Explicit Photogain Theory for Photodiode Validated by TCAD Simulation

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Abstract— ***This work presents the design and simulation of an optimized nano-scale photodiode for optical communication systems. Conventional InGaAs photodiodes suffer from efficiency loss due to dead-layer absorption and surface recombination, which reduce photon absorption and responsivity. To address this issue, an Optimized Window Layer Architecture (OWLA) based on a GaAs/InGaAs/InP heterostructure is proposed. The design improves photon penetration by reducing the GaAs window layer thickness and increasing the InGaAs absorber region. Silvaco Technology Computer-Aided Design (TCAD) simulations were used to analyze device performance. The optimized structure achieved a responsivity of 1.008 A/W and external quantum efficiency (EQE) of 96% at 1.3 µm, demonstrating improved photon absorption and carrier collection efficiency for optical communication applications.***

Index Terms— External Quantum Efficiency, InGaAs Photodiode, Optical Communication, OWLA Structure, TCAD Simulation.

I. INTRODUCTION

Optical communication systems have become essential for modern high-speed data transmission due to their ability to support large bandwidth, low signal loss, and immunity to electromagnetic interference. In these systems, photodetectors play a crucial role by converting incoming optical signals into electrical signals that can be processed by electronic devices. Among various photodetectors, InGaAs-based photodiodes are widely used because of their high sensitivity in the near-infrared wavelength region, particularly around 1.3 µm and 1.55 µm, which correspond to the main transmission windows of optical fiber communication.

However, conventional photodiode structures often suffer from efficiency limitations caused by parasitic absorption and surface recombination. In many devices, a relatively thick window or cap layer absorbs a portion of the incident photons before they reach the active absorption region, creating what is commonly referred to as the "dead layer" effect. This reduces the responsivity and external quantum efficiency of the photodiode.

To address these challenges, this work investigates an optimized photodiode architecture based on explicit photogain theory and validated using Technology Computer Aided Design (TCAD) simulations. By optimizing the window layer thickness and absorber configuration in a GaAs/InGaAs/InP heterostructure, the proposed design aims to improve photon absorption and carrier collection efficiency. The study evaluates important performance parameters such as photocurrent, responsivity, and external quantum efficiency, providing insights into the development of high-performance photodiodes for optical communication and sensing applications.

II. OBJECTIVES

The main objectives of the proposed research work are:

- To design and analyze a nanoscale photodiode structure using TCAD simulation.
- To study the impact of window layer thickness on photon absorption and carrier generation.
- To investigate the influence of doping concentration and absorber layer thickness on device performance.
- To evaluate important photodiode parameters such as photocurrent, responsivity, and external quantum efficiency.
- To optimize the photodiode architecture for

improved efficiency in optical communication systems.

III. LITERATURE REVIEW

With the rapid development of high-speed communication technologies, optical fiber communication systems have become an essential part of modern telecommunication networks. These systems require efficient photodetectors to convert optical signals into electrical signals with high sensitivity and fast response time. Among the various photodetectors available, photodiodes are widely used due to their reliability, compact size, and compatibility with semiconductor fabrication processes.

Several studies have focused on improving the performance of photodiodes used in optical communication systems. Conventional PN junction photodiodes provide basic light detection capabilities, but their response speed and sensitivity are limited for high-speed optical communication applications. To overcome these limitations, PIN photodiodes were introduced, which include an intrinsic region between the p-type and n-type layers. This intrinsic region increases the width of the depletion region, allowing more photons to be absorbed and improving carrier collection efficiency.

Recent research has also explored heterostructure photodiodes using semiconductor materials such as InGaAs and InP. These materials are particularly suitable for optical communication systems operating in the near-infrared wavelength range around 1.3 μm and 1.55 μm. InGaAs-based photodiodes provide higher responsivity and improved spectral response compared to conventional silicon photodiodes.

However, conventional heterostructure photodiodes still suffer from certain limitations, including dead layer absorption and surface recombination effects. The presence of a thick window or cap layer on the device surface can absorb a portion of the incident photons before they reach the active absorption region. This reduces the number of generated electron–hole pairs and decreases the overall efficiency of the device.

