SIM 2022
Eindhoven NL

# 101 ways to readout a photodiode

Bart Dierickx, Caeleste

# justification

caeleste

Pixels consist of photodiodes or photoreceptors and a minimal amount of circuitry to read them out.

“Classic”, “vanilla”, “consumer” pixels nowadays use PPD (pinned photodiode) based pixels, and charge-to-voltage conversion on the gate of a MOSFET.

We will show that there are so many more ways to do this.

Disclaimers

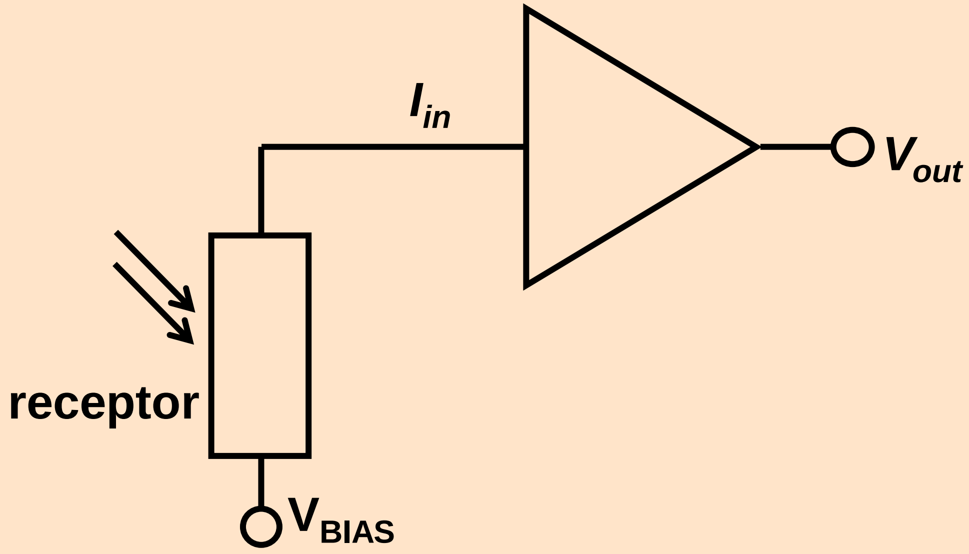
- Our list by no means has the ambition to be complete.  Large categories are even omitted, such as SPADs, CCD, TDI, binning methods, TFTs,… or forgotten.
- Many circuits shown may be patented by us or others and are not free to use.  Consider this publication as citation.
- This is not a course in pixel design.
- We refrain from comparisons, making relative performance statements, etc.

# contents

# 1. Pixels, in general

A pixel consist of

- a photoreceptor
- and circuitry to readout and multiplex its signal



# Photoreceptors, top level categories

caeleste

**Photodiodes**: the signal is +/- a current, and can be integrated to an amount of charge

- Plain PN junctions, in Silicon or other semiconductors
- “Pinned” photodiodes (PPD)
- PIN diodes
- SPADs and APDs

**Photoresistors:** the signal is +/- a (modulation of a) resistance

- Plain photoresistors in Silicon or in other semiconductors
- Bolometers
- Advanced materials, quantum dots, Graphene, Organic,

Modulation of **other** physical parameters by radiation

- Modulation of polarization: piroelectric detectors, piezoelectric elements
- Antenna’s, direct sensing of EM field, heterodyning

# Readout methods, top level categories

caeleste

1. Pixel signal readout using charge integration, whereby
    1. Charge to voltage conversion takes place on a capacitor, often called “floating diffusion”
    2. Charge to voltage takes place in a feedback element
    3. Otherwise
    4. Variations, realizing CDS, global shutter, HDR, etc.
2. Pixel signal readout based on photocurrent to voltage conversion
    1. In a resistor
    2. In a feedback element
3. Pixels signal readout based on event detection
    1. Counting these events
    2. Measuring the “time” of/between an event(s)
    3. Measuring the “magnitude” of the event

And combinations of these

# Frequent abbreviations

caeleste

| | |
|---|---|
| 3T | 3 transistor pixel |
| 4T | 4 transistor pixel, with TG and PPD |
| CCD | charge coupled device |
| FD | floating diffusion: charge sense node of a pixel |
| GS | global shutter |
| IWR | integrate while read type of globals shutter |
| PPD | pinned photodiode |
| PD | photodiode |
| $Q_{FW}$ | full well charge (saturation charge) |
| S&H | sample and hold |
| SF | source follower |
| SPAD | single photon avalanche diode |
| SiPM | silicon photomultiplier |
| SN | storage node of a charge domain global shutter |
| $t_{int}$ | integration time |
| TG | transfer gate |
| TOF | time of flight (iTOF integrating, dTOF digital) |

# 2. consumer pixels

# Consumer pixel requirements

caeleste

Economic specs

1. Being small
2. Being cheap
3. Having good yield

**Non-consumer specs:**

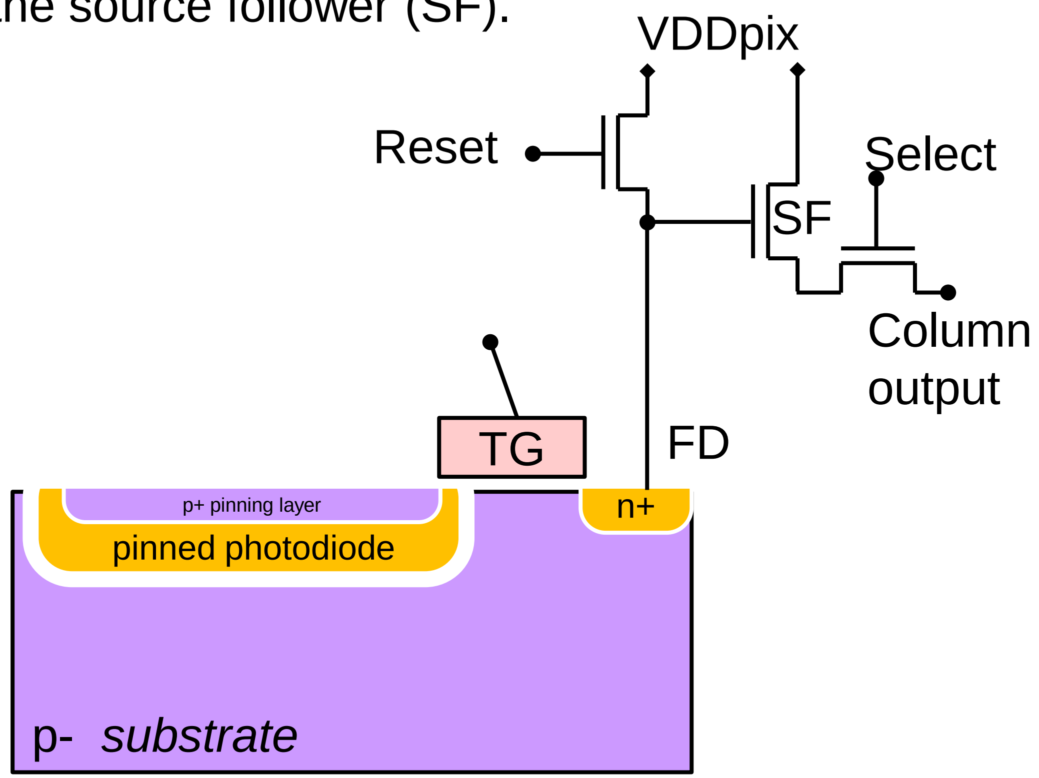
1. Fitting in the allowed space
2. Doing its job with as few as possible transistors
3. Having good yield

Human vision derived specs

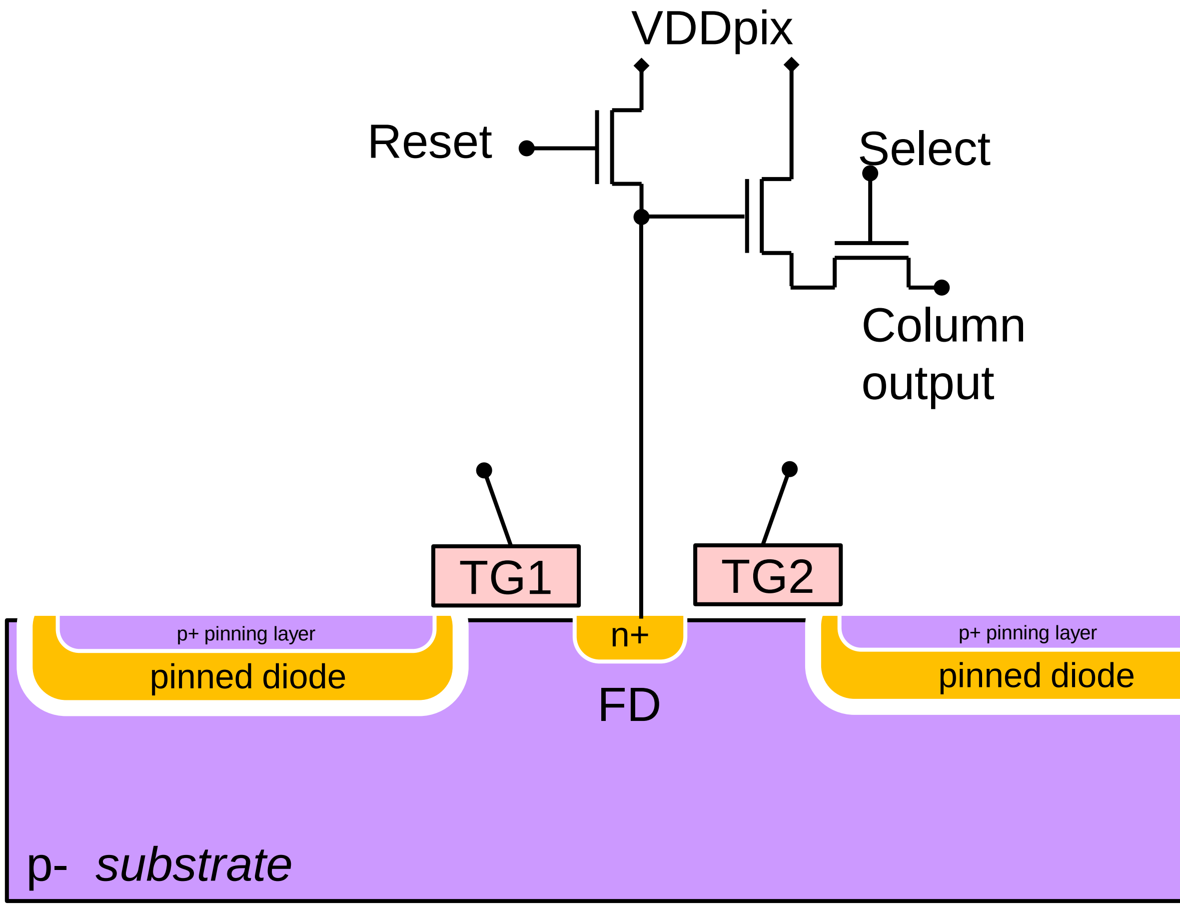
1. Making nice images for a human observer
2. Color fidelity = human vision RGB
3. Frame rate: still or few ten Hz
4. Motion artifacts, non-linearity, lag, … are allowed if not too visible
5. SNR matches that of human vision
6. Uniformity and cosmetic quality: OK if it can be masked for a human observer.

# 4T and shared 4T pixels

This is the present mainstream pixel topology.
Photo charge is integrated in the pinned photodiode (PPD).
At the end of the integration time, it is transferred to the floating diffusion (FD), where the potential drop is sensed by the source follower (SF).




The smallest consumer pixels are in fact "shared" pixels. By sharing the SF, reset and select amongst a group of pixels, pixels can be smaller.




**2x1, 2x2, 4x1 …**

# “5T” charge domain Global Shutter (GS) pixel

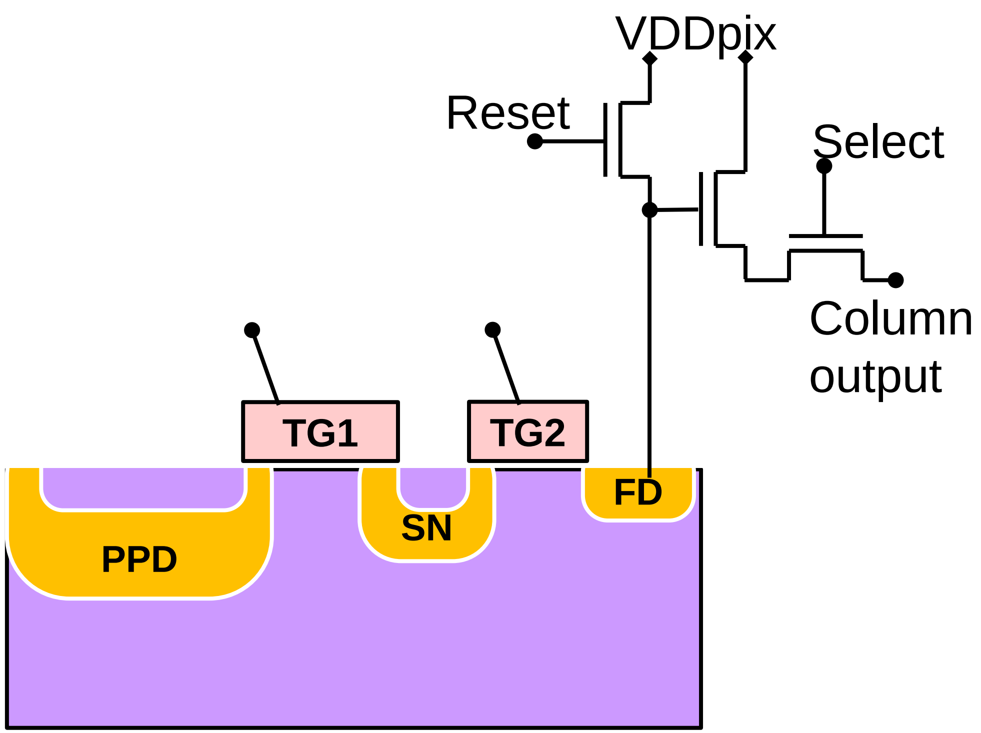



Photo-electrons generated in the Silicon are collected in the PPD during the “integration time” $t_{int}$. Which is the same for all pixels.

Charge is collectively transferred to the “storage node” SN or “memory node” by pulsing TG1.

Subsequent sequential readout happens via TG2.

This is a “**IWR**” (integrate while read) GS pixel.

# Other consumer pixels

caeleste

- Reset transistor -less variants of the previous
- Select switch -less variants of the previous
- 3D “stacked” process embodiments
- Using vertical instead of horizontal charge transfer

…

## Obsolete consumer pixel topologies

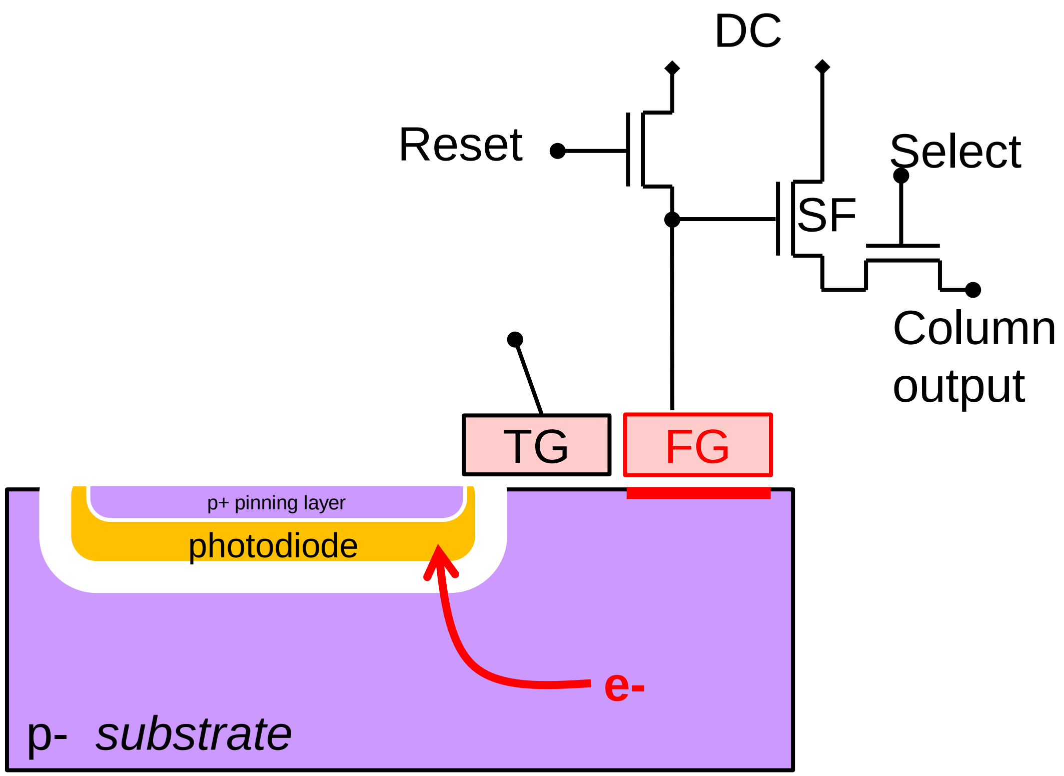
- Passive pixels, only using a photodiode and one or two switches, charge sensing happens outside the pixels
- 3T pixels, the original “active pixels” using a SF sensing the potential of a “floating diffusion”
- Floating gate pixels, using a SF to sense the potential on a capacitor coupled to the charge sensing node
- CMD, charge modulation devices, sensing the potential of a floating well by the MOSFET bulk effect.
- Photogate pixels, predecessors of the PPD pixels
- CCDs and variants
    - FFCCD, ILCCD, ILTCCD, CSD, CID, BBD, …

caeleste

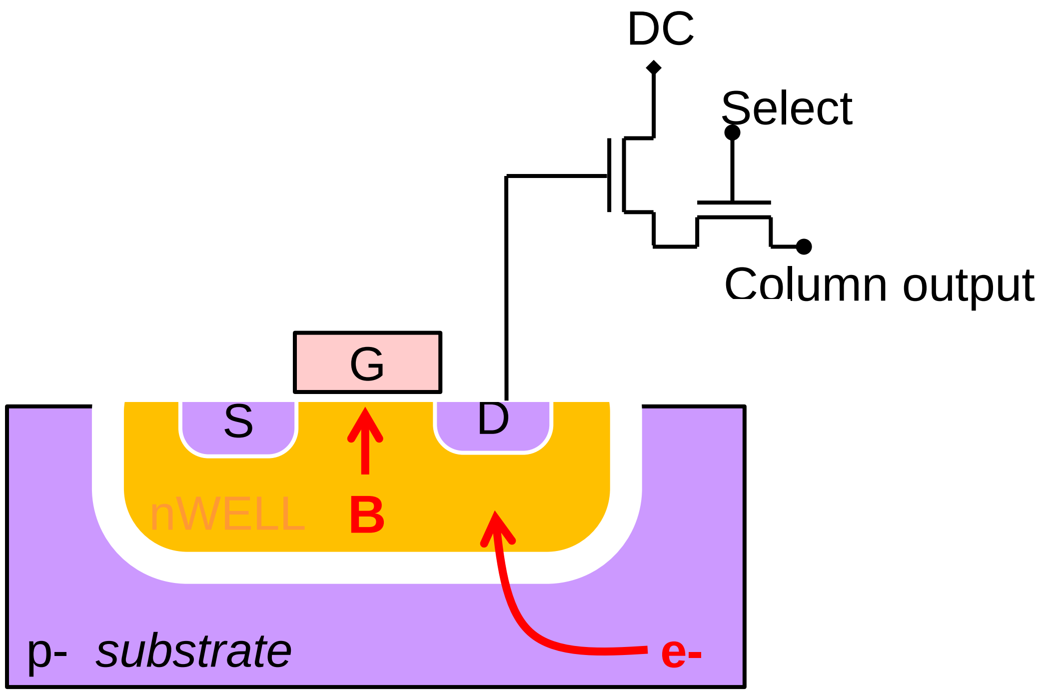
# FG

# CMD

**Floating gate:**
The photocharge transferred to an inversion layer under a floating gate (FG), where the potential drop is sensed by e.g. a source follower (SF).




**Charge modulation device:**
Photocharge is picked up by a floating (n-)WELL.
The potential change is sensed as the bulk effect of a MOSFET inside the WELL



# 3.Accurate bias

Pixels that can readout a receptor while keeping a stable and accurate bias voltage

# Accurate bias pixels, why?

caeleste

**Why would you need an accurate and stable bias voltage?**

- The photoreceptor needs a *constant* voltage bias
- The photoreceptor needs a *low* voltage bias
- The pixel performance needs a constant voltage bias, for speed, lag, …

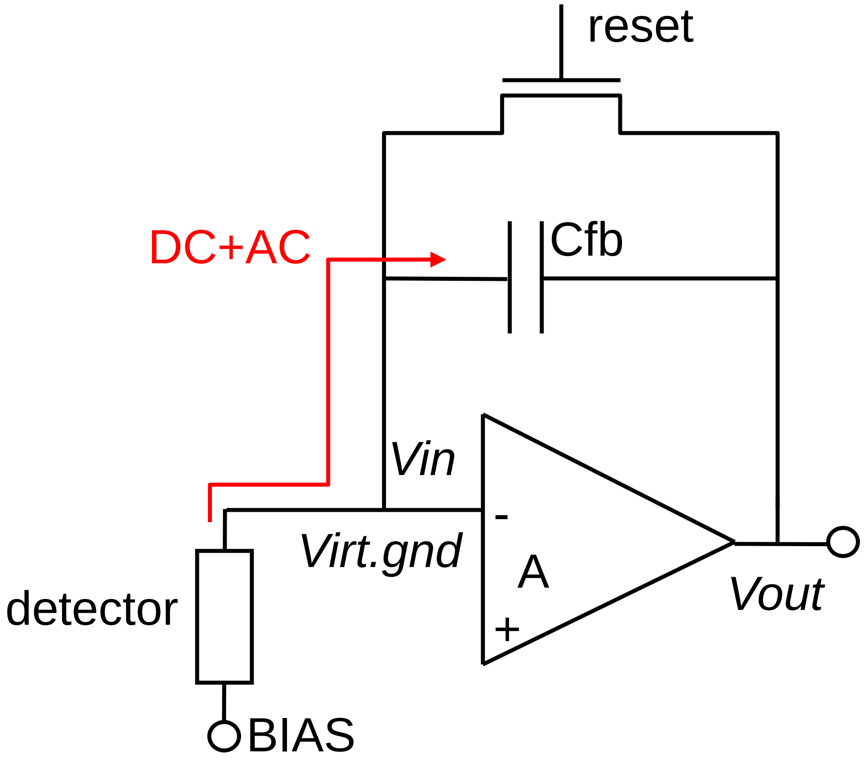
*Remark: “normal” Si photodiodes do not need an accurate and stable bias.*

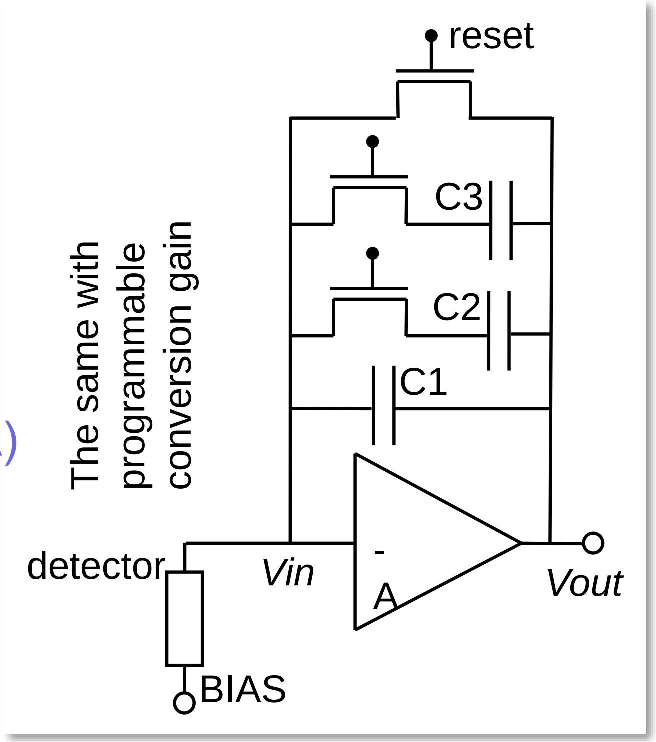
**Where**?

