Workshop on
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A 0.5 noise electrons$_{RMS}$ CMOS pixel

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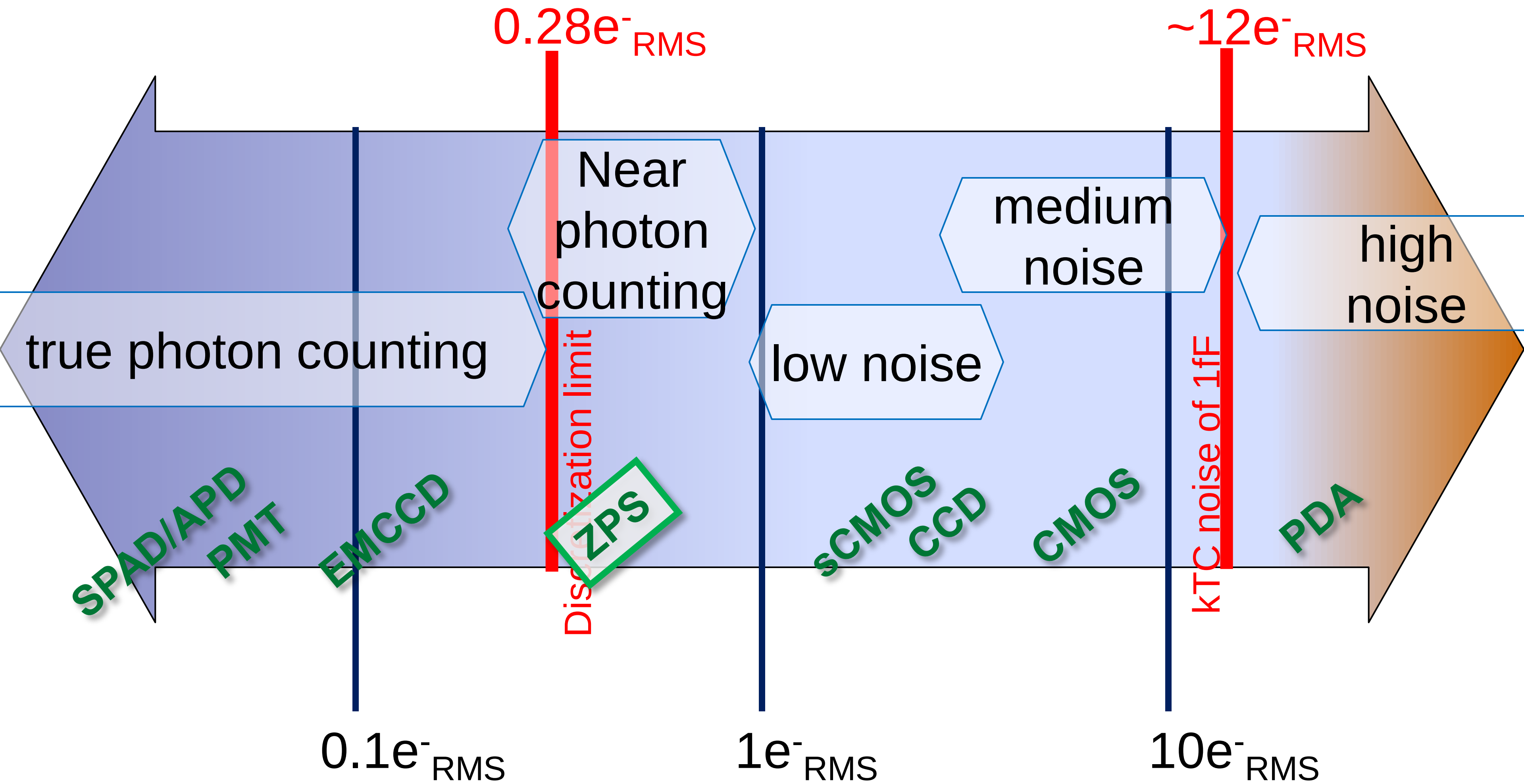
Outline

- **Introduction**
- **The principle**
- **The measurement**
- **Conclusions and further work**

What is “near” photon counting?



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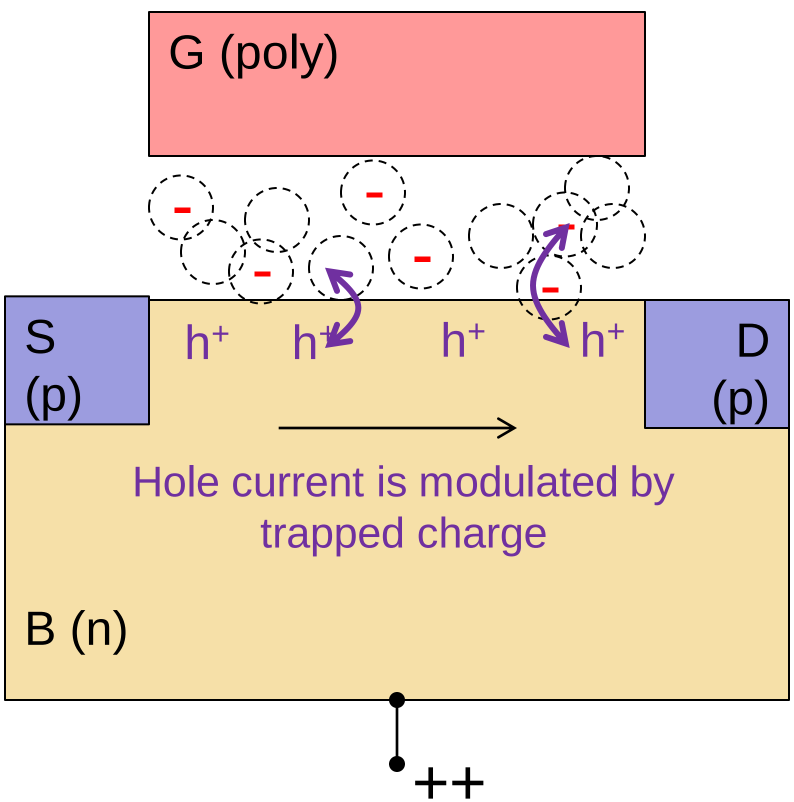
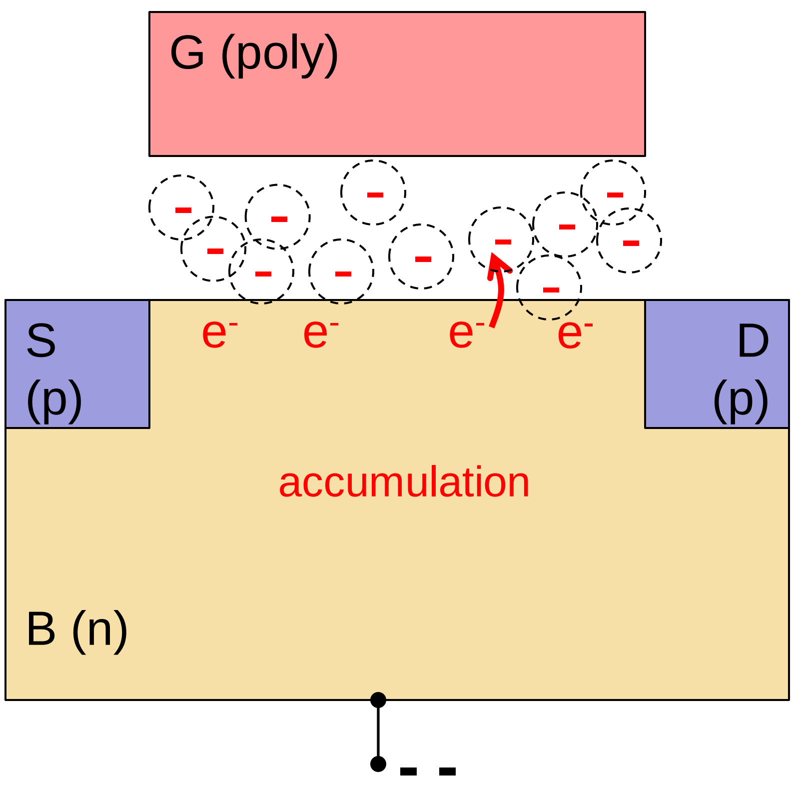
THE PRINCIPLE

