

Unified TCAD Simulation Framework for InGaAs/InP Single-Photon Avalanche Diodes

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Abstract—Designing high-performance planar InGaAs/InP single-photon avalanche diodes (SPADs) requires predictive simulation of dark count rate (DCR), photon detection efficiency (PDE), charge persistence, and timing response across the thermoelectric cooling range. We present a unified Sentaurus Technology Computer-Aided Design (TCAD) framework that predicts all four metrics within a single simulation environment. Custom temperature-dependent impact ionization and optical absorption models extend the framework across 225–300 K without external tools. A carrier-path formulation captures charge persistence invisible to standard local methods, and gated-mode transient simulations with custom Physical Model Interface (PMI) modules extract the avalanche signal response and its depth-dependent timing spread. Validated against published measurements, the framework guides the design of SPADs fabricated using a recess-etch planar technology under development at Fraunhofer IAF.

Index Terms—InGaAs/InP SPAD, TCAD, photon detection efficiency, dark count rate, timing jitter, charge persistence, carrier path tracing, transient simulation, gated quenching.

I. INTRODUCTION

Planar InGaAs/InP SPADs based on the separate absorption, grading, charge, and multiplication (SAGCM) architecture are essential single-photon detectors at 1550 nm. As shown in Fig. 1, photons are absorbed in the narrow-bandgap InGaAs active region while impact ionization is confined to the InP multiplication region; the grading and charge layers suppress hole trapping at the heterointerface and maintain the high electric field within InP, respectively.

Biased above the breakdown voltage V_{br} in Geiger mode, a photogenerated hole drifts from the active region into the multiplication region and initiates a self-sustaining avalanche that constitutes a detection event. Device performance is characterized by four interdependent figures of merit. The dark count rate (DCR) quantifies the rate of false detection events arising from thermally generated carriers that trigger the avalanche in the absence of an incident photon. The photon detection efficiency (PDE) is the probability that an incident photon produces a registered detection event. Charge persistence is a parasitic effect in which carriers generated outside the active region diffuse laterally into the multiplication region, producing false delayed triggers. Timing jitter quantifies the temporal resolution of the detector as the statistical spread in the delay between photon absorption and the registered

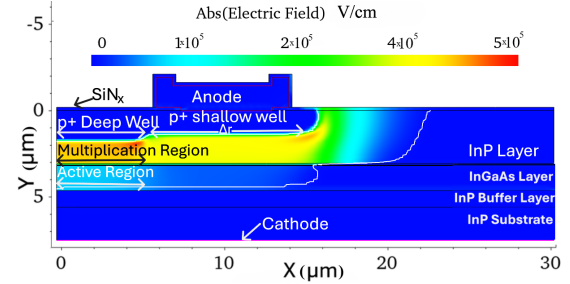


Fig. 1: Planar 10 μm InGaAs/InP SPAD device structure along with electric field distribution profile at $V_{EX} = 5$ V.

avalanche, arising from the stochastic absorption depth in InGaAs and the randomness of avalanche buildup in InP.

At Fraunhofer IAF, a recess-etch planar technology for InGaAs/InP SPAD fabrication is under development [1], requiring predictive simulation of all four figures of merit. Existing approaches address only subsets of these metrics, relying on hybrid workflows with external tools [2] or reporting PDE at discrete temperatures [3]. This work presents a unified Sentaurus TCAD framework that resolves these limitations within a single simulation environment.

II. SIMULATION FRAMEWORK AND VALIDATION

To establish and validate the simulation environment, the planar 10 μm and 25 μm SAGCM structures of [4], [5], [6] are simulated in Synopsys Sentaurus TCAD [7], with model parameters verified against the available experimental data. Since the internal design parameters of these published devices are not disclosed, the reference structures used for validation are reconstructed from the reported layer sequence and general device physics, rather than from the actual device structure.

A. Device Structure and Electrical Simulation

The reference SAGCM structure is modeled in 2-D cylindrical symmetry. Doping concentrations are modeled analytically using error functions, and the structure is calibrated to reproduce the experimental breakdown voltage of 67 V at 235 K [4]. As breakdown voltage alone admits multiple doping and field-profile combinations, this calibration is further constrained by matching the measured DCR vs. excess-bias characteristic presented later in this section. This agreement

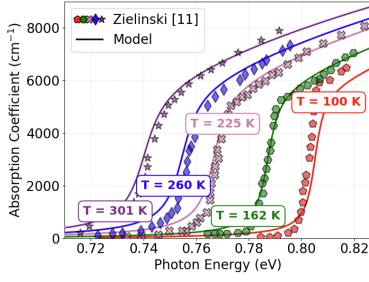


Fig. 2: Temperature-dependent absorption coefficient of InGaAs.

