Single Photon Counting in the Visible

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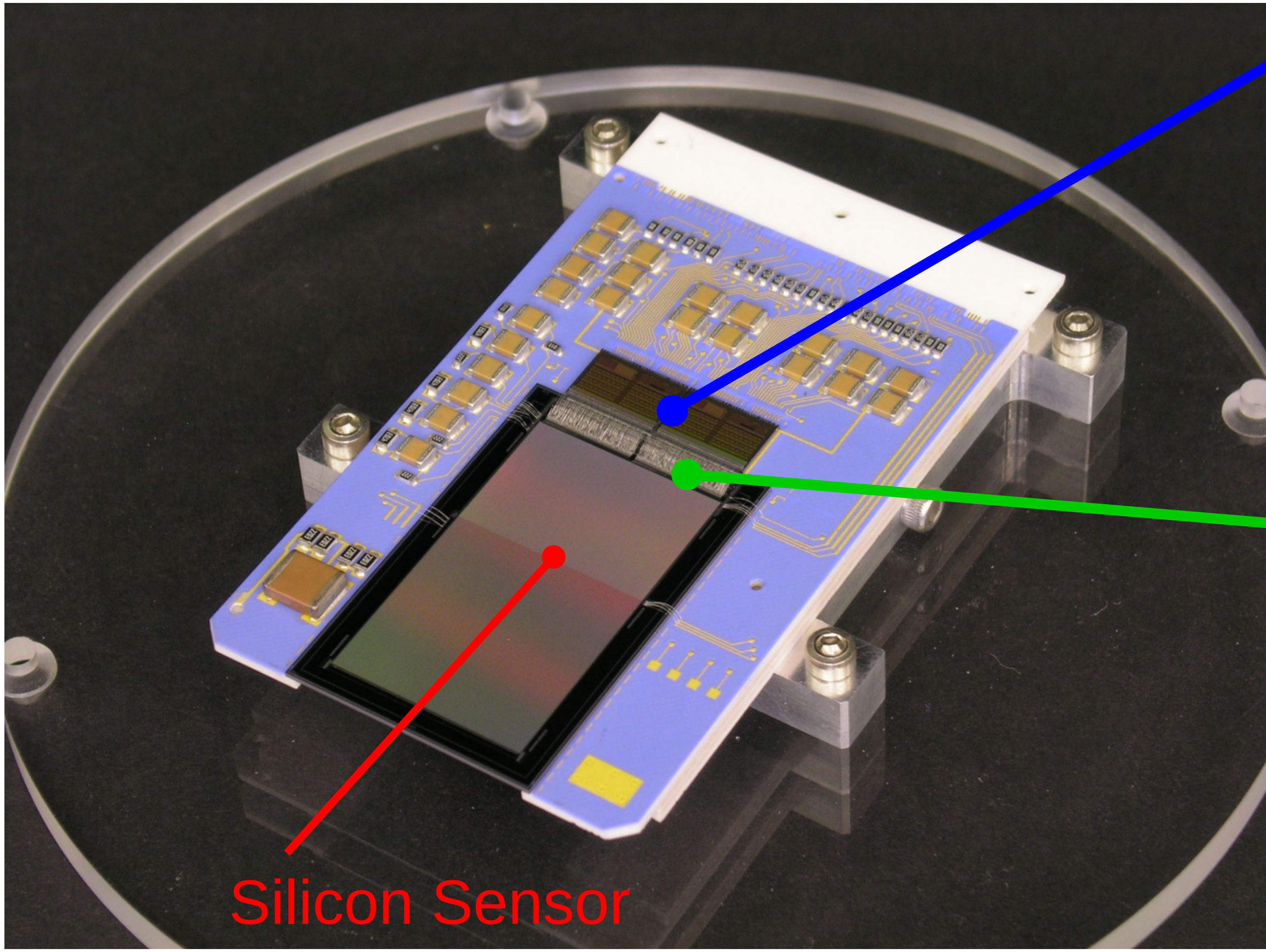
OUTLINE

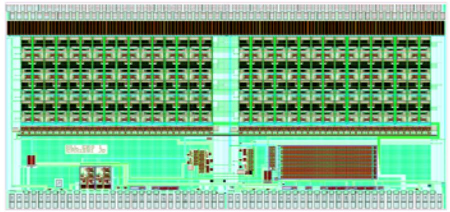
- System Definition
- DePMOS and RNDR Device Concept
- RNDR working principle
- Experimental results
- Gatable APS devices
- Achieved and achievable performance
- Conclusions

System Definition

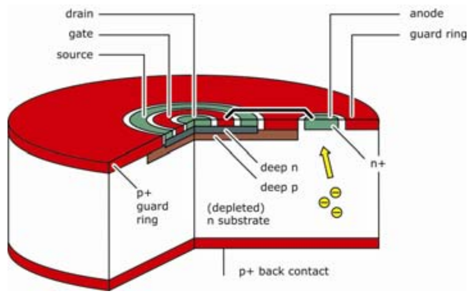


(image and frame store area)

Multi-Channel readout ASIC performing time variant filtering

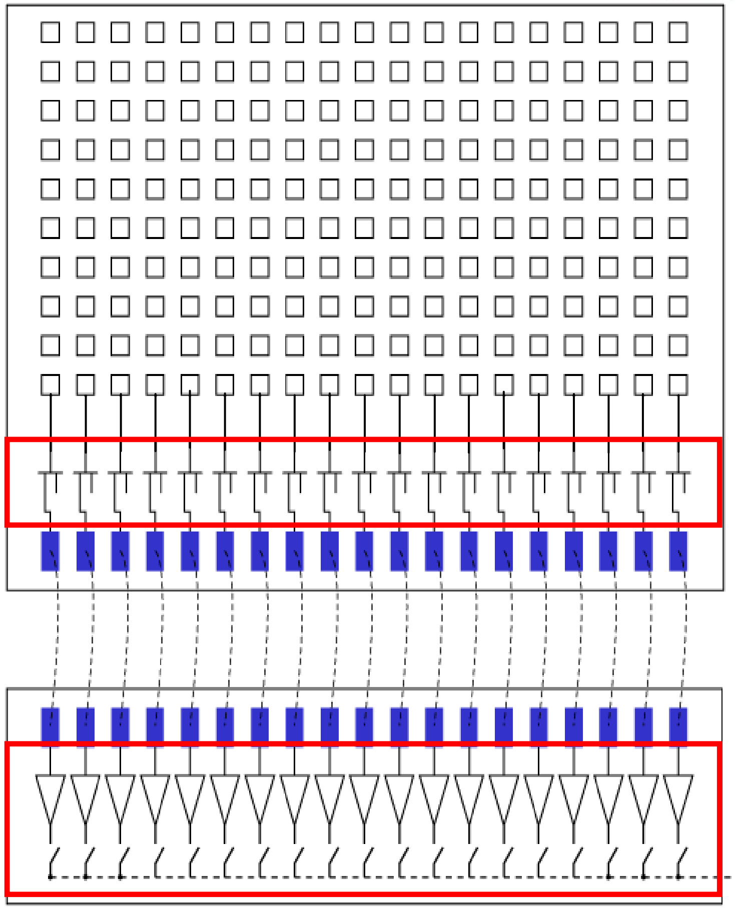


First amplification device array integrated on the sensor



pnCCD for single photon counting

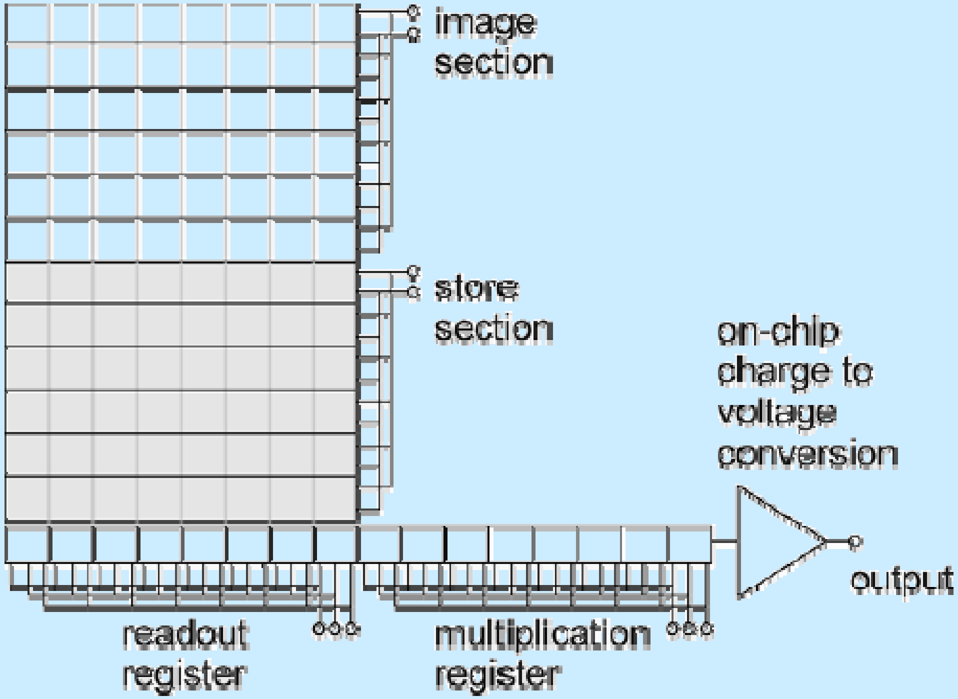
- **High readout speed (1 kHz at 256x256 formats**
- **High quantum efficiency**
- **High charge transfer efficiency**
- **High spectrocopic resolution with X-rays (2 electrons r.m.s. @ - 60 ºC, TEC)**
- **Integrated JFET as first amplification stage on every readout anode**
- **Parallel Readout (one complete readout channel per column)**
- **With anti-reflecting coating it is possible to achieve a quantum efficiency close to 100% for near infrared (300-1100 nm)**
- **2 el. r.m.s. would not allow to detect less than 10 optical photons**



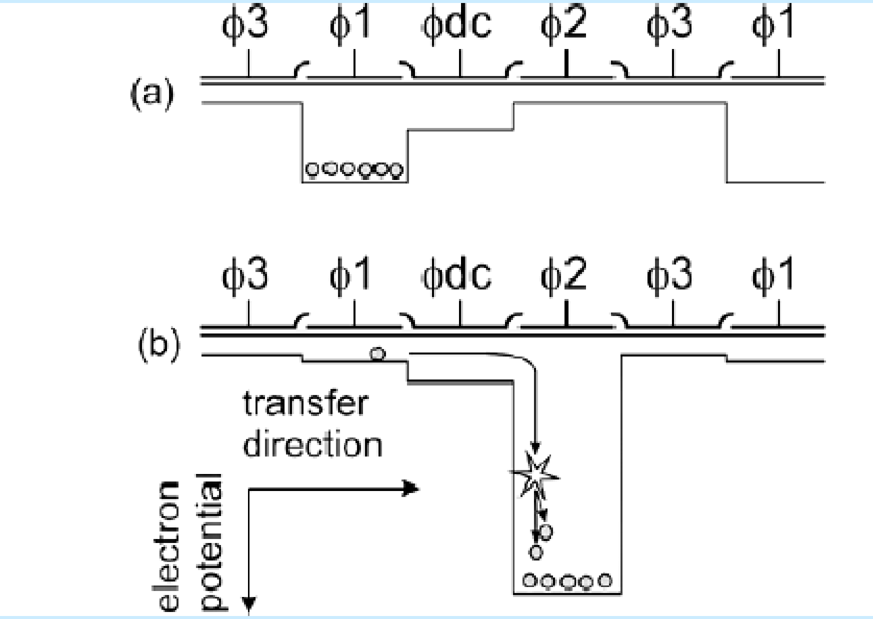
<u>To achieve single photon resolution:</u>
- use avalanche multiplication
- the on-Detector JFETs can be replaced by RNDR-DePMOS
- a suitable Multi-channel readout ASIC must be implemented