Reduction of 1/f and RTS noise by
$\Rightarrow$ Cycling the MOSFET between inversion and accumulation, creating “un-correlation”
$\Rightarrow$ Sampling the signal during inversion
$\Rightarrow$ Oversampling and averaging

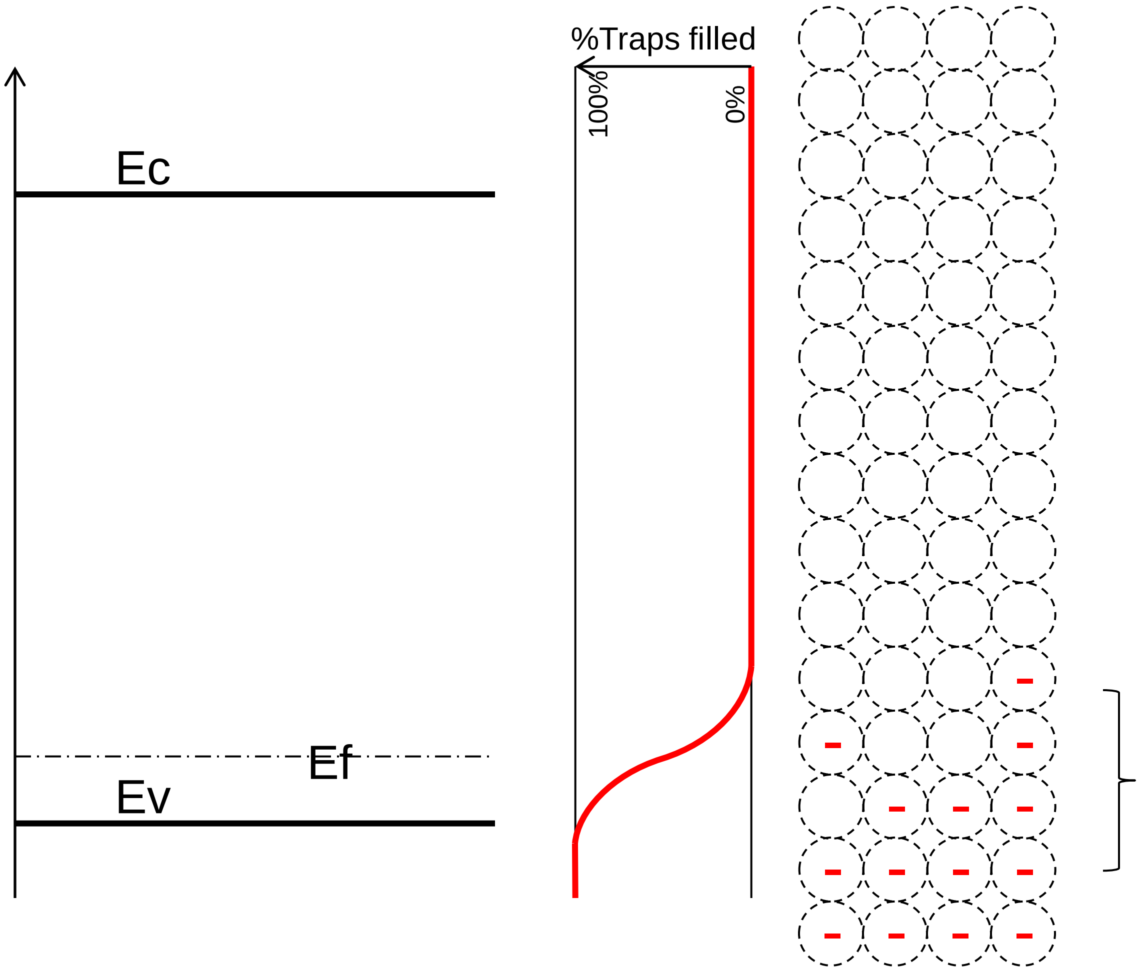
pMOSFET 1/f noise

Filled oxide state + hole ⇔ empty oxide trap empty oxide state + hole ⇔ filled oxide trap





Fermi statistics of interface states *in inversion*



This fraction of the traps interacts with the inversion layer and creates 1/f noise

Fermi statistics of interface states *in accumulation*

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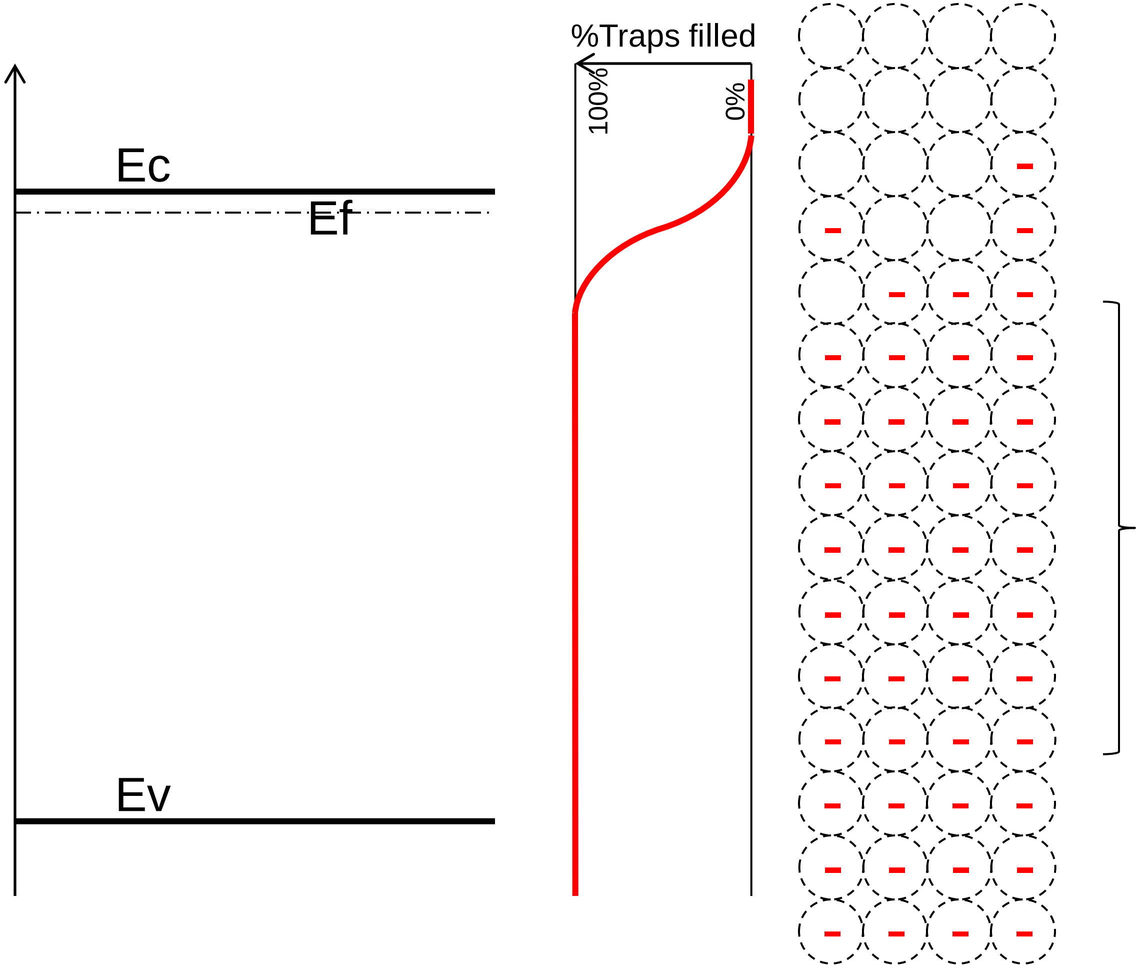

