

**CHARACTERIZATION STUDIES OF 4T
PIXEL FOR DYNAMIC PPD CAPACITANCE
AND BARRIER MODULATION IN CMOS
IMAGE SENSORS**

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(2015EEZ8307)**



**DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI**

July 2024

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CHARACTERIZATION STUDIES OF 4T PIXEL FOR DYNAMIC PPD CAPACITANCE AND BARRIER MODULATION IN CMOS IMAGE SENSORS

by

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(2015EEZ8307)

Submitted in fulfillment of the requirements of the degree of

Doctor of Philosophy

to the



DEPARTMENT OF ELECTRICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY DELHI

July 2024

Dedicated to my family

Certificate

This is to certify that the thesis entitled ”**Characterization studies of 4T pixel for dynamic PPD capacitance and barrier modulation in CMOS image sensors**”, submitted by **Ms. Uzma Khan** to the Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy** in the Department of Electrical Engineering, Indian Institute of Technology Delhi, is a record of the original, bona-fide research work carried out by her under my supervision and guidance. The results contained in this thesis have not been submitted in part or in full to any other University or Institute for the award of any degree or diploma to the best of my knowledge.

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Acknowledgements

I would like to express my deepest gratitude to my thesis supervisor, Professor Mukul Sarkar for his guidance, support, and encouragement. I am very grateful to him for introducing me to the world of CMOS image sensors. It is a great opportunity to work and learn from him.

My special thanks to Professor Abhishek Dixit, Professor Madhusudan Singh, and Professor Samaresh Das, members of my research committee for their constant input on my research work. A special mention to Professor Basabi Bhaumik and Professor Mamidala Jagdish Kumar for the knowledge and encouragement provided during the course-work.

My sincere thanks to Bhuvan for fruitful discussions and suggestions on any problem I faced during my Ph.D. research, may it be big or small. I would like to thank my lab-mates Amandeep, Chandani, Neha, and Rahul for the technical discussions and for making my Ph.D. an enjoyable journey.

I am grateful to the Department of Electrical Engineering, Indian Institute of Technology Delhi, for providing me with the facilities to carry out research work. I would specially thank the office staff, Mr. Rakesh Kumar, Mr. Yatindra and Mr. Satish, for providing the facilities needed to carry out the research work.

I would like to express my gratitude to Bartosz Banachowicz, Daniel Tekleab, and Rekha Nayak, the management of onsemi for allowing me to continue my Ph.D. work.

My deepest gratitude to my parents, who believed in me and my decisions and supported me in whatever way they could. Thanks to my husband for his patience and support throughout this long, tedious journey. Lots of love to my adorable daughter for allowing me time to work on my Ph.D.

Finally, I acknowledge all others who have helped me during the Ph.D. journey and whose names could not be accommodated in this brief acknowledgment.

Uzma Khan.

Abstract

The continuous scaling down of semiconductor technology has helped achieve low-power and low-cost image sensors. The reduction in pixel pitch has improved the resolution of the image sensors. However, the reduction in the pixel pitch due to technology scaling has made it difficult to achieve high full well capacity (FWC) and high dynamic range while maintaining high resolution. Achieving high sensitivity and high resolution while maintaining high dynamic range requires accurate and efficient estimation of the FWC of a four transistor (4T) pixel in a CMOS image sensor (CIS). The FWC of a 4T pixel depends on the pinned photodiode (PPD) capacitance, pinning voltage, potential barrier, temperature, and operating voltages. Thus, it is inevitable to understand and model the fundamental characteristics of a 4T pixel in a CIS. The thesis primarily focuses on the simulation and characterization based studies of 4T pixels for dynamic PPD capacitance and barrier modulation in CIS. In this thesis, an analytical model for the PPD capacitance is derived. The proposed model relies on the total current flowing through the PPD in low and high illumination conditions. The proposed model is further elaborated due to barrier modulation observed in the transfer gate (TG) channel at the PPD-TG interface in the absence and presence of a potential pocket. Understanding the potential changes in PPD, PPD-TG interface, and TG channel as a function of integrated PPD charges is a complex problem and needs a detailed analysis. The model is evaluated for light intensity, integration time, temperature, and transfer gate voltage values. The model is validated with technology computer-aided design (TCAD) simulations. The PPD capacitance model is validated experimentally by estimating the feedforward charges at the floating diffusion node, collected due to thermionic emission current. The non-linearity observed in the feedforward voltage is also explained using the non-linear behavior of TG channel potential. The non-linear behavior of TG channel potential influences the effective potential barrier, thereby influencing the FWC and PPD capacitance. Further, the barrier modulation study is extended by discussing the influence of interface traps in the charge transfer path. The interface traps influence the potential barrier differently when PPD is in the dark than when illuminated. The study will help better understand FWC, feedforward charges, and dark current generation mechanisms in a PPD. The results presented in the thesis can be a resource for CIS pixel designers to analyze, simulate, and optimize a 4T pixel.

