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Design and measurement of a large CMOS pixel with nanosecond collection time

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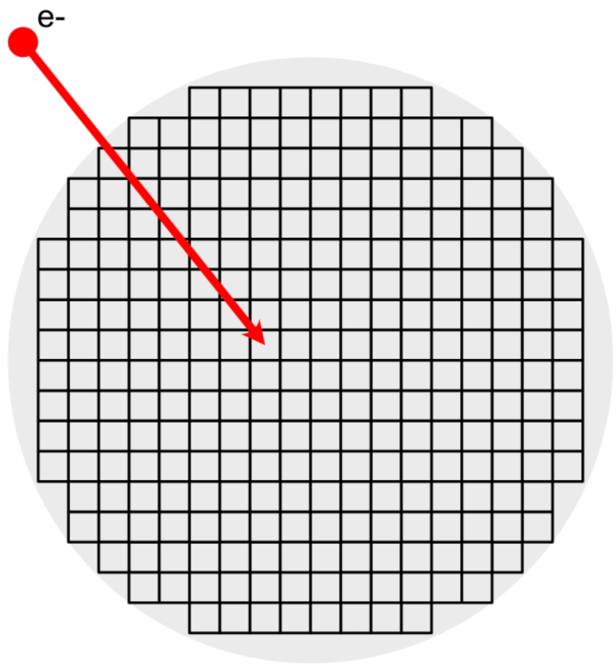
Application

- Target?
  - **Particle counting**
    - High repetition rate possible (avoid non-detection of subsequent events)
    - Should also work at low flux ($< 10e^{-}/ns$) of **incident electrons** (IE)
    - Low noise / high SNR, with underlying purpose:
      $\leftarrow$ Low False Positive (FP) rate
      $\leftarrow$ Low False Negative (FN) rate
    - Large total area of detector, subdivided in parallel operating “pixels”
    - Low energy (ke^{-}) of IEs
- We explore multiple options:
  - PIN (p – intrinsic – n diodes, direct detection)
  - APD (Avalanche Photodiodes, LGAP)
  - SPAD (Single-Photon Avalanche Diodes, Geiger mode APD)
  - Scintillators + visible light sensing.



PIN diode for particle counting

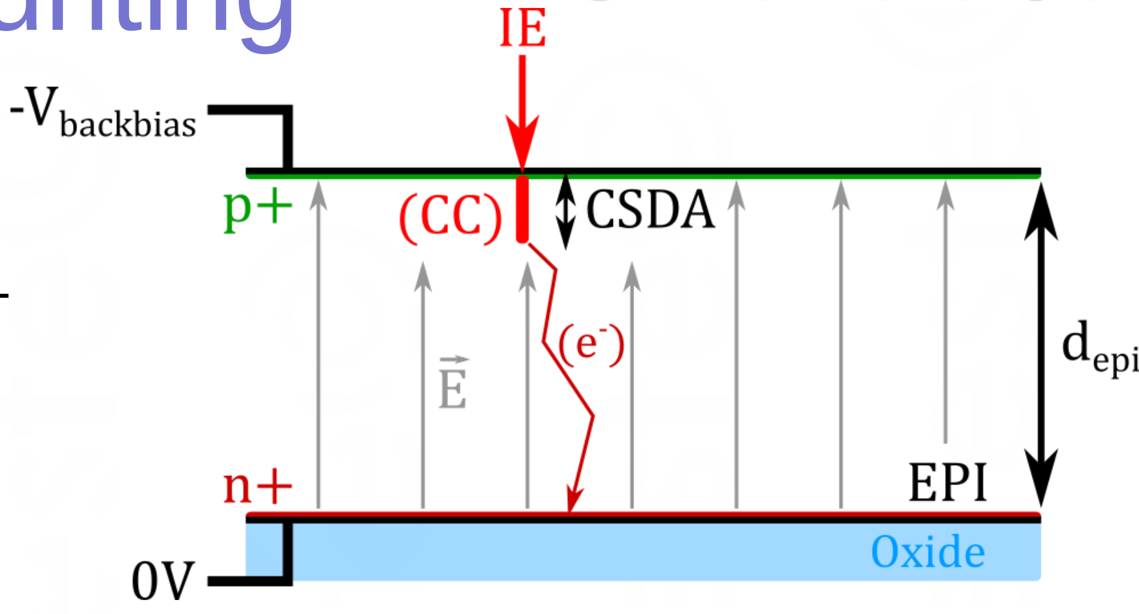
The straightforward solution: PIN

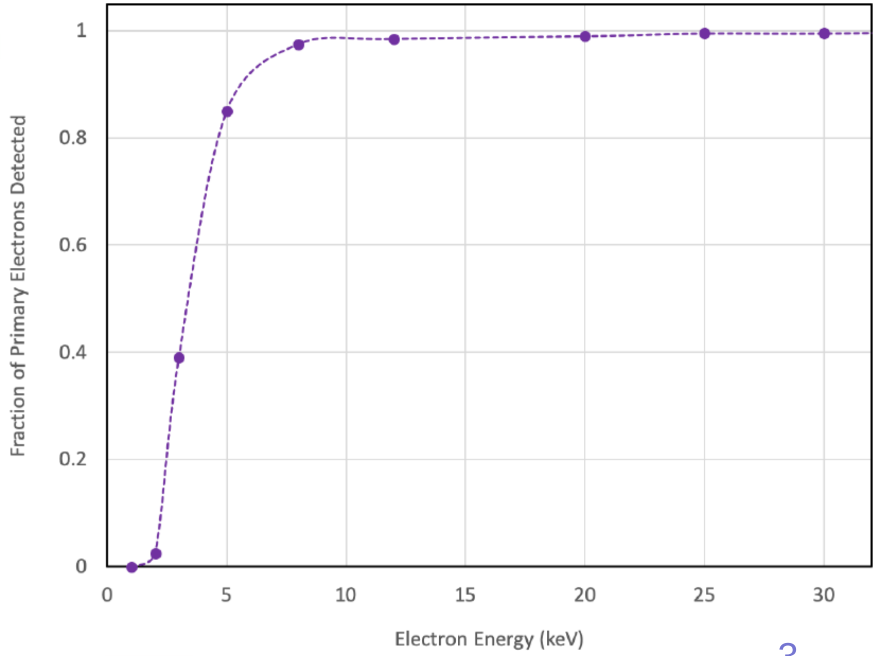
- For $\sim ke^{-}$, Backside illumination is required
- One IE will generate a **charge cloud (CC)** of electron-hole pairs
- **CSDA**: Continuous Slowing Down Approximation
- There are two important metrics here
  - τ_{tr}, the transit time (collection time), $\approx \dfrac{d_{epi}}{\mu_e|\vec{E}|}$

$$I_{photo}(j\omega) \sim \frac{1-e^{j\omega\tau_r}}{j\omega\tau_r} \Rightarrow f_{-3dB} \approx \frac{2.4}{2\pi\cdot\tau_{tr}} \qquad [1]$$