All traps below Fermi level are quickly filled and loose long term memory

McWorther theory of 1/f noise

⇒ **Oxide/interface states act as traps**

⇒ Fill or empty (capture&emission) while interacting with the inversion charges

⇒ **Time constants for capture and emission**

⇒ vary between <ns and >days

⇒ Responsible for 1/f spectrum = long correlation time

⇒ **Correlation in 1/f noise**

⇒ as consecutive samples are strongly correlated, oversampling does NOT help.

Cycling inversion-accumulation

Pulling the MOSFET in accumulation

⇒For a pMOSFET, interface is now populated by electrons

⇒Traps are now strongly pressured to be “filled”

When coming back to inversion

⇒traps are (mostly) “filled”

- Hence their memory is erased
- Hence their correlation time is reset to zero
- The spectrum of the noise of the re-created signal becomes “white”

1/f noise is whitened *"laundried"*

Does not mean that the noise is reduced!

⇒Probably the amplitude remains the same and may even have increased

Correlation time is reduced

⇒to a time shorter than the cycling period

⇒Sampling the noise over multiple inversion/accumulation cycles results in uncorrelated samples

⇒Oversampling helps to reduce the noise, ~as the square root of the number of samples.

Noise breakdown [% of raw]

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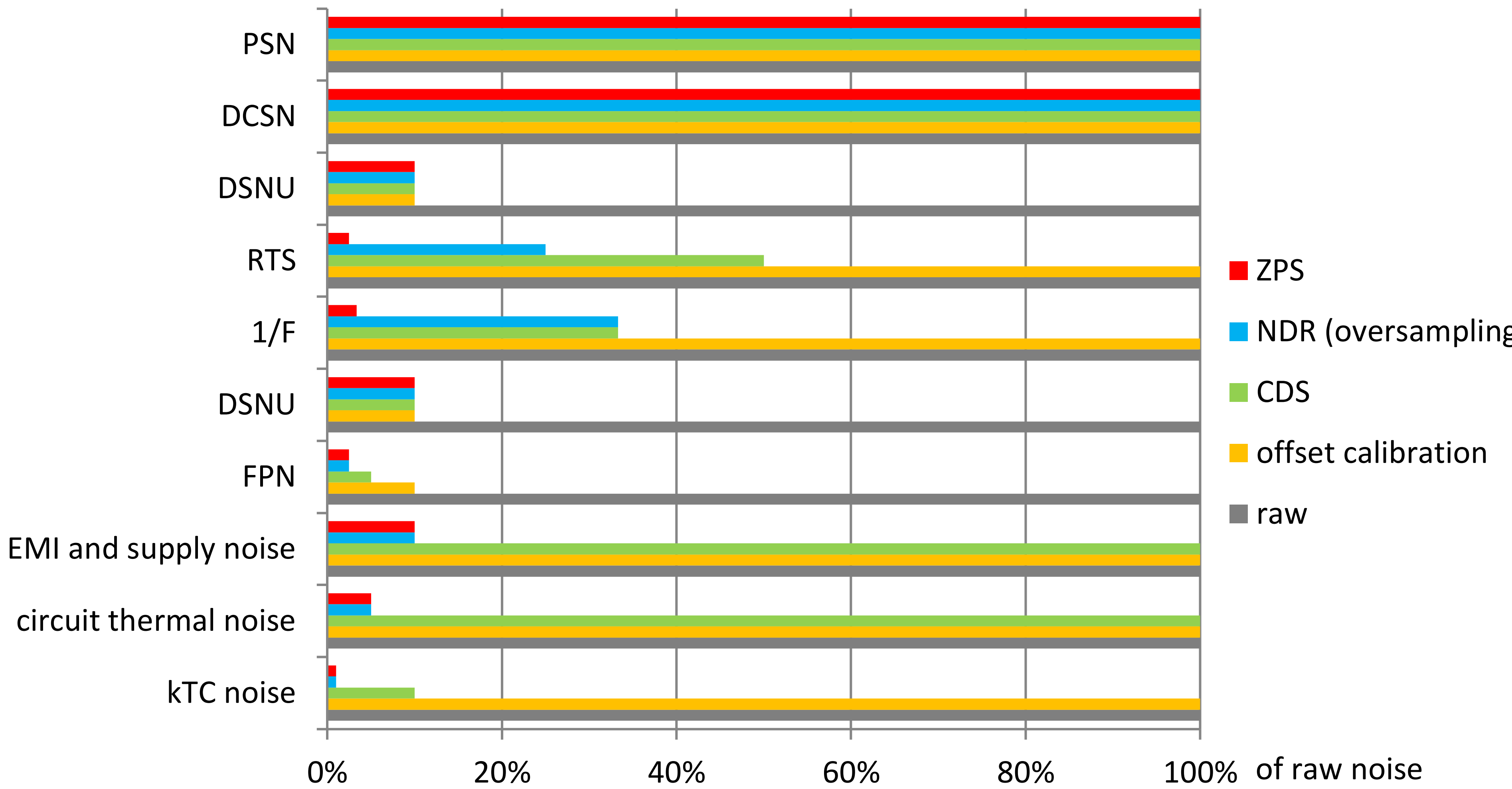
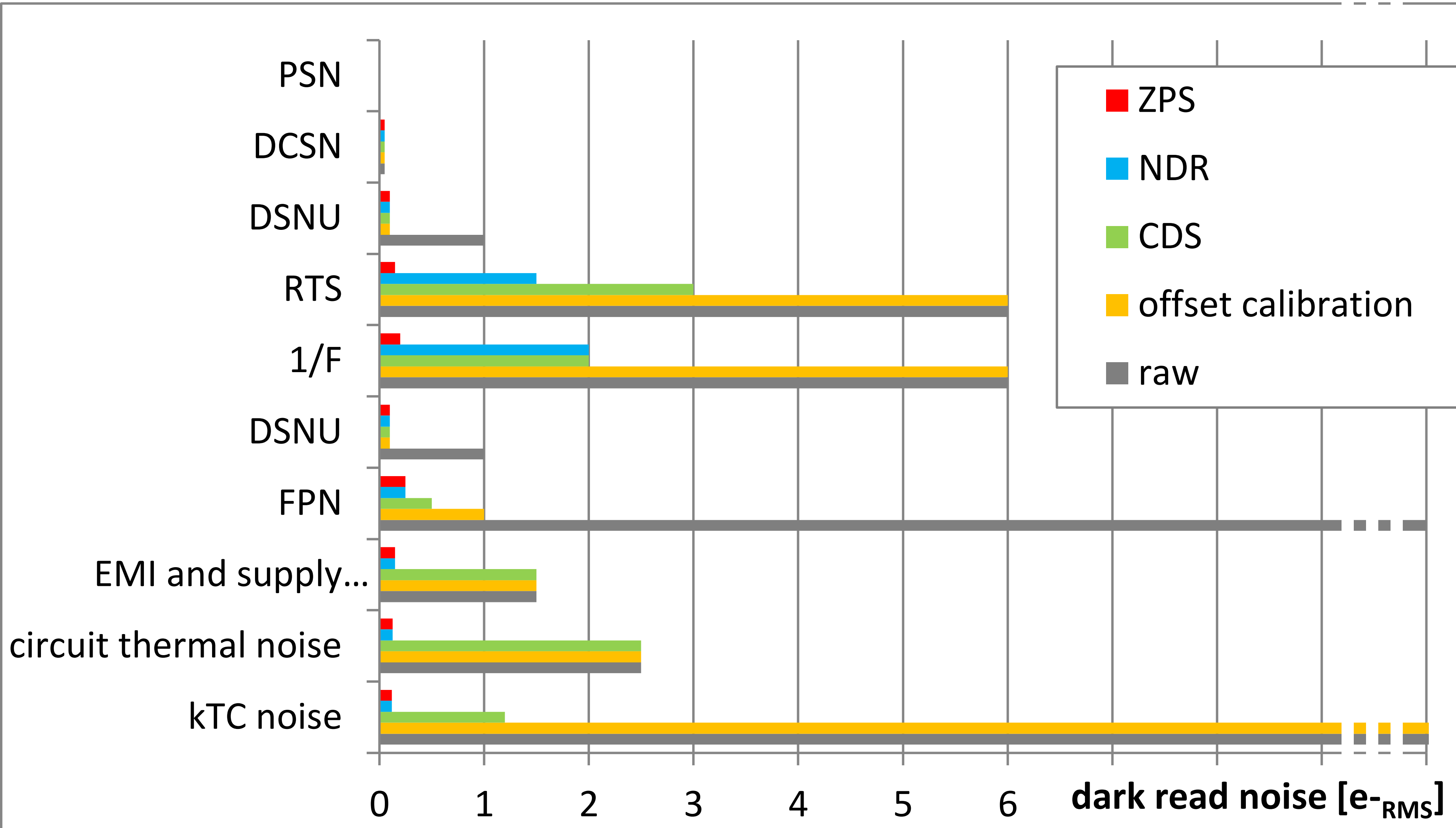


