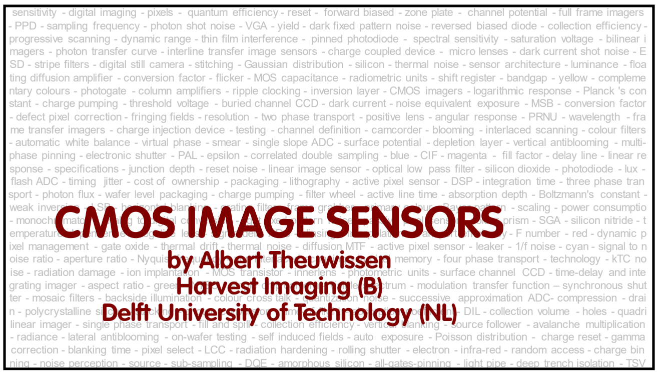
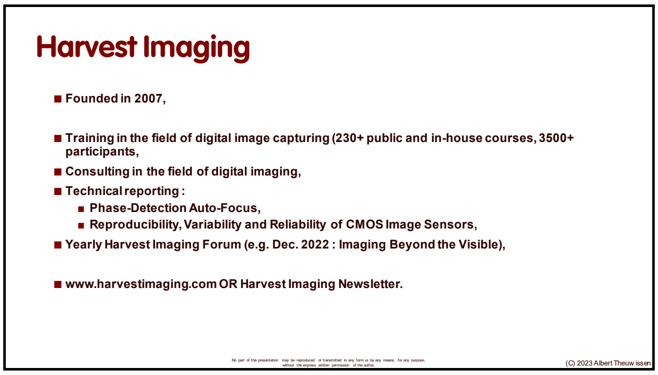


CMOS IMAGE SENSORS

by Albert Theuwissen
Harvest Imaging (B)
Delft University of Technology (NL)

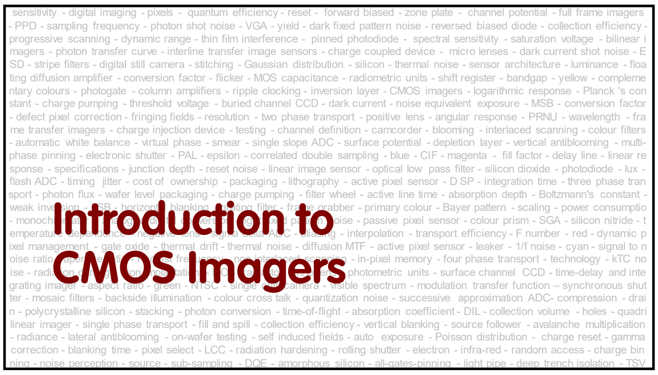


Harvest Imaging

- Founded in 2007,
- Training in the field of digital image capturing (230+ public and in-house courses, 3500+ participants,
- Consulting in the field of digital imaging,
- Technical reporting :
  - Phase-Detection Auto-Focus,
  - Reproducibility, Variability and Reliability of CMOS Image Sensors,
- Yearly Harvest Imaging Forum (e.g. Dec. 2022 : Imaging Beyond the Visible),
- www.harvestimaging.com OR Harvest Imaging Newsletter.

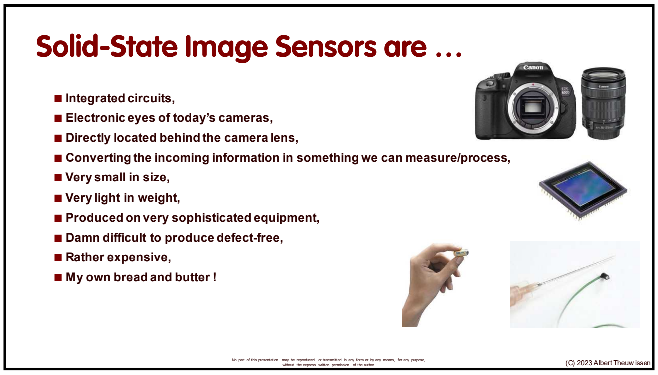
Albert Theuwissen

- '77, '83 : MSc EE and PhD, University of Leuven (B),
- '83 : Philips Research Labs, Eindhoven (Nl),
- '01 : part-time professor Delft University of Technology (Nl),
- '02 : DALSA CTO and Chief Scientist, Eindhoven (Nl),
- '07 : Harvest Imaging, Bree (B),
- Co-founder and Exec. Committee Member of the International Image Sensor Society,
- '97, '03, '09, '15 : General Chair International Image Sensor Workshop,
- '10 : Technical Program Chair of International Solid-State Circuit Conference,
- IEEE Fellow ('02), Fuji Gold Medal ('08), Electronic Imaging Scientist of the Year ('11), Exceptional IISS Service Award ('13), SEMI Award ('14), IEEE Life Fellow ('19),
- '17-'21 : President of the International Image Sensor Society.