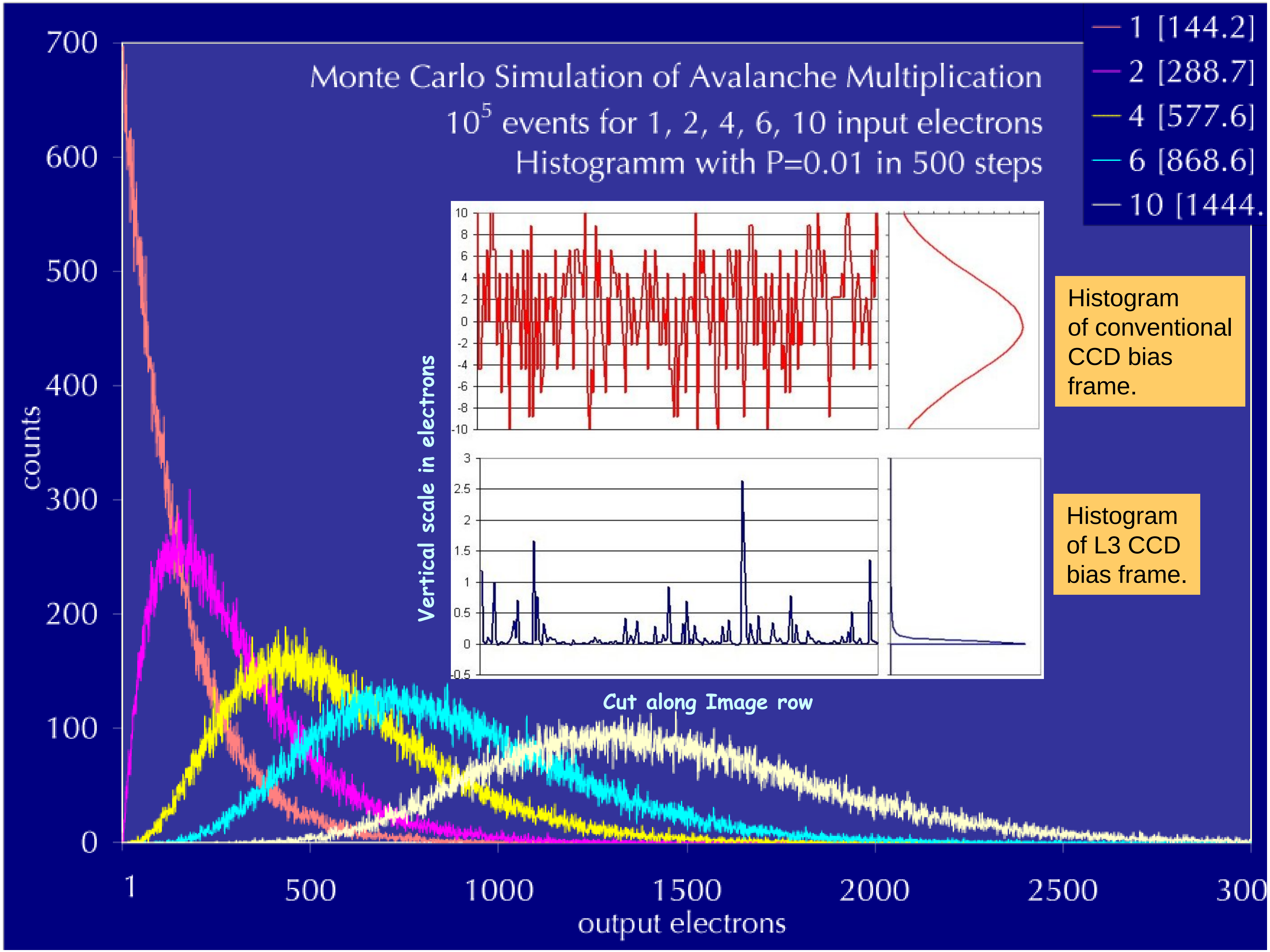
EMCCDs principles

EMCCD

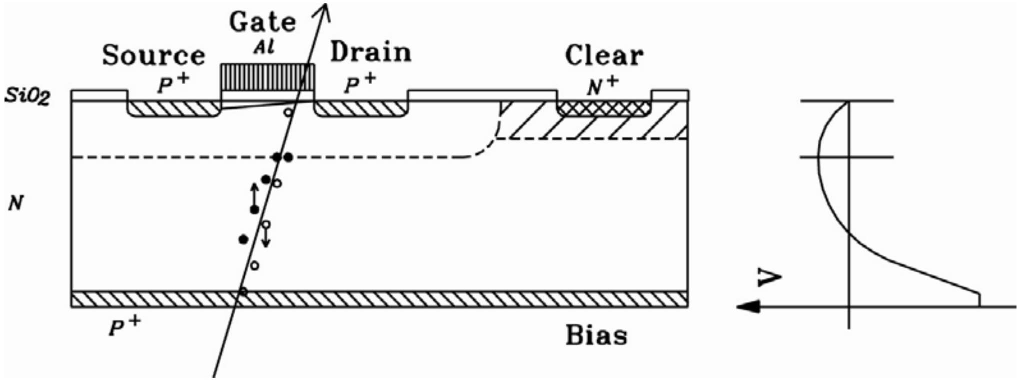


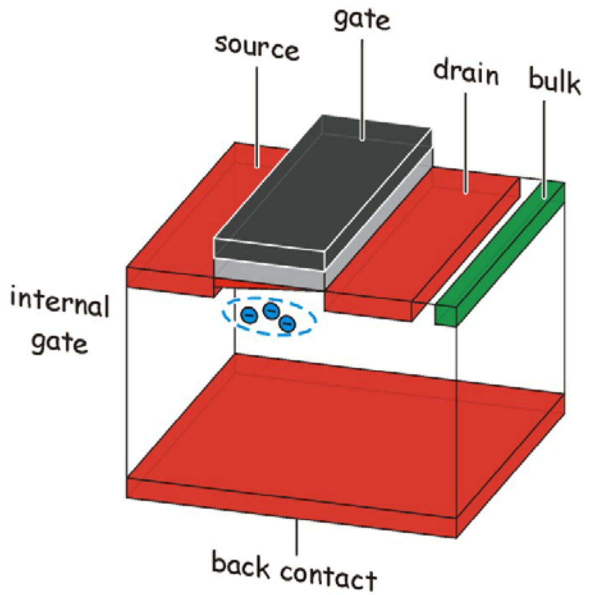
gate structure



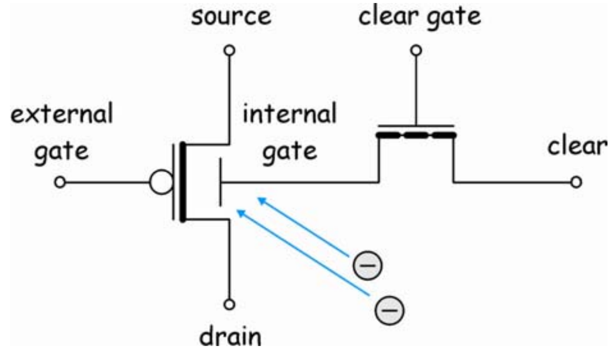

Monte Carlo Simulation of Avalanche Multiplication
10^5 events for 1, 2, 4, 6, 10 input electrons
Histogramm with P=0.01 in 500 steps
1 [144.2]
2 [288.7]
4 [577.6]
6 [868.6]
10 [1444.
counts
output electrons
Vertical scale in electrons
Cut along Image row
Histogram of conventional CCD bias frame.
Histogram of L3 CCD bias frame.

DePMOS concept

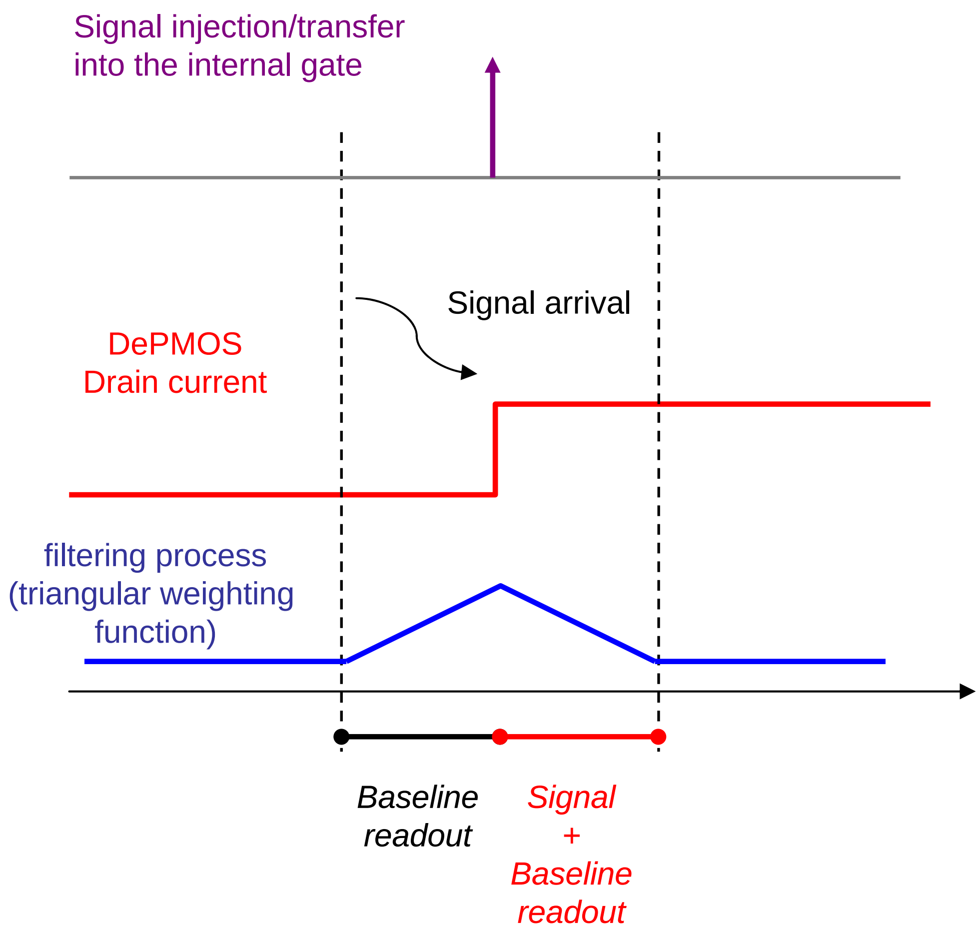




- p-channel MOSFET integrated on high-ohmic, sideward depleted n-substrate
- a potential minimum is formed by S/D potentials aided by a deep n implantation
- electrons are collected in an internal gate close to the surface
- the transistor current is modulated by charge collected in the internal gate
- the transistor can be switched on/off by an external (top) gate
- An n+ clear contact surrounded by a clear gate is used to remove the charge from the internal gate



DePMOS Readout



- The signal arrival time is known

  (the charge is tranferred from the CCD column and then switched between the two pixels clocking the tranfer gate)

- One measurement is composed of the difference of two evaluations:

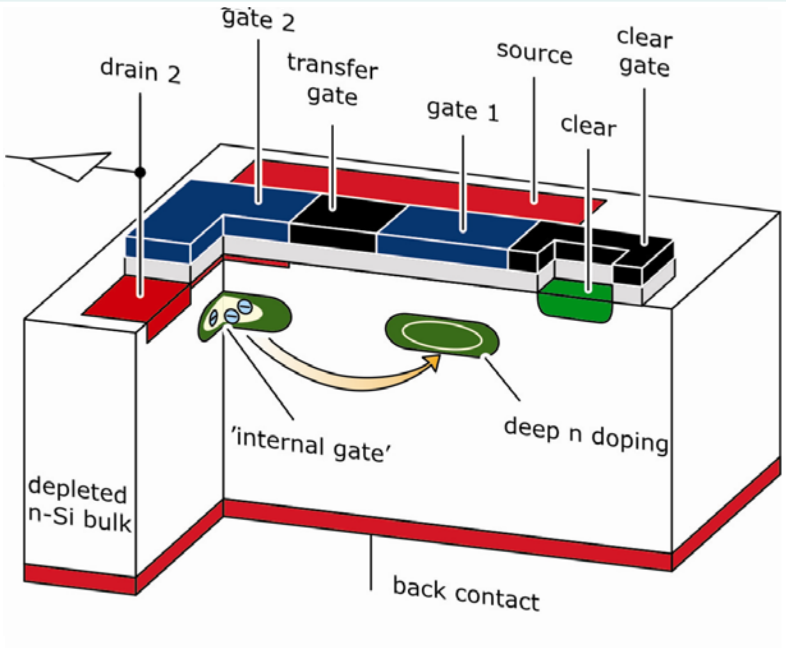
  Baseline

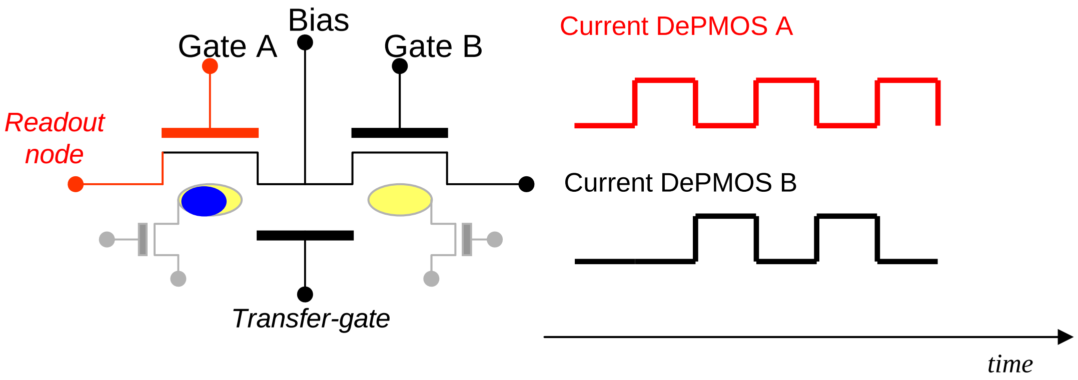
  Baseline + signal

- A time variant filter is used

- The triangular wighting function is the time limited optimum filter for voltage noise

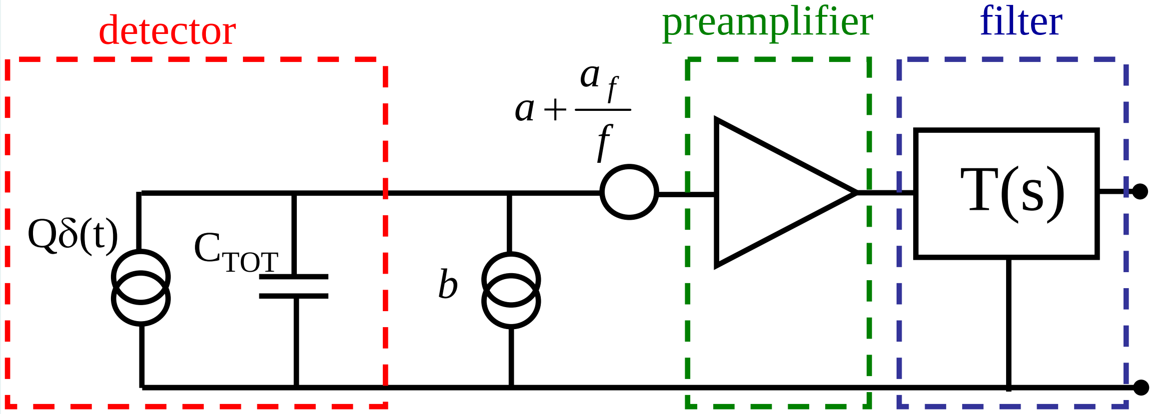
RNDR DePMOS





- RNDR Device is composed of 2 adjacent DePMOS structures
- The charge in the internal gate can be swtiched between the internal gates of the two DEPMOS, thanks to one (or more) *transfer gate(s)*
- When the internal gate of one device is full the internal gate of the other one is empty
- Moving the signal charge form one device to the other allows to reproduce the signal arbitrary often
- The main limitation is given by the leakage current that fills the internal gate
- It is possible to read out the signal from both devices or to use one device just as a storage for the charge

ENC evaluation



white voltage noise component decreases as measurement time increases

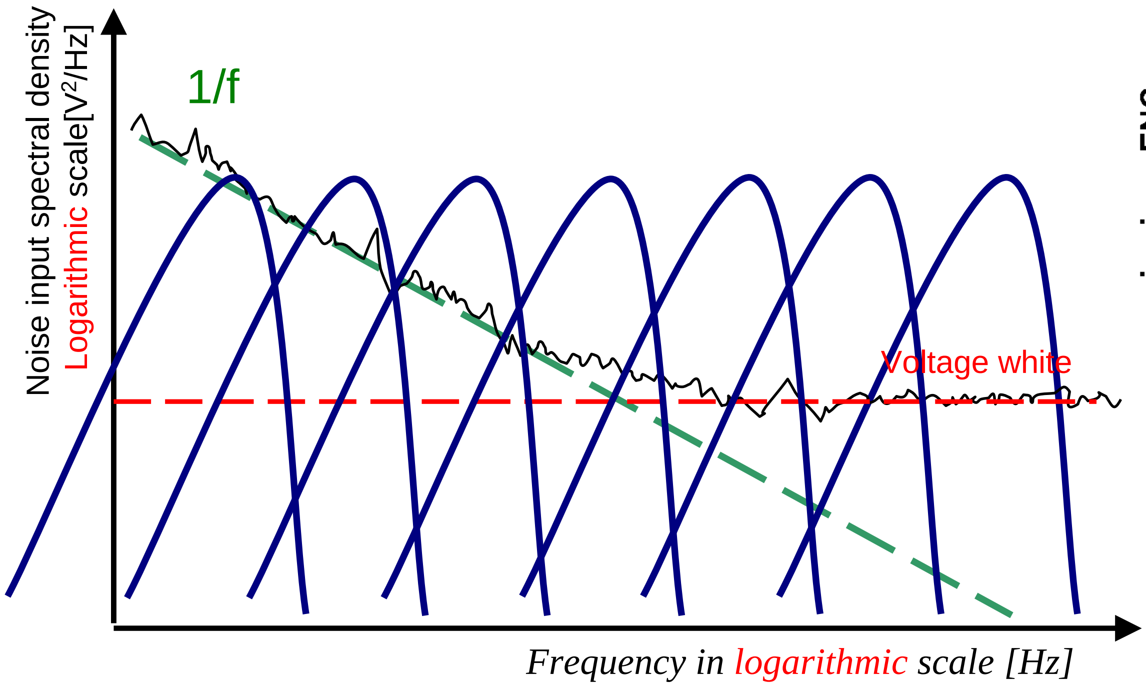
1/f voltage noise component is independent from measurement time

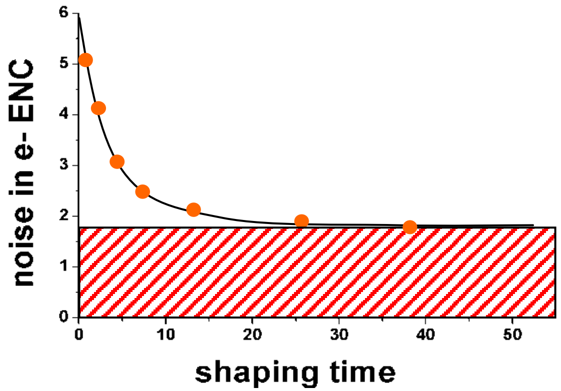
Current white noise (lorentian noise) increases with measurement time

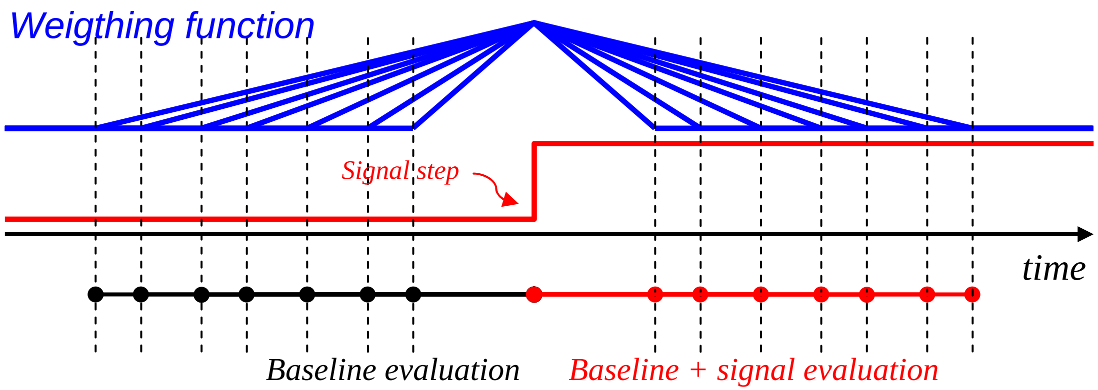
$$ENC^2 = \frac{a}{\tau} C_{TOT}^2 A_1 + 2\pi a_f C_{TOT}^2 A_2 + b\tau A_3$$

- C_{TOT} DePMOS equivalent input capacitance
- a, a_f, b physical noise sources
- $A_1\ A_2\ A_3$ filter parameters
- τ filter shaping time