Keywords: CMOS Image Sensors (CIS), Pinned Photodiode (PPD), Full Well Capacity (FWC), Feedforward effect, Photodiode capacitance, Analytical modeling, Potential barrier, Barrier modulation, Charge Transfer Potential Barrier (CTPB), interface traps.

सेमीकंडक्टर प्रौद्योगिकी के निरंतर विस्तार से कम बिजली की खपत और कम लागत वाले छवि सेंसर प्राप्त करने में मदद मिली है। पिक्सेल पिच में कमी से छवि सेंसर के रिज़ॉल्यूशन में सुधार हुआ है। हालाँकि, प्रौद्योगिकी स्केलिंग के कारण पिक्सेल पिच में कमी ने उच्च रिज़ॉल्यूशन को बनाए रखते हुए उच्च पूर्ण क्षमता (एफडब्ल्यूसी) और उच्च गतिशील रेंज हासिल करना मुश्किल बना दिया है। उच्च गतिशील रेंज को बनाए रखते हुए उच्च संवेदनशीलता और उच्च रिज़ॉल्यूशन प्राप्त करने के लिए सीएमओएस इमेज सेंसर (सीआईएस) में चार ट्रांजिस्टर (4T) पिक्सेल के एफडब्ल्यूसी के सटीक और कुशल अनुमान की आवश्यकता होती है। 4T पिक्सेल का एफडब्ल्यूसी पिन किए गए फोटोडायोड (पीपीडी) कैपेसिटेंस, पिनिंग वोल्टेज, संभावित अवरोध, तापमान और ऑपरेटिंग वोल्टेज पर निर्भर करता है। इस प्रकार, सीआईएस में 4T पिक्सेल की मूलभूत विशेषताओं को समझना और मॉडल करना अपरिहार्य है। थीसिस मुख्य रूप से सीआईएस में गतिशील पीपीडी कैपेसिटेंस और बैरियर मॉड्यूलेशन के लिए 4T पिक्सेल के सिमुलेशन और लक्षण वर्णन-आधारित अध्ययन पर केंद्रित है। इस थीसिस में, पीपीडी कैपेसिटेंस के लिए एक विश्लेषणात्मक मॉडल प्राप्त किया गया है। प्रस्तावित मॉडल कम और उच्च रोशनी की स्थिति में पीपीडी के माध्यम से बहने वाली कुल धारा पर निर्भर करता है। संभावित पॉकेट की अनुपस्थिति और उपस्थिति में पीपीडी-टीजी इंटरफ़ेस पर ट्रांसफर गेट (टीजी) चैनल में देखे गए बैरियर मॉड्यूलेशन के कारण प्रस्तावित मॉडल को और अधिक विस्तृत किया गया है। एकीकृत पीपीडी शुल्कों के कार्य के रूप में पीपीडी, पीपीडी-टीजी इंटरफ़ेस और टीजी चैनल में संभावित परिवर्तनों को समझना एक जटिल समस्या है और इसके विस्तृत विश्लेषण की आवश्यकता है। मॉडल का मूल्यांकन प्रकाश की तीव्रता, एकीकरण समय, तापमान और ट्रांसफर गेट वोल्टेज मानों के लिए किया जाता है। मॉडल को प्रौद्योगिकी कंप्यूटर-एडेड डिज़ाइन (टीसीएडी) सिमुलेशन के साथ मान्य किया गया है। पीपीडी कैपेसिटेंस मॉडल को थर्मोनिक उत्सर्जन धारा के कारण एकत्र किए गए फ्लोटिंग डिफ्यूजन नोड पर फीडफॉरवर्ड चार्ज का अनुमान लगाकर प्रयोगात्मक रूप से मान्य किया गया है। फीडफॉरवर्ड वोल्टेज में देखी गई गैर-रैखिकता को टीजी चैनल क्षमता के गैर-रैखिक व्यवहार का उपयोग करके भी समझाया गया है। टीजी चैनल क्षमता का गैर-रैखिक व्यवहार प्रभावी संभावित अवरोध को प्रभावित करता है, जिससे एफडब्ल्यूसी और पीपीडी कैपेसिटेंस प्रभावित होता है। इसके अलावा, चार्ज ट्रांसफर पथ में इंटरफ़ेस ट्रैप के प्रभाव पर चर्चा करके बैरियर मॉड्यूलेशन अध्ययन को बढ़ाया गया है। इंटरफ़ेस जाल संभावित अवरोध को अलग तरह से प्रभावित करते हैं जब पीपीडी रोशनी की तुलना में अंधेरे में होता है। अध्ययन से पीपीडी में एफडब्ल्यूसी, फीडफॉरवर्ड चार्ज और डार्क करंट जेनरेशन तंत्र को बेहतर ढंग से समझने में मदद मिलेगी। थीसिस में प्रस्तुत परिणाम सीआईएस पिक्सेल डिज़ाइनरों के लिए 4T पिक्सेल का विश्लेषण, अनुकरण और अनुकूलन करने के लिए एक संसाधन हो सकते हैं।