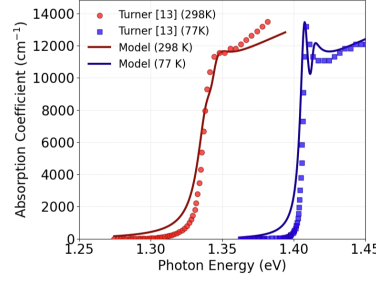


Fig. 3: Temperature-dependent absorption coefficient of InP.

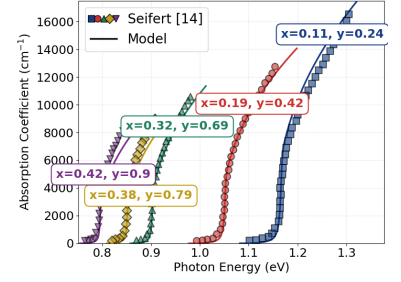


Fig. 4: Temperature-dependent absorption coefficient of InGaAsP.

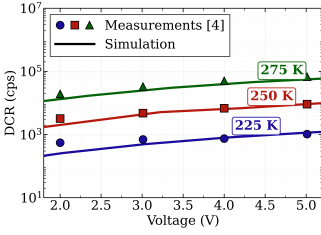


Fig. 5: DCR vs. V_{EX} .

TAT Parameter	Value
Huang-Rhys factor S	8
Phonon energy $\hbar\omega_0$	0.043 eV
Tunneling mass m_Θ	0.08 m_0
SRH Parameter	Value
Carrier lifetime τ_0	1.6 μs
trap level	0.34 eV

TABLE I: Schenk Model TAT parameters for InP.

supports the physical plausibility of the reconstructed field profile, though exact reproduction of the unpublished device structure cannot be claimed, a limitation inherent to validating against structures reconstructed from published data.

A critical component of the electrical simulation is the accurate description of impact ionization in InP. The electron and hole ionization coefficients $\alpha(E, T)$ and $\beta(E, T)$ are taken from [8], and implemented as a custom Physical Model Interface (PMI) module within Sentaurus. DCR is evaluated as:

$$DCR = \int_V G_{SRH}(\vec{r}) P_{br}(\vec{r}) dV \quad (1)$$

where P_{br} is the local breakdown probability from the McIntyre model [9], evaluated above breakdown with impact ionization disabled. G_{SRH} is Shockley-Read-Hall generation with Schenk field-enhanced trap-assisted tunneling (TAT) [10], dominant in the high-field InP multiplication region. Since the electric field in the InGaAs layer is low, TAT in that layer is negligible and omitted. The calibrated model parameters for InP are listed in Table I, and the simulated DCR as a function of excess bias shows good agreement with the measurements in [4], as shown in Fig. 5.

B. Optical Simulations and Carrier-Path Approach

The photon detection efficiency is evaluated as

$$PDE_{local} = \frac{1}{\eta} \int G_{opt}(\vec{r}) P_{br}(\vec{r}) dV, \quad (2)$$

where η is the incident photon rate, and $G_{opt}(\vec{r})$ is the optical generation rate obtained from the finite-difference time-domain (FDTD) simulations, which solves Maxwell's

equations rigorously using the complex refractive index (CRI) $\tilde{n} = n + i\kappa$ as input. Since TCAD libraries lack temperature-dependent CRI data for III-V materials, previous works [2], [3] were restricted to specific temperatures where measured absorption data existed. We resolve this by implementing the Zielinski model [11], which can be written as:

$$\alpha_0(E) = A \left(\sum_{n=1}^{\infty} \frac{2E_x}{n^3} \delta(E - E_n) + \frac{\theta(E - E_g)}{1 - e^{-2\pi Z}} \right), \quad (3)$$

$$\alpha(E) = \frac{1}{\pi} \int_{-\infty}^{\infty} \alpha_0(E') \frac{\Gamma/2}{(E - E')^2 + \Gamma^2/4} dE'. \quad (4)$$

Replacing the band gap E_g term with Varshni equation [12],

$$E_g(T) = E_g(0) - \frac{aT^2}{T + T_0}, \quad (5)$$

continuously shifts the excitonic resonances and continuum onset with temperature, yielding $\alpha(\lambda, T)$ across 225–300 K for InGaAs, as shown in Fig. 2. The model parameters are subsequently calibrated for InP to reproduce the measurements of Turner et al. [13] (Fig. 3), and for InGaAsP to match the data of Seifert et al. [14] (Fig. 4).

