

TCAD Simulation of a Silicon PIN Photodiode: Effect of Intrinsic-Layer Thickness on Optical Response

Mohit Singh[1], Ryan Kharwal[2], Jaswant K. Yadav[3*]

[1] Undergraduate Student, Department of Physics & Astrophysics, Central University of Haryana, Mahendergarh, India.
[2] Senior High School Student, Emerson High School, Frisco ISD- 6300 Collin McKinney Pkwy, McKinney, Texas, USA.
[3] Assistant Professor, Department of Physics & Astrophysics, Central University of Haryana, Mahendergarh, India.
*Corresponding Author Email: jaswantkyadav@gmail.com

(Received: 02.09.2026; Accepted: 07.10.2026)

Abstract

The intrinsic region of silicon PIN photodiodes offers a longer absorption/depletion volume for photogenerated carriers, which makes them a popular device for optical detection. Using the VICTORY/SILVACO simulation environment, a two-dimensional technology-computer-aided design (TCAD) simulation analysis of a silicon PIN photodiode is presented in this work. The device structure is made up of a lightly doped silicon region between heavily doped P+ and N+ contact regions. With a focus on the impact of increasing the intrinsic-layer thickness, the simulations investigate steady-state optical response, spectral response, and quantum efficiency. For the baseline device, the simulated spectral response extends over 100nm to 800 nm wavelength range, and the calculated quantum efficiency reaches approximately 90% near 700 nm. On increasing the thickness of the intrinsic layer to approximately 14.4 µm, the simulated photocurrent shows an increase, and the associated quantum efficiency reaches about 96% around a wavelength of 700 nm. It appears that increasing the optical absorption volume is enhancing the carrier generation and collection under the simulated conditions. The paper offers a simulation framework pertinent to photodetection and photovoltaic optoelectronic device investigations and shows the value of TCAD simulation for optimizing illuminated semiconductor architectures.

Keywords: *Silicon PIN photodiode; TCAD; Intrinsic-layer thickness; Spectral response; Quantum efficiency; Simulation*

INTRODUCTION

An electrical signal is generated when optical radiation is incident on a photodetector. Such devices play a key role in spectroscopy, sensing, imaging, optical communication, and other optoelectronic applications. A PIN photodiode consists of an intrinsic semiconductor layer between P-type and N-type semiconductor regions. This arrangement enhances the effective depletion/absorption region and provides a suitable device architecture for efficient photocarrier generation and collection. Simulations play a crucial role in understanding optical absorption, carrier generation, transport, and collection in semiconductor photodetectors.

The thickness of the intrinsic-layer is an important variable in the design of a photodetector. As one increases the thickness of the absorbing region, one is effectively increasing the number of absorbed photons and hence the generated photocurrent. The device geometry and carrier transport mechanism can also affect speed and capacitance. Previous TCAD studies of PIN photodiodes focused on fixed intrinsic-region dimensions and their influence on current-voltage characteristics and device response (Ahmad *et al.*, 2018; Othman *et al.*, 2014). The importance of geometry and capacitance control in achieving high bandwidth has aptly been demonstrated with the help of High-speed InGaAs PIN photodetectors (Wang *et al.*, 2009). More recent investigations have continued to explore the role of intrinsic-layer geometry in device optimization, including studies on Mg_2Si/Si heterojunction photodetectors that established PIN structure models using Silvaco TCAD to examine detection properties (Yu *et al.*, 2025). The effect of intrinsic-layer thickness on quantum efficiency has also been reported for amorphous silicon PIN junctions, demonstrating that spectral response is highly affected by this parameter (Lovecchio *et al.*, 2025). TCAD simulations of silicon PIN photodetectors have further been employed to analyze dark current behavior

and its dependence on Shockley-Read-Hall recombination under low carrier injection conditions (Kose *et al.*, 2025).

The purpose of this paper is to simulate a silicon PIN photodiode to compare its optical/electrical response before and after increasing the intrinsic-layer thickness. Our primary focus remains on optical-source intensity response, spectral response, and quantum efficiency. The work is presented as a device-simulation study; it does not report photovoltaic power-generation metrics such as open-circuit voltage, short-circuit current density, fill factor, or power-conversion efficiency. The organization of the paper is as follows: the section on Device Physics and Performance Metrics discusses the underlying physics and performance metrics of the device; the section on Simulation Methodology describes the simulation methodology; while the sections on Results and Discussion and Conclusions describe the results, discussion, and conclusions of the present study.