  - The junction capacitance
    - Determines input capacitance C_{in}

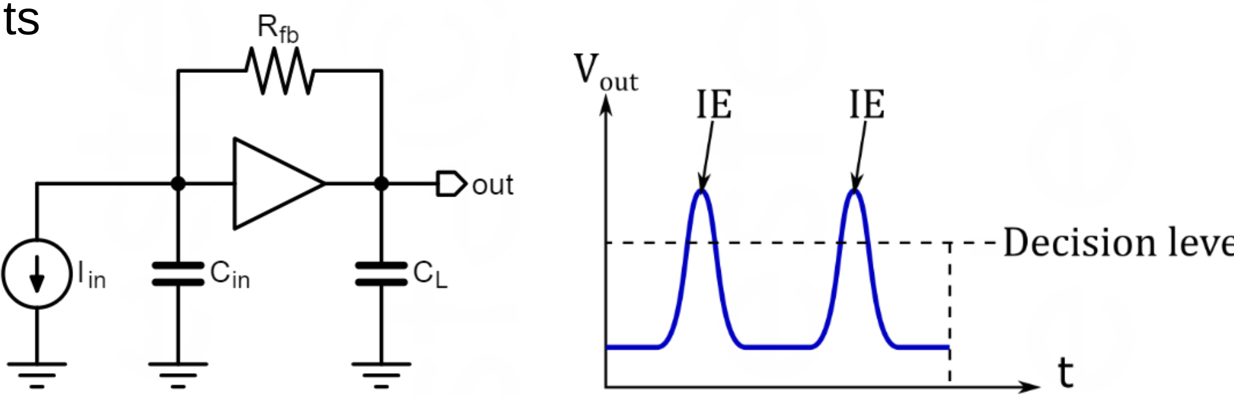
$$C_j \approx \epsilon_{Si}\frac{A_{pix}}{d_{epi}}$$

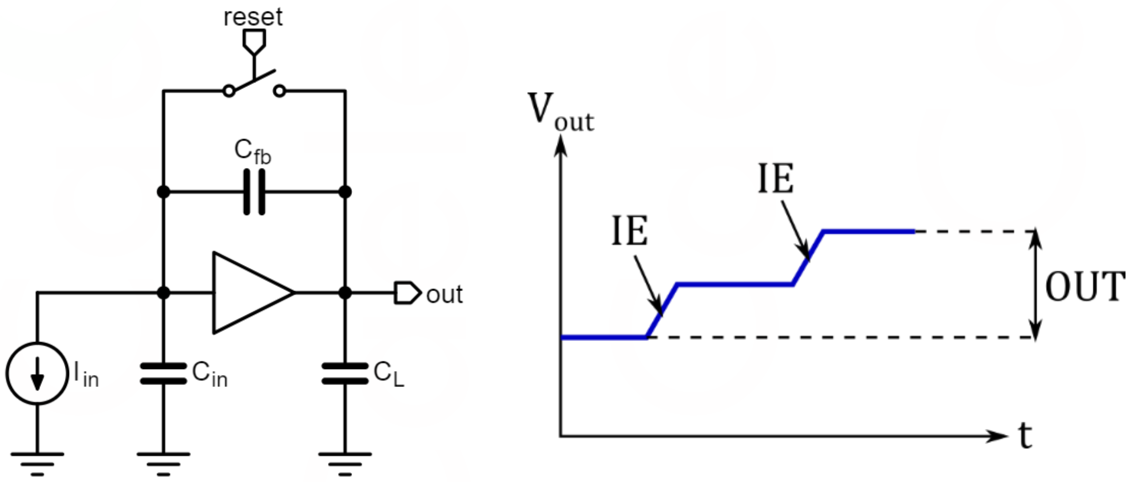




PIN diode for particle counting

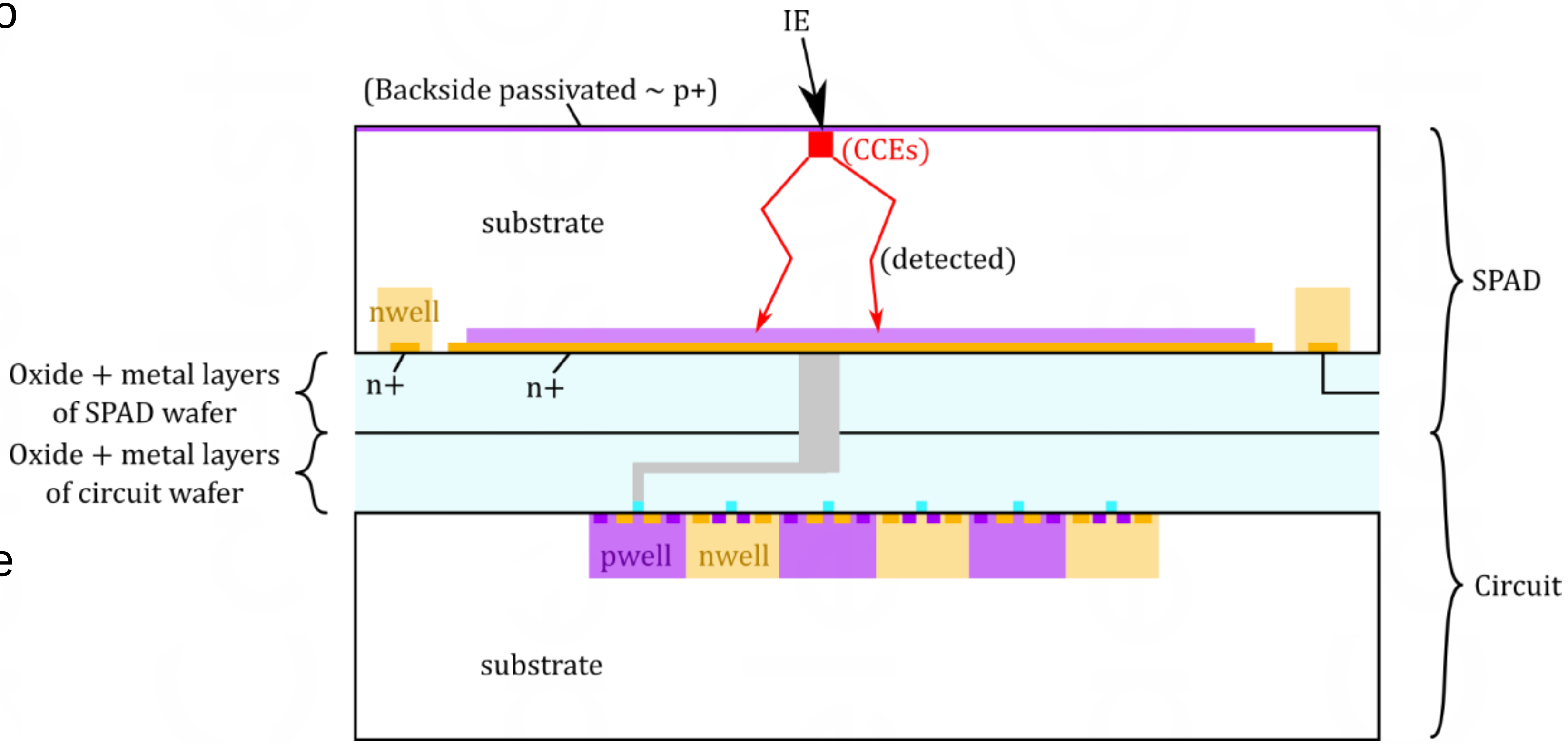
- Which readout methods do we pursue?
  - **Continuous** readout
    - Bandwidth determines how quickly successive events can still be distinguished (← “dead” time)
    - Typically, an RTIA (R-feedback Transimpedance Amplifier)
      - Transit time τ_{tr} also affects pulse amplitudes!
    - Read noise performance affected by
      - White noise: R_{fb}, C_{in}, P
      - Flicker noise: C_{in}, size
  - **Integrated/sampled** readout
    - Need to reset sometimes (= “dead” time)
    - Typically, a CTIA (Charge Transimpedance Amplifier)
      - Transit time τ_{tr} affects slope, not step height!
    - Read noise performance affected by
      - White noise: C_{in}, P
      - Flicker noise: C_{in}, size