Contents

Certificate	i
Acknowledgements	ii
Abstract	iii
Contents	vi
List of Figures	xi
List of Tables	xv
Abbreviations	xvii
Symbols	xix
1 Introduction	1
1.1 Brief history of CMOS Image Sensors	1
1.2 A four transistor (4T) pixel	6
1.3 Recent developments on PPD characteristics of a 4T pixel	7
1.4 Motivation and Thesis objective	9
1.5 Thesis organisation	10
2 Fundamental characteristics of a Pinned Photodiode in a four transistor pixel	13
2.1 Device Physics	14
2.2 Basic device structure and operation of a 4T pixel	14
2.3 Definitions	20
2.3.1 Pinning voltage	20
2.3.2 Full well capacity	21

2.3.3	Pinned photodiode capacitance	22
2.3.4	Feedforward effect	23
2.3.5	Dynamic range	23
2.3.6	Signal to noise ratio	24
2.3.7	Dark current	25
2.3.8	Image lag	25
2.3.9	Blooming	27
2.3.10	Resolution and sensitivity	27
2.3.11	Quantum efficiency	27
2.4	Simulation and measurement setup	28
2.4.1	Simulation setup	28
2.4.2	Measurement setup	28
2.5	Conclusion	29
3	Dynamic capacitance model of the Pinned Photodiode in CMOS Image Sensor	31
3.1	Introduction	31
3.2	Pinned photodiode capacitance model	32
3.3	Simulation results and model validation	38
3.3.1	Estimation of EFWC and V_{pin}	43
3.3.2	Estimation of pinned photodiode capacitance	45
3.4	Conclusion	49
4	Dynamic capacitance variations due to barrier modulation in Pinned Photodiode of a 4T pixel	51
4.1	Introduction	51
4.2	Barrier modulation in a 4T pixel	52
4.3	Influence of barrier modulation on FWC	53
4.4	Influence of barrier modulation on feedforward charges	59
4.4.1	Test chip and measurement setup	60
4.4.2	Estimation of feedforward charges: Measurement results	60
4.5	Influence of barrier modulation on photodiode capacitance modeling	63
4.6	Conclusion	68
5	Analysis of Charge Transfer Potential Barrier in Pinned Photodiode of CMOS Image Sensor	69
5.1	Introduction	69
5.2	Charge Transfer Potential Barrier in a 4T pixel	70
5.3	Estimation of the effective barrier potential for the PPD charges	77
5.4	Potential pocket and image lag in a 4T pixel	83
5.4.1	Image lag reduction techniques and their influence on CTPB	84
5.4.1.1	PPD to TG channel spacing optimization	84

