

Floating Transfer Gate-based CMOS pixel reaching $0.19 \text{ e}^-_{\text{rms}}$ noise

PRAYAG WAKALE^{1,2}, AJIT KUMAR KALGI¹, BART DIERICKX¹, FILIP TAVERNIER²

PIXEL 2026, MIYAZAKI JAPAN

¹ CAELESTE, MECHELEN, BELGIUM

² MICAS, KU LEUVEN, BELGIUM

Outline

1. Motivation for sub-electron noise levels
2. Sub-electron noise in CMOS image sensors
3. The Floating Transfer Gate (FTG) pixel topology
4. FTG Pixel operation
5. Photoresponse and noise measurement results

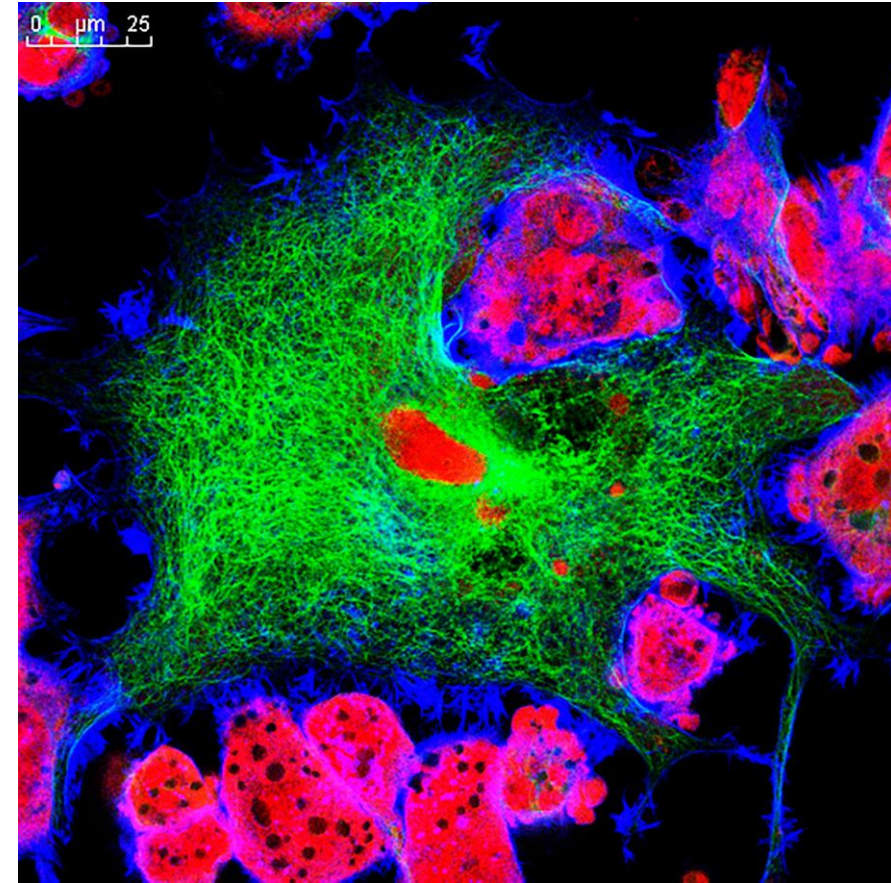


Motivation for sub-electron noise levels

Sub-electron read noise is mandatory for photon starved applications.

Example applications

- **Life science and fluorescence imaging** requires extremely low illumination to avoid phototoxicity and photobleaching
- **Astronomy and (deep) space surveillance** need single photon capturing over long exposure times (seconds – hours)
- **Trapped ion quantum computing** reads qubit states by observing if an ion emits a few fluorescent photons when excited by a laser.
- **High-end spectroscopy** requires imaging inherently weak signal like inelastic scattering of light in Raman spectroscopy.



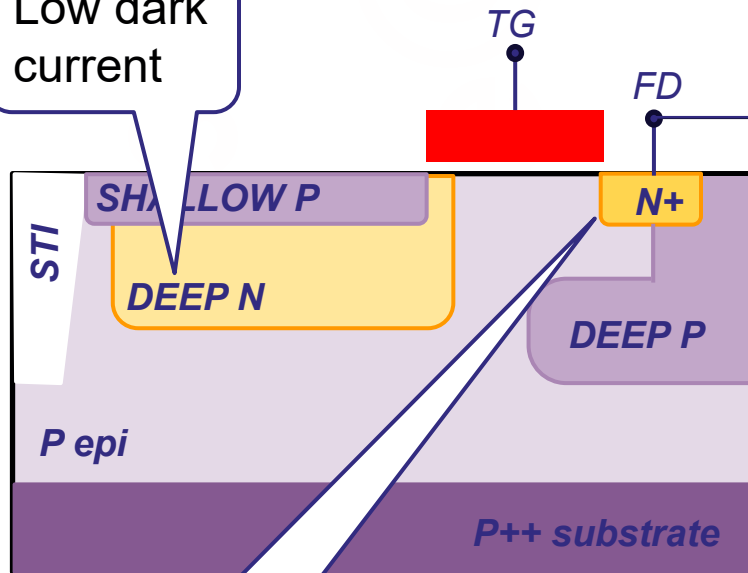
Low-light fluorescence microscopy. Source: vshivkova / Getty Images

Sub-electron noise in CMOS image sensors

Classic CMOS 4T pixel

Technology & Temperature

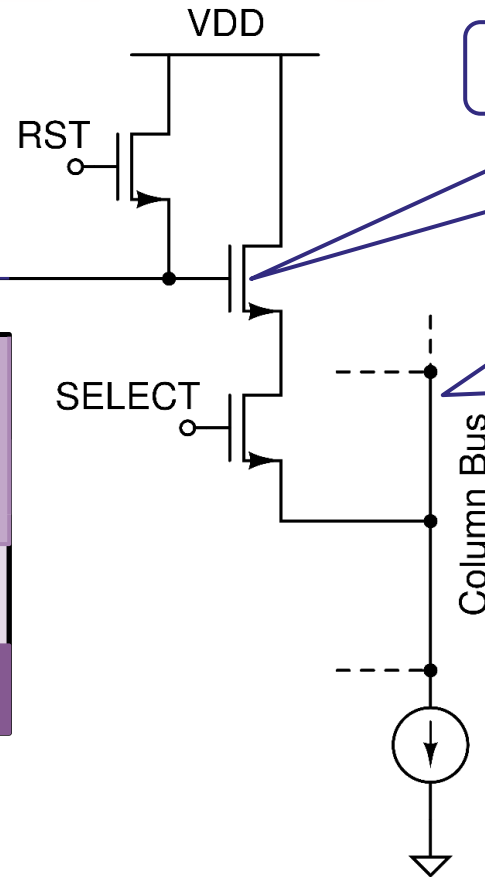
Low dark current



Low FD node capacitance

Design & Technology

CDS – Correlated Double Sampling
CMS – Correlated Multiple Sampling
FD – Floating Diffusion



Low noise and High gain transistor

Technology & Design

At column level:

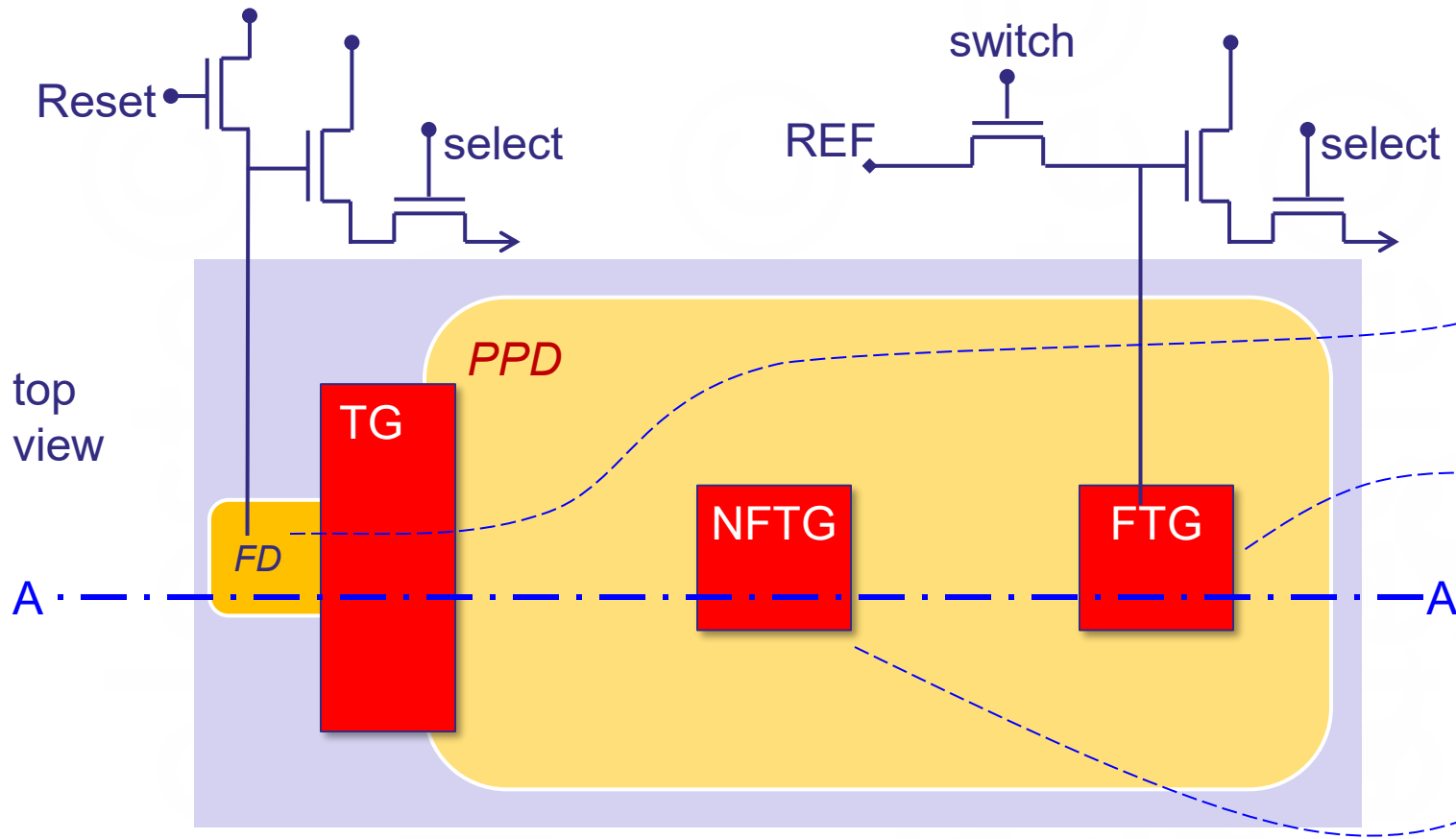
- CDS to cancel reset noise
- CMS to reduce flicker and thermal noise
- Low noise amplifier

The classic 4T pixel topology hits a noise floor, $0.5 \dots 1 e^-_{rms}$, limited by MOSFET $1/f$ noise.

How can we achieve noise level lower than this noise floor?

We propose the FTG pixel topology to break this noise floor→

FTG Pixel Topology

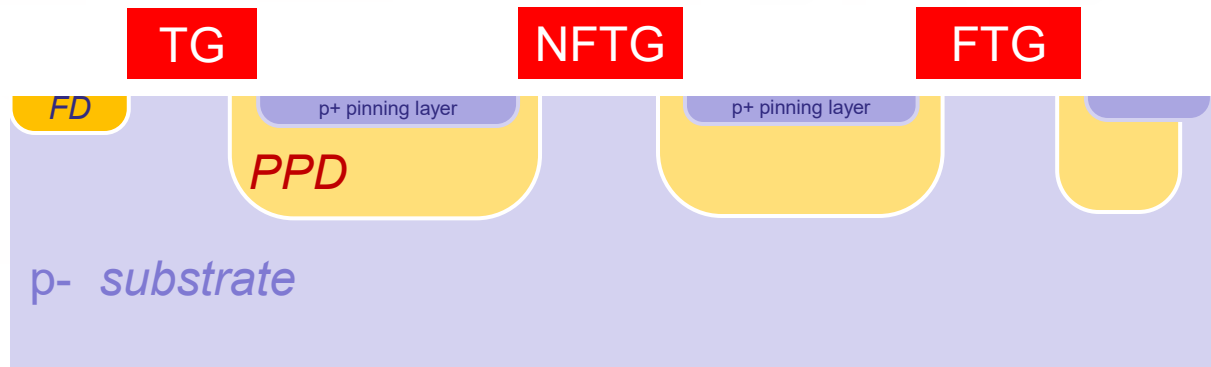


At the left side of this pixel:
“classic” floating diffusion (FD)
readout of a pinned photodiode (PPD)
over a transfer gate (TG).

At the right side a Floating Transfer Gate (FTG), with the circuit to apply a reference voltage (REF) via a switch. The charge under the FTG is sensed by a source follower.