APDs for particle counting

- Pixel is similar to a SPAD; the analog readout circuit is similar to a PIN diode readout
- **Pro**
    - Circuit solutions identical to those of PIN diodes
    - The in-device gain reduces false negatives a lot
- **Con**
    - Sensitive to Process/Voltage/Temperature (PVT) variations, not trivial to scale up, yield sensitive
    - Guard ring structures can take up significant space (fill factor, increasing FN)



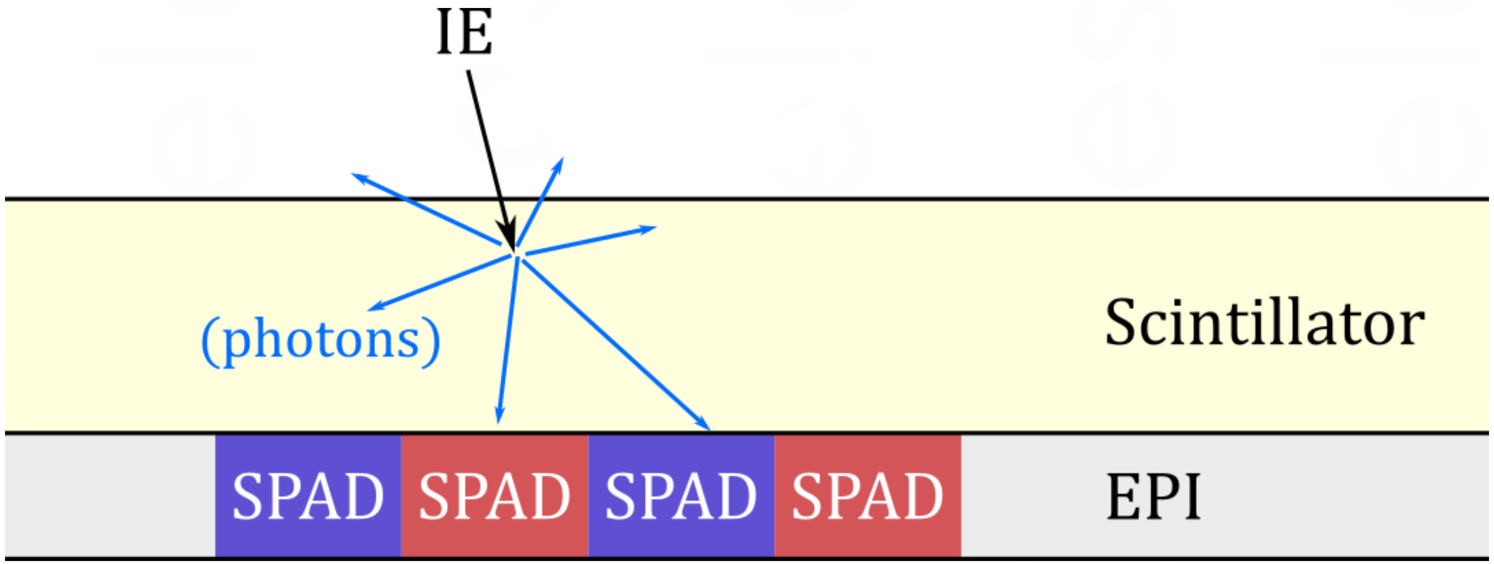
SPADs for particle counting

Need dedicated “quench-reset” readout circuit

- **Pro**
  - SPADs offer a very sharp timing resolution
- **Con**
  - *Quenching* a SPAD means “dead” time
    - Longer “dead” time means higher false negative rate
    - Longer quenching is often required to reduce afterpulsing
  - Quest for *small pixels*
    - This means: many pixels (impacting yield and power)
    - Peak currents scale with area
    - Higher avalanche currents lead to more crosstalk
    - Larger area pixels need *longer quench times*
    - *Guard ring structures* take up significant space (fill factor, charge sharing, increasing FN)
  - Sensitive to *PVT variation*, not trivial to scale up (yield)

Scintillators for particle counting

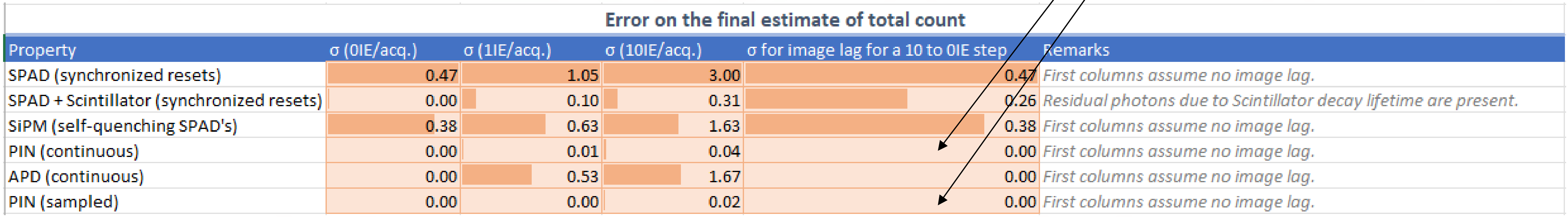
- **Pro**
  - Mature technology, shifts the “electron detection” challenge to “light detection”
- **Con**
  - Hard to find scintillators with short decay **and** low $eV/photon$
    - Hence the combination with SPADs → One photon should be enough to detect an event
  - Secondary photons can be spread over multiple pixels
    - Complication avoiding double counts by correlated events in neighboring pixels