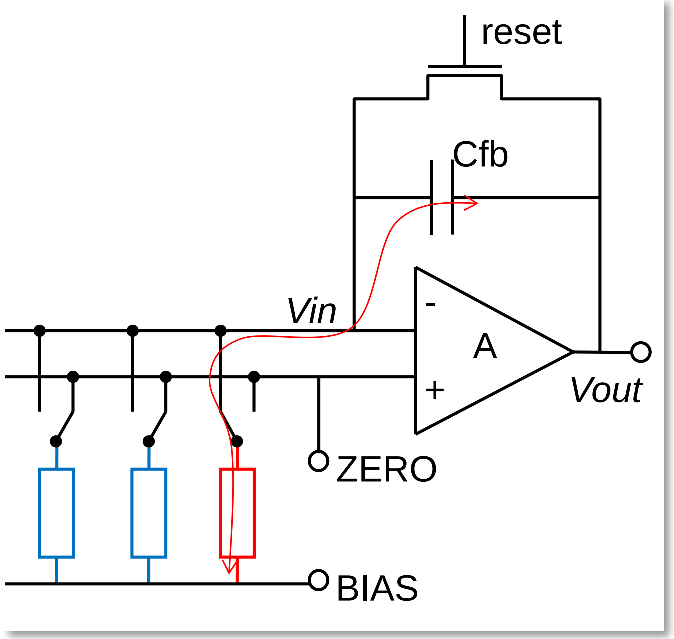
- Photo resistive detectors: $I = V/R$ thus $\Delta I = \Delta V/R$: voltage noise translates to current noise
- Diode in low band gap material, have low breakdown voltage, and a very narrow usable operating range
- Voltage dependent dark current $I = I_{signal} + V_{bias}*Z$: ideally the bias voltage should be zero
- APDs and SPADs requiring a very precise bias voltage
- Detectors with V-dependent memory effects (image lag, hysteresis)
- Cancellation of a large detector capacitance for response speed
- Cancellation of the non-linear photodiode capacitance

# CFA / CTIA

The usual suspect
“charge feedback amplifier” (CFA)
Also called
“(Charge) trans-impedance amplifier” (CTIA)

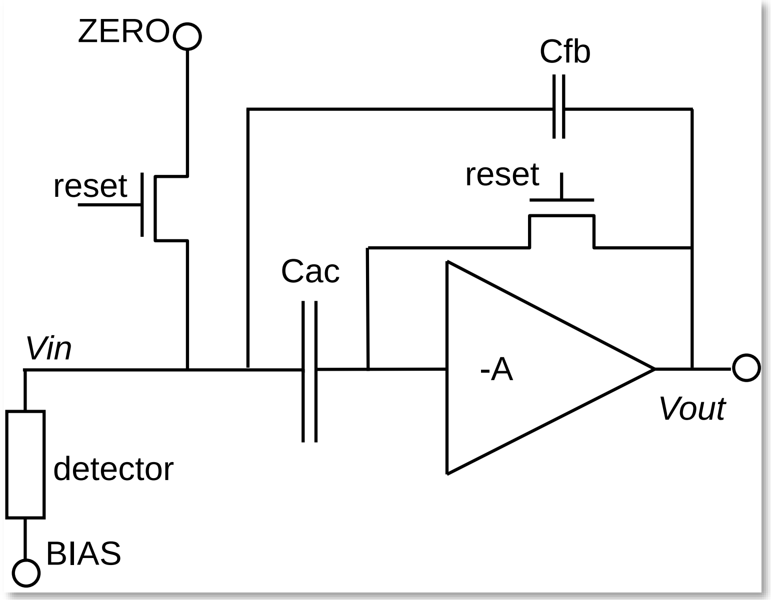


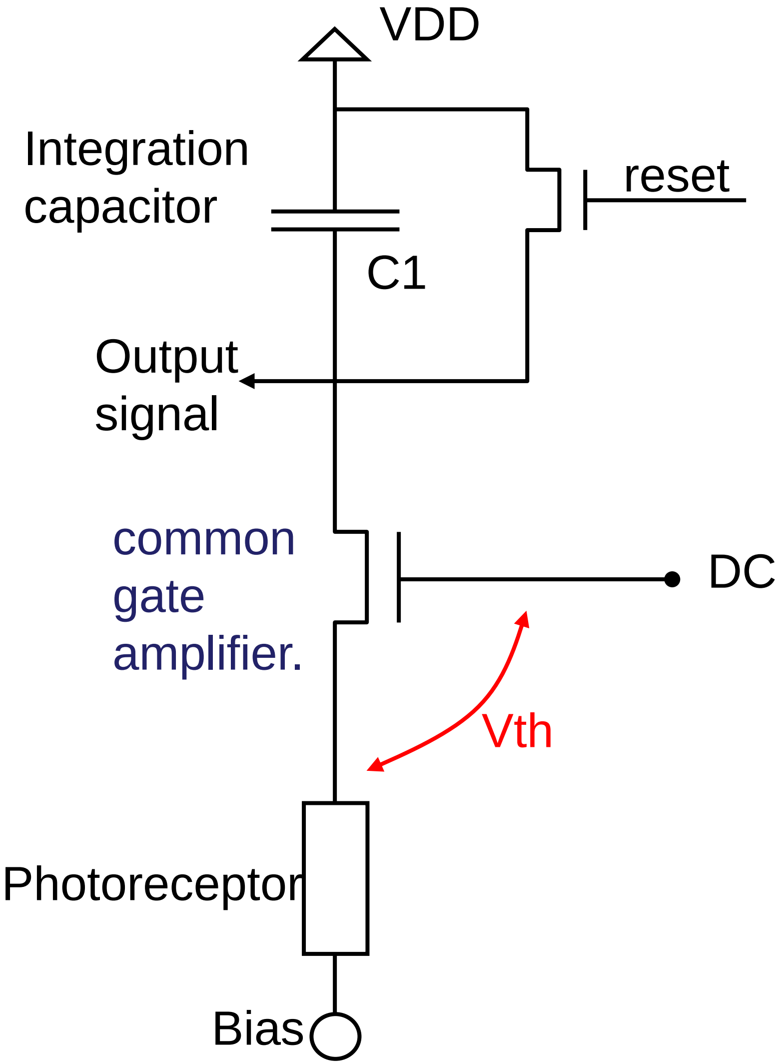

Variants for

- Programmable gain or HDR
- Sub-pixels
- Ultra-accurate bias by AC-coupling



# Direct injection

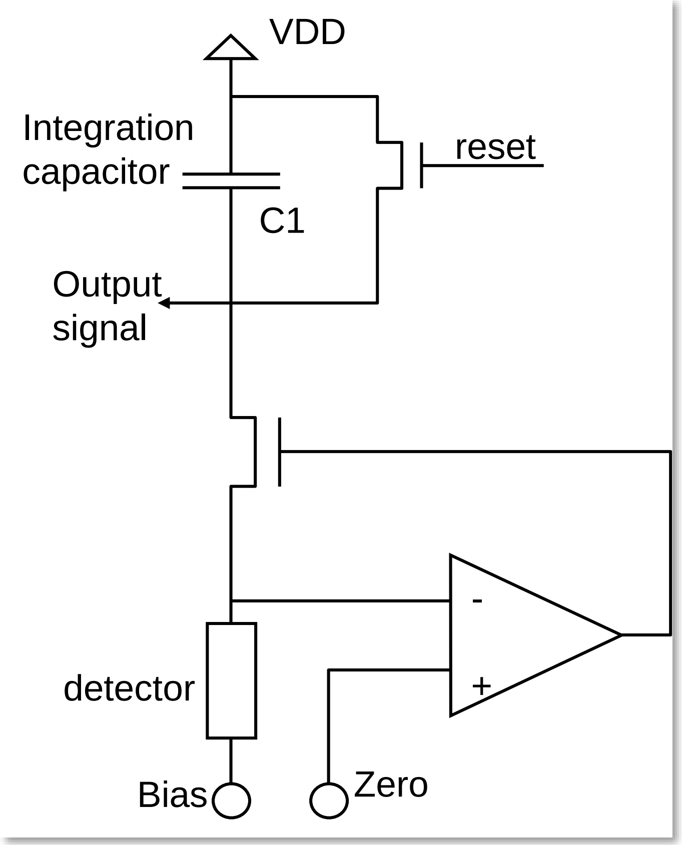


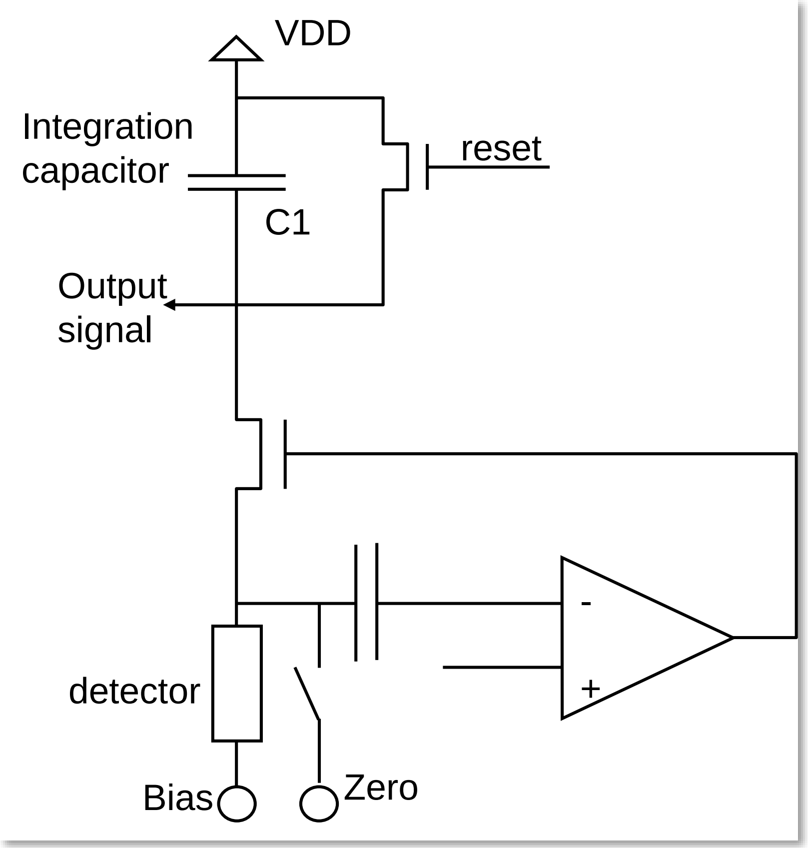



The “Direct injection” technique is popular in infrared sensing, where small bandgap diodes require a small and stable bias.

The charge is integrated on a capacitor, while keeping the voltage over the photoreceptor +/- constant.

Feedback improves the accuracy of the applied bias voltage



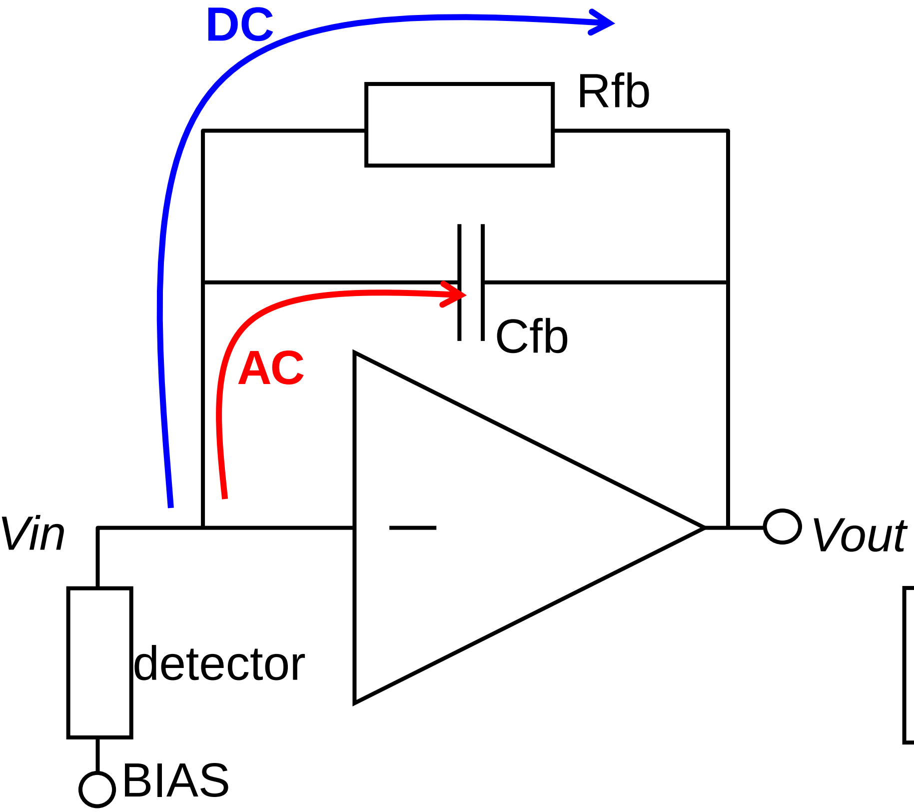
# 4. AC part of a large DC signal

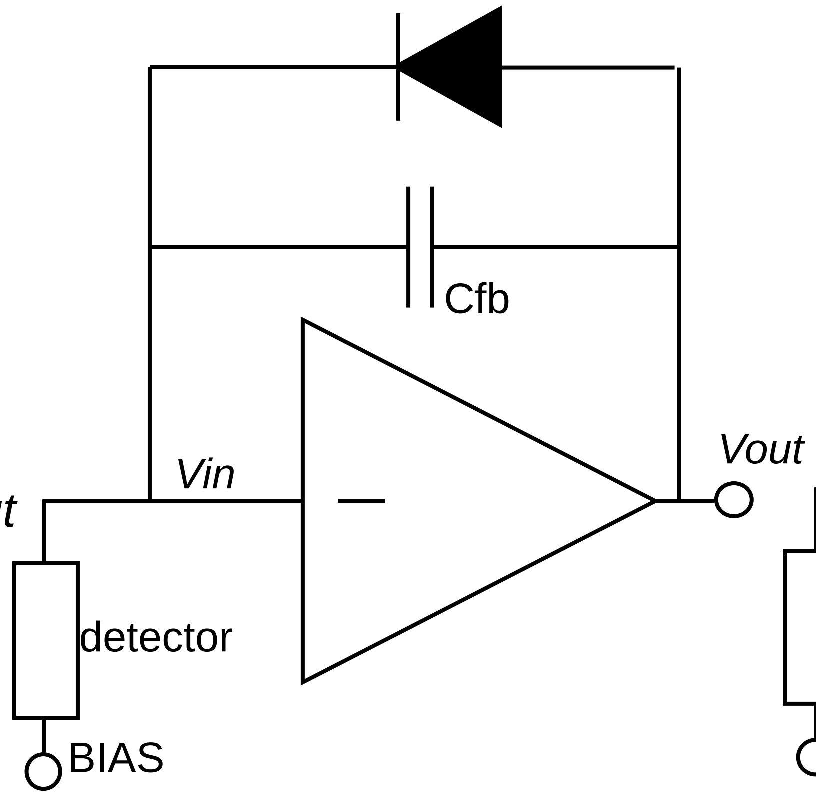
Pixels suitable to selectively readout the ~

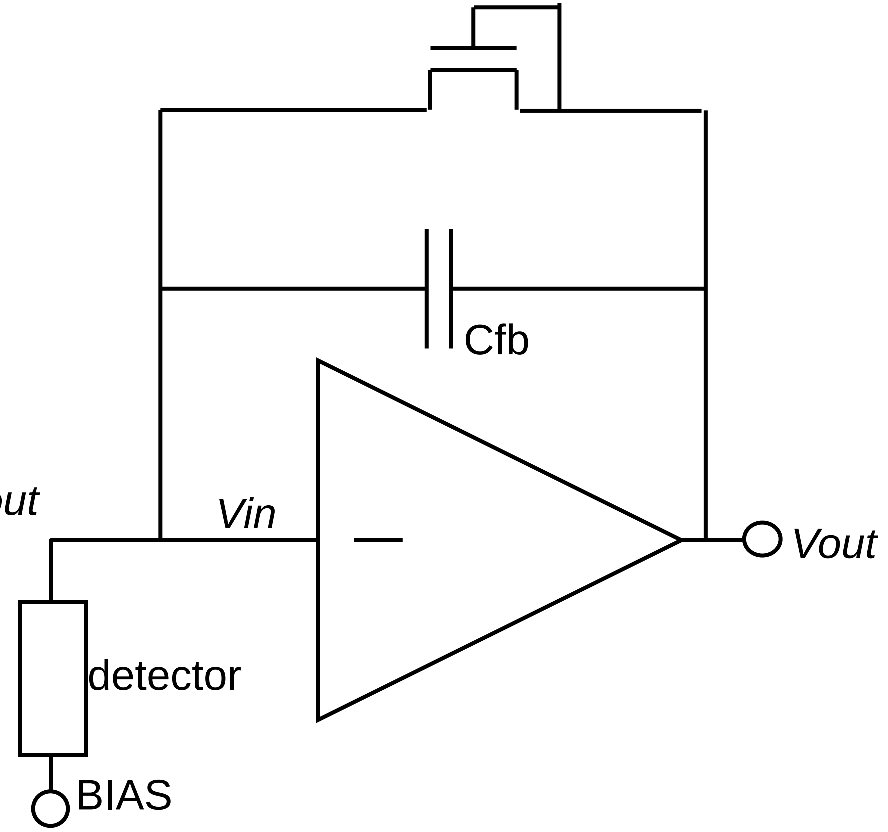
# AC from DC: When and why is this needed?

- ✓ The scene has a very wide dynamic range.
  You are only interested in a specific part of that range
  and want to read that signal with the highest accuracy
- ✓ Some applications are blinded by a large background flux hiding the small signal.
  as with thermal infrared detection, where the whole scene emits infrared
  for very intense light sources, e.g. TOF in a sunlit scene
- ✓ Large dark currents hiding a small signal current
  Image sensing of low light levels at elevated °T
- ✓ Information is modulated, with a small AC signal on a large DC background

# CTIA with extra resistor feedback



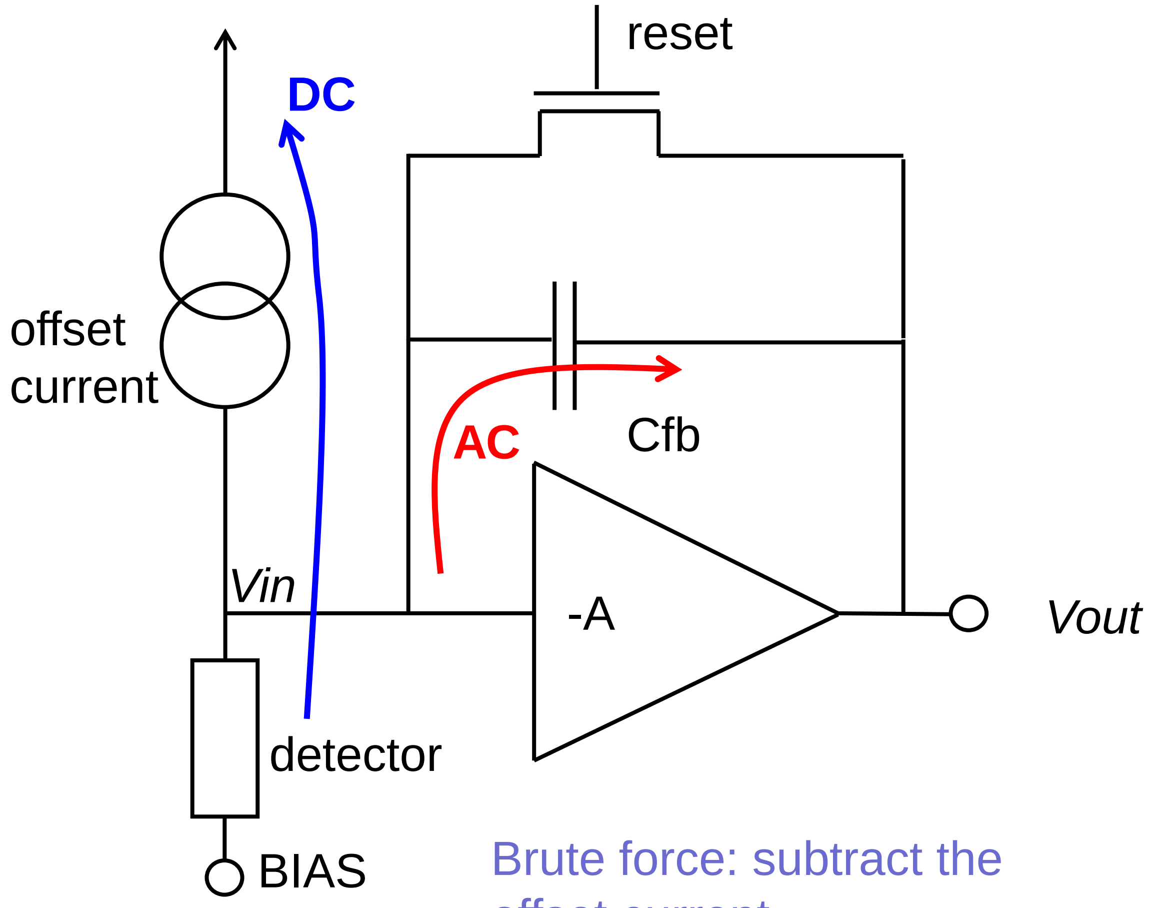




The “bandpass filter for charge” also used as “pulse shaper”

The diode results in a logarithmic compression of current to voltage.

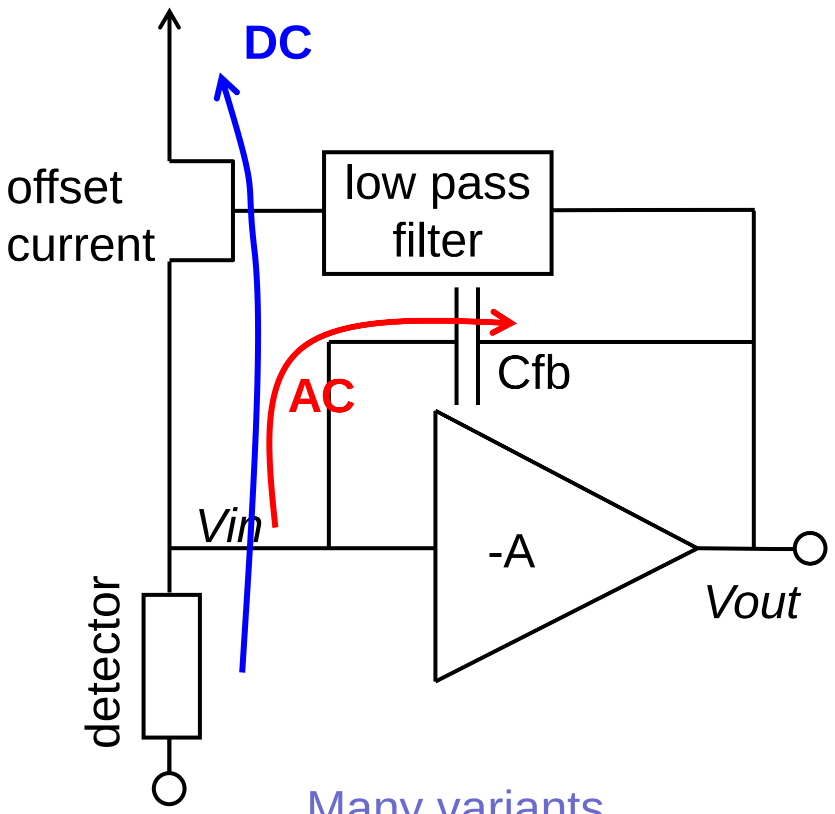
# CTIA with DC /background subtraction






Brute force: subtract the offset current.

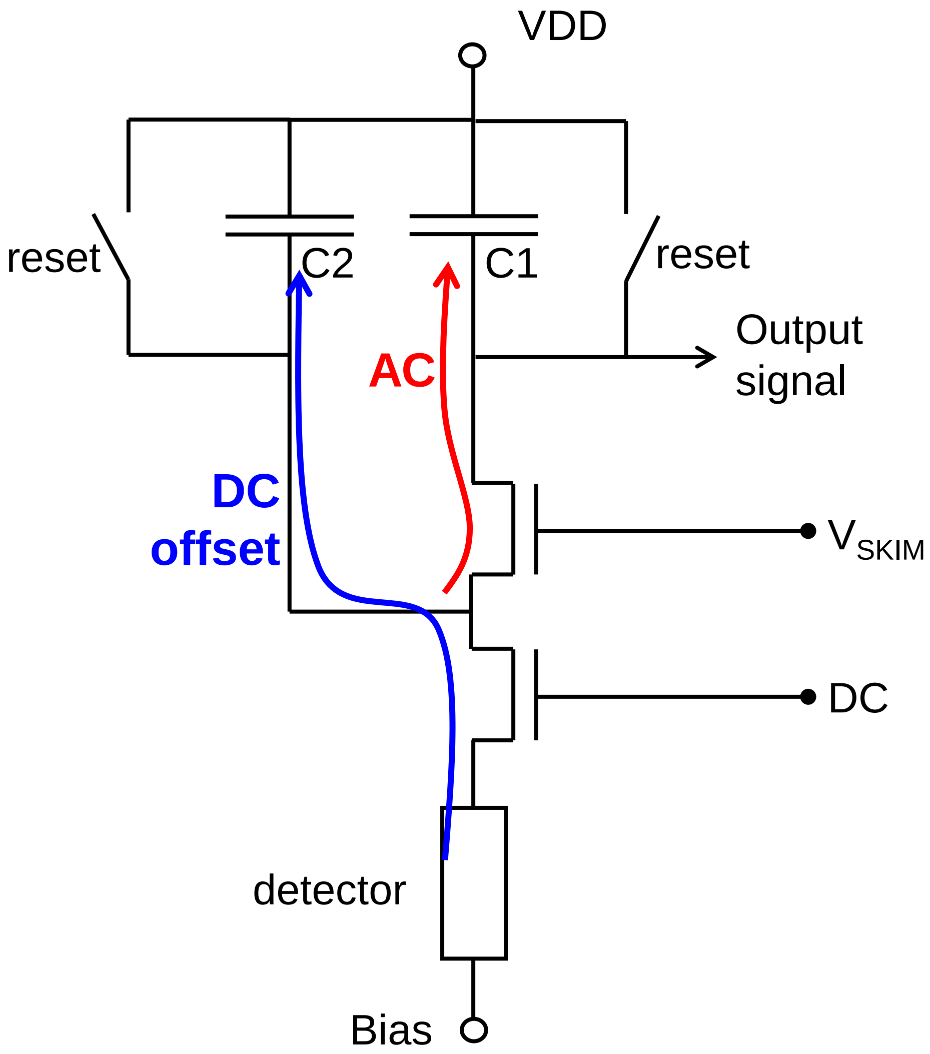
Works only if the offset is known.




Many variants
Many filters

# Direct injection with charge skimming

caeleste

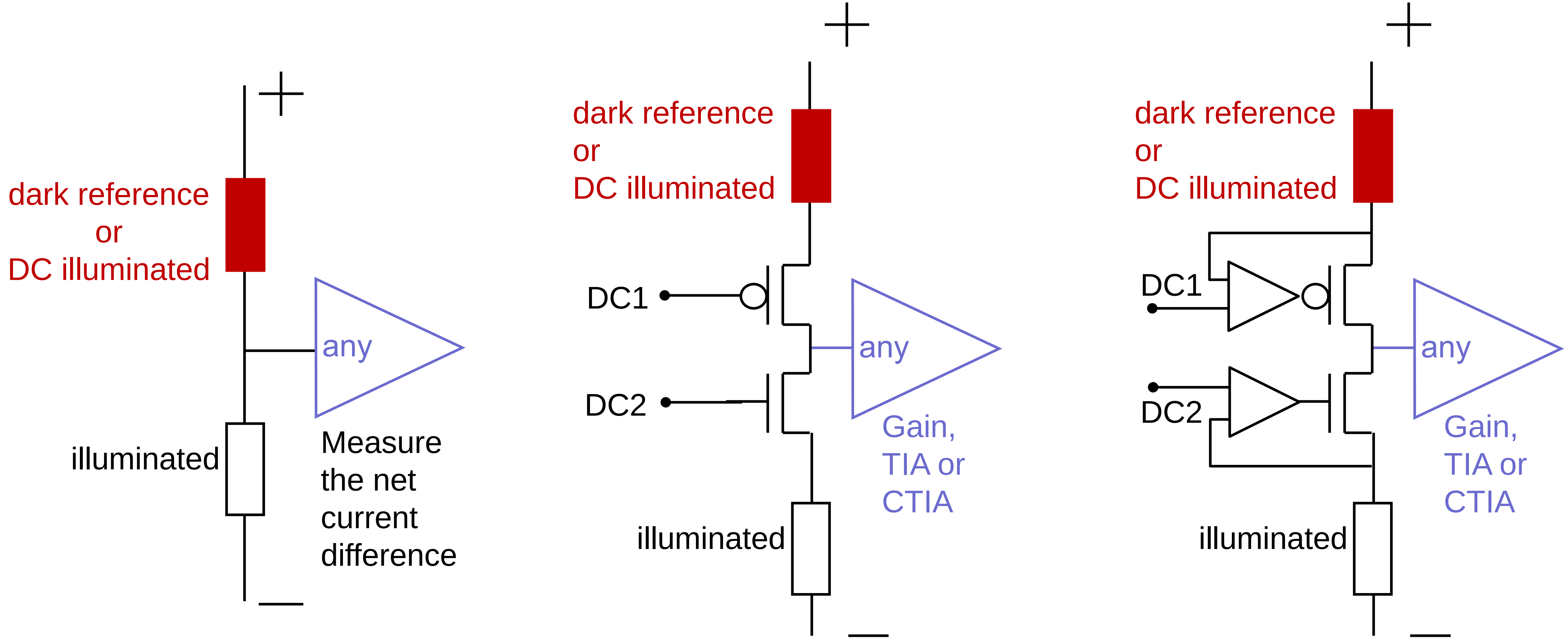



Initially all charges integrate on C2, until C2 fills up (DC)

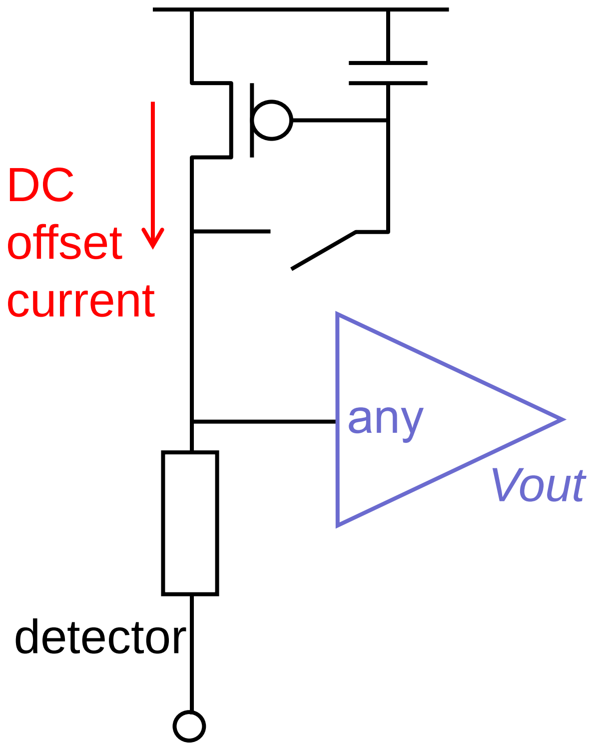
Then the remainder (AC) integrates on C1.

