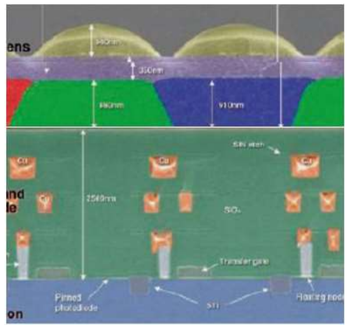
Physique d'acquisition d'images

Capteurs d'images - Jérôme Vaillant
Imagerie non-conventionnelle et co-conception – Corinne Fournier

Agenda

- (Brief) Introduction to image sensors
  - The ubiquitous CMOS image sensor
  - Smartphone camera: a co-design system
- What is a pixel?
  - How does it work
  - Design and fabrication
  - Optical elements
  - Implementation in a matrix
  - Noises
- Un-conventional / non-visible pixels
  - Depth sensing with pixels
  - Infrared pixels

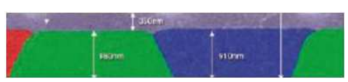
Pixel vertical cut view



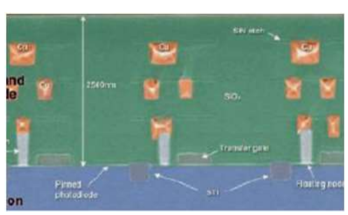
Optical elements

- Microlens

- Color filters



- Optical stack



Optical elements

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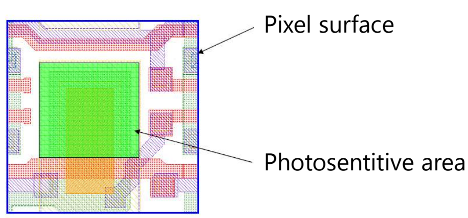
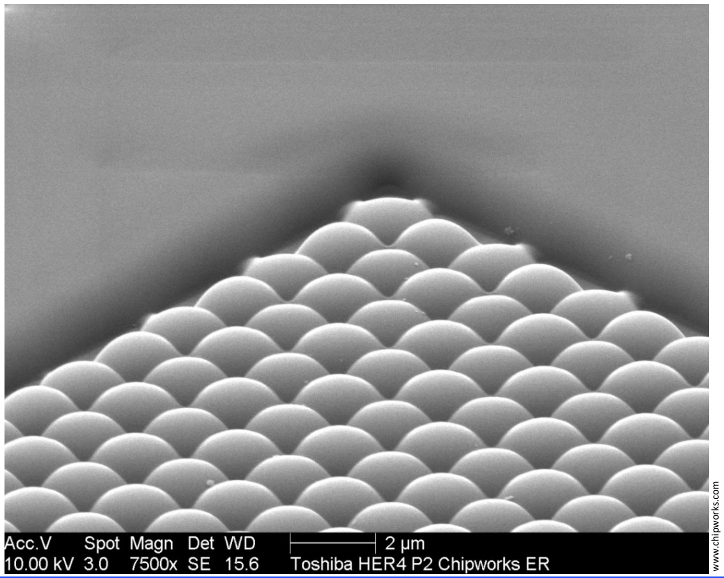
Microlens

- Primary function: compensate the photodiode fill-factor



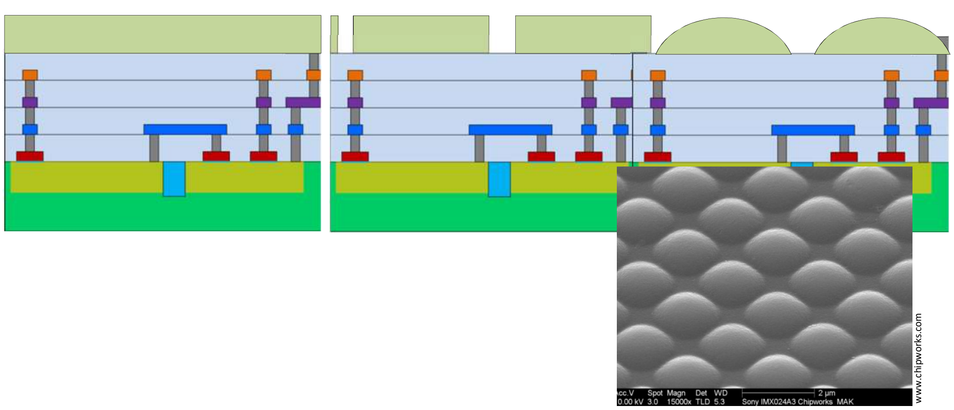
- Secondary functions
  - Spatially sample the image: when on focus, objective image plane = microlens principal plane
  - Reduce the crosstalk between pixels

Microlens



Microlens: how to process it?