DEVICE PHYSICS AND PERFORMANCE METRICS

PIN Photodiode Operation

Fig. 1 shows the carrier generation and collection in an illuminated PIN photodiode, and Fig. 2 presents the photon-induced carrier generation and energy-band representation (Sze and Lee, 2012).

P-type, intrinsic, and N-type semiconductor areas make up a PIN photodiode. Electron-hole pairs can be produced by incident photons with energy higher than the semiconductor bandgap. After the photogenerated carriers are separated by the electric field throughout the depleted/intrinsic region, electrons and holes are gathered at the appropriate contacts. Optical power, wavelength, absorption, carrier transit, and collection efficiency all affect the final photocurrent under illumination. Recent TCAD studies on PIN versus PN structures have quantified the advantage of the intrinsic layer, showing that the PIN architecture can exhibit responsivity improvements of approximately 10% and external quantum efficiency enhancements of about 18% compared with PN structures under comparable conditions (Yu *et al.*, 2025).

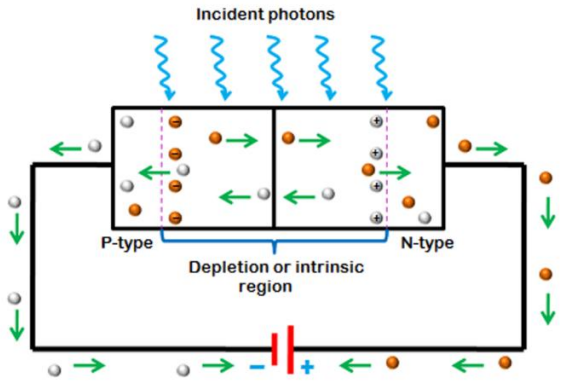


Fig. 1: Carrier generation and collection in an illuminated PIN photodiode (Schematic representation). *Source*: Sze and Lee, 2012.

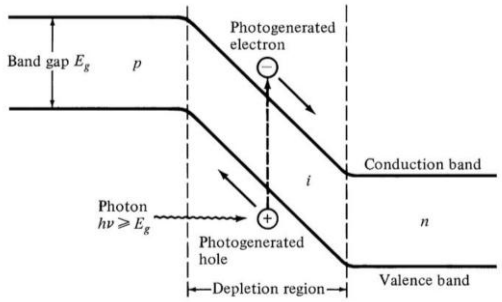


Fig. 2: Photon-induced carrier generation and Energy-band representation. *Source*: Sze and Lee, 2012.

Responsivity and Quantum Efficiency

The ratio of photocurrent Iph to incident optical power Popt defines the responsivity Rλ as:

$$R\lambda = Iph / Popt = \eta q \lambda / (h c) \quad (1)$$

here, η is the quantum efficiency, q denotes the elementary charge, λ refers to the incident wavelength, h denotes Planck's constant, and c refers to the speed of light (Sze and Lee, 2012). The external quantum efficiency from this relation can then be written as:

$$\eta = Iph\ h\ c / (Popt\ q\ \lambda) \quad (2)$$

It is to be noted that dark current is the current flowing in the absence of illumination. It is associated primarily with thermally generated carriers and recombination/generation processes. Studies on silicon PIN photodetectors have shown that dark current is strongly dependent on Shockley-Read-Hall recombination, particularly under low carrier injection conditions, and that TCAD simulations can effectively model this dependence for process control and defect analysis (Kose *et al.*, 2025). In this work, we mainly focus on the illuminated response and quantum efficiency.

SIMULATION METHODOLOGY

TCAD Environment

The device was simulated using the SILVACO VICTORY TCAD environment. Silvaco TCAD tools, including the Atlas module, have been widely employed for establishing structure models of PIN photodetectors and studying their detection properties such as energy band, current-voltage characteristics, responsivity, and external quantum efficiency (Yu *et al.*, 2025). The simulation workflow defines the computational mesh, material regions, electrodes, doping profiles, physical models, numerical solution method, and optical excitation. VICTORY solves the semiconductor device equations on a discretized mesh and provides terminal currents and other device quantities as functions of applied bias and optical excitation (SILVACO, 2023).

