Time-of-Flight sensors in standard CMOS technologies

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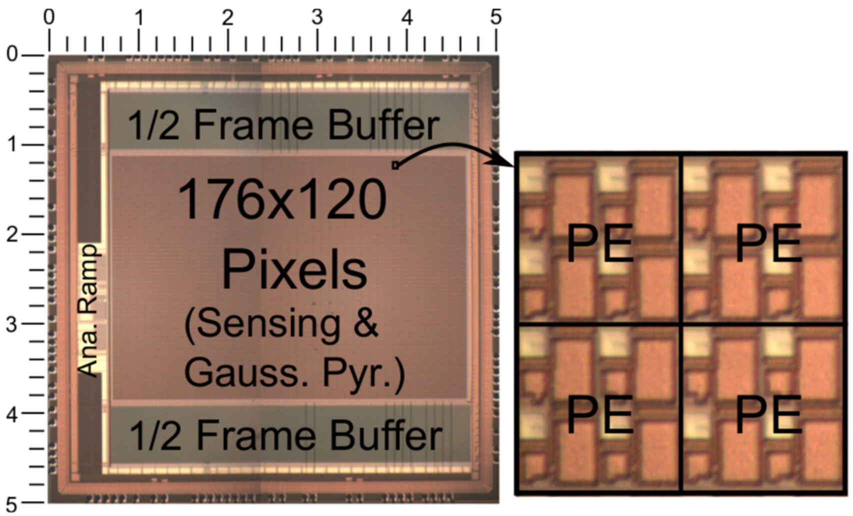
Outline

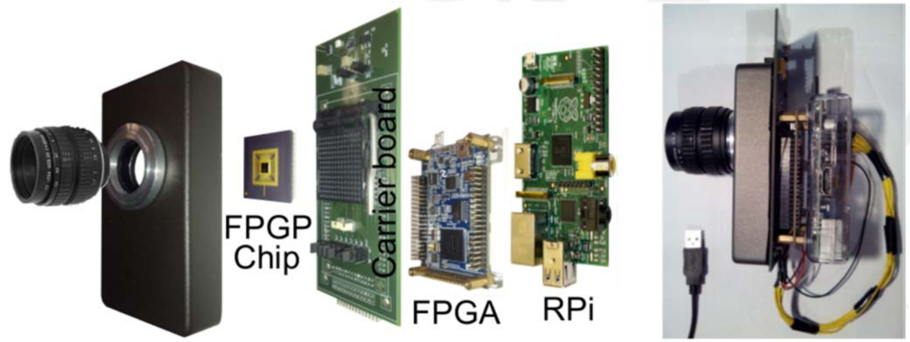
- Context & Motivation
- Research hypotheses & Objectives
- Methodology
- Achievements & Current results
- Future Work

Context & Motivation

ToF definition

- Objective of the thesis → fabrication of a ToF camera in standard CMOS technology
  - ToF camera → recording of 3D scene
  - Standard CMOS technology → Cheap technology for integrated circuits fabrication





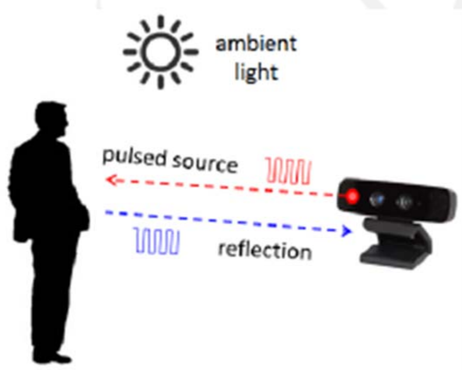
Context & Motivation

ToF definition

- Time-of-Flight (ToF) sensors are image sensors that capture the 3D information of a scene by measuring the time a light signal needs to travel back and forth to the target

- Range sensor applications include safety, healthcare, robotics, virtual or augmented reality, automotive,…

- 3D sensors technologies
  - Triangulation
    - Stereo vision
    - Structured-Light
  - Time-of-Flight

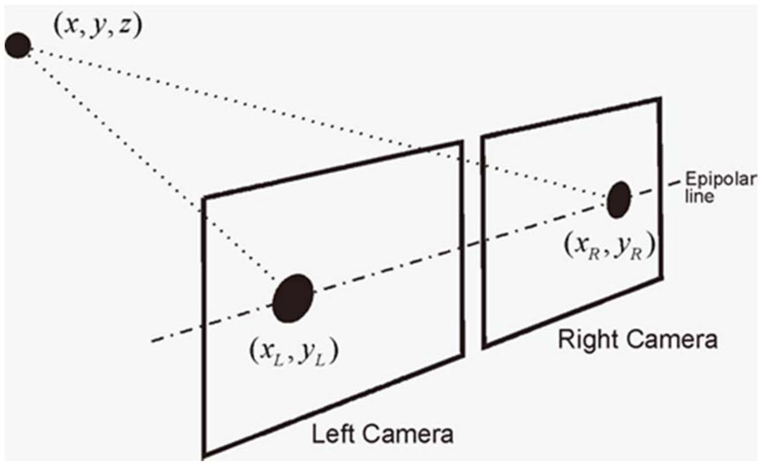


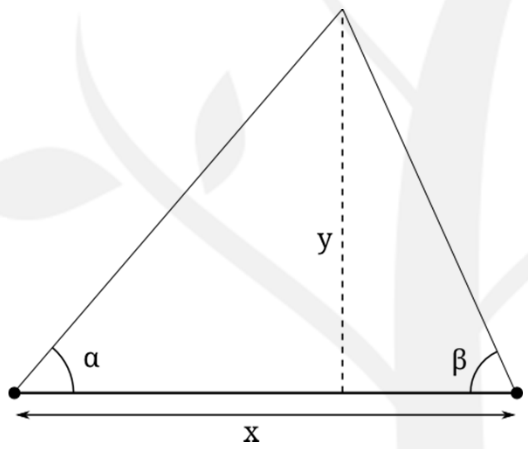
Context & Motivation

3D sensors technologies

- Stereo vision
  - Disparity of the object position in two different cameras
  - Advantages
    - Low cost implementation
    - Similar to human vision → well-suited for capturing images to humans
  - Disadvantages
    - Correspondence problem → Computational intensive

$$y = \frac{x}{\frac{1}{\tan\alpha} + \frac{1}{\tan\beta}}$$





Top figure: CALIN, G. y RODA, V. O.. Real-time disparity map extraction in a dual head stereo vision system. Lat. Am. appl. res. [online]. 2007, vol.37, n.1

Context & Motivation

3D sensors technologies

- Structured light
  - Projection of known pattern of light
  - Advantage
    - Relatively high spatial resolution
  - Disadvantage
    - Need of successive projections of patterns → Low frame rate

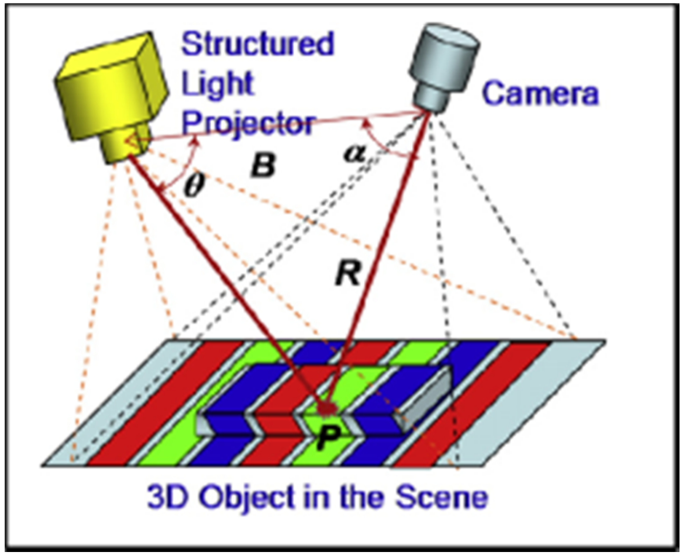


Figure: J. Geng, "Structured-light 3D surface imaging: a tutorial," Adv. Opt. Photon. 3, 128-160 (2011).

Context & Motivation

3D sensors technologies

- Time-of-Flight
  - Time delay of a light signal reflected from the scene
  - Advantages
    - Not dependent on mechanical alignment
    - Mechanically compact
  - Disadvantages
    - Specific hardware cameras needed

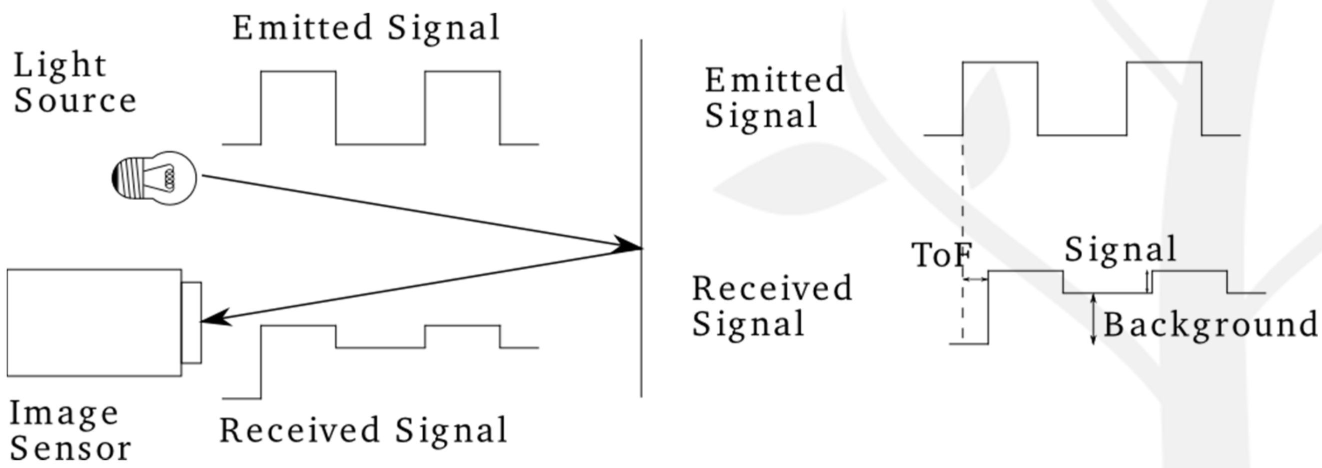


Figure: J. Illade-Quinteiro et al., “Four-transistor pinned photodiodes in standard technologies for time-of-flight sensors”, *SST, Vol. 30, No. 4, 2015*

Context & Motivation

3D sensors technologies

Considerations	Stereo vision	Structured light	Time-of-flight
SW complexity	HIGH	MEDIUM	LOW
Material cost	LOW	HIGH	MEDIUM
Compactness	LOW	HIGH	LOW
Response time	MEDIUM	SLOW	FAST
Depth accuracy	LOW	HIGH	MEDIUM
Low-light performance	WEAK	GOOD	GOOD
Bright-light performance	GOOD	WEAK	GOOD
Power consumption	LOW	MEDIUM	SCALABLE
Range	LIMITED	SCALABLE	SCALABLE

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Data from: "Time-of-Flight Camera–An Introduction", Texas Instruments Technical White paper

Context & Motivation

Commercial examples

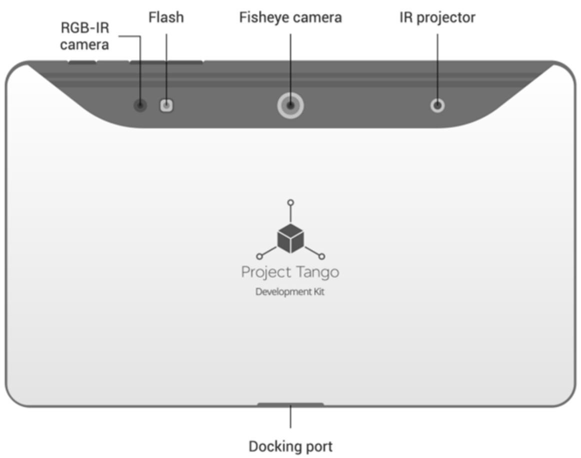
- Leap Motion → Triangulation
  - Up to 2 feet (0,6 m)
  - 2 IR cameras

https://learn.sparkfun.com/tutorials/leap-motion-teardown

Context & Motivation

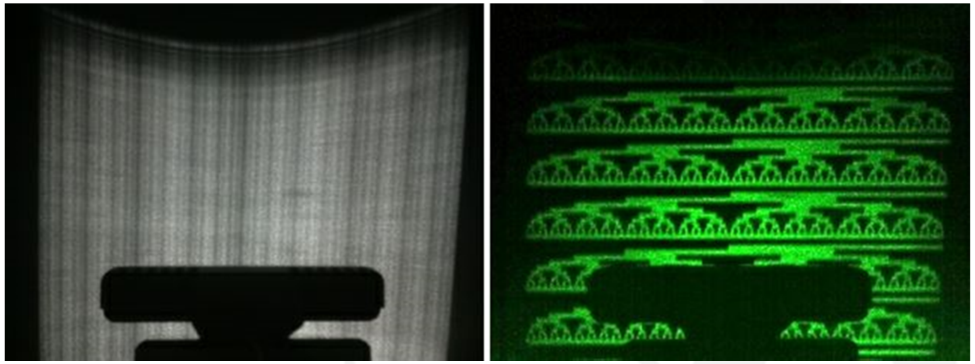
Commercial examples

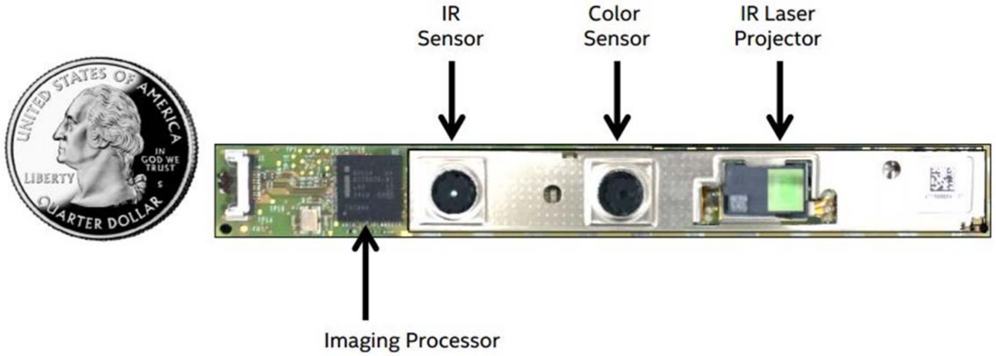
- Google Project Tango → Structured light
  - 0.5 m – 4 m
  - 4 MP 2µm RGB-IR pixel sensor



https://www.google.com/atap/projecttango/#project

- Intel RealSense→ Structured light
  - 0.2 m – 1.2 m
  - 1080p RGB-IR

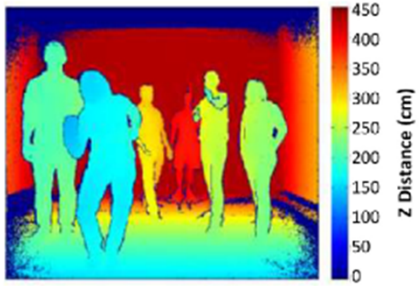




Context & Motivation

Commercial examples

- Microsoft Kinect → Time-of-Flight
  - 0.8 m – 4,2 m
  - 512x424 pixels



Research hypotheses & Objectives

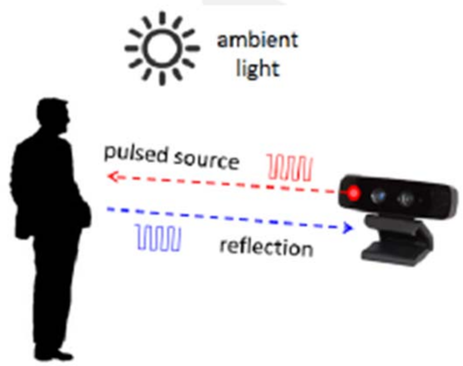
- ToF measurement technique
- Conventional image sensor pixels
  - Silicon photosensors
  - 3-Transistors (3T) pixel
  - 4-Transistors (4T) pixel
- 4T pixel for ToF
- 4T pixel in standard CMOS technology

