Charge domain binning by applying potentials between photodiodes

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Outline

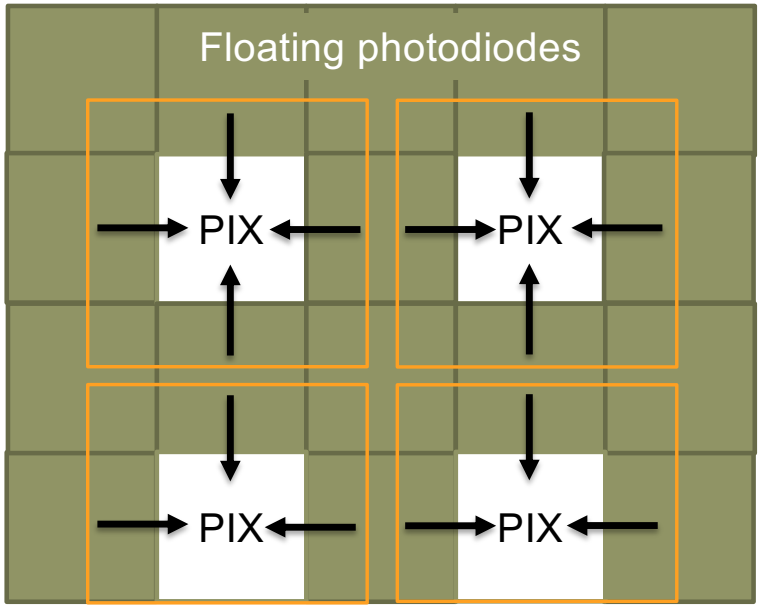
- Binning
- Charge domain binning
- TCAD simulations of charge binning concept
- Measurement results of sensor with charge binning
- Conclusions

Binning

- In image sensors, for low illumination levels, the photogenerated charges of multiple pixels are combined to improve SNR
  - E.g., In 2x2 pixel binning, we ideally have
    - 4 times more signal per “2x2 pixel”
    - 2 times higher SNR if photon shot noise limited ($\sigma_{PSN}^2 = 4 \cdot N_{e^-} \cdot q$)
    - However, spatial resolution is divided by 4
- There are 2 ways to accomplish binning
  - **Voltage domain binning**
    - Averaging 4 pixels in the voltage domain
    - Relatively easy to do, read noise is included in the averaging
  - **Charge domain binning**
    - All photogenerated charges are integrated only in a single pixel

Binning

- Charge domain binning
  - Signal is amplified at the earliest stage resulting in lower input referred noise
  - Challenges
    - Modulation of the electric field is required
    - Potentially increased dark current, try to avoid regions with trap states
    - Try to avoid “dead zones” where electrons and holes might recombine

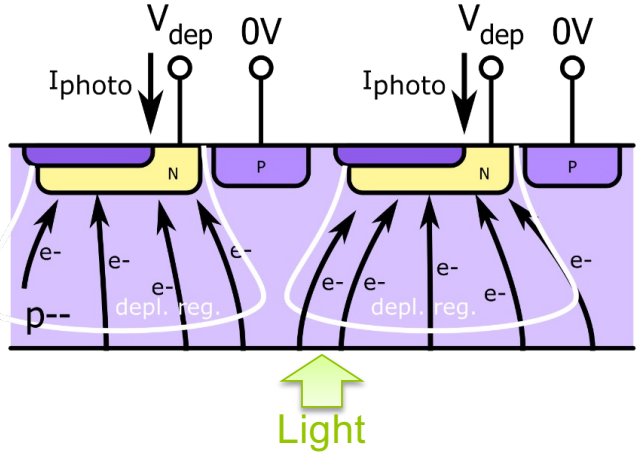


Charge binning – TCAD

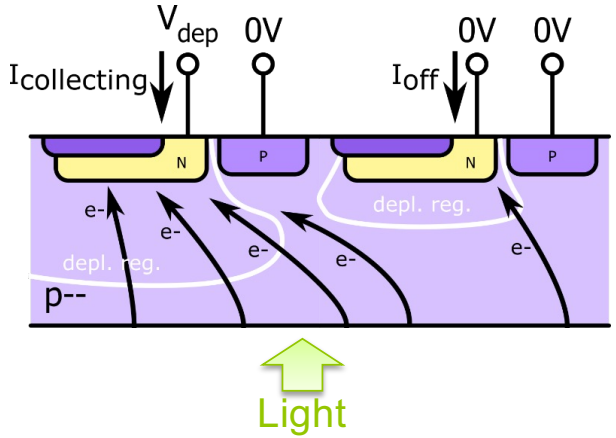
- We perform 2D TCAD simulations
  - Look at multiple EPI layer thicknesses
  - Uniform light (400nm) on the backside

  - **Reference situation**
    - What is the total available photocurrent in unbinned operation?
    - Is the EPI layer Fully depleted?
  - **Binning situation**
    - What is the total collected photocurrent?
      - Is there recombination?
      - Look at depletion regions

  - Extra:
    - Can we apply a voltage on the backside?



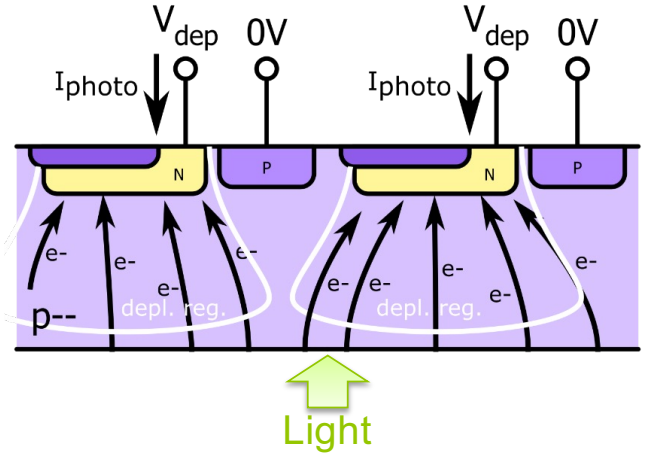
Reference case



Binning case

TCAD – Reference situation

- Normal operating pixel
  - All pixel photodiodes are tied to $V_{dep} = 1V$
  - EPI thickness is $10\mu m$
- Probe photocurrent through photodiode contacts
  - The total light to that can be collected using charge binning in total should be 2X these numbers