Comparison

- We did a comparing study of the techniques in the previous slides with first order approximations
  - $\tau_{acq} = 5ns$
  - $E_{IE} \approx 10ke^{-}$
  - Rate approx. $10e^{-}/5ns$
  - Scintillator: $LaBr_3{:}Ce\ (mono)$, $16eV/phot$, $\tau_{Sci} \approx 16ns$ [2]
  - Circular detector, $\phi_{detector} = 10mm$
  - $180nm$ technology parameters (average over multiple foundries), simplified analog circuits
  - SPAD: $FF \approx 80\%$, $DCR \approx 0.3cps/\mu m^2$, $AP \approx 0.1\%$
  - APD: $FF \approx 80\%$
  - PIN: $d_{epi} \approx 10\mu m$
  - Power max 4W for readout

Appear to be the most practical choice

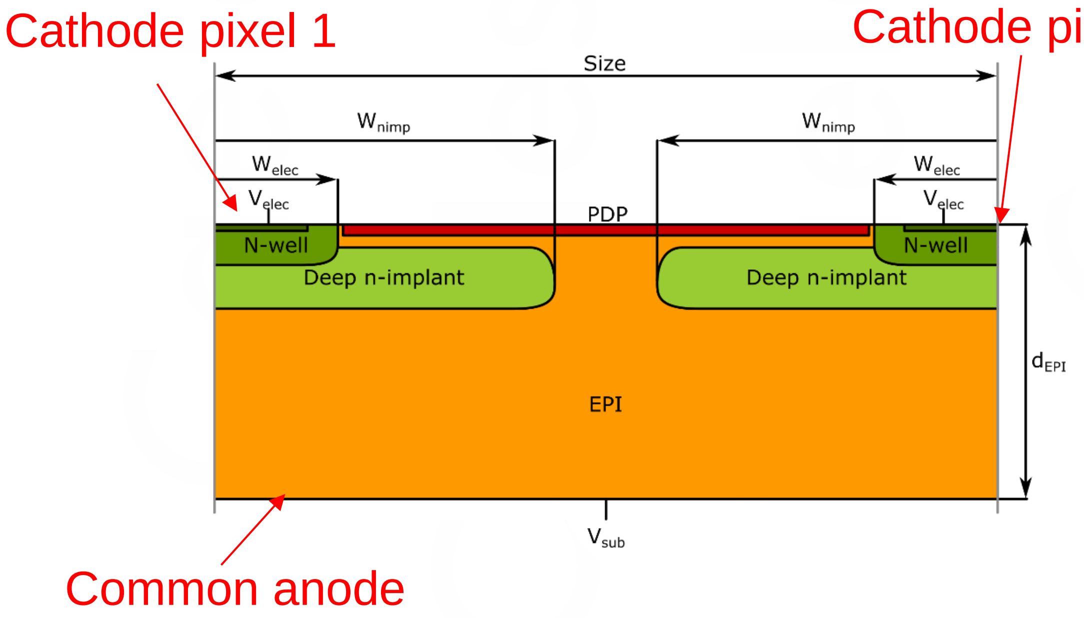


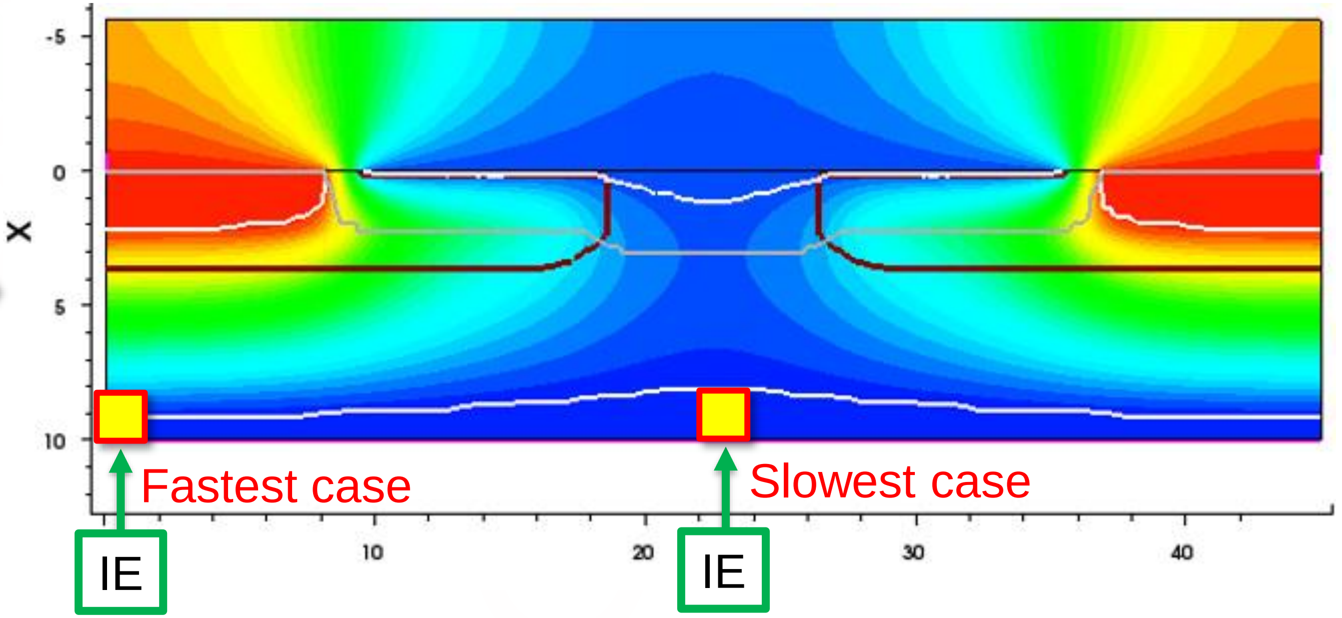
Error on the final estimate of total count