Research hypotheses & Objectives

ToF measurement technique

- Time-of-Flight sensors measure the time a light signal needs to travel back and forth to the target

$$L = \frac{c}{2} T_{oF}$$



- The light signal can be
  - continuous modulated wave
  - discrete pulses

- We will center this presentation in the pulsed ToF

- The maximum measurable distance depends on the light pulse (T_p)

$$L_{MAX} = \frac{c}{2} T_p$$

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Research hypotheses & Objectives

ToF measurement technique

- The maximum measurable distance depends on the light pulse (T_p)

$$L_{MAX} = \frac{c}{2} T_p$$

- For T_p=50 ns → L_{max}=7.5 m
  - Larger T_p reduces L_{max}
  - Shorter T_p are difficult to sense (photosensors too slow)

- Signal light power reaching the pixel is usually very low
  - Because light source must satisfy eye safety regulations
  - Example:
    - Light signal reflected from a distance of 1 m → P=9 pW/μm^2 → ~2 photons/μm^2 (in 50 ns)
    - Room well illuminated (1000 lux) → ~9.9 photons/μm^2 (in 50 ns) → Shot noise ~ 3.1 photons/μm^2
  - Solution: accumulation of the measurement over several pulses

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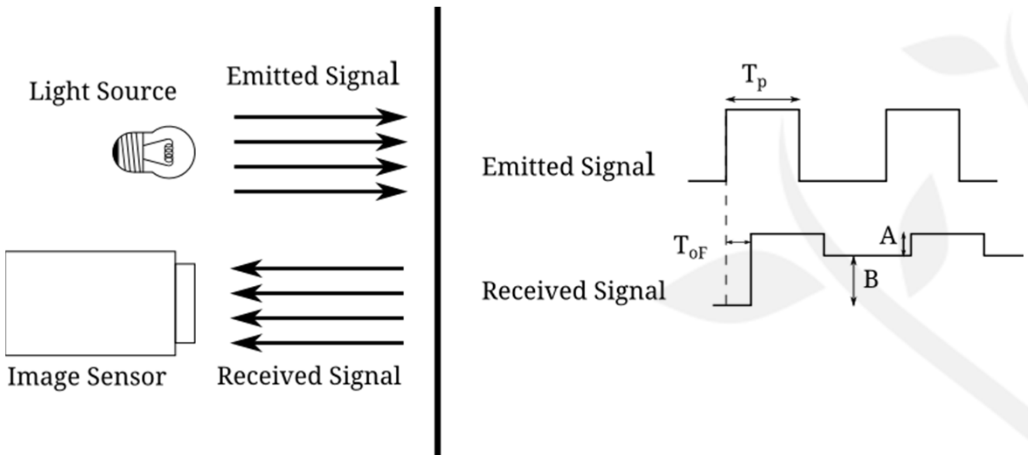
Research hypotheses & Objectives

ToF measurement technique

- Three parameters are unknown in the reflected signal reaching the camera → at least three measurements per pulse needed
  - Time-of-Flight (T_{oF})
  - Light power of the signal (A)
  - Light power of the background (B)



Research hypotheses & Objectives

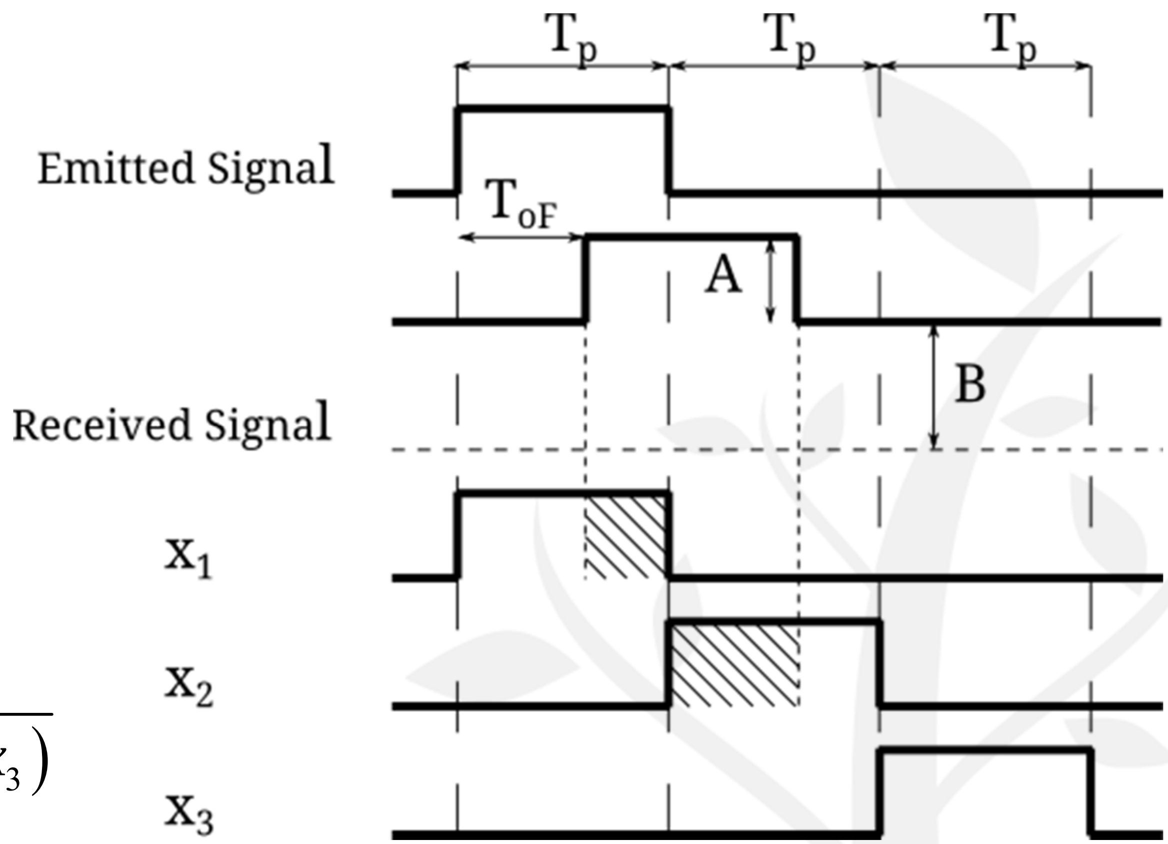
ToF measurement technique

$$x_1 = BT_p + A\left(T_p - T_{oF}\right)$$

$$x_2 = BT_p + AT_{oF}$$

$$x_3 = BT_p$$

$$L = \frac{c}{2} T_p \frac{x_2 - x_3}{\left(x_1 - x_3\right) - \left(x_2 - x_3\right)}$$



Research hypotheses & Objectives

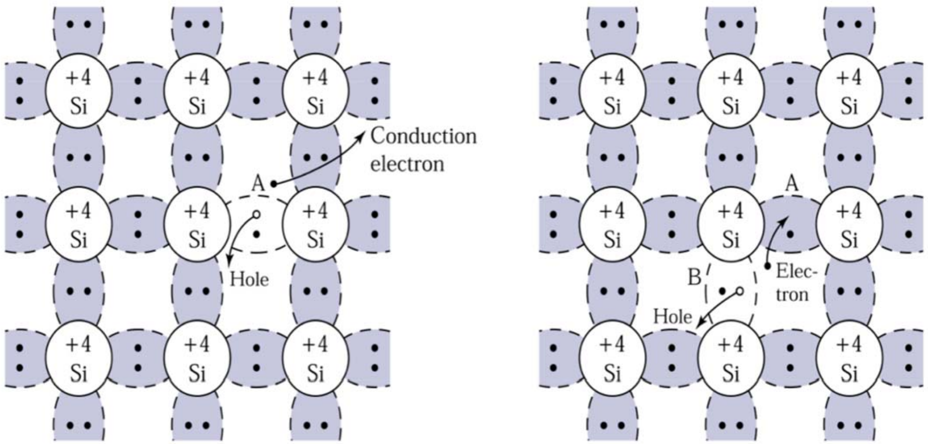
ToF measurement technique

- T_p=50 ns → Pixel must have a fast response
- Received signal with low light power → Accumulation of multiple pulses
- 3 unknown parameters in the received signal → 3 measurements per pulse

Research hypotheses & Objectives

Silicon photosensors

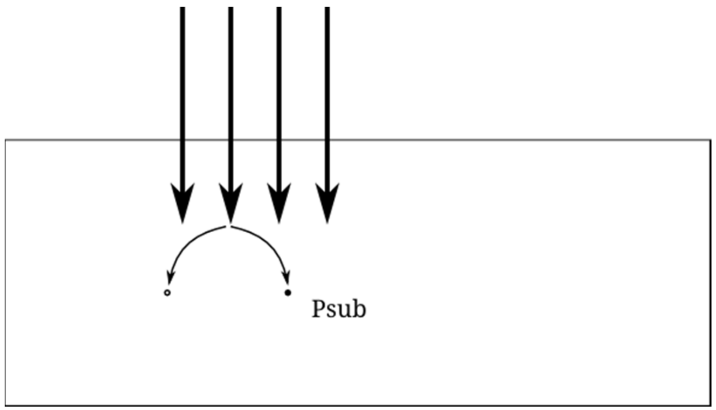
- Semiconductor materials have two different types of charge carriers
  - Negatively charged electrons
  - Positively charged holes
- Pure silicon has the same density of electrons and holes in it
- By doping the silicon with other elements it is possible to control the relation electron-hole
  - N-doped silicon has a higher density of electrons
  - P-doped silicon has a higher density of holes

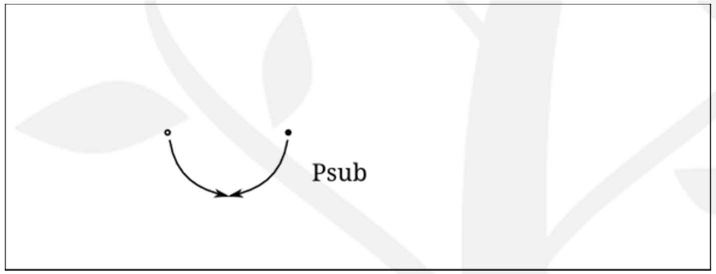


Research hypotheses & Objectives

Silicon photosensors

- Silicon for integrated circuits fabrication is usually lightly P-doped → P substrate
- Photons reaching a silicon crystal can impact in an electron, liberating it from the crystal lattice → an electron-hole pair is created
- Without an electric field he electron-hole pair ends up together in a recombination process





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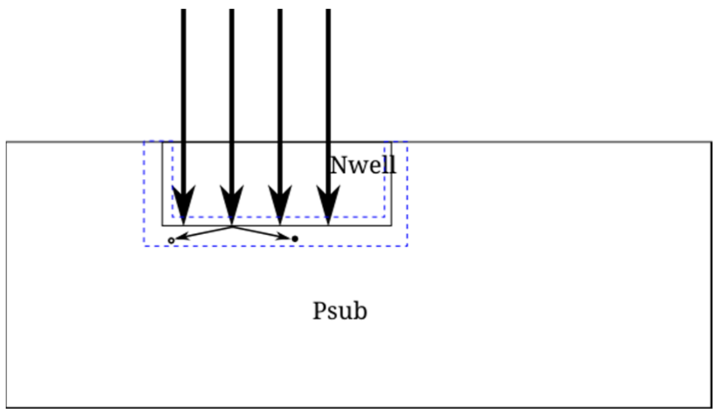
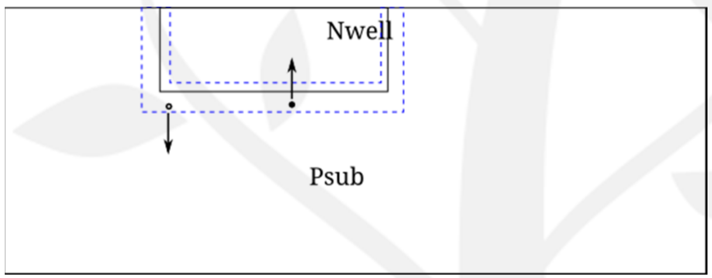
Research hypotheses & Objectives

Silicon photosensors

- For the generation of the electric field a N-doped region (N well) is added over the P substrate → PN photodiode
  - Around the PN junction an electric field is created
  - The electric field separates the electron-hole pair
  - The electrons are accumulated in the N well

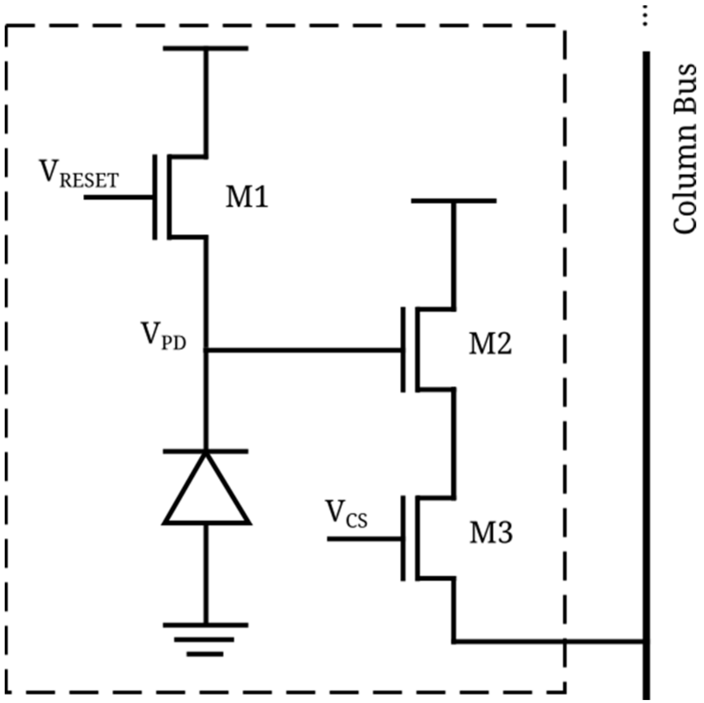


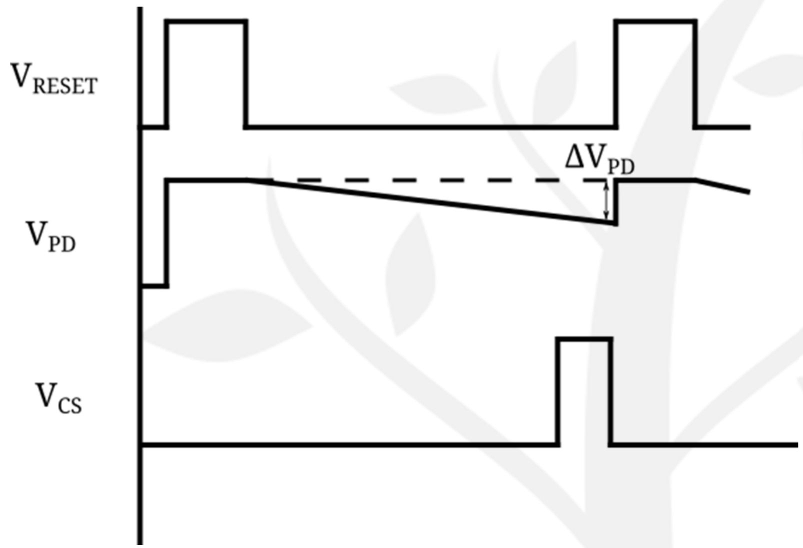


Research hypotheses & Objectives

3T pixel

- The photogenerated electrons are accumulated in V_{PD} node
- At the beginning of the measurement the node is reset
- The decrease in this node (ΔV_{PD}) is proportional to the light intensity