In the middle a non-floating transfer gate

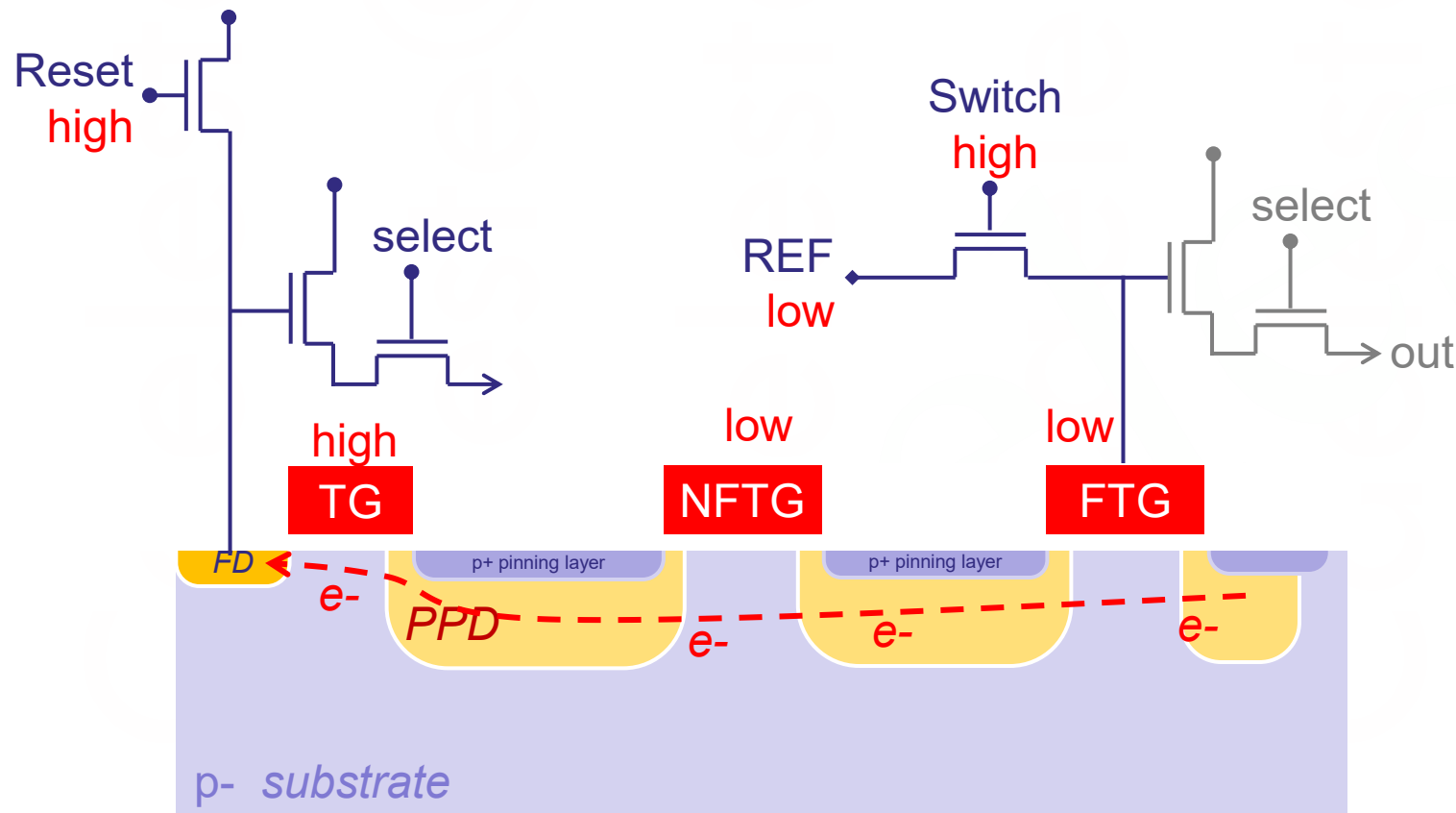
cross section
along
A-A'



Pixel operation [1]: Initial flush

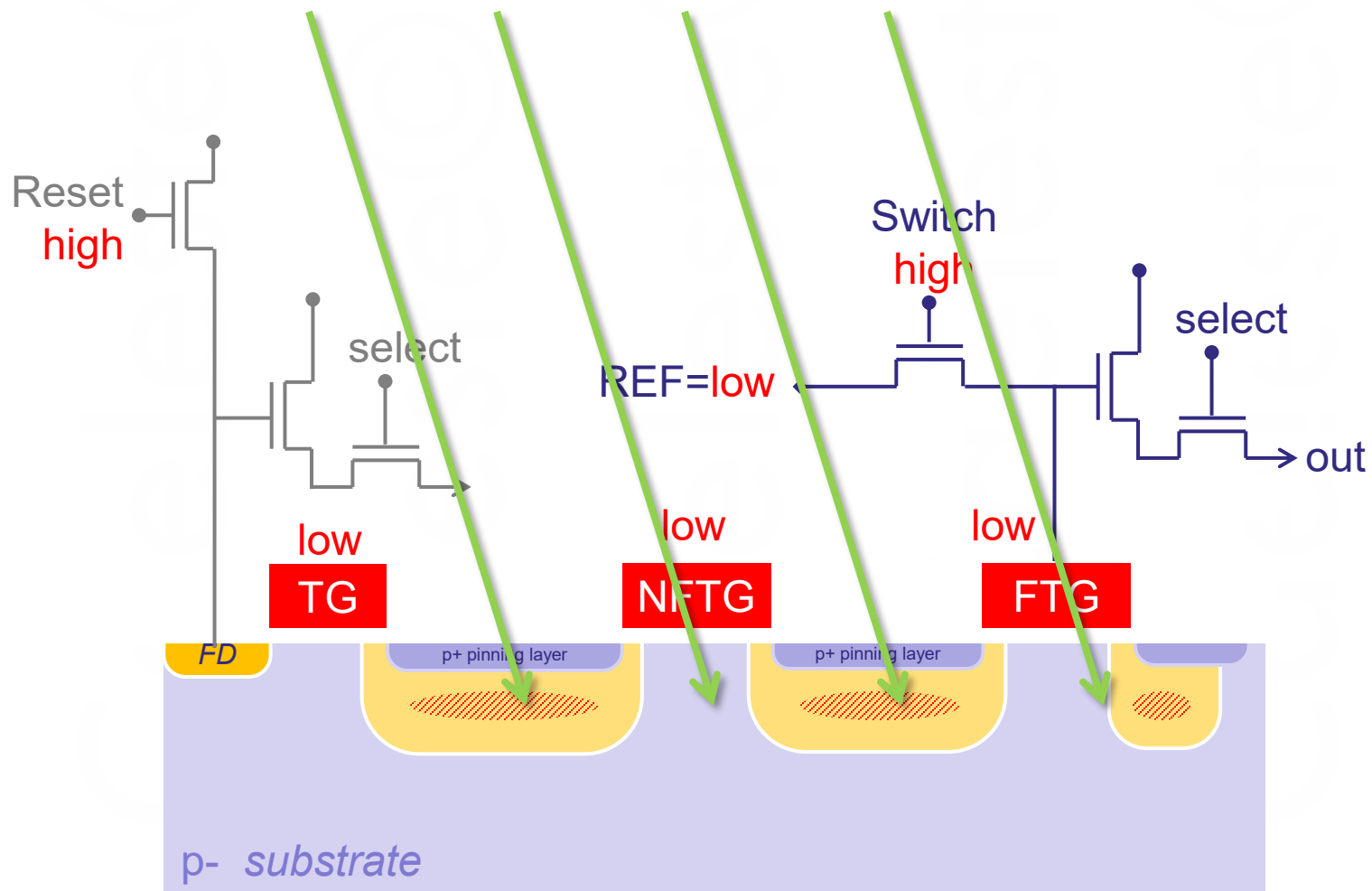
In the beginning of the cycle, the PPD as well as the FTG and the NFTG are emptied, by biasing both TG and reset high.

