

# DEVELOPMENT AND PERFORMANCE ANALYSIS OF ULTRA-THIN III-V SOLAR CELLS USING INDIUM PHOSPHIDE EPITAXIAL WAFERS

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## Abstract

This study explores the fabrication and performance analysis of ultra-thin III-V solar cells using indium phosphide (InP) epitaxial wafers through two approaches: substrate thinning via lapping and thermocompression bonding. The thinning method reduced the substrate thickness to 160  $\mu\text{m}$ , while the bonding process achieved a final thickness of 0.9  $\mu\text{m}$ . Photoluminescence (PL), internal quantum efficiency (IQE), and external quantum efficiency (EQE) measurements were conducted to evaluate the devices. Results showed that the thinned solar cells exhibited poor photovoltaic characteristics due to suboptimal n-type metal contacts and excessive electron-hole recombination, with no observable light-induced current at zero bias. Backside solar cells fabricated through bonding showed better performance, with improved IQE and EQE due to enhanced light penetration and reduced reflectance from an anti-reflection coating. PL analysis revealed a distinct 1280 nm peak for the backside structure, indicating better light interaction with the active region. Despite these advances, both methods demonstrated low open-circuit current and power efficiency, underscoring the need for further optimization to achieve commercially viable III-V solar cells.

**Keywords:** indium phosphide, Ultra-thin solar cells, III-V materials.

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## 1. Introduction

With the rapid advancement of science and technology, the depletion of Earth's natural resources has become a pressing concern. As energy demands continue to rise, the search for sustainable and renewable energy sources has gained significant attention (Metaferia et al. 2022). Among the various alternatives, solar energy stands out as one of the most promising solutions due to its abundance and environmental benefits. Harnessing solar power efficiently has become a key focus in renewable energy research, leading to the development of advanced photovoltaic technologies (Boyer et al. 2023).

Compared to conventional silicon-based solar cells, III-V solar cells offer superior power conversion efficiencies due to their direct bandgap properties (Lee and Forrest 2021). These materials can absorb and emit light more effectively, making them highly efficient for photovoltaic applications. However, the high cost of epitaxially growing III-V single-crystal materials presents a major obstacle to their widespread adoption (Daniel et al. 2023). One viable approach to reducing costs is minimizing the thickness of the active material while maintaining its performance, which can be achieved through improvements in the fabrication process (Chen and Packard 2021).

In this paper, we study two different approaches to fabricating ultra-thin solar cells using indium phosphide (InP) epitaxial wafers. The first approach involves substrate thinning via lapping, where the InP substrate is mechanically ground to reduce the overall thickness of the device. The second method utilizes thermocompression bonding, which applies high temperature and pressure to bond a micro solar cell to a supporting substrate. By comparing these fabrication techniques and analyzing their impact on device performance, we aim to optimize the manufacturing process for III-V solar cells and explore their potential for high-efficiency, cost-effective photovoltaic applications.

## 2. Literature review

Research on III-V solar cells has significantly advanced in recent years, focusing on improving efficiency and reducing manufacturing costs. One of the primary challenges in III-V solar cell development is the high cost of epitaxial growth, which has driven efforts to explore alternative fabrication techniques (Raj et al. 2020). Various studies have investigated methods to minimize material usage while maintaining high power conversion efficiency (Braun et al. 2023).

One approach to cost reduction is the development of ultra-thin solar cells by reducing the thickness of the active layer. Substrate thinning techniques, such as mechanical grinding and chemical etching, have been explored to achieve this goal (Depauw et al. 2023). These methods aim to decrease material consumption while preserving the photovoltaic performance of the device. However, thinning the substrate can lead to increased surface defects and higher recombination rates, which may negatively impact efficiency (Wulf et al. 2021).

Another promising method is indirect bonding, which involves transferring thin-film solar cells onto a new substrate using techniques such as thermocompression bonding or wafer bonding (Schygulla et al. 2020). This approach allows for the reuse of the original substrate, significantly reducing production costs. Studies have demonstrated that bonded solar cells can maintain high power conversion efficiencies while achieving ultra-thin structures (Haggren et al. 2023). However, challenges remain in ensuring strong adhesion, minimizing thermal stress, and optimizing the electrical contact quality (Cappelluti et al. 2020).

Recent advancements in anti-reflection coatings and surface passivation techniques have also contributed to performance improvements in III-V solar cells. These enhancements help to reduce optical losses and improve carrier collection efficiency (Reeves et al. 2022). Additionally, innovations in multi-junction solar cell designs have enabled higher efficiency by utilizing a broader spectrum of sunlight. While these approaches show

promising results, further optimization is necessary to achieve commercially viable solutions for large-scale production (Schygulla et al. 2021).