Noise breakdown [e^-_{RMS}]



THE MEASUREMENT

On a 4T CMOS pixel

⇒ In CTIA configuration to obtain a ~1000µV/e- charge conversion factor

⇒ Obtain 0.5 noise electrons RMS

⇒ Patents pending

Setup of demonstrator

4T CMOS pixel test structure

⇒ 100µm standalone test structure, ~7µm MOSFET area

⇒ Special 4T topology (CTIA/SF) using nMOS+pMOS

⇒ high fill factor; compatible with backside illumination.

⇒ Used in CTIA mode

Result obtained

⇒ Very high charge to voltage conversion: >1000µV/e-

⇒ Zero point something (0.5) electrons$_{RMS}$ read noise in the dark.

⇒ Uncertainty of accuracy

⇒ Invitation to interested groups & PhD to provide independent confirmation of results.

The XCNOV/B/TI “1 pixel test structure”

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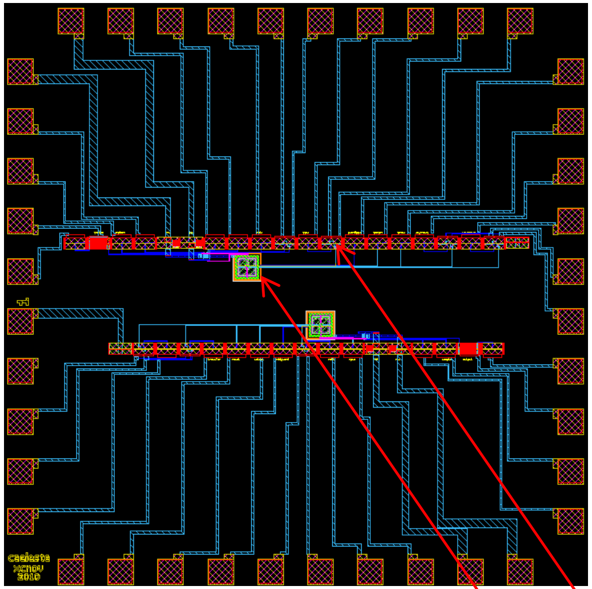
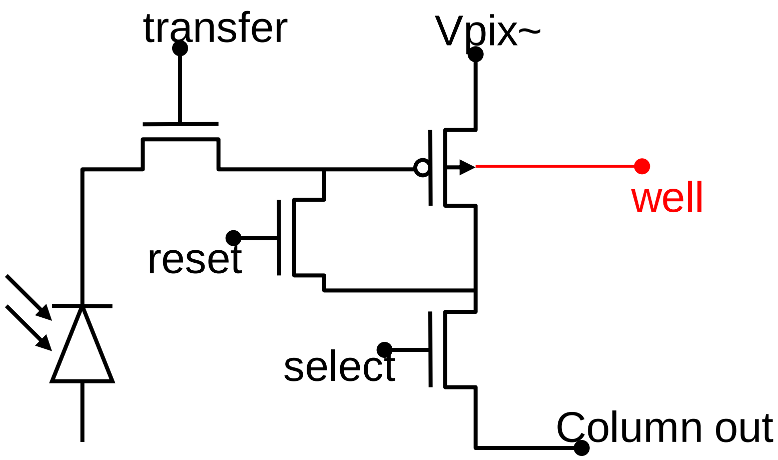
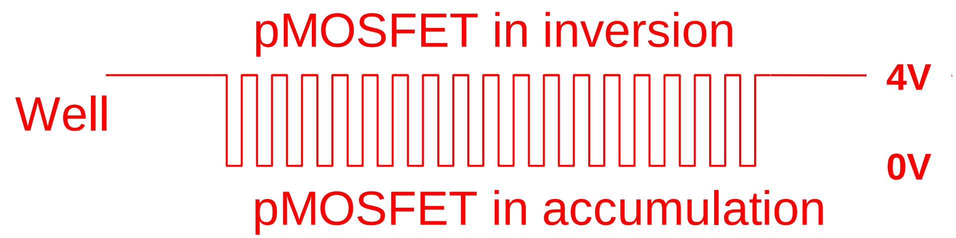