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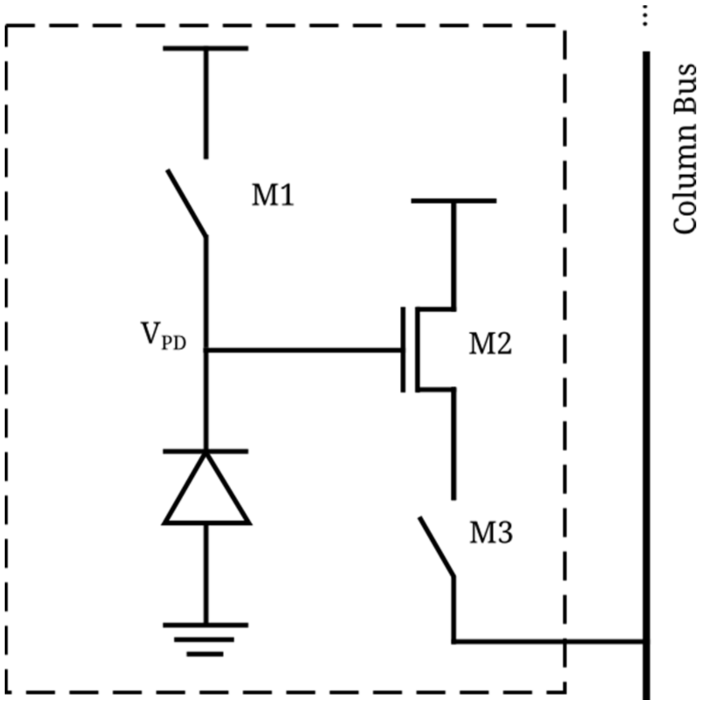

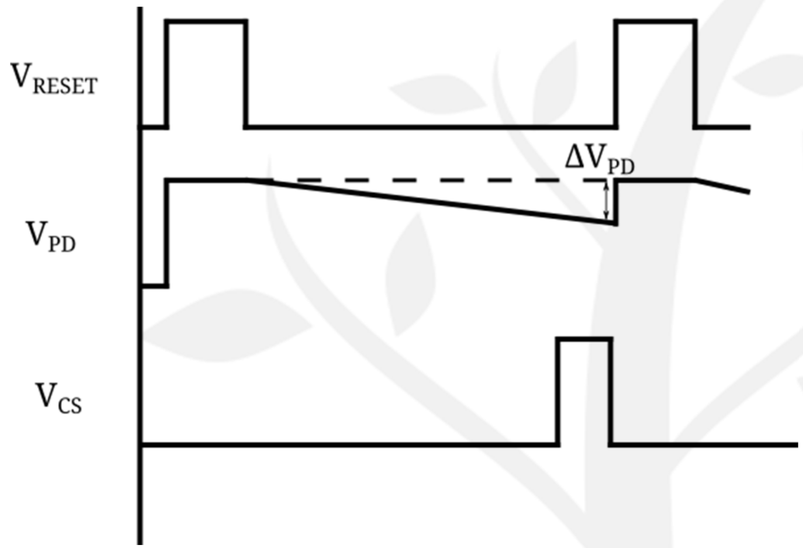

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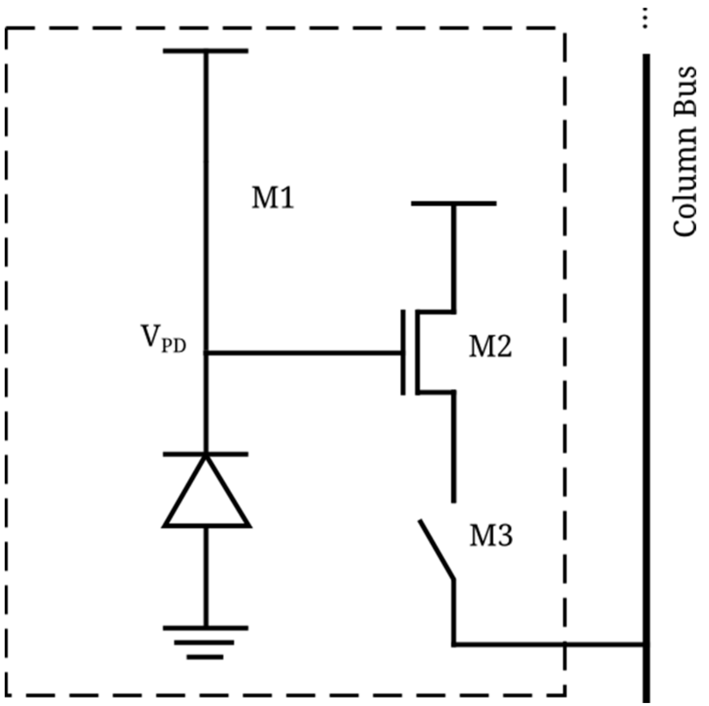

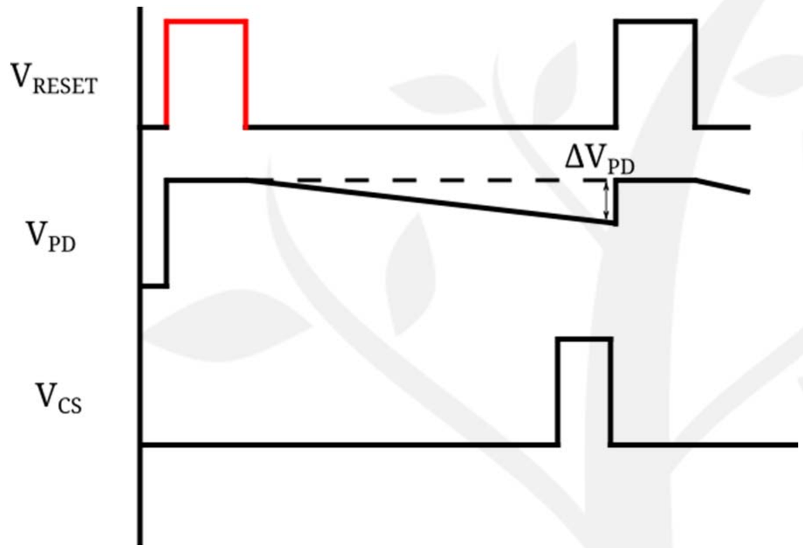

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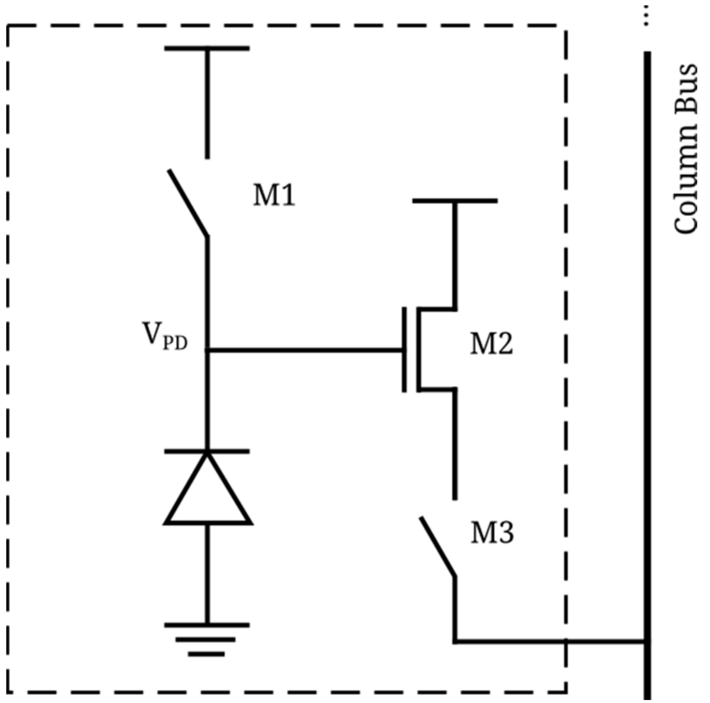

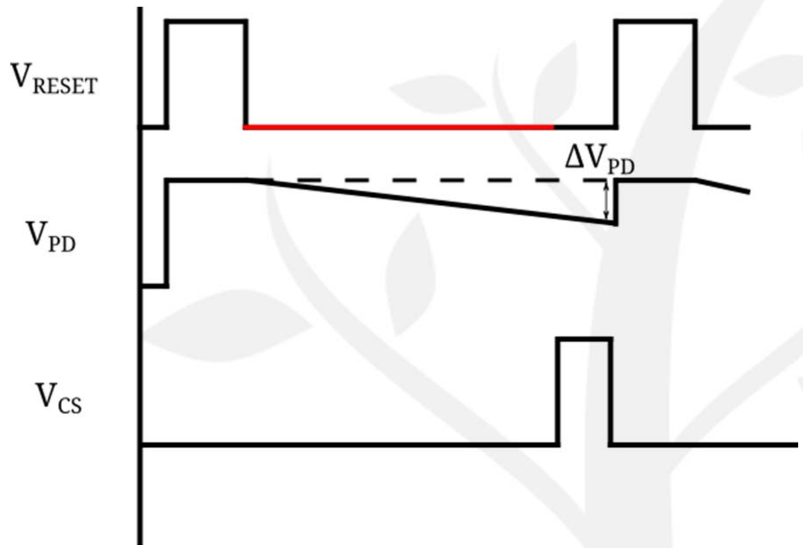

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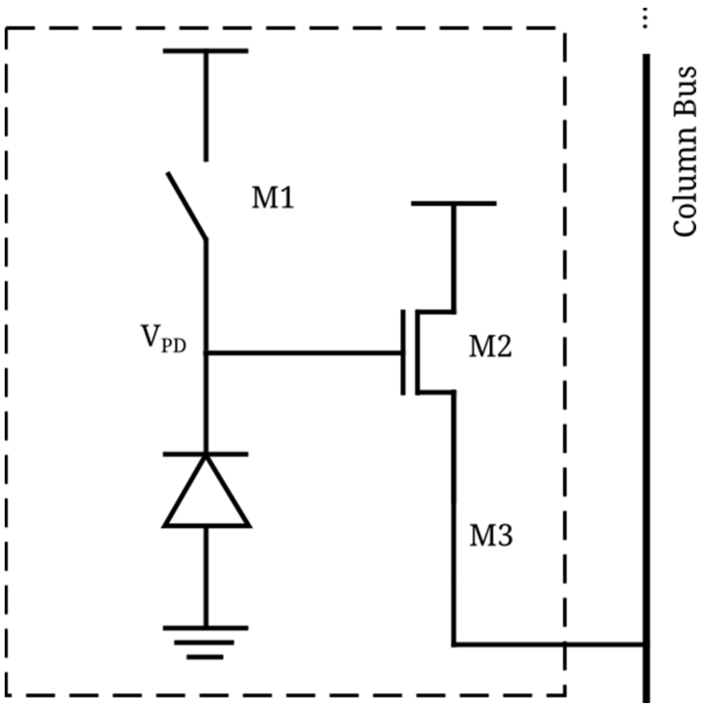
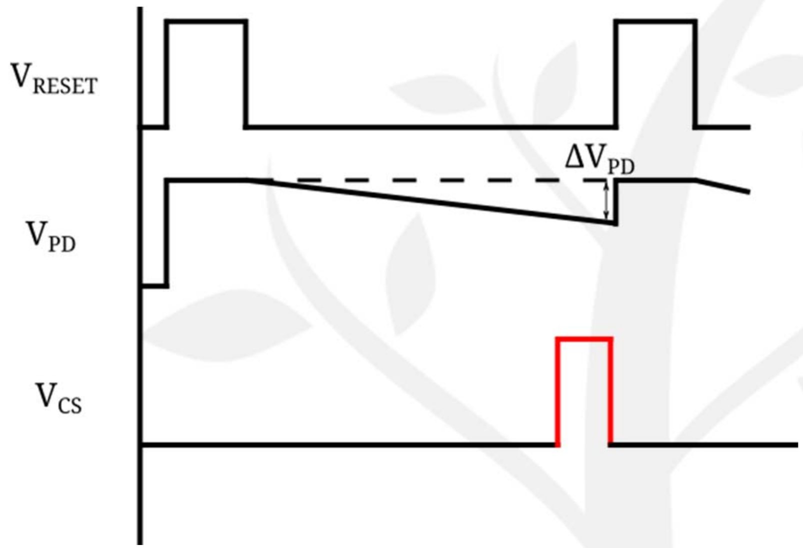
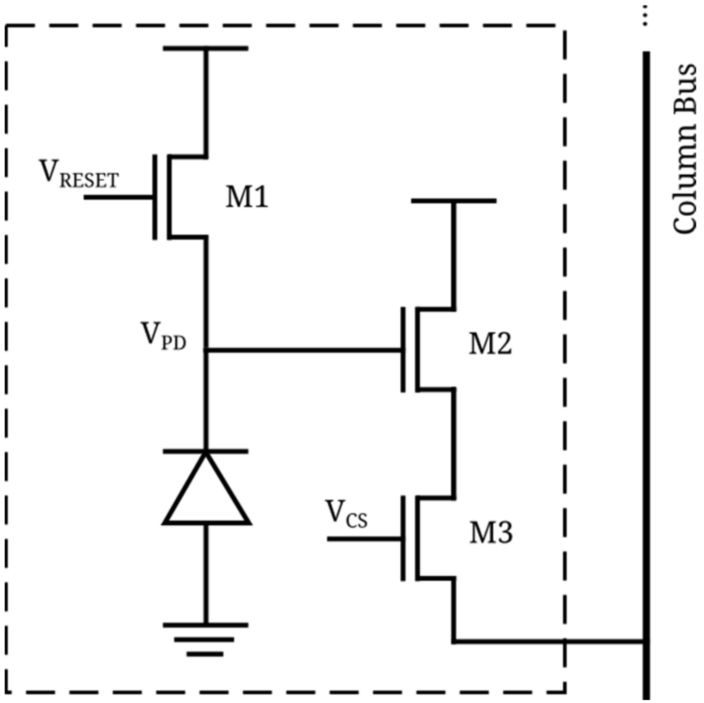


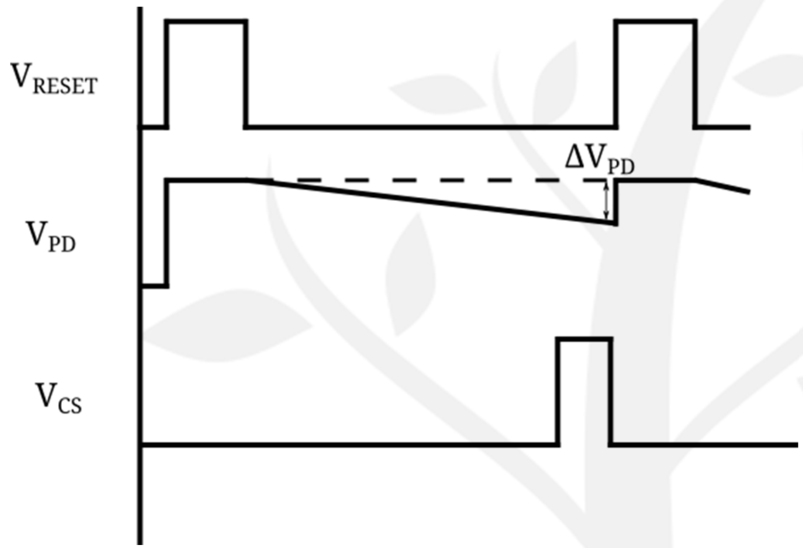


Research hypotheses & Objectives

3T pixel

- Principal problems of 3T pixels
  - KTC noise → Thermal noise generated in V_{PD}