- Fabrication
  1. Photoresist deposition (spin-coat)
  2. Definition of blocks by photolithography
  3. Formation of convex lens by reflow

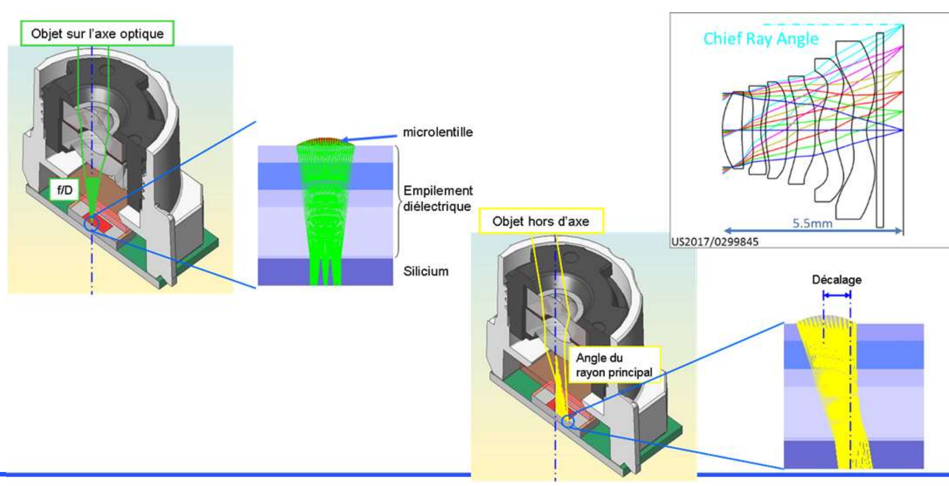


Microlens: where to place it?

- Obvious placement :
  - Above the photodiode

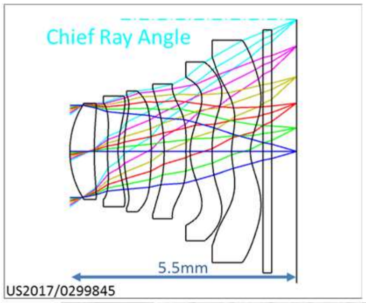
Microlens: where to place it?

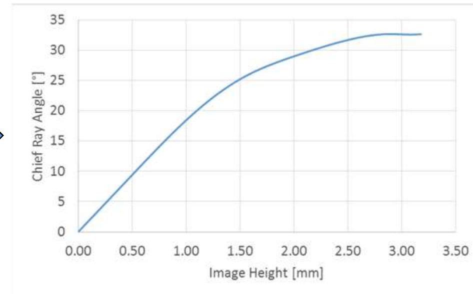
- No so obvious placement:
  - Above the photodiode – OK at the center of the sensor (on axis), but at the edge, Chief Ray Angle (CRA) must be taken into account

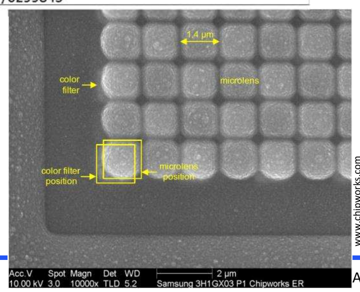


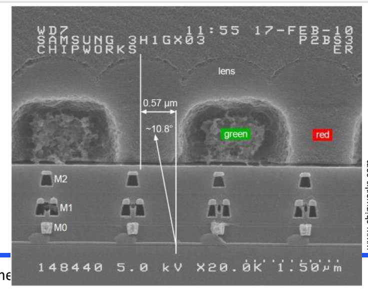
Microlens: where to place it?