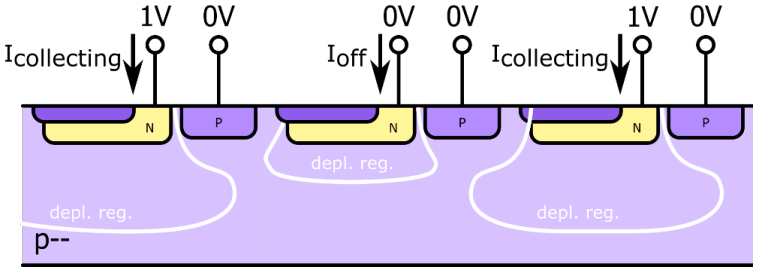
Reference case

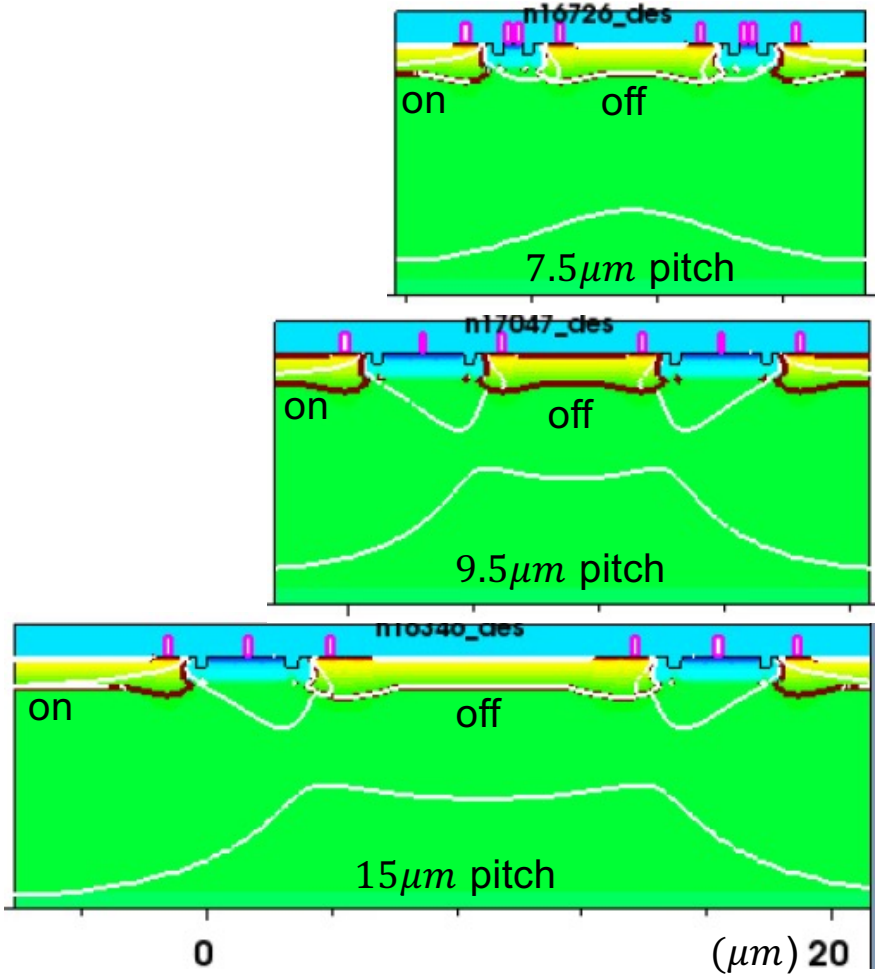
Pitch [μm]	Photocurrent per pixel [$pA/\mu m$]
7.5	1.1
9.5	1.4
15	2.2

Photocurrents for $10\mu m$ EPI thickness, $V_{on} = 1V$

TCAD – Binning situation

- Modulation of the electric field by asymmetrical expansion of the depletion region is possible
- One pixel at $V_{dep} = 1V$, the other is at $V_{off} = 0V$
- Probe photocurrent through the collecting and non-collecting photodiode





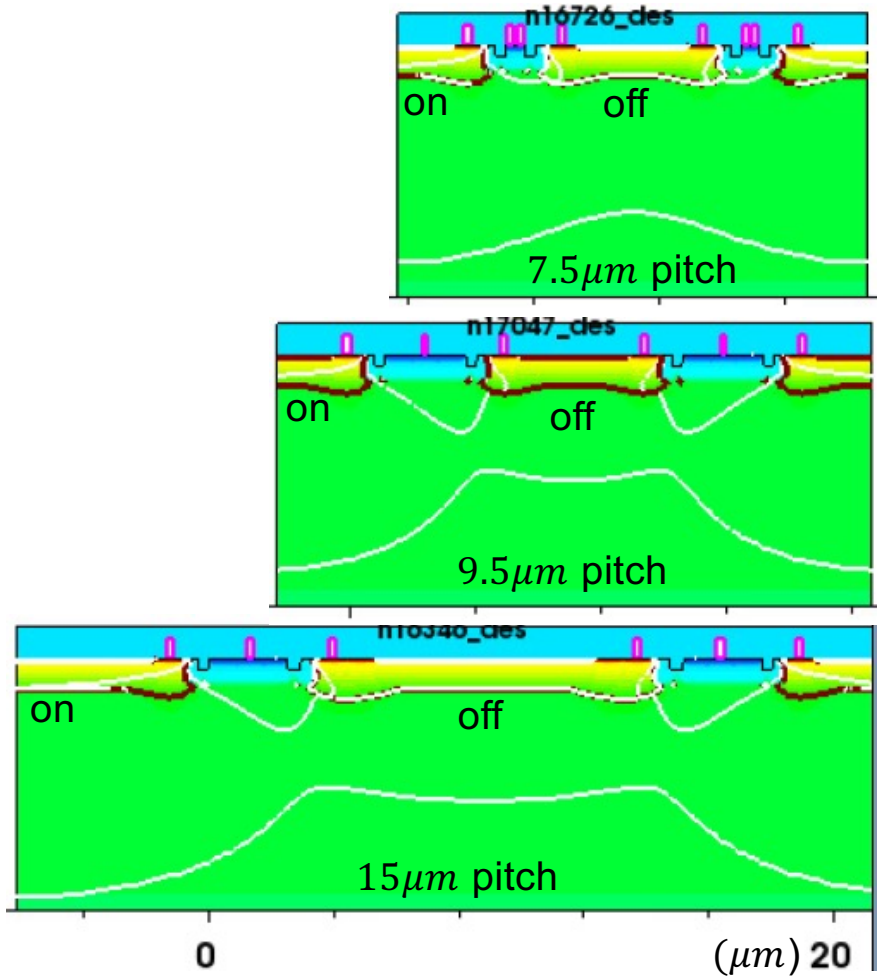
2D TCAD setup – doping profile (colors) and depletion region (white lines)