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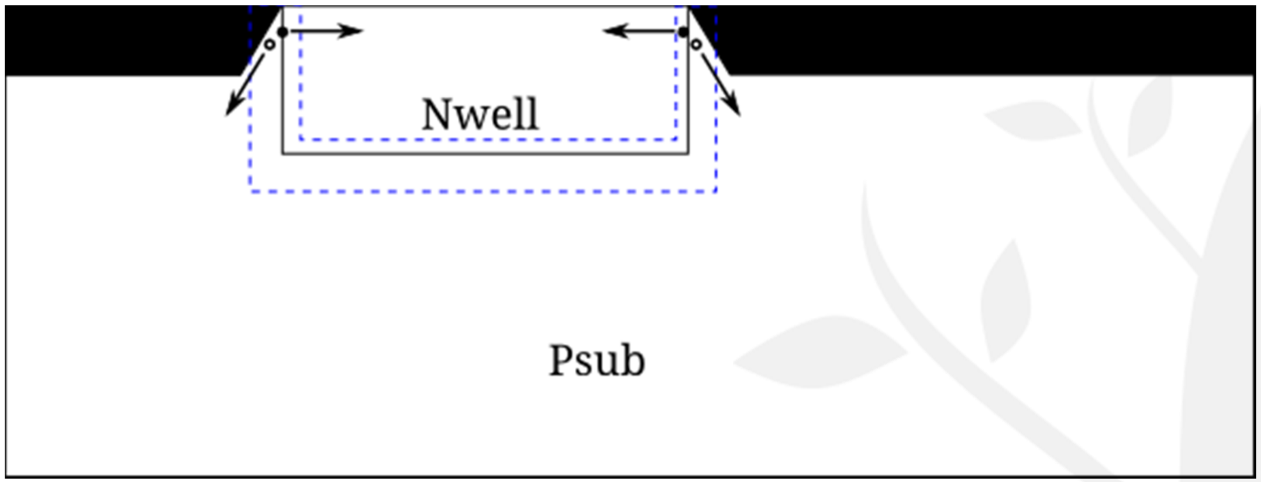
Research hypotheses & Objectives

3T pixel

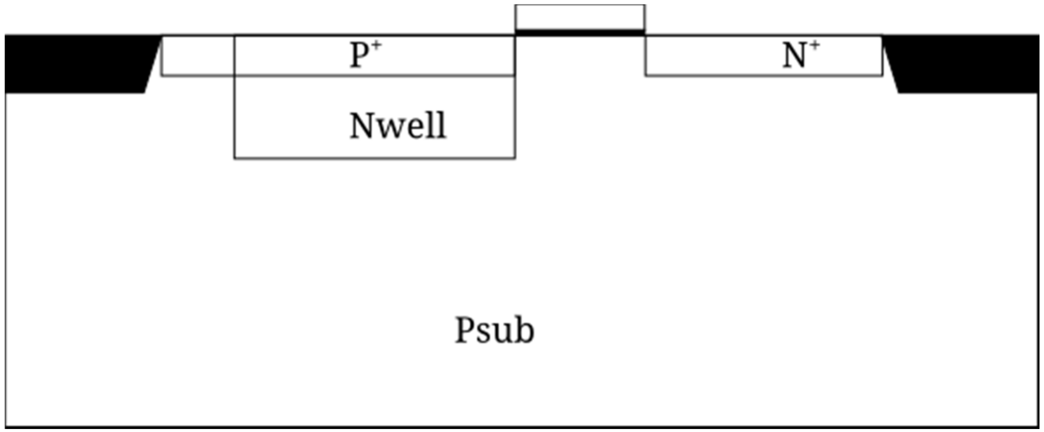
- Principal problems of 3T pixels
  - KTC noise → Thermal noise generated in V_{PD}
  - Dark Current → electron-hole pairs generated in the silicon-oxide interface

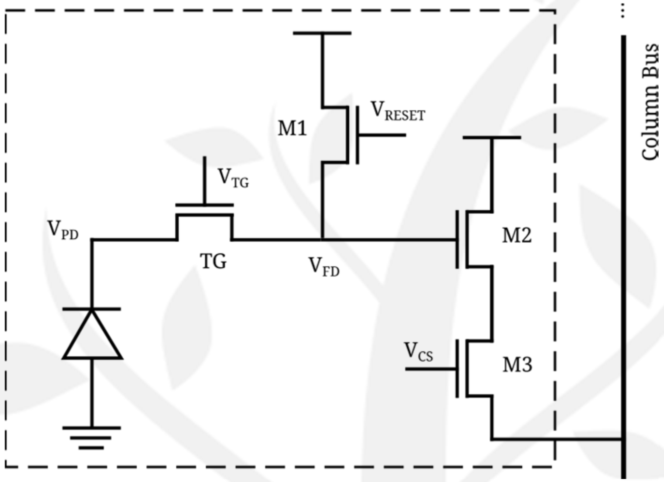


Research hypotheses & Objectives

4T pixel

- Improve the 3T problems:
  - KTC noise → addition of a Transmission Gate (TG) to perform CDS
  - Dark Current → P^+ over N well

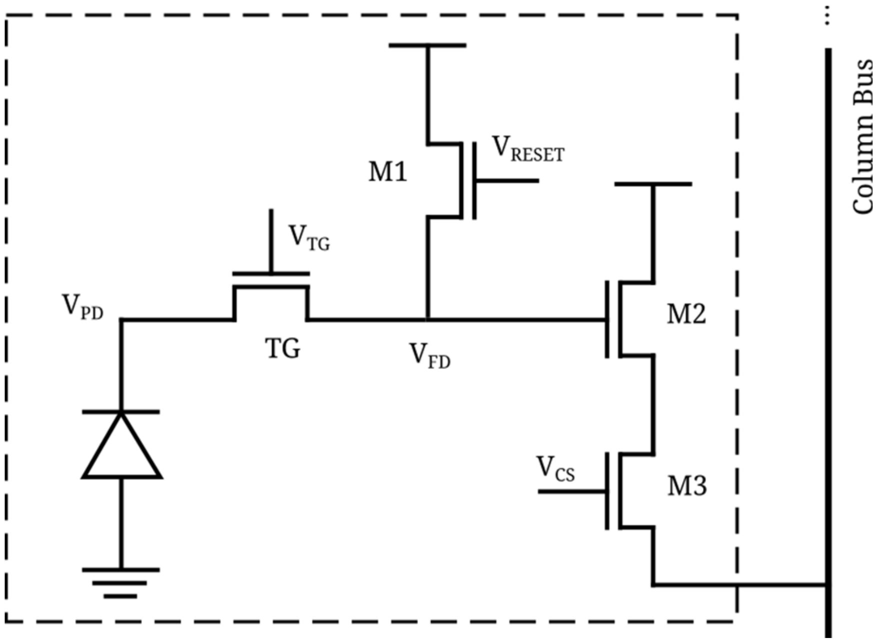


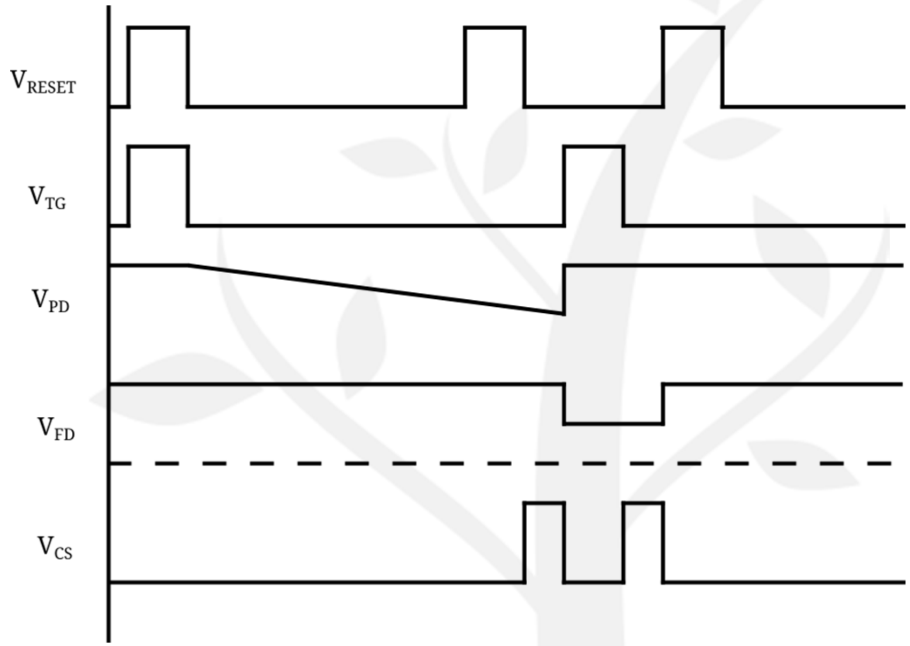


Research hypotheses & Objectives

4T pixel

- The photogenerated electrons are accumulated in V_{PD} node
- At the beginning of the measurement V_{FD} is reset
- At the end of the measurement charges are transferred from PD to FD
- Correlated double sampling (CDS) is performed





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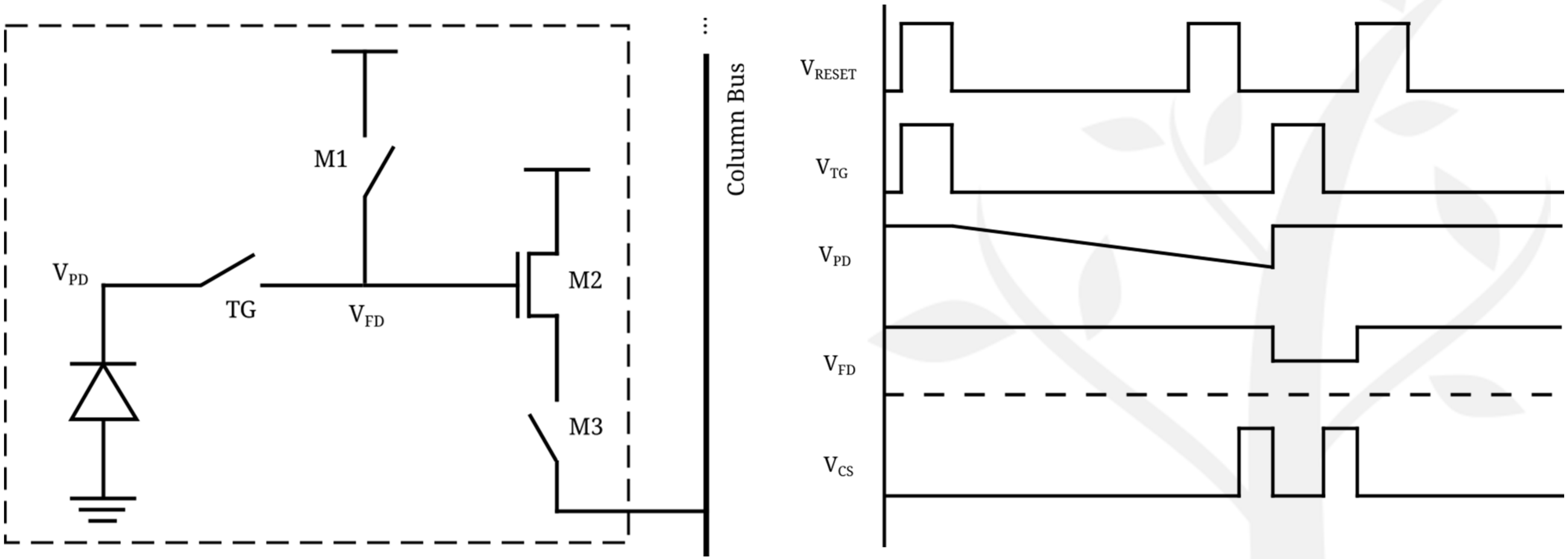

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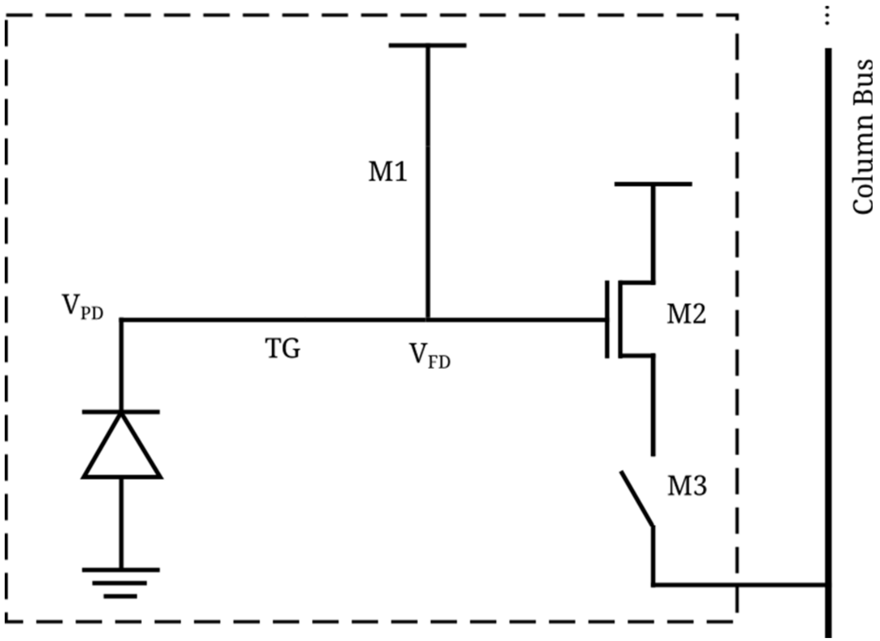