Single Readout noise filtering

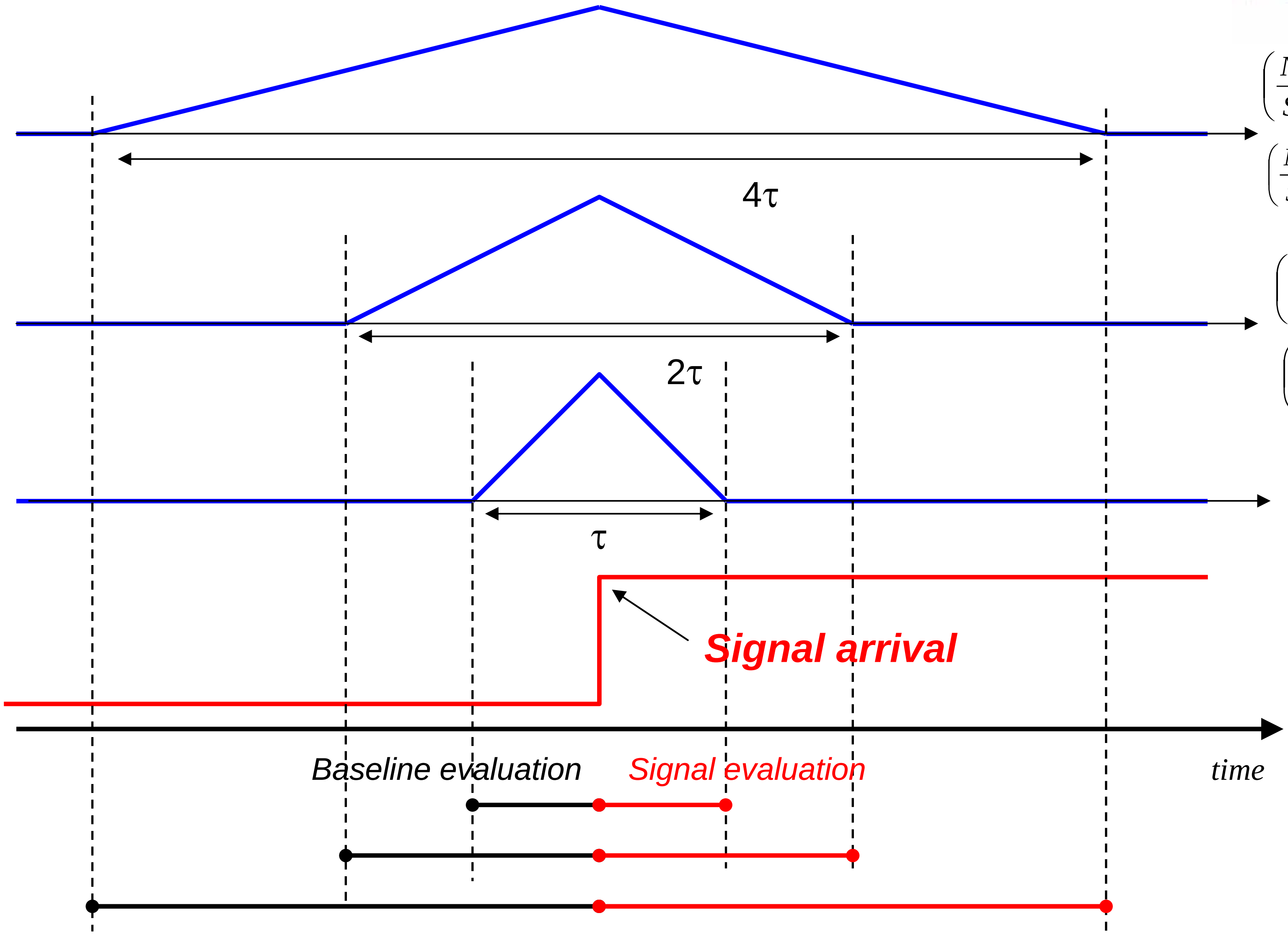






- The weigthing function is fixed
- The measurement time changes (shaping time)
- This means to translate the transfer function in the frequency plot in LOGARITHMIC scale
- The same signal amplitude is measured for different WFs
- Different WFs integrate diffent regions of the input noise spectral density
- Every decade of the spectrum contains the same r.m.s. value of 1/f noise

Single Readout noise filtering



$$\left(\frac{N}{S}\right)^2_{white} \propto a \cdot A_1 \frac{1}{4 \cdot \tau}$$

$$\left(\frac{N}{S}\right)^2_{1/f} \propto a_f \cdot A_2$$

$$\left(\frac{N}{S}\right)^2_{white} \propto a \cdot A_1 \frac{1}{2 \cdot \tau}$$

$$\left(\frac{N}{S}\right)^2_{1/f} \propto a_f \cdot A_2$$

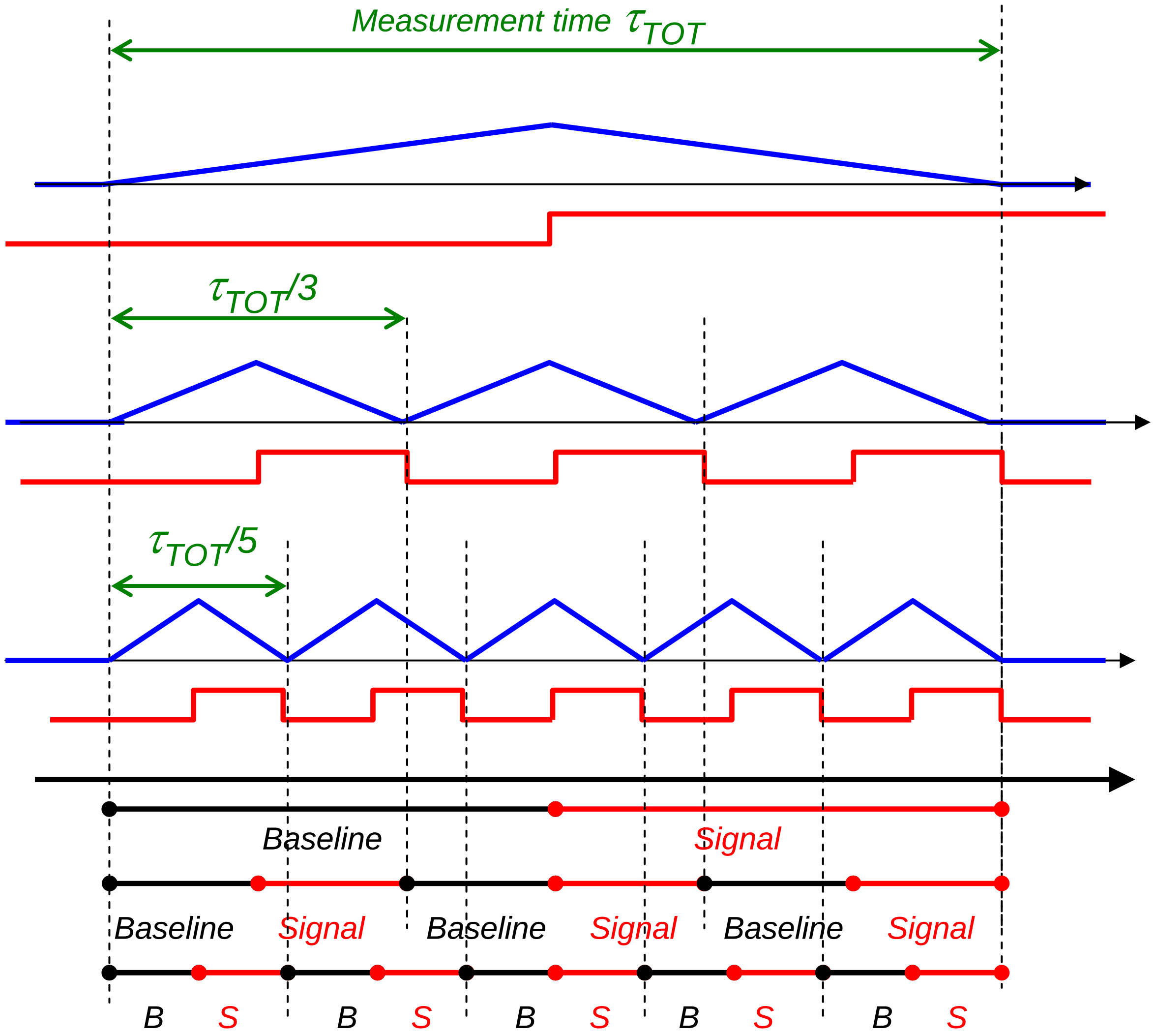
$$\left(\frac{N}{S}\right)^2_{white} \propto a \cdot A_1 \frac{1}{\tau}$$

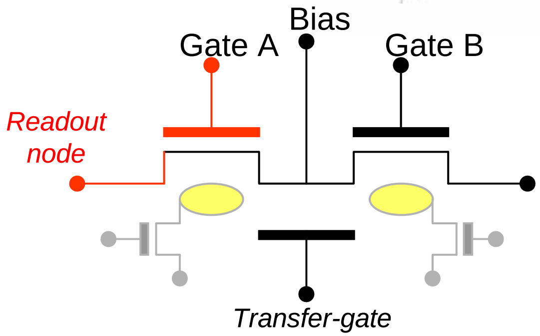
$$\left(\frac{N}{S}\right)^2_{1/f} \propto a_f \cdot A_2$$

Repetitive non Destructive Readout

- We fix the total measurement time τ_{TOT} (e.g. such that the *1/f* noise is dominant)
- We reproduce the signal *n* times, moving the charge back and forth from the internal gate of one DePMOS to the internal gate of the other one.
- We measure the signal *n* times and we make an average of the measurments
- The signal we reproduce is always the same, i.e. the signal charge is not spoiled by leakage current electrons that can cumulate in the internal gate
- Every signal measurement is the *diffence* of the "*baseline*" and the *"baseline+signal"* evaluation (that is why we need to move the signal charge back and forth from one DePMOS to the other one)
- Since τ_{TOT} fixed the time available for each single measurement is τ_{TOT}/n
- The noise of the *n* measurements sums up quadratically
- The signal sums up linearly

Repetitive Non Destructive Readout





- We readout one DePMOS, e.g. DePMOS *A*
- The other DePMOS is used to store the signal charge when the baseline of DePMOS *A* is evaluated
- The signal can be reproduced (transferred back and forth into DePMOS *A*) *n* times

$$\left(\frac{N}{S}\right)^2_{White} \propto \frac{3A_1\left(\frac{1}{3}\frac{1}{\tau_{TOT}}\right)}{(signal)^2} = A_1\frac{1}{\tau_{TOT}}$$

$$\left(\frac{N}{S}\right)^2_{1/f} \propto \frac{3\cdot A_2}{(3\,signal)^2} \cdot 3 = A_2$$

RNDR: properties and considerations

When total measurement time is fixed:

- White noise is independent form the number of measurements
- 1/f scales approximately as *1/n*
  (It scales as $1/n^x$ where x is close to 1. For an exact calculation see: E. Gatti et. Al. *"Multiple read-out of signals in presence of arbitrary noises. Optimum filters",* NIM A 417, 1998)
- White current noise scales like $1/n^2$.
- The noise relative to the leakage current in the internal gate does not scale and increases with the toal measurement time (see S. Woelfel et al. *"A Novel Way of Single Optical Photon Detection: Beating the 1/f Noise Limit With Ultra High Resolution DEPFET-RNDR Devices"*, IEEE TNS Volume 54, issue 4, Part 3, Aug. 2007)

When the single maesurement time is fixed (total time increases with number of measurements):
- all the three components scale as 1/n
- the noise of the leakage current in the internal gate increases with the measurement time

- RNDR must be used when *1/f* noise is dominant
- It is possible :

  1) to increase the total measurement time to make white voltage noise negligible
  2) to use multiple readout to decrease 1/f noise contribution

- The total measurement time is limited by:

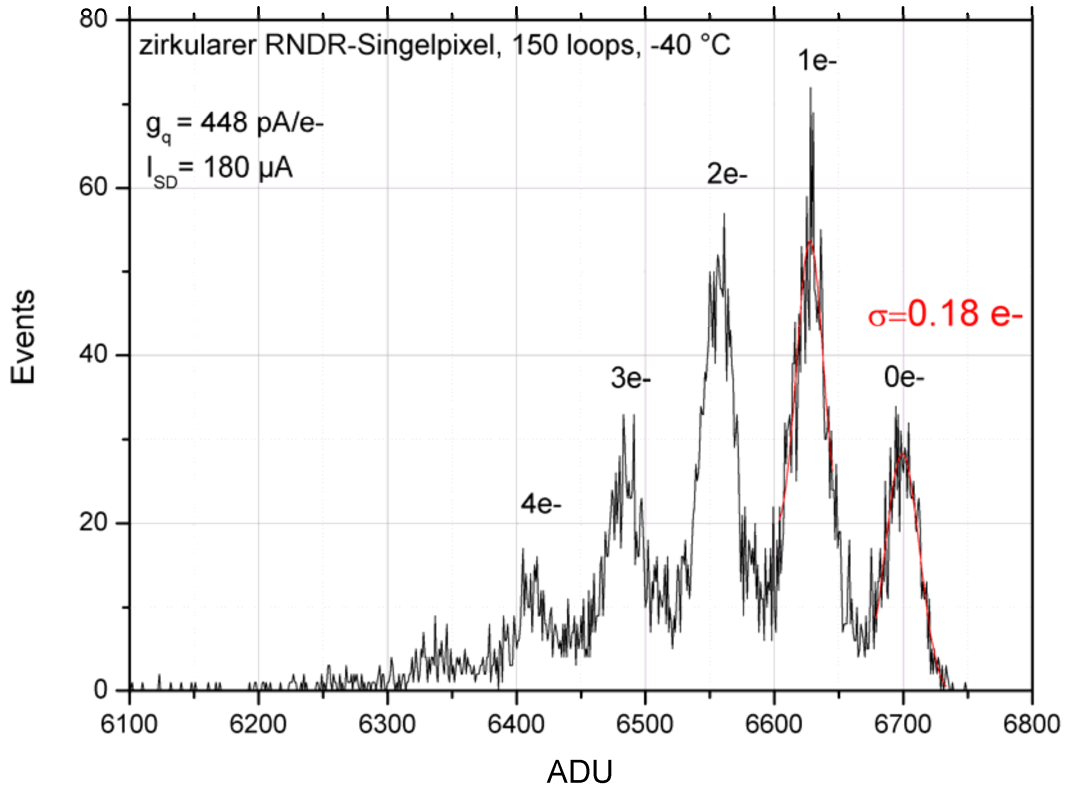
  - experimental constraints
  - leakage current that fills the internal gate