5.4.1.2	TG channel doping optimization	86
5.4.1.3	p^+ and n_{well} separation in PPD	88
5.5	Estimation of the feedforward charges from PPD to FD node	88
5.6	Estimation of the PPD capacitance	92
5.7	Conclusion	95
6	Simulation studies on the influence of interface traps on barrier modulation in CMOS Image Sensors	97
6.1	Introduction	97
6.2	Influence of interface traps on barrier modulation	100
6.3	Results and discussion	106
6.4	Measurement Results	112
6.5	Conclusion	115
7	A low power readout mechanism with improved low light performance in CMOS Image Sensors	117
7.1	Introduction	117
7.2	Proposed methodology	118
7.3	Results and discussion	123
7.4	Conclusion	126
8	Conclusion	127
	Scope for Future Work	131
	Bibliography	131
	List of Publications	143
	About the Author	145

List of Figures

1.1	Schematic representation of a 3T pixel.	4
1.2	Schematic representation of PPD in a 4T pixel.	5
1.3	Block diagram representation of photons-charge-voltage conversion in the pixel.	7
2.1	A four transistor (4T) pixel.	15
2.2	Standard timing diagram used in simulations for 4T pixel operation. .	17
2.3	Timing diagram used in simulations to estimate feedforward charges in a 4T pixel.	18
2.4	Simplified representation of potential well diagram showing PPD, TG, and FD regions.	19
3.1	(a) Schematic of a 4T pixel (b) Simplified potential well diagram of a 4T pixel (c) Representation of depletion region width in a PPD. . .	33
3.2	A front side vertically illuminated PPD 4T pixel simulated in TCAD.	39
3.3	Capacitance of the pinned photodiode (C_{PPD}) for varying light intensity.	39
3.4	Comparison of the modeled and simulated C_{PPD} for varying light intensity [Inset: Light intensity on the linear scale].	40
3.5	Number of integrated electrons (N_{PPD}) for varying light intensity at different temperatures [Inset: Light intensity on the linear scale]. . . .	41
3.6	Potential of n_{well} (V_n) for varying light intensity at different temperatures [Inset: Light intensity on log scale].	42
3.7	Capacitance of pinned photodiode (C_{PPD}) for varying light intensity and temperature [Inset: Light intensity on log scale].	43
3.8	Simplified potential well diagram of PPD, TG, and FD regions, for no direct charge injection in PPD ($V_{inj} = V_{RST_high}$ and $V_{inj} > V_{pin}$). .	44
3.9	Simplified potential well diagram of PPD, TG and FD regions, for direct charge injection in PPD ($V_{inj} = V_{RST_low}$ and $V_{inj} < V_{pin}$).	44
3.10	Number of integrated electrons (N_{PPD}) for varying injection voltage (V_{inj}) [Inset: C_{PPD} for varying V_{inj}].	45
3.11	Comparison of measured, modeled, and simulated capacitance of photodiode for varying hold time [Inset: C_{PPD} estimation for varying V_{RST_low}].	47