Device Structure and Mesh

The baseline device is a rectangular silicon PIN structure with a lightly doped N-type region and heavily doped P+ and N+ regions at the front and back surfaces, respectively. The baseline simulation uses a nominal mesh dimension of 10 µm × 15 µm for the initial structure. A second structure uses a 15 µm × 15 µm mesh and an intrinsic-layer thickness of approximately 14.4 µm, while retaining the stated doping and mesh-multiplication settings of the earlier structure. Fig. 3 shows a representative computational mesh used for the PIN

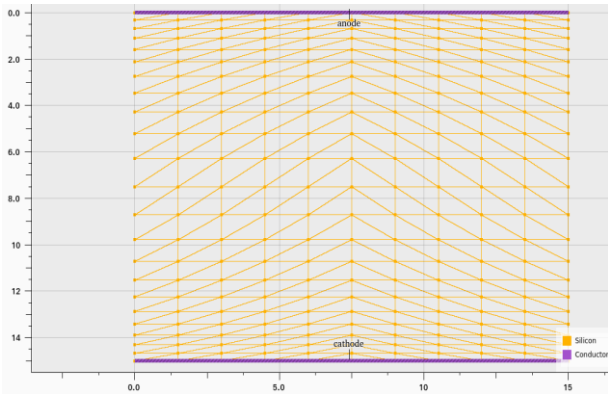


Fig. 3: Representative computational mesh used for the PIN photodiode simulation.

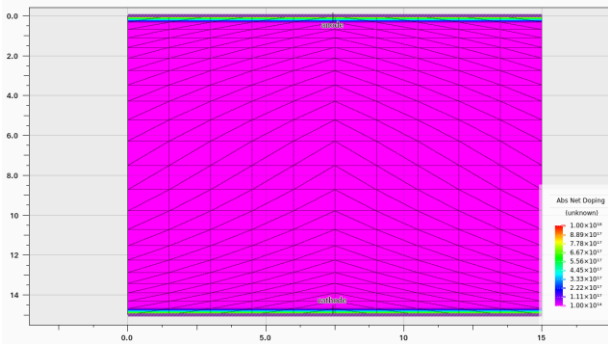


Fig. 4: Simulated device/doping distribution associated with the PIN structure.

photodiode simulation, and Fig. 4 presents the simulated device/doping distribution associated with the PIN structure. Table 1 lists the principal simulation conditions and values of the parameters.

Physical Models and Numerical Solution

The simulation methodology includes concentration- and field-dependent mobility, Shockley–Read–Hall recombination, Auger recombination, and Boltzmann carrier statistics. Nonlinear semiconductor equations are solved iteratively using a Newton-based method. The DC solution begins from thermal equilibrium and proceeds through applied-bias steps. Optical and small-signal responses can be obtained using the corresponding VICTORY solution commands.

Table 1: Principal simulation conditions and values of the parameters.

Parameter	Baseline simulation	Increased-I-layer simulation
Device material	Silicon	Silicon
Device type	P-i-N photodiode	P-i-N photodiode
Reported mesh dimension	10 µm × 15 µm	15 µm × 15 µm
Intrinsic-layer thickness	Baseline structure	≈14.4 µm
Background doping	N-type, 1.0×10^{14} cm^{-3}	Same as baseline
Front/back contacts	P+ / N+	P+ / N+
Optical source direction	Normal to front surface	Normal to front surface
Operating bias	2.0 V	2.0 V
Optical intensity sweep	0–1 W cm^{-2}	0–1 W cm^{-2}
Spectral investigation	0.1–0.8 µm	0.1–0.8 µm

The simulation deck uses mesh, region, electrode, and doping statements to construct the device. Uniform and Gaussian doping profiles are supported by the methodology. Terminal voltages and currents are recorded in log files, and device parameters can be extracted using the EXTRACT functionality.

Optical Excitation

For the steady-state optical simulation, the source is positioned approximately 1 µm above the device and directed normal to the front surface. The optical intensity is ramped from 0 to 1 W cm−2 at an operating bias of 2.0 V. Spectral-response calculations are performed at discrete wavelengths in the 0.1–0.8 µm range, with the source document reporting a wavelength step of 0.01 µm for the spectral sweep.

RESULTS AND DISCUSSION

Baseline Device Under Optical Excitation

For the baseline silicon PIN photodiode, the simulated source and cathode currents were extracted while optical intensity was increased from 0 to 1 W cm−2 at a 2.0 V operating bias. We find an approximately linear relationship between optical-source intensity and terminal response over the investigated range (Fig. 5).