This may as well be realized by the previous classic readout of the PPD



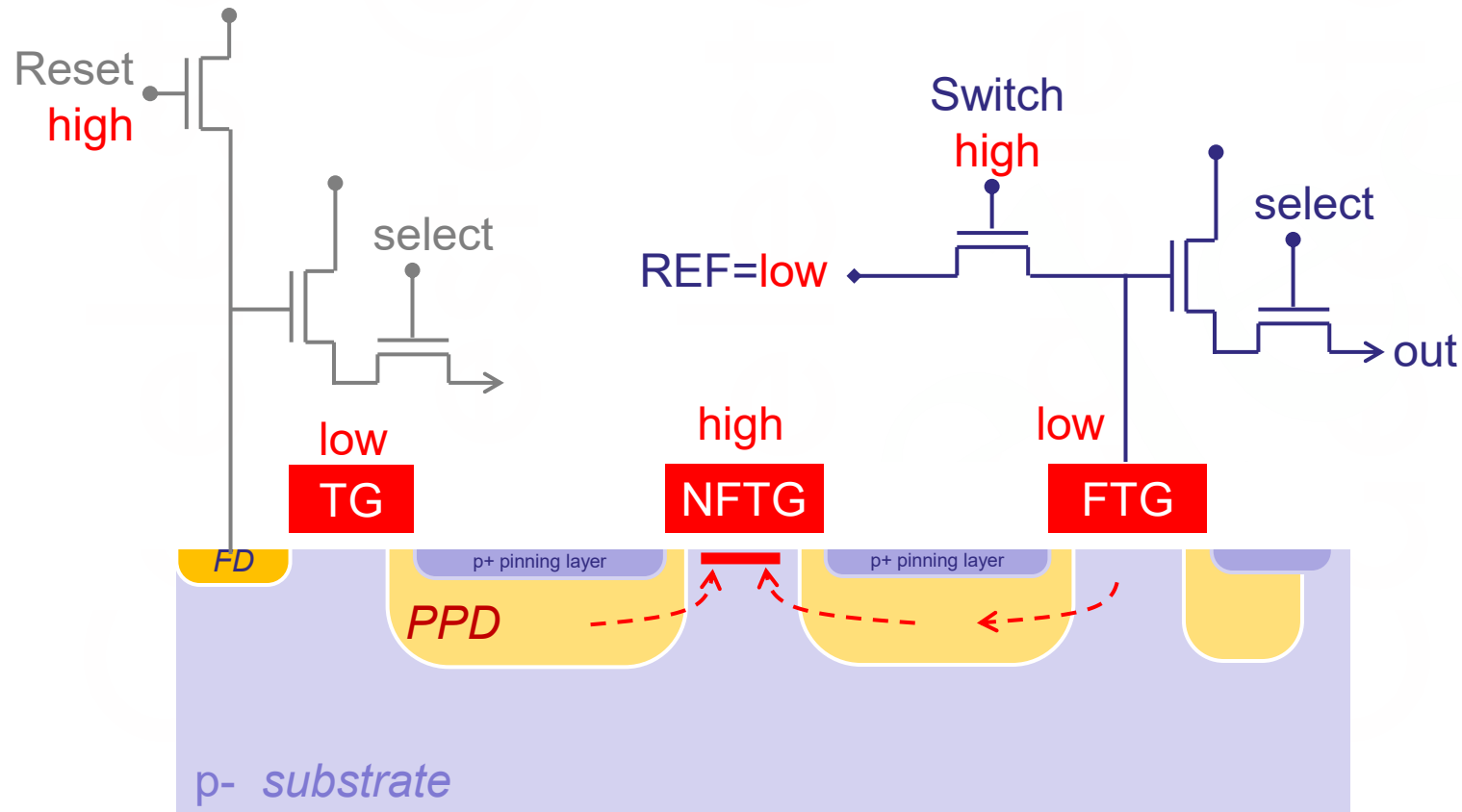
Pixel operation [2]: Integration

After flushing, the PPD is ready to accept photocharges.
These charges are integrated in the PPD.



Pixel operation [3]: NFTG high

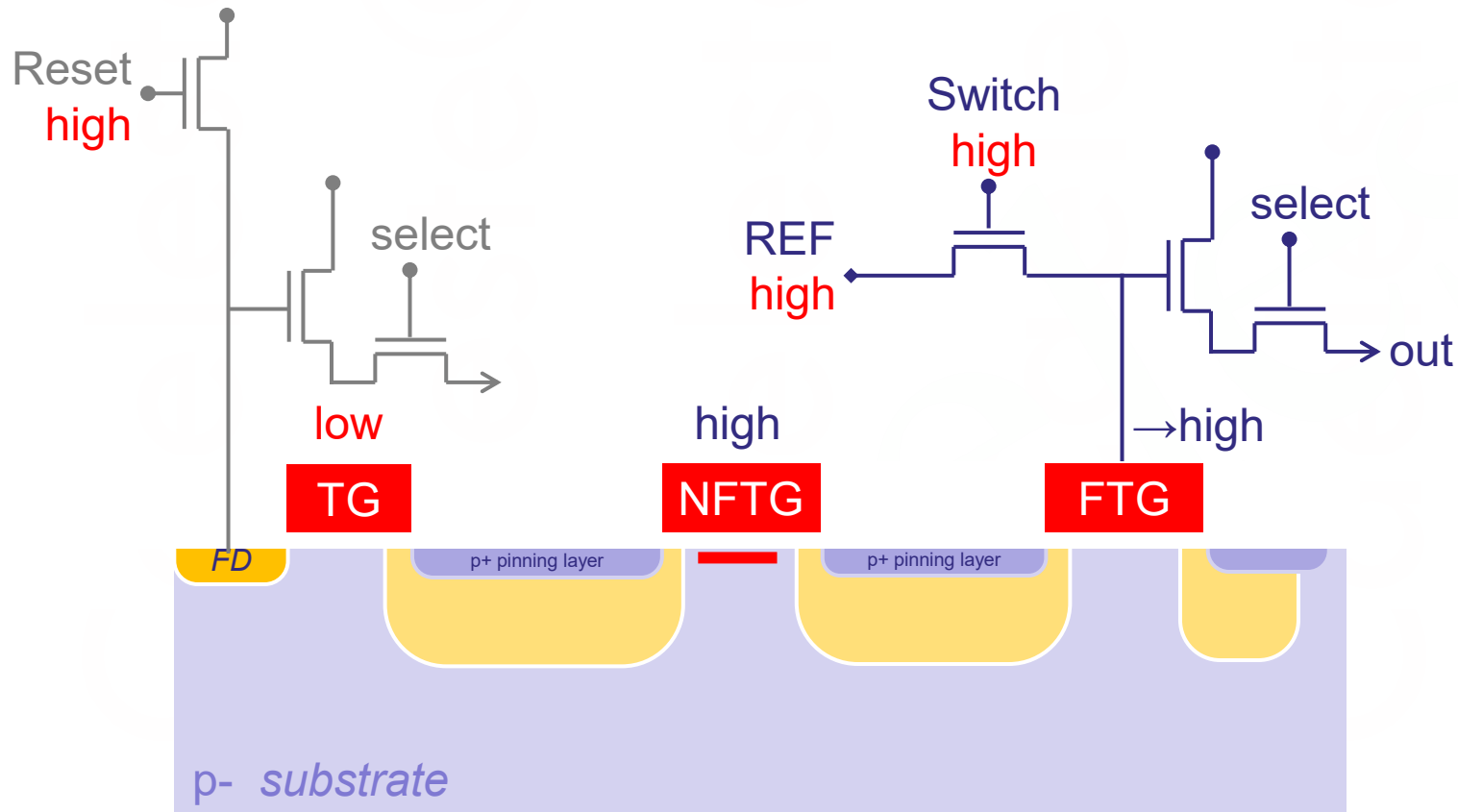
After charge integration, FTG is biased low, NFTG is biased high, collecting an amount of charge from the PPD, to a certain maximum Q_{FW0}