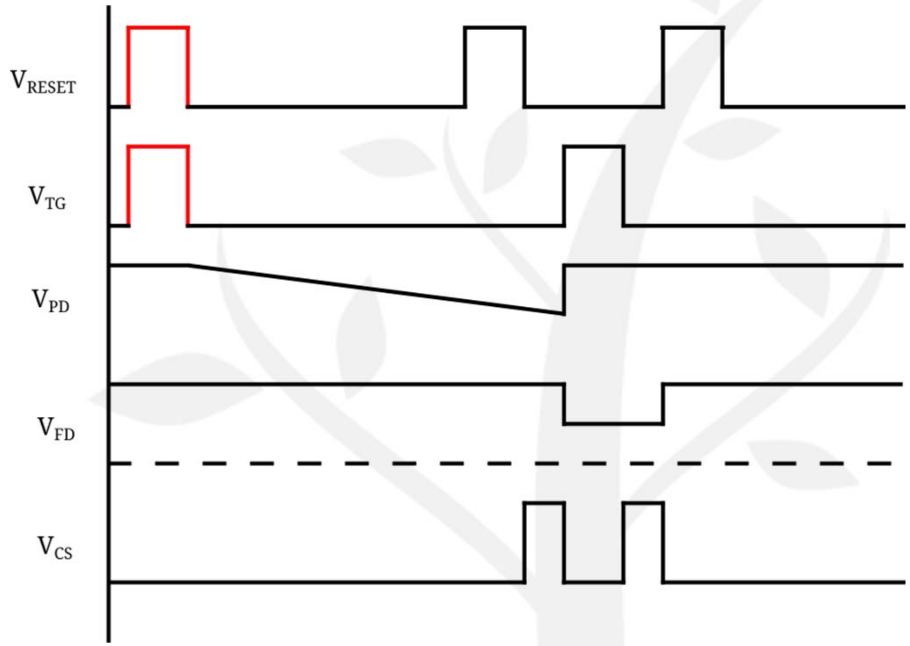

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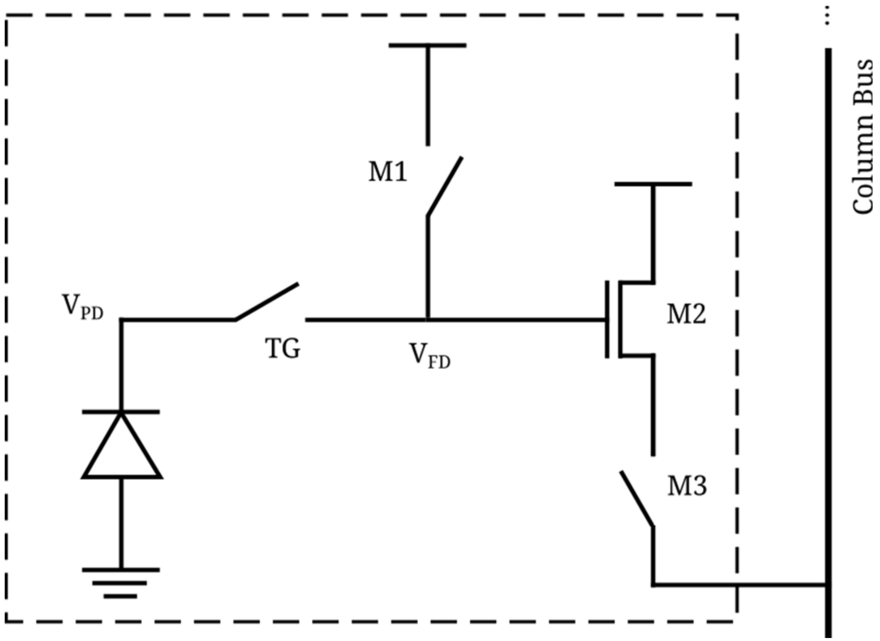

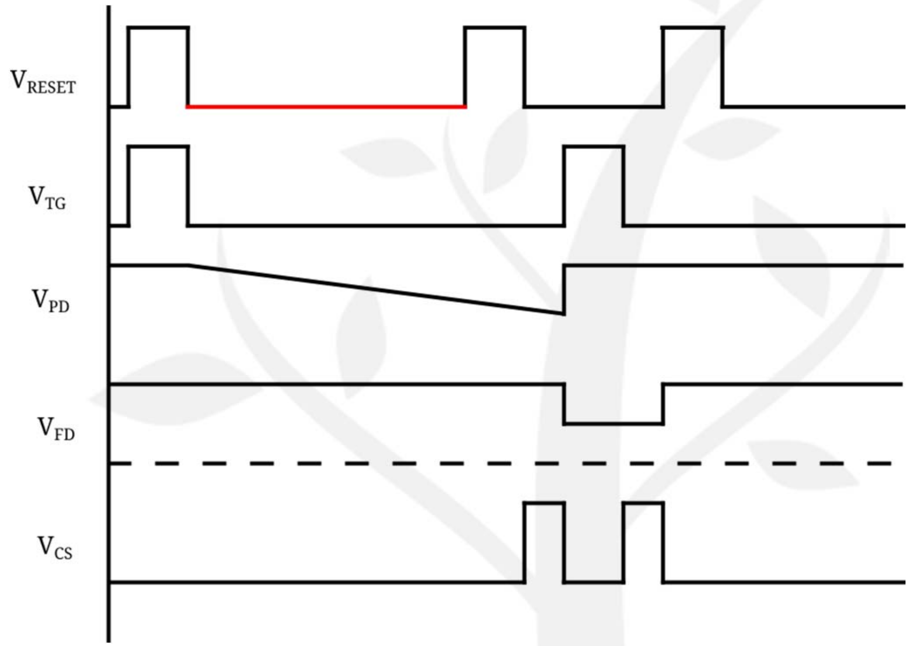

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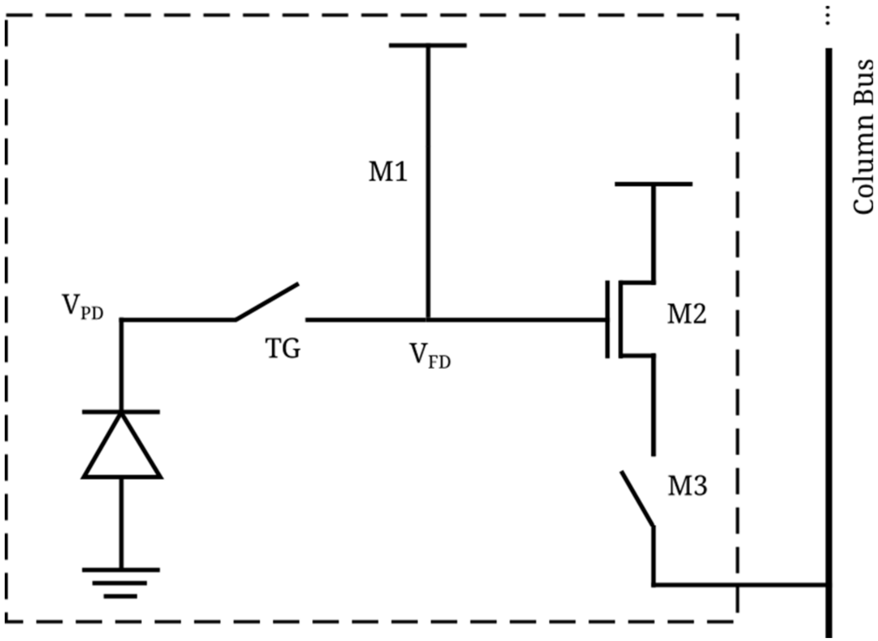

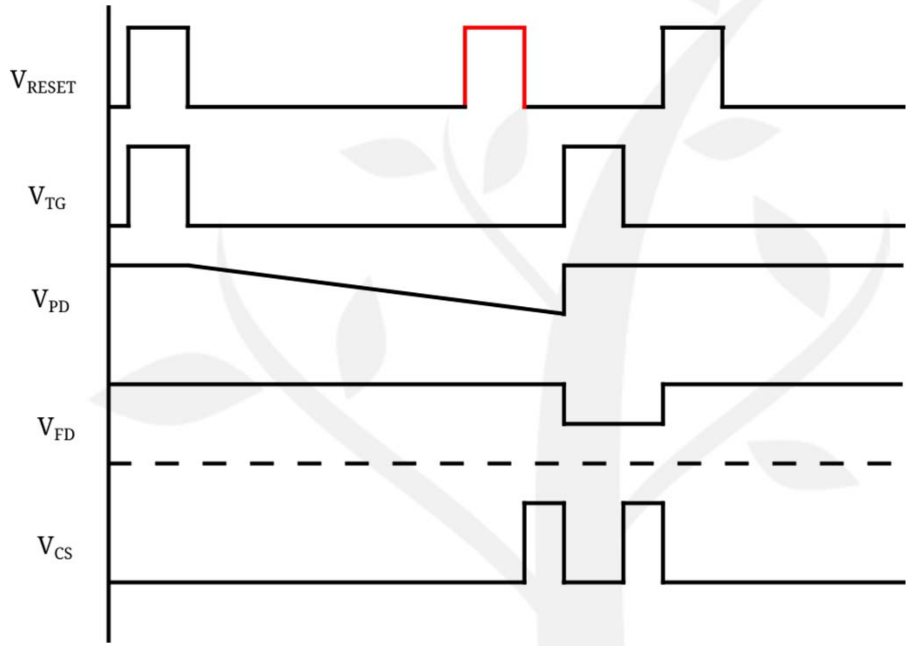

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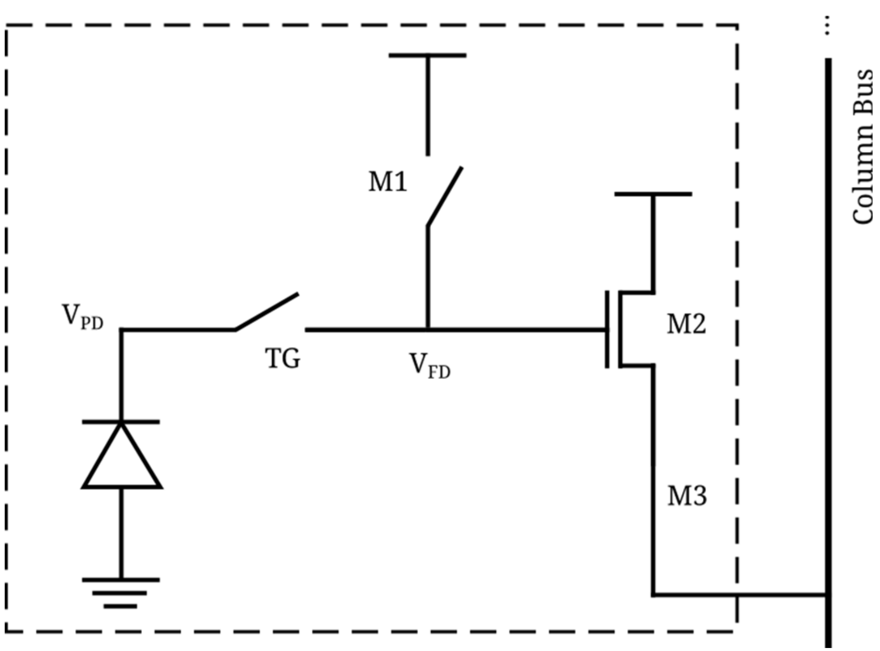

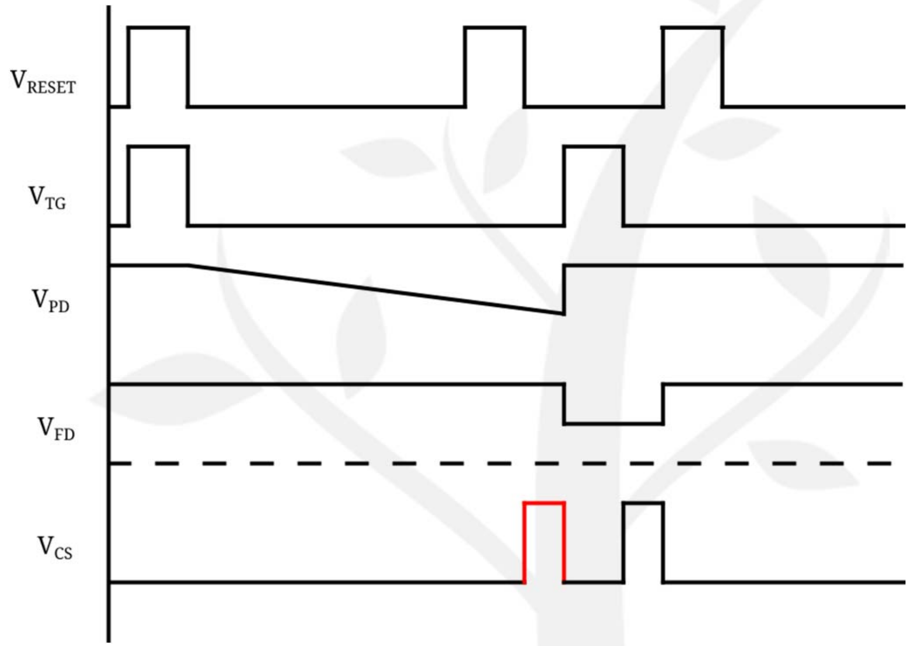

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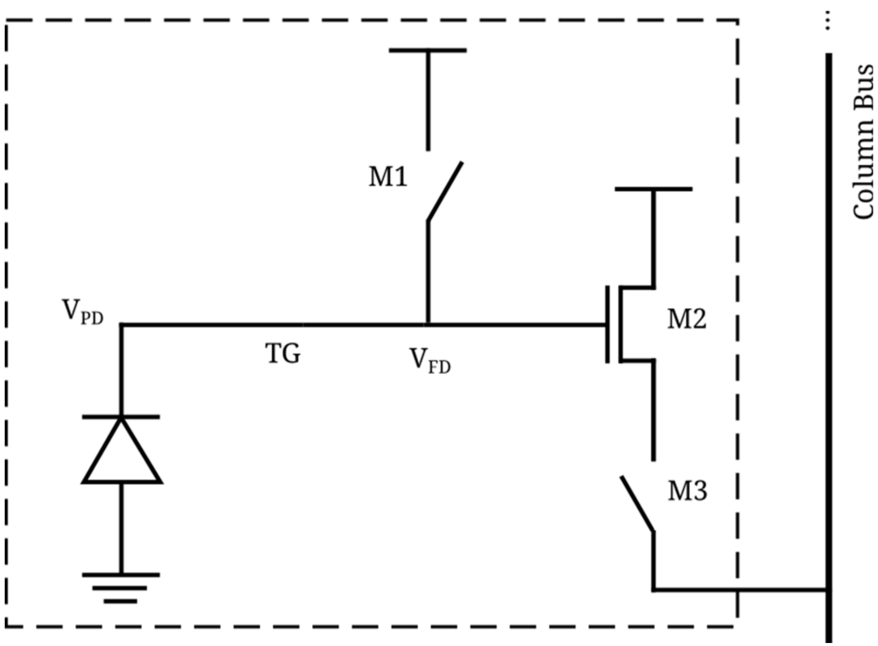