Property	σ (0IE/acq.)	σ (1IE/acq.)	σ (10IE/acq.)	σ for image lag for a 10 to 0IE step	Remarks
SPAD (synchronized resets)	0.47	1.05	3.00	0.47	*First columns assume no image lag.*
SPAD + Scintillator (synchronized resets)	0.00	0.10	0.31	0.26	*Residual photons due to Scintillator decay lifetime are present.*
SiPM (self-quenching SPAD's)	0.38	0.63	1.63	0.38	*First columns assume no image lag.*
PIN (continuous)	0.00	0.01	0.04	0.00	*First columns assume no image lag.*
APD (continuous)	0.00	0.53	1.67	0.00	*First columns assume no image lag.*
PIN (sampled)	0.00	0.00	0.02	0.00	*First columns assume no image lag.*

PIN pixel

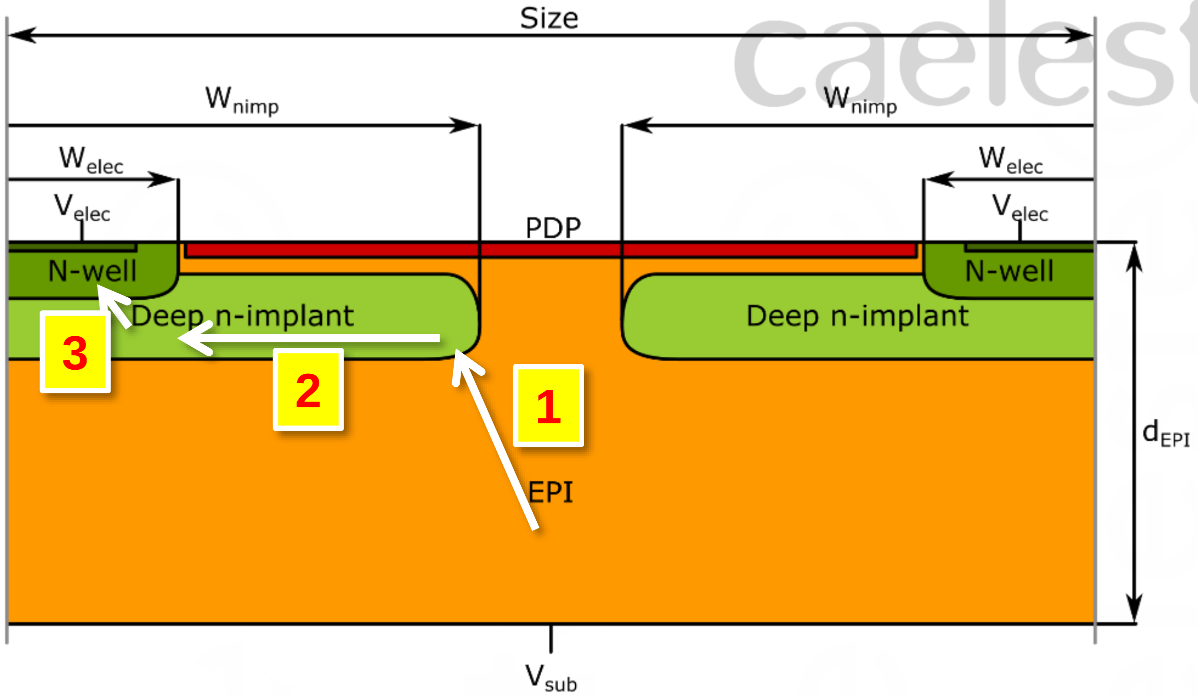
- For the pixel, we wish to have
  - The **largest** possible pixel (for total power consumption)
  - A **low junction capacitance** C_j (for noise)
  - A **short transit time** $\tau_{tr} \sim ns$
- For that, extra TCAD efforts were made (in collaboration with Etesian)
  - To avoid any badly defined behavior near the surface, we use a pinning layer
  - To improve τ_{tr} and deplete the substrate, we need to apply a voltage to the backside

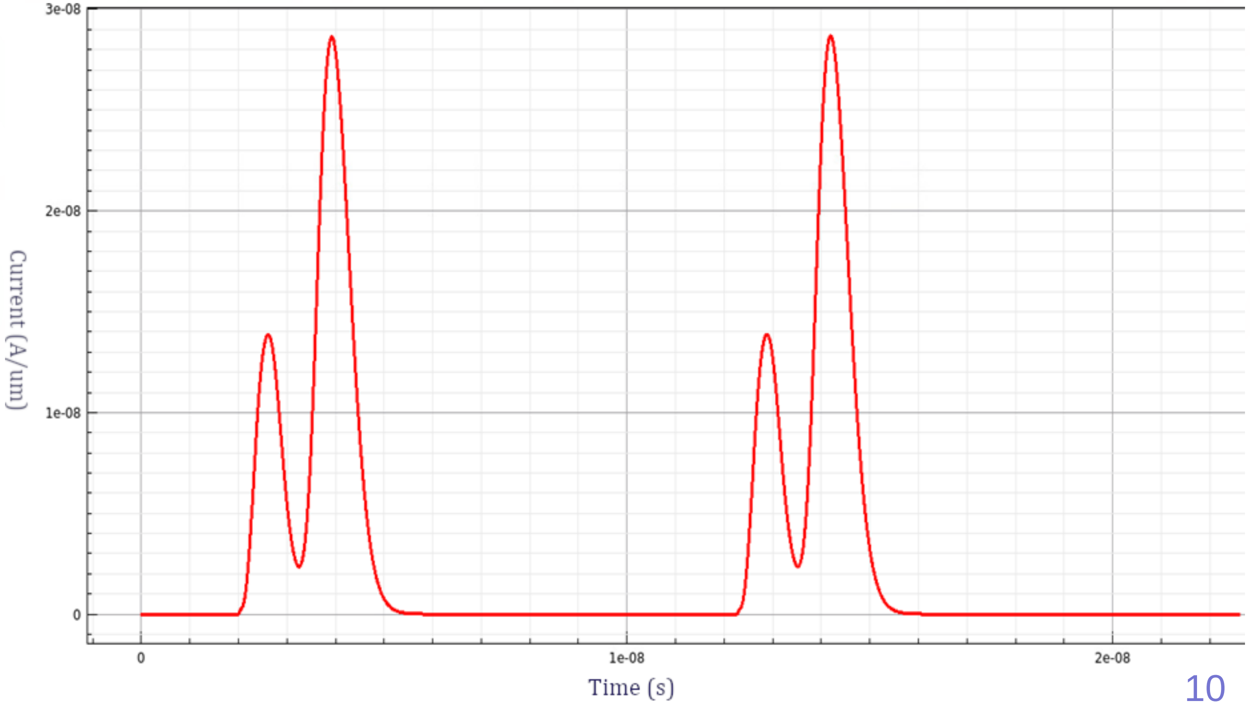




PIN pixel

- Worst case τ_{tr} happens when the IE lands near the edge of the pixel
  - We observe in TCAD simulation “double peaking”
  - Working hypothesis:
    - 3 “phases” of the charge cloud
    - 1) Fast drift from backside to deep N
    - 2) Slower drift/diffusion along deep N
    - 3) Fast drift from deep N to N-well/cathode