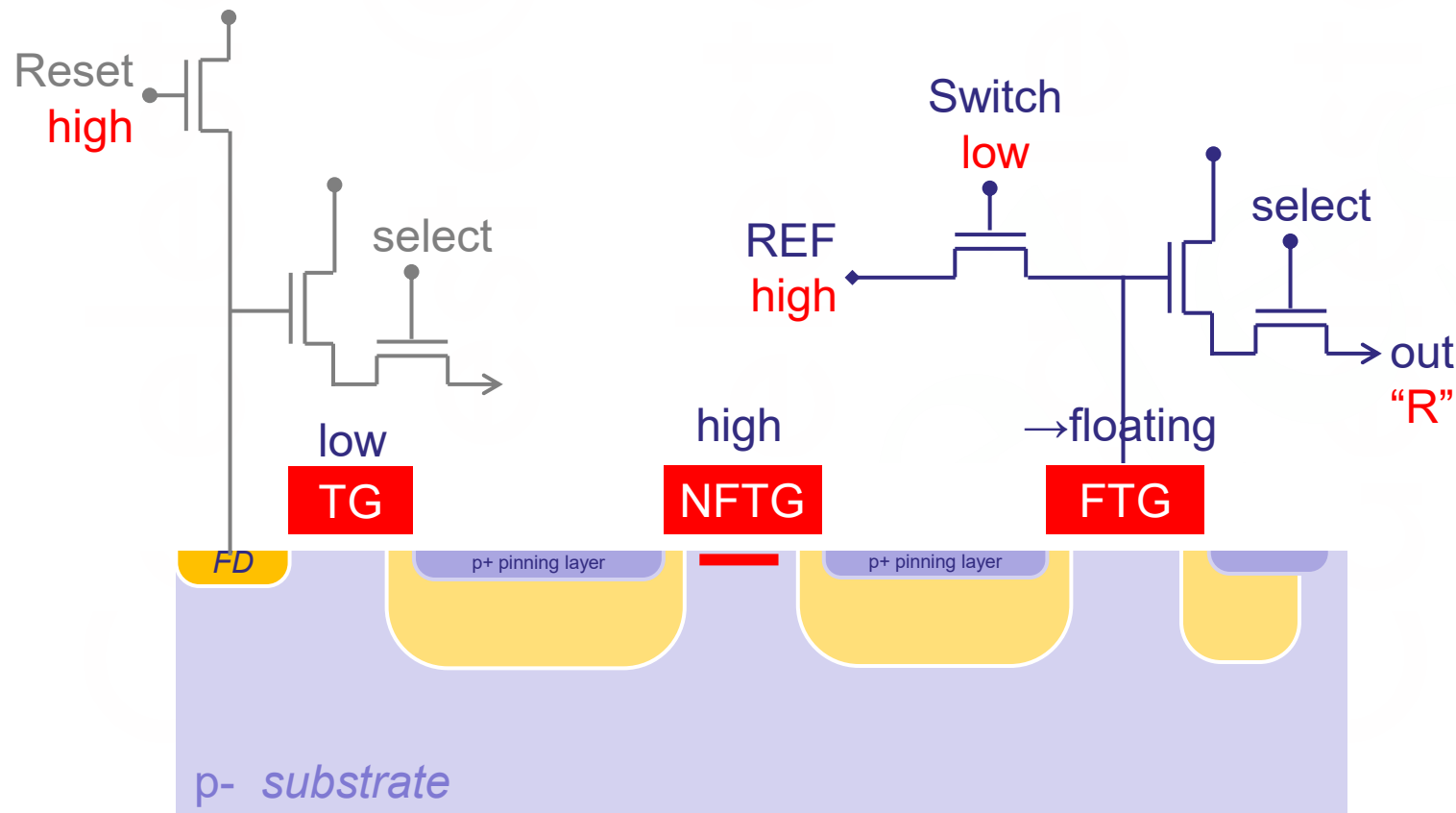
Pixel operation [4]: set FTG high

REF is set high while switch is still closed. As a consequence, FTG goes high.

However, no charge is collected under FTG as the PPD is essentially empty.