The previous research has focused on reducing material costs, enhancing efficiency, and developing advanced fabrication techniques for III-V solar cells. This study builds upon these efforts by comparing substrate thinning and thermocompression bonding methods to evaluate their impact on device performance and feasibility for practical applications (Woo et al. 2022).

### 3. Methodology

In this study, two fabrication techniques were employed to develop ultra-thin III-V solar cells using indium phosphide (InP) epitaxial wafers: substrate thinning via lapping and thermocompression bonding. The performance of the fabricated solar cells was evaluated using photoluminescence (PL), internal quantum efficiency (IQE), and external quantum efficiency (EQE) measurements.

#### 3.1 Substrate Thinning via Lapping

The first fabrication approach involved mechanical grinding to reduce the thickness of the InP substrate. The process began with the deposition of a thin SiO<sub>2</sub> anti-reflection (AR) coating using Plasma-Enhanced Chemical Vapor Deposition (PECVD). A photolithography system was then used to define the contact areas, followed by dry etching to remove 111 nm of SiO<sub>2</sub>.

The p-type metal was deposited using an electron-beam evaporation technique. The excess photoresist was lifted off, and the n-metal contact was subsequently deposited. The InP substrate was then thinned down to 160 μm using a precision lapping process. Rapid Thermal Annealing (RTA) was performed on some samples to improve the metal contact quality. The thickness of the solar cell affects carrier transport and recombination. The absorption coefficient of the material is given by equation (1):

$$I(x) = I_0 e^{-\alpha x} \quad (1)$$

where:

- $I(x)$  is the light intensity at depth  $x$ ,
- $I_0$  is the incident light intensity,
- $\alpha$  is the absorption coefficient of InP.
- $x$  is the penetration depth

Reducing the substrate thickness impacts the ability of photogenerated carriers to reach the junction before recombining, which directly affects the efficiency of the device.

#### 3.2 Thermocompression Bonding

The thermocompression bonding was used to attach a micro solar cell to a dummy wafer. P-type metal was first deposited on both the epitaxial and dummy wafers. The two wafers were then bonded under a temperature of 300°C and a total force of 750 kg in a vacuum chamber with a pressure of 0.27 Torr.

To remove excess material, wet etching was performed using hydrochloric acid (HCl) with an InGaAsP etching stop layer to ensure uniform thickness. A Crystalbond™

adhesive was applied around the device to protect it during the etching process. After etching, acetone was used to remove the adhesive, and a second photolithography step was performed before n-metal deposition.

The thickness of the bonded structure was measured using an Alpha-step stylus profiler, revealing a final thickness of 0.9  $\mu\text{m}$ . The electrical characteristics of the bonded solar cell were evaluated using current-voltage (I-V) measurements, given by the diode equation (2):

$$I = I_s \left( e^{\frac{qV}{nkT}} - 1 \right) \quad (2)$$

where:

- $I$  is the output current,
- $I_s$  is the reverse saturation current,
- $q$  is the elementary charge,
- $V$  is the applied voltage,
- $n$  is the ideality factor,
- $k$  is the Boltzmann constant,
- $T$  is the absolute temperature.

### 3.3 Performance Evaluation

The optical and electrical properties of the fabricated solar cells were analyzed using PL, IQE, and EQE measurements. IQE is calculated using the relation, equation (3):

$$\text{IQE} = \frac{\text{EQE}}{(1-R)} \quad (3)$$

where:

- $\text{EQE}$  the external quantum efficiency,
- $R$  is the reflectance of the solar cell surface.

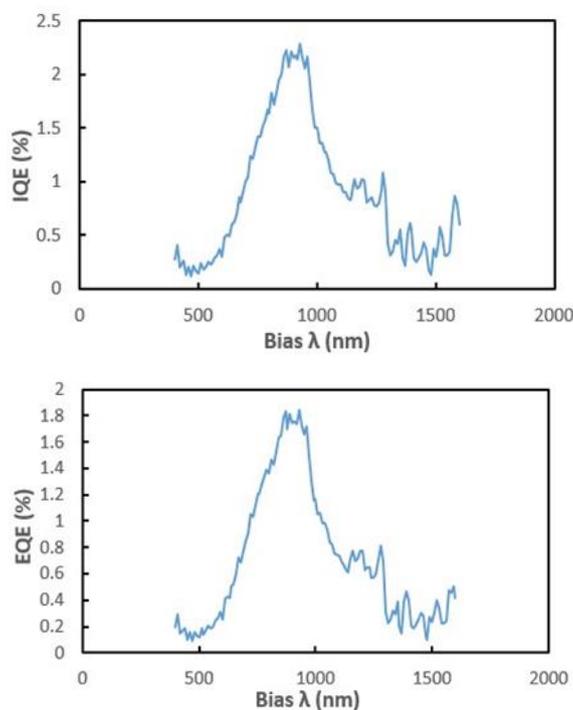
The EQE values were compared for both the topside and backside solar cells. The backside solar cell demonstrated better performance due to enhanced light penetration and reduced reflectance from the AR coating. By analyzing these parameters, the study evaluates the effectiveness of thinning and bonding techniques in improving III-V solar cell performance

## 4. Experimental Setup and Measurements

To evaluate the performance of the fabricated III-V solar cells, a series of experiments were conducted, including structural analysis, electrical characterization, and optical measurements. These experiments aimed to compare the effectiveness of substrate thinning via lapping and thermocompression bonding in achieving high-efficiency ultra-thin solar cells.

