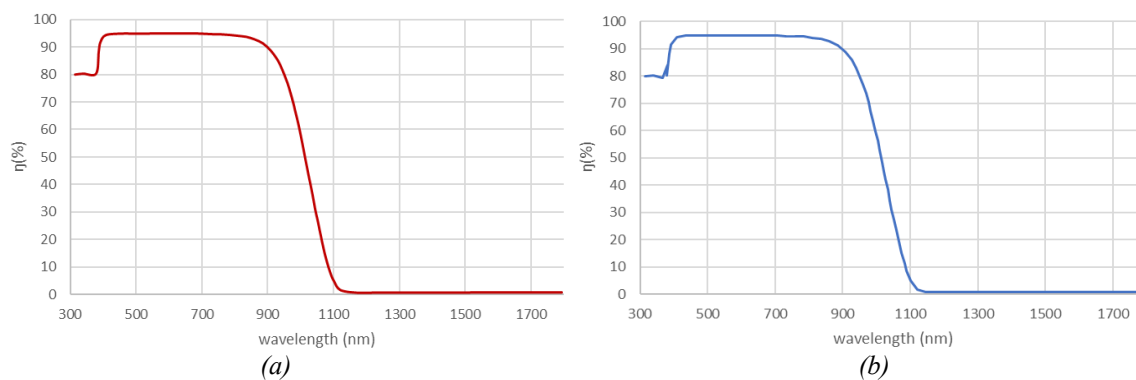


Fig. 3. Quantum efficiency (a) referenced (b) simulation.

Quantum efficiency (QE), which offers a quantitative assessment of the solar cell's capacity to convert incident photons into electrical current over a variety of wavelengths, is a valuable parameter for evaluating SCAPs simulation. The correctness and dependability of the simulation model may be evaluated by researchers by comparing the simulated quantum efficiency data with experimental observations.

This demonstrated that the SCAPs simulation had a graph pattern that matched the results reported in the paper. The efficiency at the simulated graph and the referenced graph is the same, where it started at 80%, according to the QE result. However, a little distortion occurred at a wavelength of 400 nm when quantum efficiency was approximated.

3.1. Proposed ultra-thin CIGS solar cell with GNP as absorber layer

Using SCAPs simulation, Figure 4 depicts the schematic view of the proposed Ultra-thin CIGS solar cell. GnP is suggested as their absorber layer to be doped with CIGS absorber layer, which had been displayed in red colour layer.

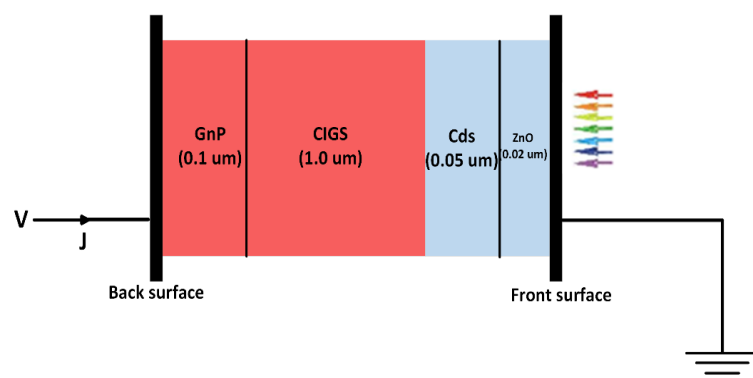


Fig. 4. Schematic view for ultra-thin CIGS solar cell with proposed GNP as absorber layer.

Figure 5(a) demonstrates that J_{sc} grew continuously as thickness increased, although V_{oc} declined gradually. This is due to a lack of voltage sufficient to boost the V_{oc} , which would otherwise drive the terminal's short circuit current. Meanwhile, Figure 5(b) shows the same graph pattern as the V_{oc} and J_{sc} graphs, with efficiency increasing and fill factor decreasing as the CIGS absorber layer thickness increased. This depicts how recombination losses impact the material's absorption coefficient. However, the proposed CIGS absorber layer thickness of 1 μm was chosen since it had the maximum efficiency. Furthermore, the GnP absorber layer is chosen with a thickness of 0.1 μm because it has the best $\eta\%$ in the CZTS solar cell, with a value of 17.14% [20].