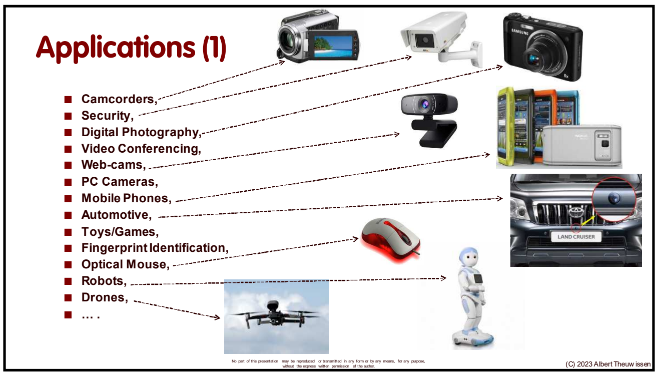
Introduction to CMOS Imagers

sensitivity - digital imaging - pixels - quantum efficiency - reset - forward biased - zone plate - channel potential - full frame imagers - PPD - sampling frequency - photon shot noise - VGA - yield - dark fixed pattern noise - reversed biased diode - collection efficiency - progressive scanning - dynamic range - thin film interference - pinned photodiode - spectral sensitivity - saturation voltage - bilinear imagers - photon transfer curve - interline transfer image sensors - charge coupled device - micro lenses - dark current shot noise - ESD - stripe filters - digital still camera - stitching - Gaussian distribution - silicon - thermal noise - sensor architecture - luminance - floating diffusion amplifier - conversion factor - flicker - MOS capacitance - radiometric units - shift register - bandgap - yellow - complementary colours - photogate - column amplifiers - ripple clocking - inversion layer - CMOS imagers - logarithmic response - Planck 's constant - charge pumping - threshold voltage - buried channel CCD - dark current - noise equivalent exposure - MSB - conversion factor - defect pixel correction - fringing fields - resolution - two phase transport - positive lens - angular response - PRNU - wavelength - frame transfer imagers - charge injection device - testing - channel definition - camcorder - blooming - interlaced scanning - colour filters - automatic white balance - virtual phase - smear - single slope ADC - surface potential - depletion layer - vertical antiblooming - multi-phase pinning - electronic shutter - PAL - epsilon - correlated double sampling - blue - CIF - magenta - fill factor - delay line - linear response - specifications - junction depth - reset noise - linear image sensor - optical low pass filter - silicon dioxide - photodiode - lux - flash ADC - timing jitter - cost of ownership - packaging - lithography - active pixel sensor - D SP - integration time - three phase transport - photon flux - wafer level packaging - charge pumping - filter wheel - active line time - absorption depth - Boltzmann's constant - weak inversion - LSB - horizontal blanking - grating filter - frame grabber - primary colour - Bayer pattern - scaling - power consumption - monochromator - analog-digital conversion - light - fixed pattern noise - passive pixel sensor - colour prism - SGA - silicon nitride - temperature dependence - negative lens - sigma delta ADC - aliasing - interpolation - transport efficiency - F number - red - dynamic pixel management - gate oxide - thermal drift - thermal noise - diffusion MTF - active pixel sensor - leaker - 1/f noise - cyan - signal to noise ratio - aperture [illegible] - Nyquist frequency - non-interlaced scanning - in-pixel memory - four phase transport - technology - kTC noise - radiation damage - ion implantation - MOS transistor - [illegible] - photometric units - surface channel CCD - time-delay and integrating imager - aspect ratio - green - NTSC - single chip camera - visible spectrum - modulation transfer function – synchronous shutter - mosaic filters - backside illumination - colour cross talk - quantization noise - successive approximation ADC- compression - drain - polycrystalline silicon - stacking - photon conversion - time-of-flight - absorption coefficient - DIL - collection volume - holes - quadrilinear imager - single phase transport - fill and spill - collection efficiency - vertical blanking - source follower - avalanche multiplication - radiance - lateral antiblooming - on-wafer testing - self induced fields - auto exposure - Poisson distribution - charge reset - gamma correction - blanking time - pixel select - LCC - radiation hardening - rolling shutter - electron - infra-red - random access - charge binning - noise perception - source - sub-sampling - DQE - amorphous silicon - all-gates-pinning - light pipe - deep trench isolation - TSV



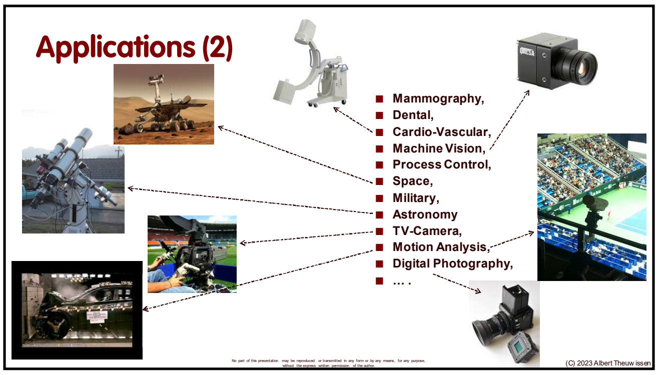
Solid-State Image Sensors are …

- **Integrated circuits,**
- **Electronic eyes of today's cameras,**
- **Directly located behind the camera lens,**
- **Converting the incoming information in something we can measure/process,**
- **Very small in size,**
- **Very light in weight,**
- **Produced on very sophisticated equipment,**
- **Damn difficult to produce defect-free,**
- **Rather expensive,**
- **My own bread and butter !**



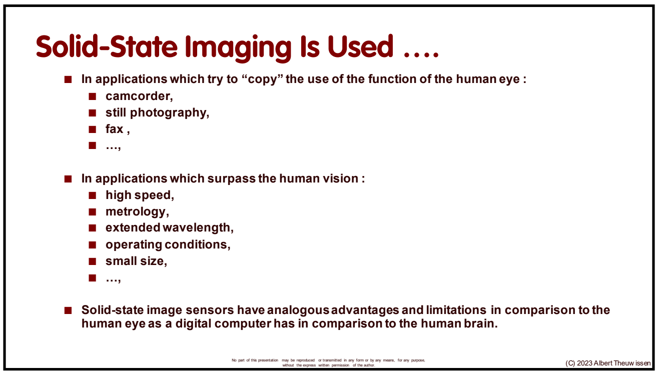
Applications (1)

- **Camcorders,**
- **Security,**
- **Digital Photography,**
- **Video Conferencing,**
- **Web-cams,**
- **PC Cameras,**
- **Mobile Phones,**
- **Automotive,**
- **Toys/Games,**
- **Fingerprint Identification,**
- **Optical Mouse,**
- **Robots,**
- **Drones,**
- **… .**



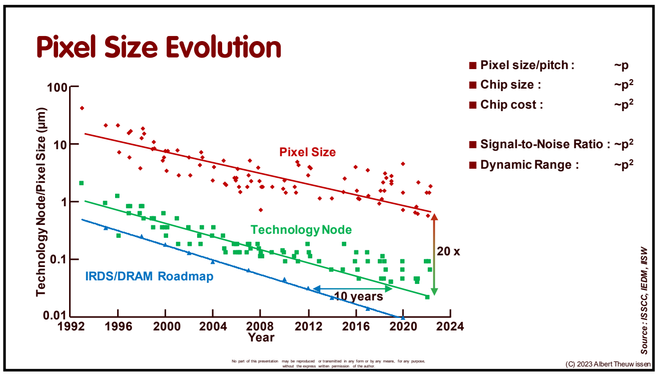
Applications (2)

- Mammography,
- Dental,
- Cardio-Vascular,
- Machine Vision,
- Process Control,
- Space,
- Military,
- Astronomy
- TV-Camera,
- Motion Analysis,
- Digital Photography,
- … .



Solid-State Imaging Is Used ….

- In applications which try to “copy” the use of the function of the human eye :
  - camcorder,
  - still photography,
  - fax ,
  - …,
- In applications which surpass the human vision :
  - high speed,
  - metrology,
  - extended wavelength,
  - operating conditions,
  - small size,
  - …,
- Solid-state image sensors have analogous advantages and limitations in comparison to the human eye as a digital computer has in comparison to the human brain.



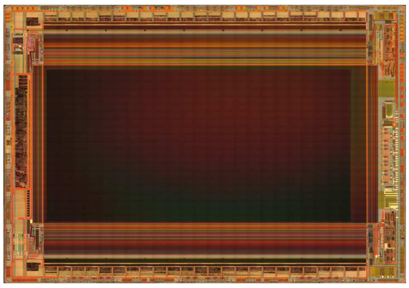
Pixel Size Evolution

- Pixel size/pitch : ~p
- Chip size : $\sim p^2$
- Chip cost : $\sim p^2$

- Signal-to-Noise Ratio : $\sim p^2$
- Dynamic Range : $\sim p^2$

Source : ISSCC, IEDM, IISW

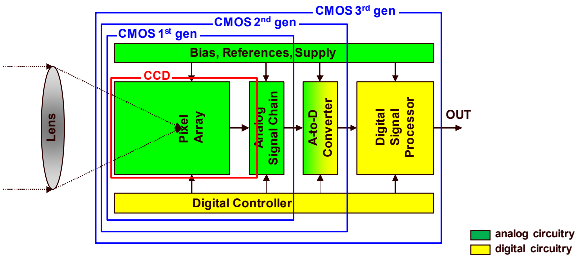
CMOS Image Sensor Floorplan



- Pixel size :
  - 0.6 µm … 20 µm …,
- Number of pixels :
  - 320 x 240 (76k) …
  - 10k x 10k (100M) …,
- Chip Size :
  - 0.5 mm² … 40k mm².