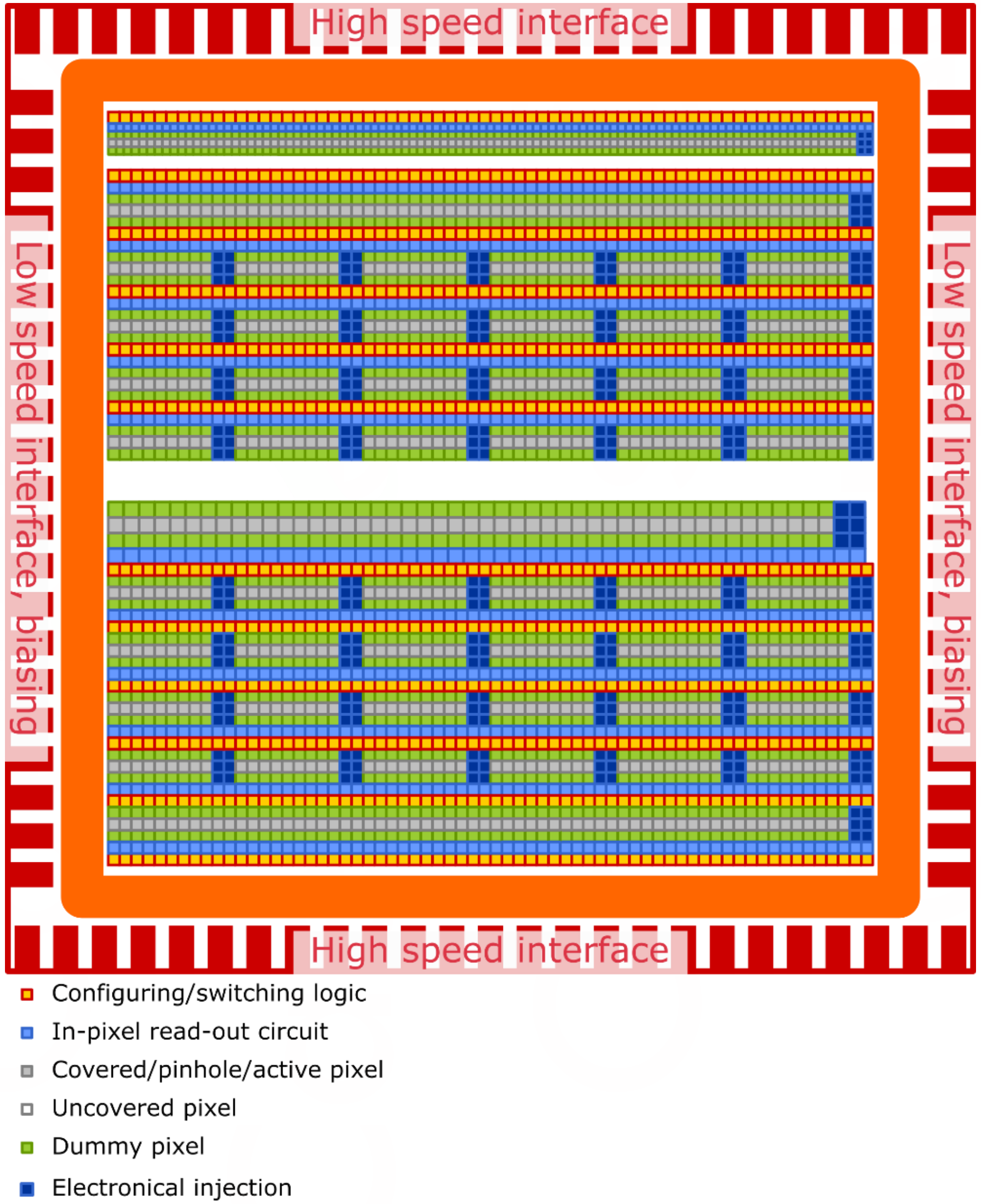




Measurements

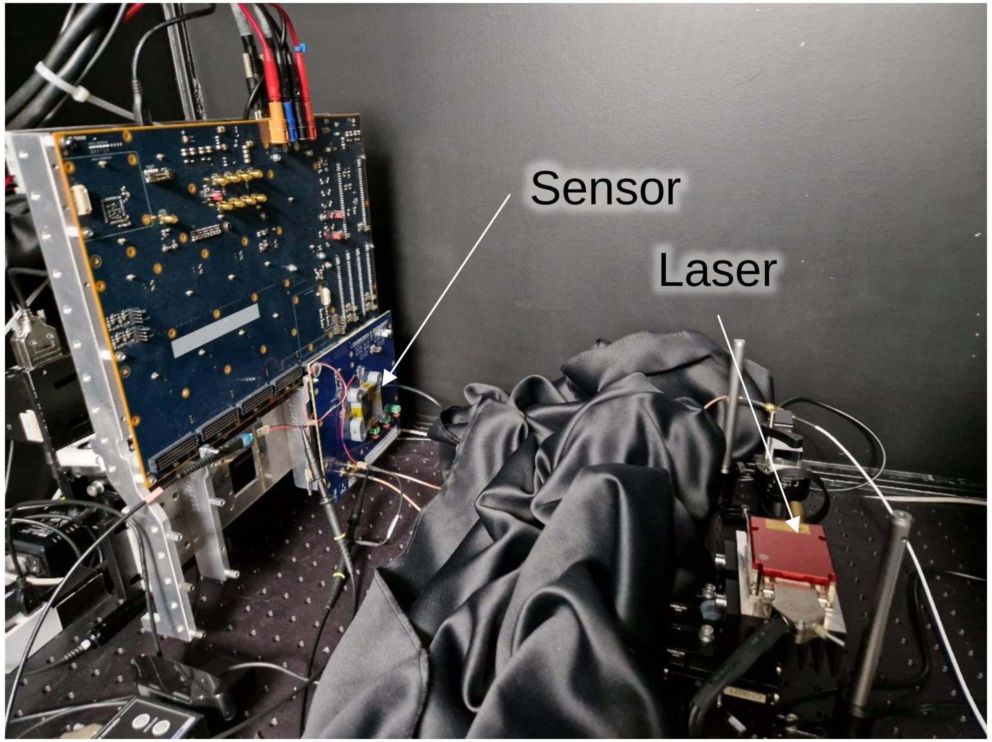
- A test chip was made to verify results
  - Backside illuminated
  - ~45 variants
    - Focus on CTIA-based PIN variants
    - Some RTIA-based variants also available
    - Fast RTIAs dedicated to measurement of photocurrent