The structural integrity and thickness of the fabricated solar cells were measured using an Alpha-step stylus profiler. The results confirmed that the thinned solar cell had a final

thickness of 160  $\mu\text{m}$ , while the bonded solar cell achieved an ultra-thin structure of 0.9  $\mu\text{m}$ . These measurements validated the effectiveness of both fabrication methods in reducing material usage while maintaining structural stability, shown in Figure 1.



**Figure 1. The simulation result of IQE(left) and EQE(right) of the topside solar cell.**

Source: Author, 2025

The current-voltage (I-V) measurements were performed using a source meter unit (SMU) under controlled illumination. The diode equation was used to analyze the photovoltaic properties of the devices. The open-circuit voltage (VOC) and short-circuit current (ISC) were extracted from the I-V curves. Results showed that the bonded solar cell exhibited extremely low open-circuit current and power efficiency, likely due to excessive photon absorption before reaching the active region, leading to poor carrier collection.

The photoluminescence (PL), internal quantum efficiency (IQE), and external quantum efficiency (EQE) measurements were conducted. The PL spectrum revealed peaks at 1.04  $\mu\text{m}$  and 1.1  $\mu\text{m}$  for the thinned solar cell, while the bonded solar cell exhibited a clear 1280 nm peak, indicating improved light interaction with the active region. IQE and EQE measurements provided insight into carrier collection efficiency, with the backside solar cell showing better EQE values compared to the topside solar cell. This improvement was attributed to enhanced light penetration and reduced optical losses due to an anti-reflection (AR) coating.

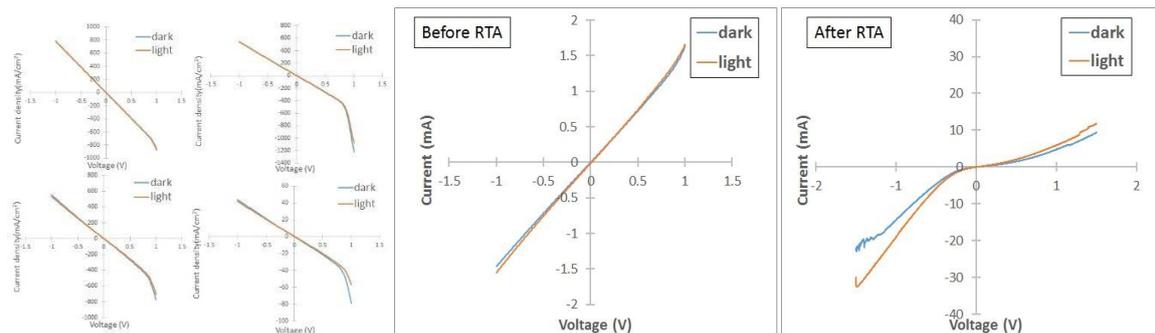
A spectrophotometer was used to measure the reflectance of both topside and backside solar cells. The results demonstrated that the backside solar cell had lower reflectance, confirming the effectiveness of the AR coating in improving light absorption. This contributed to better overall quantum efficiency and performance.

The experimental results indicated that both thinning and bonding methods were successful in achieving ultra-thin III-V solar cells. However, electrical characterization highlighted performance limitations, particularly in the bonded solar cell, where photon

absorption and recombination losses reduced efficiency. Further process optimization, including improving metal contacts and refining the bonding method, is necessary to enhance charge carrier extraction and overall photovoltaic performance.