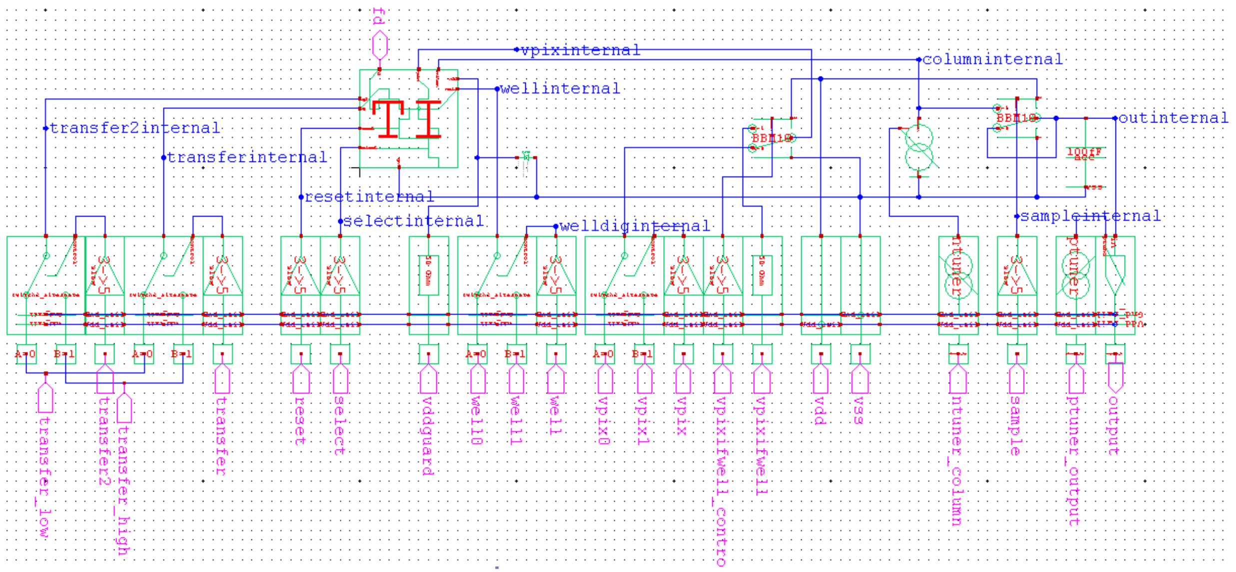
XCNOV

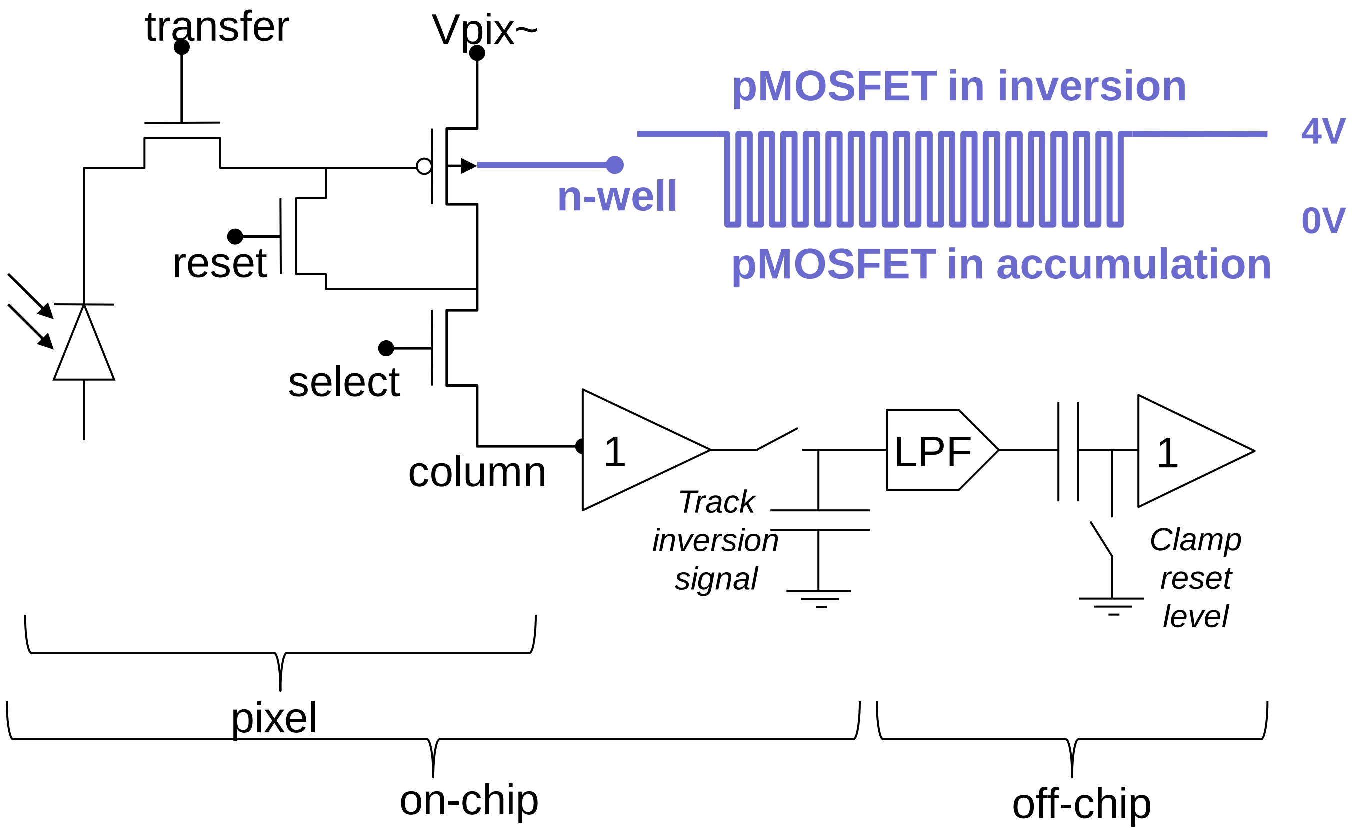
A B
C D

The XCNOV/B/TI pixel



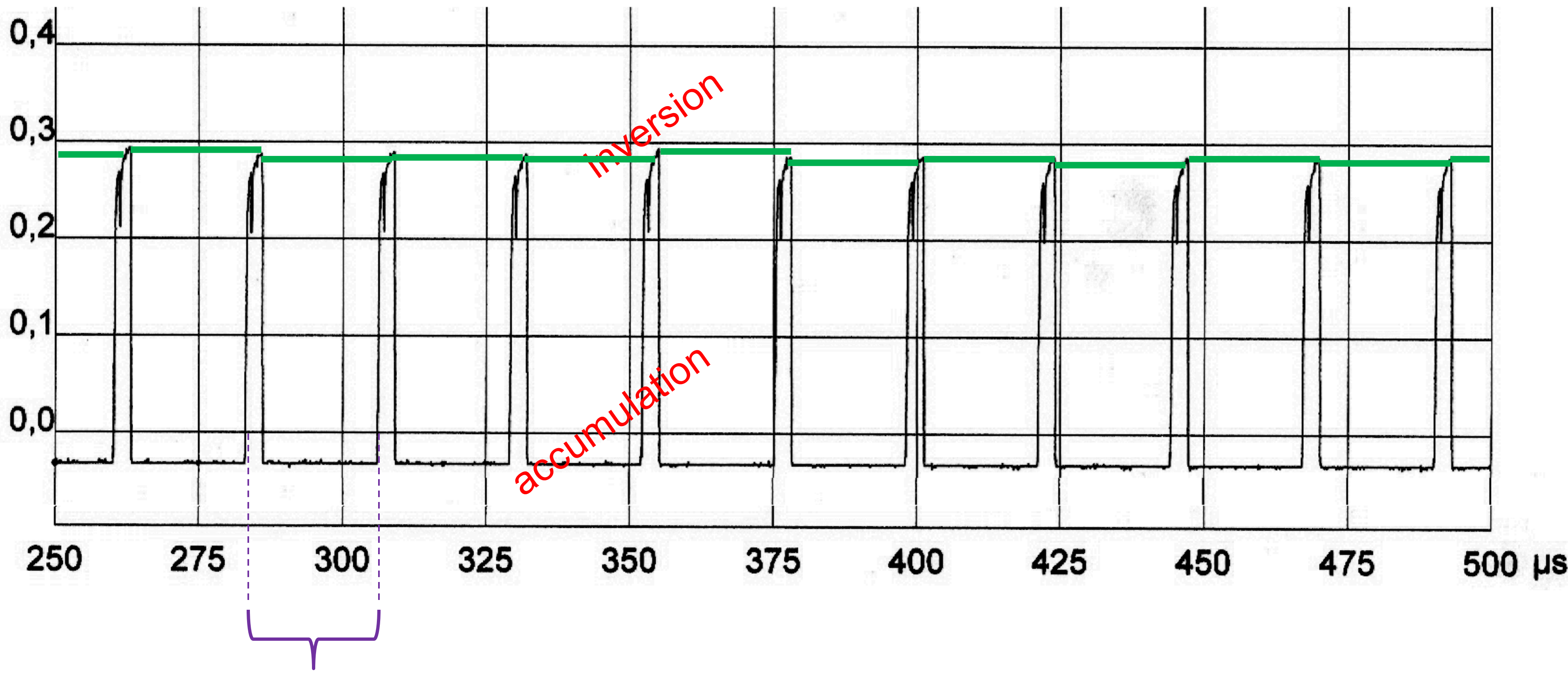





transfer
Vpix~
pMOSFET in inversion
4V
n-well
0V
reset
pMOSFET in accumulation
select