To address these issues, researchers have proposed various structural optimization techniques, such as reducing the window layer thickness, increasing the absorber layer thickness, and optimizing the doping profile. In addition, simulation tools such as Silvaco TCAD have been widely used to analyze semiconductor device behavior and evaluate different photodiode structures before fabrication.

In this work, an optimized photodiode architecture is investigated using TCAD simulation techniques. By modifying the window layer thickness and improving the absorber configuration, the proposed structure aims to enhance photon absorption and carrier collection efficiency. The simulation results are further analyzed using OriginPro to evaluate the electrical and optical performance of the device.

IV. PROPOSED SYSTEM

The proposed system focuses on the design of an optimized photodiode architecture to improve the performance of optical photodetectors used in fiber communication systems.

The device is based on a GaAs/InGaAs/InP heterostructure and is analyzed using TCAD simulation tools. Conventional photodiodes often suffer from the dead layer effect, where a thick window layer absorbs incident photons before they reach the active region.

This reduces photon absorption efficiency and limits device performance.

To overcome this limitation, the proposed structure reduces the thickness of the GaAs window layer and optimizes the InGaAs absorber layer.

This modification allows more photons to reach the active region, increasing electron–hole pair generation and improving carrier collection efficiency.

As a result, the optimized photodiode structure enhances important performance parameters such as photocurrent, responsivity, and external quantum

efficiency. The proposed photodiode is based on a

GaAs/InGaAs/InP heterostructure designed to improve photon absorption and carrier collection efficiency. Each layer performs a specific role in the device operation.

Table 1: MATERIAL JESTIFICATIOZ

Material	Role	The Engineering Logic
GaAs	The Cap	High Hole Mobility: Ensures the electrical signal moves fast and exits the device with Low Resistance.
InGaAs	The Absorber	Tunable Bandgap: Perfectly matches the wavelength for maximum light capture.
InP	The Buffer	Lattice Matching: Acts as a "perfect template" for InGaAs, preventing structural defects that kill efficiency.

•GaAs Window LayerA thin GaAs window layer is used at the top of the device. In conventional designs this layer is thick and causes dead-layer losses. In the proposed structure, its thickness is reduced to allow more photons to reach the active region.

• InGaAs Absorber Layer: The InGaAs layer acts as the main absorption region where incident photons generate electron–hole pairs. This layer provides high sensitivity for near-infrared optical communication wavelengths.• InP Substrate Layer: The InP layer serves as the substrate and provides lattice matching and structural support, improving carrier transport and overall device stability.

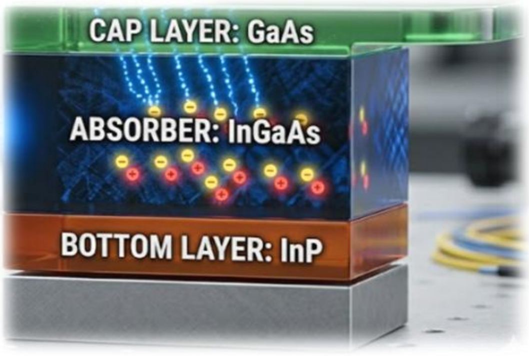
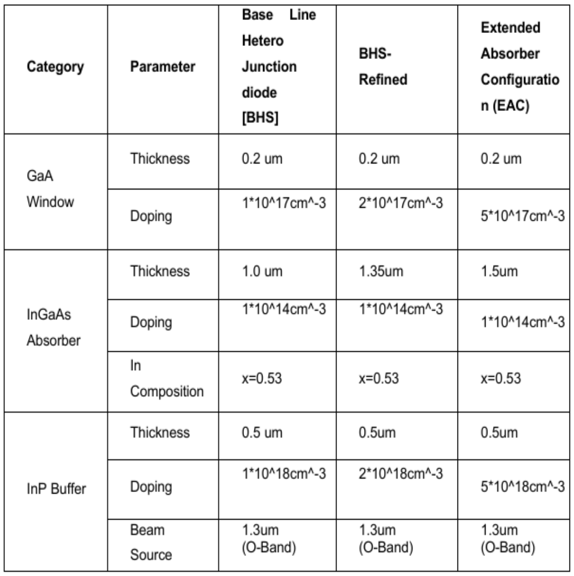