For spot illumination, where the illuminated beam is confined within the active area, PDE is simulated at 235 K for a 10 μm device using Eq. (2) to validate the implemented models and compared against published measurements [4]. The simulated DCR-PDE trade-off shows good agreement with the reported data, as shown in Fig. 6. Further validation is provided by the spectral PDE of a 25 μm device at 275 K, where simulated results match measured values across the wavelength range of interest (Fig. 8).

Under flood illumination, however, photons can be absorbed outside the active area and generate holes that drift laterally and either inject into the multiplication region, causing delayed avalanches known as charge persistence [6], or drain vertically beneath the shallow p-well. Since $P_{br} = 0$ at these peripheral sites, Eq. (2) fails to account for their contribution. We therefore adopt an approach that traces each hole from its generation site $\vec{r}$ along $\vec{J}_p$ to its injection point $\vec{m}(\vec{r})$ at the multiplication region boundary, redefining PDE as:

$$PDE_{path \text{ based}} = \frac{1}{\eta} \int G_{opt}(\vec{r}) \cdot P_{br}(\vec{m}(\vec{r})) dV, \quad (6)$$

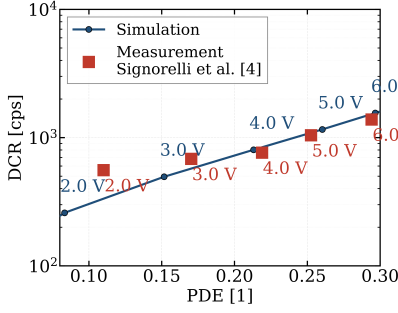


Fig. 6: DCR-PDE trade-off [4].

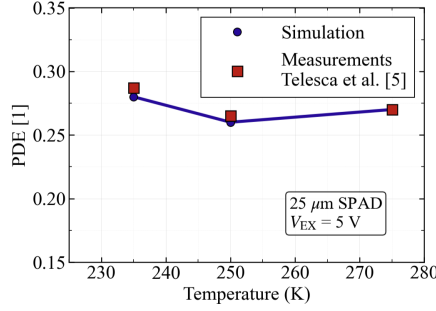


Fig. 7: PDE vs. Temperature.

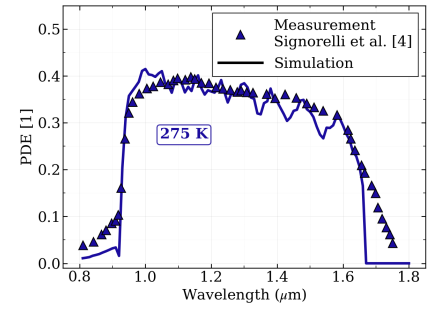


Fig. 8: Spectral PDE at 275 K [4].

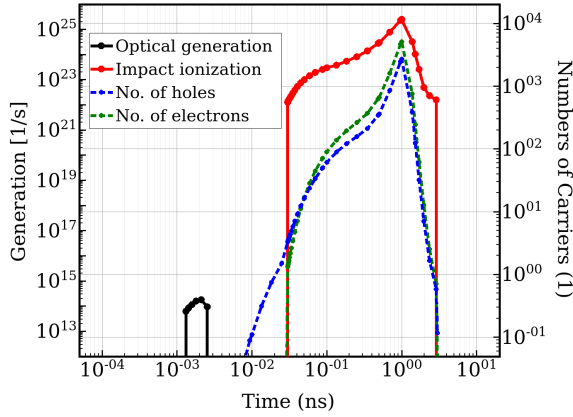


Fig. 9: PMI modules in operation.

which reduces to Eq. (2) under spot illumination. Applying this formulation to the flood illumination scenario, the simulated PDE as a function of temperature for the 25 μm device shows good agreement with the measurements [5], as shown in Fig. 7.

C. Transient Simulation

Transient mixed-mode simulations are carried out to characterize the timing behavior of the SPAD, i.e. its signal response. To ensure that this response originates solely from the incident optical pulse, several custom physical model interfaces (PMIs),

illustrated in Fig. 9, are implemented. With the device biased above breakdown, a 1 ps optical pulse delivers a sufficient photon flux at a specified depth in the InGaAs absorption layer to ensure the generation of a single electron-hole pair; once the hole population reaches unity in the multiplication region, a monitoring module activates impact ionization. All background generation mechanisms are disabled so that only photon-triggered avalanches are captured.