column
1
LPF
1
Track
inversion
signal
Clamp
reset
level
pixel
on-chip
off-chip

Measurements

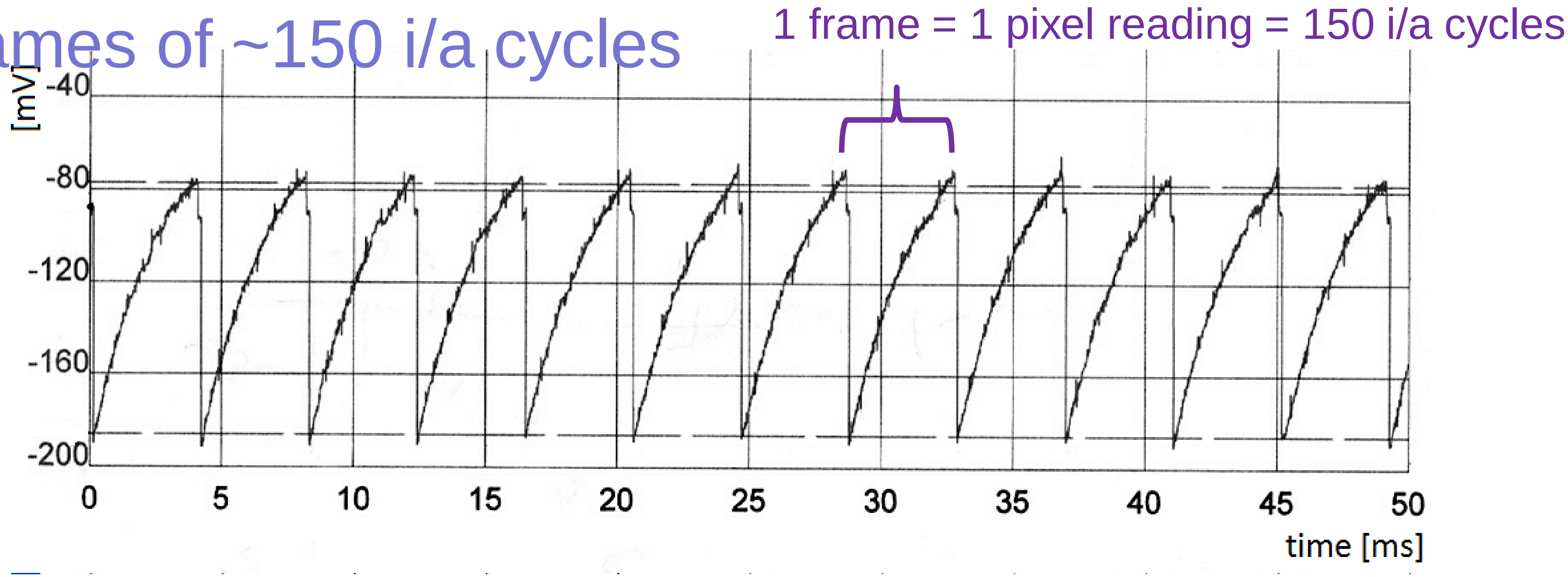
raw output while inversion/accumulation cycling



~150 such i/a cycles make up 1 measurement (1 frame, 1 pixel reading)