TCAD – Recombination

- Total available photocurrent matches the total collecting + off current
  - This means **limited recombination**

Pitch $[\mu m]$	Total avail. photocurrent $[pA/\mu m]$	Collecting $[pA/\mu m]$	Off $[pA/\mu m]$	Total collecting + off $[pA/\mu m]$
7.5	2.2	10.0	-7.9	2.1
9.5	2.8	2.0	0.8	2.8
15	4.4	2.8	1.5	4.3

(Photo)currents for $10\mu m$ EPI thickness, $V_{on} = 1V$, $V_{off} = 0V$



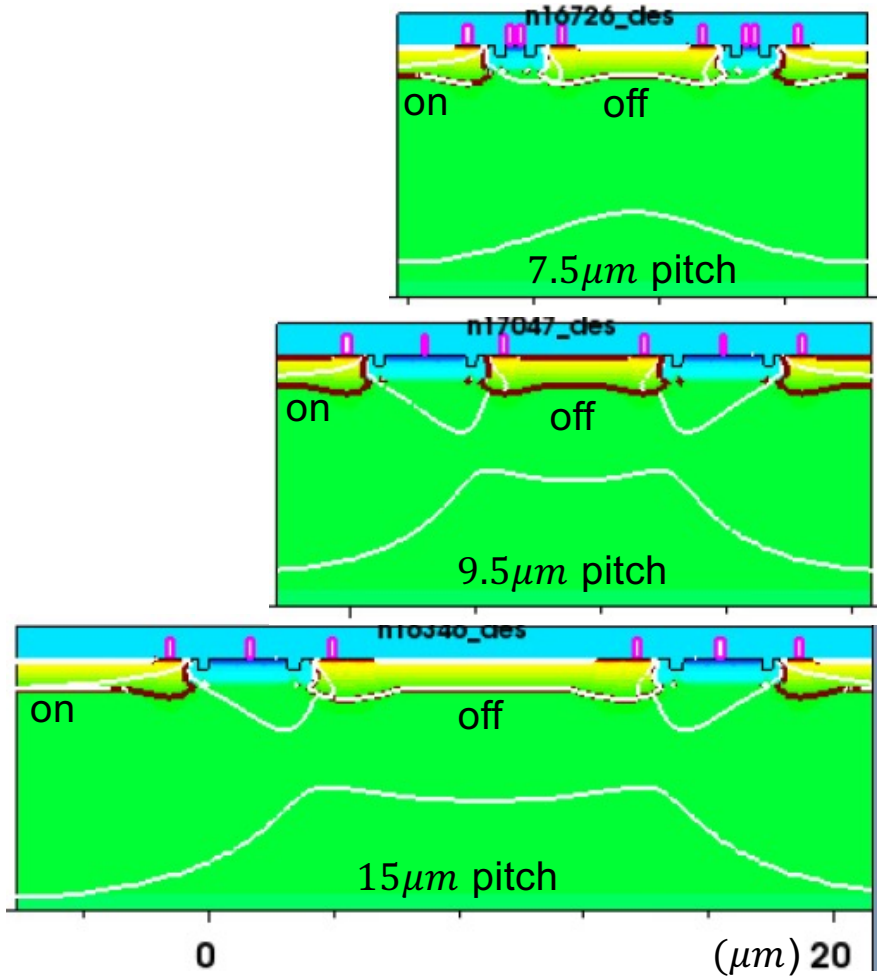
2D TCAD setup – doping profile (colors) and depletion region (white lines)

TCAD – Leakage

- **Leakage current** (light-signal independent) for $7.5\mu m$ pitch
  - Will appear in the image as dark current
  - Further investigation yielded:
    - Leakage↑ if thicker EPI
    - Leakage↑ if larger V differences on PDs
    - Leakage↑ if smaller pitch/p-well widths

Pitch $[\mu m]$	Total avail. photocurrent $[pA/\mu m]$	Collecting $[pA/\mu m]$	Off $[pA/\mu m]$	Total collecting + off $[pA/\mu m]$
7.5	2.2	10.0	-7.9	2.1
9.5	2.8	2.0	0.8	2.8
15	4.4	2.8	1.5	4.3