- The sytem properties are tunable: it is possible to trade speed with resolution

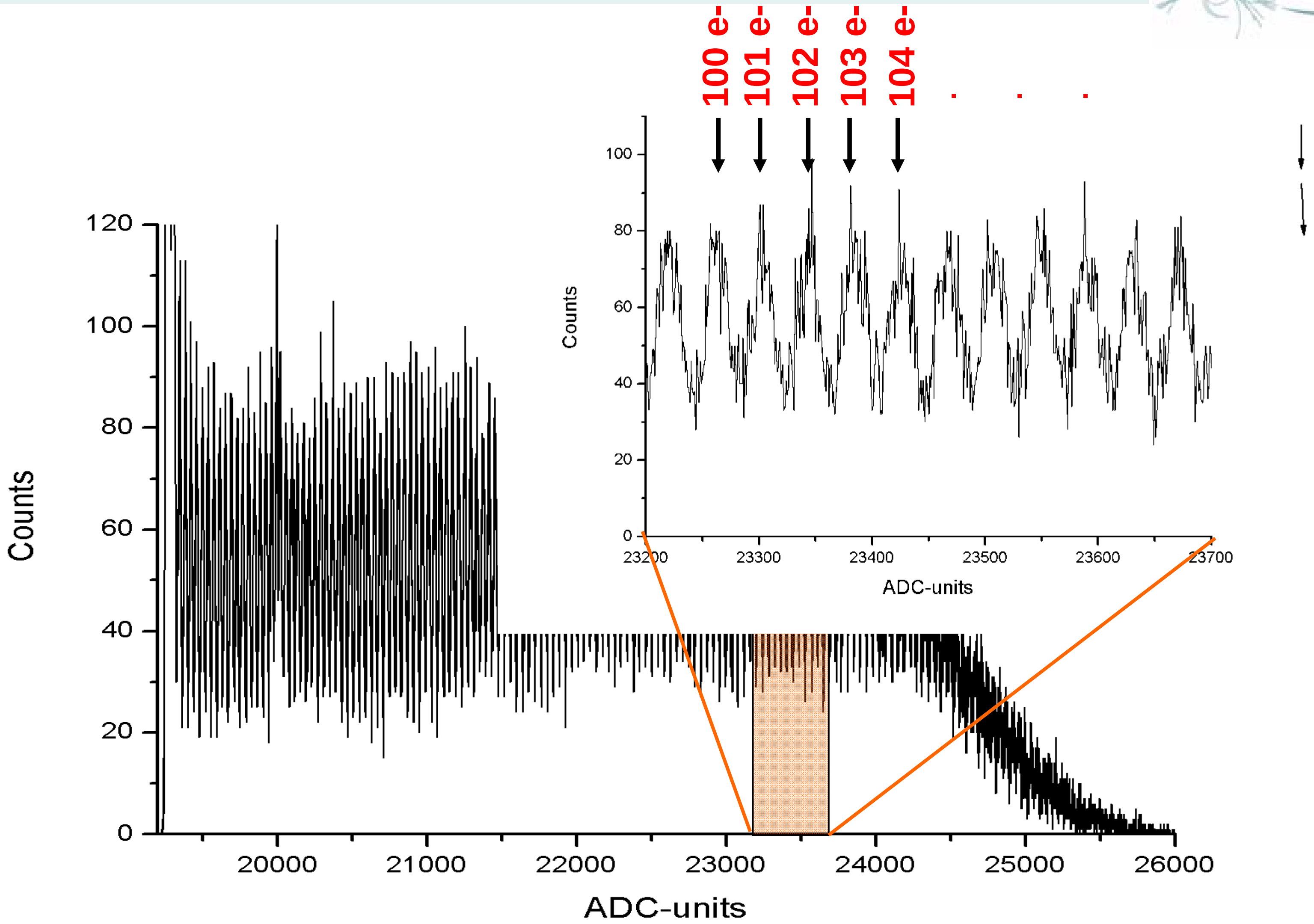
RNDR-DEPFET

- **Single pixel structure: ENC for one readout: 2.1 electrons (rms)**

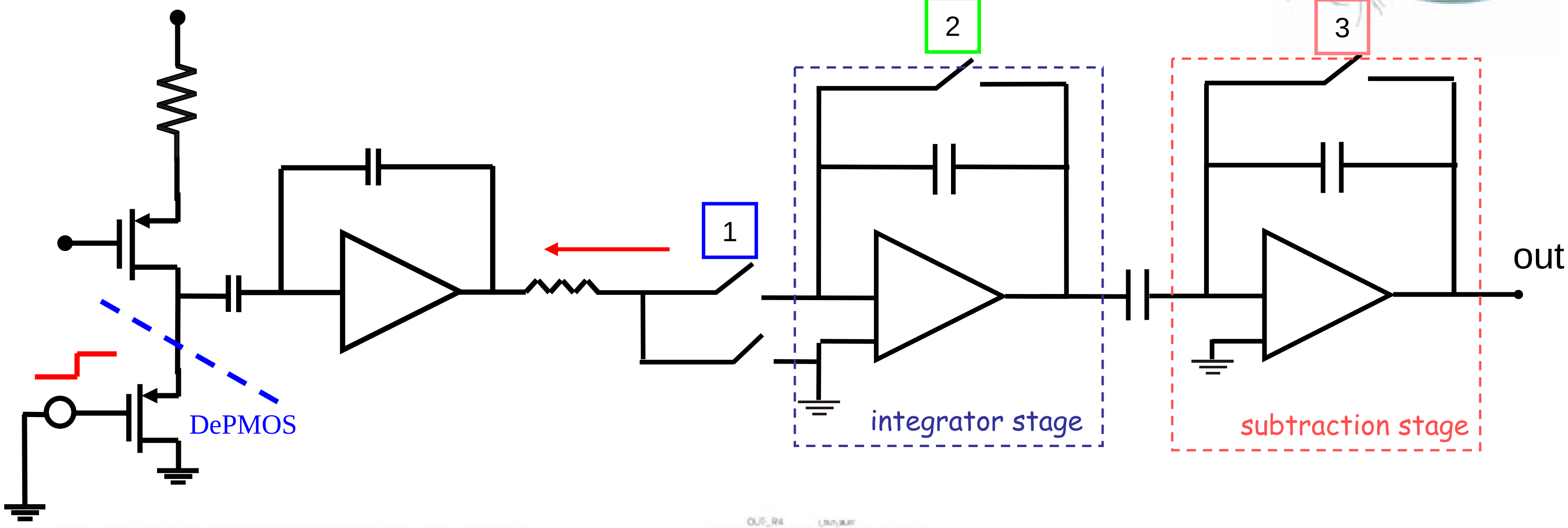
- Smaller gate-length -> higher g_q -> higher S/N

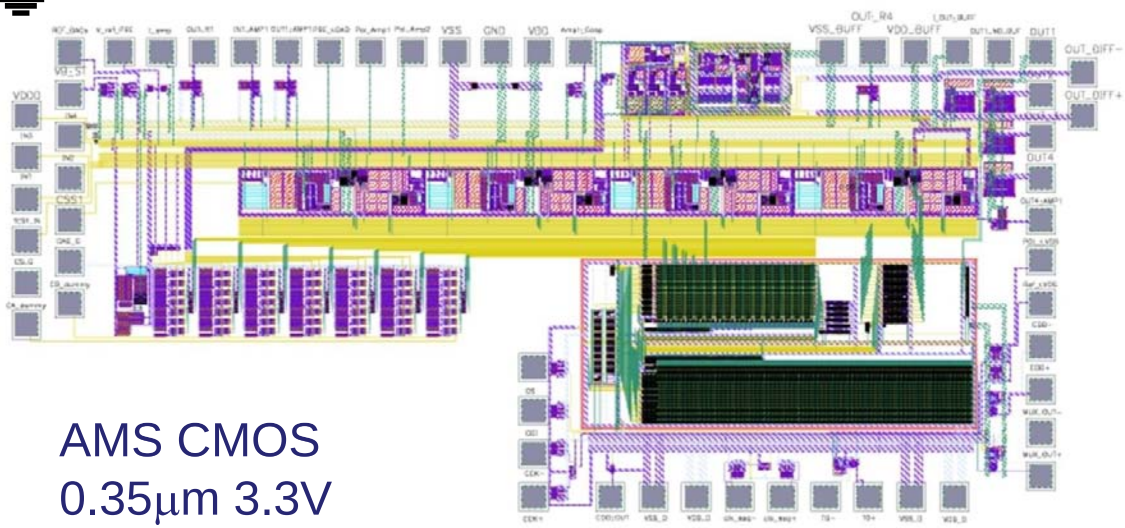


How to distinguish 100 electrons from 101?