Measurements

frames of ~150 i/a cycles



Noise as function of inversion/accumumation amplitude

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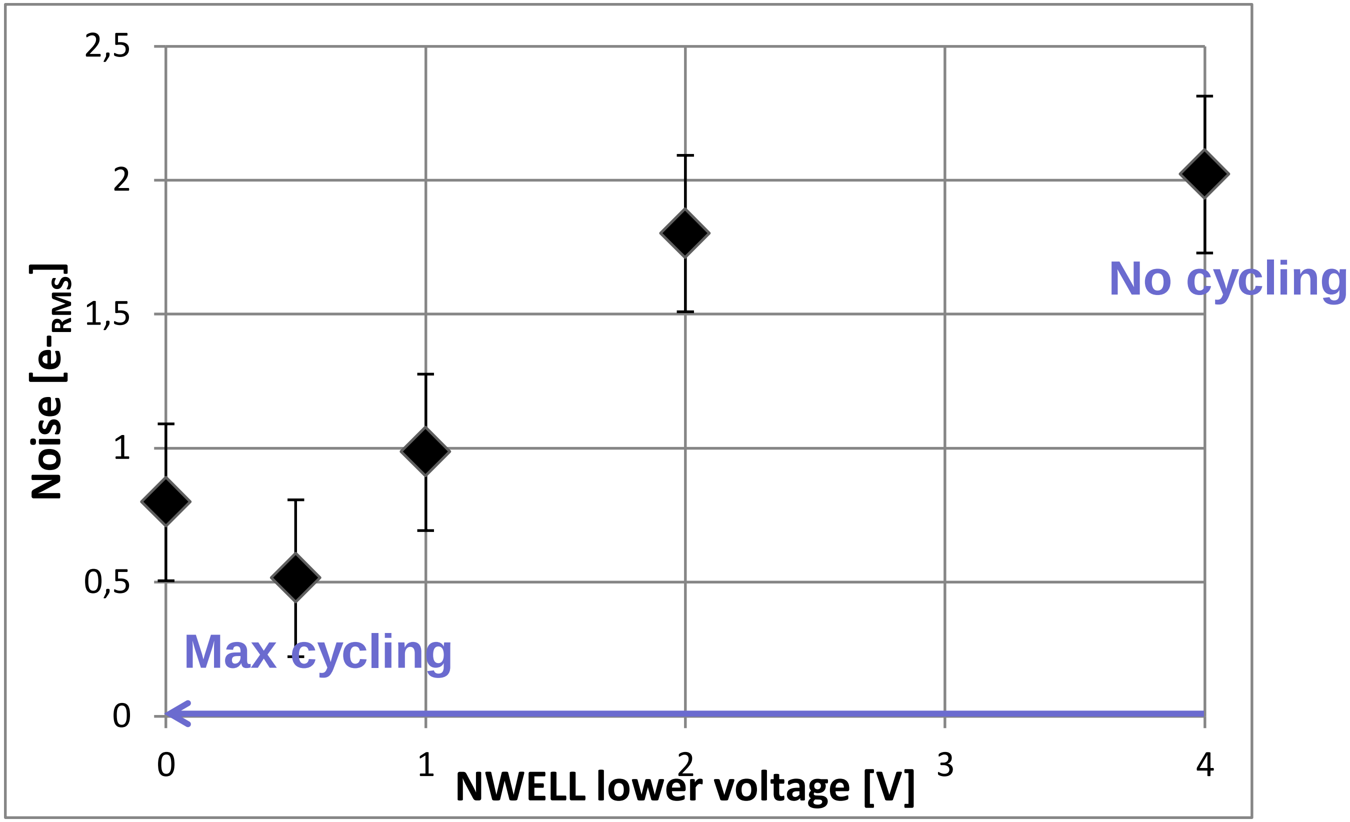
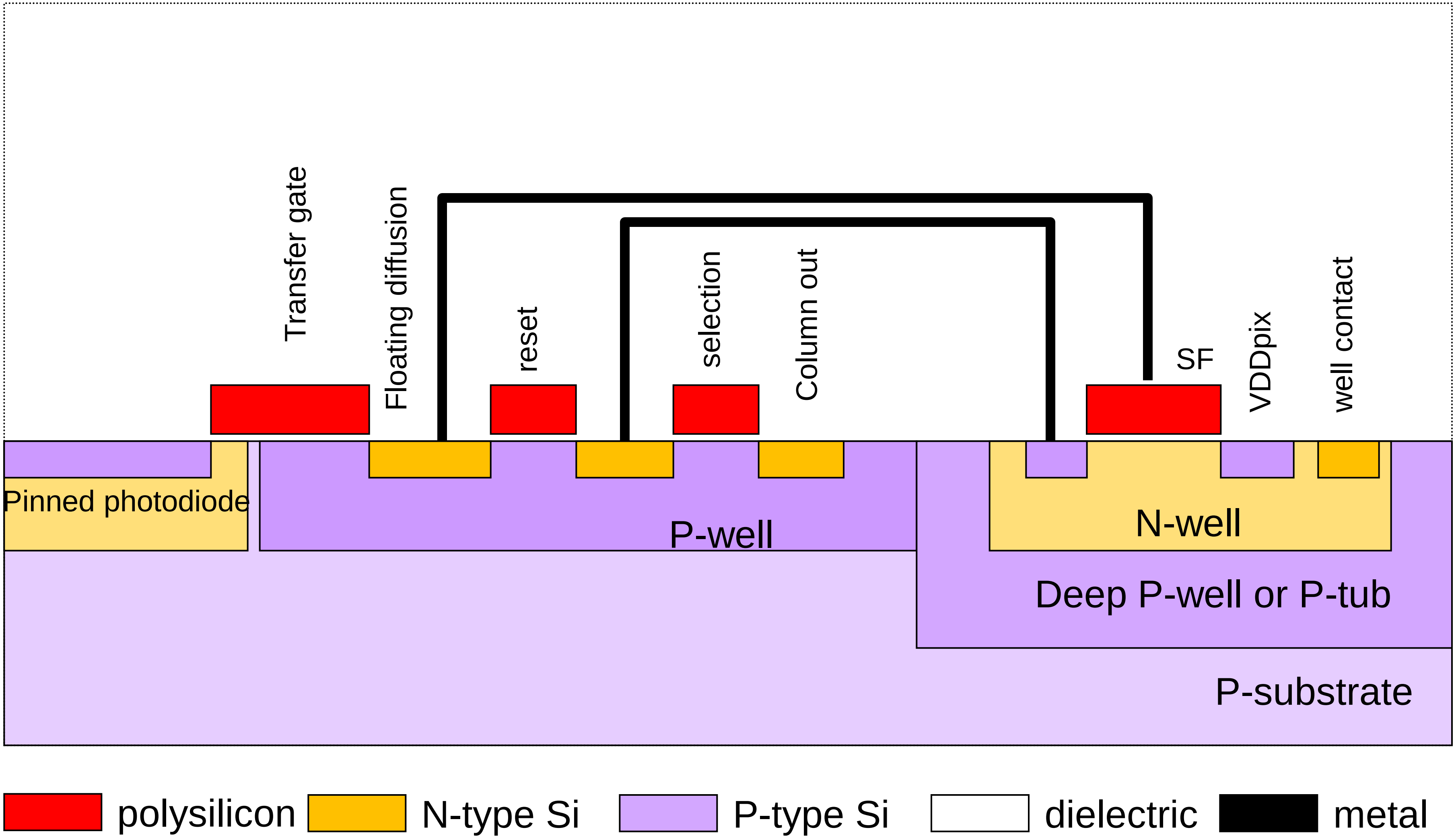


Measurement inaccuracy mainly due to difficulty to measure CVF

Further observations

- ✓ **Yes, one can use such pixel as a synchronous pixel too**
  - But remember that DCSN becomes extremely critical: cool down or use very short storage times
- ✓ **Use the same pixel as**
  - As a shared pixel
  - As CTIA (high gain) or as a SF (low gain)
- ✓ **The price of oversampling**
  - 10x noise reduction $\Rightarrow$ $\geq$100x oversampling? *Yes*
  - But 2x noise reduction $\Rightarrow$ just $\geq$4x oversampling
  - Even without oversampling the noise is decent (2e-)

Pixel cross section to obtain high FF



CONCLUSIONS AND FURTHER WORK

⇒ Conclusions and further works
⇒ Annexes

Conclusions and further work

- $\Rightarrow$ **Significant effect on 1/f & RTS noise**
- $\Rightarrow$ **Pixel with ~0.5 e^{-}_{RMS} demonstrated**

- $\Rightarrow$ **Refine readout/column structure**
- $\Rightarrow$ **Oversampling ADC architectures**
- $\Rightarrow$ **Large array design**

Thank you!