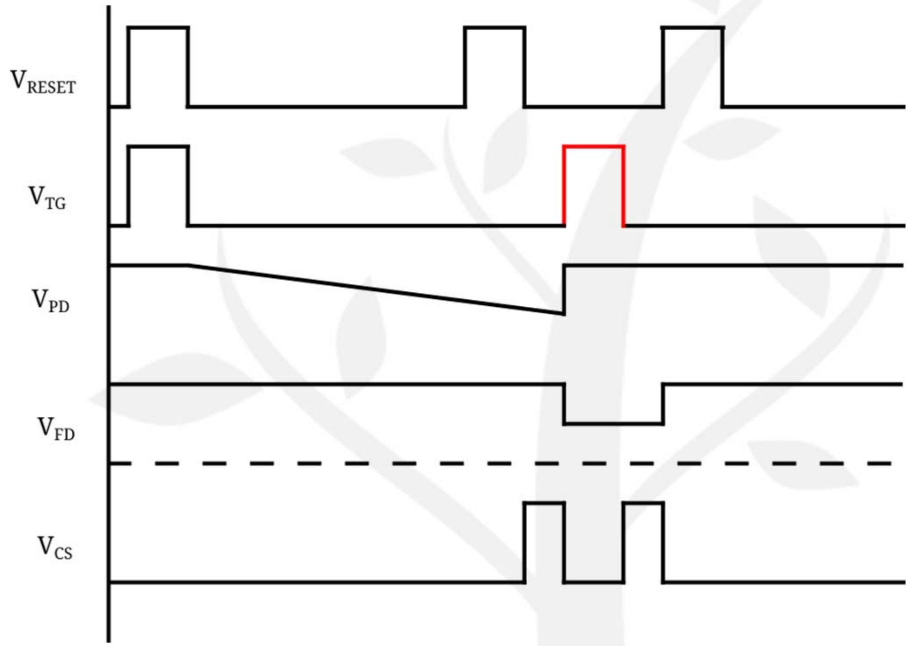

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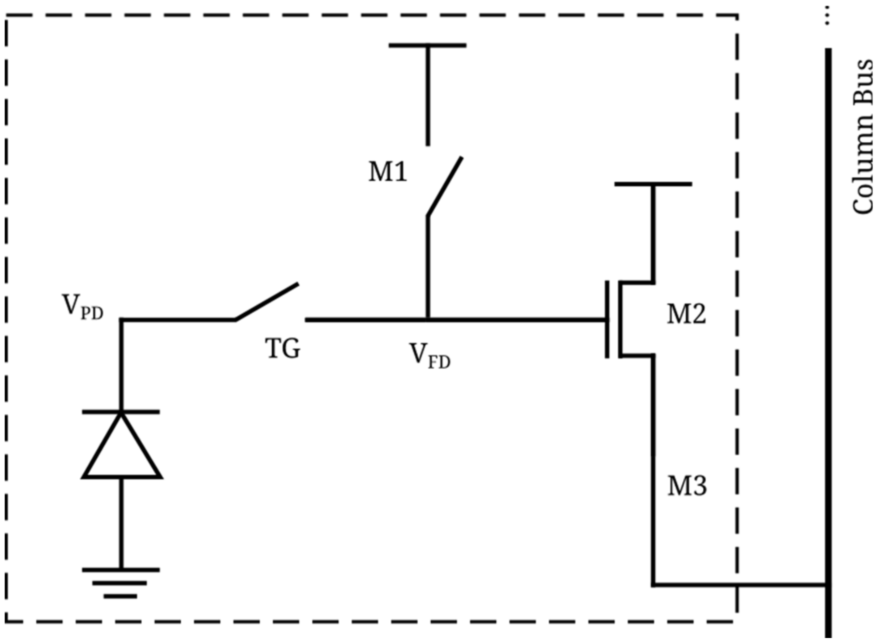
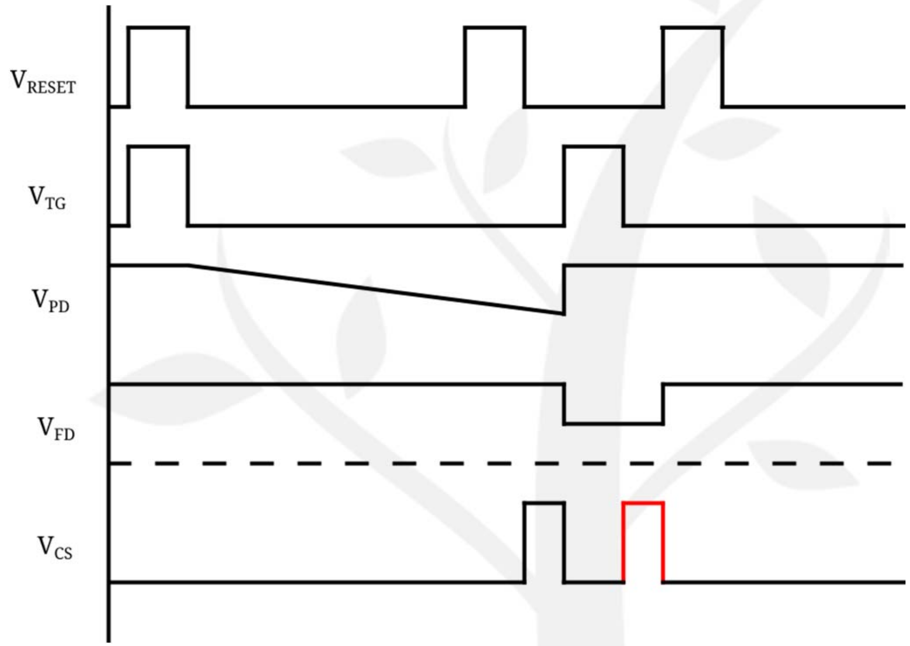
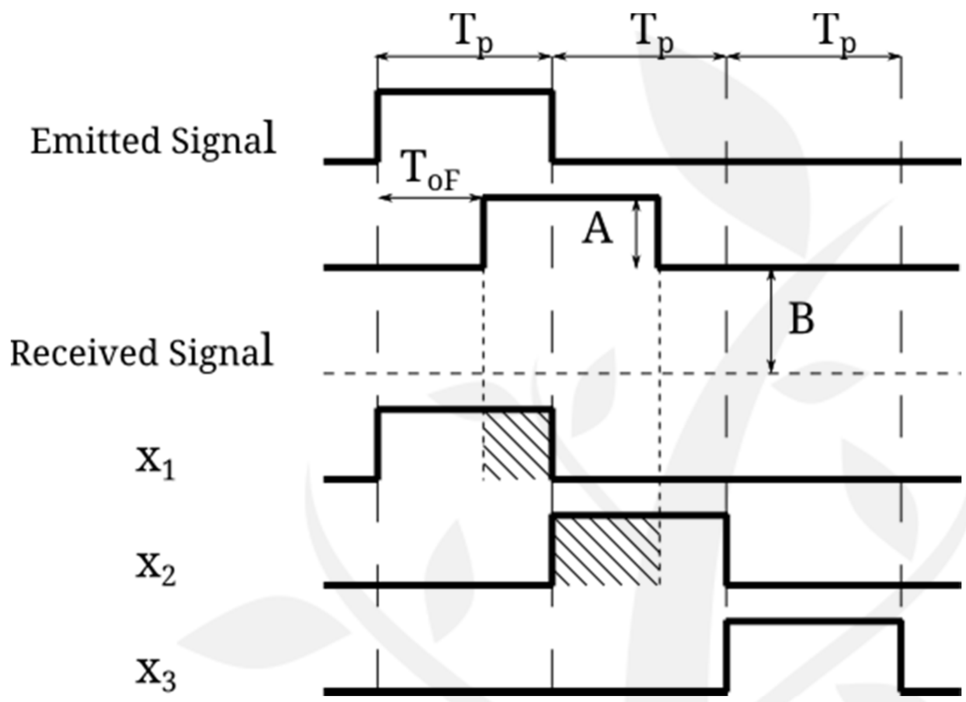




Research hypotheses & Objectives

4T pixel for ToF

- T_p=50 ns → Pixel must have a fast response
- Received signal with low light power → Accumulation of multiple pulses
- 3 unknown parameters in the received signal → 3 measurements per pulse



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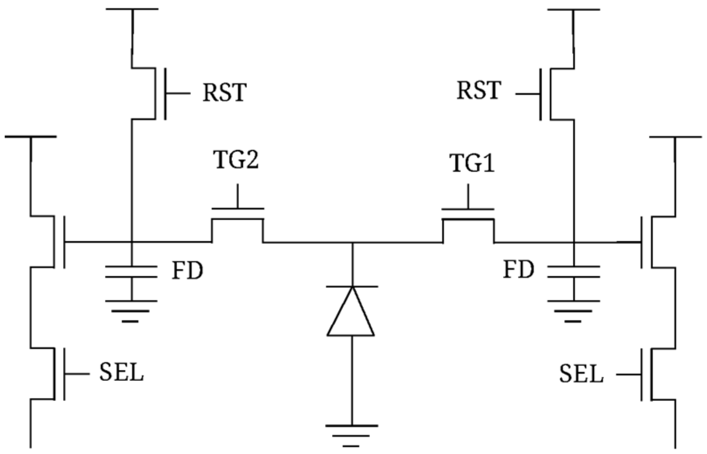
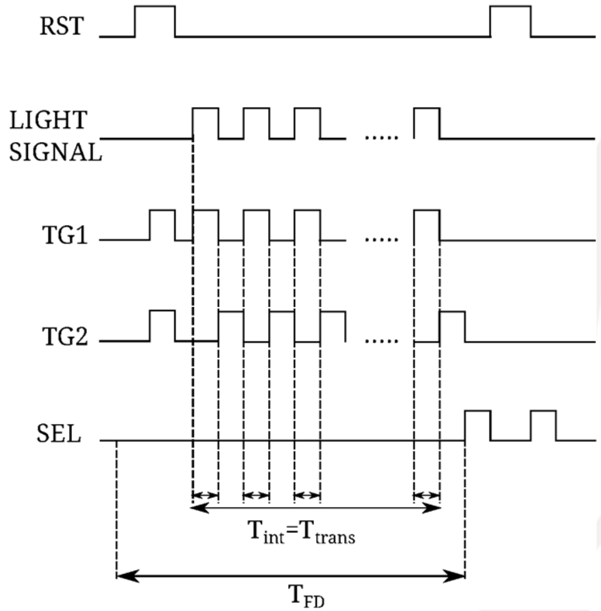
4T pixel for ToF

- The TG control the transmission of the charges to the FD
- After several accumulations the voltage in the FD is measured





Research hypotheses & Objectives

4T pixel in standard CMOS technology

- Commercial PPD need a careful control of the doping concentrations
- Standard CMOS Technologies do not provide PPD 4T structures
- Design of P^+ over Nwell with TG can be done violating layout rules
- To ensure correct behavior → Simulations with device-level simulator (ATLAS from Silvaco)
- 2-D simulations
- Parameters needed
  - Doping profiles
  - Horizontal Parameters
  - Vertical Parameters

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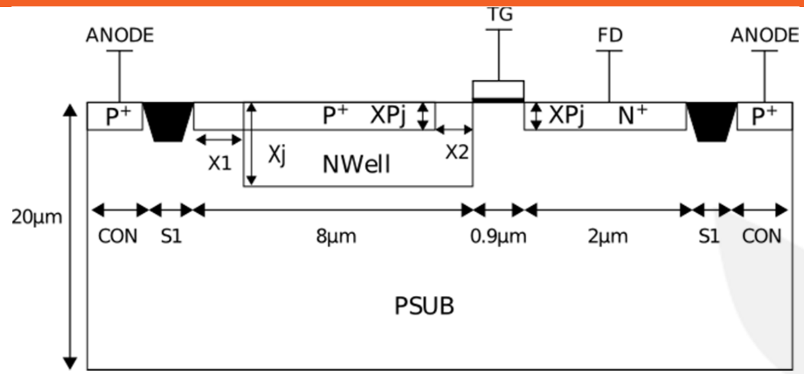
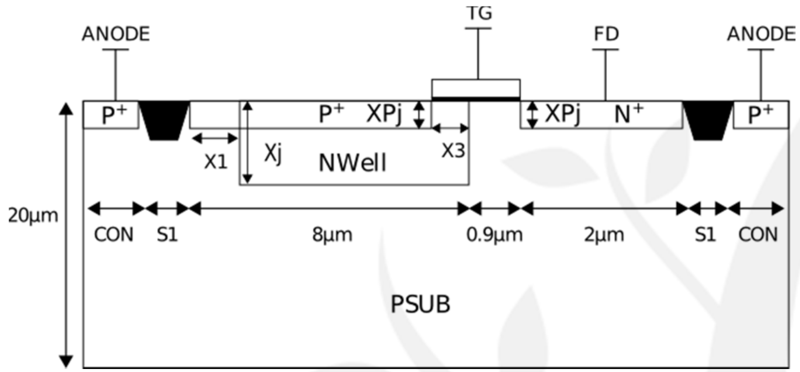
Research hypotheses & Objectives

4T pixel in standard CMOS technology

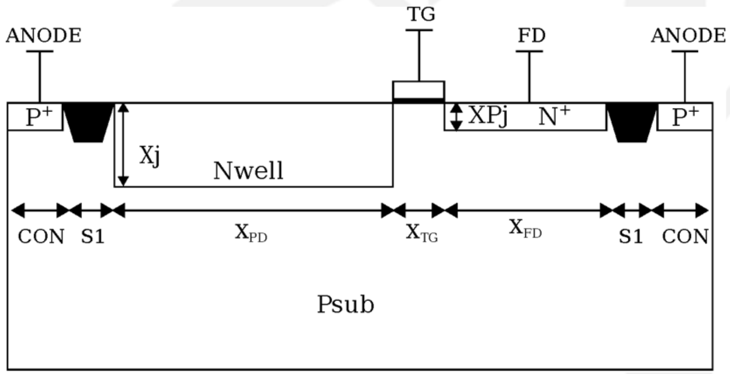
- NWell-aligned PPD:



- P+-aligned PPD:



- NWell PD:



Achievements & Current results

- Simulation parameters estimation
- Geometrical parameters optimization
- Dark current comparison
- Reset noise analysis
- Transient response

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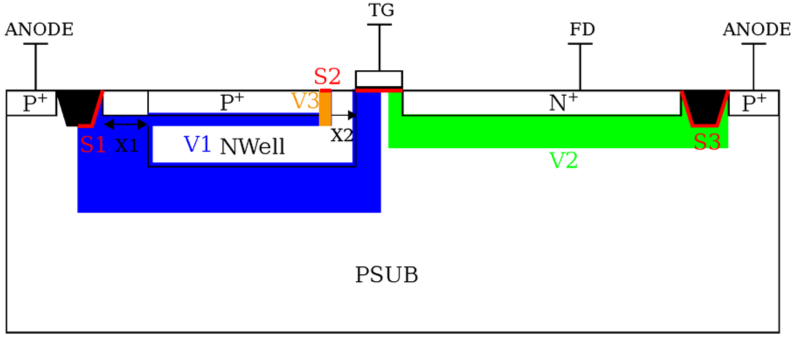
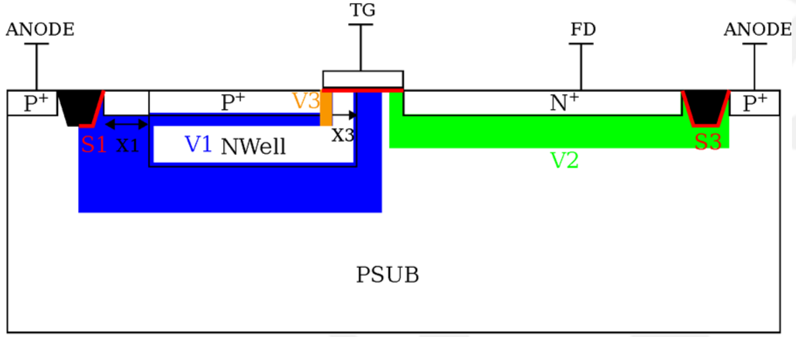
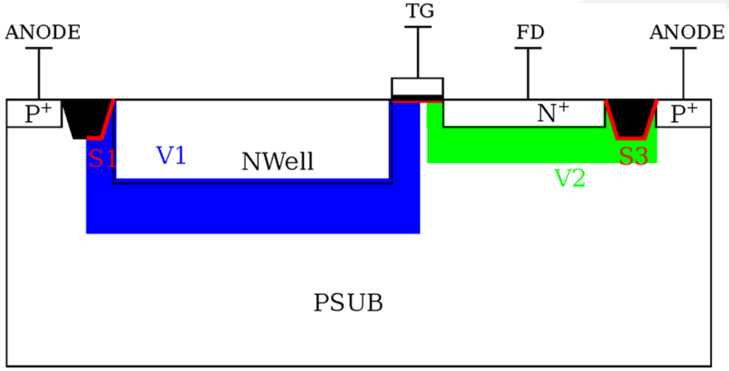
- Dark current (DC) effects:
  - Thermal DC
  - Surface DC
  - Band-to-band Tunneling DC