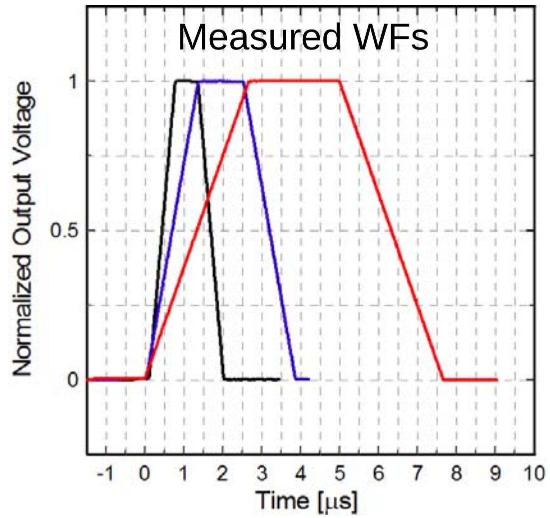


Trapezoidal Filter Readout ASIC

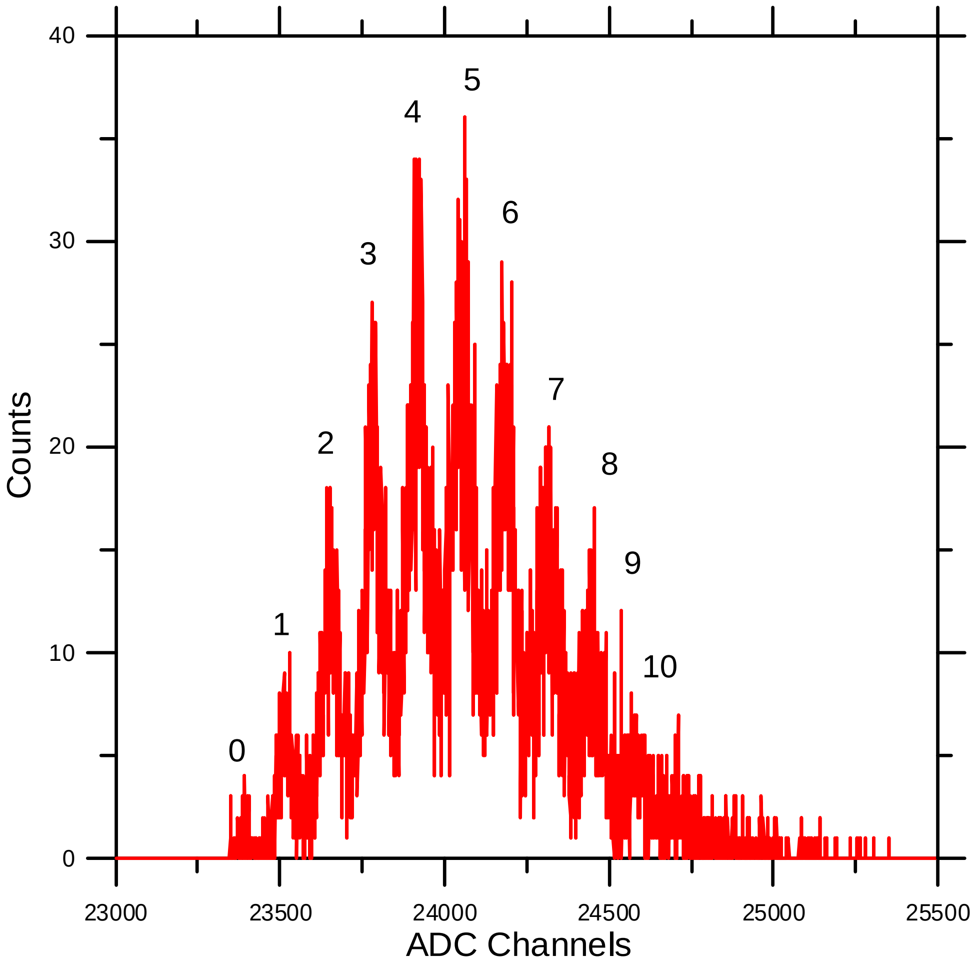




AMS CMOS
0.35µm 3.3V

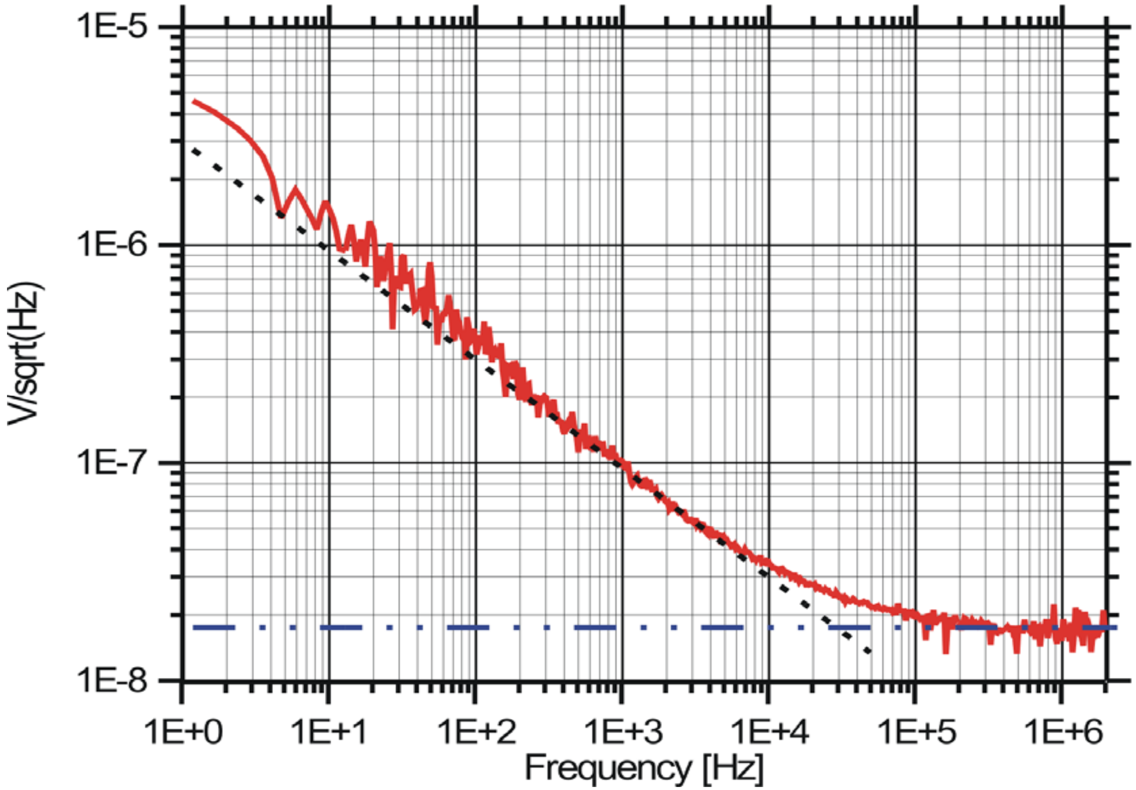


Single Photon Resolution



- A weak intensity laser has been used to inject electrons into the RNDR-DePMOS
- The laser injects in average 5 electrons
- T=- 50 °C
- A trapezoidal weighting function has been used with a total processing time of 20 µs
- ENC ~0.25 el. r.m.s.

Achievable Performance

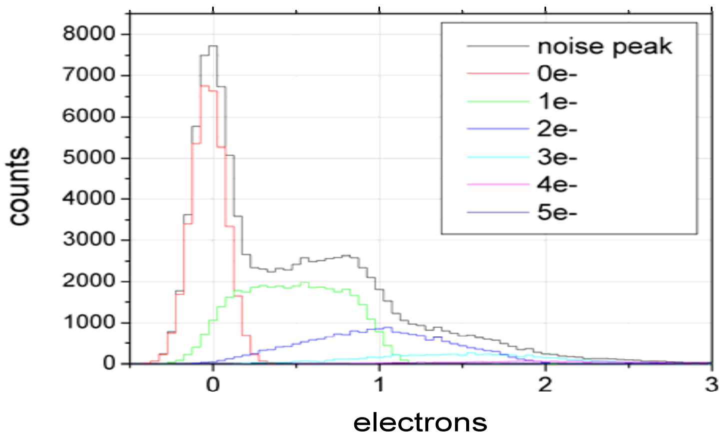


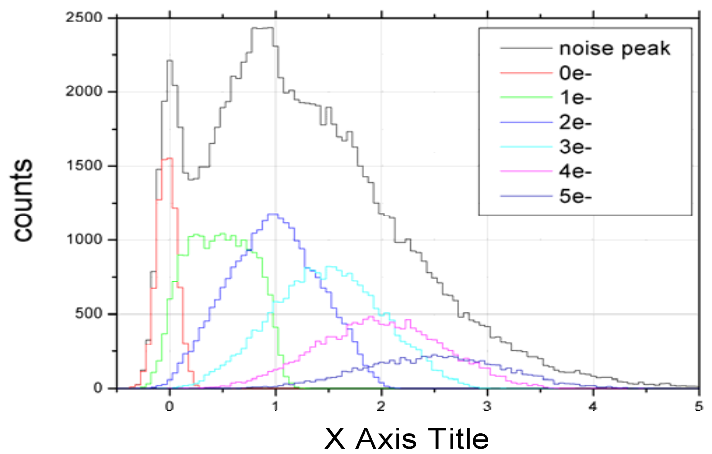
DePMOS with lower 1/f noise are available

They have been implemented in the RNDR geometry and will be tested soon

- **White voltage noise:**
  A1=2
  a=1.5x10^{-16} V^2/sqrt(Hz)
- **1/f noise**
  A2=1.26
  a_f=4.5x10^{-12} V^2
- **One readout:**
  12.5 µs
  White: 1.8 el
  1/f: 1.37 el
- **80 readouts:**
  total time=1.000 µs
  White: 0.18 el. r.m.s.
  1/f: 0.16 el
  Total noise: 0.2 el. r.m.s.
- Readout Speed: 1 KHz

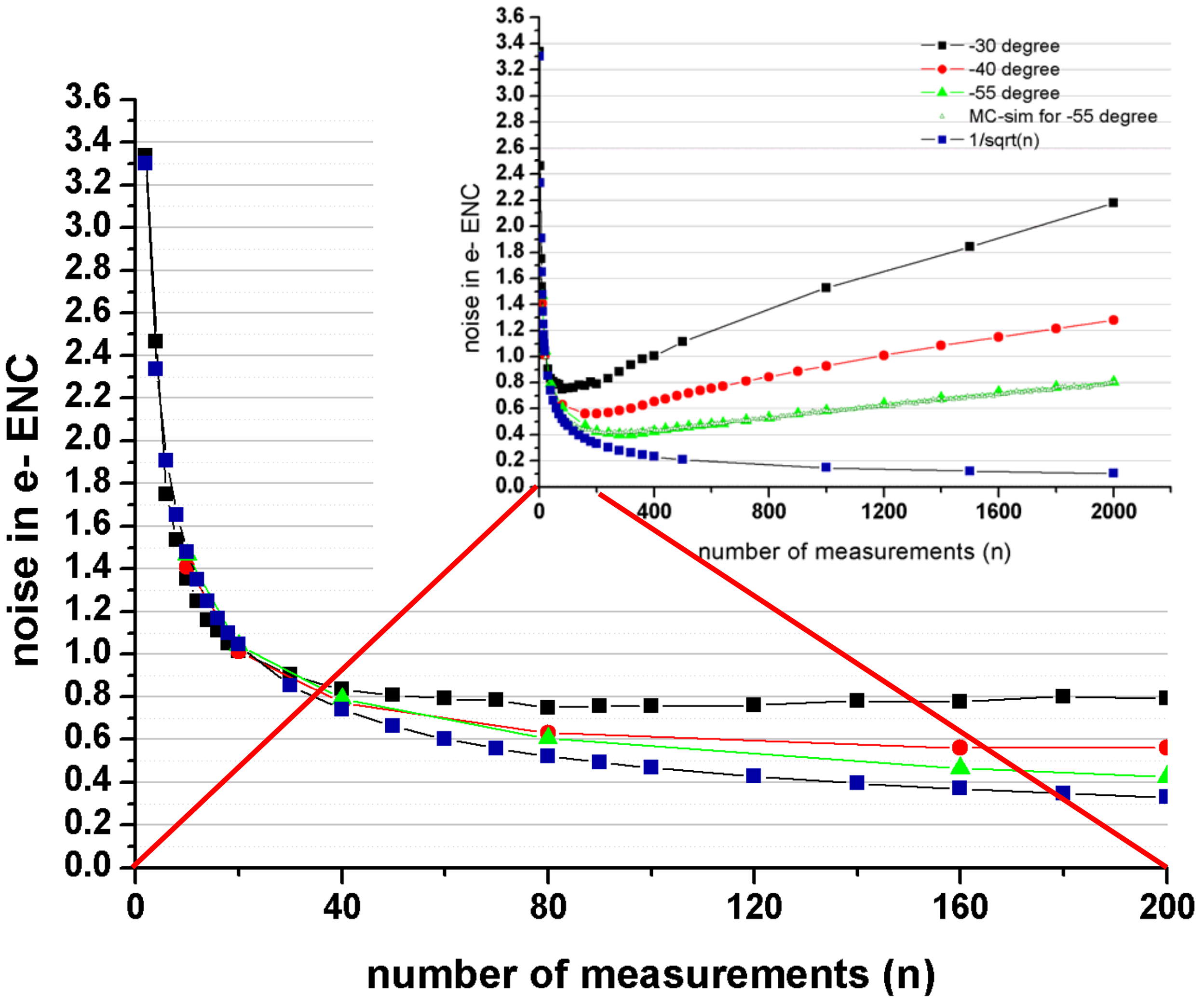
RNDR-Detectors
Influence ofleakage current