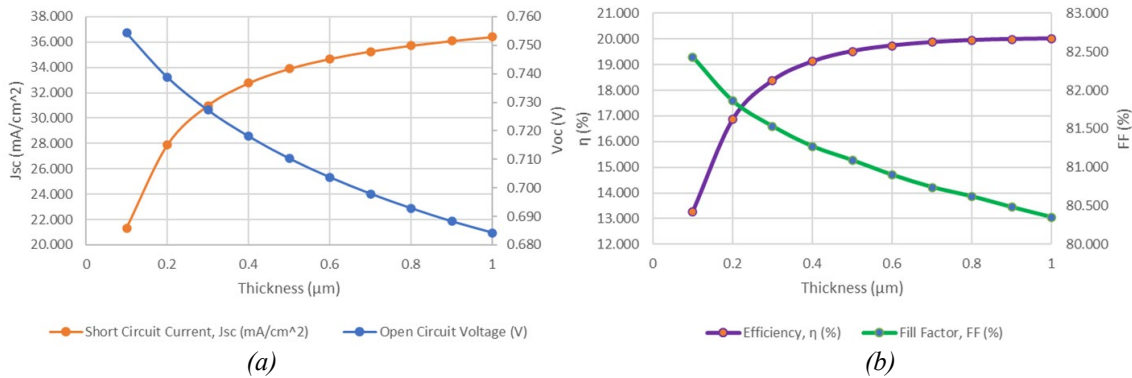


Fig. 5. (a) Relation of J_{sc} and V_{oc} , (b) Relation of efficiency and FF to Ultra-thin CIGS thickness with proposed absorber layer.

Figure 6 illustrate the electrical characteristics V_{oc} , J_{sc} , FF, and $\eta\%$ decrease as temperature rises. This demonstrated that the Ultra-thin CIGS solar cell had surpassed its saturation threshold and had begun to degrade. The trend indicates that it starts to break down near 300K.

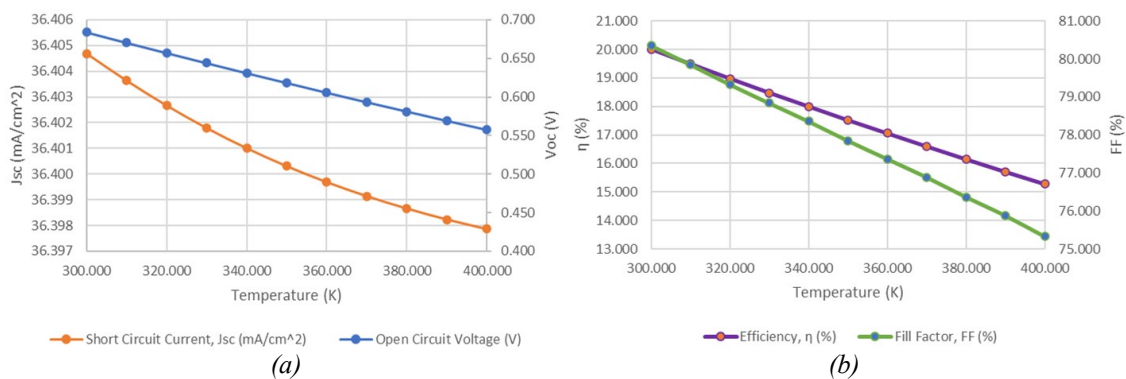


Fig. 6. (a) Relation of J_{sc} and V_{oc} , (b) Relation of efficiency and FF to Ultra-thin CIGS with proposed absorber layer operating temperature.