Figure 1: Proposed GaAs/InGaAs/InP Photodiode Structure

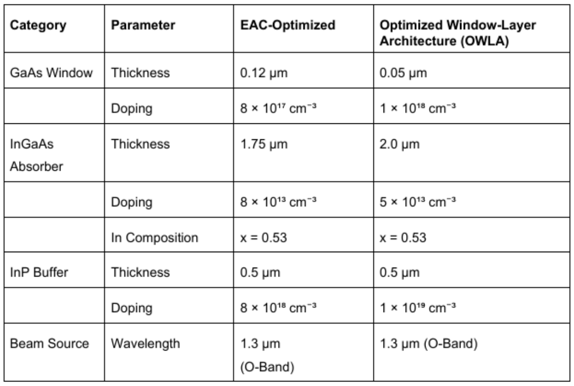
V. SIMULATION FRAMEWORK

The proposed photodiode structure was analyzed using Silvaco TCAD simulation tools to evaluate its electrical and optical performance. TCAD provides a virtual platform for modeling semiconductor devices and studying internal physical processes such as carrier transport, electric field distribution, optical absorption, and recombination mechanisms.



Category	Parameter	Base Line Hetero Junction diode [BHS]	BHS-Refined	Extended Absorber Configuratio n (EAC)
GaA Window	Thickness	0.2 um	0.2 um	0.2 um
	Doping	1*10^17cm^-3	2*10^17cm^-3	5*10^17cm^-3
InGaAs Absorber	Thickness	1.0 um	1.35um	1.5um
	Doping	1*10^14cm^-3	1*10^14cm^-3	1*10^14cm^-3
	In Composition	x=0.53	x=0.53	x=0.53
InP Buffer	Thickness	0.5 um	0.5um	0.5um
	Doping	1*10^18cm^-3	2*10^18cm^-3	5*10^18cm^-3
	Beam Source	1.3um (O-Band)	1.3um (O-Band)	1.3um (O-Band)

Table 2: CASES 1,2,3



Category	Parameter	EAC-Optimized	Optimized Window-Layer Architecture (OWLA)
GaAs Window	Thickness	0.12 μm	0.05 μm
	Doping	8×10^{17} cm^{-3}	1×10^{18} cm^{-3}
InGaAs Absorber	Thickness	1.75 μm	2.0 μm
	Doping	8×10^{13} cm^{-3}	5×10^{13} cm^{-3}
	In Composition	x = 0.53	x = 0.53
InP Buffer	Thickness	0.5 μm	0.5 μm
	Doping	8×10^{18} cm^{-3}	1×10^{19} cm^{-3}
Beam Source	Wavelength	1.3 μm (O-Band)	1.3 μm (O-Band)

Table 3: CASES 4,5

A. Device Simulation using Silvaco TCAD

The photodiode structure was created and simulated using the Silvaco TCAD environment. The simulation process was performed through DeckBuild, which allows users to define semiconductor layers, doping concentrations, and simulation parameters using command scripts.

DeckBuild was used as the command interface to create the device structure and execute the simulation scripts. It defines the material properties, layer thickness, and boundary conditions required for the simulation.

The electrical and optical behavior of the photodiode was simulated using the ATLAS module.

ATLAS solves fundamental semiconductor equations such as Poisson's equation and carrier transport equations to analyze the device operation under illumination.

TonyPlot was used to visualize the simulation results and analyze parameters such as carrier concentration, electric field distribution, and generation rate inside the photodiode structure.

VI. RESULTS AND DISCUSSION

The performance of the proposed photodiode was evaluated using Silvaco TCAD simulations. Different structural configurations were analyzed to study the effect of device optimization on parameters such as photocurrent, responsivity, and external quantum efficiency (EQE). The simulation results were visualized using TonyPlot

Relationship Between Quantum Efficiency and Responsivity

The performance of a photodiode can be evaluated using parameters such as responsivity (R) and quantum efficiency (η). Quantum efficiency represents the ratio of the number of collected electrons to the number of incident photons.

$$\eta = (\text{Electrons per second}) / (\text{Photons per second})$$

Using measurable quantities, the electron generation rate can be expressed as Iph/q and the photon rate as Popt/Eph, where Iph is the photocurrent, q is the electron charge, Popt is the optical power, and Eph is the photon energy.