- Supported measurements
  - Equivalent Time Sampling
  - Digital readout method for FP and FN



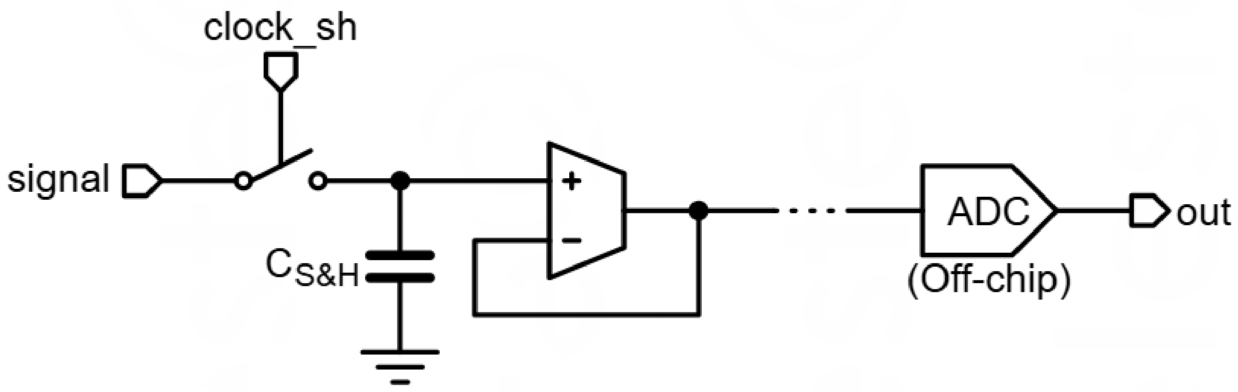
Measurements

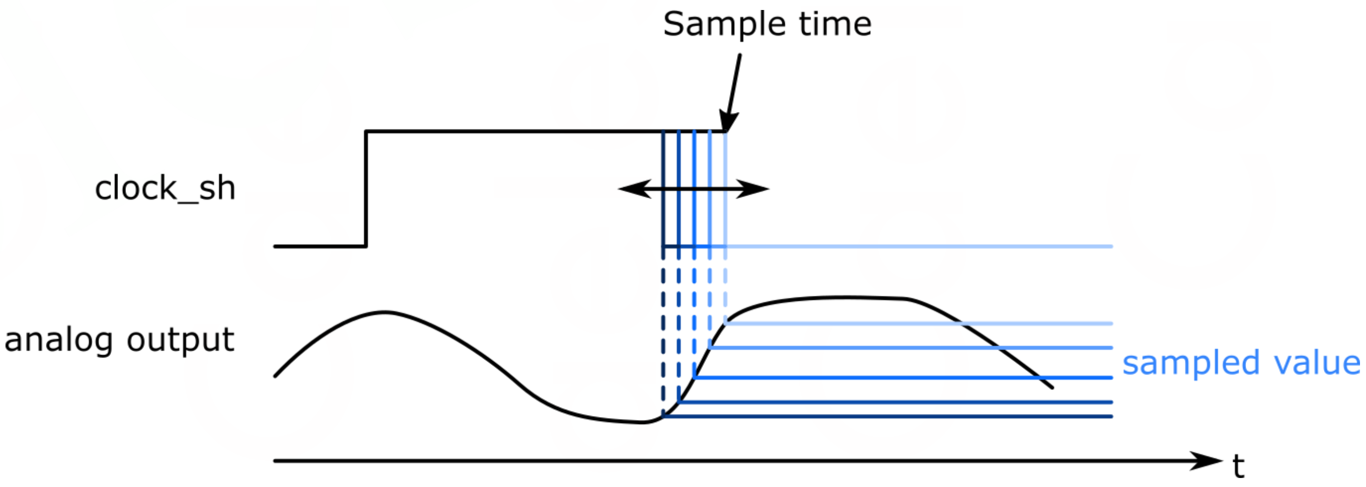
- Emulating an **incident electron** (IE)
  - Use a laser
    - Laser pulse width should be negligible compared to τ_{tr}
    - Emulating the small charge cloud
      - Laser spot should be focused
        - → Maybe possible with optics, but likely not easy
        - → We attempt to use pinholes in a backside metal
      - Wavelength should be chosen to have a similar penetration depth as CSDA of an IE
      - Optical power should be attenuated such that the same number of electrons are generated inside the silicon
    - Emulating noise
      - A real IE-caused charge cloud will exhibit Fano noise which is typically smaller than photon shot noise!



Measurements

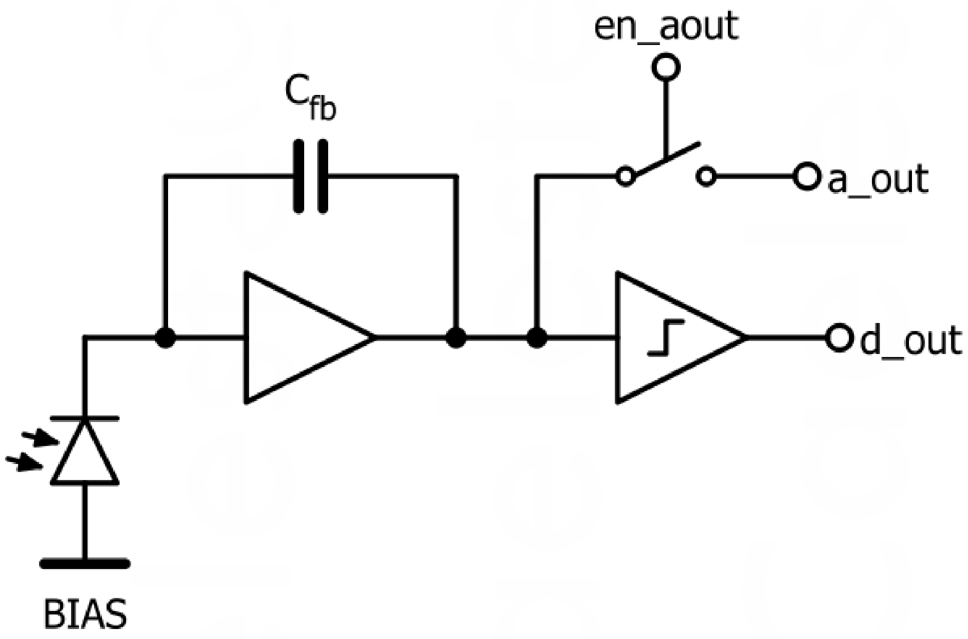
- Support for **analog measurements**
  - Measuring high bandwidths on-chip is not straightforward
    - Measurement circuitry will always “distort” due to parasitic capacitances
  - **Equivalent Time Sampling** [3]
    - Open the S&H switch with low jitter at a point t_{sh}, measure slowly after
    - Use minimum $C_{S\&H}$, and very small buffer to minimize added capacitance
      - Large kTC noise, so might want average over multiple identical experiments
    - Slightly shift t_{sh} and repeat the experiment
    - You can then reconstruct the waveform