# bridge topology
# cancel DC with reference detector

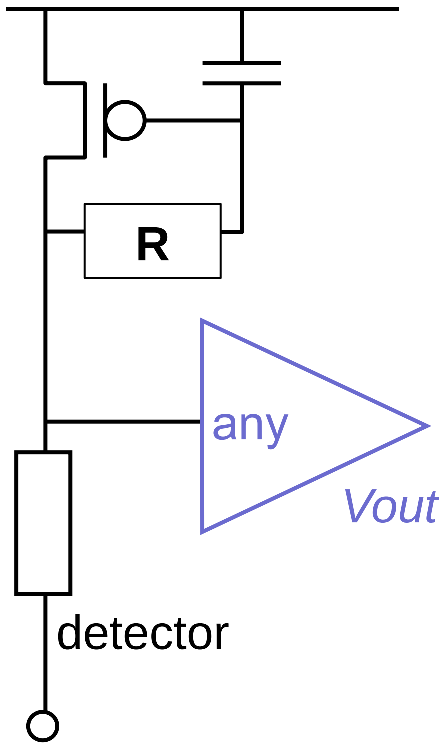




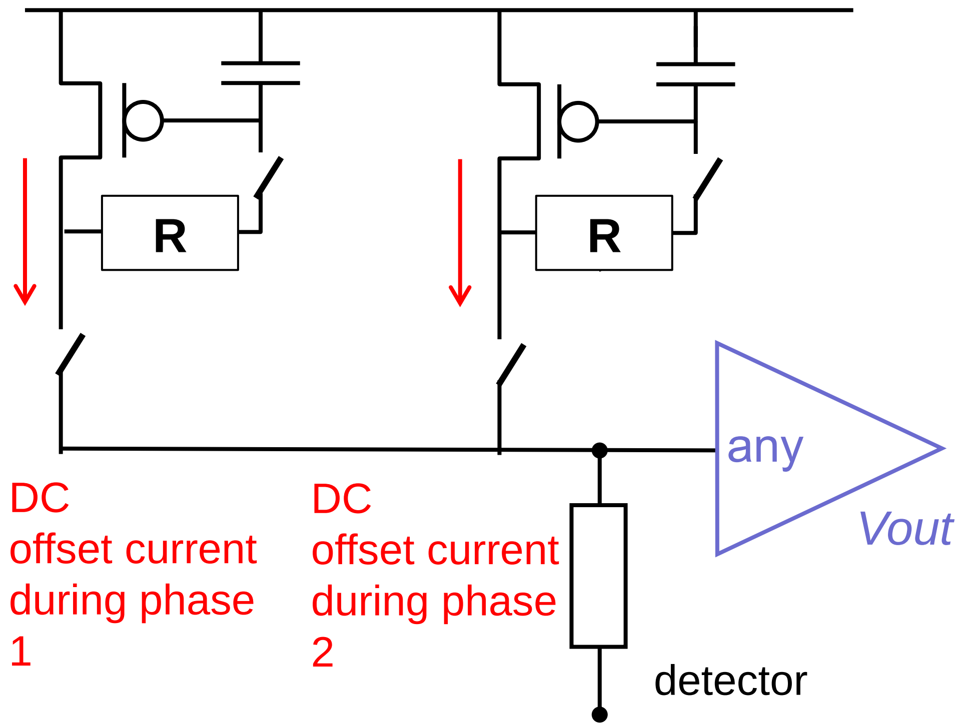
# Auto-set subtracted current




The required offset current is measured during calibration or reference cycles



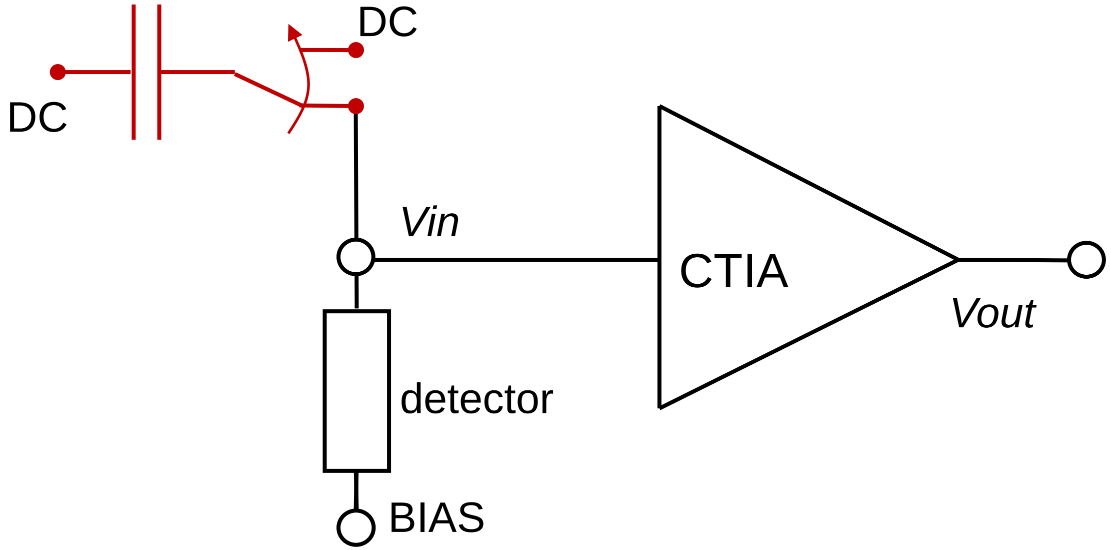

a low pass filtered offset current

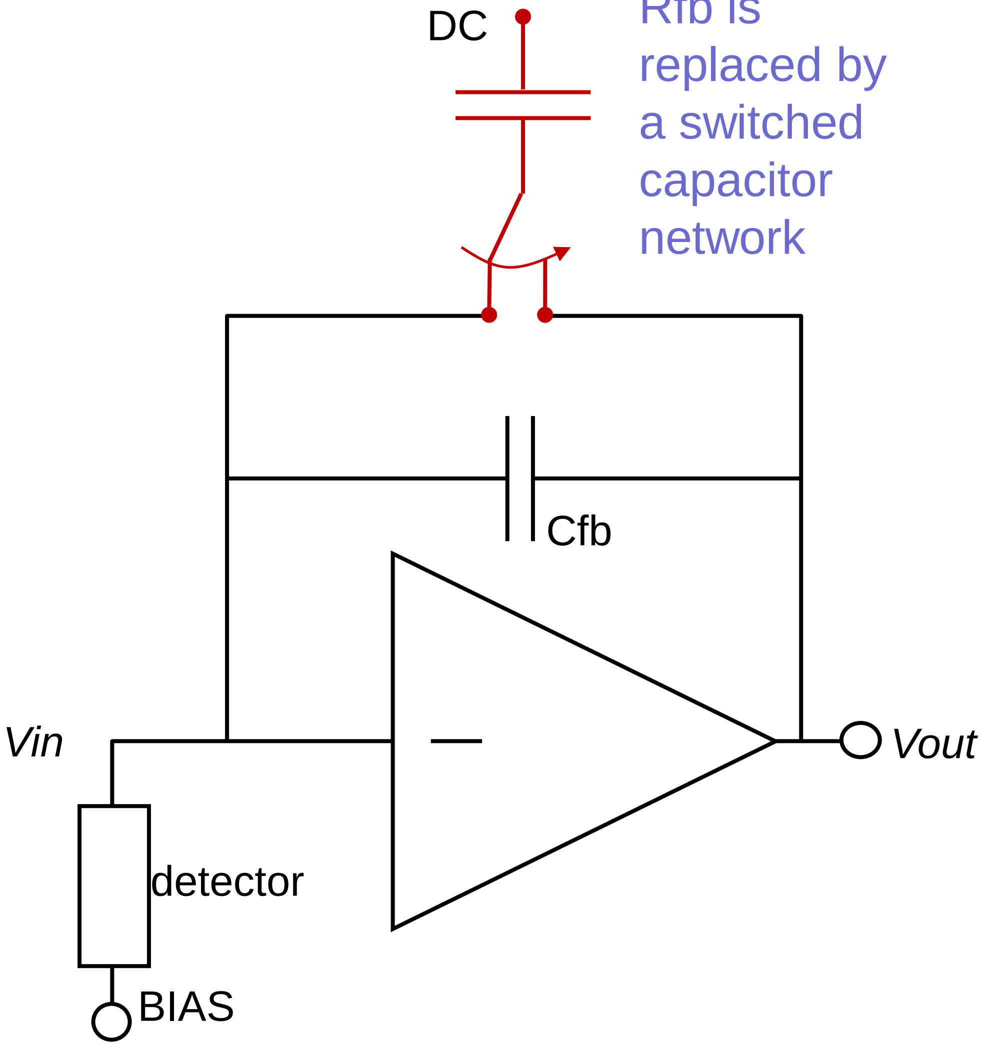



Useful to match two different average currents during two phases of a chopper.

# Two ways to generate the offset *current* with a switched capacitor

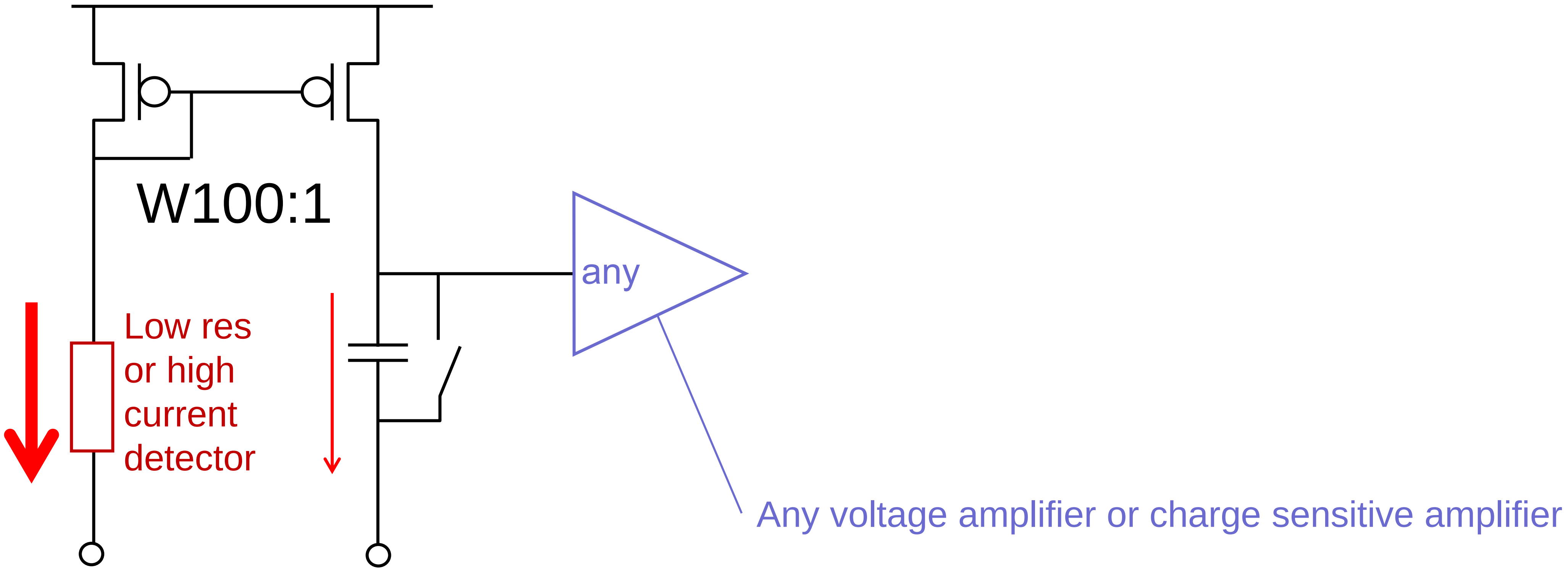
caeleste



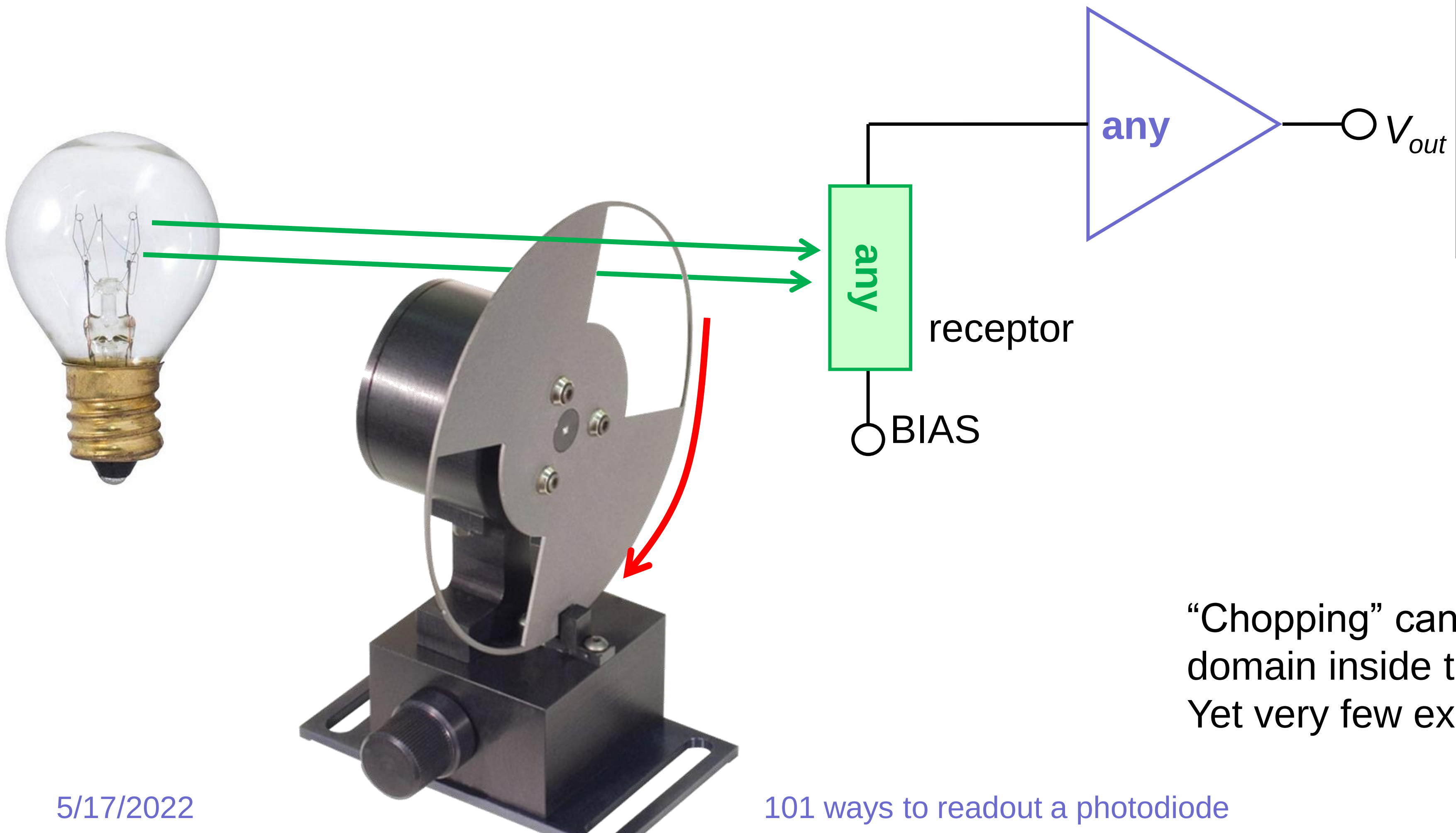

Rfb is replaced by a switched capacitor network

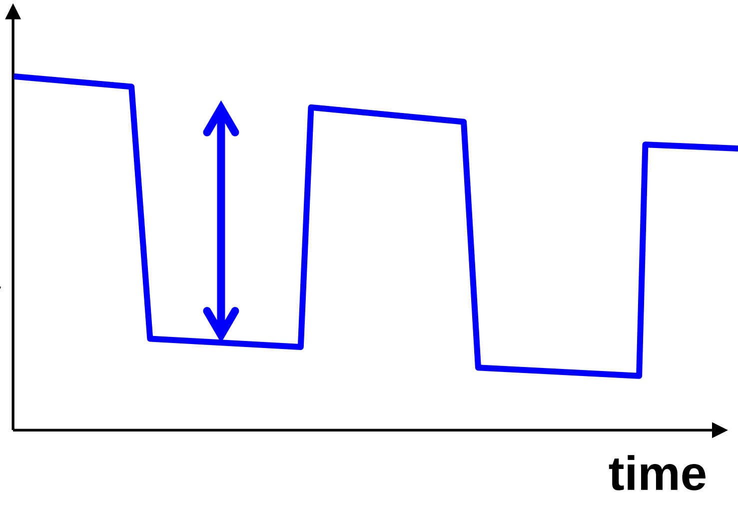
# How to handle huge currents



# Chopping

Modulate the input light flux.
The output modulated amplitude is the signal
In principle, chopping can be applied to any readout concept.



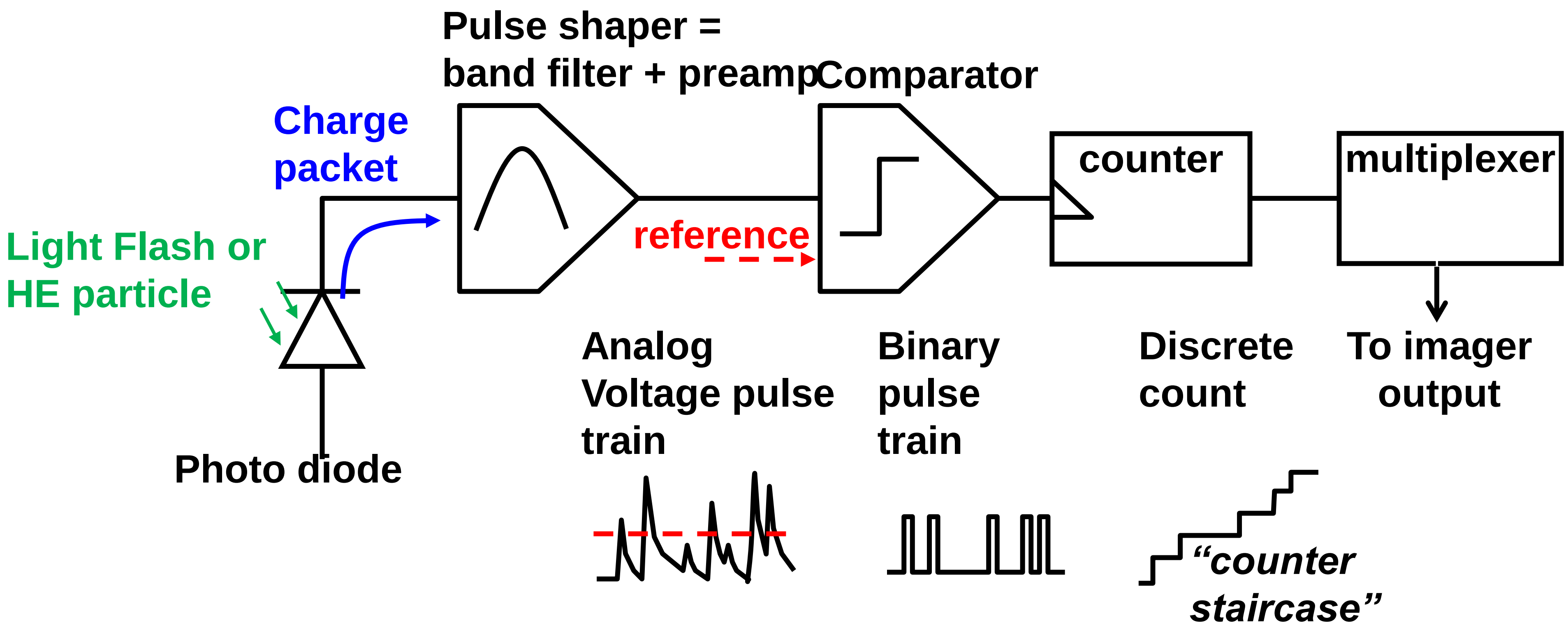

“Chopping” can also be applied in electrical domain inside the amplifier itself.
Yet very few examples are successful.

# 5. Photon/event counting

- Visible
- X-ray
- particles

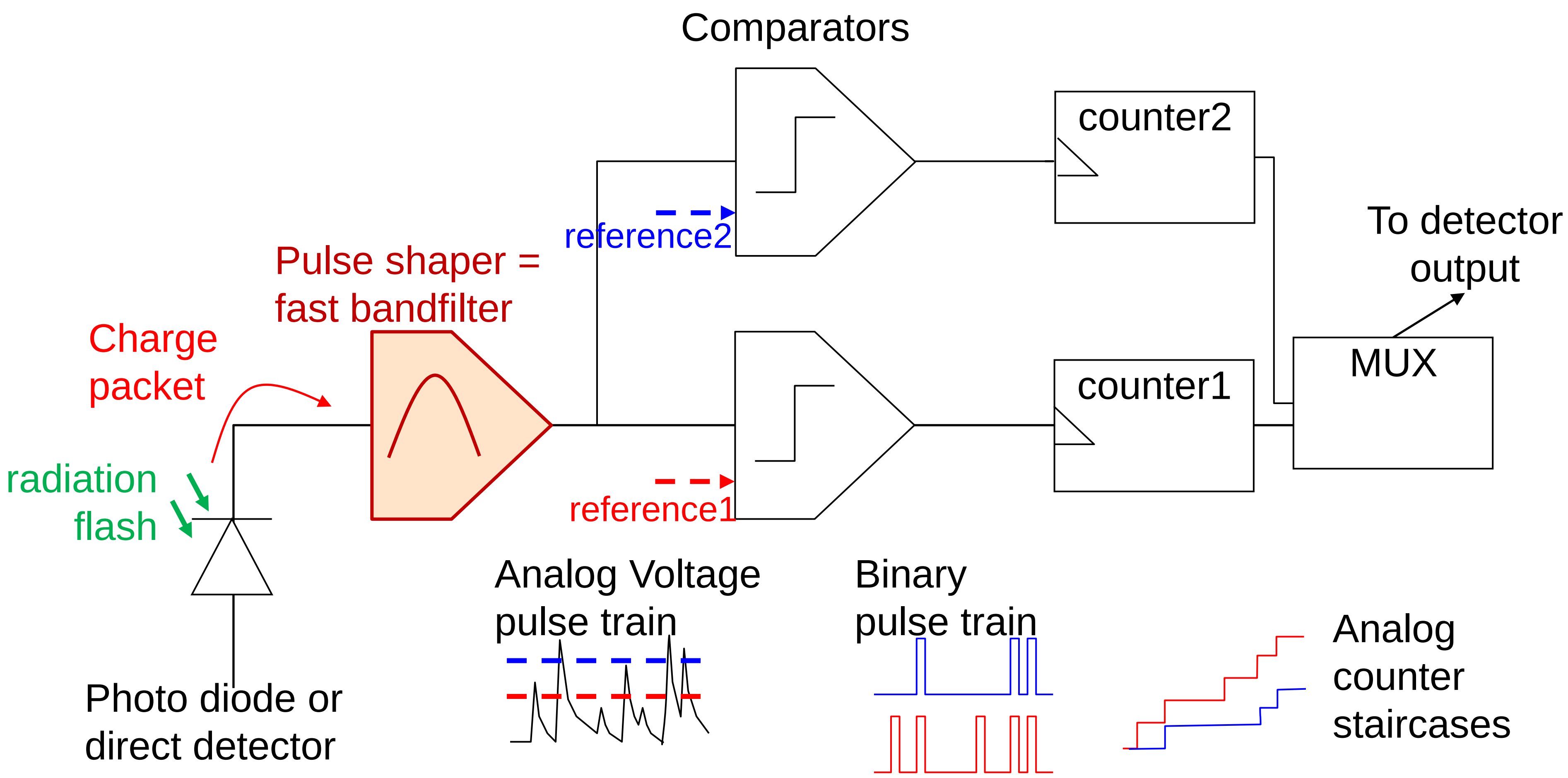
# Generic counting pixel topology



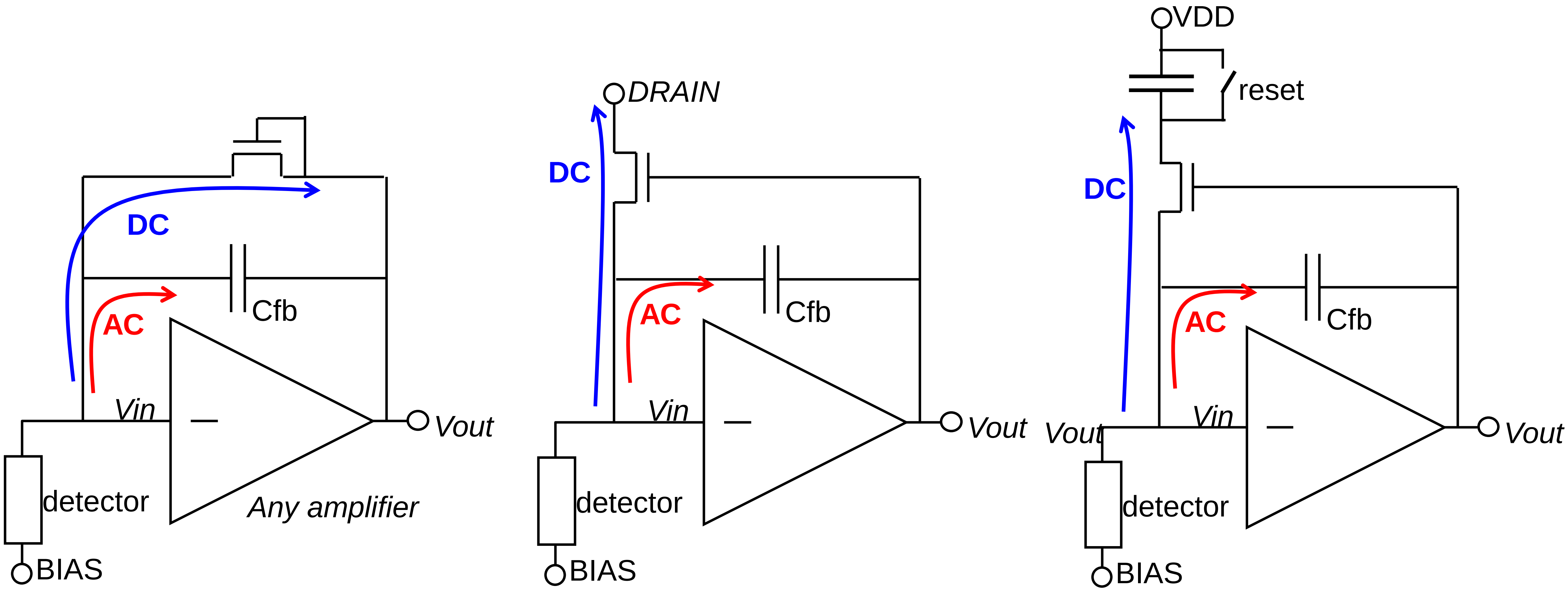


# Multi-energy photon counting pixel

caeleste

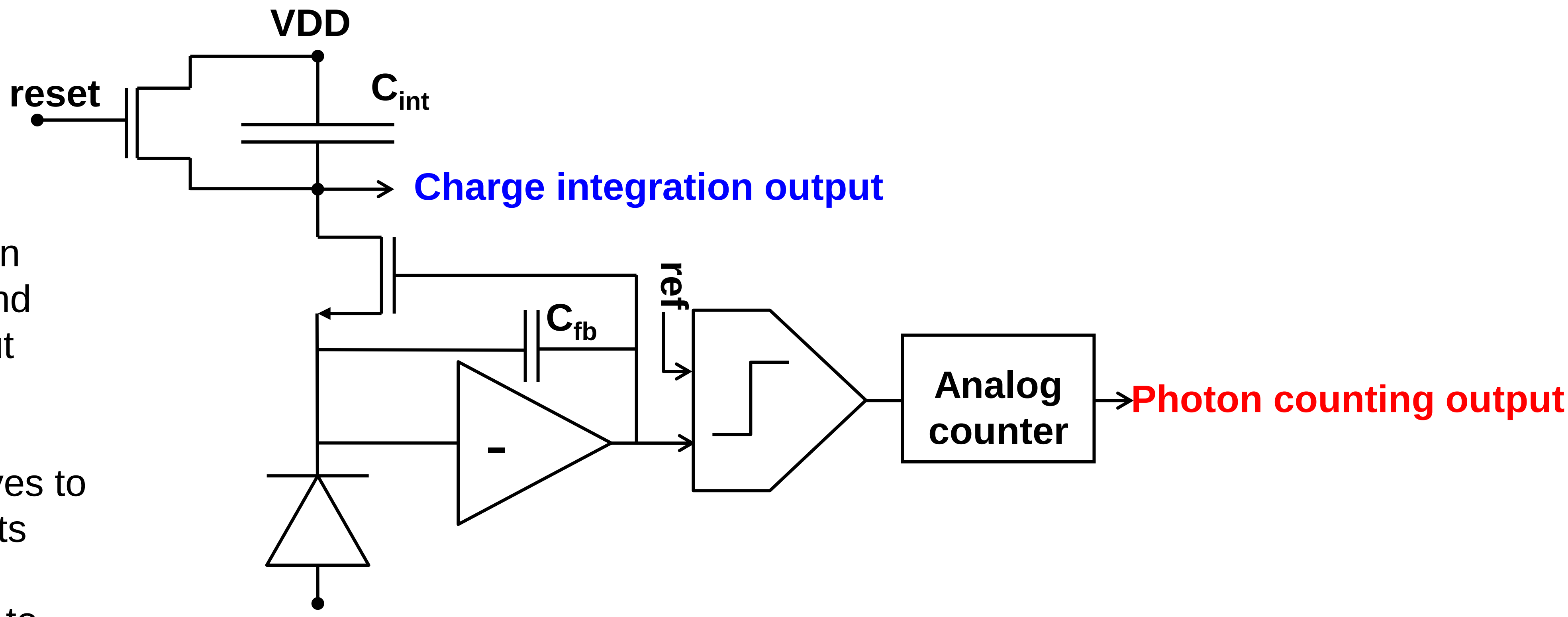


# This pulse shaper: (C)TIA with diode feedback



# integration and counting in the same pixel

using the same photocurrent




This further evolution separates the AC and DC parts of the input signal.