3.12	Capacitance of photodiode measured for varying hold time at different temperatures.	48
4.1	A 4T pixel simulated in TCAD for barrier modulation study.	53
4.2	Representation of potential profile in PPD, TG channel potential [in dark (solid line) and for varying light intensity (dashed lines)] and FD node.	53
4.3	Potential profile of PPD, TG and FD (along the cutline A-A' shown in figure 4.1) for varying light intensities (0.1 W/cm^2 to 100 W/cm^2) [Inset: potential profile in the (a) channel of TG and (b) FD node].	55
4.4	Variation of (a) V_{PPD} and (b) $\Psi_{\text{TG.ch}}$ for increasing percentage of FWC of the PPD for varying L_{PPD} and L_{TG}	56
4.5	Variation of (a) V_B , (b) ΔV_B and (c) $V_{B.\text{eff}}$ for increasing percentage of FWC of PPD for varying L_{PPD} and L_{TG}	58
4.6	Measured feedforward charges (Q_{FF}) for varying V_{inj} (on left y-axis and bottom x-axis) and Q_{FF} for a varying percentage of FWC (on the right y-axis and top x-axis).	61
4.7	Variation of C_{PPD} with V_{PPD} for varying light intensities.	64
4.8	Comparison of measured and modeled C_{PPD} for varying hold time (t_{hold}).	66
4.9	Measured C_{PPD} for varying V_{TG} (on left y-axis and bottom x-axis) and simulated $V_{B.\text{eff}}$ for the varying percentage of FWC (on the right y-axis and top x-axis).	67
5.1	A 4T pixel [Inset: PPD-TG interface region showing offset length 1 ($L_{\text{os.1}}$) and offset length 2 ($L_{\text{os.2}}$)].	72
5.2	Potential profile (along cutline A-A' in figure 5.1) for varying light intensity using TCAD in PPD, TG channel potential ($\Psi_{\text{TG.ch}}$), PPD-TG interface potential ($\Psi_{\text{TG.int}}$), pocket potential (V_{pocket}), change in FD node potential (ΔV_{FD}) and potential at drain of reset transistor ($V_{\text{DD_RST}}$). CTPB 1, CTPB 2, and V_B are charge transfer potential barriers.	73
5.3	Potential profile in PPD-TG transition region for varying % of FWC.	77
5.4	Variation of V_{PPD} , V_{pocket} and $\Psi_{\text{TG.int}}$ [on left y-axis] and $\Psi_{\text{TG.ch}}$ [on right y-axis] for varying % of FWC.	79
5.5	Variation in depth and lateral extent of potential pocket for varying light intensity (along cutline A-A' shown in figure 5.1).	80
5.6	Variation of CTPB 1, CTPB 2, overall CTPB and V_B for varying % of FWC.	81
5.7	Variation of effective potential barrier for varying % of FWC.	82
5.8	Potential variation in a 4T pixel.	83
5.9	Potential profile for varying offset length 1 ($L_{\text{os.1}}$).	85