The link between the series resistance, FF, and $\eta\%$ was examined in Figure 7. V_{oc} and J_{sc} were not involved because CIGS materials have excellent carrier mobility, which allows charge carriers (such as electrons and holes) to travel across the material rather readily [21]. Due to their high mobility, V_{oc} and J_{sc} are less negatively impacted by series resistance. The graph's analysis of series resistance also revealed that $\eta\%$ and FF% values drop as series resistance rises. This is brought on by voltage within the solar cell caused by series resistance. A part of the voltage formed across the absorber layer is lost as the current produced by the cell passes through the

series resistance. This lowers the fill factor and decreases the effective voltage available for power production. In addition, the existence of series resistance may be able to restrict the flow of current inside the solar cell. It limits the motion of charge carriers (holes and electrons) and raises the effective resistance such carriers must overcome. This limitation causes the J_{sc} generated by the cell to diminish, which lowers the FF% and lowers overall $\eta\%$ [22]. From the analysis shown the series resistance were optimum to set to $0 \Omega/\text{cm}^2$.

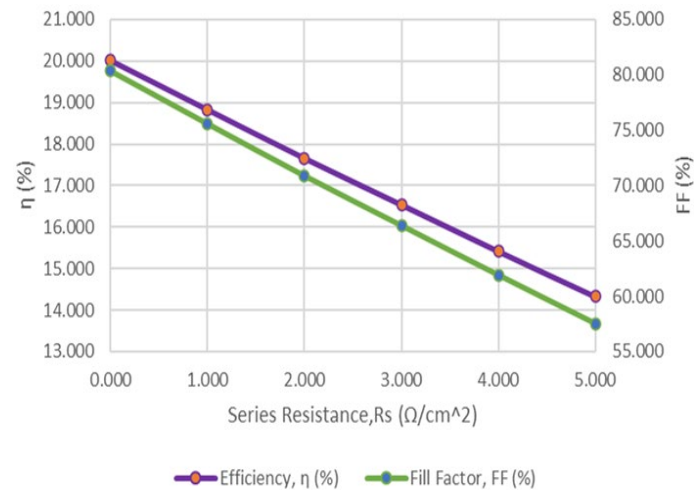


Fig. 7. Relation of efficiency and FF to Ultra-thin CIGS with proposed absorber layer series resistance.

3.2 Comparison between conventional CIGS solar cell with ultra-thin CIGS solar cell with proposed GnP absorber layer

Table 2 presents a comparison of the abilities of conventional and ultra-thin CIGS solar cells with proposed GnP absorber layer. Decreased CIGS absorber layer thickness may therefore lead to greater efficiency than traditional CIGS with the p-GnP absorber layer. This is shown by the fact that typical CIGS solar cells' efficiency has grown by 30.02%. V_{oc} also demonstrates that the greatest voltage may be generated with an increase of 33.33%. According to a study, both configurations of ultra-thin CIGS solar cells with GnP absorber layer outperform normal CIGS solar cells [23]. However, because GnP is not a stand-alone material, it cannot replace the electrical features of Ultra-thin CIGS solar cells.

Since GnP is only one atom thick, it absorbs very little incident light. A solar cell's material should ideally absorb a considerable percentage of the solar spectrum to efficiently convert sunlight into power. Although GnP absorbs light over a wide spectrum, its absorption efficiency is somewhat poor, which restricts its capacity to produce significant electrical power. In order to boost the capabilities of GnP materials, different materials must be combined.

Table 2. Comparison between performances of conventional and ultra-thin CIGS solar cell with proposed GnP absorber layer.

PV performance parameter	Conventional CIGS solar cell	Ultra-thin CIGS solar cell with Proposed GnP Absorber Layer	Percentage of increasing/decreasing for both solar cell (%)
Efficiency (%)	15.39	20.01	+ 30.02
FF (%)	79.53	80.35	+ 1.03
J_{sc} (mA/cm^2)	37.96	36.41	- 4.08
V_{oc} (V)	0.51	0.68	+33.33

3.3. Material finding to increase the GnP absorber layer's capabilities

Since the GnP material is a 2D material and cannot operate at its peak level without doping, additional materials were added to the research to enhance its capabilities. Silicon (Si) and copper gallium selenite (CGS) were chosen as the two materials because they both provided increased efficiency when combined to create a CIGS solar cell.