The AC current serves to count charge packets

The DC part serves to integrate charge.

patent US8426828

# 6.Time of flight

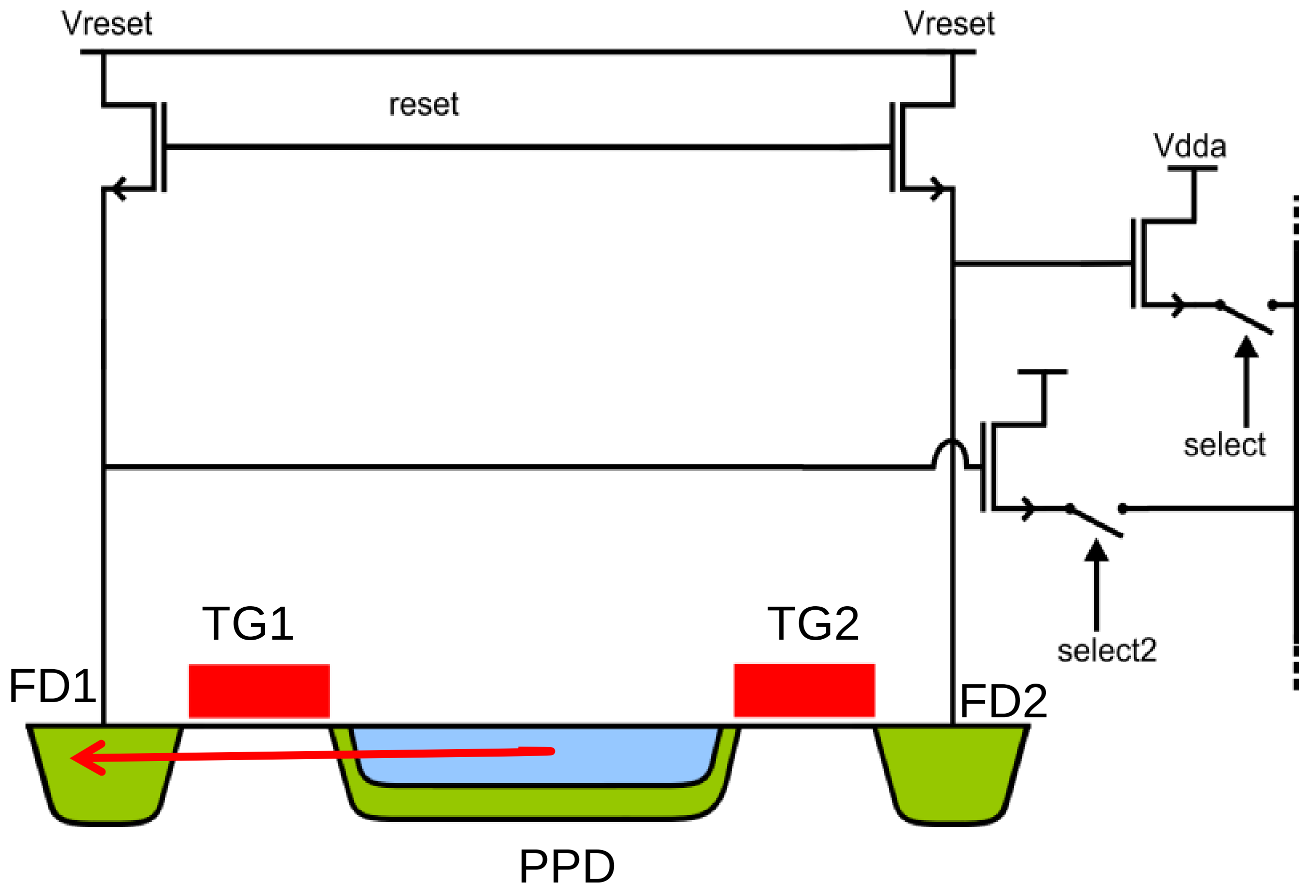
Using charge integration = “iTOF”

Using time gating: modulating the light sensitivity of a pixel at a very short time scale

Also known as “LIDAR”, “3D”, “iTOF”, “distance ranging”

# iTOF
## using CCDs, or PPD and TG

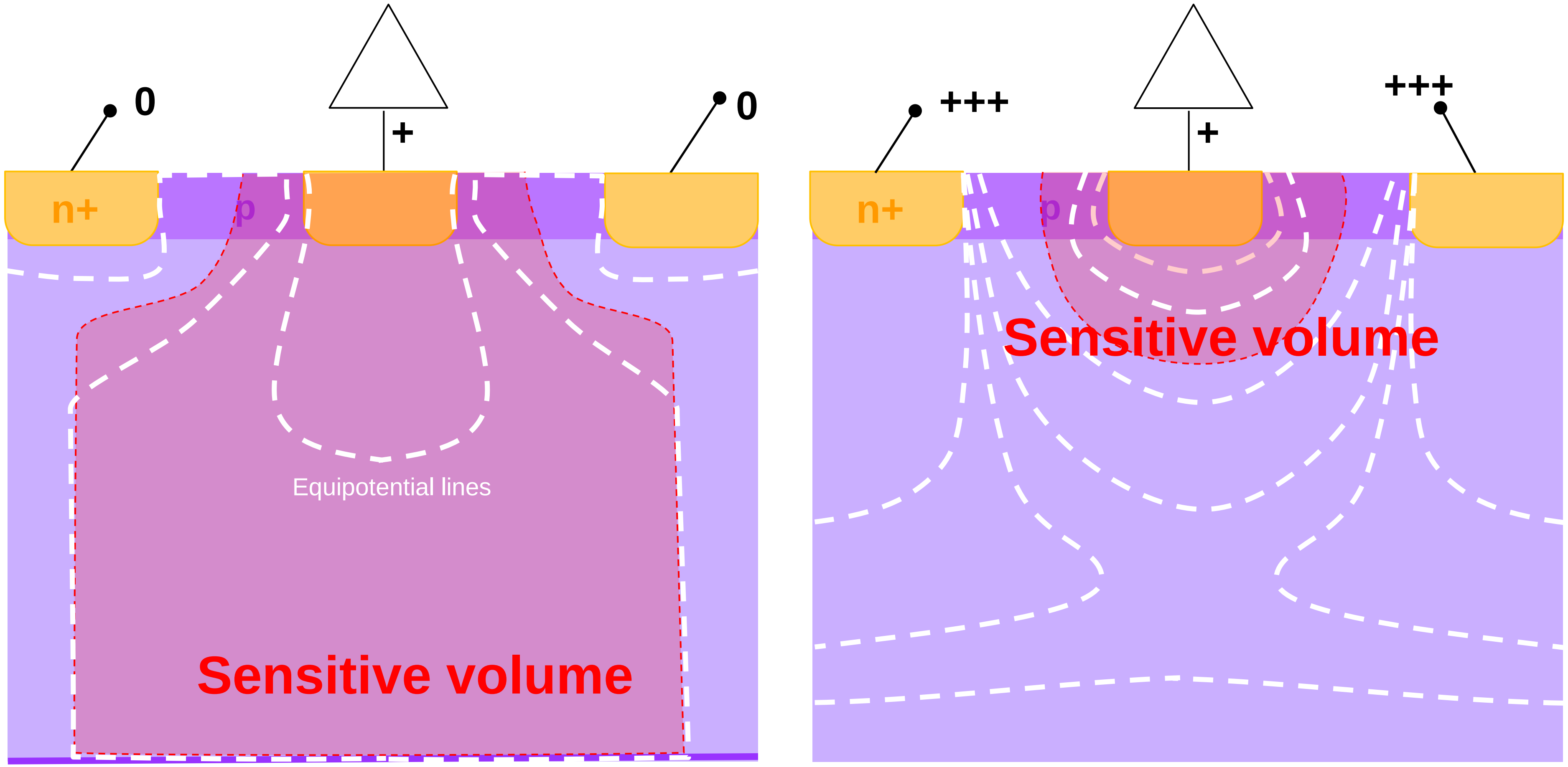
caeleste




- The photocharge can be collected by either “bin”, controlled by TG1/TG2
- Can switch at ns time scale.
- The concept is a descendent of the oldest of all TOF concepts using ILCCD.
- Speed is limited by the charge transfer from PPD to FD.
- In use in many variations:
  - number of transfer gates of “bins”
  - Variants on the read out structures
  - Enhancements for high speed readout.
  - …

# In this pixel the sensitivity of the photodiode itself is modulated

caeleste




- The sensitivity of the photodiode itself is modulated by surrounding junctions.
- Can switch at ns timescale
- Speed is limited by the driving voltage on the junctions.
- Weaker point compared to the CCD-like methods: pixel is not completely blind in off state.

patent US7564022

# 7. Direct access pixels

Not integrating
Not counting
Not even TOF

# True random addressing

caeleste

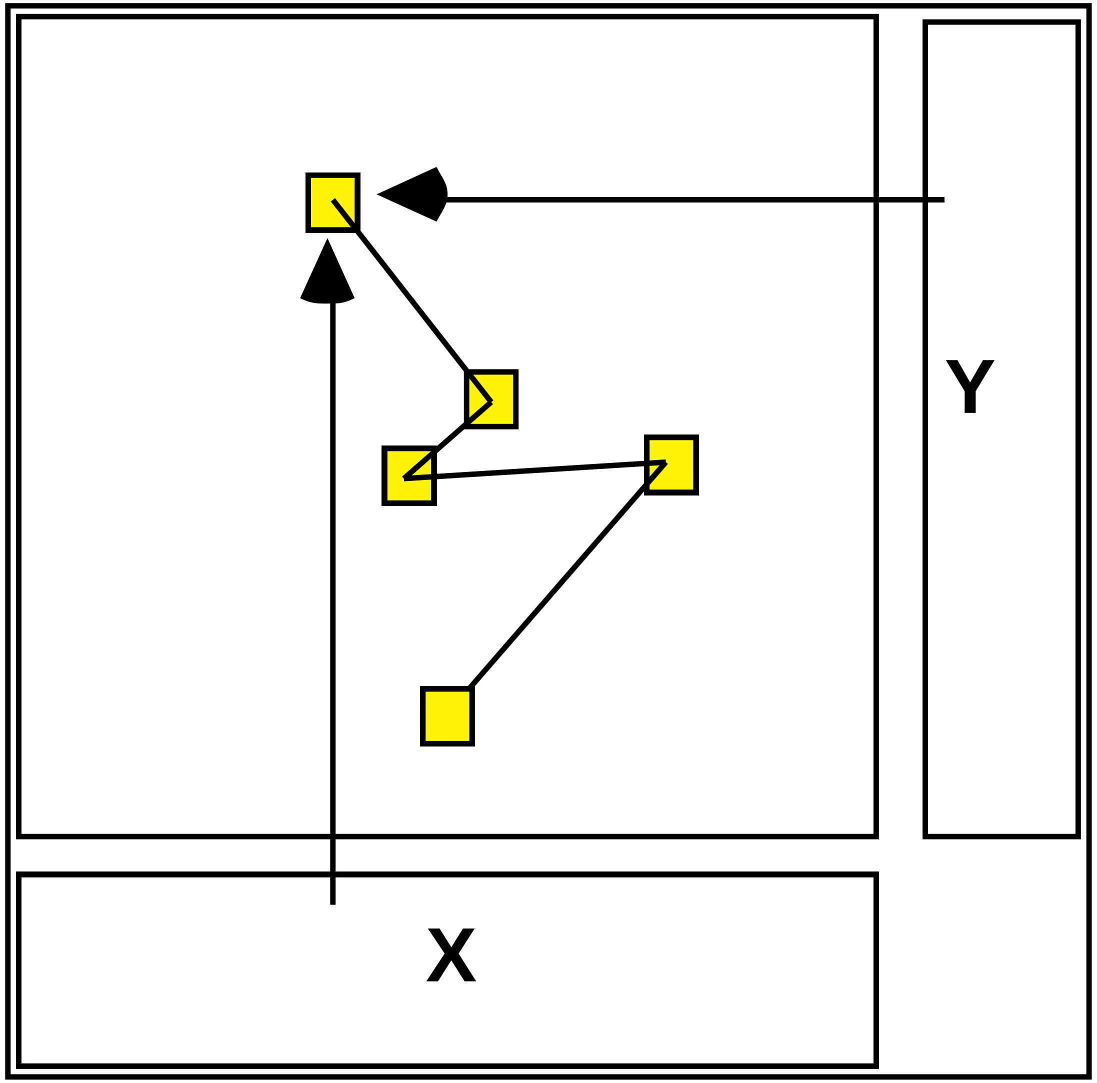
Any pixel can be addressed in any sequence

Needs direct access pixels

- = non-integrating pixels
- = pixels that convert photocurrent to voltage instantanously

This is not the same as
Random *row addressing* in integrating imagers

- In many imagers pixel rows can be addressed randomly
- within the row, full serial scan or windowing takes place.
- There is still a deterministic, fixed integration time

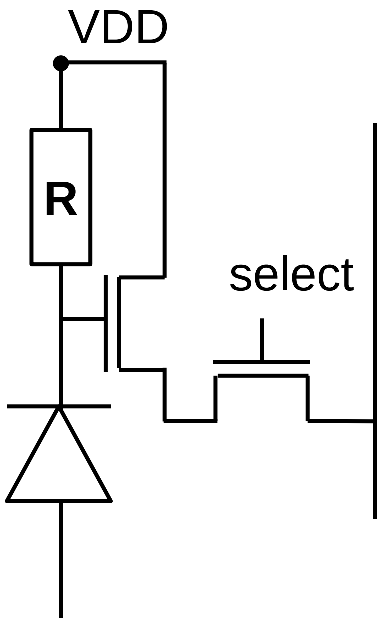


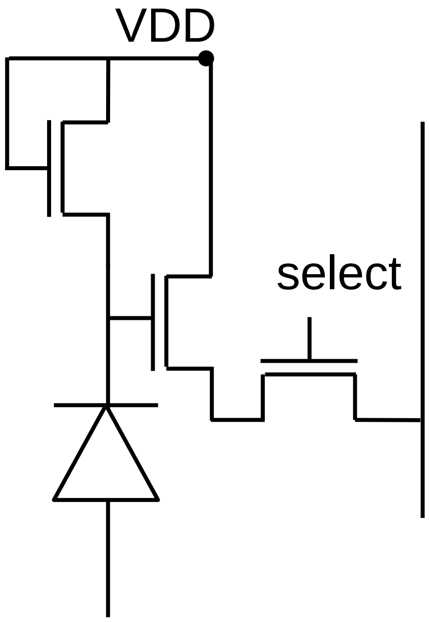
# Direct access pixels

caeleste

Such pixel must permanently translate photocurrent to voltage.

The simplest ways to do so are shown here.



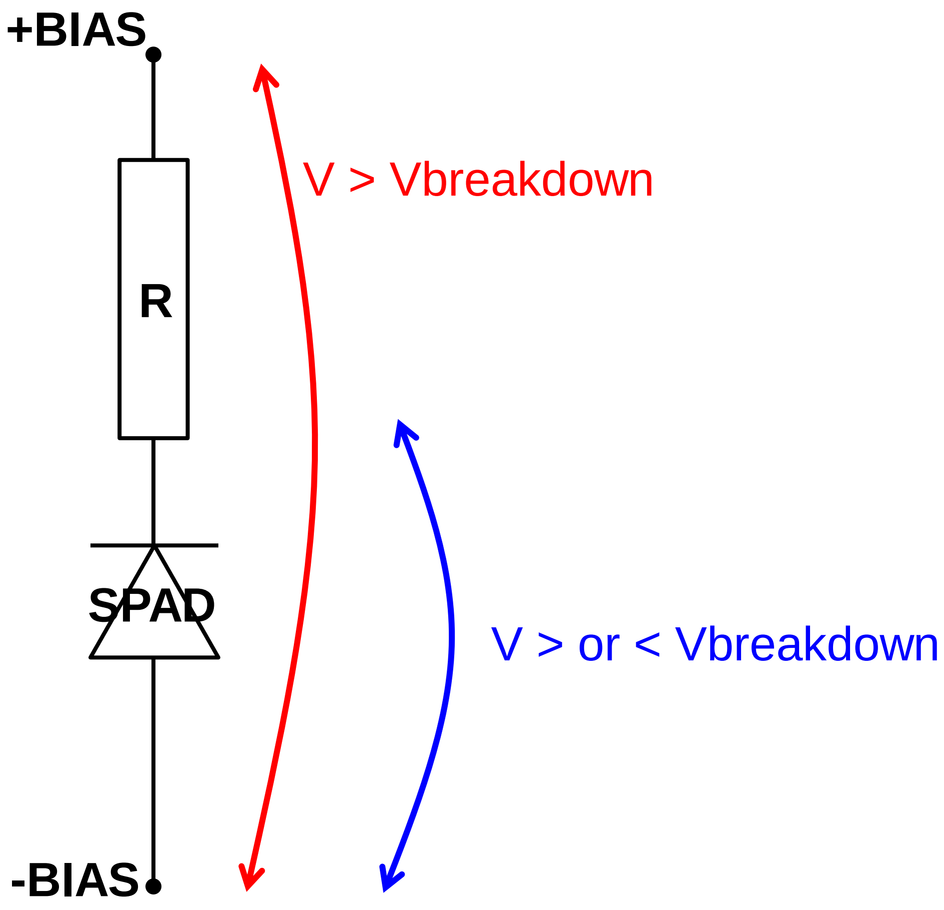
# 8.SPAD and SiPM

Single Photon Avalance Diode

Silicon Photomultiplier

dTOF

# “Passive” quenching of a SPAD




Elementary background on SPADs is assumed.

When carrying no current, the full bias voltage stands over the SPAD.
It will eventually break down once a photon is absorbed.
Then the series resistor reduces the SPAD voltage below breakdown, thus “quenching” the current, and allowing the SPAD to self-recover

PRO:

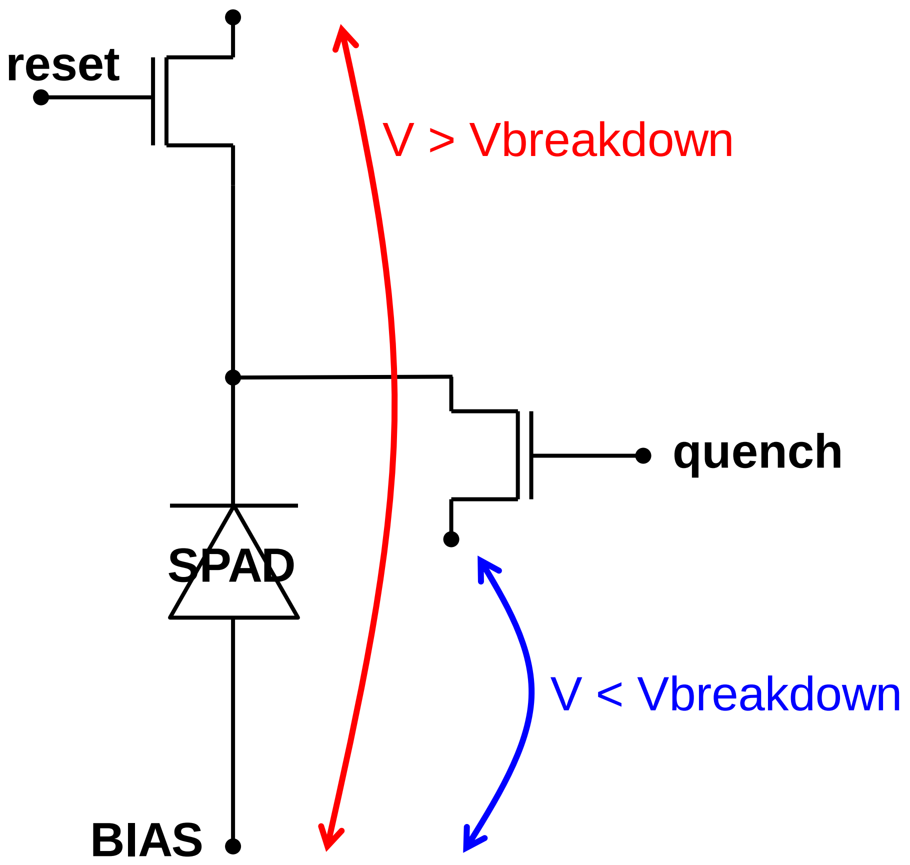
Easy, compact

Con:

Recovery may become very slow, and may result in afterpulsing.

# Active quench&reset with a SPAD

caeleste

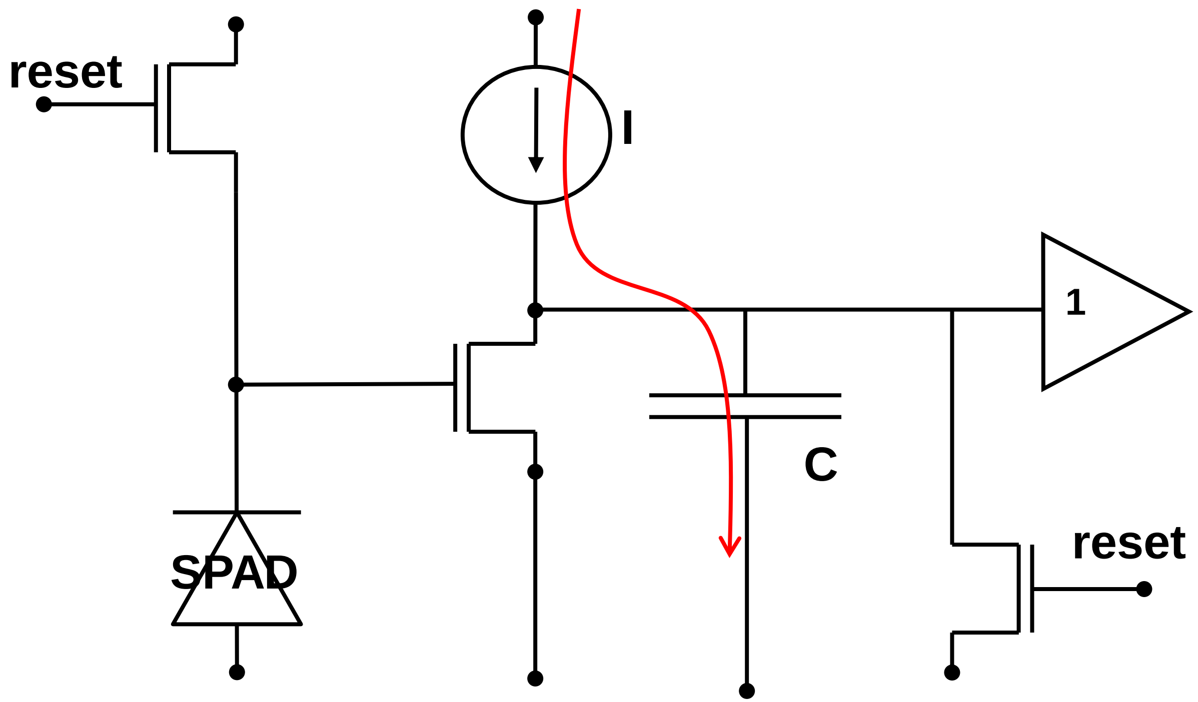



The SPAD is brought beyond breakdown by the reset switch.

Once a photon initiates breakdown, a sense circuit will activate the quench MOSFET for fast quenching and fast recovery.

Many variations on quench/reset circuits exist.

# Time to voltage with SPAD




One particularly compact circuit that translates time to voltage.
~~Tens~~ hundreds of alternatives exist.

The current I is integrated on C, as soon as the SPAD breaks down.

This can be used in a distance ranging application. It is then a **"dTOF"** pixel.

# SiPM "Silicon photomultiplier"

caeleste

from ON / SensL website

Is a solid state approximation of the functionality of a vacuum tube photomultiplier.

Is an array of SPADs each biased with a resistor, as "passive quenching"

- Biased beyond $V_{breakdown}$
- A single charge from a single photon initiates an unbounded avalanche multiplication
- Due to the high breakdown current, the voltage across the resistor rises and the voltage across the diode drops below $V_{breakdown}$ and ceases.