(Photo)currents for $10\mu m$ EPI thickness, $V_{on} = 1V$, $V_{off} = 0V$



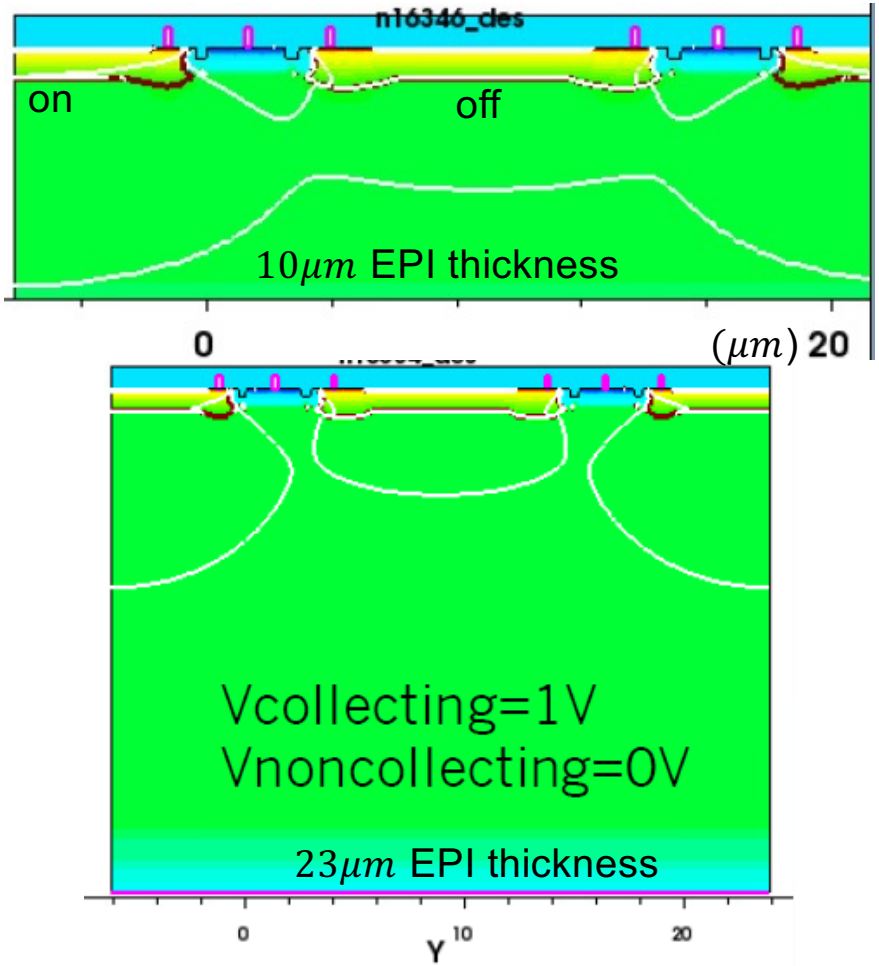
2D TCAD setup – doping profile (colors) and depletion region (white lines)

TCAD – EPI thickness

- As pixel pitch grows larger than the **EPI thickness**, the modulation depth becomes smaller
  - Electrons have to diffuse in weak electric fields
  - Thicker EPI also means that it is harder to achieve full depletion

EPI $[\mu m]$	Total avail. photocurrent $[pA/\mu m]$	Collecting $[pA/\mu m]$	Off $[pA/\mu m]$	Total collecting + off $[pA/\mu m]$
10	4.4	2.8	1.5	4.3
23	3.3	2.8	0.5	3.3

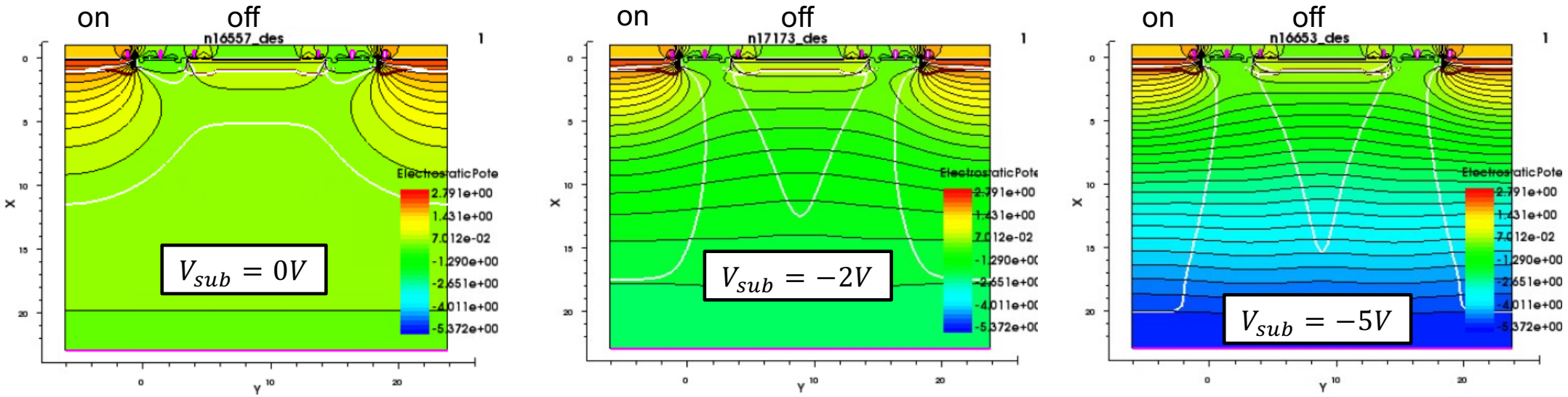
(Photo)currents for $15\mu m$ pitch, $V_{dep} = 1V$, $V_{off} = 0V$



2D TCAD setup – doping profile (colors) and depletion region (white lines)

TCAD – Backside voltage

- Applying a backside biasing voltage to …
  - Extend depletion regions towards the backside, and
  - Increase the electric field strength such that electrons are not diffusing

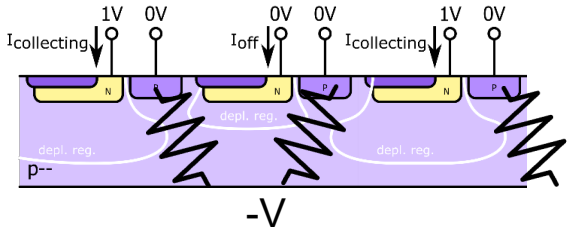


2D TCAD setup for EPI thickness $23\mu m$, $V_{on} = 2V$, $V_{off} = 0V$ – Electrostatic potential (colors and black lines) and depletion region (white lines)

TCAD – Backside voltage

caeleste

- Applying a backside biasing voltage will result in a majority carrier current (hole current)
  - Current flows from pixel substrate to backside surface P+ layer (P+/P--/P+ junctions)
  - It means a significant DC current per pixel