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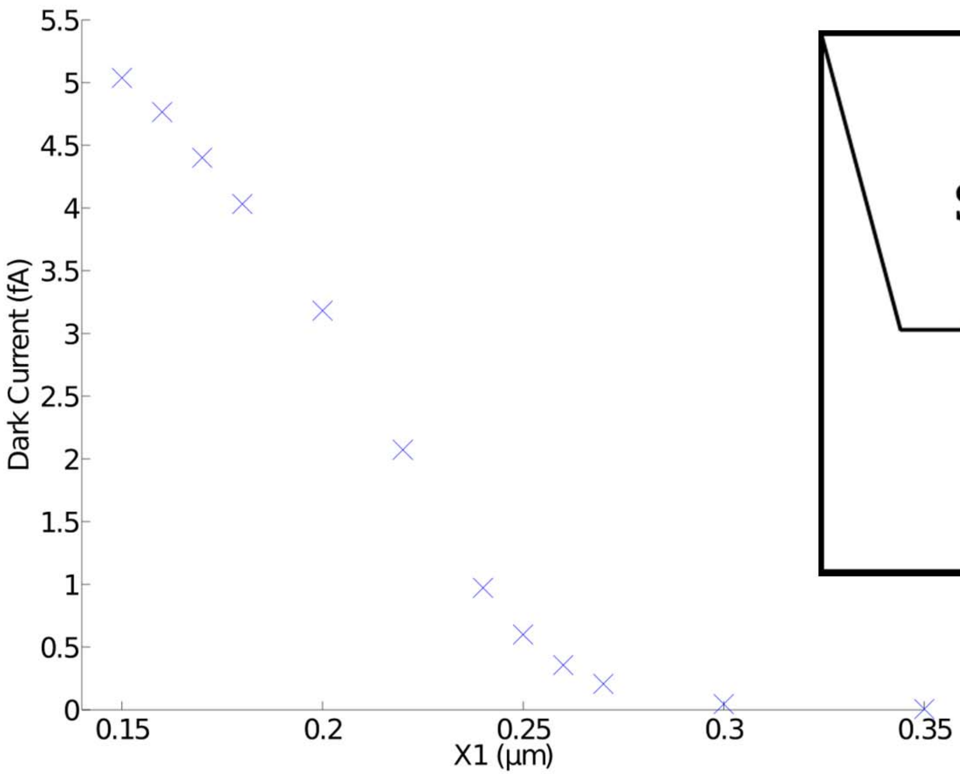
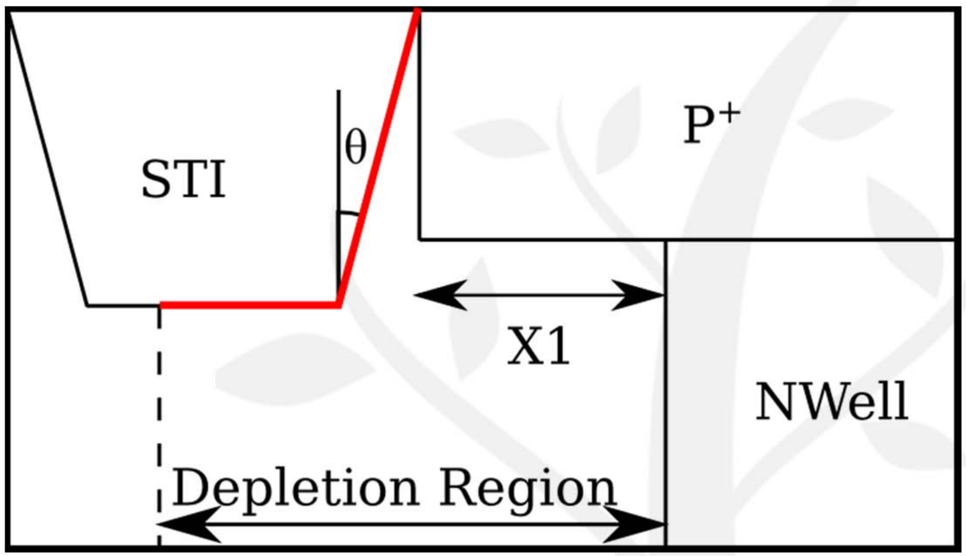
Achievements & Current results

Geometrical parameters optimization – X1 value

- Minimum value of 0.13 µm to ensure the correct biasing of the P^+ layer
- Increasing X1 increases the area of the pixel but reduces the superficial DC generated in the NWell/Psub interface (red area)
- Selected optimum value: 0.3 µm

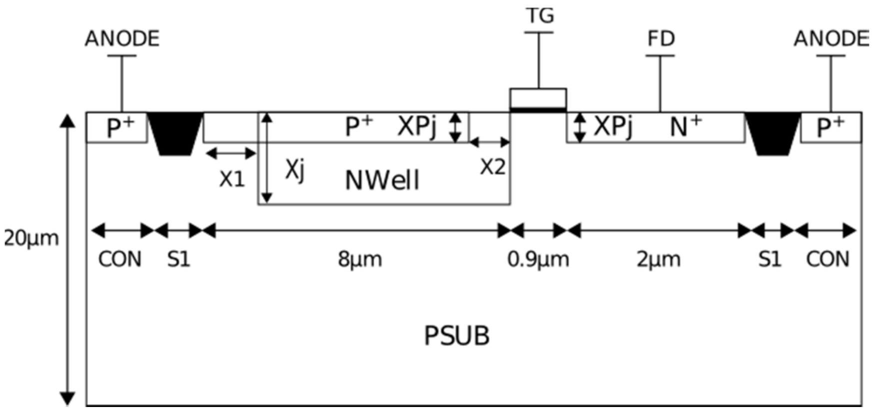


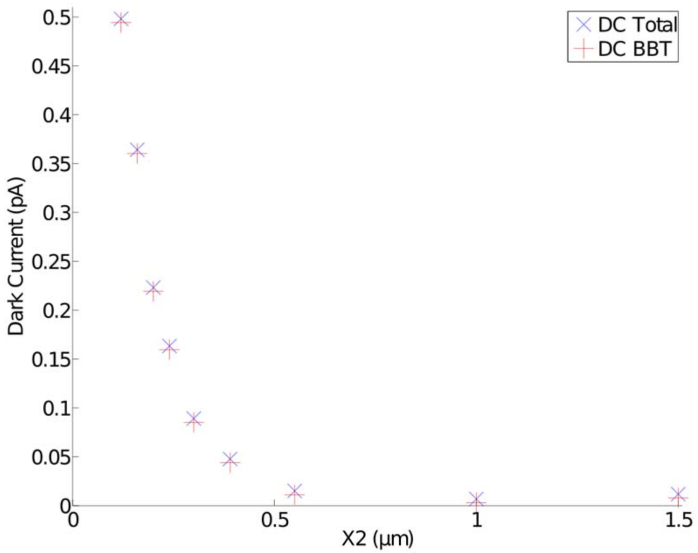


Achievements & Current results

Geometrical parameters optimization – X2 value

- A minimum distance of 0.12 µm necessary to provide a path between the photodiode and the TG for the photocharges transference.
- P+/NWell junction with both sides heavily doped ➔ Band-to-Band DC
- Decreasing X2 bring closer this junction and the NWell/Psub juntion ➔ increase in the curvature of the energy bands ➔ increase in the BTB-DC
- BTB-DC in this junction is the principal DC source of the NWell-aligned device
- Selected optimum value: 0.1 µm ➔ 40% of the total DC is generated by this BTB-DC





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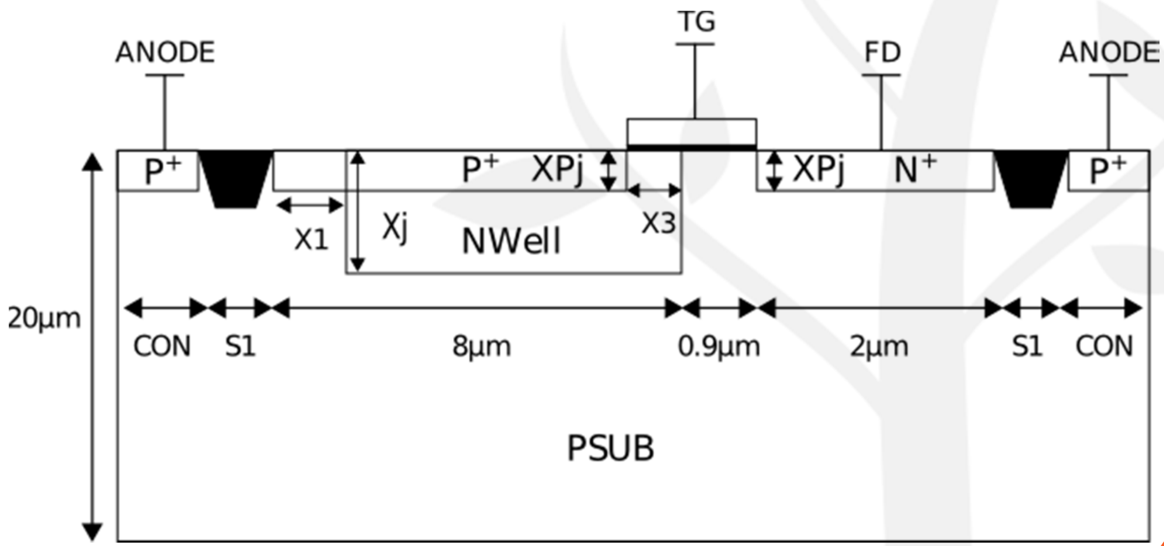
Achievements & Current results

Geometrical parameters optimization – X3 value

- A minimum distance of 0.11 µm necessary to provide a path between the photodiode and the TG for the photocharges transference.
- NWell under the TG with positive voltage ➔ NWell operates in accumulation ➔ behaves as being more doped ➔ more BTB-DC
- The BTB-DC is 6 orders of magnitude larger than in the other case
- Commercial PPD 4T pixels probably use this structure but with a P layer under the TG to alleviate the BTB-DC:

  I.Inoue et al.,“Low-Leakage-CurrentandLow-Operating-VoltageBuried Photodiode for a CMOS Imager,”

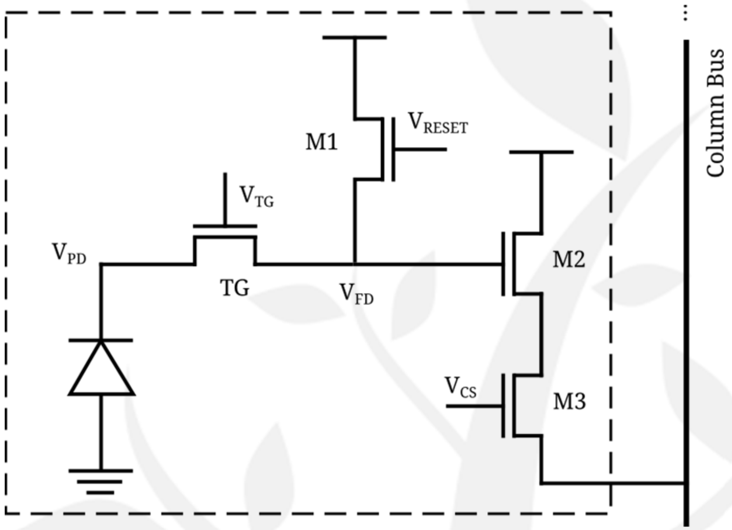


Achievements & Current results

Reset noise analysis

- The reset operation efects degrades the performance of the pixel
- Only depends on the capacitance of the FD node → Equal for the 3 studied structure
- Reset noise effects
  - Thermal noise (random)
  - Clock feedthrough (systematic)
  - Reset dependence with the illumination (systematic)
  - Leakage currents (systematic)
- ΔV_{FDmax}=150 mV
- $V_{swing,max}=\Delta_{VFDmax} - \Delta V_{syst,total}$
- Best case scenario

$$\Delta L = \frac{L_{\max}}{2\sqrt{2}} \frac{\Delta V_{thermal}}{V_{swing,\max}}$$

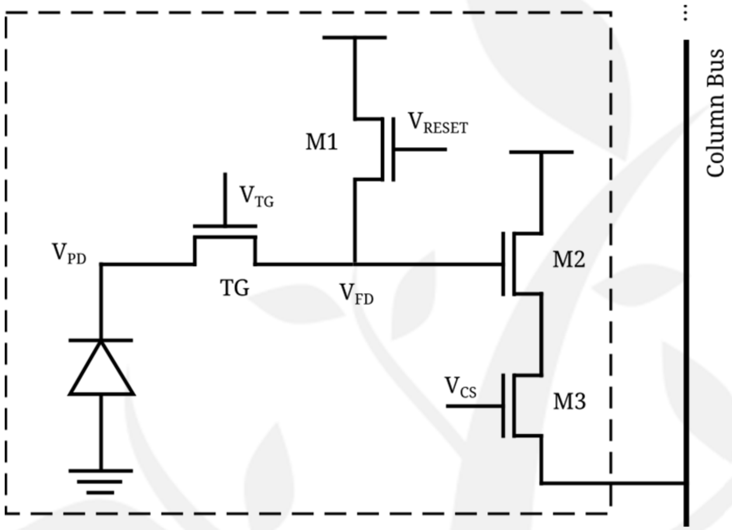


Achievements & Current results

Reset noise analysis

- Thermal noise:
  - Random movement of the electrons through the reset transistor

$$\Delta V_{thermal} = \sqrt{\frac{kT}{C_{FD}}}$$



$$\Delta V_{thermal} \approx 7\ mV \quad \rightarrow \quad \Delta L \approx 7.07\ cm$$

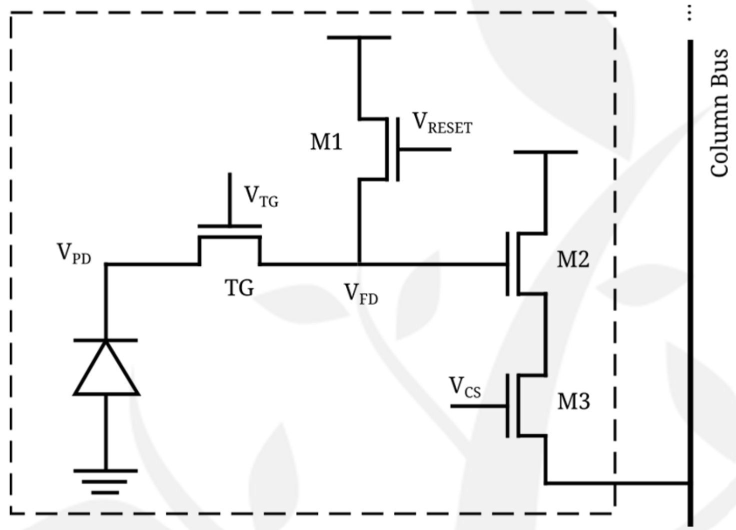
Achievements & Current results

Reset noise analysis

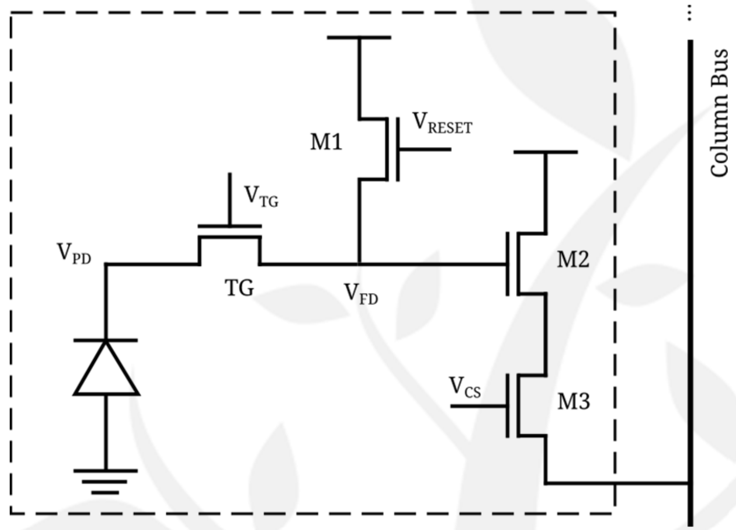
- Clock feedthrough:
  - Coupling of the V_{RESET} signal and the V_{FD} node through the C_{gs} capacitance

$$\Delta V_{syst,clk} = \Delta V_g \frac{C_{gs}}{C_{gs} + C_{FD}}$$

W (µm)	X_{FD} (µm)	$\Delta V_{syst,clk}$ (mV)	ΔL (cm)
1	1	133.1	62.76
1	2	121.5	37.22
1	4	103.4	22.76
0.5	2	69.6	13.19
0.25	2	36.15	9.32