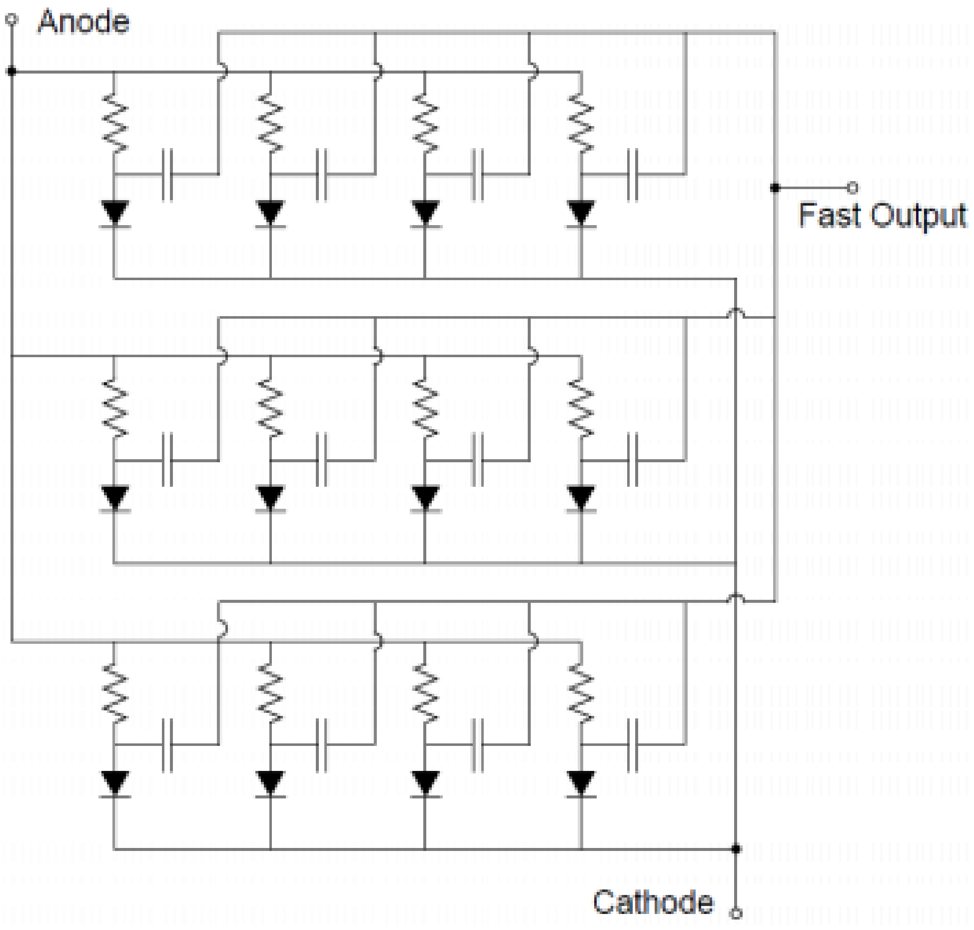



*Figure 4, An SiPM consists of an array of microcells (photodiode plus quench resistor) with summed output. The fast output is discussed in section 1.5.*

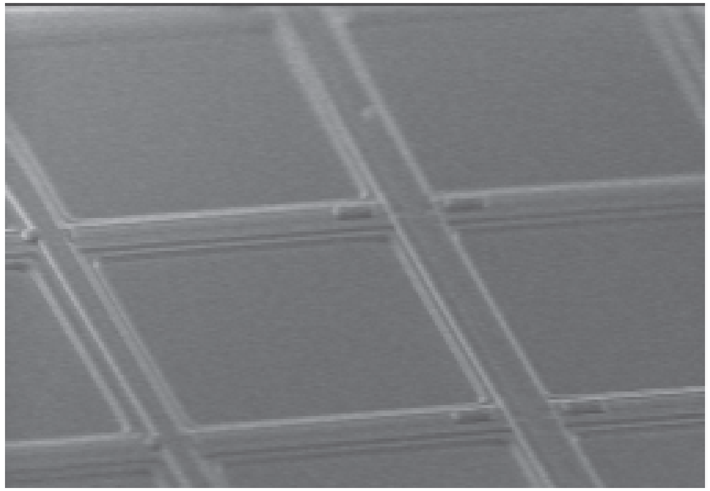


*Figure 5, Image showing the microcell structure of the SiPM surface*

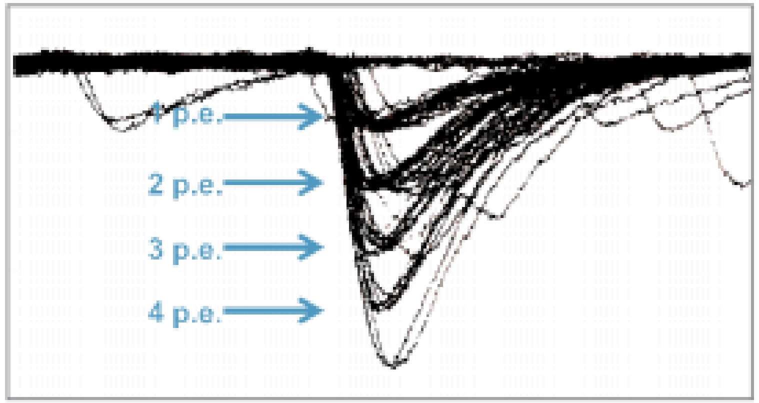


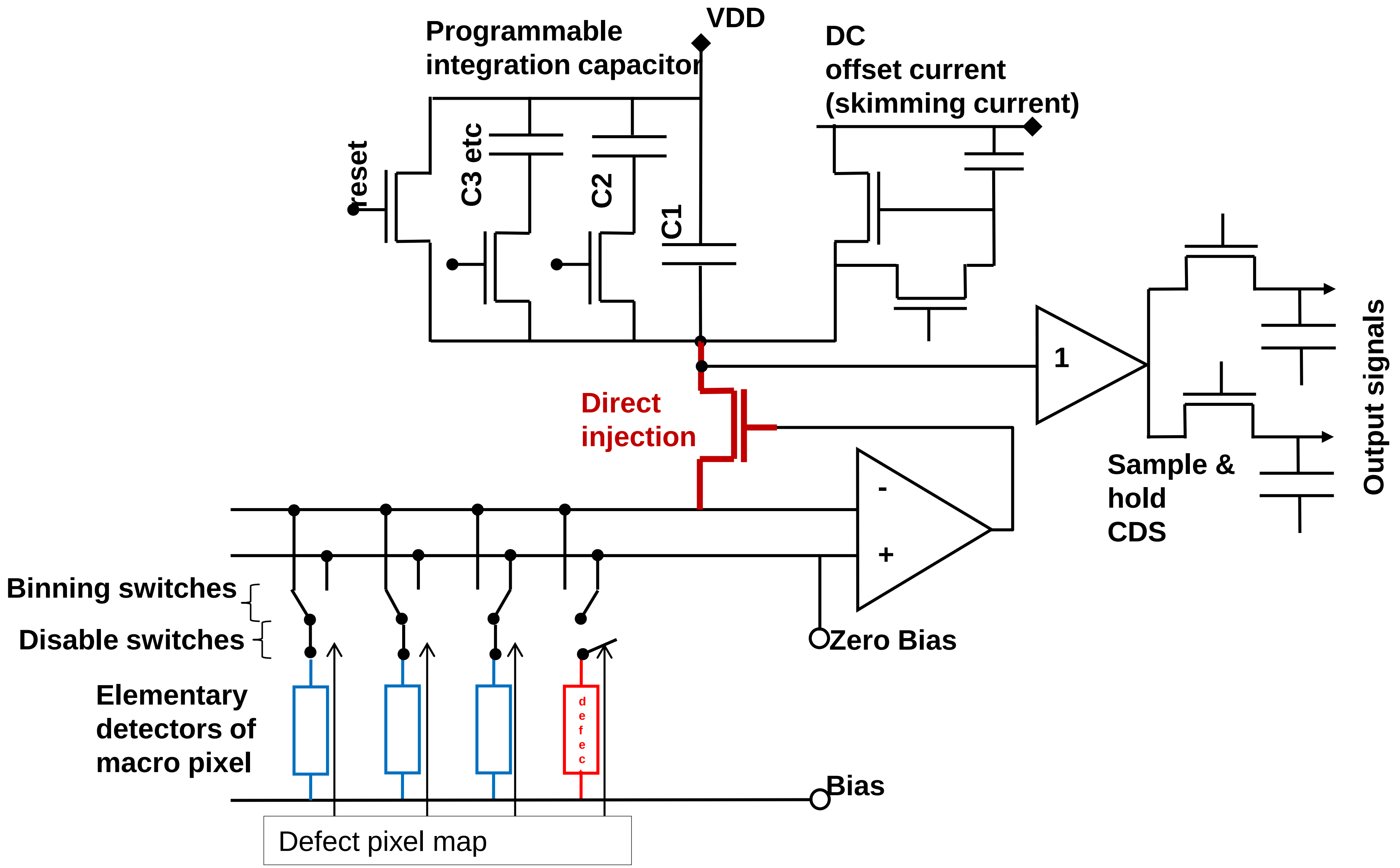

*Figure 6, Oscilloscope shot showing the discrete nature of the SiPM output when illuminated by brief pulses of low-level light.*

# 9.Highly programmable pixels

Just a few examples of real pixel designs

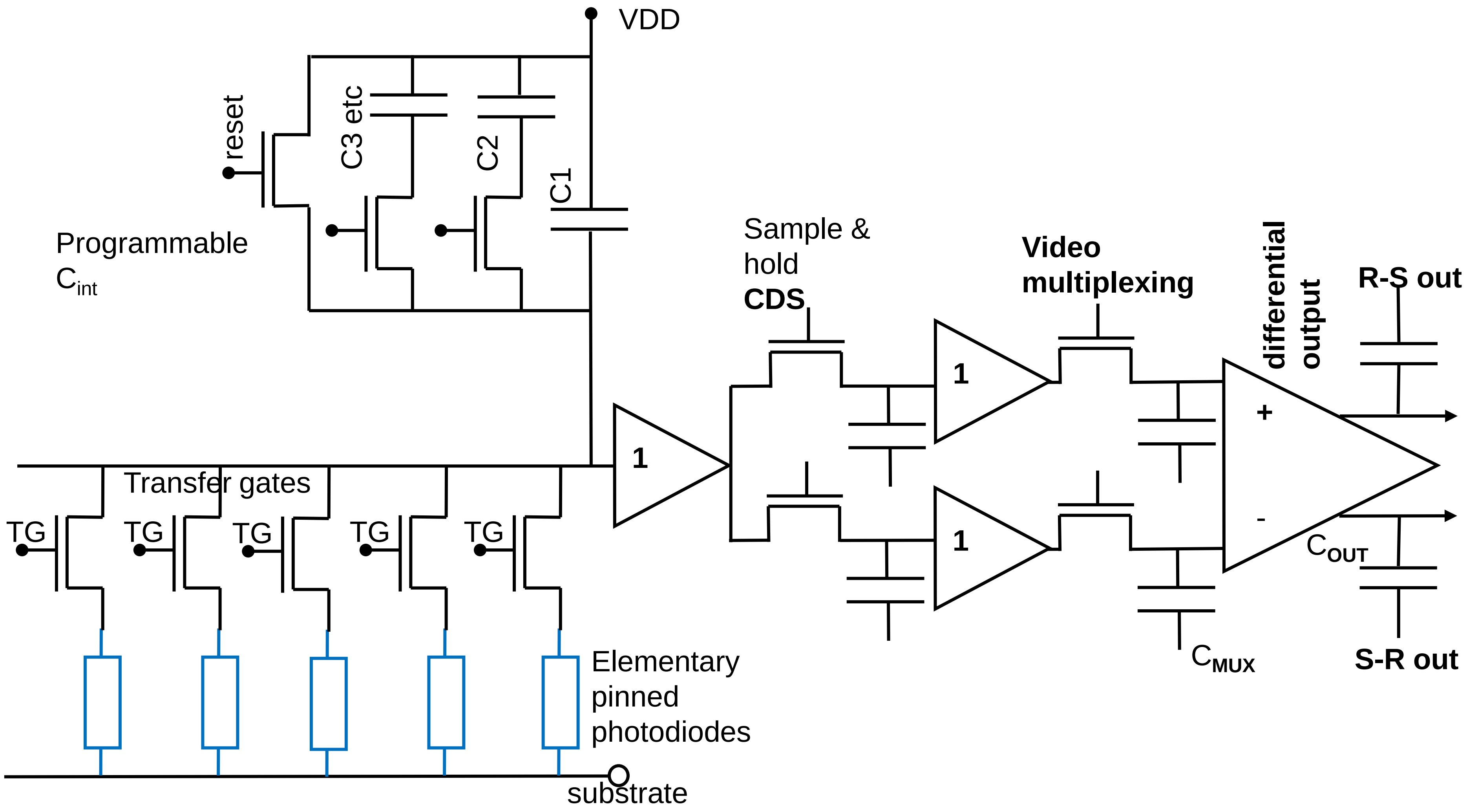
# Highly programmable DI pixel

caeleste

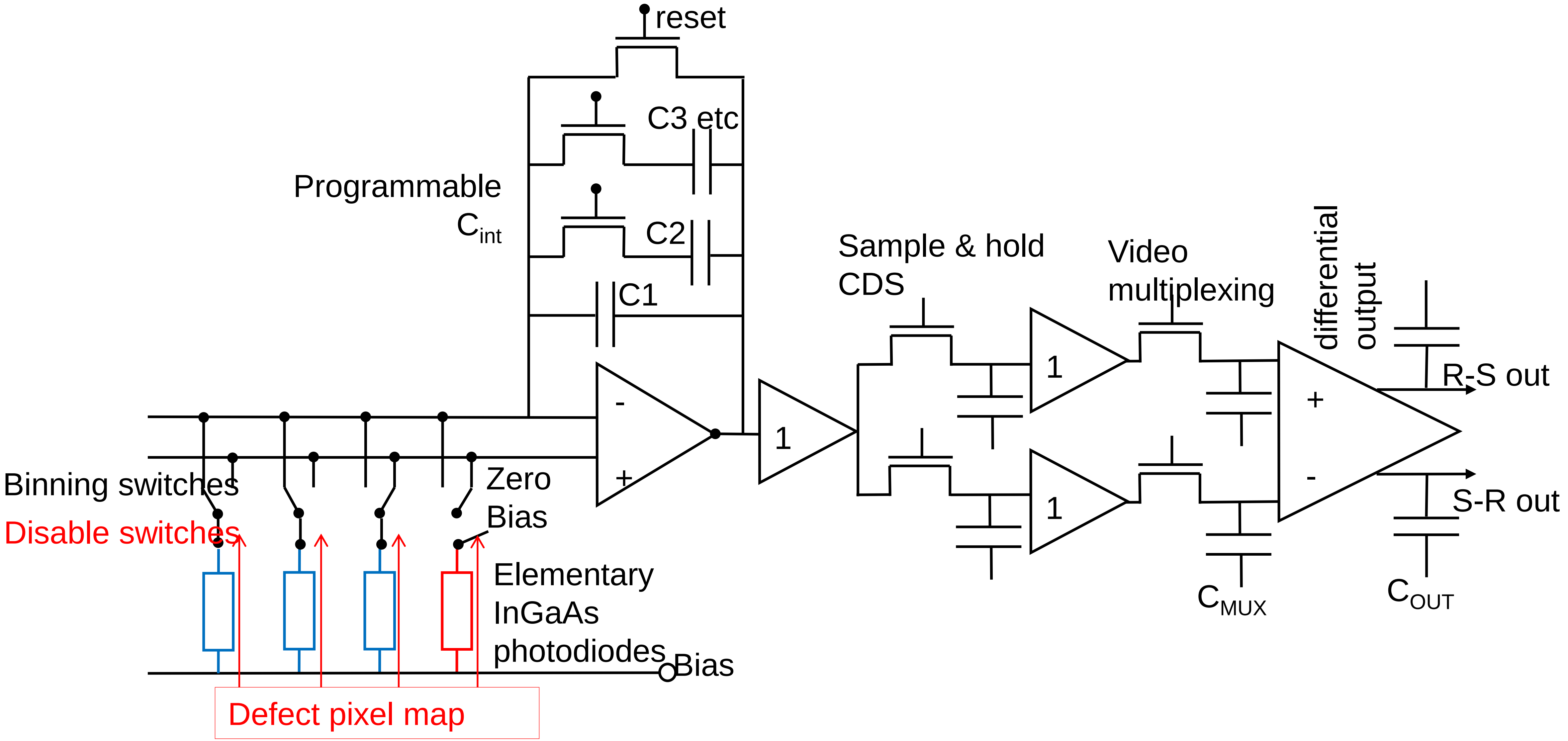


# Highly programmable “4T” pixel

caeleste



# Highly programmable CTIA pixel



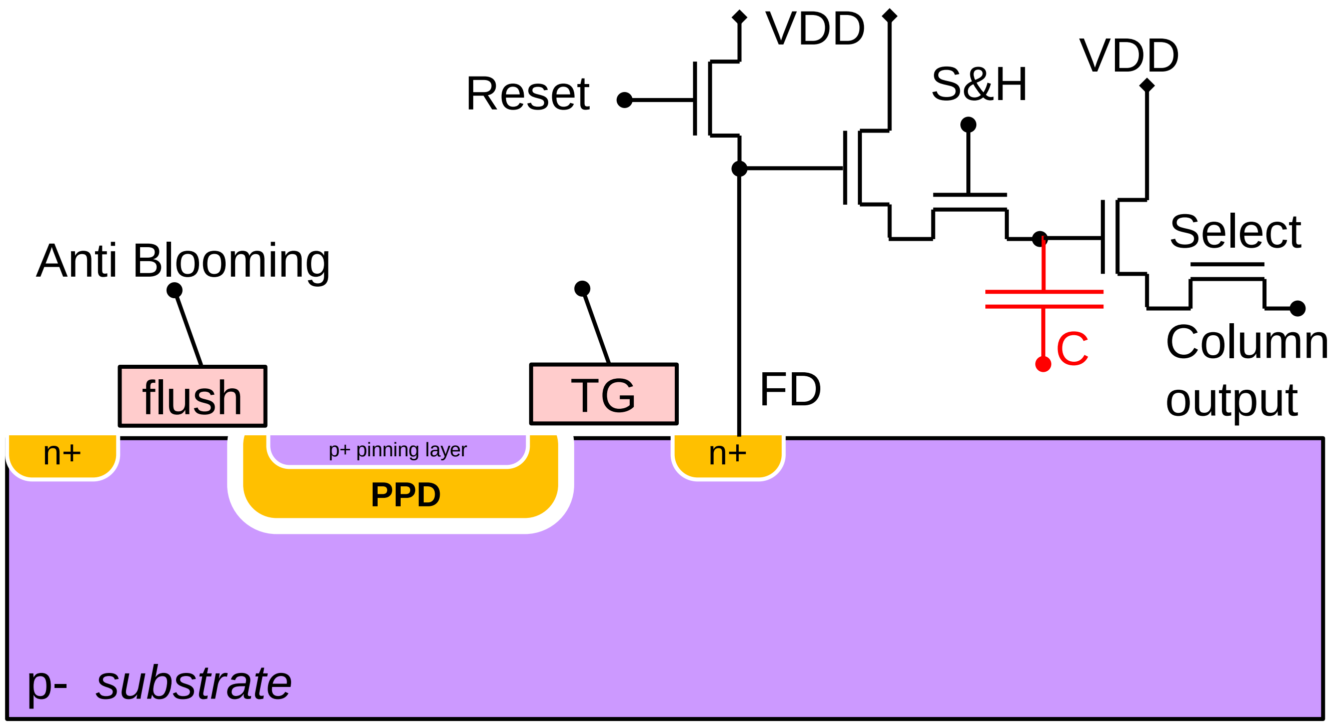
# 10.GLOBAL SHUTTER

Basic examples of

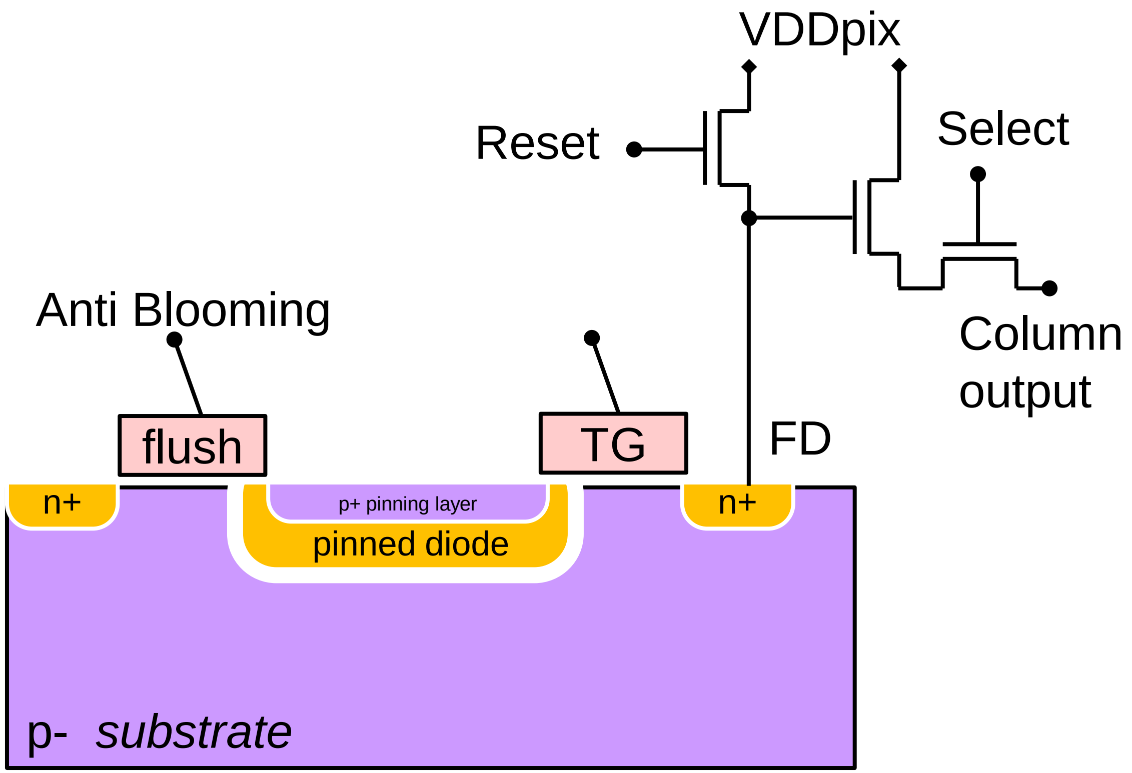
- voltage domain global shutter pixels: the information is stored as voltage
- charge domain global shutter pixels: the photocharge itself is stored

# “voltage domain” GS with a PPD pixel

A “6T” pixel.
Can do “IWR” (integrate white read)
but not CDS (correlated double sampling)



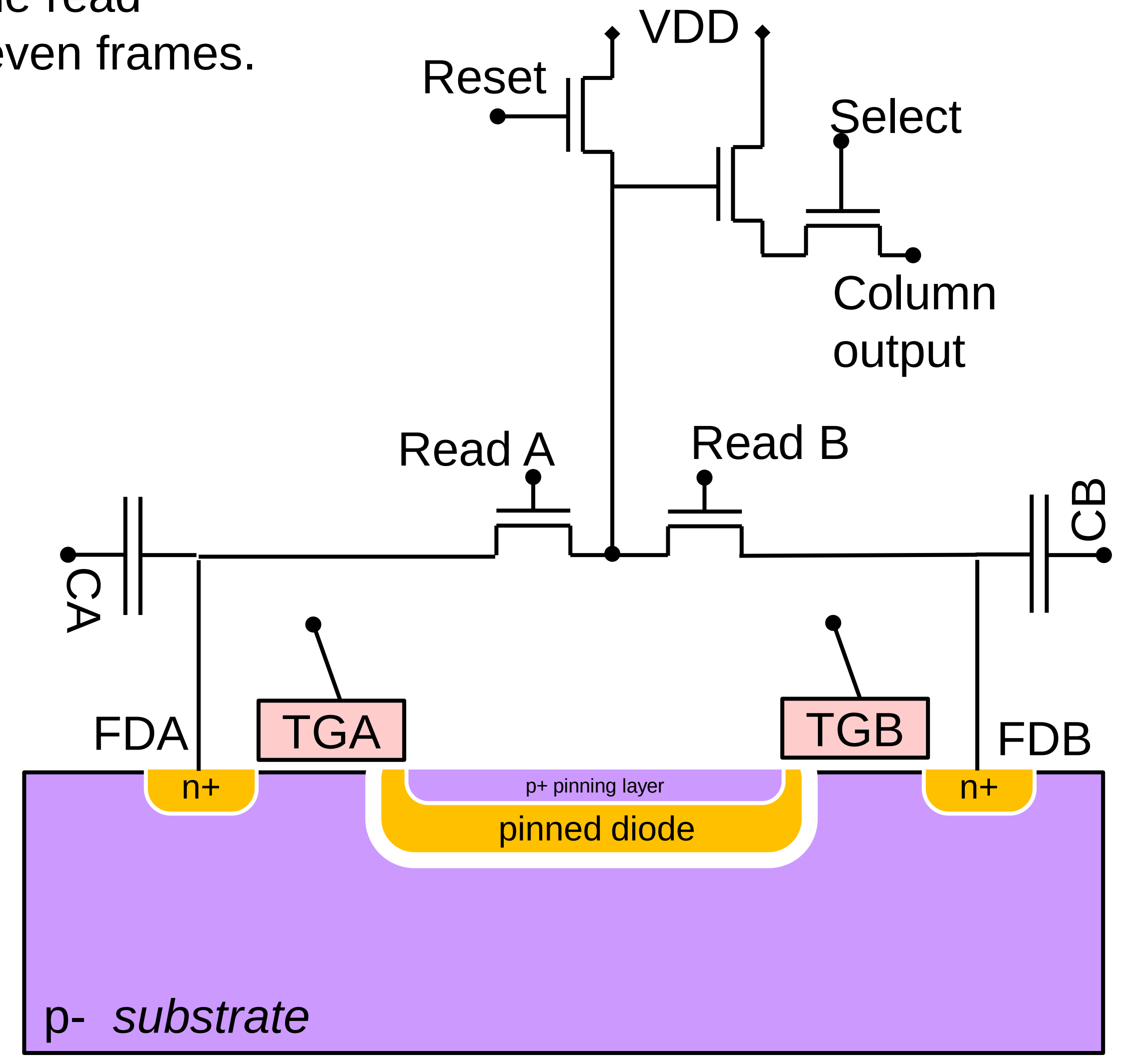

Simplification of the previous.
In fact here the FD itself serves
as S&H capacitor.



# GS and real “integrate while read” (IWR)

Can do full IWR = integrate while read
By using TGa and TGb in odd/even frames.

Still voltage domain!