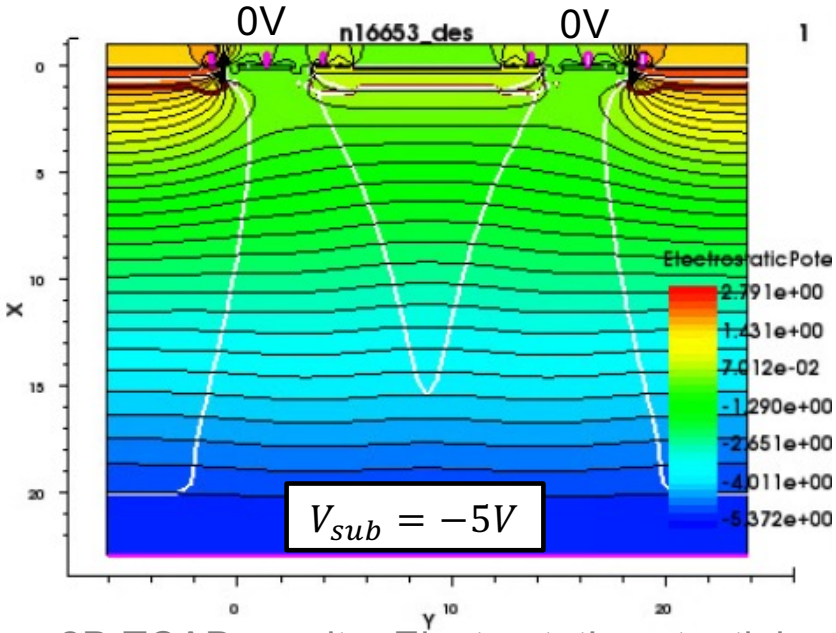
Pitch $[\mu m]$	Total avail. photocurrent $[pA/\mu m]$	Backside voltage $[V]$	Collecting $[pA/\mu m]$	Off $[pA/\mu m]$	Collecting + off $[pA/\mu m]$	Hole current $[nA/\mu m]$
15	3.3	0	5.8	-2.6	3.2	0
15	3.3	-1	2.6	0.7	3.2	2.2
15	3.3	-2	3.4	1.0	4.4	14
15	3.3	-3	2.3	1.1	3.4	36
15	3.3	-5	2.1	1.2	3.3	110

(Photo)currents for $23\mu m$ EPI thickness, different backside voltages, $V_{on} = 2V$, $V_{off} = 0V$

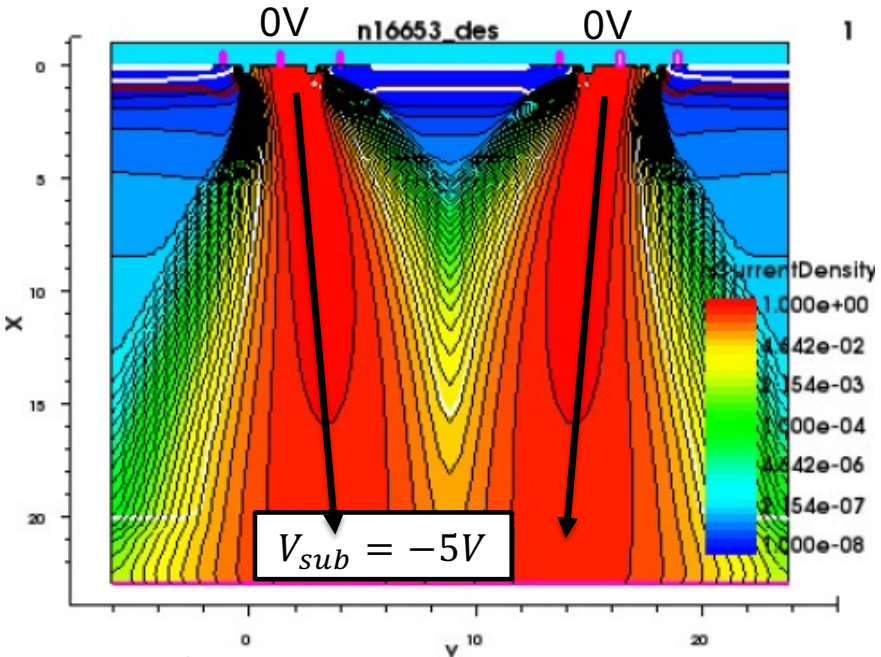
- Curiously, this results in some photo-gain for $V_{backside} = -2V$

Charge binning – TCAD – Backside voltage

- Majority carrier current



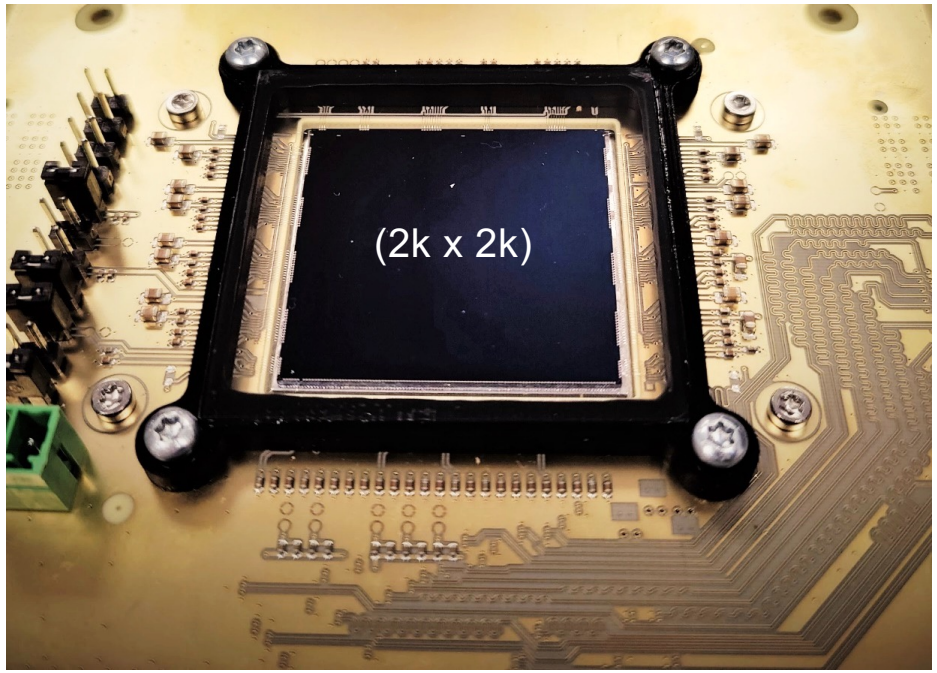
2D TCAD result – Electrostatic potential (colors, black lines) and depletion region (white lines)



2D TCAD result – Hole current density (colors, black lines) and depletion region (white lines)