- Part of co-design of smartphone camera





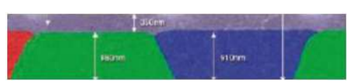




Optical elements

- Microlens

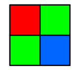
- Color filters

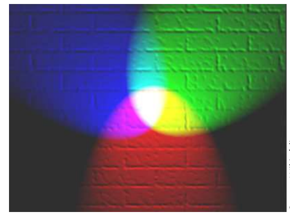


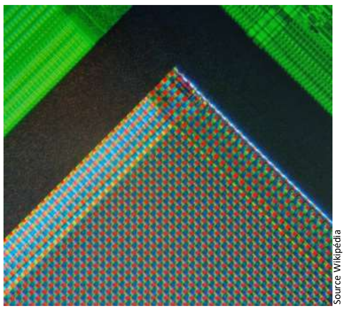
- Optical stack

Color filters

- Primary function: encoding of color seen by human
  - Trichromatic theory: 3 independent colors need to be captured
  - Usually in camera we used Red / Green / Blue color filters
  - Most used pattern: Bayer RGGB (patented in 1974)



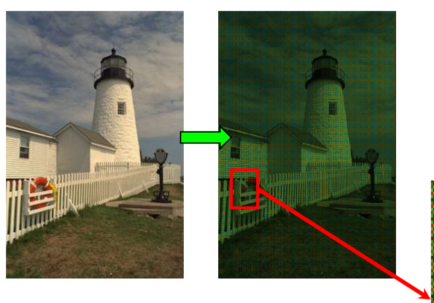


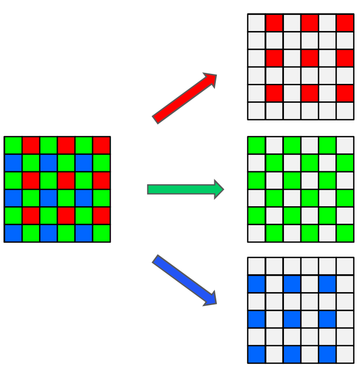


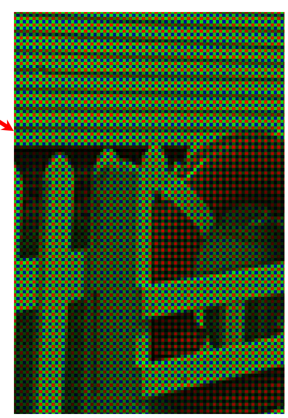
- Secondary function (drawback)
  - Image undersampling: 1 color = 1 pixel

Color filters

- Spatial undersampling:
  - Red ¼ undersampling
  - Green ½ undersampling
  - Blue ¼ undersampling