Photo by Chipworks/TechInsights

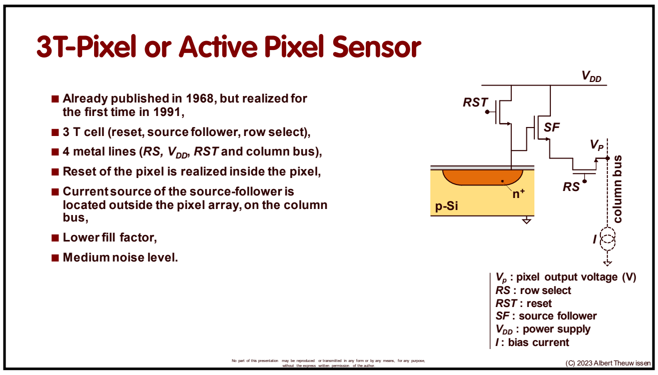
CMOS versus CCD



CCD versus CMOS

- CCD : contains only the (analog) pixel array and the analog output amplifier (source-follower),
- First generation CMOS : contains all the analog parts as well as the digital timing and driving circuitry,
- Second generation CMOS : first generation CMOS plus an additional analog-to-digital converter (ADC),
- Third generation CMOS : second generation CMOS plus the complete digital signal processor (DSP),

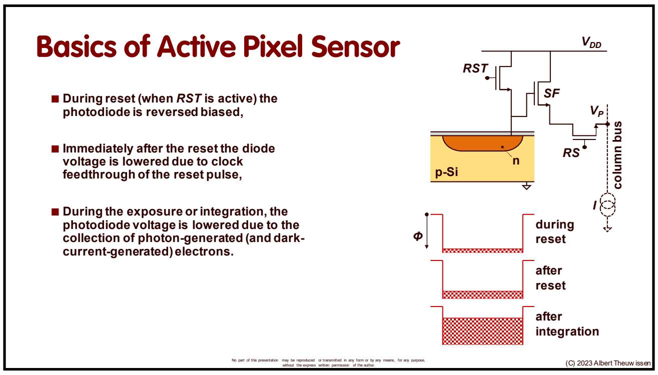
- Third generation looks like the ultimate solution, but that is not always the case :
  - Many applications have already a DSP on board and do not need a second one,
  - A DSP benefits from a very aggressive CMOS technology, the pixel array mostly not,
  - Digital circuitry can introduce extra noise, picked up by the pixels,
  - An extra on-chip DSP makes the image sensor die more expensive.



3T-Pixel or Active Pixel Sensor

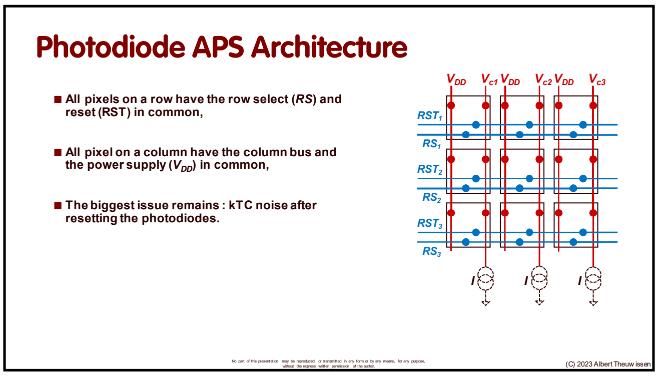
- Already published in 1968, but realized for the first time in 1991,
- 3 T cell (reset, source follower, row select),
- 4 metal lines (*RS*, V_{DD}, *RST* and column bus),
- Reset of the pixel is realized inside the pixel,
- Current source of the source-follower is located outside the pixel array, on the column bus,
- Lower fill factor,
- Medium noise level.

V_p : pixel output voltage (V)
RS : row select
RST : reset
SF : source follower
V_{DD} : power supply
I : bias current



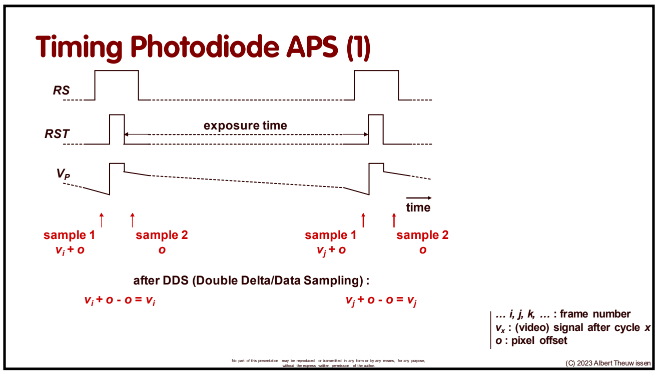
Basics of Active Pixel Sensor

- During reset (when *RST* is active) the photodiode is reversed biased,
- Immediately after the reset the diode voltage is lowered due to clock feedthrough of the reset pulse,
- During the exposure or integration, the photodiode voltage is lowered due to the collection of photon-generated (and dark-current-generated) electrons.



Photodiode APS Architecture

- All pixels on a row have the row select (*RS*) and reset (RST) in common,
- All pixel on a column have the column bus and the power supply (V_{DD}) in common,
- The biggest issue remains : kTC noise after resetting the photodiodes.



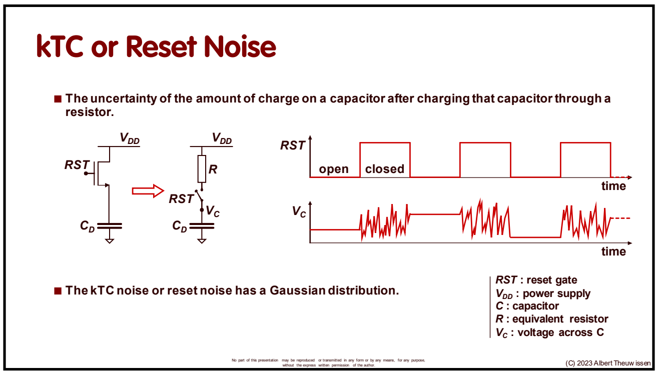
Timing Photodiode APS (1)

after DDS (Double Delta/Data Sampling) :

$v_i + o - o = v_i$

$v_j + o - o = v_j$

… *i*, *j*, *k*, … : frame number
v_x : (video) signal after cycle *x*
o : pixel offset

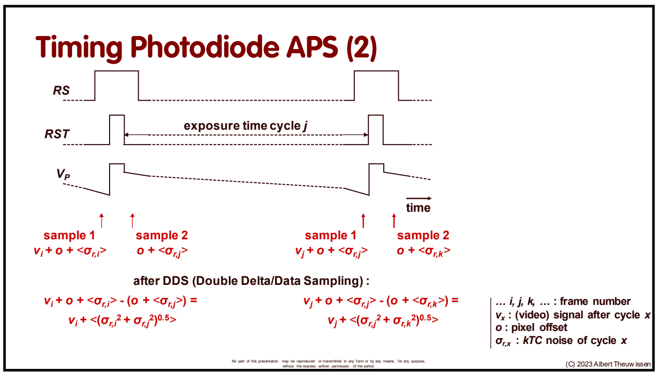


kTC or Reset Noise

- The uncertainty of the amount of charge on a capacitor after charging that capacitor through a resistor.