Project

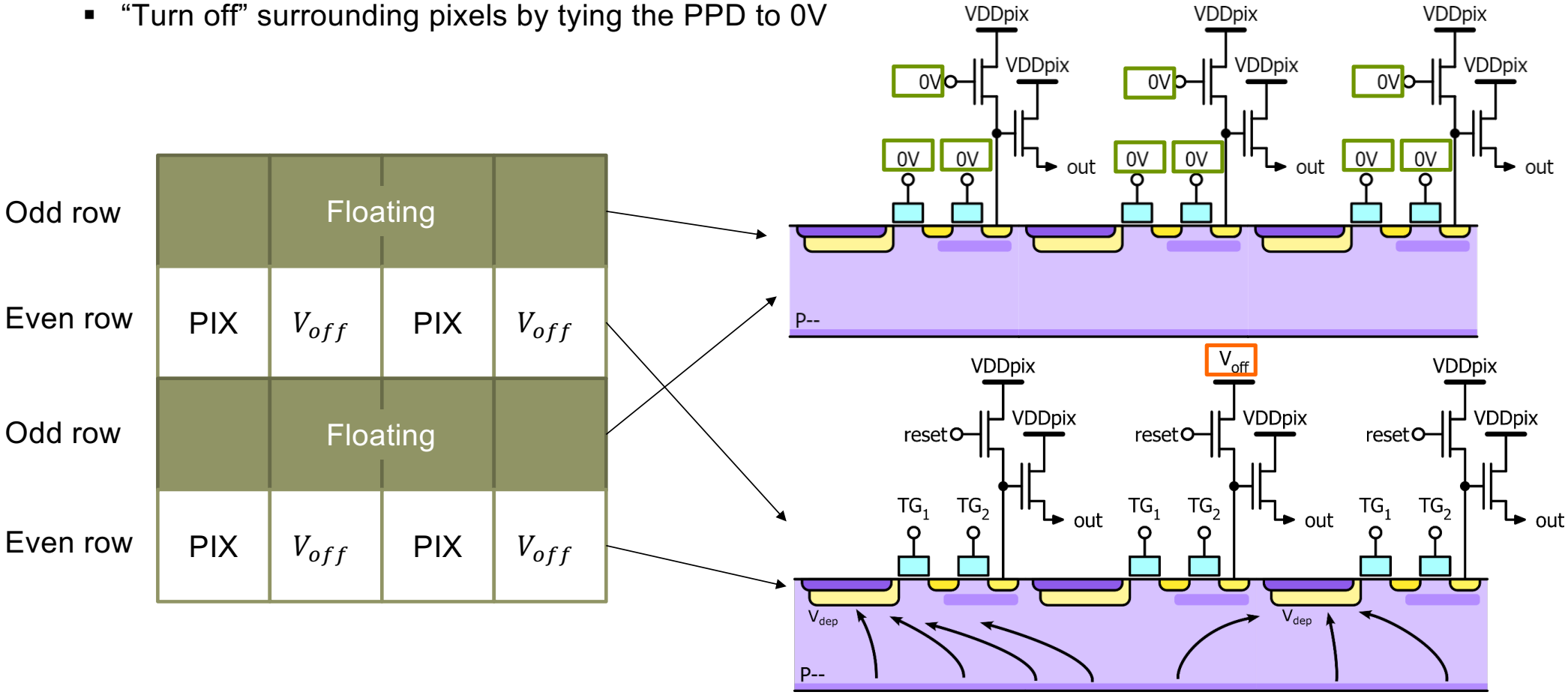
- ELFIS2
  - Backside illumination (BSI)
    - High QE at near-infrared wavelengths
  - TID and SEL/SEU radiation-hard design
  - “True”, Motion-Artifact Free (MAF), High Dynamic Range (HDR)
    - Reads same photogenerated charges on two different conversion capacitances
    - Full dynamic range for single integration time
  - Integrate-While-Read (IWR) Global Shutter (GS) CMOS technology, allowing
    - Low noise readout using Correlated Double Sampling (CDS)
    - Global shutter without dark current penalty
  - Goal:
    - Binning in charge domain



ELFIS2 is the successor of ELFIS
Dierickx & al,"A rad-hard, global shutter, true HDR, backside illuminated image sensor", Space & Scientific CMOS Image Sensors Workshop, Toulouse, 26-27 Nov 2019