Tandem cell design takes into account the Si absorber layer. The tandem cell may provide a larger absorption spectrum and improved efficiency by fusing CIGS top and Si bottom cells. Shorter-wavelength light that travels through the CIGS layer may be effectively absorbed by the Si layer, maximising light utilisation and total power conversion. The Si layer can then aid in enhancing light absorption inside the solar cell's framework. It is possible to texture or pattern the Si layer to build a powerful light-trapping mechanism that will increase solar absorption and minimise optical losses. This results in increased device effectiveness and higher overall light absorption.

However, because of its compositional tunability, the CGS absorber layer is thought to mix with the GnP absorber layer. By changing the ratios of copper (Cu), gallium (Ga), and selenium (Se), CGS enables fine-tuning of the material composition. With this tunability, the absorber layer's bandgap may be optimised, which is important for matching the solar spectrum and obtaining high efficiency. Other than that, compared to certain other thin-film solar cell technologies, CGS has demonstrated high stability and endurance with enhanced resistance to deterioration and ageing [24]. This stability may lead to CIGS solar cells that are more dependable and long-lasting. The performance ratings for both absorber layers that can work well with GnP absorber layers are shown in the Table 3. It was shown that the CGS absorber layer performed more efficiently than the Si absorber layer. Both absorber layers have the same thickness of 1 μm . In order to achieve high performance, the CGS absorber layer is picked from the comparison and paired with the GnP absorber layer.

Table 3. Comparison between performances of ultra-thin CIGS solar cell with referenced Si absorber layer and ultra-thin CIGS solar cell with referenced CGS absorber layer.

PV performance parameter	Ultra-thin CIGS solar cell with referenced Si absorber Layer	Ultra-thin CIGS solar cell with referenced CGS absorber layer
Efficiency (%)	19.78	19.95
FF (%)	79.94	79.35
Jsc (mA/cm^2)	36.40	36.42
Voc (V)	0.68	0.69

3.4. Proposed ultra-thin CIGS solar cell with GNP+CGS as absorber layer

The suggested ultra-thin CIGS solar cells with a GnP+CGS absorber layer are shown schematically in Figure 8. The p-type absorber layer is visible in red and ranges in thickness from 0.1 to 1 μm for CIGS, 0.1 μm for GnP, and 1 μm for CGS. This 2-D carbon and semiconductor material combination of GnP and CGS has the ability to extract and lower interfacial resistance in solar cells.

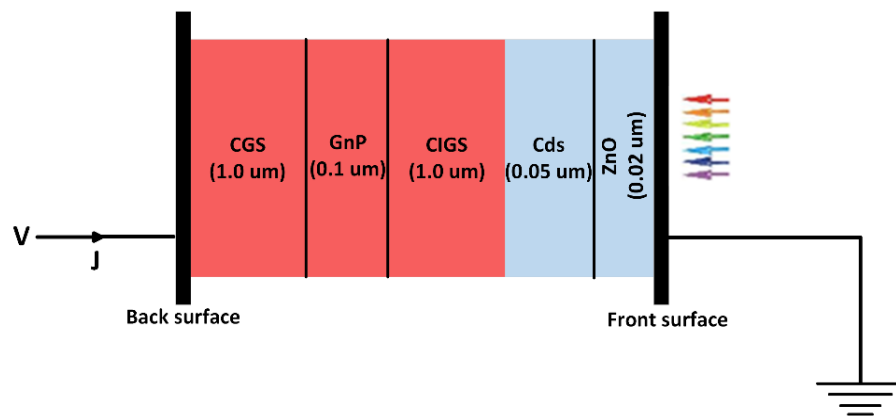


Fig. 8. Schematic view for ultra-thin CIGS solar cell with proposed GNP+CGS as absorber layer.