- The kTC noise or reset noise has a Gaussian distribution.

RST : reset gate
V_{DD} : power supply
C : capacitor
R : equivalent resistor
V_C : voltage across C



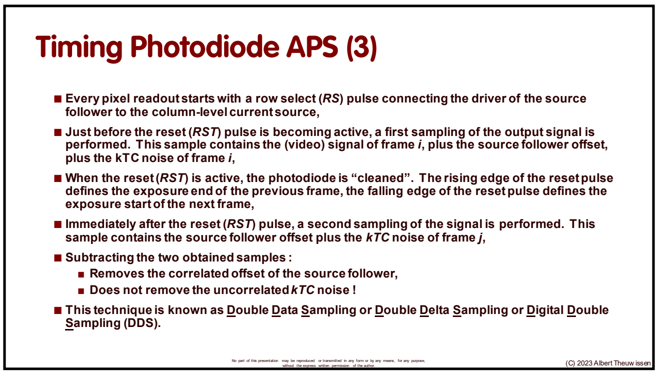
Timing Photodiode APS (2)

after DDS (Double Delta/Data Sampling) :

$v_i + o + <\sigma_{r,i}> - (o + <\sigma_{r,j}>) =$
$v_i + <(\sigma_{r,i}^2 + \sigma_{r,j}^2)^{0.5}>$

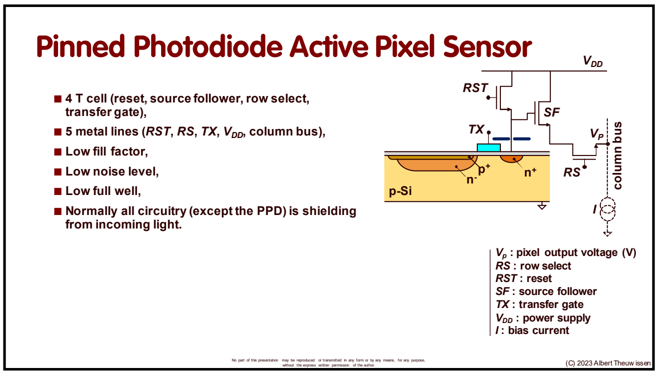
$v_j + o + <\sigma_{r,j}> - (o + <\sigma_{r,k}>) =$
$v_j + <(\sigma_{r,j}^2 + \sigma_{r,k}^2)^{0.5}>$

… *i*, *j*, *k*, … : frame number
v_x : (video) signal after cycle *x*
o : pixel offset
$\sigma_{r,x}$: *kTC* noise of cycle *x*



Timing Photodiode APS (3)

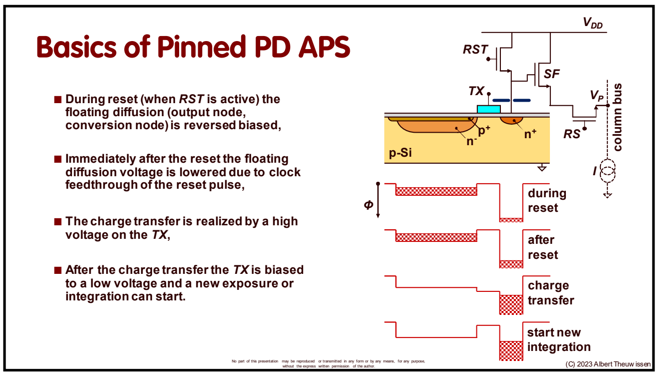
- Every pixel readout starts with a row select (*RS*) pulse connecting the driver of the source follower to the column-level current source,
- Just before the reset (*RST*) pulse is becoming active, a first sampling of the output signal is performed. This sample contains the (video) signal of frame *i*, plus the source follower offset, plus the kTC noise of frame *i*,
- When the reset (*RST*) is active, the photodiode is “cleaned”. The rising edge of the reset pulse defines the exposure end of the previous frame, the falling edge of the reset pulse defines the exposure start of the next frame,
- Immediately after the reset (*RST*) pulse, a second sampling of the signal is performed. This sample contains the source follower offset plus the *kTC* noise of frame *j*,
- Subtracting the two obtained samples :
  - Removes the correlated offset of the source follower,
  - Does not remove the uncorrelated *kTC* noise !
- This technique is known as Double Data Sampling or Double Delta Sampling or Digital Double Sampling (DDS).



Pinned Photodiode Active Pixel Sensor

- 4 T cell (reset, source follower, row select, transfer gate),
- 5 metal lines (*RST*, *RS*, *TX*, V_{DD}, column bus),
- Low fill factor,
- Low noise level,
- Low full well,
- Normally all circuitry (except the PPD) is shielding from incoming light.

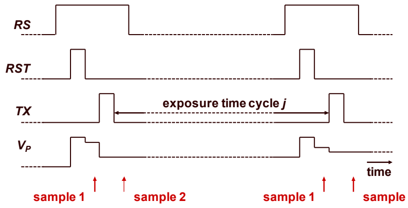
V_p : pixel output voltage (V)
RS : row select
RST : reset
SF : source follower
TX : transfer gate
V_{DD} : power supply
I : bias current



Basics of Pinned PD APS

- During reset (when *RST* is active) the floating diffusion (output node, conversion node) is reversed biased,
- Immediately after the reset the floating diffusion voltage is lowered due to clock feedthrough of the reset pulse,
- The charge transfer is realized by a high voltage on the *TX*,
- After the charge transfer the *TX* is biased to a low voltage and a new exposure or integration can start.

Timing Pinned Photodiode APS (1)



sample 1 $o + <\sigma_{r,i}>$

sample 2 $v_i + o + <\sigma_{r,i}>$

sample 1 $o + <\sigma_{r,j}>$

sample 2 $v_j + o + <\sigma_{r,j}>$

after CDS (Correlated Double Sampling) :

$v_i + o + <\sigma_{r,i}> - (o + <\sigma_{r,i}>) = v_i$

$v_j + o + <\sigma_{r,j}> - (o + <\sigma_{r,j}>) = v_j$

… *i, j, k,* … : frame number
v_x : (video) signal after cycle *x*
o : pixel offset
$\sigma_{r,x}$: *kTC* noise of cycle *x*

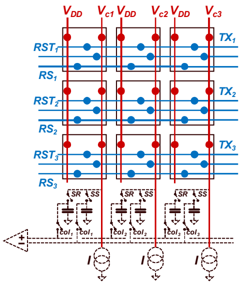
Timing Pinned Photodiode APS (2)

- Every pixel readout starts with a row select (*RS*) pulse connecting the driver of the source follower to the column-level current source,
- When the reset (*RST*) is active, the floating diffusion (readout/conversion/output node) is "cleaned",
- Immediately after the reset (*RST*) pulse, a first sampling of the signal is performed. This sample contains the source follower offset, plus the *kTC* noise of frame *i*,
- Next the charge present in the pinned photodiode is transferred towards the floating diffusion by means of a positive pulse on the transfer gate (*TX*),
- Once the charge is transferred, a second sampling of the signal is performed. This sample contains the video signal v_i of frame *i*, plus the source follower offset, plus the *kTC* noise of frame *i*,
- Subtracting the two obtained samples :
  - Removes the correlated offset of the source follower,
  - Removes the correlated *kTC* noise !