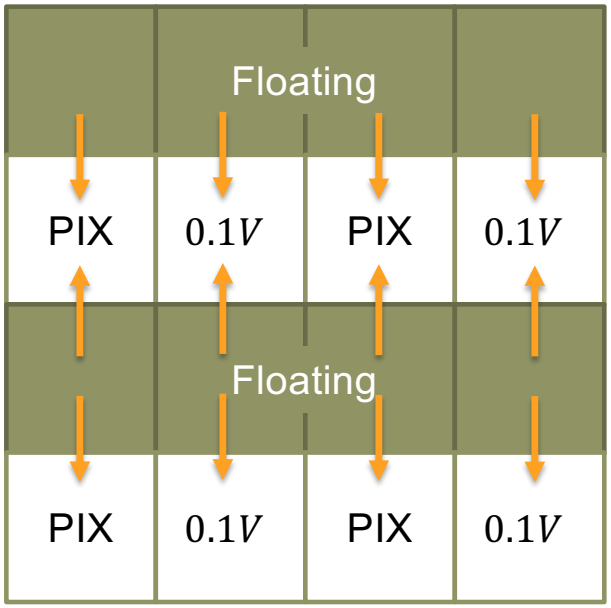
Charge binning implementation

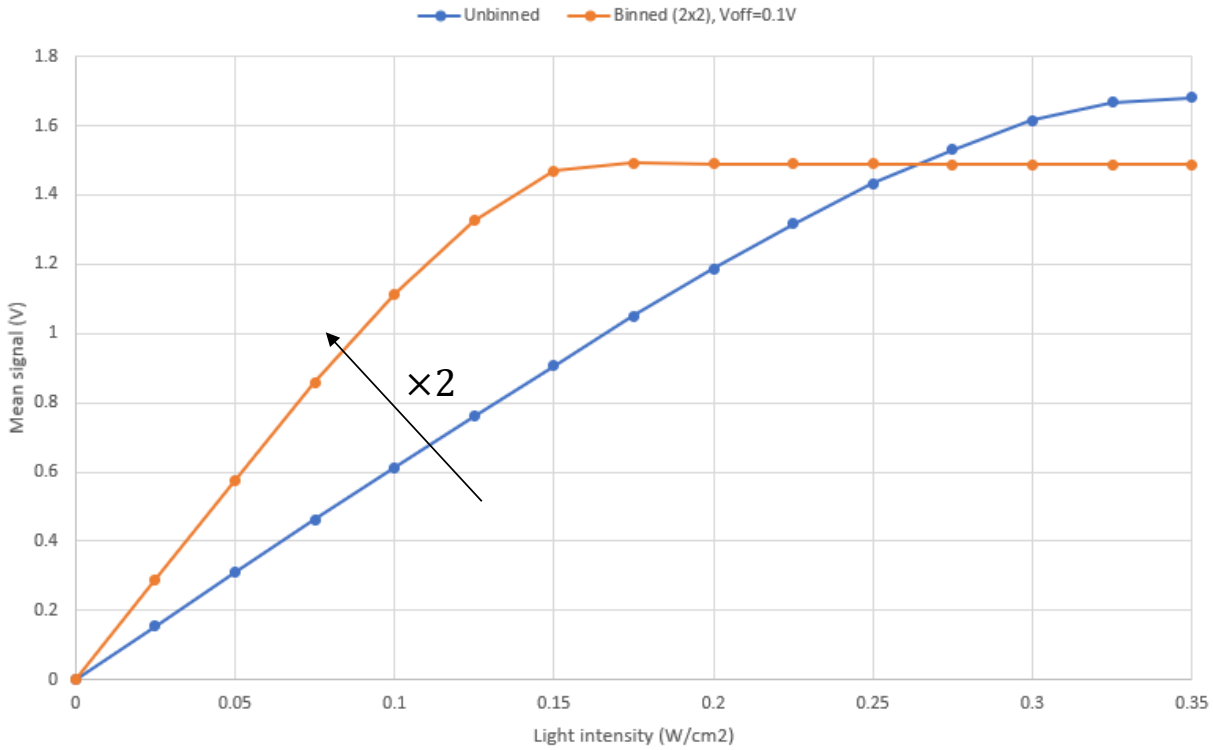
- Charge domain binning gathers all photogenerated charges into a single pixel
  - "Turn off" surrounding pixels by tying the PPD to 0V



Charge binning measurements

- Implemented on ELFIS2
  - Ideal: 4X higher curve
  - Actual: 2X higher response curve
    - $15\mu m$ pitch
    - $22\mu m$ EPI thickness
    - ¼ pixels are fixed at 0.1V
    - $V_{dep} = \sim 0.1V$





Conclusions

- We performed TCAD simulations for enabling charge binning
  - Electric field can be changed applying potentials
    - Applying a backside potential also causes a DC current from PWELL to backside
  - EPI layer thickness and size of the P-WELLs for transistors are critical
  - Leakage current was observed, which can cause an increase in dark current

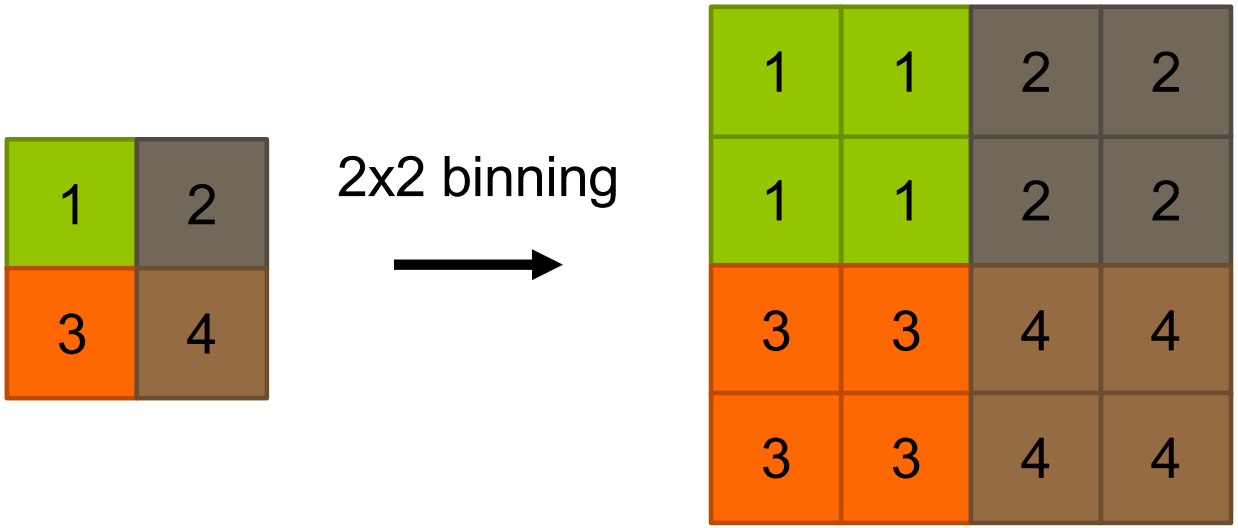
- We have implemented charge binning on ELFIS2
  - A factor 2 gain improvement was achieved
    - The low depletion voltage $V_{dep} \sim 0.1V$ was the main limitation
  - Backside biasing was not possible due to limited conductivity in the backside passivation layers

- Future improvements
  - Avoid low depletion voltages
  - Avoid applying a voltage
    - Disable TG/TG2 for odd columns (not just the rows)
  - Process optimization to be able to have full lateral depletion and low resistivity back side p+ implant.

THANK YOU

HDR operation to charge binning

- HDR allows us to extend the range on the “high signal” side
- What about the “low signal” side?
  - Perhaps we can trade of pixel area for SNR?
  - Binning!