The suggested solar cell's band diagram with the GNP+CGS absorber layer is shown in Figure 9. The projected CIGS solar cell's thickness, the 1 μm CGS, 0.1 μm GnP, and 1 μm CIGS from 0 to 2 μm thickness are displayed starting from the left. Due to the absorber layer's anticipated thickness of 2 μm , the distance was more than 2.0 μm . Compared to the suggested GnP, which has a band gap of 1.91 eV, this proposed solar cell has a greater band gap. The introduction of extra materials and interfaces can affect the band diagram of such a solar cell. One unusual two-dimensional substance with unique electrical characteristics is GnP [25]. While CGS has a different composition that results in a bigger bandgap, when GnP is included in the structure, it can contribute additional energy levels or change the electrical structure of the device.

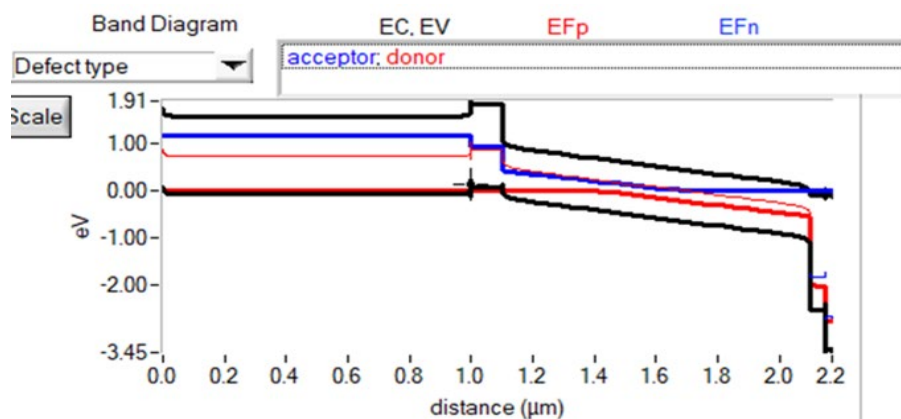


Fig. 9. Band diagram for ultra-thin CIGS solar cell with proposed GNP+CGS as absorber layer.

Variations in the absorber layer's thickness have a detailed impact on the SCAPs simulation's parameters V_{oc} , J_{sc} , $\eta\%$, and $FF\%$, as shown in Figure 10, respectively. When the thickness increases, both an increase in J_{sc} and $\eta\%$ as well as a drop in V_{oc} and $FF\%$ are readily visible. The electrical properties $\eta\%$, V_{oc} , J_{sc} , FF of this suggested CIGS solar cell with GnP and CGS absorber layer, however, are all greater. This is because the absorber layer's carrier collection was improved and the recombination losses were decreased.

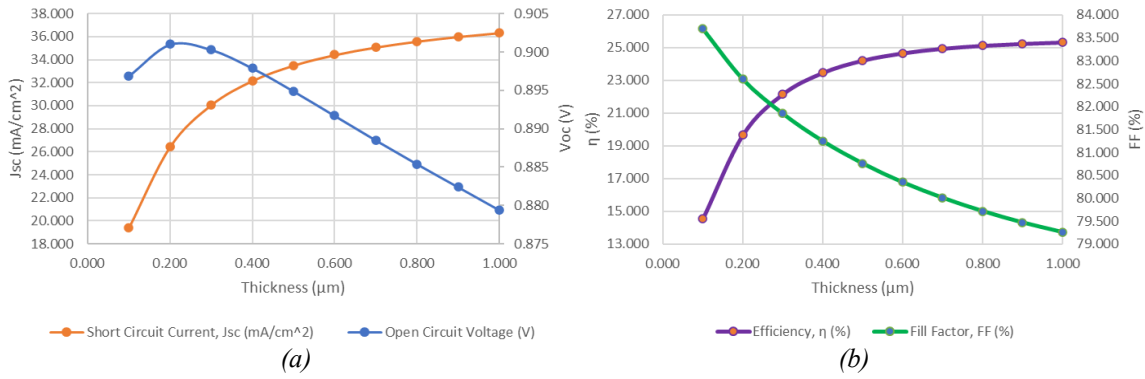


Fig. 10. (a) Relation of J_{sc} and V_{oc} , (b) relation of efficiency and FF to ultra-thin CIGS thickness with proposed absorber layer.