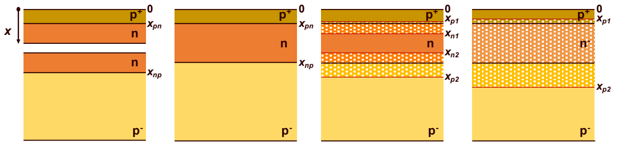
  This technique is known as <u>C</u>orrelated <u>D</u>ouble <u>S</u>ampling (CDS),
- The timing of the transfer gate *TX* defines the exposure time.

Photodiode APS Architecture

- All pixels on a row have the row select (*RS*), the reset (*RST*) and the transfer gate (TX) in common,
- All pixel on a column have the column bus and the power supply (V_{DD}) in common,
- The kTC noise issue is solved by Correlated Double Sampling (CDS).



Pinned Photodiode (1)



Two diodes

x_{pn} : depth p⁺n⁻ junction
x_{np} : depth n⁻p⁻ junction

Stacked diodes

x_{pn} : depth p⁺n⁻ junction
x_{np} : depth n⁻p⁻ junction

Non-depleted diodes

x_{p1} : top 1st depletion
x_{n1} : bottom 1st depletion
x_{p2} : bottom 2nd depletion
x_{n2} : top 2nd depletion

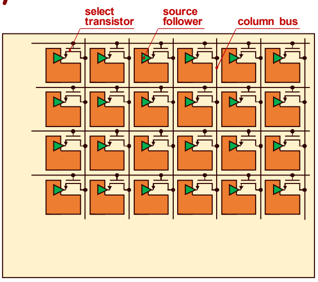
Fully-depleted diodes

x_{p1} : top depletion
x_{p2} : top 2nd depletion

▨ depletion region in p⁺ ▨ depletion region in n ▨ depletion region in n⁻ ▨ depletion region in p⁻

CMOS Image Sensor (1)

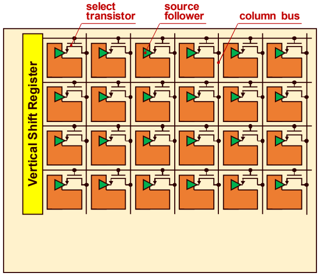
- A 2D CMOS image sensor is organized in the same way as a digital memory,
- Every photodiode is provided with :
  - an in-pixel source follower,
  - a select transistor, the gates of the selectors are connected row-wise, the drains of the selectors are connected column-wise,



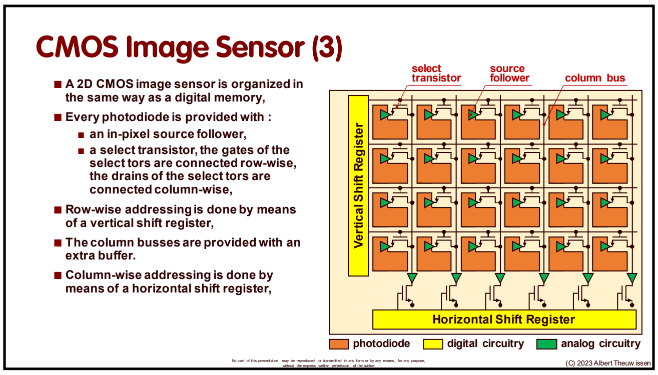
🟧 photodiode 🟩 analog circuitry

CMOS Image Sensor (2)

- A 2D CMOS image sensor is organized in the same way as a digital memory,
- Every photodiode is provided with :
  - an in-pixel source follower,
  - a select transistor, the gates of the selectors are connected row-wise, the drains of the selectors are connected column-wise,
- Row-wise addressing is done by means of a vertical shift register,

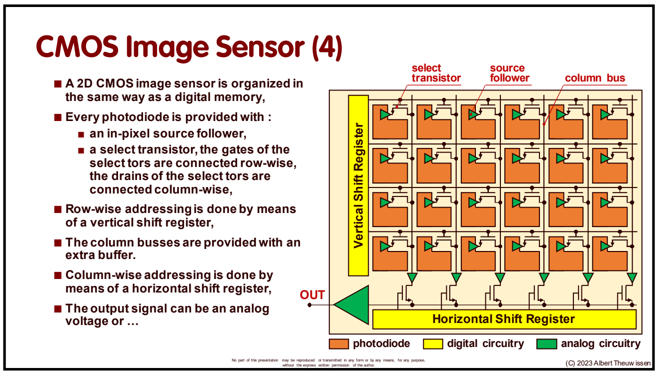


🟧 photodiode 🟨 digital circuitry 🟩 analog circuitry



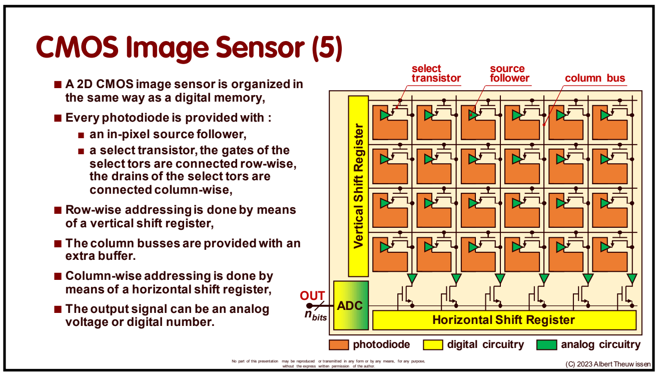
CMOS Image Sensor (3)

- A 2D CMOS image sensor is organized in the same way as a digital memory,
- Every photodiode is provided with :
  - an in-pixel source follower,
  - a select transistor, the gates of the selectors are connected row-wise, the drains of the selectors are connected column-wise,
- Row-wise addressing is done by means of a vertical shift register,
- The column busses are provided with an extra buffer.
- Column-wise addressing is done by means of a horizontal shift register,



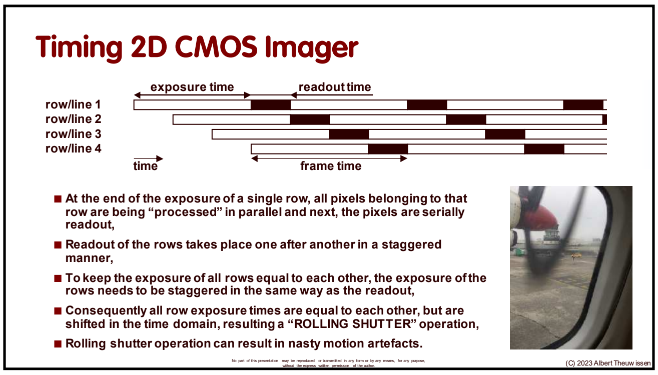
CMOS Image Sensor (4)