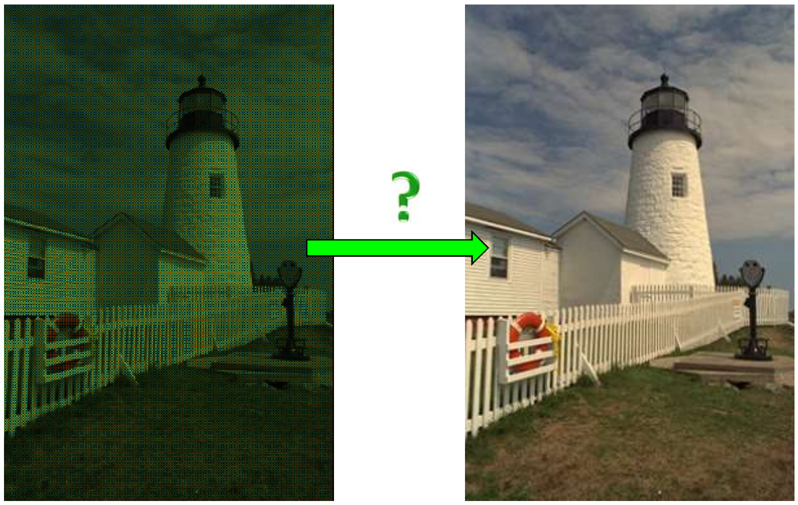






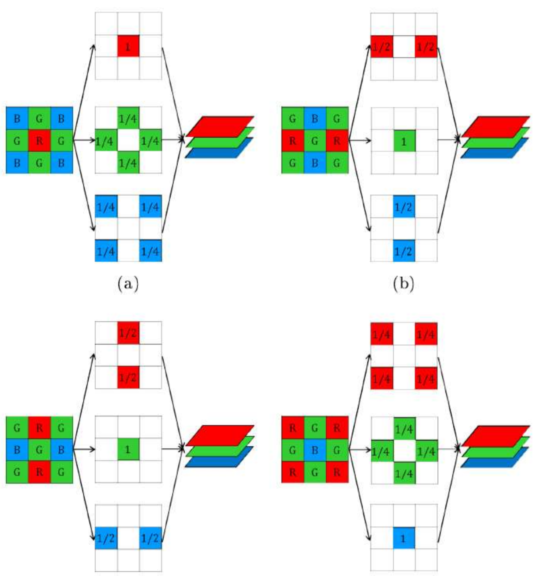
Demosaicing

- Try to recover information



Demosaicing – the traditional approach

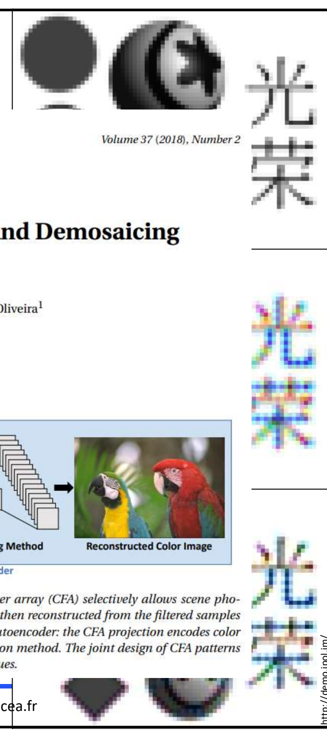
- Bilinear interpolation



Demosaicing – the traditional approach

- Artifacts

Alternative ways for demosaicing



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Deep Joint Design of Color Filter Arrays and Demosaicing

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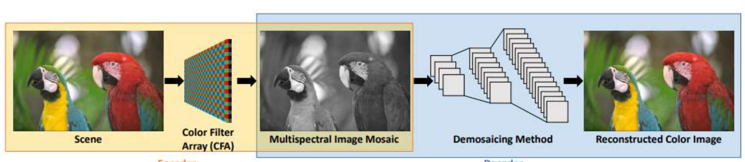


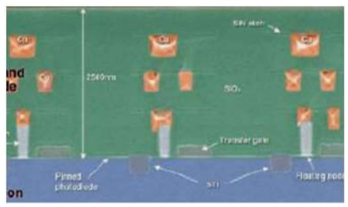
Figure 1: *Capture and reconstruction of color images on single-sensor cameras. A color filter array (CFA) selectively allows scene photons with certain wavelengths to reach portions of a monochromatic sensor. A color image is then reconstructed from the filtered samples (multispectral image mosaic) using a demosaicing algorithm. We model this process as an autoencoder: the CFA projection encodes color information onto the monochromatic sensor, which is later decoded by the color-reconstruction method. The joint design of CFA patterns and demosaicing produces high-quality color reconstruction, outperforming existing techniques.*

Optical elements

- Microlens

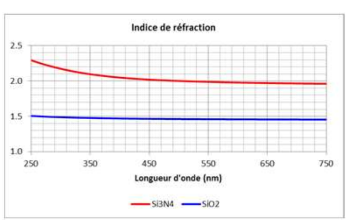
- Color filters

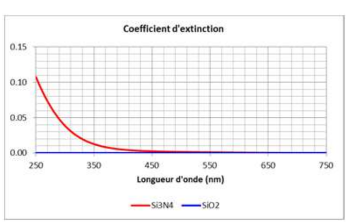
- Optical stack

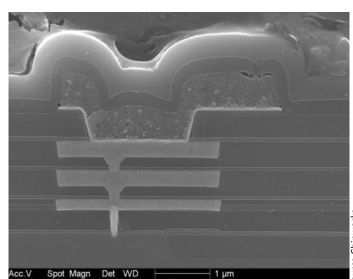


Interconnection stack = Optical stack

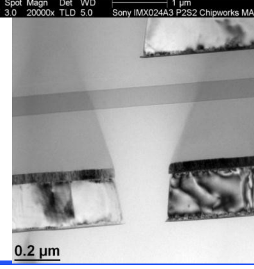
- Stack silicon oxide and silicon nitride used to insulate the metallic interconnections