The suggested solar cell's quantum efficiency was similar to that of the ultra-thin CIGS solar cell with a GnP absorber layer, which started at 80% and grew to 90% until 850 nm before breaking down as illustrated in Figure 11. The use of various materials will prevent the graph from being steady.

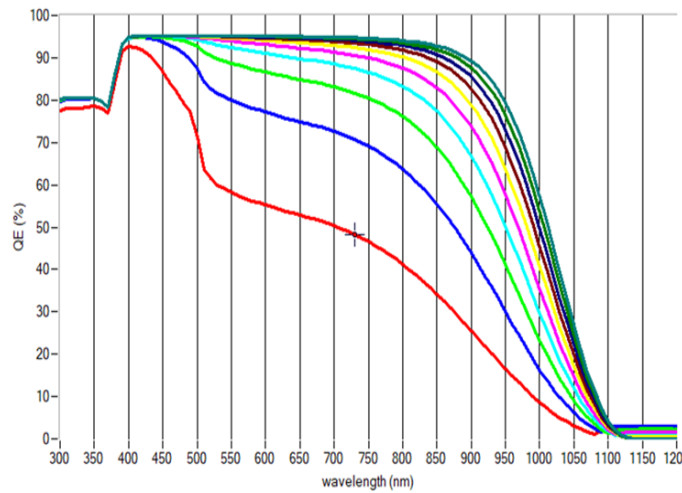


Fig. 11. Quantum Efficiency for Ultra-thin CIGS solar cell with GNP + CGS Absorber layer.

Figure 12 show the detailed effect of varying the operating temperature on the parameters V_{oc} , J_{sc} , η and FF %, respectively, from the SCAPs simulation. From Figure 12 it can be observed that all electrical qualities deteriorate as temperatures rise. As a result of the bandgap narrowing, the value of the electrical characteristics is higher than the suggested GnP absorber layer. Due to the effects of thermal expansion, the bandgap of CIGS and other semiconductors tends to gradually decrease as the temperature rises. Because of this, the absorption edge may move towards longer wavelengths, decreasing the efficiency of light absorption and, by extension, the efficiency of the solar cell.

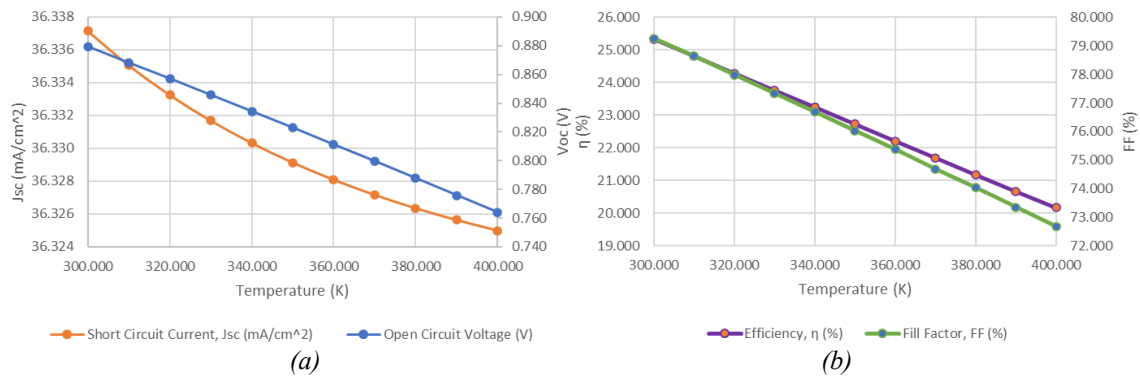


Fig. 12. (a) Relation of J_{sc} and V_{oc} , (b) relation of efficiency and FF to ultra-thin CIGS with proposed absorber layer operating temperature.