# “charge domain” global shutter using “GS technology”



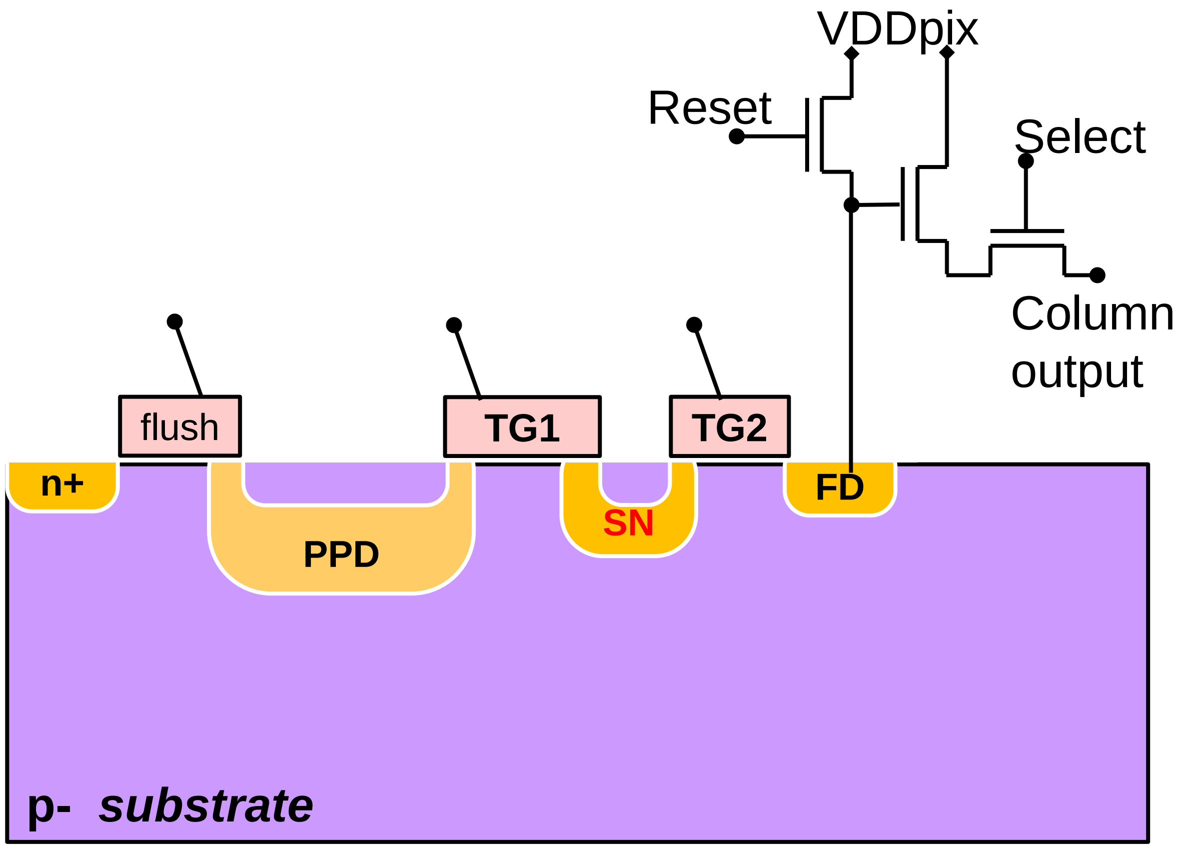



Photo-electrons generated in the Silicon are collected in the PPD during the “integration time” $t_{int}$.

At the moment of “global transfer”, all charges are transferred simultaneously to the SN “storage node”, using TG1

At readout, a “rolling” readout is done using TG2

# 11. “true” high dynamic range pixels

Why HDR?

- *Dynamic range* is a property of the scene or the thing to be measured. The pixel should handle it.

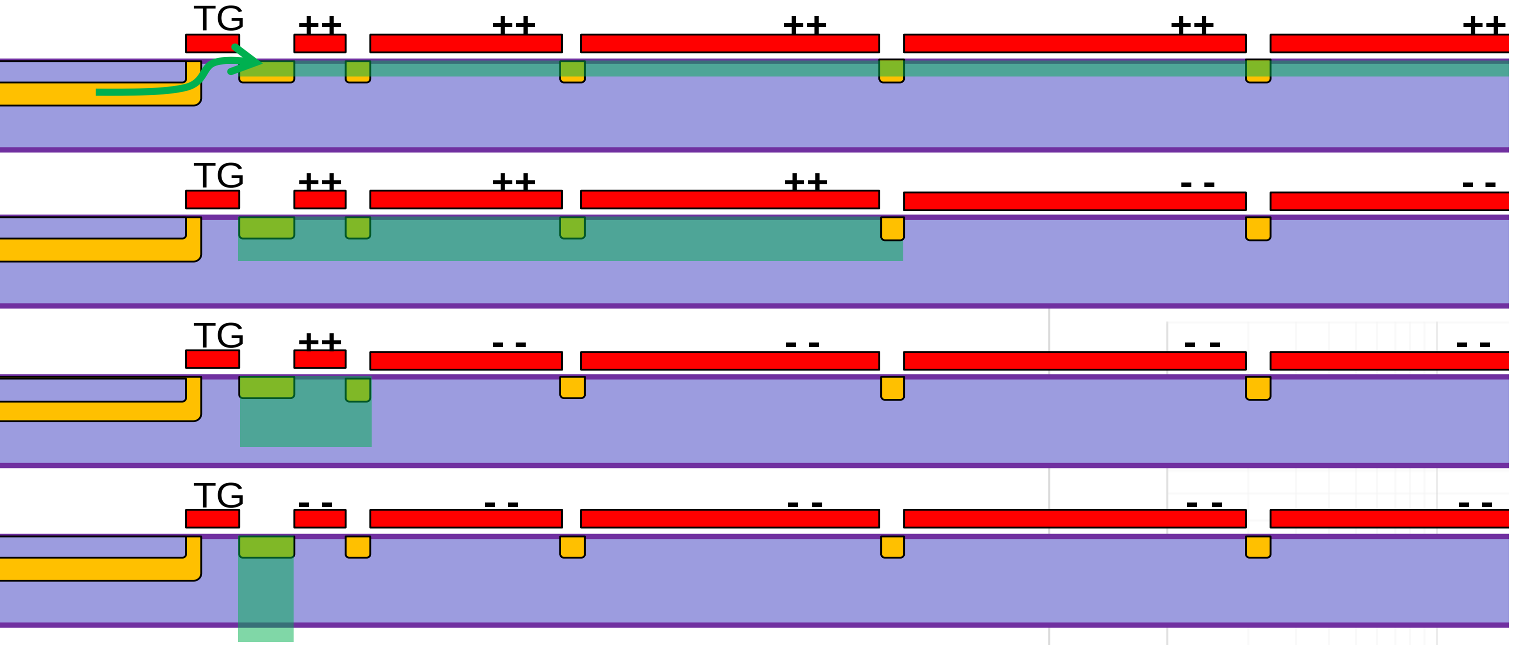
“True” means:

- For a given pixel, all ranges have identical integration time, thus being “Motion Artifact Free” (MAF)
- After reconstruction, the HDR is **PSN-limited** over the whole range
- CDS is possible

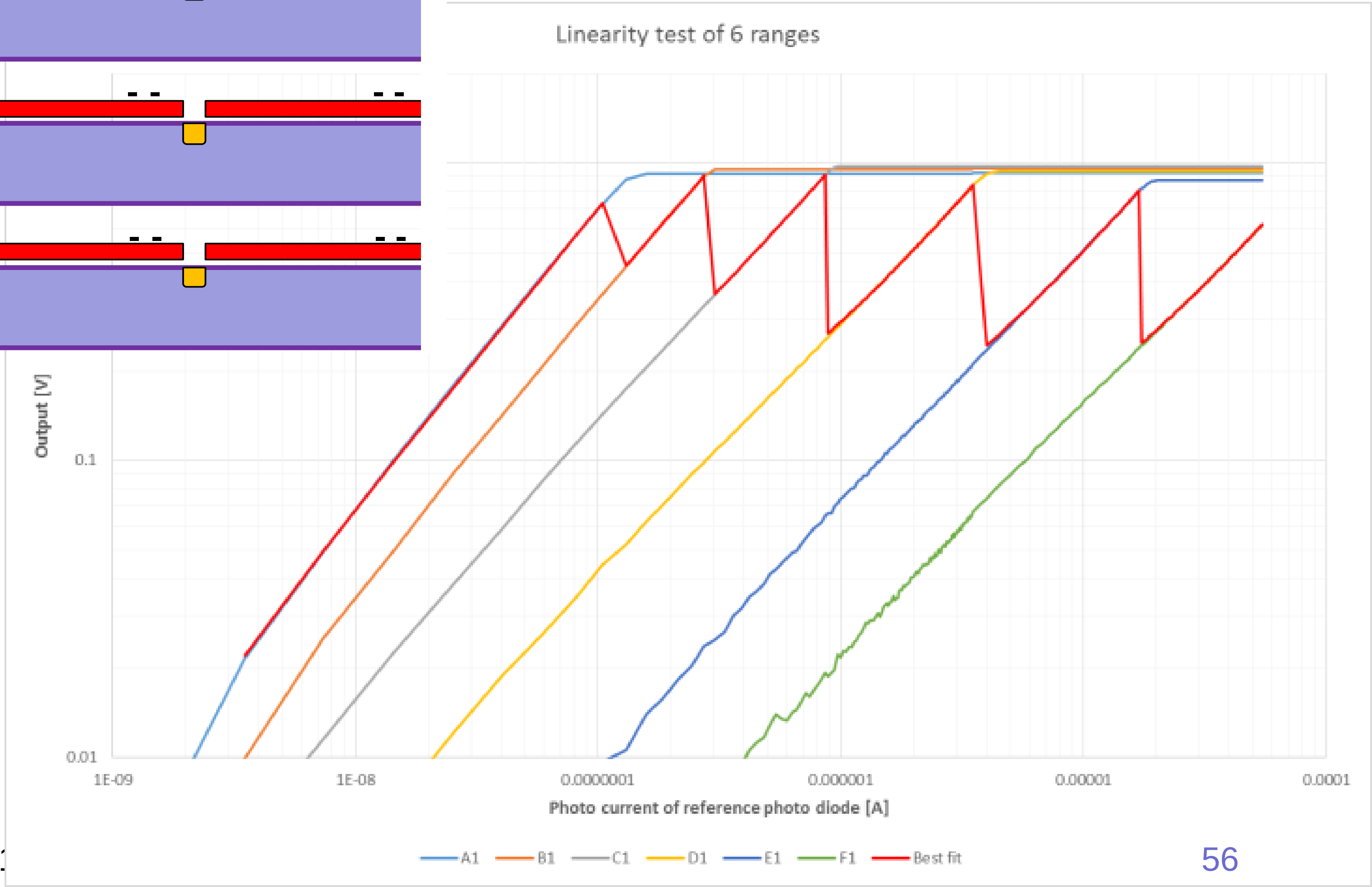
- Our examples executes integration and charge-to-voltage conversion on multiple capacitances *at the same time*, each having a different “range” or “$Q_{FW}$”
- All ranges are combined into one “high” dynamic range, off chip.

# The HDR “pushback” method



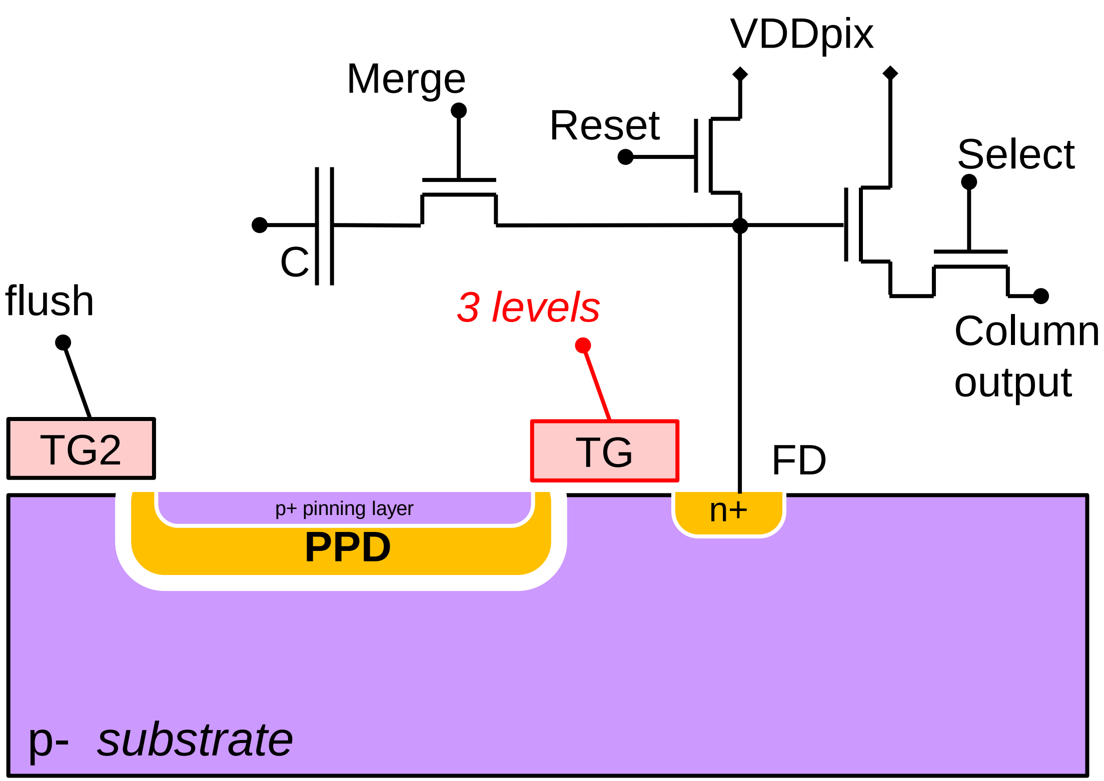



The photocharge is first collected in all inversion layers combined, in parallel to the FD.
Then the charge is pushed back, and each time the FD is read out.

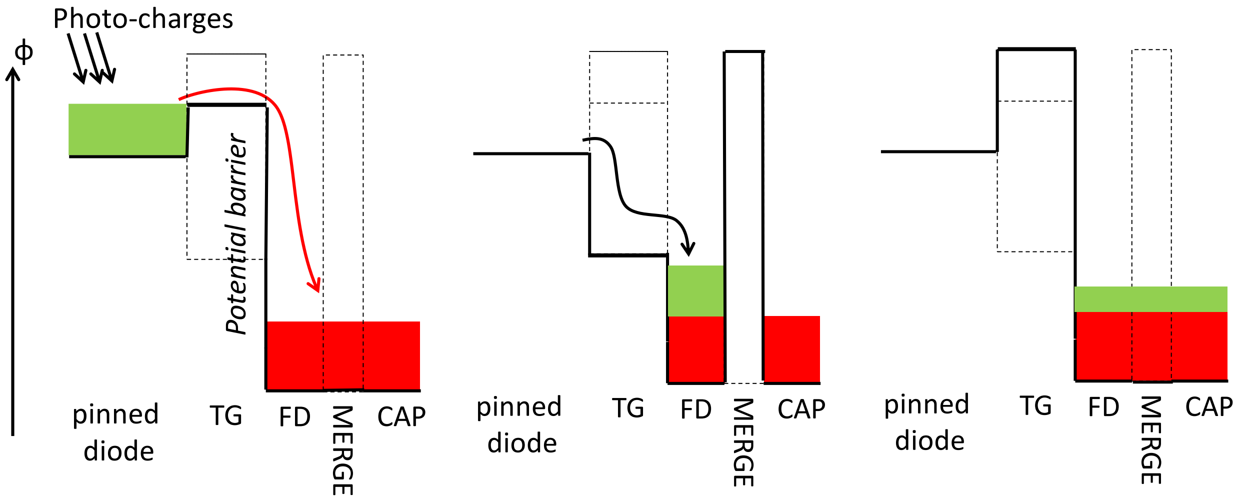


Gaozhan Cai & al., “A method to increase DR using column-level automatic gain selection”, IISW, May 31, 2017, Hiroshima

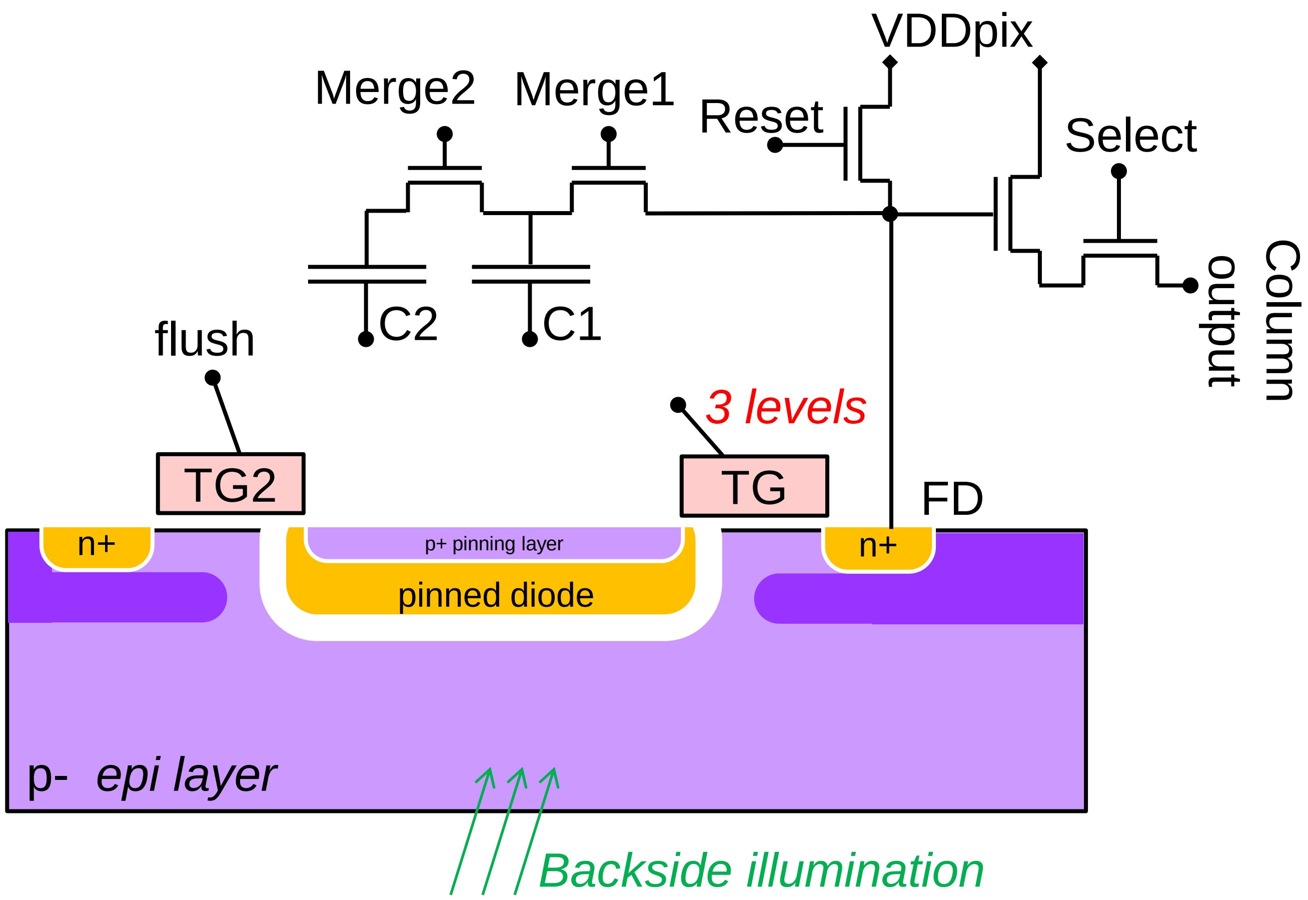
# 3-Level TG Method




- The photocharge that does not fit in the PPD overflow during integration into the FD.
- It is collected by the overflow capacitor “C”
- At readout time, first we isolate C, thereafter we read the PPD charge in the classical way
- Thereafter we shunt C to the FD again and readout the total charge.



# 3-level TG with 3 (4…) ranges



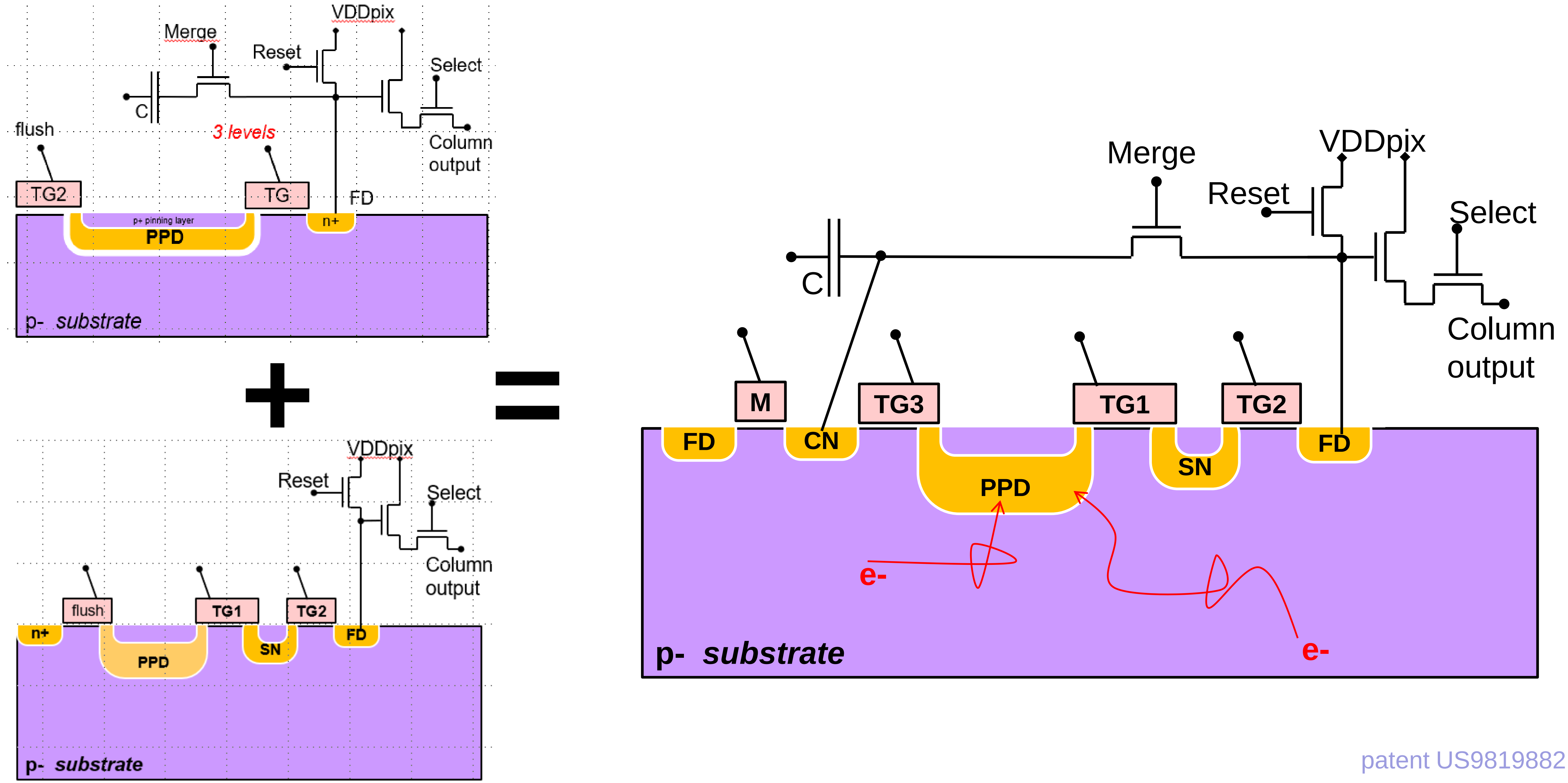

- A further elaboration of the previous with 3 $Q_{FW}$ ranges

# 12.True HDR in GS pixels

True HDR and also “MAF” (motion artifact free)

# Charge domain GS + HDR



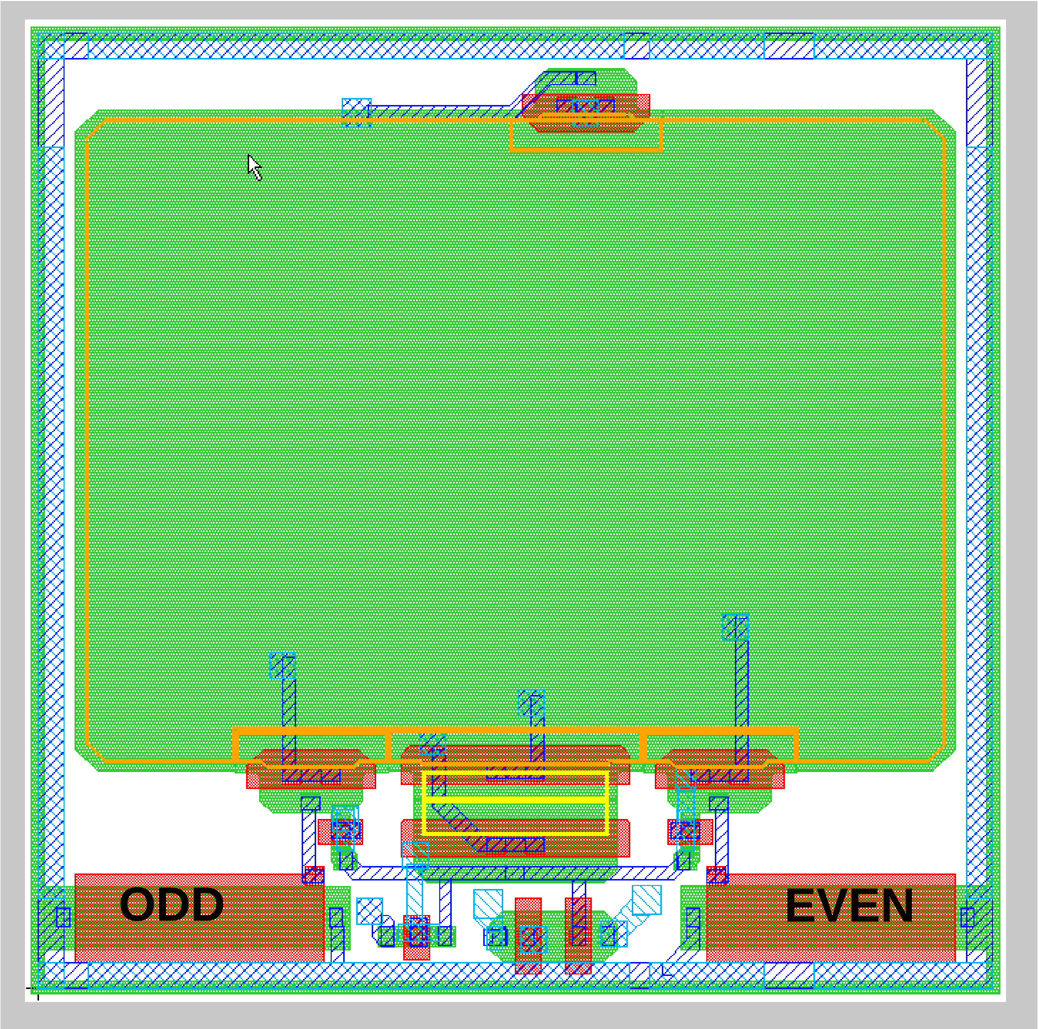


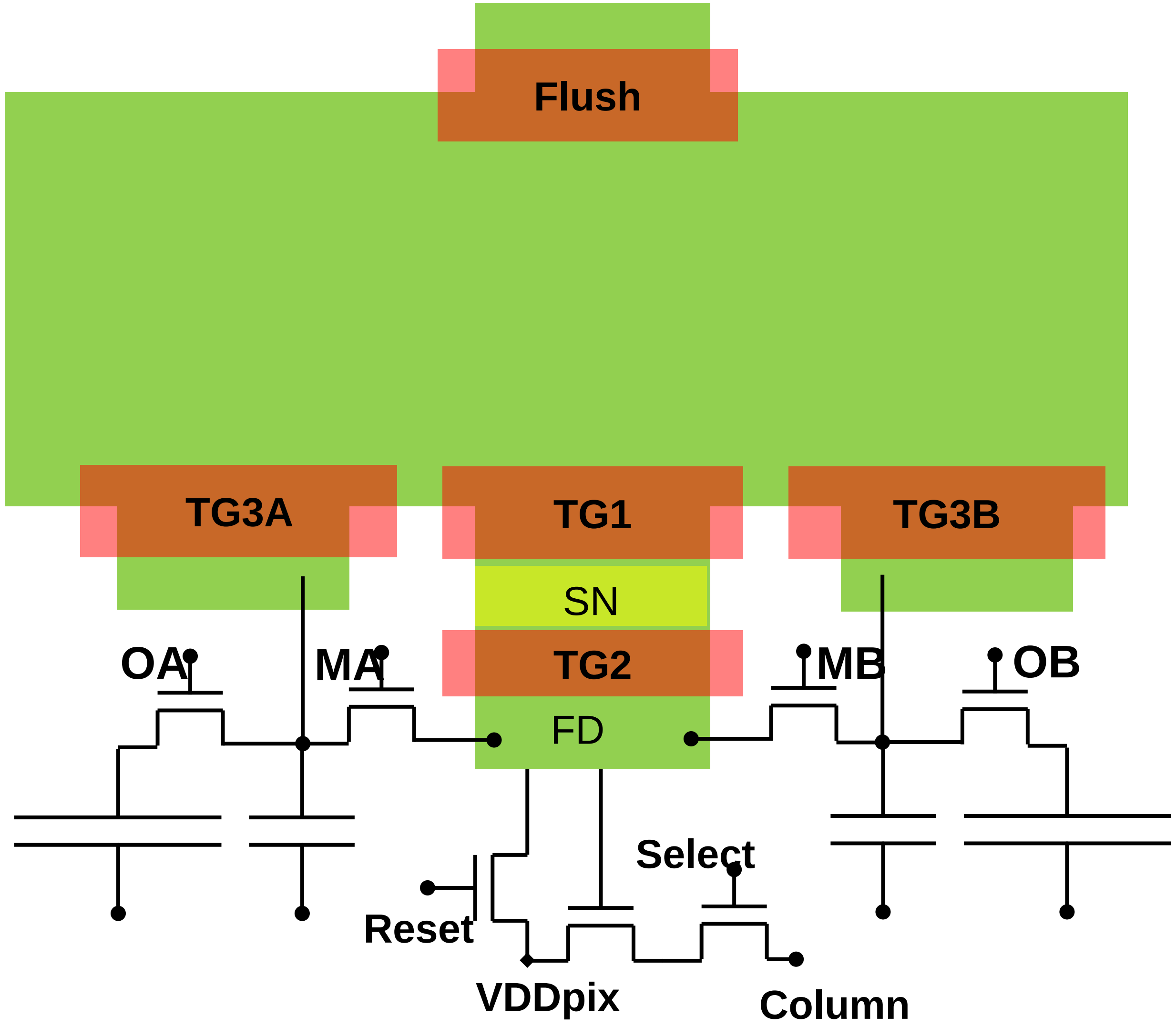

patent US9819882

# GS+HDR + *IWR*

The same, extended to 3 ranges HDR
This is a 12T pixel (5TG, 7MOSFET, 4C)






patent US9819882

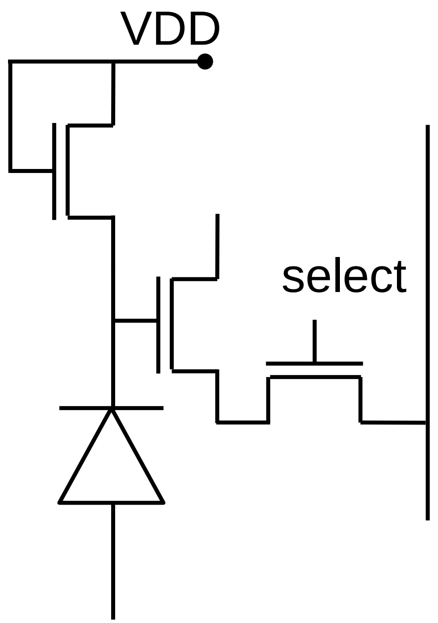
# 13. "other" high dynamic range pixels

Not "true" i.e. not MAF (motion artifact free) and not maximizing PSN.