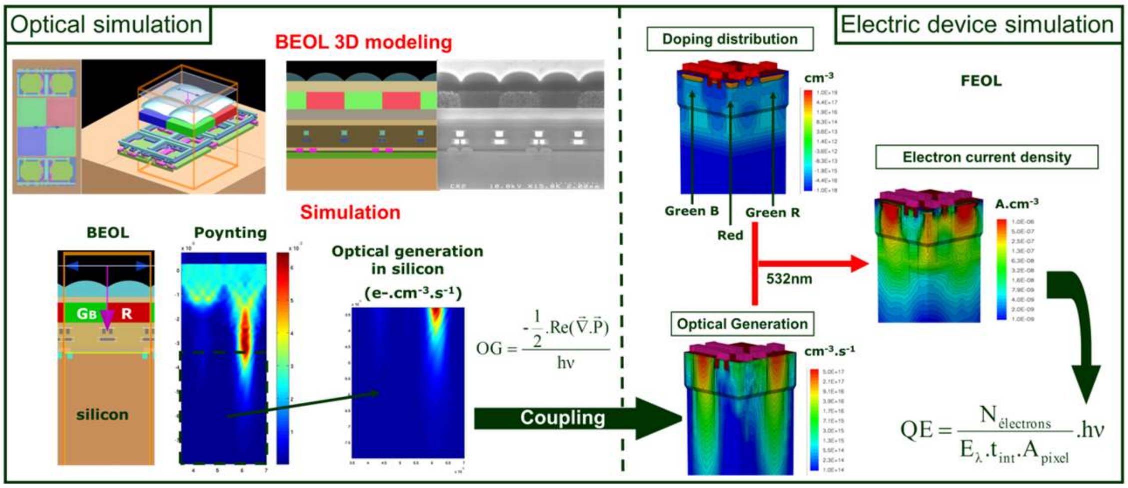


Source Chipworks



Source Chipworks

3D opto-electrical simulation of pixel



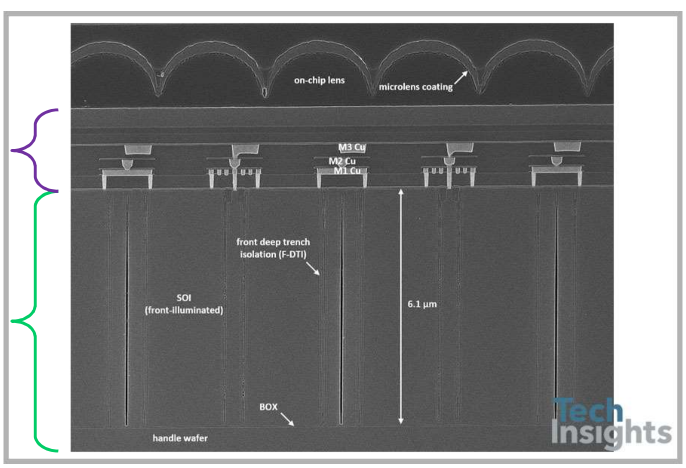
Crocherie *et al.*, From photons to electrons: a complete 3D simulation flow for CMOS image sensor, IISW2009

Frontside illumination (FSI)

- Standard technology for CMOS integrated circuits
  - Light passes through the interconnection stack

Interconnections

Silicon

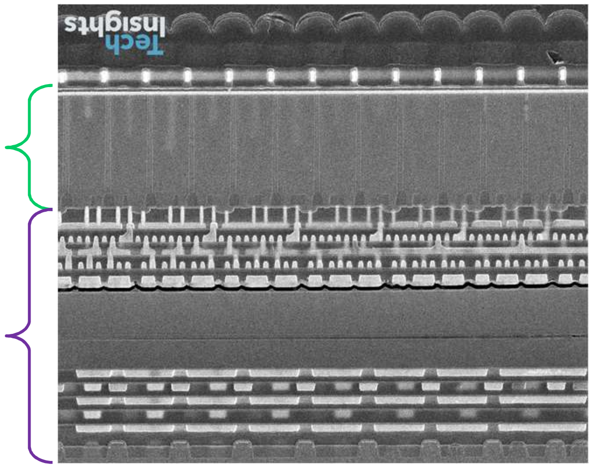


Backside illumination (BSI)

- Wafer is turned over and thinned
  - Light enters the silicon "directly"

Silicon

Interconnections



FSI vs BSI

FSI		BSI	
Simpler process	Lower native fill-factor	High native fill-factor	More complex process: substrate thinning, mechanical handle, …
	Lower density for electronic components Management of light path through interconnection	Higher density for electronic components No constraints on interconnection density	
Thick silicon: better for NIR application	Thicker stack between microlens and photodiode	Minimal stack between microlens and photodiode	Thin silicon (typically 3-6µm): lower performance in NIR
	Impact of interconnection layers	Few layers, optimizable for antirefective effect	