Responsivity is defined as the ratio of photocurrent to incident optical power:

$$R = I_{ph} / P_{opt}$$

Combining these expressions gives:

$$R = \eta \times (q / E_{ph})$$

Using the Planck–Einstein relation $E_{ph} = hc/\lambda$, the final expression becomes:

$$R\ (\text{A/W}) = \eta \times (\lambda / 1.24)$$

This relationship shows that the responsivity of a photodiode increases with both quantum efficiency and the wavelength of incident light.

Case 1: Baseline Heterostructure

This case represents the conventional GaAs/InGaAs/InP photodiode structure used as a reference model. The performance obtained from this structure serves as a baseline for comparison with the optimized designs.

Case 2: Enhanced Absorber Layer

In this case, the thickness of the InGaAs absorber layer is increased to improve photon absorption. This modification enhances photocurrent generation and improves the responsivity compared to the baseline structure.

Case 3: Optimized Window Layer Architecture (OWLA)

This case represents the proposed optimized design where the GaAs window layer thickness is reduced to minimize photon loss. This allows better photon penetration into the absorber layer, resulting in the highest responsivity and improved quantum efficiency.

A. Baseline Heterostructure (BHS)

The first case represents the conventional photodiode structure used as the reference device. The structure consists of a 0.2 µm GaAs window layer, a 1.0 µm InGaAs absorber layer, and a 0.5 µm InP buffer layer.

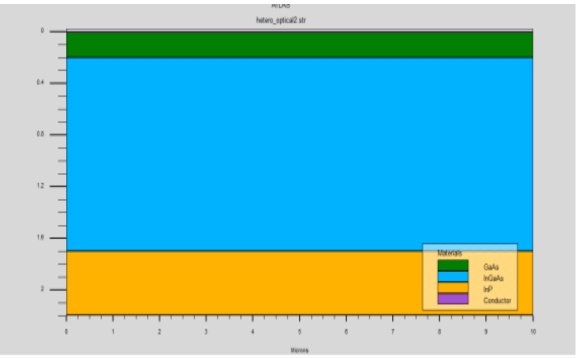


Figure 2: Baseline Heterostructure Photodiode Structure

Due to the relatively thick GaAs window layer, part of the incident photons are absorbed before reaching the active region. This phenomenon is known as the dead-layer effect, which reduces the responsivity of the device.

The simulation results obtained for this structure are:

Dark Current: 18.33 Pa

Light Current: 102.23 pA

Photocurrent: 83.90 pA

Responsivity: 0.849 A/W

External Quantum Efficiency: 80.03 %

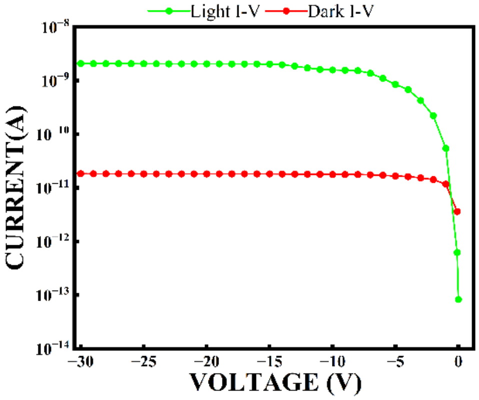


Figure 3: The I-V Characteristics of Case 1 Baseline Photodiode

B. BHS Refined Structure

In the second configuration, the doping profile of the device layers was modified while keeping the structural thickness unchanged. This modification improves carrier transport and reduces recombination losses.

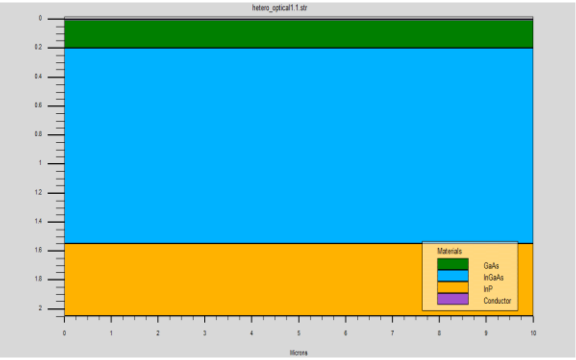


Figure 4: Refined BHS Device Structure

The refined structure shows improved performance with responsivity reaching 0.93 A/W and quantum efficiency increasing to approximately 88%.