- A 2D CMOS image sensor is organized in the same way as a digital memory,
- Every photodiode is provided with :
  - an in-pixel source follower,
  - a select transistor, the gates of the selectors are connected row-wise, the drains of the selectors are connected column-wise,
- Row-wise addressing is done by means of a vertical shift register,
- The column busses are provided with an extra buffer.
- Column-wise addressing is done by means of a horizontal shift register,
- The output signal can be an analog voltage or …



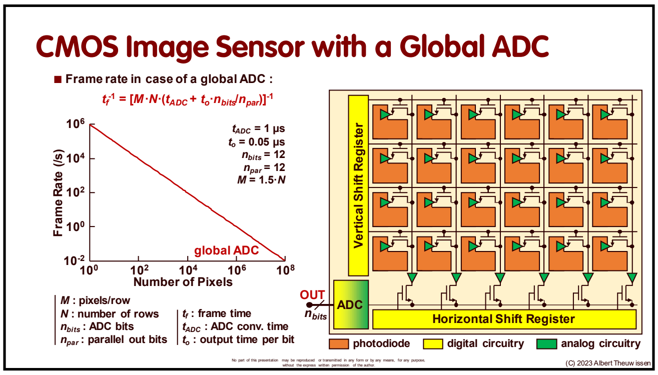
CMOS Image Sensor (5)

- A 2D CMOS image sensor is organized in the same way as a digital memory,
- Every photodiode is provided with :
  - an in-pixel source follower,
  - a select transistor, the gates of the selectors are connected row-wise, the drains of the selectors are connected column-wise,
- Row-wise addressing is done by means of a vertical shift register,
- The column busses are provided with an extra buffer.
- Column-wise addressing is done by means of a horizontal shift register,
- The output signal can be an analog voltage or digital number.



Timing 2D CMOS Imager

- At the end of the exposure of a single row, all pixels belonging to that row are being "processed" in parallel and next, the pixels are serially readout,
- Readout of the rows takes place one after another in a staggered manner,
- To keep the exposure of all rows equal to each other, the exposure of the rows needs to be staggered in the same way as the readout,
- Consequently all row exposure times are equal to each other, but are shifted in the time domain, resulting a "ROLLING SHUTTER" operation,
- Rolling shutter operation can result in nasty motion artefacts.



CMOS Image Sensor with a Global ADC

- Frame rate in case of a global ADC :

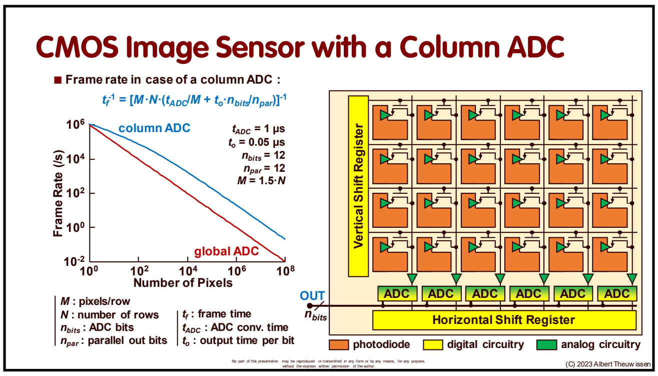
$$t_f^{-1} = [M \cdot N \cdot (t_{ADC} + t_o \cdot n_{bits}/n_{par})]^{-1}$$

t_{ADC} = 1 μs
t_o = 0.05 μs
n_{bits} = 12
n_{par} = 12
$M = 1.5 \cdot N$

M : pixels/row
N : number of rows
n_{bits} : ADC bits
n_{par} : parallel out bits

t_f : frame time
t_{ADC} : ADC conv. time
t_o : output time per bit

🟧 photodiode 🟨 digital circuitry 🟩 analog circuitry



CMOS Image Sensor with a Column ADC

- Frame rate in case of a column ADC :

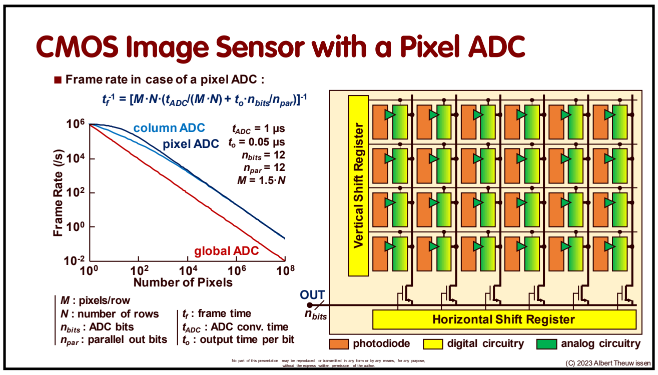
$$t_f^{-1} = [M \cdot N \cdot (t_{ADC}/M + t_o \cdot n_{bits}/n_{par})]^{-1}$$

t_{ADC} = 1 μs
t_o = 0.05 μs
n_{bits} = 12
n_{par} = 12
$M = 1.5 \cdot N$

M : pixels/row
N : number of rows
n_{bits} : ADC bits
n_{par} : parallel out bits

t_f : frame time
t_{ADC} : ADC conv. time
t_o : output time per bit

🟧 photodiode 🟨 digital circuitry 🟩 analog circuitry



CMOS Image Sensor with a Pixel ADC

- Frame rate in case of a pixel ADC :

$$t_f^{-1} = [M \cdot N \cdot (t_{ADC}/(M \cdot N) + t_o \cdot n_{bits}/n_{par})]^{-1}$$

$t_{ADC} = 1$ µs
$t_o = 0.05$ µs
$n_{bits} = 12$
$n_{par} = 12$
$M = 1.5 \cdot N$

M : pixels/row
N : number of rows
n_{bits} : ADC bits
n_{par} : parallel out bits

t_f : frame time
t_{ADC} : ADC conv. time
t_o : output time per bit

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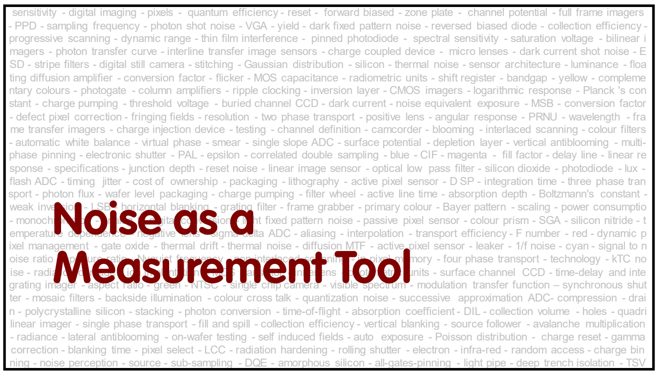
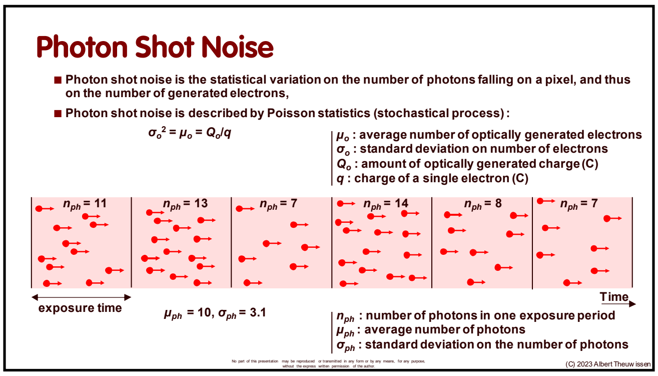