For the suggested GnP and CGS absorber layer, Figure 13 examined the relationship between the series resistance, $\eta\%$ and FF%. The mismatch of the voltage and current as the series resistance rises is seen in the figure. The solar cell cannot provide the load with its full power because of this imbalance. The efficacy of the cell's ability to deliver electricity was also reflected in its efficiency. However, this suggested solar cell has a 26.59% improvement over the proposed GnP solar cell in terms of $\eta\%$ and FF%.

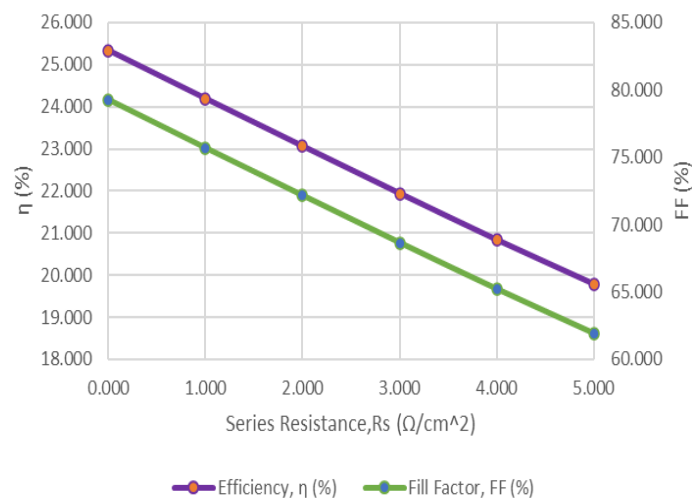


Fig. 13. Relation of efficiency and FF to ultra-thin CIGS with proposed absorber layer series resistance.

Table 4 compares the proposed ultra-thin CIGS solar cell with the proposed GnP+CGS absorber layer to the conventional CIGS solar cell. It shows that the proposed absorber layer increases its performance in terms of $\eta\%$ and V_{oc} . However, the FF and J_{sc} are declining. This is the material coefficient that affected the p-n region for FF, while J_{sc} will decrease when V_{oc} is increased. However, same as expectations, the performance of ultra-thin CIGS solar cells was improved by the addition of GnP+CGS material. Then, it continued to perform the competition.

Table 4. Comparison between performances of ultra-thin CIGS solar cell and ultra-thin CIGS solar cell with proposed GnP+CGS buffer layer.

PV performance parameter	Ultra-Thin CIGS solar cell	Proposed ultra-thin CIGS solar cell with GnP + CGS absorber layer	Percentage of increasing/decreasing for both solar cell (%)
Efficiency (%)	19.780	25.330	+ 28.059
FF (%)	79.940	79.260	-0.850
Jsc (mA/cm ²)	36.402	36.337	-0.179
Voc (V)	0.680	0.879	+ 29.265

4. Conclusion

In conclusion, the numerical simulation utilizing SCAPs software may be altered to study the performance of CIGS solar cells in every layer for Voc, Jsc, FF, and efficiency. This is done by selecting the thickness of the absorber layer, the operating temperature that has to be researched, and the effect of series resistance in the solar cell. Additionally, it was discovered that the ultra-thin CIGS solar cell with the proposed GnP+CGS absorber layer was capable of producing higher efficiency than a conventional CIGS solar cell through the absorber layer thickness analysis made in this research, with a value of efficiency of 25.33%, while the optimum value of series resistance is 0 Ω/cm^2 . While the operating temperature in this study is shown to be typical, a 300K temperature set in SCAPs simulation can still produce power with greater efficiency than a conventional CIGS solar cell. Ultra-thin CIGS solar cells with Si have a lower efficiency than ultra-thin CIGS solar cells with GnP+CGS because of the instability of their band gap when paired with CIGS solar cells.

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