Pixel operation [5]: make FTG floating

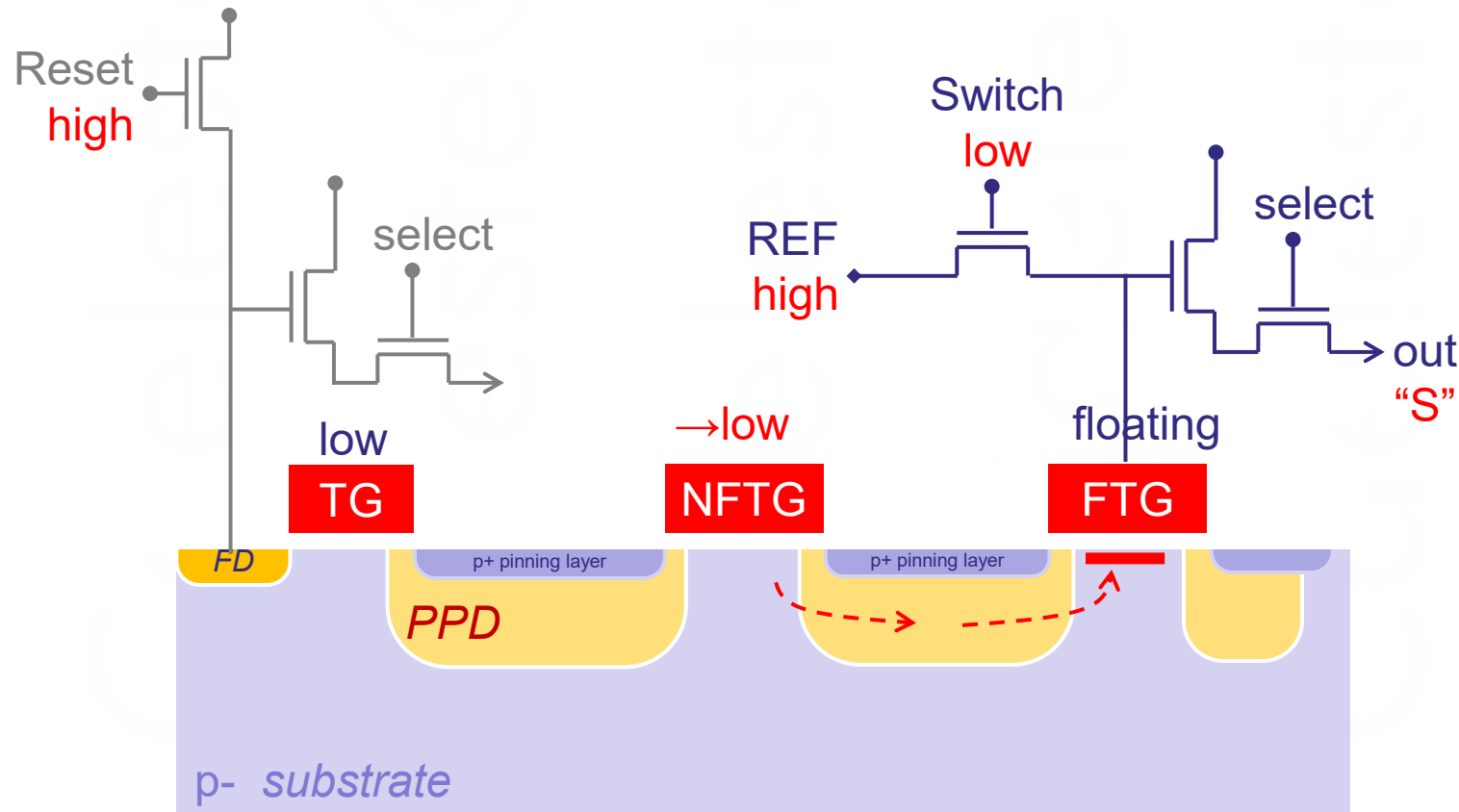


Switch is opened. As a consequence, FTG becomes floating.

still no charge is collected under FTG as the PPD is essentially empty and charge is retained under NFTG.

At the terminal "out", one samples the "empty" level "R".

Pixel operation [6]: NFTG set low



The charge under NFTG is pushed to the PPD, from where it is collected by the FTG.

This charge displacement is sensed by the floating FTG and is sensed by the source follower as a second sample "S".

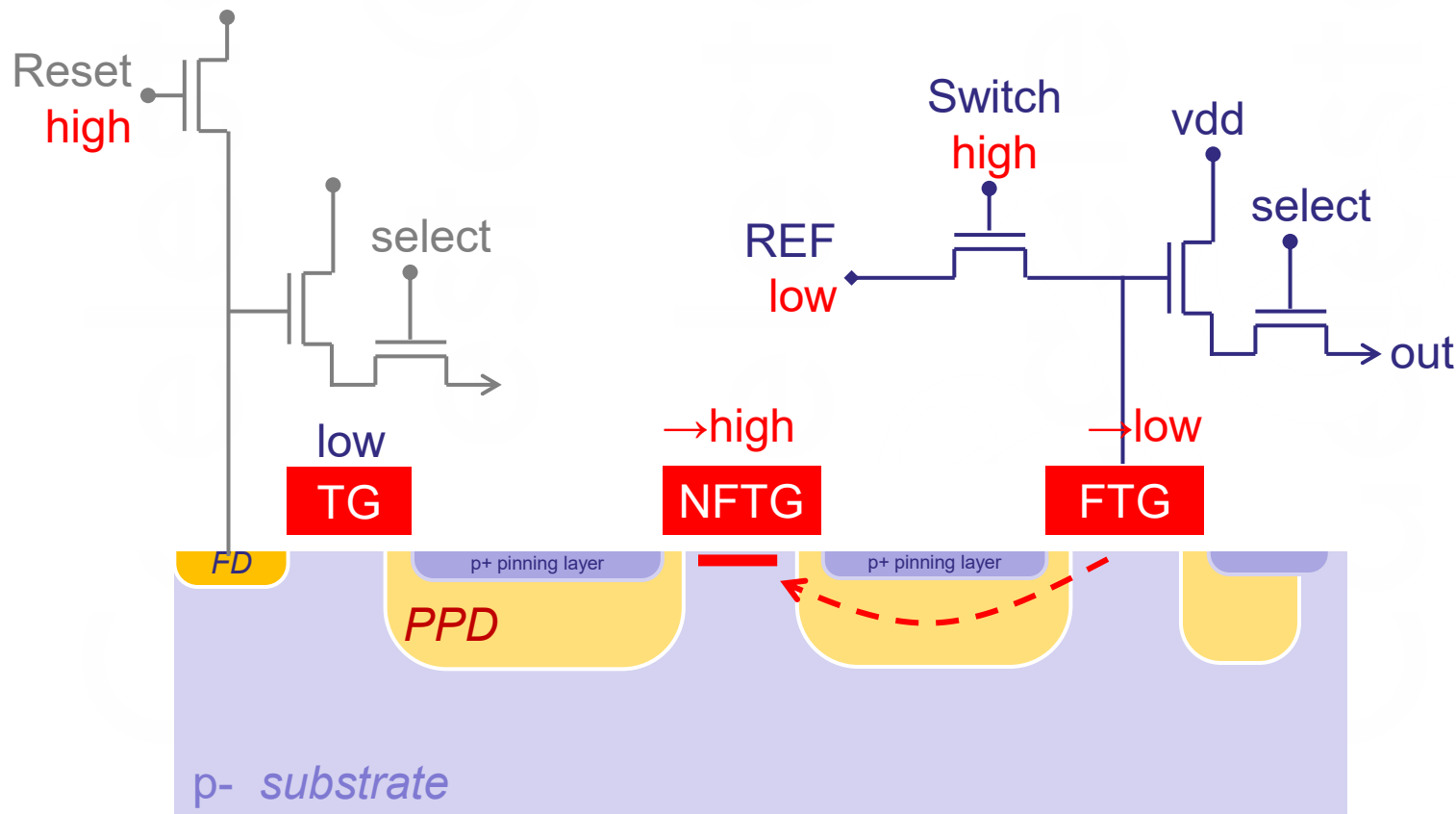
The (CDS-) difference S-R is a measure of the photo charge contained in the PPD.

This CDS difference is non-destructive. The charge can be put back to its initial point.

Pixel operation [7]: NFTG high and FTG low

NFTG is set high again and REF to low, thus FTG, is set low.

The charge contained under FTG moves back to NFTG.