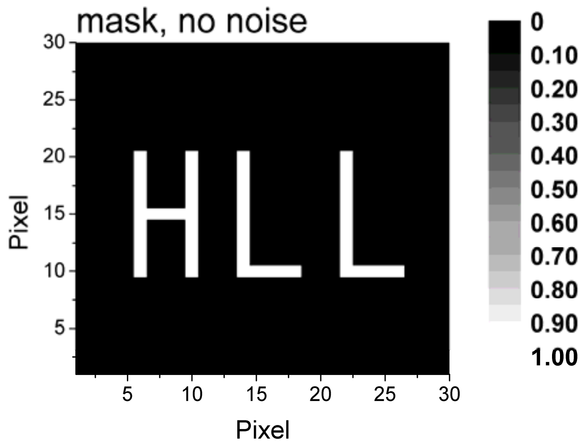


- **100.000 measurement cycles**
- **100 loops each**
- **3.3 e- noise for one readout cycle (loop)**
- **In mean 1 electron during one readout cycle t_{acq}**
- **In mean 2.5 e- during t_{acq}**

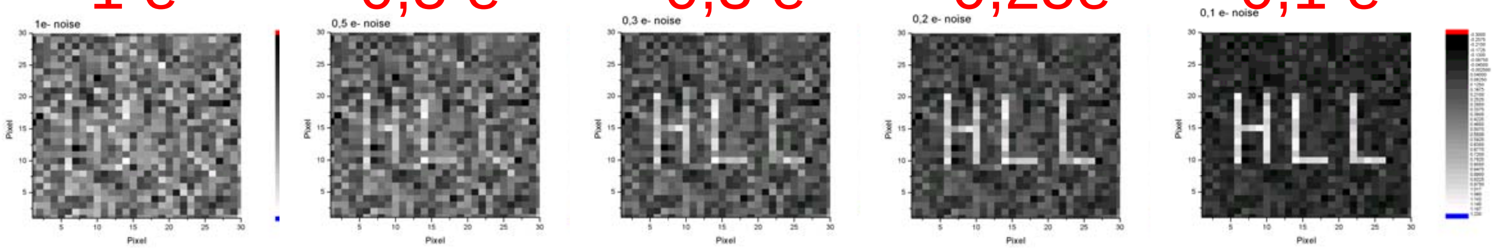
Noise measurements with HL-devices



What does a certain resolution mean in terms of contrast?



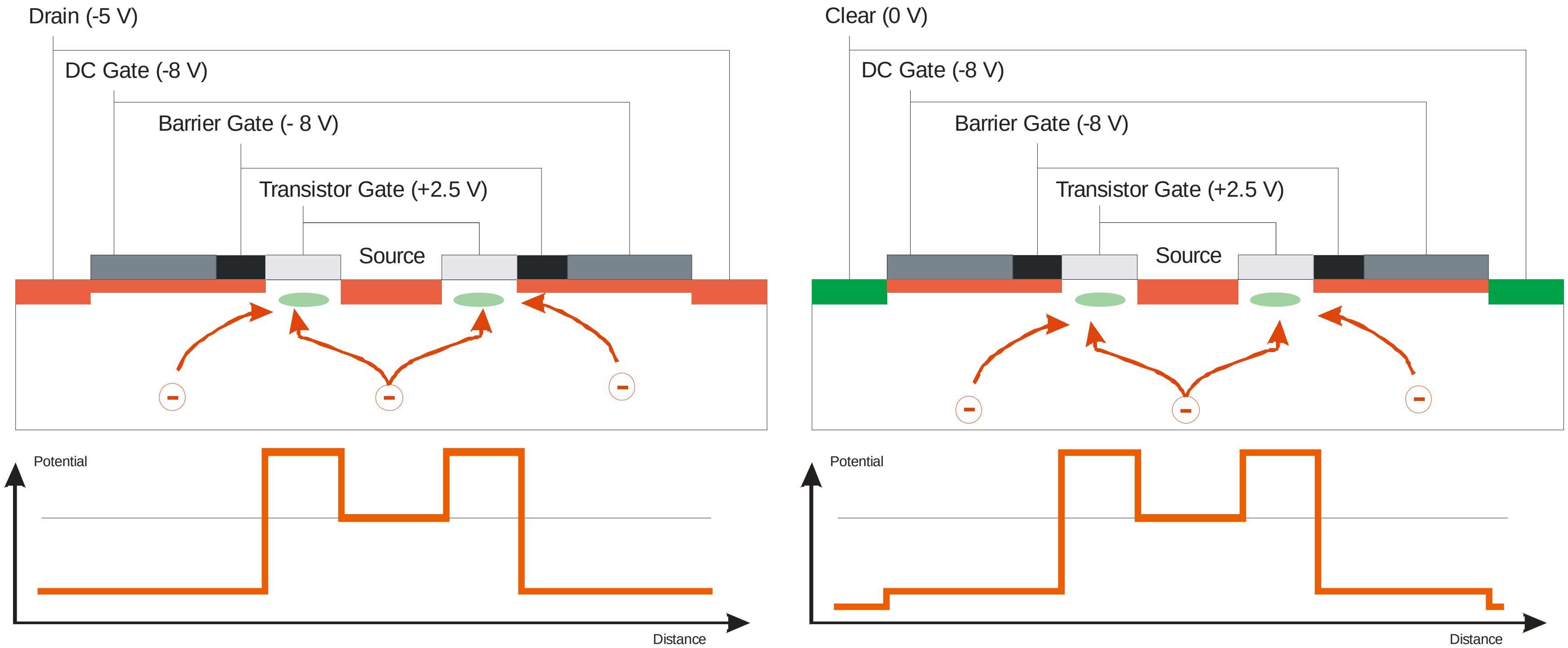
σ = 1 e- 0,5 e- 0,3 e- 0,25e- 0,1 e-



Working principle I

MPI Halbleiterlabor

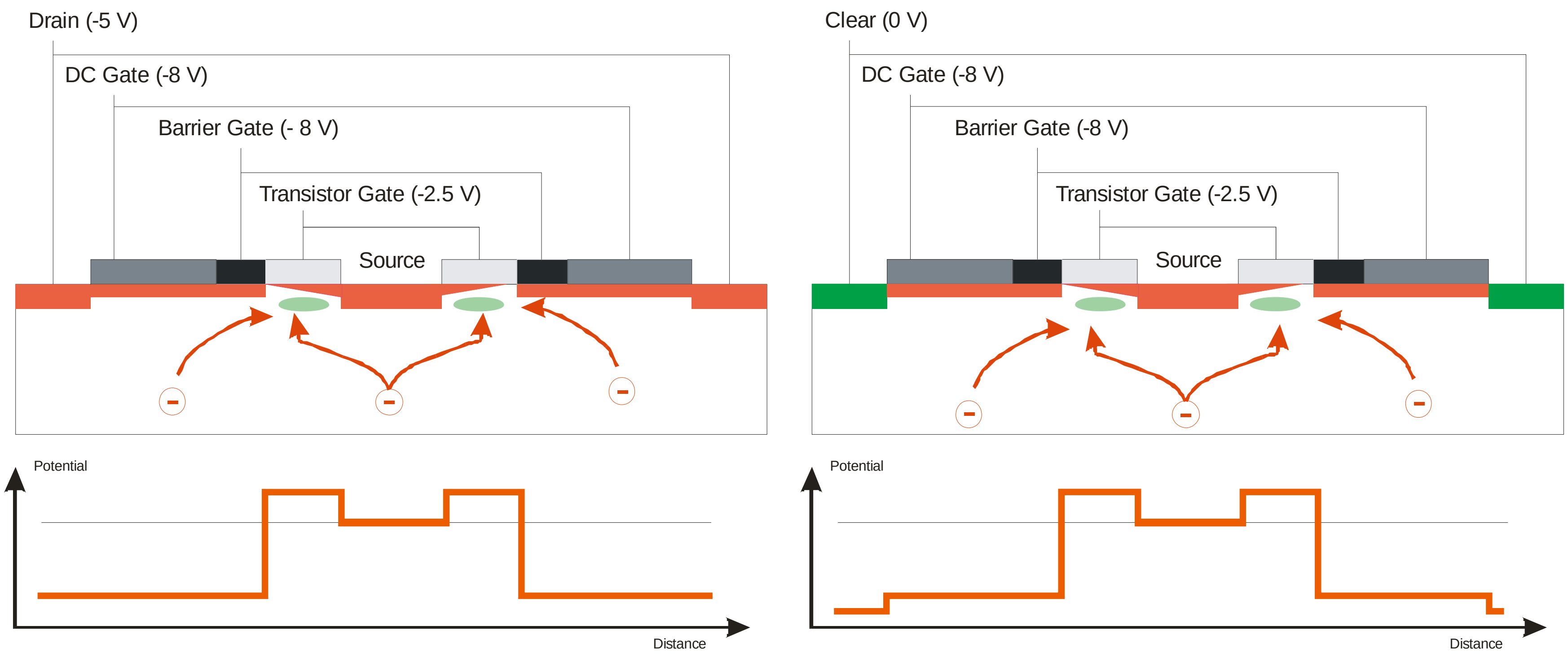
Integration mode



- „Normal" DEPFET operation
- Charge is collected in internal gate
- No transistor current flowing

Working principle II

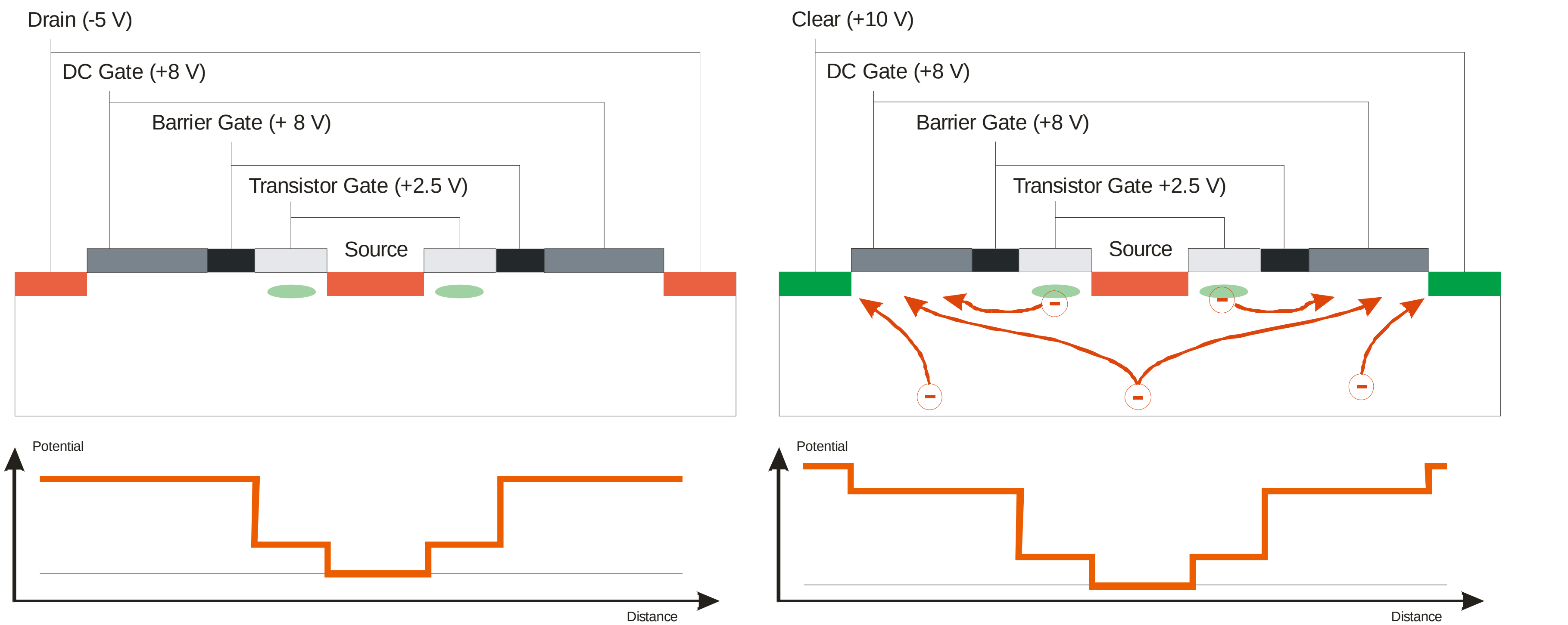
Readout mode



- „Normal" DEPFET operation
- DCGate generates „dynamic drain"