Spectral Response

The spectral response (Fig. 6) was evaluated under an optical intensity of 1 W cm−2. The simulation indicates appreciable

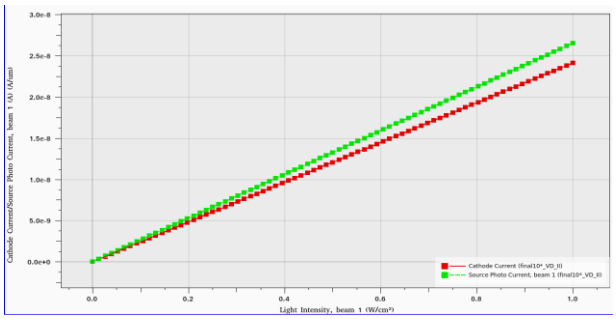


Fig. 5: Simulated source/cathode current for the baseline silicon PIN photodiode versus optical-source intensity.

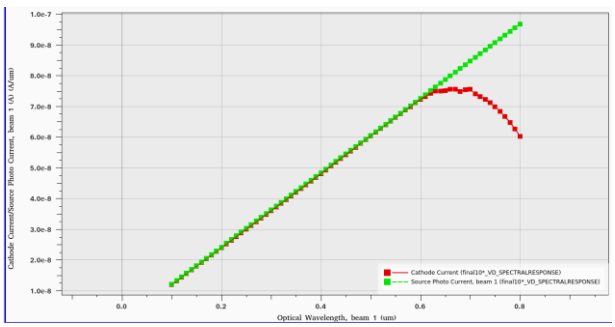


Fig. 6: Spectral response of the simulated baseline silicon PIN photodiode.

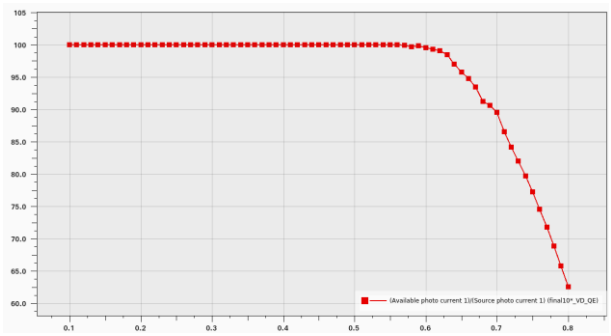


Fig. 7: Quantum efficiency of the simulated baseline PIN photodiode as a function of optical wavelength.

response over the investigated spectral interval, with good quantum efficiency below approximately 700 nm. The response is consistent with the wavelength-dependent absorption of silicon and the carrier-generation process in the device.

Quantum Efficiency of the Baseline Structure

Fig. 7 depicts that in the baseline simulation, the calculated quantum-efficiency curve reaches approximately 90% near 700 nm. This value represents the simulated device result and should be interpreted within the specified optical-source, bias, geometry, and material-model conditions as described in the section on Simulation Methodology.

Increasing the Intrinsic-Layer Thickness

To study the effect of the change in thickness of the intrinsic region, a second device structure was simulated after increasing the intrinsic layer to approximately 14.4 µm. We find that the increased intrinsic-layer structure produces a higher cathode current than the baseline structure and retains good linearity between optical-source intensity and photocurrent (Fig. 8). The physical interpretation of this finding is that the larger intrinsic/absorption volume permits greater optical absorption. It increases photogenerated carrier generation under the simulated conditions. This observation aligns with recent findings that the intrinsic layer in PIN architectures extends the depletion width, thereby enhancing long-wavelength absorption through increased photon interaction volume (Yu *et al.*, 2025). Similar thickness-dependent effects have been reported for amorphous silicon PIN junctions, where the spectral response was found to be

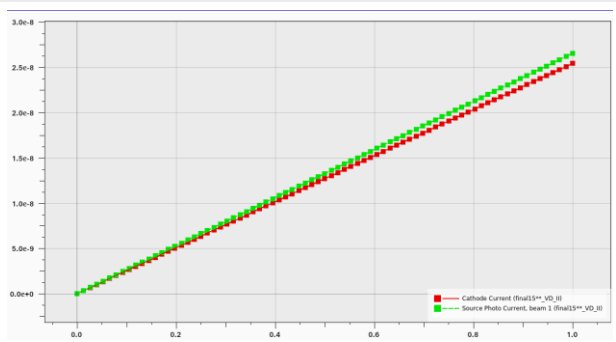


Fig. 8: Simulated source/cathode current versus optical-source intensity after increasing the intrinsic-layer thickness.