After that one may repeat the cycle at [4]

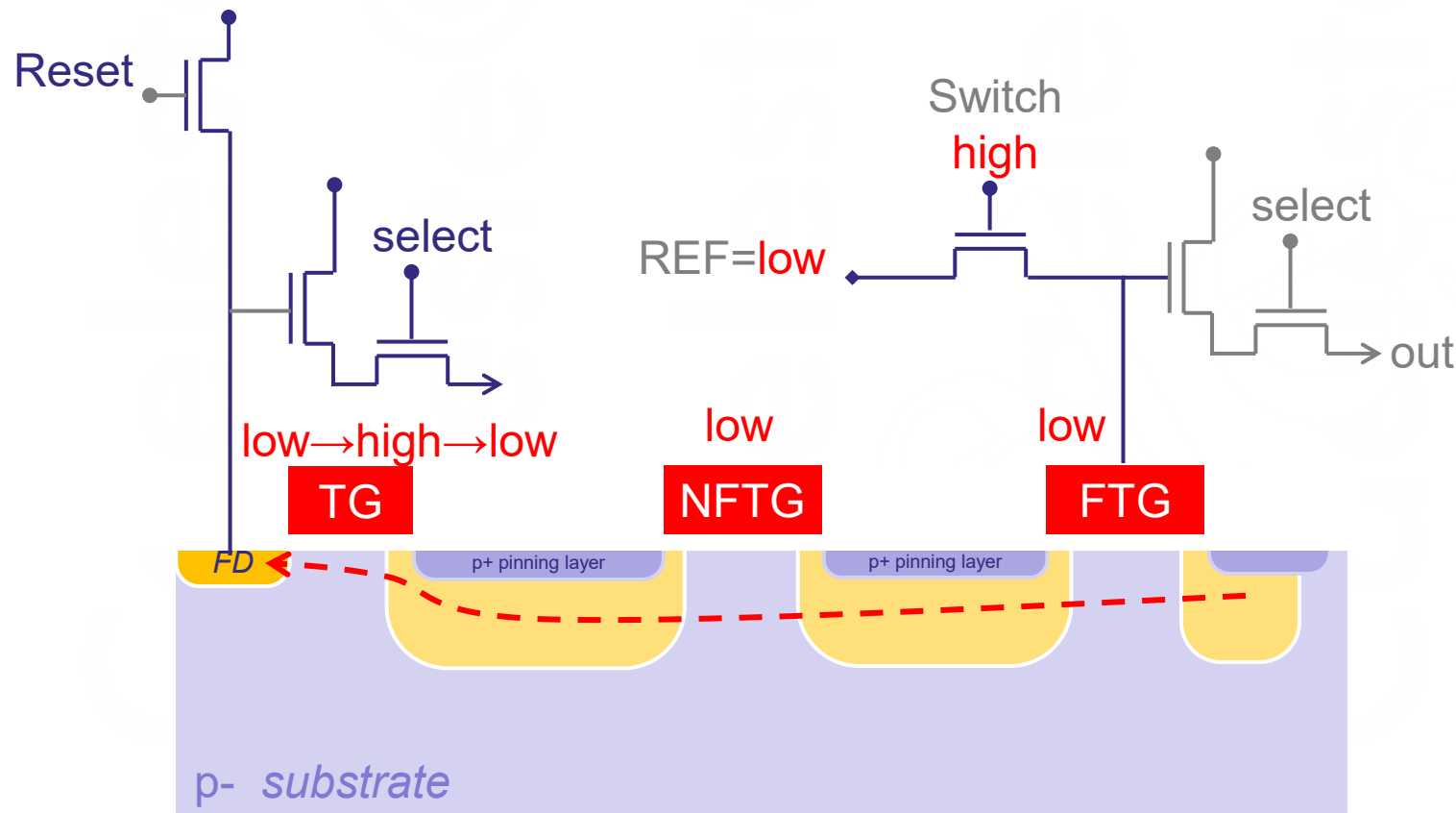
A large number of S-R CDS samples will be obtained in a non-destructive way, and averaged to reduce the noise.

Multiple CDS = "MCDS"

Pixel operation [n+1]: classic readout of the PPD

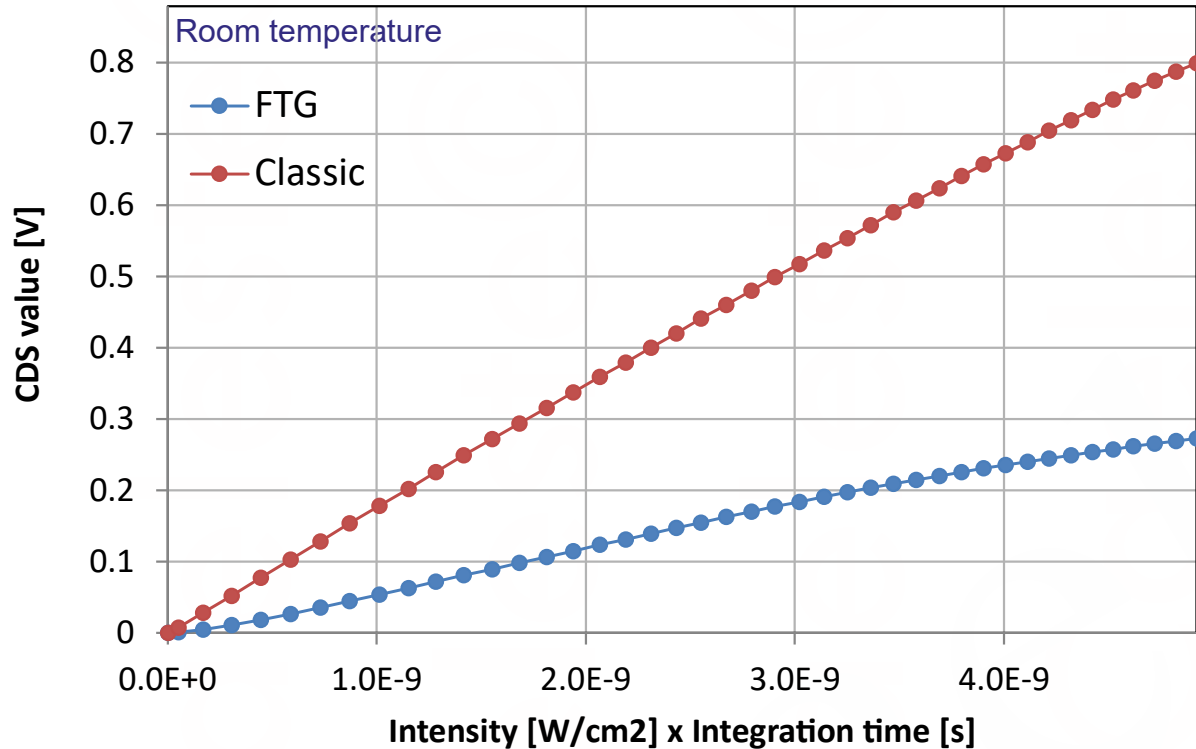
The end, one can evacuate the PPD completely

- Through the classic output while toggling TG to transfer charges from PPD to FD