Working principle III

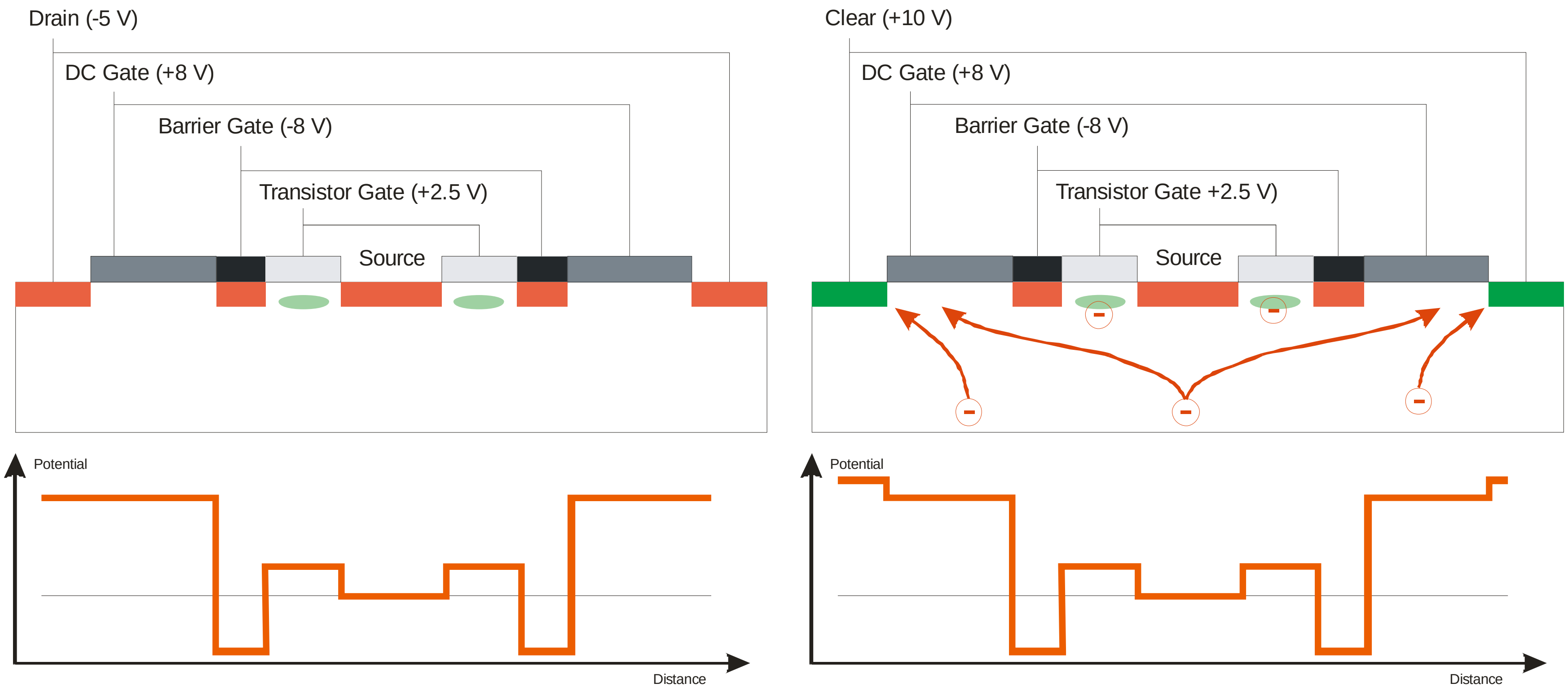
Clear mode



- Normal DEPFET clear
- All charge is removed from internal gate
- Charge from bulk directly drifts to clear

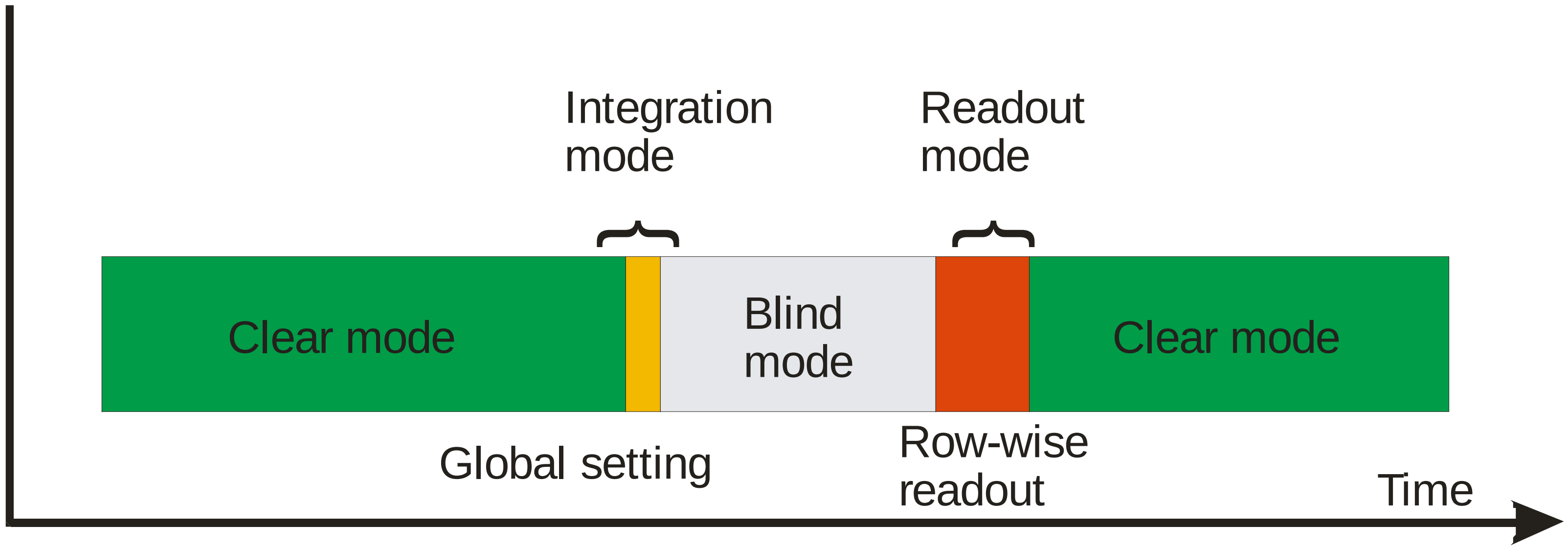
Working principle IV

Blind mode



- New operating state
- Charge from the bulk drifts to the clear contact
- Barrier keeps charge in the internal gate

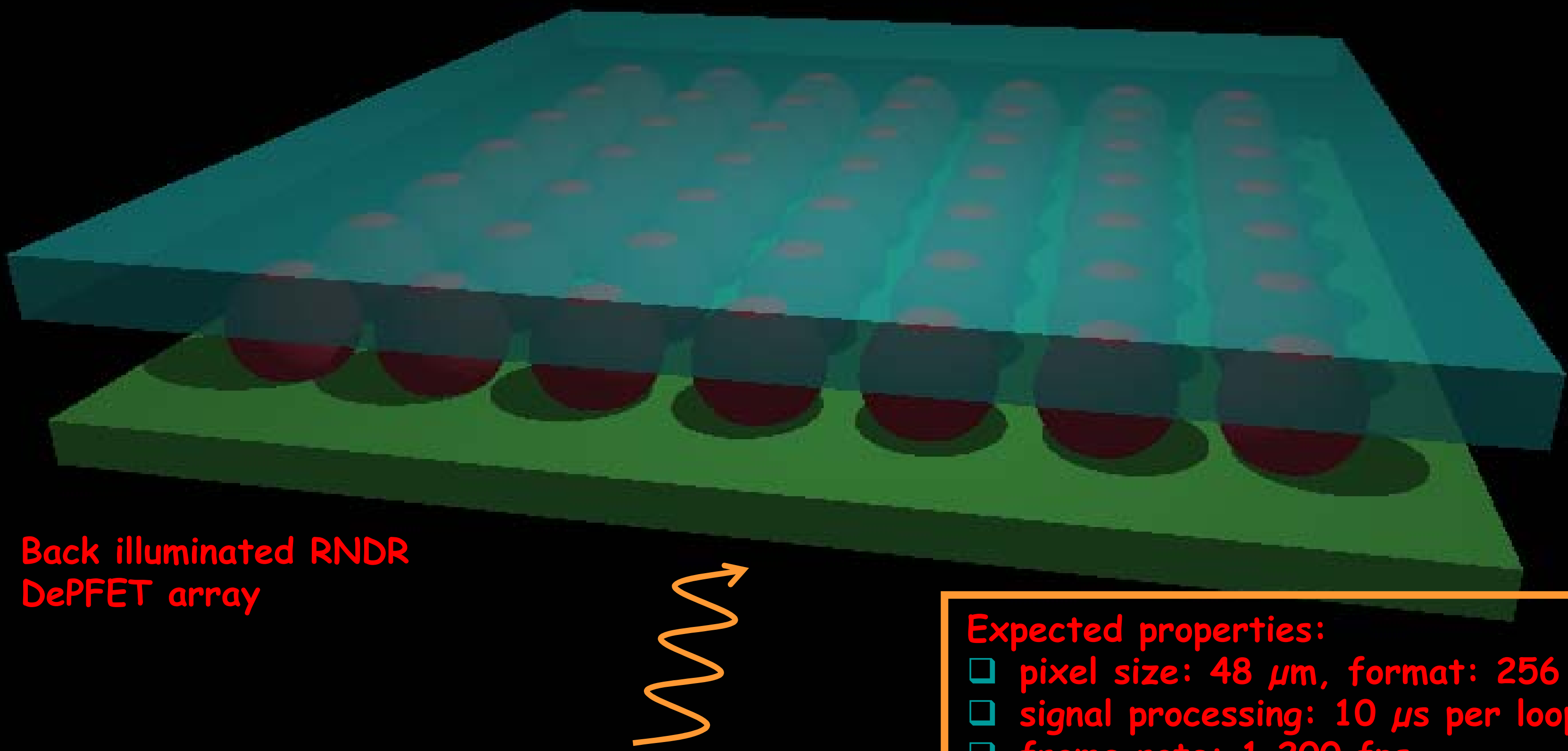
Operation cycle



Applications:

- Selective tagging of time-discrete signal
- Scanning of time continuous, periodic signals
- Run-time detection
- Fluorescence light detection
- etc...

Expected properties:
- 130 nm process
- bonding area: 30x30 μm^2
- pixel size 50x50 μm^2
- amplifier area 40x40 μm^2



Expected properties:
- pixel size: 48 μm, format: 256 x 256
- signal processing: 10 μs per loop
- frame rate: 1.200 fps
- NIR sensitive
- Readout noise: 0.25 e^- @ 64 loops at -40° C

Conclusions

- We have presented a concept for a system with single optical photon resolution capability based on a linear RNDR-DePMOS amplifier array

- The working principle of the system has been experimentally demonstrated using:

  - A prototype of a single RNDR-DEPMOS device
  - A prototype of a Multi-channel Low-noise ASIC performing a Trapezoidal Filtering

- A readout noise of 0.18 el. r.m.s. has been obtained at -40 ˚C showing single photon resolution and confirming theoretical predictions

- A fast gating was implemented and experimentally verified

- Using a new kind of RNDR DePMOS device already partially characterized a resolution of 0.25 el. r.m.s. is foreseen with a readout speed of 1.2 kHz

- An optimized circuit already implemented will allow to readout the two DePMOSs of the RNDR device simultaneously, reducing the total readout time of a factor 2