5.10	(a) V_{PPD} [on left y-axis] and V_{pocket} [on right y-axis] (b) V_B , CTPB 1, CTPB 2 and CTPB for varying offset length 1.	85
5.11	Potential profile along PPD-TG interface for varying N_{ch}	87
5.12	(a) V_{PPD} , V_{pocket} , $\Psi_{\text{TG_int}}$ [on left y-axis] and $\Psi_{\text{TG_ch}}$ [on right y-axis] (b) V_B , CTPB 1, CTPB 2 and CTPB for varying N_{ch}	87
5.13	(a) V_{PPD} [on left y-axis] and V_{pocket} [on right y-axis] (b) Potential variation across PPD-TG transition region for varying offset length 2.	88
5.14	Variation of simulated feedforward charge (Q_{FF}) for the varying percentage of FWC (on the left y-axis and bottom x-axis) and measured Q_{FF} for varying injection voltage (V_{inj}) (on the right y-axis and top x-axis).	90
5.15	Variation of measured and modeled C_{PPD} for varying hold time.	93
6.1	A 4T pixel with interface traps	99
6.2	Potential profile (along cutline A-A' in figure 6.1) for varying interface donor traps in dark and illuminated conditions (100% of FWC) [Inset: CTPB 1 and CTPB 2].	102
6.3	Timing diagram used in simulations to estimate feedforward charges in a 4T pixel.	105
6.4	Potential variation in (a) PPD (V_{PPD}), PPD-TG interface ($\Psi_{\text{TG_int}}$), pocket (V_{pocket}), TG channel ($\Psi_{\text{TG_ch}}$), (b) CTPB 1, CTPB 2, CTPB, V_B and (c) $V_{B,\text{eff}}$ for varying interface donor traps when PPD is in the dark.	108
6.5	Potential variation in (a) PPD (V_{PPD}), PPD-TG interface ($\Psi_{\text{TG_int}}$), pocket (V_{pocket}), TG channel ($\Psi_{\text{TG_ch}}$), (b) CTPB 1, CTPB 2, CTPB, V_B and (c) $V_{B,\text{eff}}$ for varying interface donor traps when PPD is illuminated (100% of FWC).	109
6.6	Variation in N_{PPD} when PPD is illuminated for varying % of FWC and N_{TD}	111
6.7	Variation in N_{PPD} for varying N_{TD} and V_{TG}	112
6.8	Variation in Q_{FF} for varying N_{TD} and V_{TG}	113
6.9	Measurement results for variation in Q_{FF} with varying V_{TG} and V_{inj} [Inset: Q_{FF} for varying V_{inj}]	114
7.1	Block diagram representation of photons-charge-voltage conversion in the pixel.	119
7.2	Block diagram representation of light-charge-voltage conversion (a) linear input-output relationship (b) nonlinear input-output relationship at the integration node.	120
7.3	Number of integrated charges in the PPD (N_{PPD}) estimated using TCAD and linear approximation for fixed light intensity and varying integration time.	121

7.4	C_{PPD} for varying light intensity [Inset: N_{PPD} and V_{PPD} for varying light intensity].	122
7.5	ΔV estimated using TCAD at two light intensities for varying integration time.	124
7.6	PPD capacitance (C_{PPD}) and step size (ΔV) for the entire full scale range.	125

List of Tables

5.1	Summary: Potentials for varying % of FWC	82
5.2	Comparison of C_{PPD} models	94
7.1	Relative power reduction in the proposed approach over the conventional approach for 10 bit 1 V full scale ADC	126

Abbreviations

3T	3 Transistor
4T	4 Transistor
ADC	Analog Digital Converter
APS	Active Pixel Sensor
BBD	Bucket Brigade Device
BSI	Back Side Illuminated
CCD	Charge Coupled Device
CDS	Correlated Double Sampling
CIS	CMOS Image Sensor
CMOS	Complimentary Metal Oxide Semiconductor
CRA	Chief Ray Angle
CTPB	Charge Transfer Potential Barrier
CVF	Charge Voltage Factor
DIBL	Drain Induced Barrier Lowering
DN	Digital Number
DR	Dynamic Range
DTI	Deep Trench Isolation
EFWC	Equilibrium Full Well Capacity
FB	Forward Bias
FD	Floating Diffusion
FSI	Front Side Illuminated
FWC	Full Well Capacity
ILT	Inter Line Transfer
MOS	Metal Oxide Semiconductor
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
PD	Photo Diode

PPD	P inned P hoto D iode
PPS	P assive P ixel S ensor
QE	Q uantum E fficiency
QV	Q (charge) V oltage
RB	R everse B ias
RS	R ow S elect
RST	R eset
SF	S ource F ollower
SNR	S ignal N oise R atio
STI	S hallow T rench I solation
T	T emperature
TG	T ransfer G ate