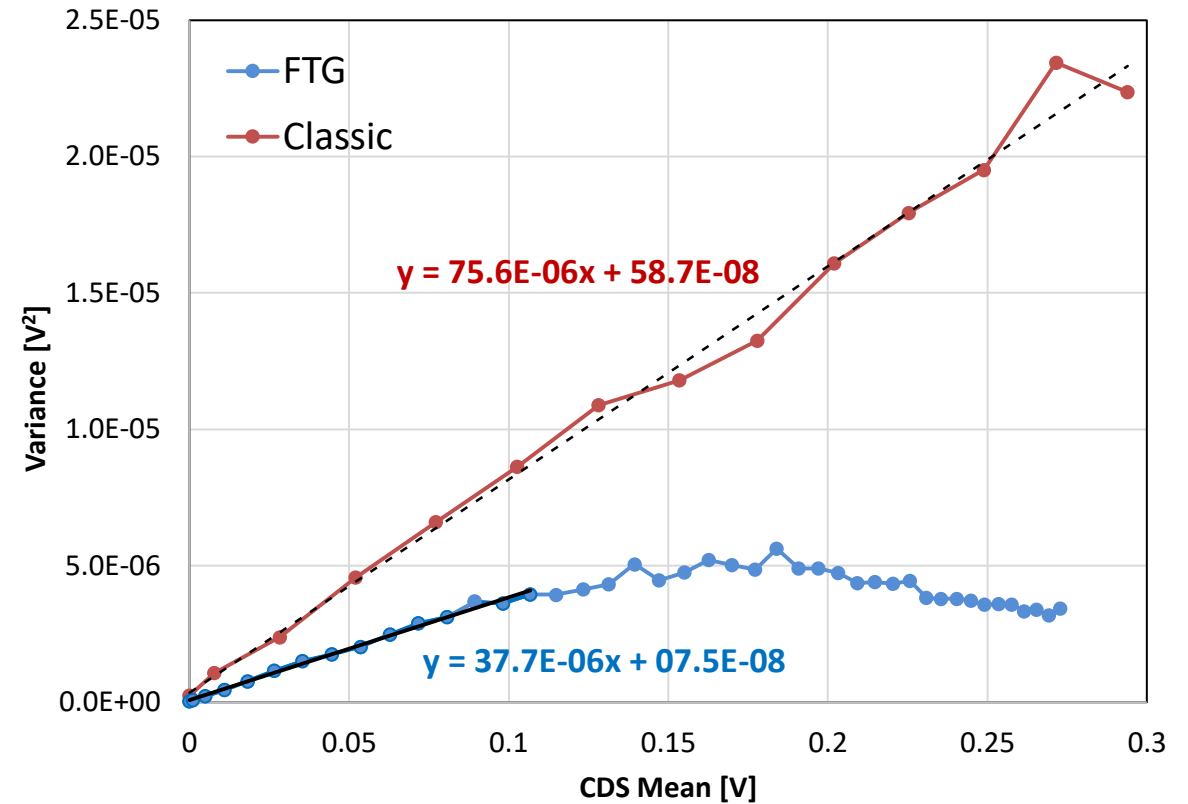


Measurement Results

Photo Response (offset-normalized)



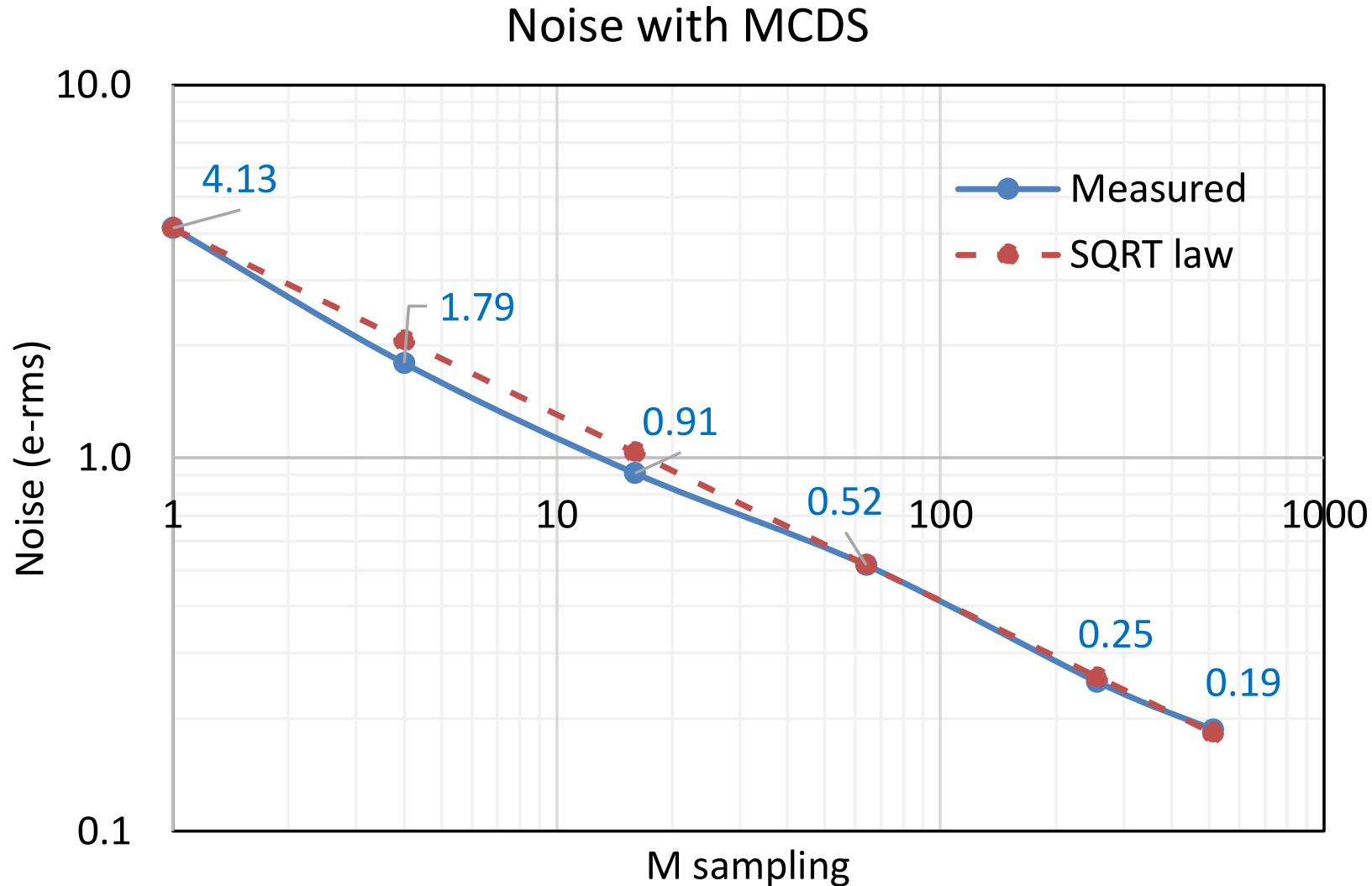
Mean - Variance plot



Remark that the “classic” photoresponse is higher than the FTG response.

This is due to the fact that the charge detected under the floating gate is diluted by the capacitances in series.

Noise at -50°C



Preliminary result of measured noise at -50 °C.

The reported noise is the average of M non-destructive readings. Noise scales as a square root of the number of samples M .

In this case, $0.19 \text{ e}^-_{\text{rms}}$ is reached for $M=512$.

Thank you