(see also: www.caeleste.be)

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Do we need sub-electron noise?

image peak	2
noise RMS	0,1

ima 2 without photon shot noise

0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0,2
0	0	0	0	0	0	0	0	0	0	0,4
0	0	0	0	0	0,2	0	0	0	0	0,6
0	0	0	0	0,4	1	0,4	0	0	0	0,8
0	0	0	0,2	1	2	1	0,2	0	0	1
0	0	0	0	0,4	1	0,4	0	0	0	1,2
0	0	0	0	0	0,2	0	0	0	0	1,4
0	2	0	0	0	0	0	0	0	0	1,6
0	0	0	0	0	0	0	0	0	0,5	1,8
0	0	0	0	0	0	0	0	0,5	1	2
0	0	0	0	0	0	0	0,5	1	0,5	2,2
0	0	0	0	0	0	0,5	1	0,5	0	2,4
0	0	0	0	0	0,5	1	0,5	0	0	2,6
0	0	0	0	0,5	1	0,5	0	0	0	2,8
0	0	0	0,5	1	0,5	0	0	0	0	3

all: image + shot noise + read noise

-0	-0	-0	0	-0	-0	0,2	-0	0	-0	0
-0	0	0,1	0,1	-0	-0	0	-0	-0	-0	0,2
-0	-0	0,1	-0	0,1	0	-0	-0	-0	0,1	0,4
-0	-0	-0	-0	0	-0	-0	-0	-0	0,1	0,6
-0	-0	0,1	0,2	0	-0	0	0,1	-0	-0	0,8
-0	-0	0,1	-0	3,9	1,1	0,8	0,1	-0	-0	1
-0	-0	-0	-0	0	2	0,1	0,1	0,1	0	1,2
0,2	-0	-0	-0		-0	0,2	0,2	0	0,2	1,4
0	2	0	-0	-0	0,2	0	-0	-0	0,1	1,6
0,1	0,1	0	-0	-0	-0	-0	0	0	0,9	1,8
0	-0	-0	0,1	0,1	0,1	0,1	0	0,1	2,1	2
-0	0,1	0,1	0,2	-0	0,2	-0	1,2	0,1	1	2,2
-0	0	-0	0	0	-0	0,9	0,9	0,1	-0	2,4
0,1	-0	-0	0	0,2	-0	0,1	0,1	0	0,1	2,6
-0	0,2	0,1	-0	-0	0,8	0,9	0	-0	0	2,8
0,2	0,1	0,1	1,1	-0	1,1	0,1	-0	-0	0	3

image * WITH photon shot noise

0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0,2
0	0	0	0	0	0	0	0	0	0	0,4
0	0	0	0	0	0	0	0	0	0	0,6
0	0	0	0	0	0	0	0	0	0	0,8
0	0	0	0	4	1	1	0	0	0	1
0	0	0	0	0	2	0	0	0	0	1,2
0	0	0	0	0	0	0	0	0	0	1,4
0	2	0	0	0	0	0	0	0	0	1,6
0	0	0	0	0	0	0	0	0	1	1,8
0	0	0	0	0	0	0	0	0	2	2
0	0	0	0	0	0	0	1	0	1	2,2
0	0	0	0	0	0	1	1	0	0	2,4
0	0	0	0	0	0	0	0	0	0	2,6
0	0	0	0	0	1	1	0	0	0	2,8
0	0	0	1	0	1	0	0	0	0	3

all, rounded to closest integer

										1
										1
										1
										1
										1
										2
										2
										2
										2
										2
										3
										3
										3

Cycling inversion-accumulation

The decrease of "random telegraph signal" noise in metal-oxide-semiconductor field-effect transistors when cycled from inversion to accumulation

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The low-frequency (LF) noise behavior of metal-oxide-semiconductor field-effect transistors (MOSFETs) is studied when cycled between inversion and accumulation. On large-area devices the decrease of the LF noise is systematically found, and supports the observations by Bloom and Nemirovsky [Appl. Phys. Lett. **58**, 1664 (1991)]. The random telegraph signal (RTS) noise observed in small (submicrometer) devices disappears when the transistor is cycled into accumulation. The drop in LF noise observed may thus be explained by the fact that most or all of the RTSs, which are caused by carrier trapping into slow oxide states, no longer contribute to the noise of the system. The method indicates a possibility to separate the contributions of different sources of $1/f$ noise in MOSFETs.

ANNEX 2

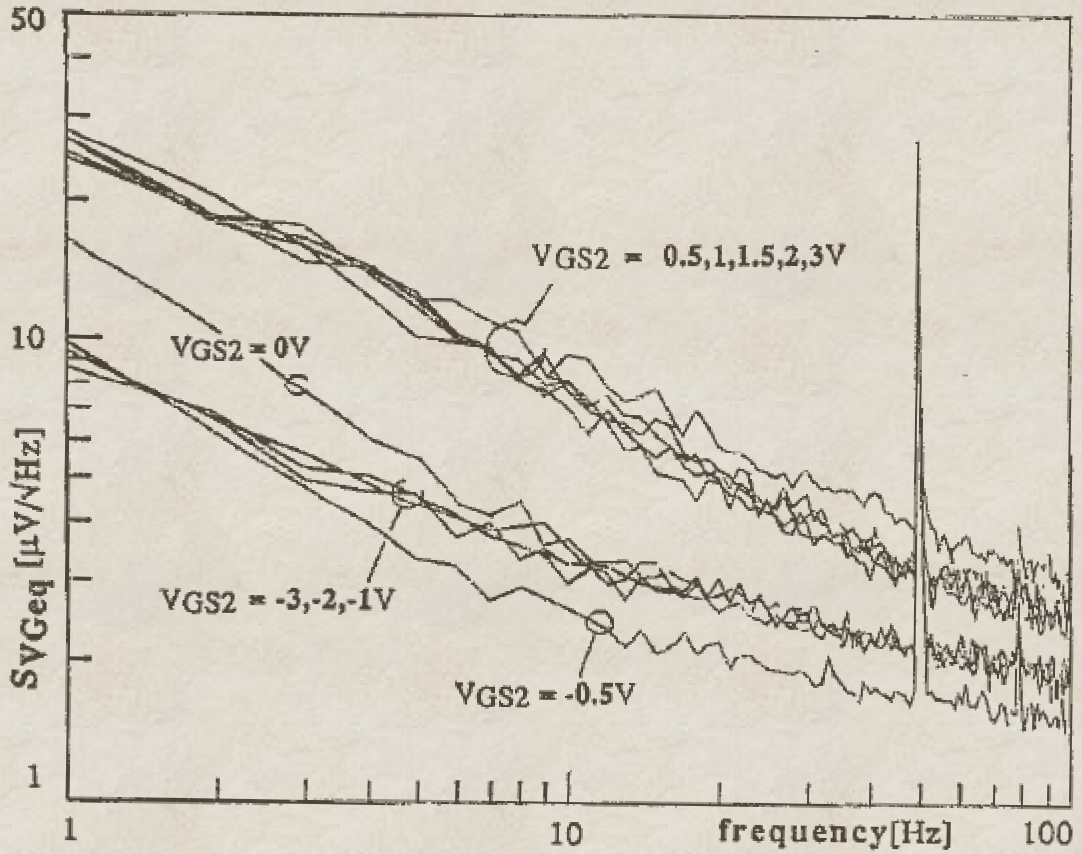

FIG. 1. Equivalent noise voltage spectra for an *n*MOSFET when cycled from normal operation to different states. $W \times L = 3.5 \times 3.5$ μm (effective). $I_{DS} = 10$ μA, $V_{GS1} = 1.38$ V, $V_{GS2} =$ indicated, $V_{DS} = 1$ V, $f_{cycle} = 10$ kHz.