- Dependence of the reset voltage with the illumination:
  - Initial reset voltage depends on the photogenerated current



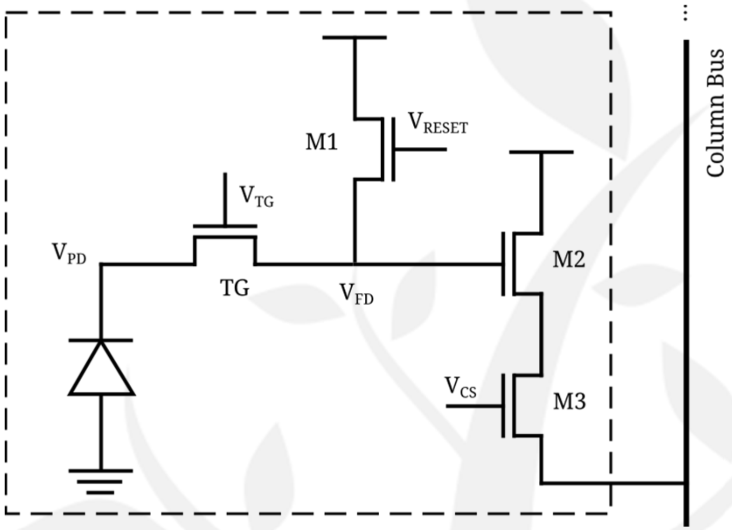
I_{ph} (pA)	$\Delta V_{syst,light}$ (mV)	ΔL (cm)
200	0.5	7.09
500	1.4	7.14
2000	5.1	7.32
5000	11.2	7.64

Achievements & Current results

Reset noise analysis

- Leakage current:
  - Through the reset transistor flows some current even being cut off

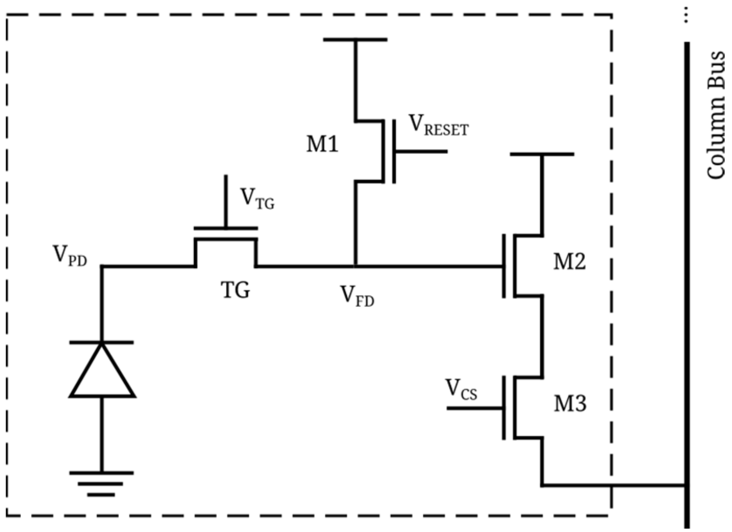
$$\Delta V_{syst,leakage} \approx 10\ mV \quad \rightarrow \quad \Delta L \approx 7.57\ cm$$

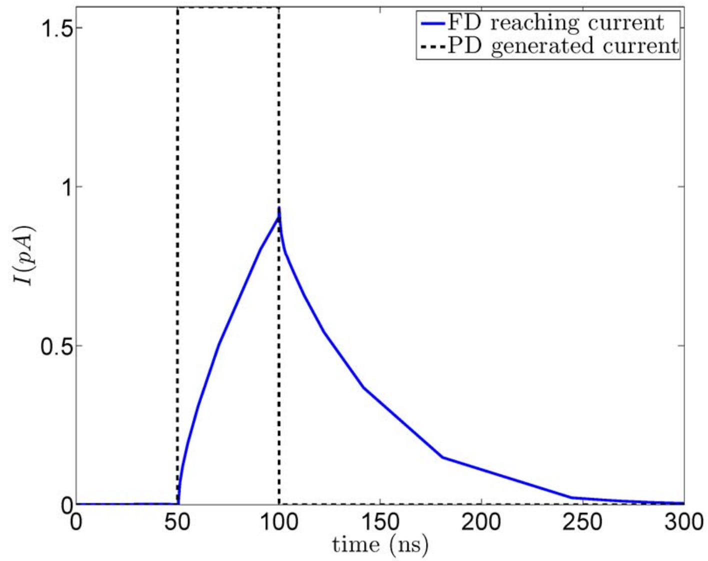


Achievements & Current results

Transient analysis

- Square light pulses are assumed for the ToF calculation
- The transmission of the electrons from the PD to the FD needs a finite amount of time
- This generates a deviation from square pulses

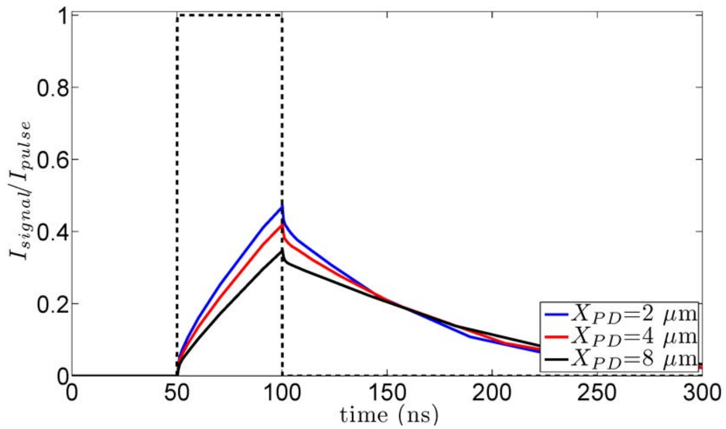


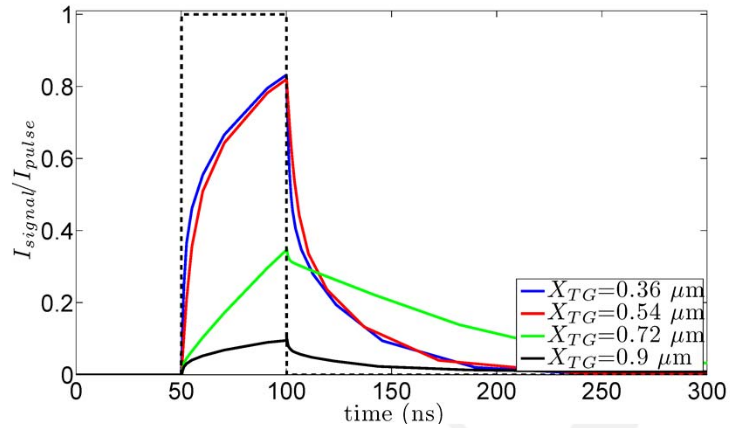


Achievements & Current results

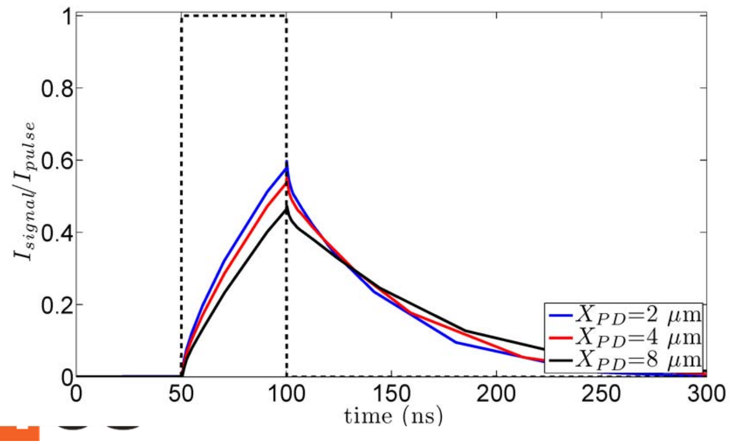
Transient analysis

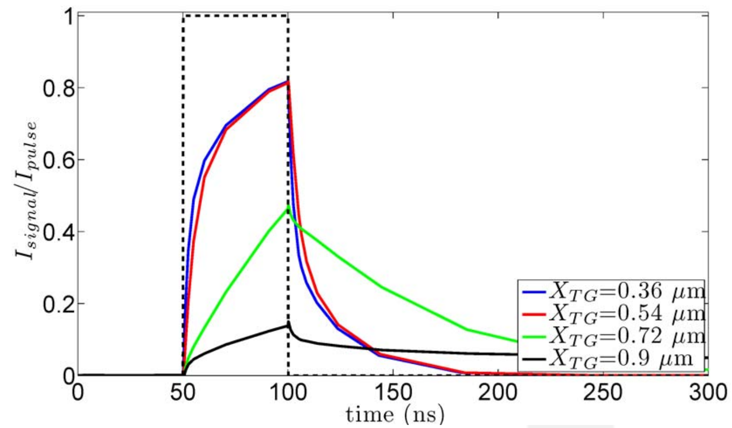
- NWell-aligned PPD:





- NWell PD:





Achievements & Current results

Transient analysis

- Deviation from the square signal

$$I_{signal} = \begin{cases} I_m\left[1-e^{-\frac{t}{\tau}}\right] & if \quad 0<t<T_p \\ I_m e^{-\frac{t}{\tau}} & if \quad 0<t<T_p \\ 0 & if \quad t<0 \end{cases}$$

$$L_{meas} = \frac{L + L_{\max} f\left(T_{oF}\right)}{g\left(T_{oF}\right)}$$

$$f\left(T_{oF}\right) = \frac{1+e^{-n}\left[1-2e^{n\frac{T_{oF}}{T_p}}\right]}{n}$$

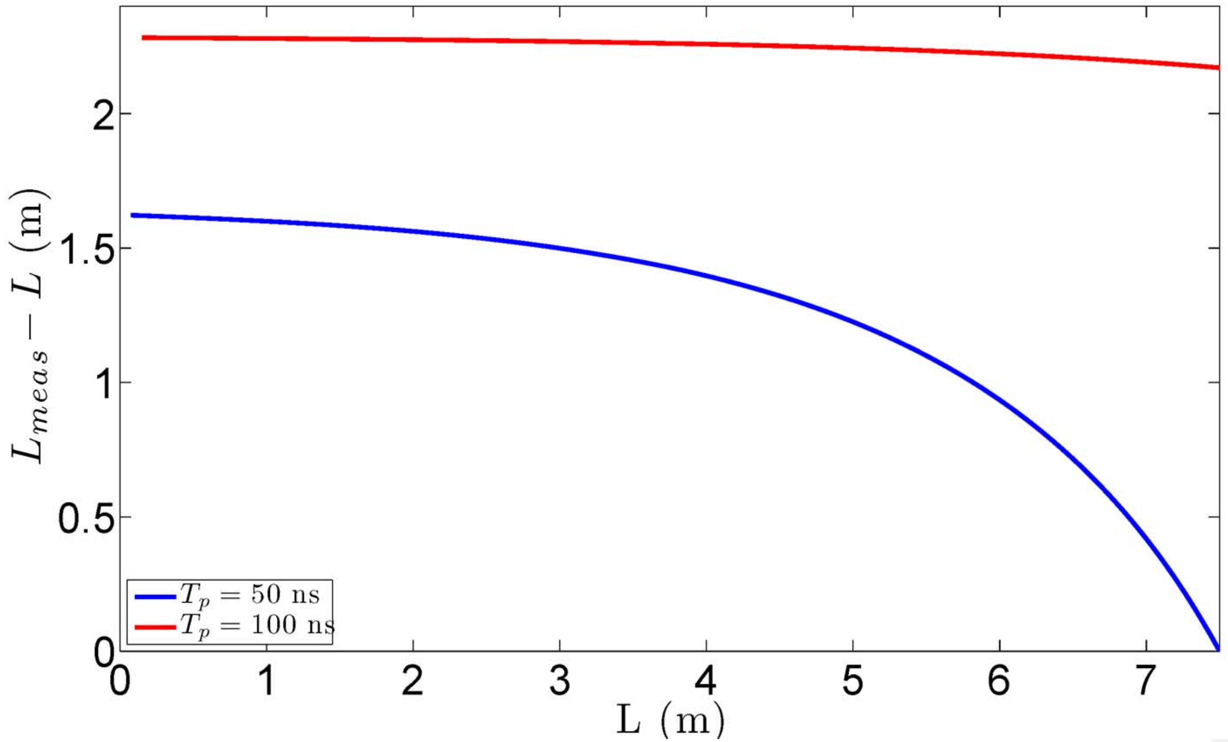
$$g\left(T_{oF}\right) = 1 + e^{-n\frac{1-e^{n\frac{T_{oF}}{T_p}}}{n}}$$

$$n = \frac{T_p}{\tau}$$

Achievements & Current results

Transient analysis

- Deviation from the square signal



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Achievements & Current results

Publications

- Conferences:
  - J. Illade-Quinteiro, V. Brea, P. López et al. “Comparison of Photosensing Structures in CMOS Standard Technology for Time-of-Flight Sensors”, *XXVIII Conference on Design of Circuits and Integrated Systems (DCIS),* 2013, San Sebastián (Spain)
  - J. Illade-Quinteiro, V. Brea, P. López et al. "Dark current in standard CMOS pinned photodiodes for Time-of-Flight sensors," *Microelectronics And Electron Devices (WMED), 2014 IEEE Workshop On* , pp.1,4, 18-18 April 2014
  - J. Illade-Quinteiro, P. López, V. Brea et al. "Custom design of pinned photodiodes in standard CMOS technologies for time-of-flight sensors," Cellular Nanoscale Networks and their Applications (CNNA), 2014 14th International Workshop on , vol., no., pp.1,2, 29-31 July 2014
  - J. Illade-Quinteiro, P. López, V. Brea et al. “Dark Current Optimization of 4-Transistor Pixel Topologies in Standard CMOS Technologies for Time-of-Flight Sensors” , IEEE International Symposium on Circuits & Systems (ISCAS), 2015

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Achievements & Current results

Publications

- Accepted publications:
  - J. Illade-Quinteiro, P. López, V. Brea et al. “Four-Transistor Pinned Photodiodes in Standard CMOS Technologies for Time-of-Flight Sensors”, *Semiconductor Science and Technology Journal,* 2015, Vol. 30, Num. 4, JCR (Q1)
  - J. Illade-Quinteiro, V. Brea, P. López et al. “Distance Measurement Error in Time-of-Flight Sensors Due to Shot Noise”, *Sensors Journal* JCR (Q1)

- 7 months of internship in Fondazione Bruno Kessler (FBK), Trento, Italy

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Future work

- Design of an appropriate pixel for ToF in CMOS standard technology
- Fabrication of the chip in 0.18 µm technology
- Test of the chip
- Defense of the thesis in the first trimester of 2016

Gracias por su atención

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