Noise as a Measurement Tool



Photon Shot Noise

- Photon shot noise is the statistical variation on the number of photons falling on a pixel, and thus on the number of generated electrons,
- Photon shot noise is described by Poisson statistics (stochastical process) :

$$\sigma_o^2 = \mu_o = Q_o/q$$

μ_o : average number of optically generated electrons
σ_o : standard deviation on number of electrons
Q_o : amount of optically generated charge (C)
q : charge of a single electron (C)

$\mu_{ph} = 10$, $\sigma_{ph} = 3.1$

n_{ph} : number of photons in one exposure period
μ_{ph} : average number of photons
σ_{ph} : standard deviation on the number of photons

Theory (1)

- The output signal S_{tot} of the sensor/camera can be written as :

$$S_{tot} = S_o + S_d + S_{off} = k \cdot N_o \cdot t_{exp} + k \cdot N_d \cdot t_{exp} + S_{off}$$

S_{tot} : output signal of the sensor [DN],
S_o : light signal at the output [DN],
S_d : dark signal at the output [DN],
S_{off} : offset of the output signal [DN],
k : conversion gain [DN/e$^-$],
N_o : light signal [e$^-$/(pixel·s)],
N_d : dark current [e$^-$/(pixel·s)],
t_{exp} : exposure time [s].

- The temporal noise, measured at the output can be written as :

$$\sigma_{temp}^2 = \sigma_o^2 + \sigma_d^2 + \sigma_e^2$$

σ_{temp} : temporal noise at the output [DN],
σ_o : photon shot noise [DN],
σ_d : dark current shot noise [DN],
σ_e : noise of the electronic parts [DN].

Theory (2)

- The photon shot noise present in the output signal can be written as :

$$\sigma_o = k \cdot (N_o \cdot t_{exp})^{0.5}$$

- The dark current shot noise present in the output signal can be written as :

$$\sigma_d = k \cdot (N_d \cdot t_{exp})^{0.5}$$

- Combining the formulas gives :

$$\begin{aligned}\sigma_{temp}^2 &= k^2 \cdot N_o \cdot t_{exp} + k^2 \cdot N_d \cdot t_{exp} + \sigma_e^2 \\ &= k \cdot (k \cdot N_o \cdot t_{exp} + k \cdot N_d \cdot t_{exp}) + \sigma_e^2 \\ &= k \cdot (S_{tot} - S_{off}) + \sigma_e^2\end{aligned}$$

- If the (measured temporal) variance is plotted as a function of the (measured) output signal (corrected for the offset), the (inverse of) the conversion gain can be found as the slope of the “Mean-Variance Curve”.

Measurement Method (1)

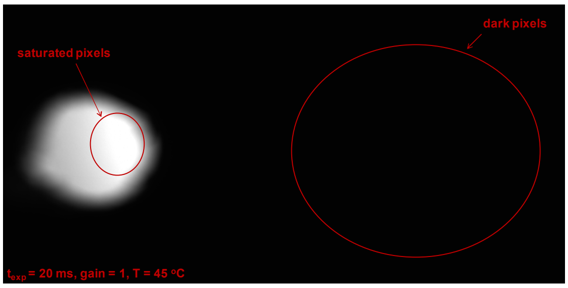
- Grab an image cube (e.g. 50 identical images) of a scenery with :
  - Saturated pixels (to characterize full-well capacity),
  - Dark pixels (to characterize noise in dark),

- Calculate on pixel level :
  - The average value,
  - The standard deviation,

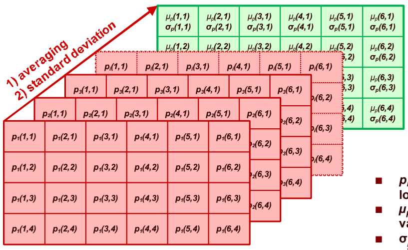
- For every pixel, two values are found (average value and temporal noise).

Measurement Method (2)

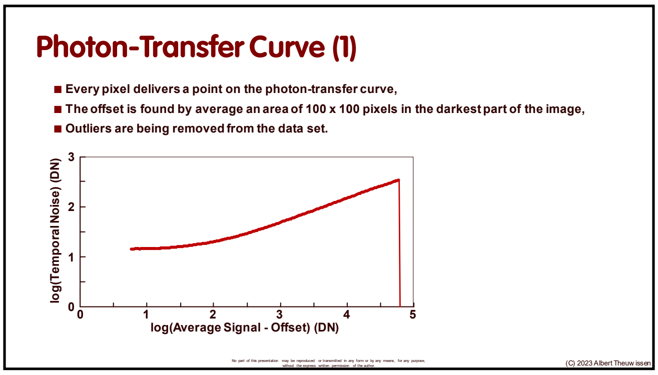
Measurement Method (3)



Calculations

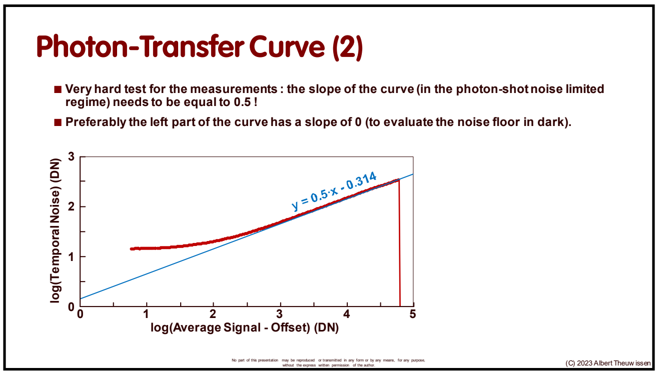


- $p_i(x,y)$: pixel value in frame *i* at location *(x,y)*,
- $\mu_p(x,y)$: average value of all pixel values at *(x,y)*,
- $\sigma_p(x,y)$: standard deviation on all pixel values at *(x,y)*.



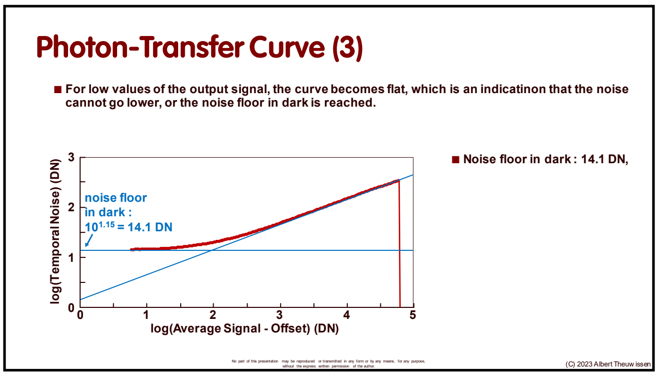
Photon-Transfer Curve (1)

- Every pixel delivers a point on the photon-transfer curve,
- The offset is found by average an area of 100 x 100 pixels in the darkest part of the image,
- Outliers are being removed from the data set.