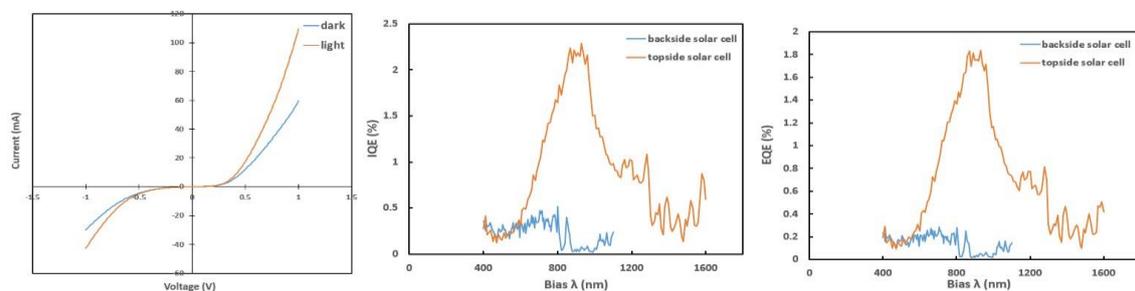
## 5. Results and Discussion

The fabricated III-V solar cells were analyzed based on their electrical, optical, and structural characteristics. The comparison between substrate thinning via lapping and thermocompression bonding provided valuable insights into their advantages and limitations in achieving high-efficiency ultra-thin solar cells, shown in Figure 2.



**Figure 2.** The J-V characteristics of four samples before the RTA process (left), the I-V response of a sample prior to RTA (middle), and the I-V response after RTA treatment (right)

Source: Author, 2025



**Figure 3.** The I-V characteristics of the backside solar cell (left), the internal quantum efficiency (IQE) comparison (middle), and the external quantum efficiency (EQE) comparison (right) between the backside and topside solar cells.

Source: Author, 2025

### 5.1 Electrical performance analysis

The electrical properties of the solar cells were evaluated through current-voltage (I-V) measurements. The results for the thinned solar cells before the rapid thermal annealing (RTA) process showed poor photovoltaic behavior, which was attributed to ineffective n-type metal contact. After RTA, the electrical characteristics improved slightly, but the devices still exhibited low photovoltaic response, suggesting that electron-hole recombination and charge transport inefficiencies were significant issues.

For the bonded solar cells, the I-V curves indicated normal semiconductor behavior, but the devices did not produce a noticeable difference between dark and light current when no external voltage was applied. This suggested that insufficient photon absorption in the

active region prevented effective charge carrier generation, leading to low open-circuit voltage and poor overall efficiency.

### ***5.2 Optical performance analysis***

Photoluminescence (PL) measurements provided further insights into the optical properties of the fabricated devices. The thinned solar cell exhibited emission peaks at 1.04  $\mu\text{m}$  and 1.1  $\mu\text{m}$ , indicating that most of the light was absorbed before reaching the active region. In contrast, the bonded solar cell showed a clear emission peak at 1280 nm, which suggested that light penetration was improved in this structure, allowing better interaction with the active layer.

The quantum efficiency of the devices was further evaluated through internal quantum efficiency (IQE) and external quantum efficiency (EQE) measurements. The results showed that the backside solar cell exhibited higher EQE values compared to the topside solar cell. This improvement was attributed to the anti-reflection (AR) coating, which reduced optical losses and allowed lighter to pass through to the active region.

### ***5.3 Structural and thickness impact***

The structural properties of the devices played a significant role in determining their efficiency. The topside solar cell had a measured thickness of 166  $\mu\text{m}$ , which resulted in inefficient carrier transport. The excessive thickness of the n-region caused electron-hole recombination before the carriers could reach the junction, leading to a lower photocurrent.

The bonded solar cell had a much thinner structure of 0.9  $\mu\text{m}$ , which allowed better light penetration. However, due to the nature of the bonded structure, photon absorption was still not optimal, and a significant portion of the light energy was lost before generating electrical current. These factors contributed to the low power conversion efficiency observed in the bonded devices.

## **6. Conclusion**

This paper study the fabrication and performance evaluation of ultra-thin III-V solar cells using indium phosphide (InP) epitaxial wafers through two approaches: substrate thinning via lapping and thermocompression bonding. The objective was to assess the effectiveness of these methods in reducing material usage while maintaining photovoltaic performance.

The results revealed that substrate thinning successfully reduced the InP thickness to 160  $\mu\text{m}$ , but the excessive thickness of the n-region led to high recombination rates and poor carrier transport, ultimately limiting the device's efficiency. On the other hand, thermocompression bonding achieved an ultra-thin structure of 0.9  $\mu\text{m}$ , yet suffered from inefficient photon absorption in the active region, resulting in low open-circuit current and power conversion efficiency.

Electrical characterization through I-V measurements showed that both methods exhibited semiconductor behavior, but the photovoltaic response was weak due to either poor metal contact (in the thinned solar cell) or excessive photon absorption before reaching the active layer (in the bonded solar cell). Photoluminescence (PL) measurements confirmed that the bonded solar cell exhibited a distinct 1280 nm peak,

indicating improved light penetration compared to the thinned device. Reflectance and quantum efficiency (IQE and EQE) analyses demonstrated that the backside solar cell performed better than the topside solar cell due to the presence of an anti-reflection (AR) coating, which enhanced light absorption.

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