Measurements

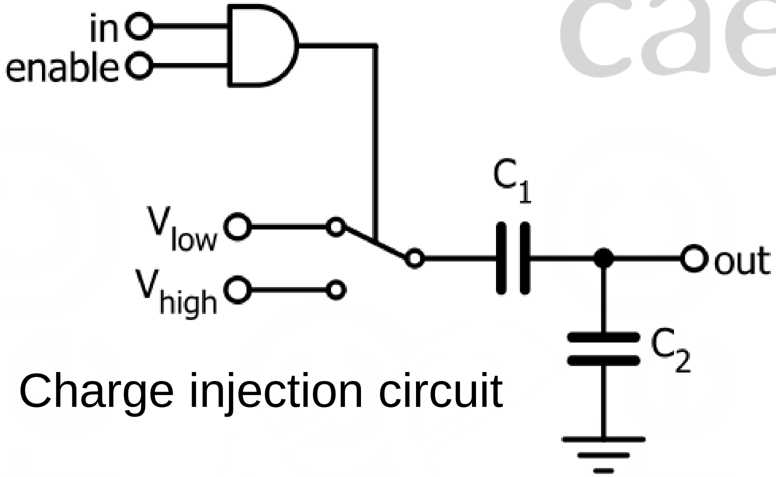
- Support for **digital measurements**
  - Measuring of false positives and false negatives using laser pulses
    - FN: Apply/inject pulses and find out whether an event was detected
      - Assess mismatch variation
    - FP: Dark current will always cause a trigger with CTIA-based variants if you wait long enough!
    - Should be able to reconstruct a probability density function
  - Laser shot noise vs. Fano noise
    - We will measure a worse case, but can be modeled
    - Or use actual particles…



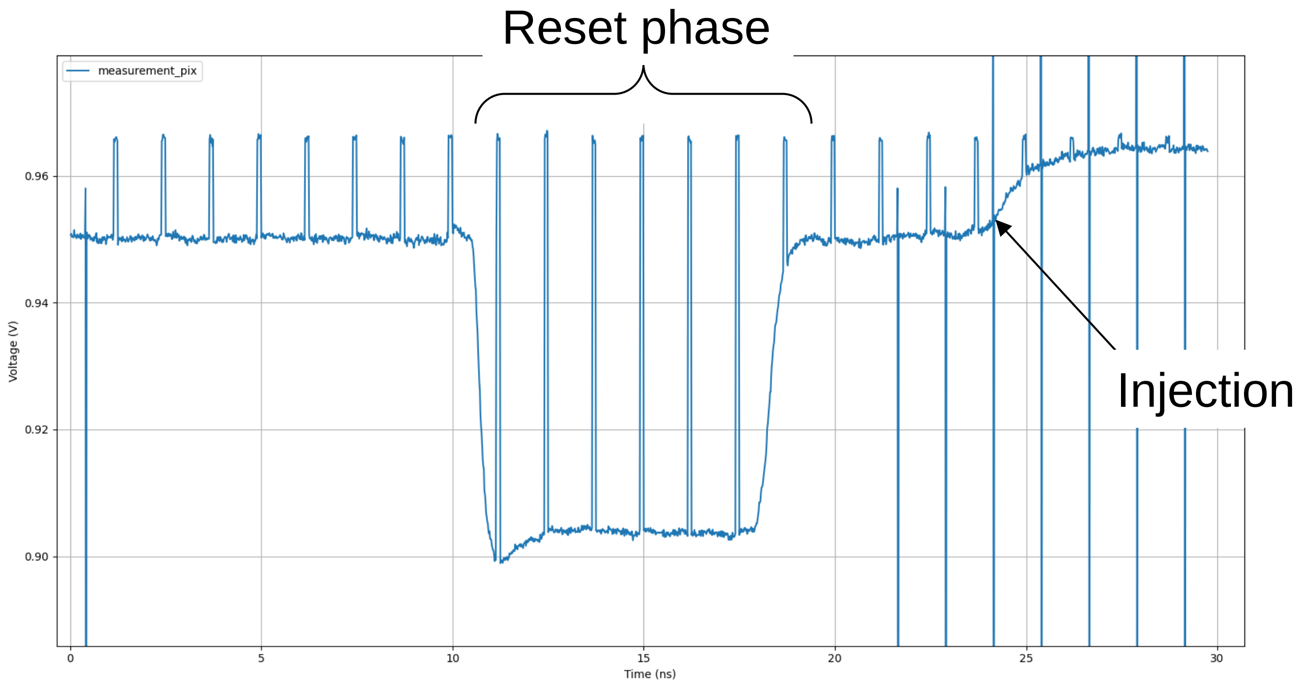
Measurements

- Example result
  - No pixel yet, instead we use capacitive **charge injection**
    - CTIA example variant
    - $Q_{injected} \approx 7.5ke^{-}$
    - $P \approx 180uW$
    - Spikes are caused by external clock edges
    - Time resolution $\sim 150ps$

- No measurement yet with laser pulses
- No FP/FN measurement yet (also with laser pulses)



Charge injection circuit



Reset phase

Injection

Voltage (V)

Time (ns)

References

- [1] Wolfgang W. Gärtner. “Depletion-Layer Photoeffects in Semiconductors.” *Physical Review*, 116(1):84–87, October 1959.
- [2] E. V. D. van Loef, P. Dorenbos, C. W. E. van Eijk, K. W. Kramer and H. U. Gudel. "Scintillation properties of LaBr3 : Ce3+ crystals: fast, efficient and high-energy-resolution scintillators. Nuclear Instruments & Methods in Physics Research Section A-Accelerators Spectrometers Detectors and Associated Equipment", 486:254-258, 2002.
- [3] K. Rush, D. J. Oldfield “A Data Acquisition System for 1-GHz Digitizing Oscilloscope,” Hewlett-Packard Journal, vol. 37, No. 4, pp. 4- 11, April 1986.

Thank you