The SPAD may be operated above breakdown and quenched in several ways. In the gated mode of operation a 1 ns gate pulse biases the device above breakdown and quenches it below breakdown at the end of the gate. Since gating superimposes a fast capacitive transient on the avalanche signal, the response of a reference (dummy) SPAD without photon injection is subtracted from the illuminated device, yielding a differential current that isolates the actual avalanche response. Fig. 10 shows the differential current response for the gated mode of operation of the SPAD and also the response without gated quenching.

The SPAD is then treated as a binary counter: a detection event is registered once the differential current exceeds 1 μA , i.e. the counter switches from 0 to 1. Fig. 11 shows this counting response together with the optical pulse and the gate pulses for several excess-bias voltages V_{EX} . Higher bias accelerates the avalanche buildup, so the 0-to-1 transition occurs earlier, reducing the detection delay.

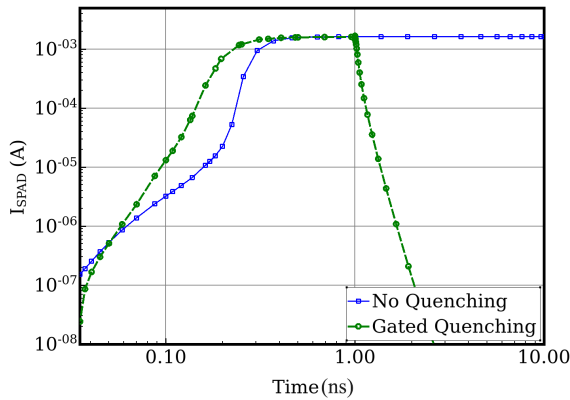


Fig. 10: Signal Response of the SPAD.

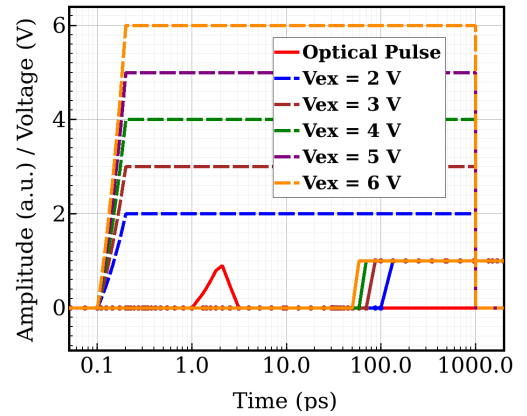


Fig. 11: SPAD as counter for several V_{EX} .

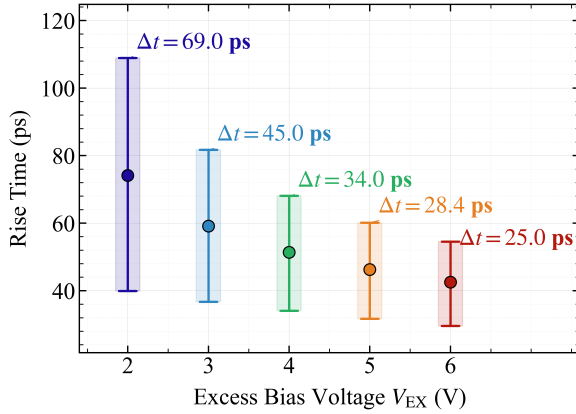


Fig. 12: Detection time spread vs. V_{EX} .

Finally, the photon injection point is varied across 10 depths at each of two lateral locations, the center and the edge of the active area. The corresponding distribution of detection times is extracted. This spread constitutes the timing jitter: carriers generated near the top of the absorber reach the multiplication region sooner, yielding faster detection than those generated deeper. Fig. 12 plots this jitter for several values of V_{EX} ; it narrows with increasing bias, as the stronger field compresses the transit-time distribution, in agreement with the trend observed in measurements [4]. Although a finer sampling of injection points would refine the estimate, this coarse set already captures the device-level jitter trend relevant for design; quantitative agreement with measurements would additionally require the system jitter contributions (laser, electronics) not included here.

