

A Python-Based Analytical Framework for Electrostatic Modeling of Semiconductor Photodetectors

Introduction

- Depletion width, electric field, built-in potential, and capacitance-voltage behavior are key design parameters in p-i-n photodiodes.
- These quantities directly influence responsivity, dark current, and bandwidth.

As photodetector structures become more layered and compositionally complex, accurate electrostatic modeling becomes both more important and more computationally demanding. Current simulation tools fall short for early-stage design:

- Commercial (Silvaco, Synopsys Sentaurus):** Cost-prohibitive, slow, opaque
 - Open-source (Solcore):** Photovoltaics-only, not generalizable
- No modular, analytically grounded pipeline exists for multi-layer photodetector design.** This work fills that gap.

Theory

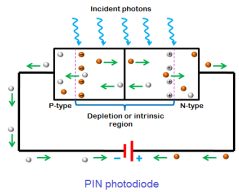
Under the depletion approximation, the one-dimensional electric field satisfies **Poisson's equation**

$$(1) \quad \frac{dE}{dx} = \frac{\rho(x)}{K\epsilon_0}, \quad \int_{x_p}^{x_n} \rho(x) dx = 0$$

For constant doping, closed-form depletion boundaries and junction capacitance follow directly:

$$(2) \quad x_p = \sqrt{\frac{2K\epsilon_0 V}{e} \cdot \frac{N_D}{N_A(N_A+N_D)}}, \quad x_n = \sqrt{\frac{2K\epsilon_0 V}{e} \cdot \frac{N_A}{N_D(N_A+N_D)}}$$

$$(3) \quad C = \frac{K\epsilon_0}{\omega}, \quad V_{b,i} = \frac{kT}{q} \ln\left(\frac{N_A N_D}{x_{i2}}\right)$$



Proposed Approach

p-i-n Extension

Since $\rho = 0$ in the intrinsic layer, the electric field, $\frac{dE}{dx} = 0$ is spatially uniform across it. Treating the full structure as a **unified three-region system** rather than two independent junctions, charge neutrality yields a quadratic in the peak field:

$$(4) \quad A \cdot E_{\max}^2 + W_i \cdot E_{\max} - V_{\text{eff}} = 0$$

$$(5) \quad E_{\max} = \frac{-W_i + \sqrt{W_i^2 + 4A \cdot V_{\text{eff}}}}{2A}, \quad A = \frac{\epsilon}{2q} \left(\frac{1}{N_A} + \frac{1}{N_D} \right)$$

$$(6) \quad K_i E_i = K_{i+1} E_{i+1}$$

Implementation

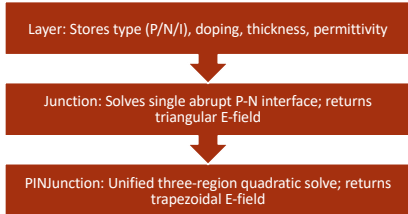


Figure 1: Flowchart featuring an object-oriented pipeline with 3 core classes.

Simulator auto-detects junction boundaries, groups p-i-n triplets, distributes applied voltage, superimposes field contributions, and integrates for potential. Outputs: NumPy arrays, Matplotlib plots.

Results

The pipeline recovers the correct $W \propto \sqrt{V}$ dependence across 0–10 V, a built-in potential of $V_{bi} = 0.9323$ V consistent with theory as shown in Figure 3, and symmetric depletion for equal doping, which are the three independent validations confirming physical self-consistency. For the **p-i-n** structure, the unified quadratic formulation correctly produces the flat field plateau in the intrinsic layer. A naive two-junction treatment misses this entirely and significantly overestimates $E_{\max}$.

All profiles are being validated analytically. Benchmarking is ongoing.

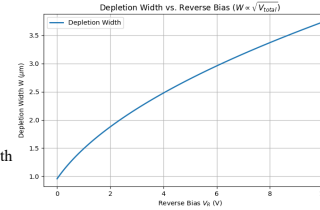
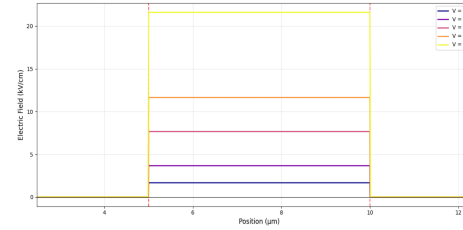


Figure 3: Depletion Width vs. Reverse Bias



Figures 4 and 5: Electric field profile of 3 layers of p-i-n structure

Conclusion

- Closed-form modeling yields physically consistent p-n and p-i-n electrostatic profiles
- Unified three-region formulation is necessary for correct p-i-n field reconstruction
- Design-space exploration achievable without TCAD overhead

Future Work

- Multi-material heterostructure stacks extension
- Quantitative TCAD benchmarking

Two device configurations are considered, summarized in Table 1.

Table 1: Layer parameters for the simulated structures. All layers are silicon ($K = 11.7$, $n_i = 1.5 \times 10^{10} \text{ cm}^{-3}$, $T = 300 \text{ K}$).

Structure	Layer	Type	Doping (cm^{-3})	Thickness (μm)
P-N junction	p-layer	P	1×10^{18}	10
	n-layer	N	1×10^{18}	10
P-I-N photodiode	p-layer	P	1×10^{18}	0.5
	i-layer	I	0 (ideal intrinsic)	2.0
	n-layer	N	1×10^{18}	0.5

References & Acknowledgements

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