Project ELFIS2

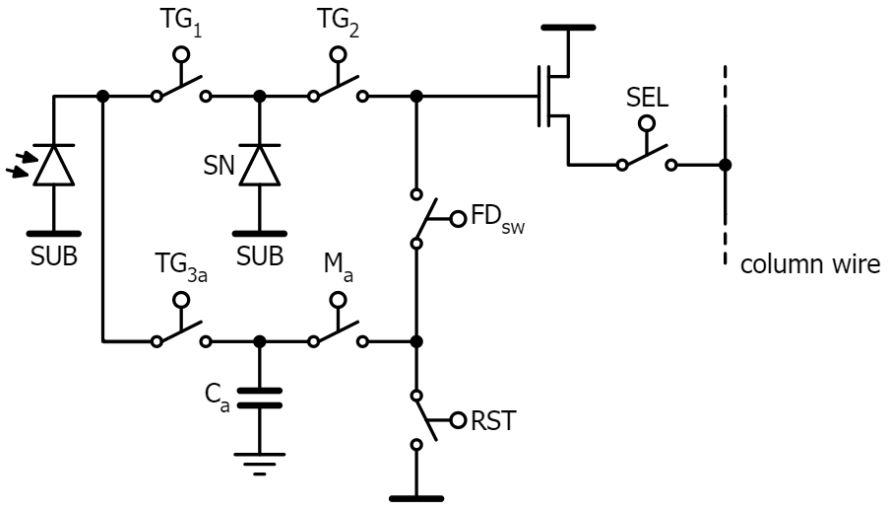
- Specifications (measured)

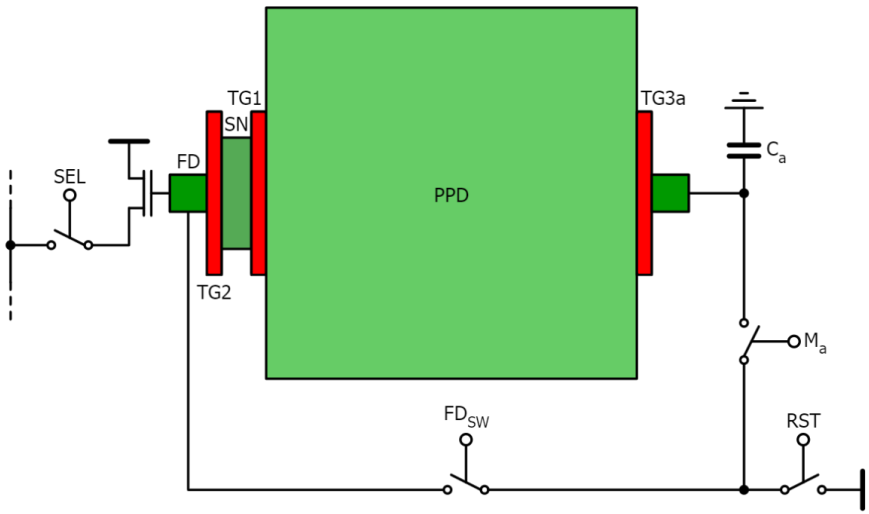
- Other properties
  - Stitched design
  - Region Of Interest in Y-direction
  - Fixed Pattern Noise reduction
  - Voltage domain binning
  - Charge domain binning
  - Low noise mode
  - High-resistive epitaxial layer
  - Back-side illumination
  - Back-bias capability
  - Analog outputs

Specification	Value
Stitch block size	1024 x 512
Possible resolutions	1024 x 512, **2048 x 2048**, 9k x 9k
High-gain full well	$13ke^-$
Low-gain full well, integrate-while-read	$180ke^-$
Low gain full well, integrate-then-read	$360ke^-$
Region of interest in Y	
Read noise (nominal, global shutter)	$3.5e^-_{RMS}$
EPI thickness	$6.5\mu m$, $\mathbf{12\mu m}$, $\mathbf{22\mu m}$
Quantum efficiency ($22\mu m$ EPI)	~80%@400nm, ~85%@540-700nm, ~30%@1000nm
MTF ($12\mu m$ EPI)	0.52
PLS	1/4000@630nm, 1/600@830nm
Image lag	<0.5%
PPD dark current	$< 500e^-/s$
Output channels (2k x 2k)	16
Nominal channel rate	40MHz
Frame rate (2k x 2k)	150fps

ELFIS2 operation

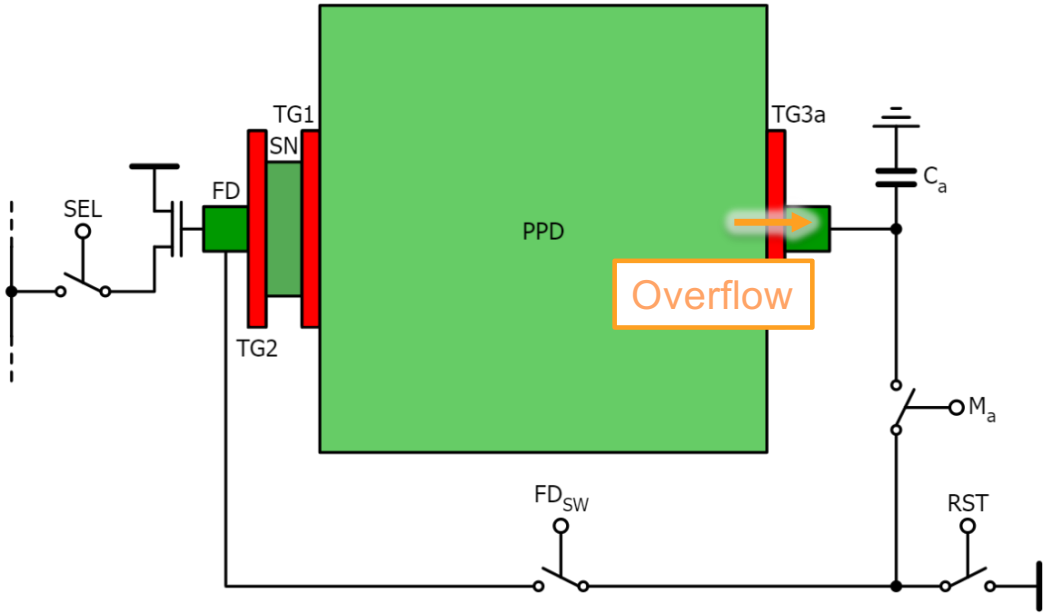
- During integration
  - Charges overflow from PPD to C_a through TG_{3a}
- Global operation
  - PPD to SN through TG_1
  - PPD to C_a through TG_{3a} to transfer remaining charges
- Readout
  - High-gain: SN to FD through TG_2
  - Low-gain: Averaging of FD and C_a





HDR operation

- During integration
  - Excess of charges can overflow from PPD to the extra capacitor C_a
    - Apply a voltage to TG3a to control for how much photogenerated charge the overflow starts to happen



HDR operation

- During readout
  - Step 1: transfer all the remaining charges from PPD to the storage node SN.
  - Step 2: after reading the reset, transfer those charges from SN to the floating diffusion FD.
  - Step 3: after reading the signal, short the switches to read the voltage on C_a.