III. CONCLUSION

This work demonstrates that the four key figures of merit of an InGaAs/InP SPAD, can be captured within a single TCAD environment. The Zielinski absorption model with a temperature-dependent bandgap makes the framework predictive across the full cooling range, while the carrier-path formulation captures the peripheral photon collection that governs charge persistence under flood illumination. Gated transient simulations with custom PMI models isolate the intrinsic timing behaviour, and a digital-counter treatment of the Geiger-mode response extracts well-defined detection timestamps and the resulting depth-dependent timing jitter. DCR, PDE, and charge persistence agree well with independent published measurements, and the extracted jitter follows the expected bias-dependent trend. The validation presented here confirms the soundness of the simulation methodology, although the reconstructed reference structures do not permit exact verification against known device structures. Establishing predictive accuracy for a device with fully known design parameters is therefore the next step, to be addressed through application of the framework to the recess-etch planar SPAD technology currently under development at Fraunhofer IAF.

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REFERENCES

- [1] F. Rutz, A. Wörl, A. Bächle, J. Niemasz, and R. Rehm, "Progress on InGaAs-based SPAD fabrication for SWIR detection and imaging," in *Electro-Optical and Infrared Systems: Technology and Applications XXI*, International Society for Optics and Photonics, vol. 13200, SPIE, 2024, 132000Z. DOI: 10.1117/12.3031445.
- [2] F. Telesca, F. Signorelli, and A. Tosi, "Temperature-dependent photon detection efficiency model for InGaAs/InP SPADs," *Opt. Express*, vol. 30, no. 3, pp. 4504–4514, Jan. 2022. DOI: 10.1364/OE.444536.
- [3] E. Kizilkan et al., "Extended Temperature Modeling of InGaAs/InP SPADs," in *ESSDERC 2023 - IEEE 53rd European Solid-State Device Research Conference (ESSDERC)*, 2023, pp. 140–143. DOI: 10.1109/ESSDERC59256.2023.10268545.
- [4] F. Signorelli et al., "Low-noise InGaAs/InP Single-Photon Avalanche Diodes for Fiber-Based and Free-Space Applications," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 28, no. 2: Optical Detectors, pp. 1–10, 2022. DOI: 10.1109/JSTQE.2021.3104962.
- [5] F. Telesca, F. Signorelli, and A. Tosi, "Double Zinc Diffusion Optimization for Charge Persistence Reduction in InGaAs/InP SPADs," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 30, no. 1: Single-Photon Technologies and Applications, pp. 1–7, 2024. DOI: 10.1109/JSTQE.2023.3332767.
- [6] N. Calandri, M. Sanzaro, A. Tosi, and F. Zappa, "Charge persistence in InGaAs/InP Single-Photon Avalanche Diodes," *IEEE Journal of Quantum Electronics*, vol. 52, no. 3, pp. 1–7, 2016. DOI: 10.1109/JQE.2016.2526608.
- [7] Synopsys, Inc., *Sentaurus™ device user guide*, Version X-2025.06, 2025.
- [8] F. Zappa, P. Lovati, and A. Lacaita, "Temperature dependence of electron and hole ionization coefficients in InP," in *Proceedings of 8th International Conference on Indium Phosphide and Related Materials*, 1996, pp. 628–631. DOI: 10.1109/ICIPRM.1996.492327.
- [9] R. McIntyre, "On the avalanche initiation probability of avalanche diodes above the breakdown voltage," *IEEE Transactions on Electron Devices*, vol. 20, no. 7, pp. 637–641, 1973. DOI: 10.1109/T-ED.1973.17715.
- [10] A. Schenk, "A model for the field and temperature dependence of Shockley-Read-Hall lifetimes in silicon," *Solid State Electronics*, vol. 35, no. 11, pp. 1585–1596, Nov. 1992. DOI: 10.1016/0038-1101(92)90184-E.
- [11] E. Zielinski, H. Schweizer, K. Streubel, H. Eisele, and G. Weimann, "Excitonic transitions and exciton damping processes in InGaAs/InP," *Journal of Applied Physics*, vol. 59, pp. 2196–2204, 1986. DOI: https://doi.org/10.1063/1.336358.
- [12] Y. Varshni, "Temperature dependence of the energy gap in semiconductors," *Physica*, vol. 34, no. 1, pp. 149–154, 1967, ISSN: 0031-8914. DOI: https://doi.org/10.1016/0031-8914(67)90062-6.
- [13] W. J. Turner, W. E. Reese, and G. D. Pettit, "Exciton Absorption and Emission in InP," *Phys. Rev.*, vol. 136, A1467–A1470, 5A Nov. 1964. DOI: 10.1103/PhysRev.136.A1467.
- [14] S. Seifert and P. Runge, "Revised refractive index and absorption of $\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}$ lattice-matched to InP in transparent and absorption IR-region," *Optical Materials Express*, vol. 6, pp. 629–639, Jan. 2016. DOI: 10.1364/OME.6.000629.