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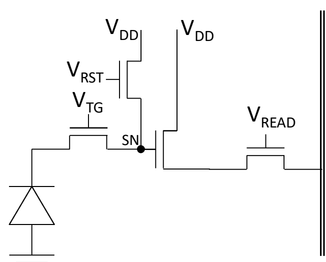
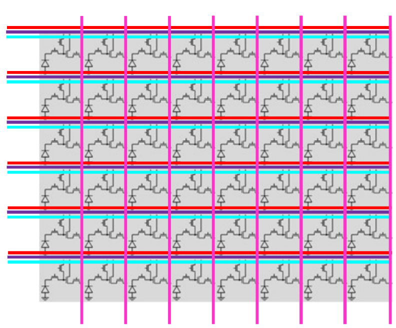
Implementation in a matrix

- Row signals
  - V_{RST}, V_{READ}, V_{TG}
- Column signal
  - V_{OUT}





Two main architectures

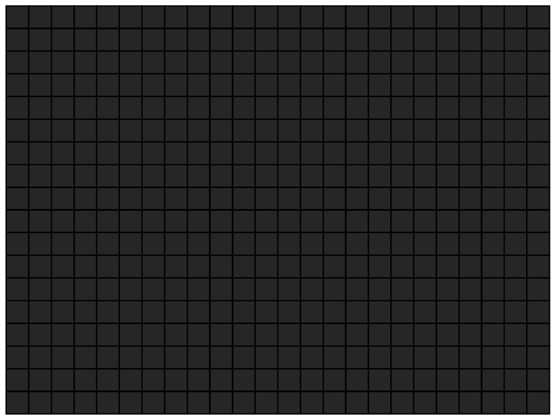
- Two types of sensor depending on their integration strategy
  - Rolling Shutter
  - Global Shutter

Two main architectures

- Two types of sensor depending on their integration strategy
  - **Rolling Shutter**
  - Global Shutter

Rolling shutter

- Command signals send through a shift register line by line



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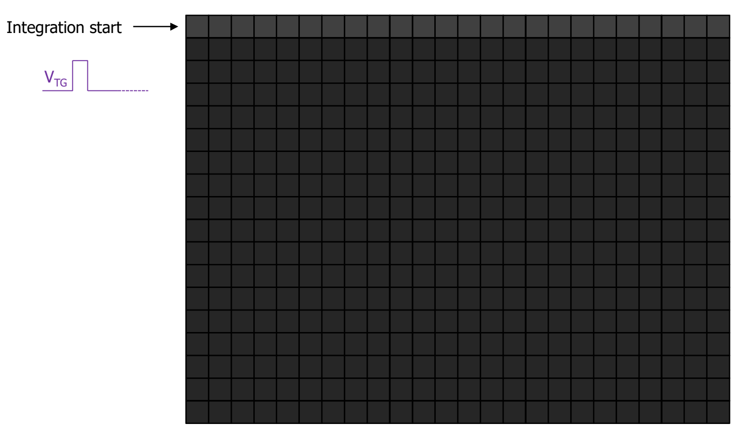

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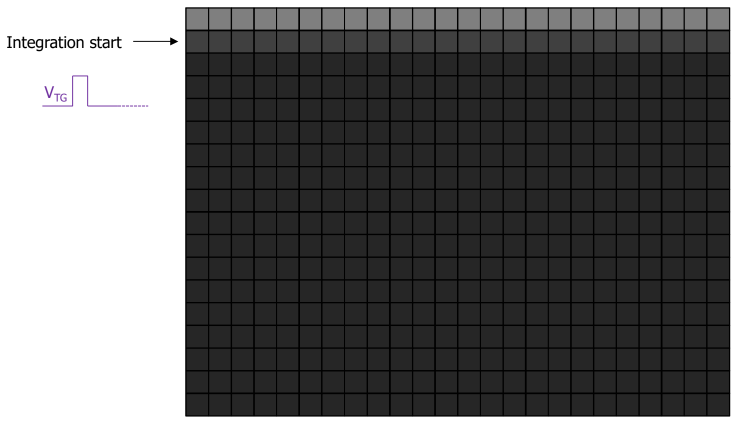