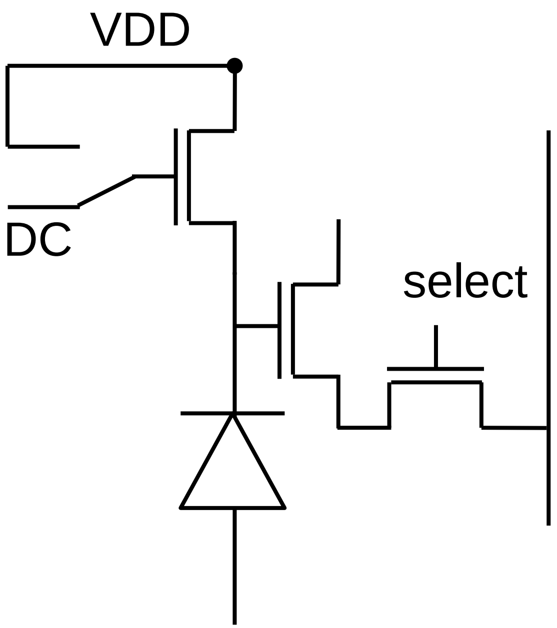
Some of these techniques can be realized with basic (consumer) pixels, 4T or 3T.

# Logarithmic, lin-log and classic 3T

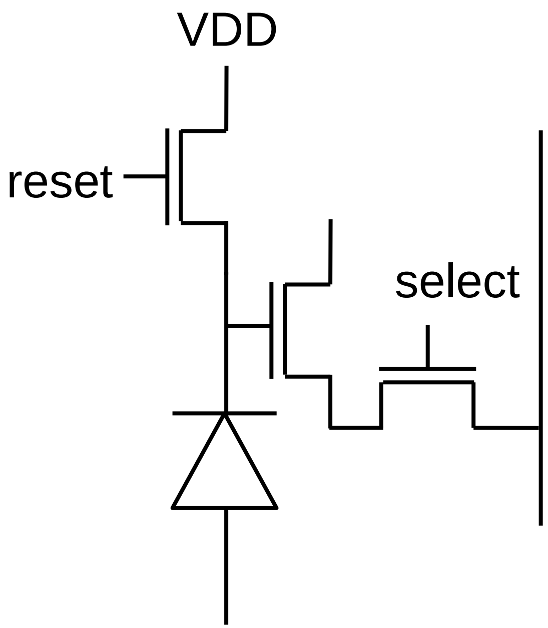





**Logarithmic pixel**
instantaneously compresses the photocurrent to voltage.
Is a “direct” access pixel.
The logarithmic compression offers a huge dynamic range.

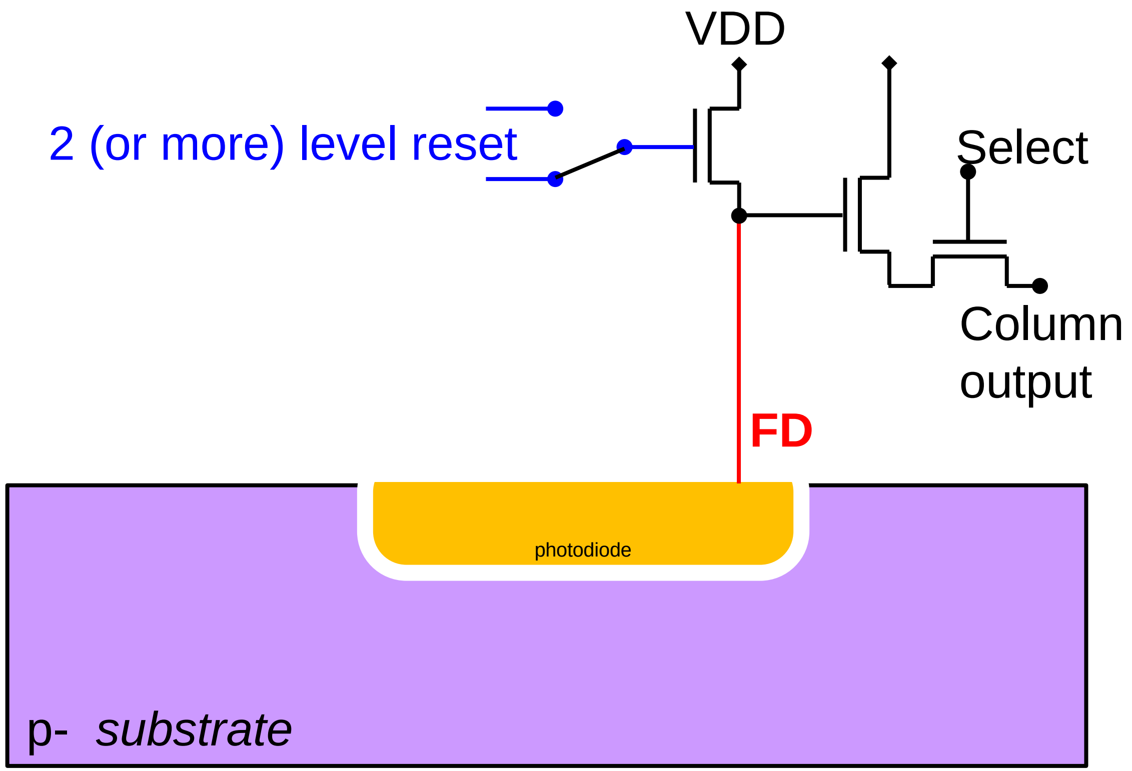


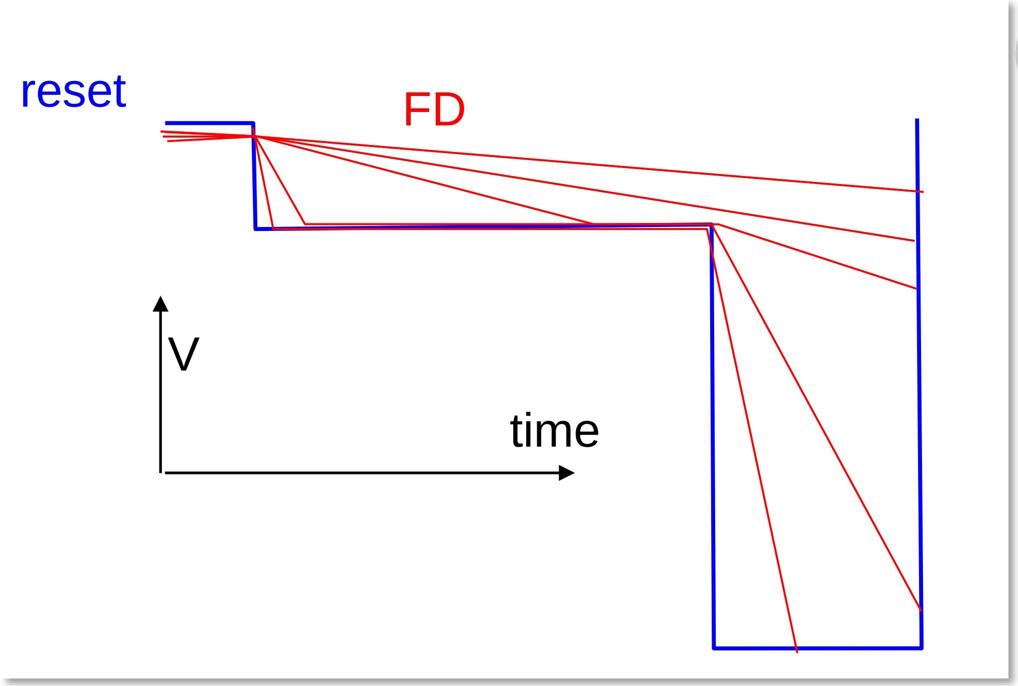

**Lin-log pixel**
The same, yet keeps a linear piece in the dark, which improves uniformity and settling time.

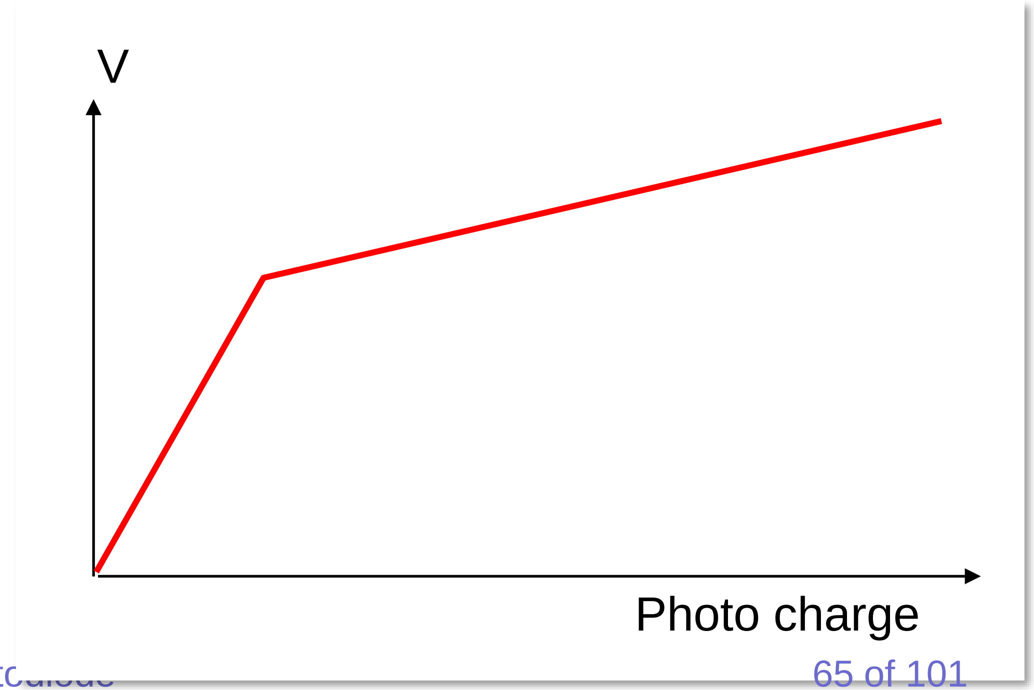



**The classic 3T pixel**
Normally not suspected of high dynamic range, but…
It can be operated as the two previous

# Multiple slope by Reset level modulation




- 3T pixel as-is
- Integration times of slopes is different: *not MAF*

# Multiple accumulation HDR



Can be done with all “rolling shutter” pixels.

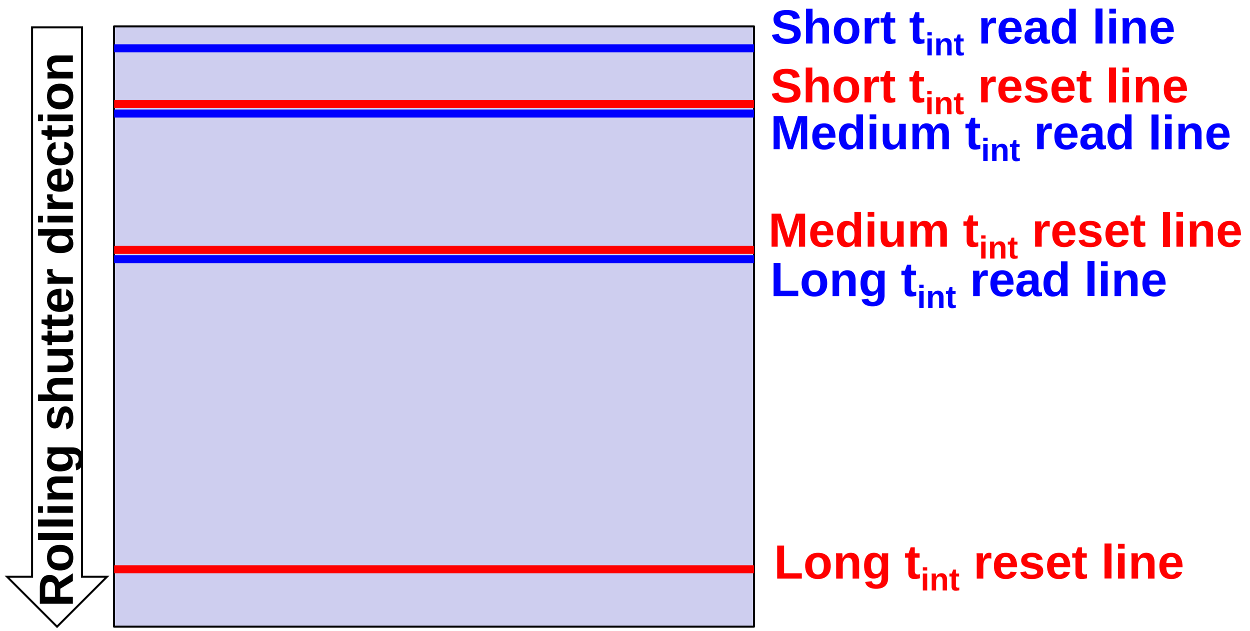
Many consumer imager HDR are of this nature.

It is also called “bracketing”, “multiple integration time”, “multiple slope” and other synonyms.

In these methods the image is taken multiple times at *approximately* the same moment, with different integration times.

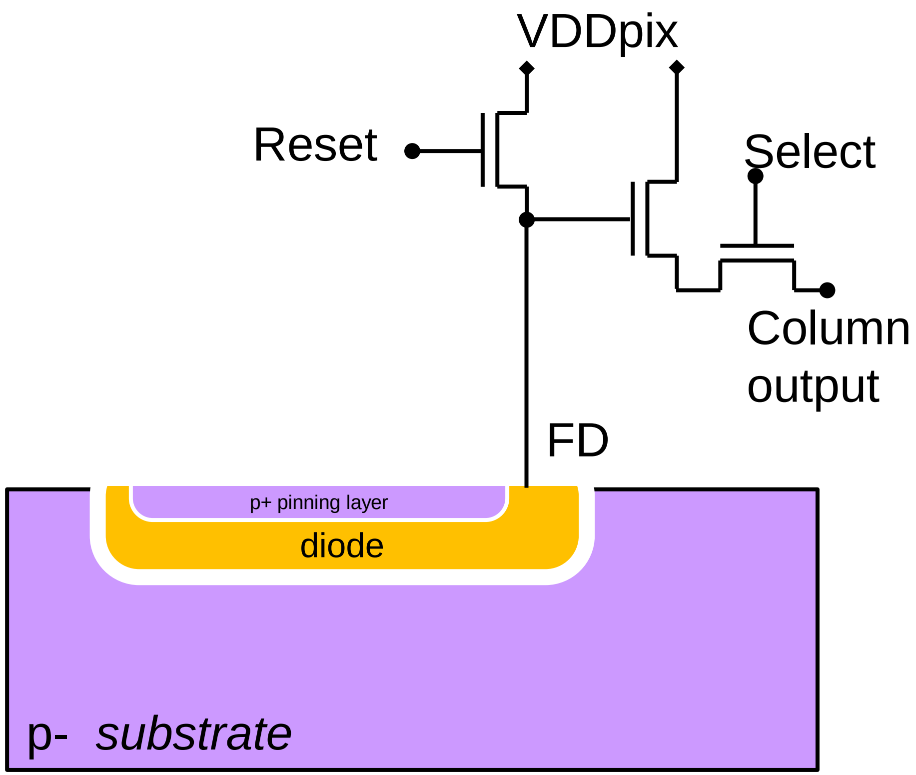
In the present example the 3 integration times are

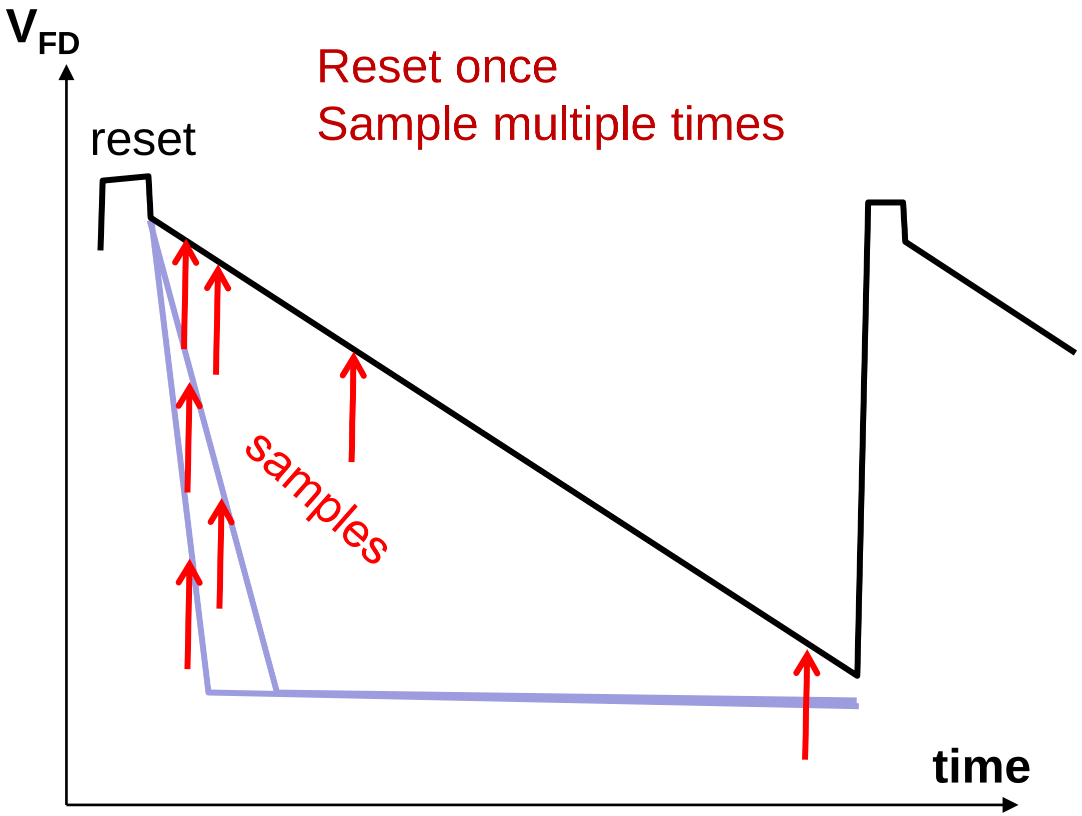
1/2th
1/4th
1/8th of the frame readout time.



# NDR “non-destructive readout”

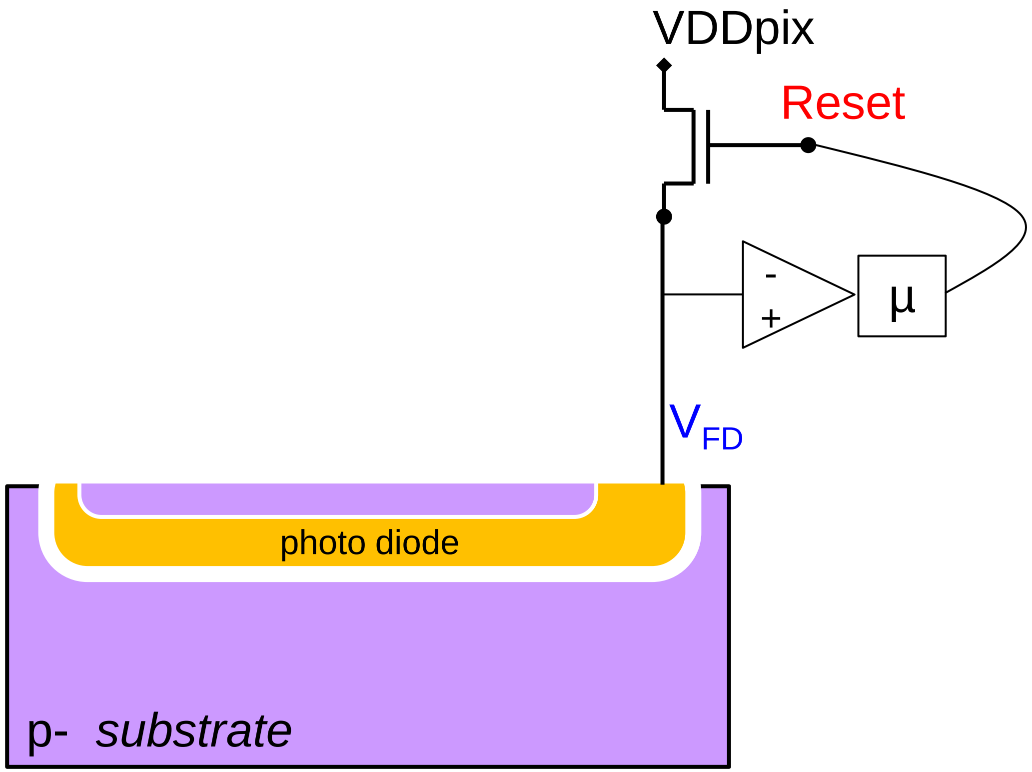
(Engemann sampling)