Symbols

α	Absorption coefficient
A_{PPD}	Cross-sectional area of PPD
C_1	Parallel plate capacitance of $p^+ - n_{\text{well}}$ region in PPD
C_2	Parallel plate capacitance of $n_{\text{well}} - p_{\text{epi}}$ region in PPD
C_{DEP}	Depletion capacitance
C_{DEP_0}	Depletion capacitance at equilibrium
C_{diff}	Diffusion capacitance
C_{PPD}	Pinned photodiode capacitance
C_{var}	Variable capacitance
δ_z	Distance traveled by incident light inside semiconductor
e^-	Electron
ϵ_0	Permittivity of free space
ϵ_r	Relative permittivity of silicon
E_1	Electric field from n_{well} to p^+ region of PPD
E_2	Electric field from n_{well} to p_{epi} region of PPD
E_{cn}	Conduction band energy of n region
E_{cp^+}	Conduction band energy of p^+ region
E_{Fn}	Electron quasi Fermi energy
E_{Fp^+}	Holes quasi Fermi energy
E_t	Trap energy level
E_v	Valence band energy level
h	Planck's constant
I_0	Reverse saturation current through PPD
I_ϕ	Light intensity
$I_{D'}$	MOS technological parameter
I_f	Forward current

I_{ph}	Photocurrent
I_{st}	Saturation current
$I_{\text{sub_TG}}$	Subthreshold leakage current below TG
$I_{\text{sub_TG1}}$	Subthreshold leakage current from PPD to potential pocket
$I_{\text{sub_TG2}}$	Subthreshold leakage current from potential pocket to TG/FD
I_{th}	Thermionic emission current
I_{total}	Total current flowing across the PPD
k	Boltzmann constant
l_{abs}	Length of absorption
λ	Wavelength of light
η_{noise}	Total noise at given signal level
η_{psn}	Total photon shot noise at given signal level
n	Resolution of ADC
N_{max}	Maximum output signal
N_{min}	Minimum detectable signal
N_{PPD}	Number of PPD charges
$N_{\text{PPD_left}}$	Number of charges left in the PPD
N_{sig}	Signal level
N_t	Trap density
N_{TD}	Donor trap density
ϕ	photon flux
$\Psi_{\text{TG_ch}}$	TG channel potential
$\Psi_{\text{TG_int}}$	PPD-TG interface potential
$\Psi_{\text{TG_inv}}$	TG channel inversion potential
p_0	Equilibrium hole concentration
q	Electronic charge
Q_{FIX}	Temperature dependent fixed PPD charge
Q_{inj}	Injected charge in PPD
Q_{PPD}	PPD charge
$Q_{\text{PPD_i}}$	Instantaneous PPD charge
Q_{VAR}	Light intensity dependent variable PPD charge
σ_t	Capture cross section area of interface traps
τ	Recombination lifetime of minority charge carriers
T	Temperature
t_{int}	Integration time

t_{hold}	Hold time
ν	Frequency of light
V_B	Potential barrier
$V_{B\text{-eff}}$	Effective potential barrier
V_{bi}	Built-in potential
V_{DD}	Supply voltage
$V_{\text{DD_RST}}$	Drain voltage of reset transistor
V_{FS}	Full scale voltage of ADC
V_{FW}	Full well voltage of PPD
V_{inj}	Injection voltage
V_n	Potential of n_{well} in PPD
V_{OC}	Open circuit voltage of PPD
V_{p^+}	Potential of p^+ in PPD
V_{epi}	Potential of p_{epi} in PPD
V_{pin}	Pinning potential of PPD
V_{PPD}	PPD potential
ΔV_{PPD}	Change in PPD potential
$V_{\text{RST_low}}$	Reset transistor low voltage
$V_{\text{RST_high}}$	Reset transistor high voltage
V_T	Threshold voltage
V_{TG}	Transfer gate voltage
$V_{\text{TG_low}}$	Transfer gate low voltage
$V_{\text{TG_high}}$	Transfer gate high voltage
V_{th}	Thermal voltage
w_0	Width of the depletion region of PPD at equilibrium
$w_{n\text{-epi}}$	Width of depletion region of $n_{\text{well}} - p_{\text{epi}}$ in PPD
$w_{p^+ - n}$	Width of depletion region of $p^+ - n_{\text{well}}$ in PPD
Δx	Reduction in width of the depletion region in PPD on illumination