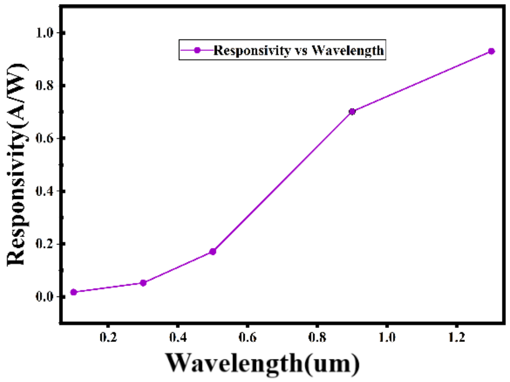


Figure 5: Spectral Response of BHS Refined Structure

C. Extended Absorber Configuration (EAC)

In this configuration, the thickness of the InGaAs absorber layer was increased from 1.0 µm to 1.5 µm to improve photon absorption. A thicker absorber region allows more photons to interact with the semiconductor material. As a result, the probability of electron–hole pair generation increases, leading to enhanced photocurrent. This structural modification improves the overall responsivity of the photodiode compared to the baseline design. This structural modification improves the overall responsivity of the photodiode compared to the baseline design.

Additionally, the enhanced absorption contributes to better detection efficiency of the device.

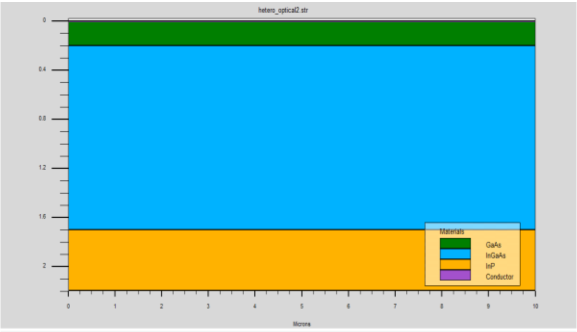


Figure 6: Extended Absorber Configuration (EAC) Structure

Simulation results for the EAC structure are:

Dark Current: 26.90 pA
Light Current: 122.65 pA
Photocurrent: 95.75 pA
Responsivity: 0.957 A/W

External Quantum Efficiency: 91.33 %

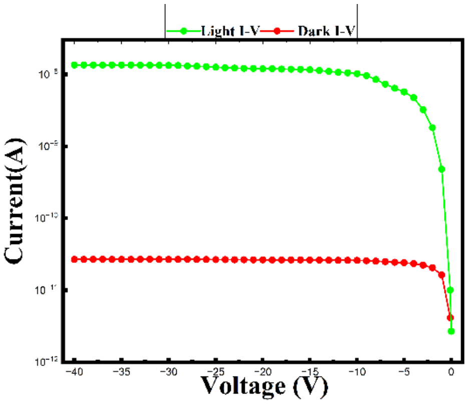


Figure 7: V–I Characteristics of EAC Structure

- The graph shows the current–voltage (I–V) characteristics of the photodiode under dark and illuminated conditions.
- The Light I–V curve (green) shows a significantly higher current because incident photons generate additional electron–hole pairs in the device.
- The Dark I–V curve (red) represents the dark current, which is the small leakage current present when no light is applied.
- The large difference between light current and dark current indicates good photodetector sensitivity and efficient photoresponse.

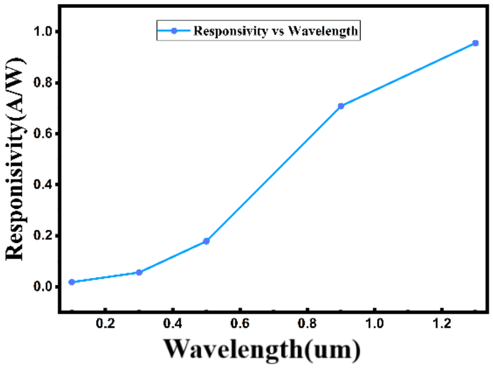


Figure 8: Spectral response

D. EAC Optimized Structure

Further improvement was achieved by reducing the window layer thickness to 0.12 µm and increasing the absorber thickness to 1.75 µm. This modification allows better optical penetration into the active region.