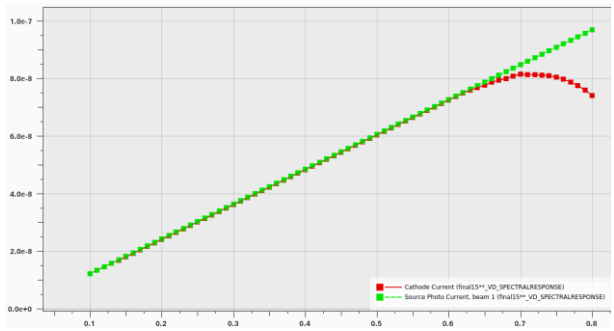


Fig. 9: Simulated spectral response after increasing the intrinsic-layer thickness.

highly affected by the i-layer thickness (Lovecchio *et al.*, 2025).

New Spectral Response

The simulated cathode current is comparatively higher over the investigated spectral region of 100 to 800 nm, particularly below approximately 700 nm (Fig. 9), after increasing the intrinsic-layer thickness. The increase can be attributed to the larger absorption region. It allows more incident photons to contribute to electron-hole-pair generation.

Enhanced Quantum Efficiency

Fig. 10 exhibits a quantum efficiency of approximately 96% near 700 nm for the increased-I-layer simulation device, compared with approximately 90% for the baseline structure. Thus, under the reported simulation conditions, increasing the intrinsic-layer thickness improves the simulated quantum efficiency by about six percentage points at the wavelength where the comparison is reported.

Discussion

The simulations show a clear relationship between intrinsic-layer thickness and optical response. Increasing the intrinsic region increases the available volume for photon absorption and photocarrier generation, which is reflected in the higher simulated photocurrent and quantum efficiency. This observation is qualitatively consistent with earlier PIN-photodiode simulation studies that examined the role of intrinsic-region dimensions (Othman *et al.*, 2014). Recent TCAD-based investigations have similarly demonstrated that the intrinsic layer in PIN structures enhances responsivity and external quantum efficiency through extended depletion

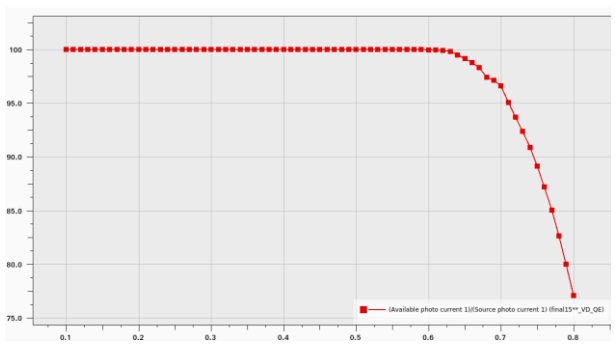


Fig. 10: Simulated quantum efficiency after increasing the intrinsic-layer thickness.

width and increased photon interaction volume (Yu *et al.*, 2025).

The result should, however, be considered together with the usual device-design trade-offs. A thicker intrinsic/absorption region can increase carrier transit distance and may influence junction capacitance, bandwidth, and temporal response. TCAD simulations validated against experimental measurements have shown that device simulation can effectively model complex carrier dynamics in silicon PIN structures, providing a reliable framework for such trade-off analyses (Alasio *et al.*, 2024; Pape *et al.*, 2024). In a future extension of this work, we would include transit-time, capacitance, bandwidth, dark-current, responsivity-in-A/W, or temperature-dependent simulations for the two silicon structures. These quantities would be valuable additions for a complete device-optimization study.