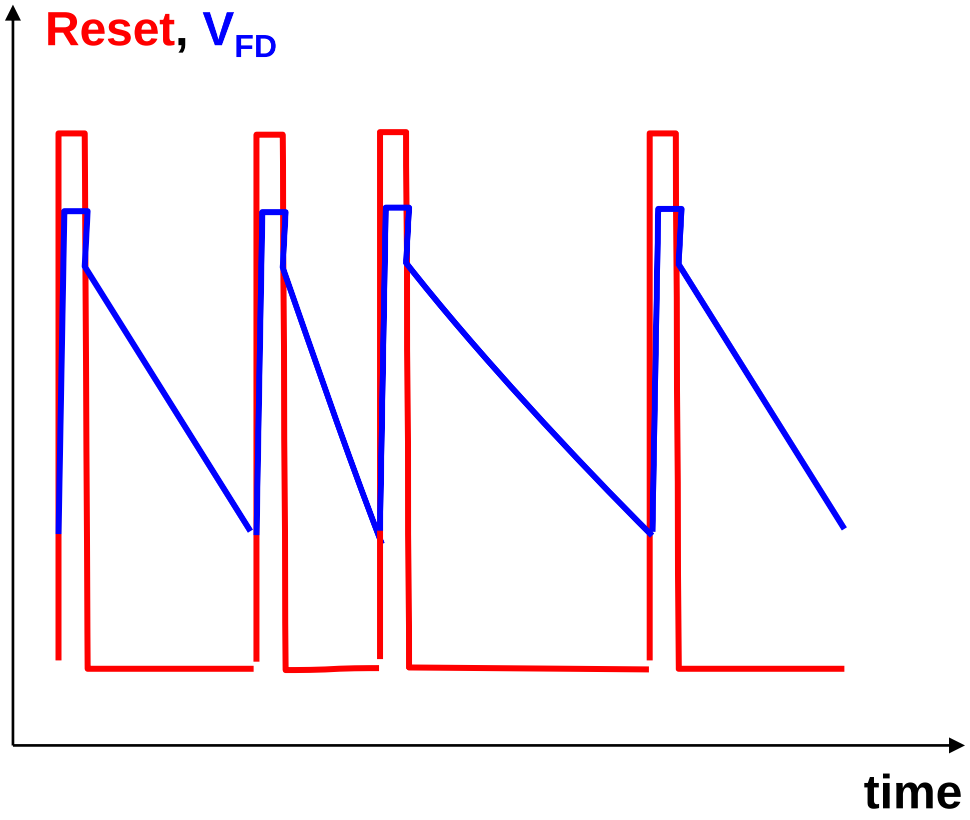


# HDR by auto-reset, smart reset

caeleste

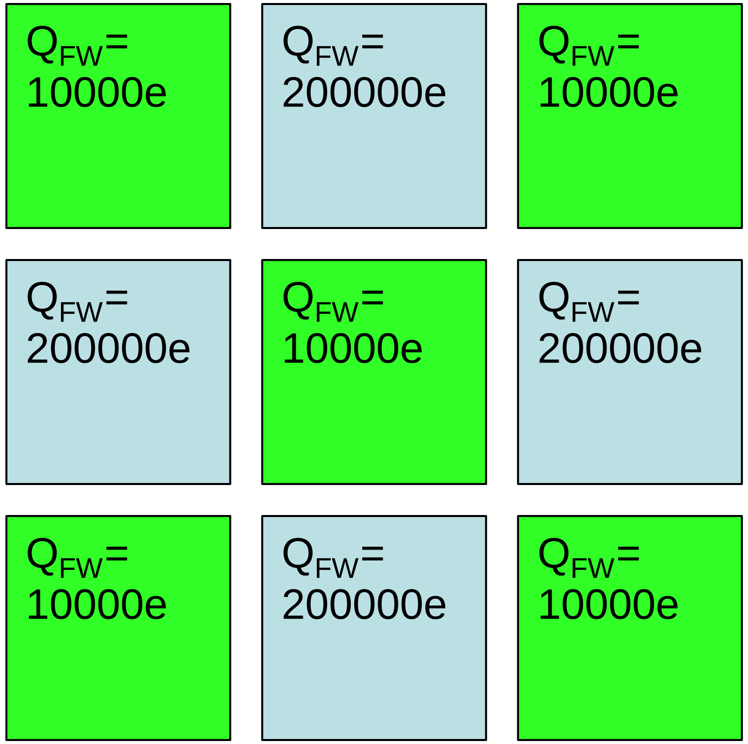



Many variations on this theme have been published

# Checkerboard HDR (sorry this is not really a pixel ☺)

- In a fashion similar to (CFA-) color imagers, pixels in a kernel and even inside the same pixel, are given different sensitivities or $Q_{FW}$.
- This can be
  - Hardwired
  - programmable/reconfigurable




caeleste

Pixel topologies suitable for ~

# 14.HYBRIDS and ROICs

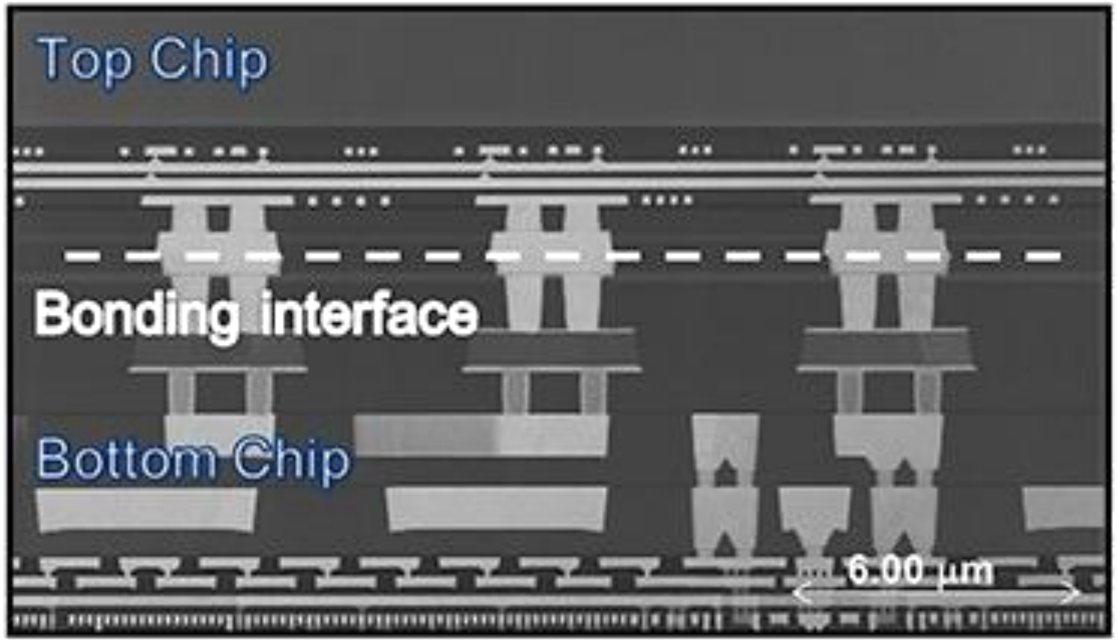
1. “Pixel – processor” hybrids

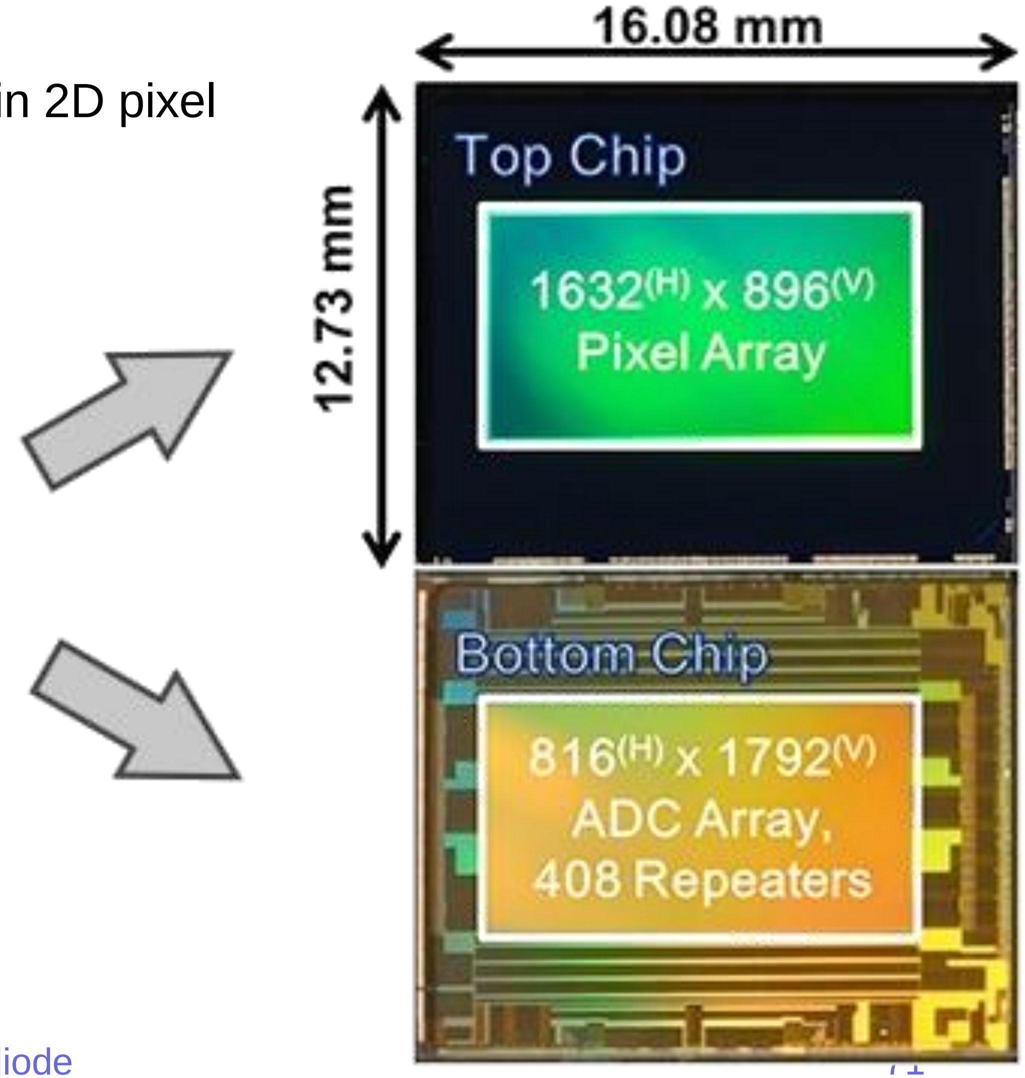
2. “Detector – readout” hybrids
   - Based on 3T pixel topology
   - Based on Direct Injection pixel topology
   - Based on CTIA topology

# Pixel – processor hybrids

3D-integration as used in advanced consumer imagers are pixel-processor hybrids

The pixel layer uses the same pixel topologies as previously found in 2D pixel arrays.



# “Detector-readout hybrids”

caeleste

Hybrid imagers combine

- ✓ **A Silicon (CMOS) ROIC (readout IC)**
  - ✓ Contains the readout electronics part of “pixels”, one by one connected to
- ✓ **A separate layer containing the radiation sensitive detectors,** such as
  - ✓ Other semiconductor photodiodes or photoresistors
  - ✓ Scintillators, Bolometers, Piro-electric detectors, …

Coupling happens by bumps bonds, wafer bonding, TSV, optical coupling, …

The pixel topologies can be largely the same as with monolithic imagers, however,

← Total depletion and thus total charge transfer is not possible in a hybrid: *no PPD and imperfect CDS.*

← No *charge domain* global shutters

← Silicon is in total available for readout: *complex pixels with high fill factor, and often ideal PLS.*

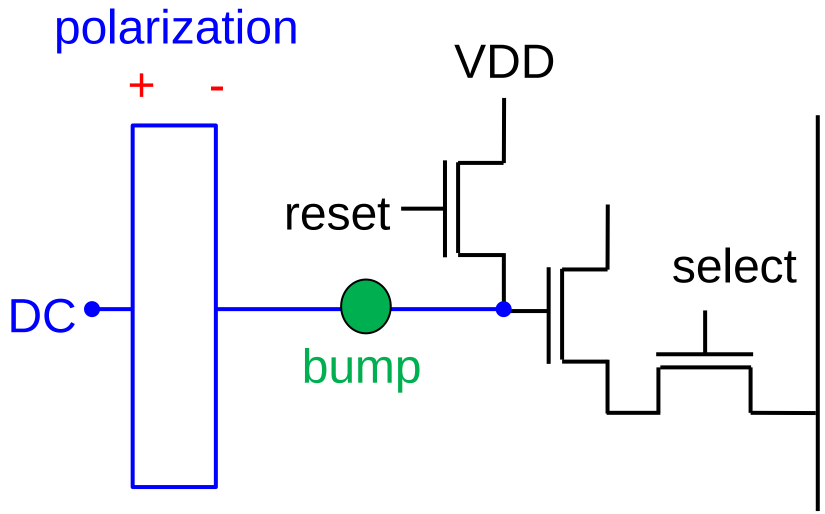
← Often the detectors are by far not as ideal as Silicon photodiodes.

# 3T pixel topology

caeleste

The oldest, simplest and quite popular pixel topology. The sense node potential is buffered by the source follower.

In this example used to *sense the potential* of a “Piroelectric” polarising detector

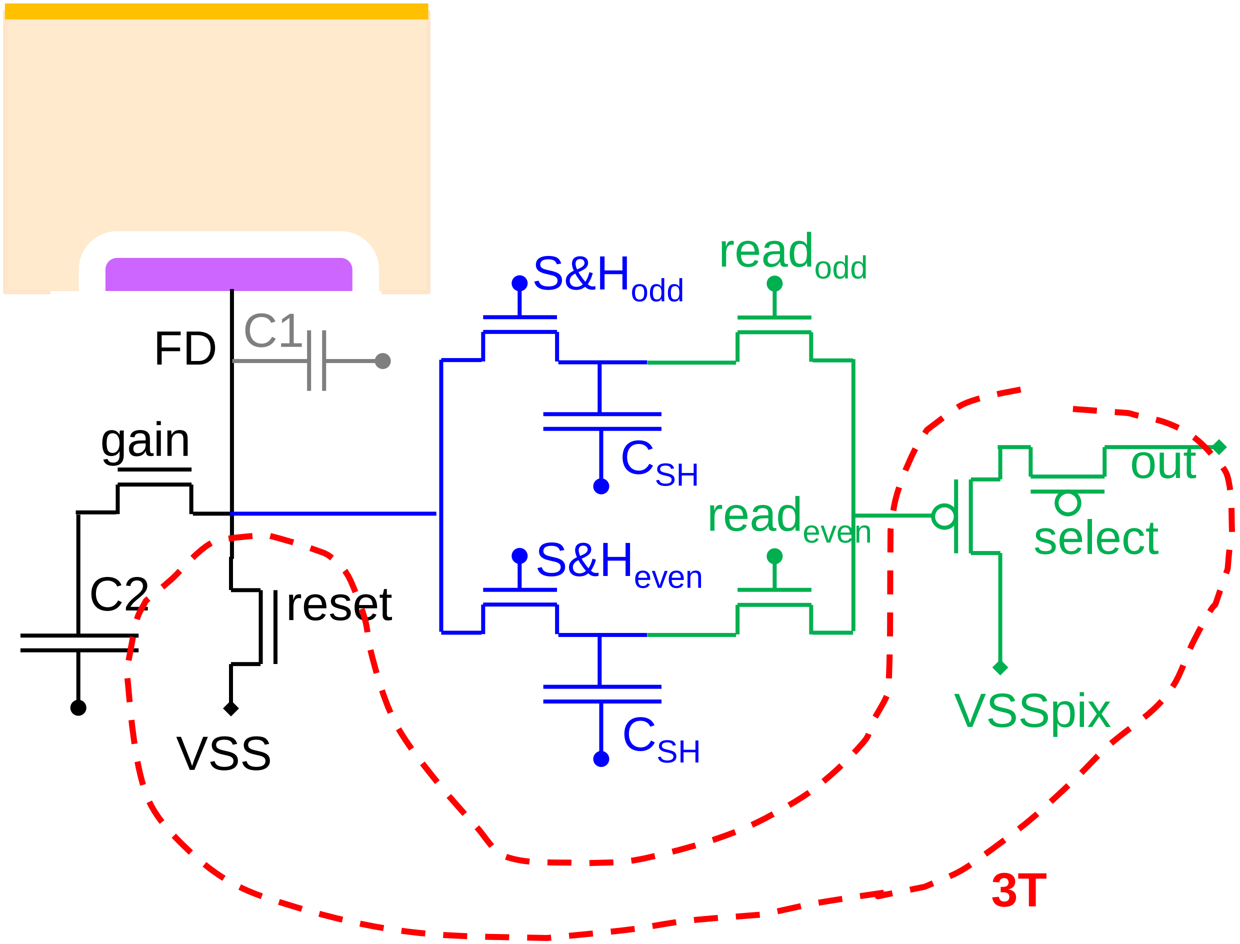


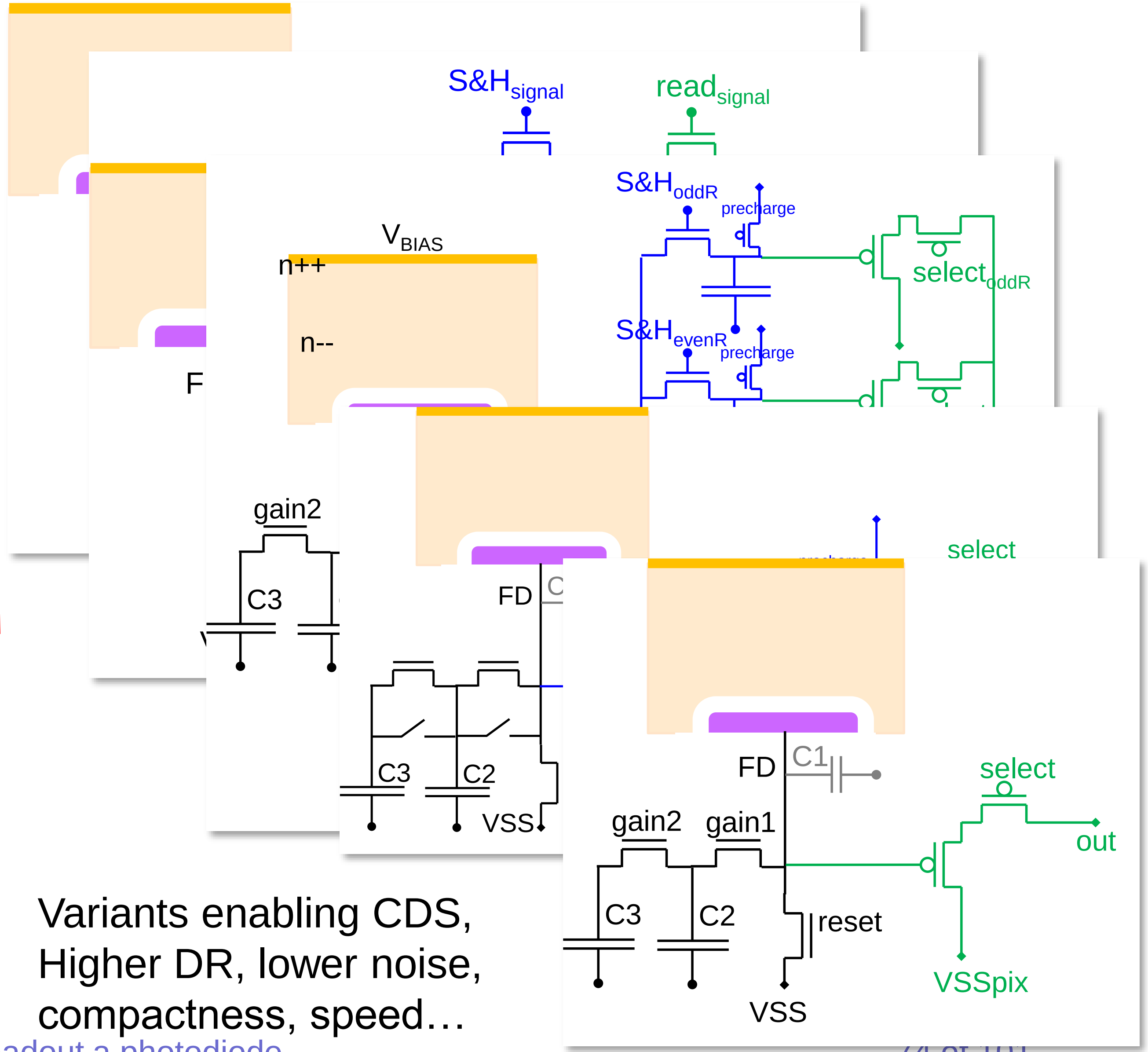

Many of the pixel topologies hereafter have the 3T pixel as core + extra circuits for S&H, $Q_{FW}$ programming, HDR, …

# Global shutter and two gain ($Q_{FW}$) ranges



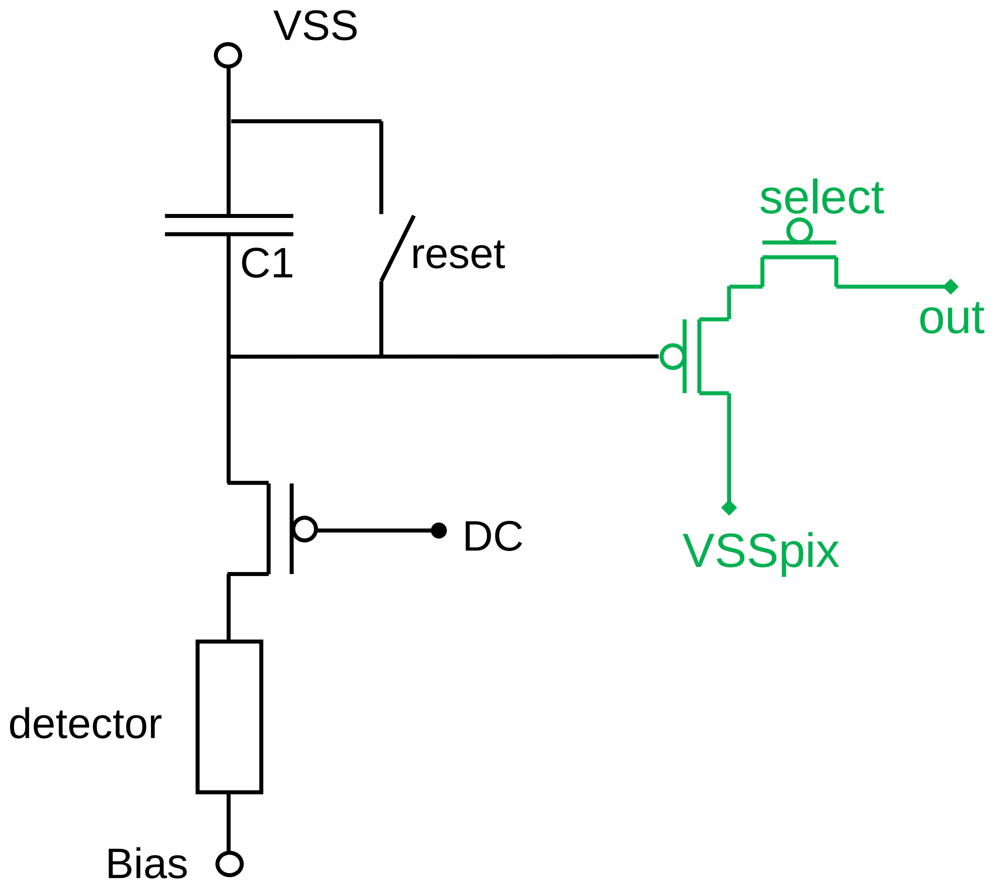
Basic circuit that can do IWR GS
and having two ranges HDR
Cannot do CDS.

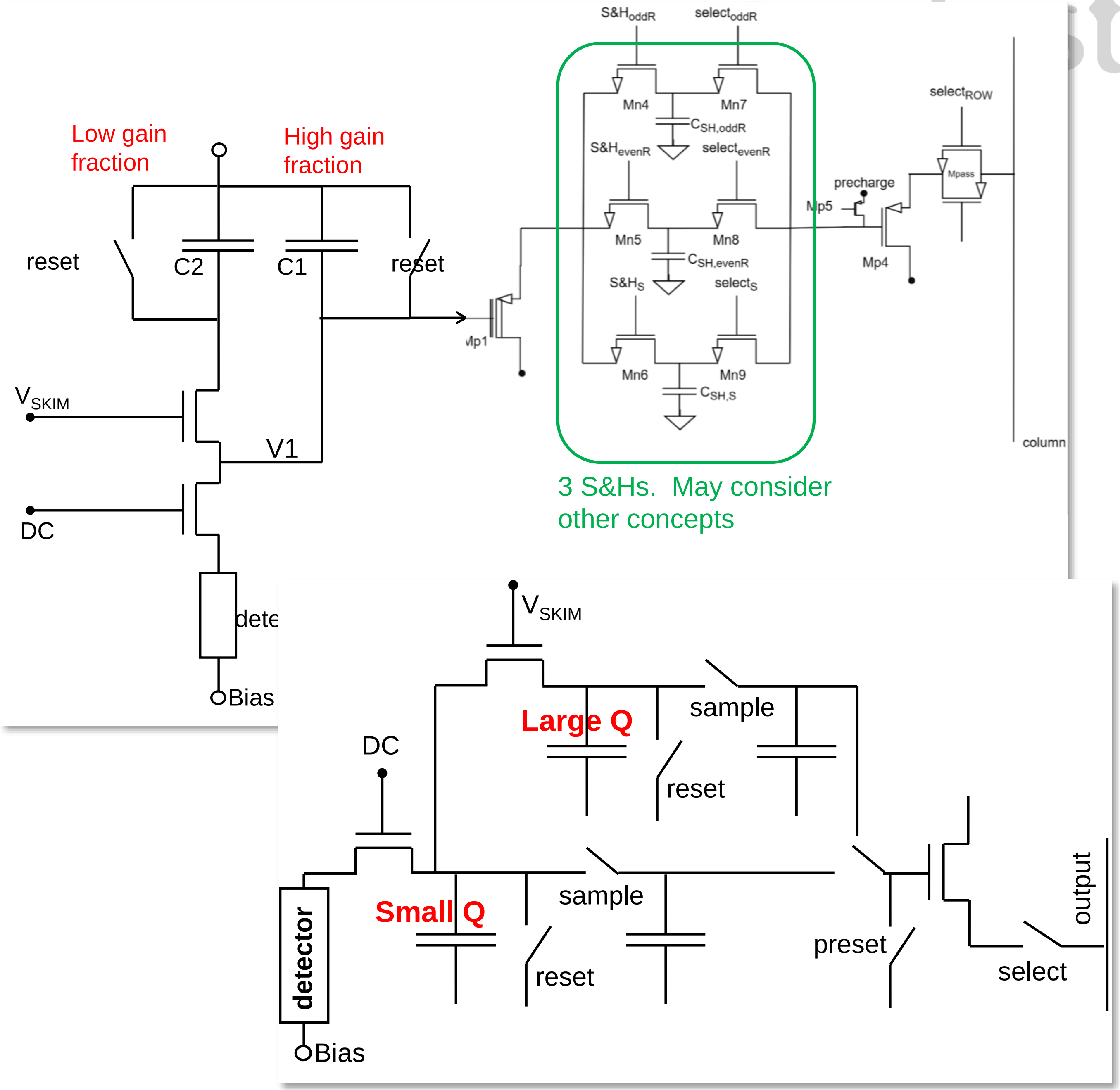



Variants enabling CDS,
Higher DR, lower noise,
compactness, speed…

# Direct injection



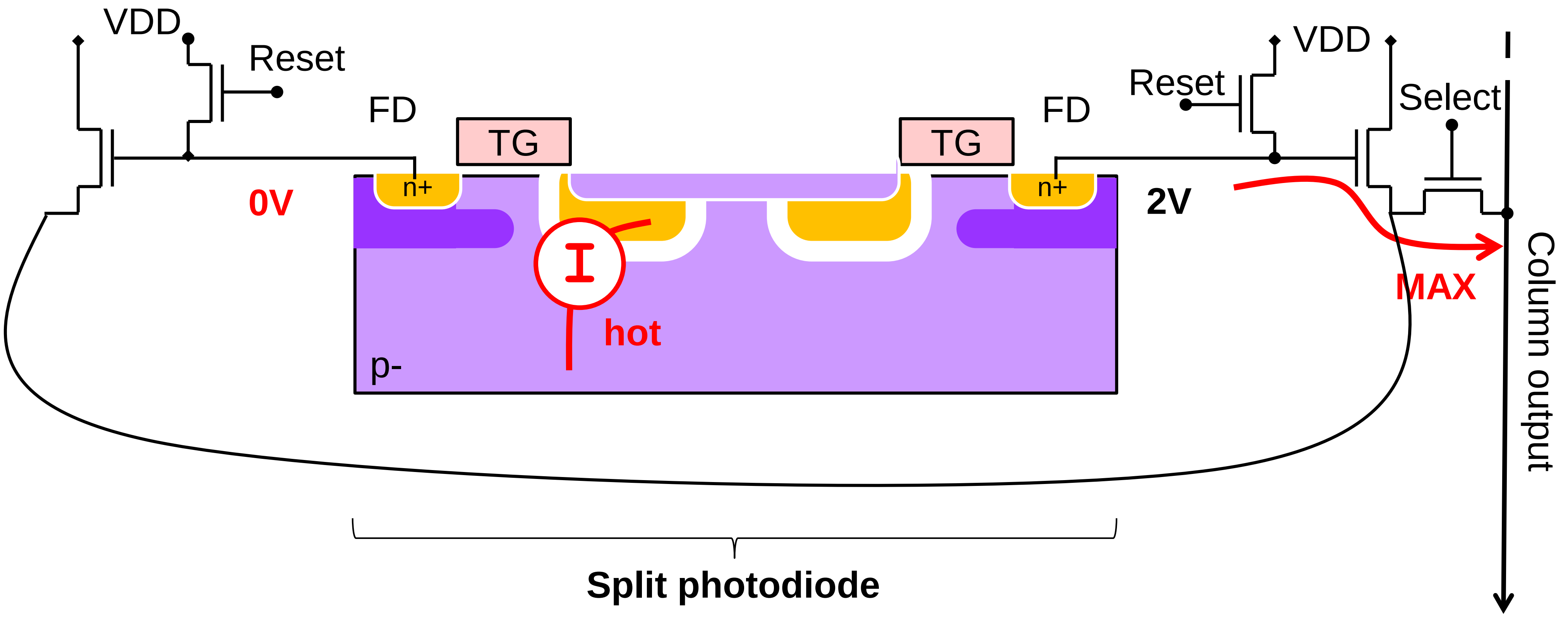




The input transistor is a "common gate amplifier. It keeps the source voltage +/- at constant bias, and collects the current.

# 15.Radiation hard pixel

# Proton resilience inside the pixel

A proton or high energy particle saturates
or damages half a pixel.
The other half pixel remains operational.



# Take home message

**The original claim was a huge underestimation**
**There are far more than 101 ways to readout a photodiode.**

**Q: Do we really need more than 101 ways?**

**No, you need only one.**
**The one that depends on the actual requirements.**