Photon-Transfer Curve (2)

- Very hard test for the measurements : the slope of the curve (in the photon-shot noise limited regime) needs to be equal to 0.5 !
- Preferably the left part of the curve has a slope of 0 (to evaluate the noise floor in dark).



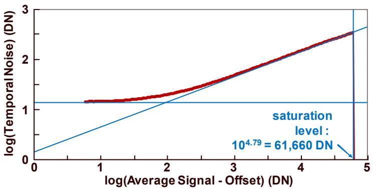
Photon-Transfer Curve (3)

- For low values of the output signal, the curve becomes flat, which is an indicatinon that the noise cannot go lower, or the noise floor in dark is reached.

- Noise floor in dark : 14.1 DN,

Photon-Transfer Curve (4)

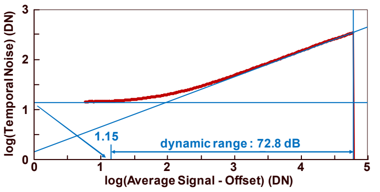
- At high output signal levels, the vertical part of the curve indicates where the signal cannot go higher, or the saturation level is reached,
- At saturation the temporal noise diminishes.



- Noise floor in dark : 14.1 DN,
- Saturation level : 61,660 DN,

Photon-Transfer Curve (5)

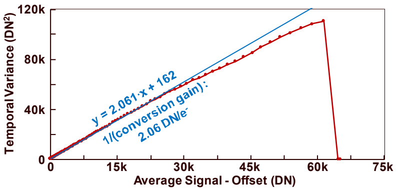
- The “distance” between saturation and noise floor in dark is equal to the dynamic range.



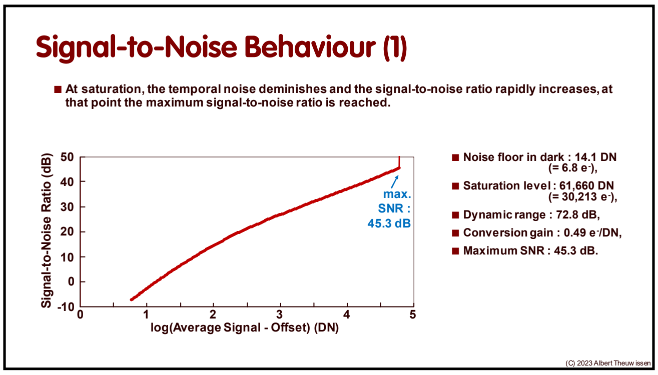
- Noise floor in dark : 14.1 DN,
- Saturation level : 61,660 DN,
- Dynamic range : 72.8 dB,

Mean-Variance Curve

- The slope of the mean-variance curve is equal to the (inverse of the) conversion gain.



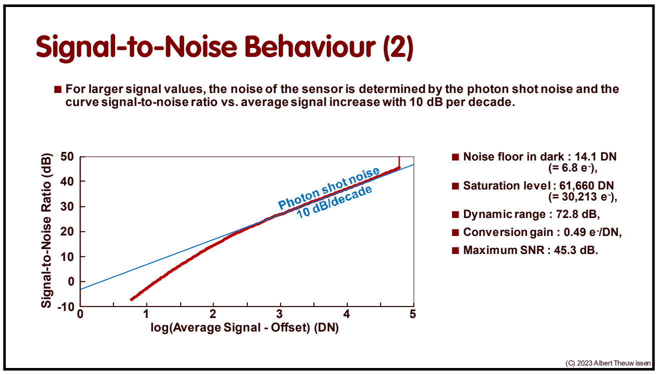
- Noise floor in dark : 14.1 DN (= 6.8 e^-),
- Saturation level : 61,660 DN (= 30,213 e^-),
- Dynamic range : 72.8 dB,
- Conversion gain : 0.49 e^-/DN,



Signal-to-Noise Behaviour (1)

- At saturation, the temporal noise deminishes and the signal-to-noise ratio rapidly increases, at that point the maximum signal-to-noise ratio is reached.

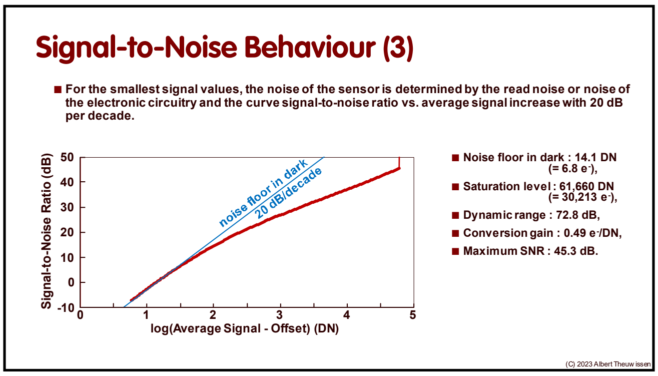
- Noise floor in dark : 14.1 DN (= 6.8 e^-),
- Saturation level : 61,660 DN (= 30,213 e^-),
- Dynamic range : 72.8 dB,
- Conversion gain : 0.49 e^-/DN,
- Maximum SNR : 45.3 dB.



Signal-to-Noise Behaviour (2)

- For larger signal values, the noise of the sensor is determined by the photon shot noise and the curve signal-to-noise ratio vs. average signal increase with 10 dB per decade.

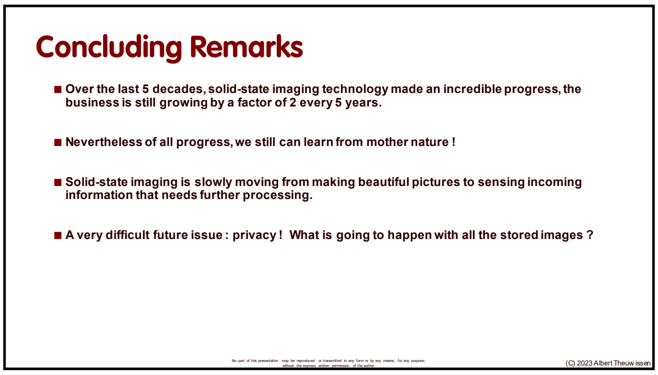
- Noise floor in dark : 14.1 DN (= 6.8 e^-),
- Saturation level : 61,660 DN (= 30,213 e^-),
- Dynamic range : 72.8 dB,
- Conversion gain : 0.49 e^-/DN,
- Maximum SNR : 45.3 dB.



Signal-to-Noise Behaviour (3)

- For the smallest signal values, the noise of the sensor is determined by the read noise or noise of the electronic circuitry and the curve signal-to-noise ratio vs. average signal increase with 20 dB per decade.

- Noise floor in dark : 14.1 DN (= 6.8 e^-),
- Saturation level : 61,660 DN (= 30,213 e^-),
- Dynamic range : 72.8 dB,
- Conversion gain : 0.49 e^-/DN,
- Maximum SNR : 45.3 dB.



Concluding Remarks

- Over the last 5 decades, solid-state imaging technology made an incredible progress, the business is still growing by a factor of 2 every 5 years.
- Nevertheless of all progress, we still can learn from mother nature !
- Solid-state imaging is slowly moving from making beautiful pictures to sensing incoming information that needs further processing.
- A very difficult future issue : privacy ! What is going to happen with all the stored images ?