CONCLUSIONS

A two-dimensional TCAD simulation study of a silicon PIN photodiode has been presented using the SILVACO VICTORY framework. The simulated device was evaluated under optical excitation in terms of optical-source intensity response, spectral response, and quantum efficiency. The baseline structure exhibits approximately 90% quantum efficiency near 700 nm under the reported simulation conditions. Increasing the intrinsic-layer thickness to approximately 14.4 μm increases the simulated cathode current and raises the reported quantum efficiency to approximately 96% near 700 nm. The results demonstrate that intrinsic-layer engineering can be used to modify the optical response of silicon PIN structures. These findings are consistent with recent TCAD studies that have established the intrinsic layer as a critical design parameter for optimizing photodetector performance, including improvements in responsivity, external quantum efficiency, and detectivity (Yu *et al.*, 2025). The methodology provides a useful basis for further TCAD optimization of illuminated semiconductor devices, including future studies that explicitly evaluate photovoltaic operating metrics (Fukuchi *et al.*, 2001).

ORCID iD

Jaswant K. Yadav: 0000-0002-9543-683X

Data and Reproducibility Information

The complete numerical simulation deck, exact material parameters, mesh files, solver tolerances, and raw log files have been archived at the source and will be made available upon reasonable request so that our work can be reproduced.

Acknowledgement

We thank the Department of Physics and Astrophysics, Central University of Haryana, for providing the necessary infrastructural and computational support to carry out this work. MS and RK would also like to thank Jai Prakash for useful discussions regarding the working of different modules in the software.

Grant Support Details

The present research did not receive any financial support to conduct the research.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy, have been completely observed by the authors.

REFERENCES

1) Ahmad, W., Ali, M.U., Laxmi, V., *et al.* (2018) 'Simulation and characterization of PIN photodiode for photonic applications', *Asian Journal of Nanoscience and Materials*, 1(3), pp. 122-134. https://doi.org/10.26655/ajnanomat.2018.6.3
2) Alasio, M.G.C., Vallone, M., Tibaldi, A., *et al.* (2024) 'TCAD-assisted progress on the Cisco platform toward low-bias 200 Gbit/s vertical-pin Ge-on-Si waveguide photodetectors', *Journal of Lightwave Technology*, 42(9), pp. 3269-3276. https://ieeexplore.ieee.org/document/10387676
3) Fukuchi, K., Kasamatsu, T., Morie, M., *et al.* (2001) '10.92-Tb/s (273 x 40-Gb/s) triple-band/ultra-dense WDM optical-repeatered transmission experiment', *Optical Fiber Communication Conference and International Conference on Quantum Information*. Anaheim, USA, Paper PD24.
4) Kose, Y.M., Guney, U., Mert, E., *et al.* (2025) 'Dark current analysis in silicon PIN photodetectors: TCAD, lifetime and statistical process control', *Proceedings of the 2025 IEEE International Conference on Electrical, Computer and Energy Technologies (ICECET)*. Istanbul, Turkiye, pp. 07-10. https://ieeexplore.ieee.org/document/11091985
5) Lovecchio, N., Casalinuovo, S., Nascetti, A., *et al.* (2025) 'Effect of intrinsic layer thickness on the performances of amorphous silicon P-I-N junction', *Lecture Notes in Electrical Engineering*, 1263, pp. 199-204. https://doi.org/10.1007/978-3-031-71518-1_22
6) Othman, M.A., Yasin, N.Y.M., Napiah, Z.A.F.M., *et al.* (2014) 'Comparison of intrinsic width for InGaAs PIN photodiode', *AIP Conference Proceedings*, 1586, pp. 147-153. https://doi.org/10.1063/1.4866750
7) Pape, S., Moll, M., García, M.F., *et al.* (2024) 'TCAD simulation of two photon absorption—transient current technique measurements on silicon detectors and LGADs', *Sensors*, 24(24), 8032. https://doi.org/10.3390/s24248032
8) SILVACO International (2023) *VICTORY device simulation user manual.* Santa Clara, CA: SILVACO International.
9) Sze, S.M. and Lee, M.K. (2012) *Semiconductor devices physics and technology.* 3rd ed. Hoboken, NJ: John Wiley & Sons, Inc.
10) Wang, Y.S., Chang, S.J., Tsai, C.-L., *et al.* (2009) 'High-speed InGaAs P-I-N photodetector with planar buried heterostructure', IEEE Transactions on Electron Devices, 56(6), pp. 1347-1350. https://doi.org/10.1109/TED.2009.2018170
11) Yu, H., Chen, Q. and Gao, C. (2025) 'Performance engineering of eco-friendly Mg_2Si/Si photodetectors: TCAD-validated advantages of PIN over PN structures for visible-NIR detection', *AIP Advances*, 15(7), 075112. https://doi.org/10.1063/5.0275284