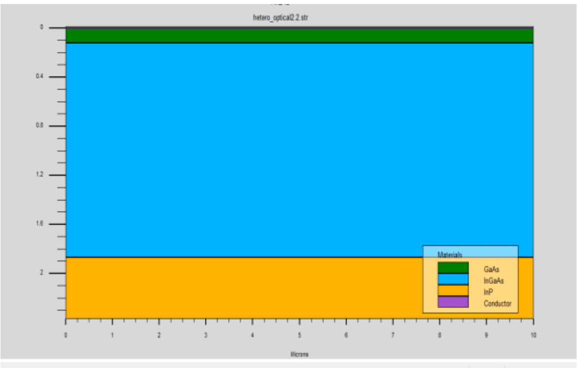


Figure 9: Optimized EAC Structure

The optimized configuration achieved:

Responsivity: 0.98 A/W
Quantum Efficiency: 94 %

E. Optimized Window Layer Architecture (OWLA)

n this configuration, the thickness of the InGaAs absorber layer was increased from 1.0 µm to 1.5 µm to improve photon absorption. A thicker absorber region allows more photons to interact with the semiconductor material. As a result, the probability of electron–hole pair generation increases, leading to enhanced photocurrent. This structural modification improves the overall responsivity of the photodiode compared to the baseline design. Additionally, the enhanced absorption contributes to better detection efficiency of the device. The improved carrier generation also helps in achieving stronger electrical output under optical illumination. Consequently, the device shows better sensitivity for optical communication applications. This modification demonstrates how absorber layer optimization can significantly enhance photodiode performance.

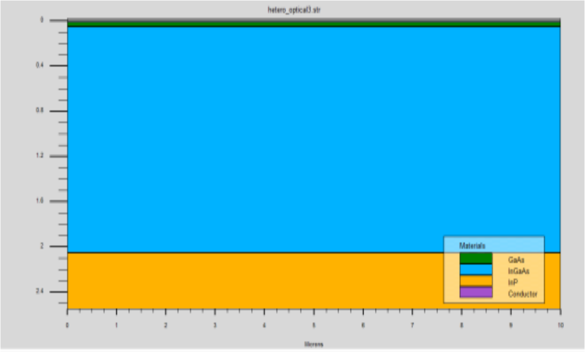


Figure 10: Optimized Window Layer Architecture (OWLA)
(Insert TCAD device structure image)

Simulation results for the OWLA structure are:

Dark Current: 35.90 pA
Light Current: 136.90 pA
Photocurrent: 101.0 pA
Responsivity: 1.008 A/W

External Quantum Efficiency: 96.34 %

The figure shows the heterostructure cross-section of the simulated photodiode, consisting of GaAs, InGaAs, and InP layers.

The GaAs layer acts as the window layer, allowing incident light to enter the device with minimal surface recombination.

The InGaAs layer serves as the absorption region where photons generate electron–hole pairs, while the InP layer acts as the substrate for structural support.

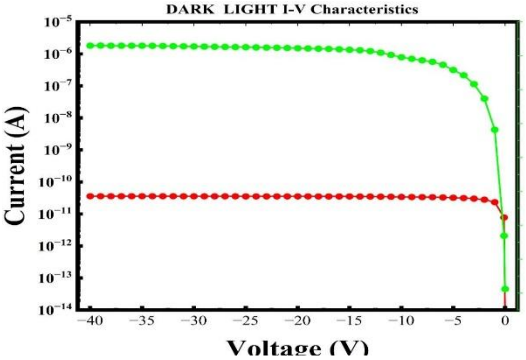


Figure 11: V–I Characteristics of OWLA Structure (Insert TonyPlot I-V graph)

Figure 17: Spectral Response of OWLA Structure

F. Comparative Performance Analysis

Table summarizes the performance comparison of all simulated photodiode structures.

Metric	**Baseline Hetero Junction Diode (BHS)**	**Extended Absorber Configuration (EAC)**	**Optimized Window-Layer Architecture (OWLA)**
Dark Current	18.33 pA	26.90 pA	35.90 pA
Light Current	102.23 pA	122.65 pA	136.90 pA
Photocurrent	83.90 pA	95.75 pA	101.0 pA
Responsivity	0.849 A/W	0.957 A/W	1.008 A/W
External Quantum Efficiency (EQE)	80.03 %	91.33 %	96.34 %

Figure 12: Graphical Comparison of Responsivity for All Structures

The results clearly show that the proposed OWLA structure provides the highest responsivity and quantum efficiency due to reduced window layer thickness and improved absorber design. This optimization allows more photons to reach the InGaAs absorption region, increasing carrier generation. Consequently, the device demonstrates improved photocurrent and overall detection performance.

This improvement leads to higher photocurrent generation in the device.

As a result, the photodiode exhibits better sensitivity and performance for optical communication applications.

Case	Description	Responsivity (A/W)
Case 1	Baseline Heterostructure	0.84
Case 2	Enhanced Absorber Configuration	0.95
Case 3	Proposed OWLA Structure	1.0084

Table: Comparison of Simulated Cases

Graphical Comparison

The responsivity values clearly show a progressive improvement from Case 1 to Case 3.

Observation:

- Case 1 provides the lowest responsivity
- Case 2 improves due to better absorber thickness
- Case 3 gives the highest responsivity due to

combined structural optimization

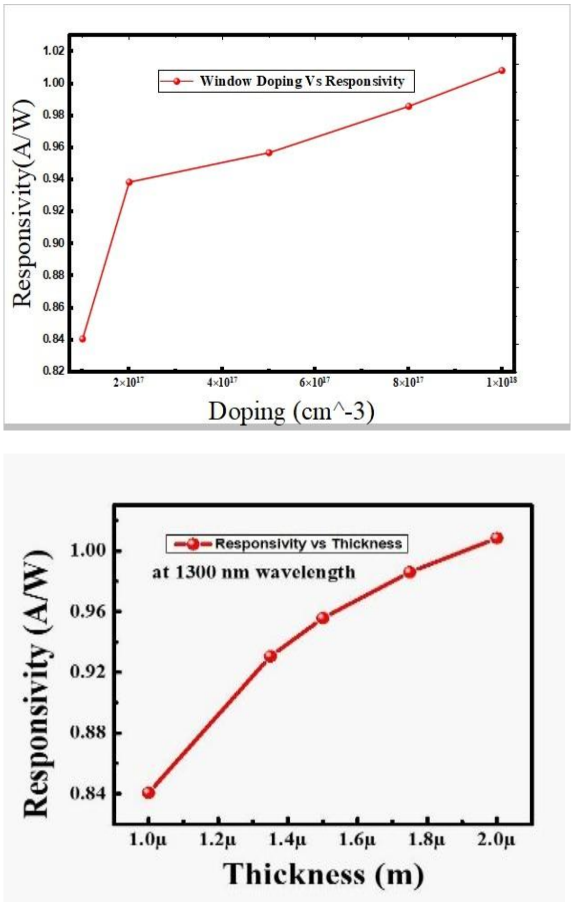


Figure 13 : Graphical Comparison of all cases

VII. CONCLUSION

This paper presented the design and simulation of an optimized photodiode architecture using Silvaco TCAD simulation tools. The proposed structure was developed to improve photon absorption and carrier collection efficiency in optical photodetectors used for communication systems. The simulation results showed that reducing the window layer thickness and optimizing the absorber region significantly improves device performance.

Key parameters such as photocurrent, responsivity, and external quantum efficiency were analyzed to evaluate the effectiveness of the proposed structure. The optimized design achieved higher responsivity and improved quantum efficiency compared to the baseline configuration. The analytical relationship between quantum efficiency and responsivity also supports the simulation results.

Overall, the proposed photodiode architecture demonstrates improved performance and can be considered suitable for high-sensitivity and low-power optoelectronic applications in optical communication, sensing, and environmental monitoring systems.

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