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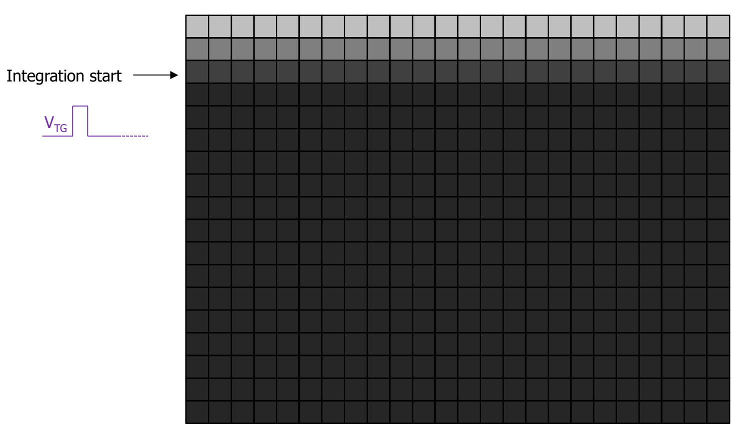

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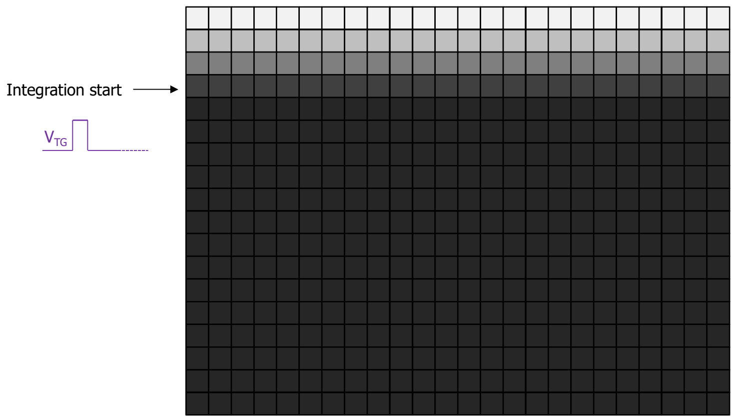

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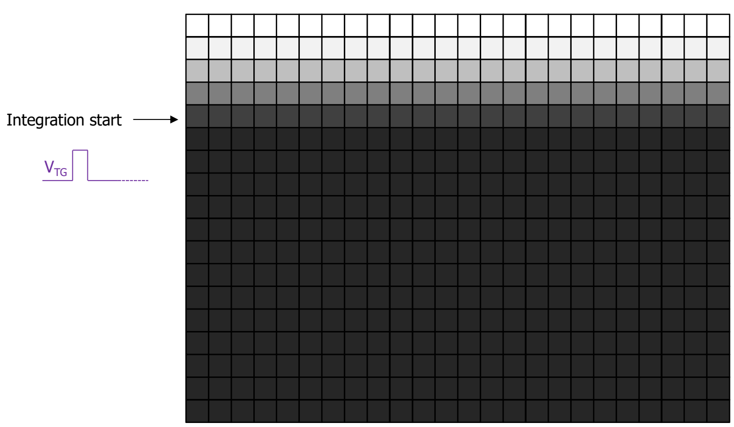

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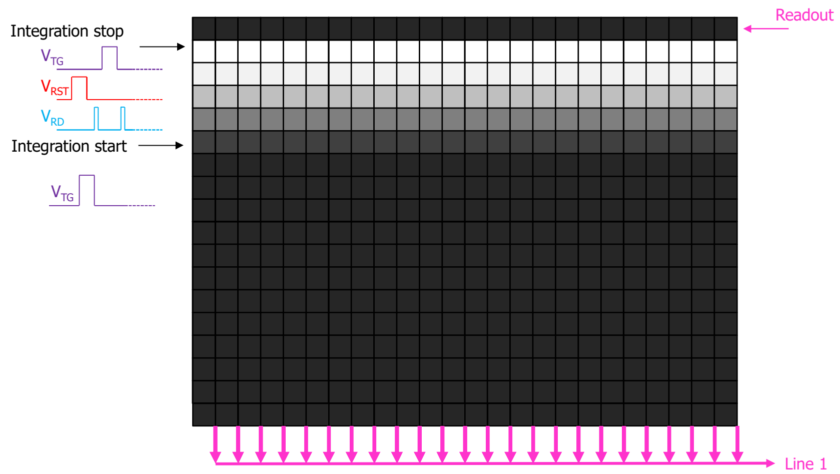

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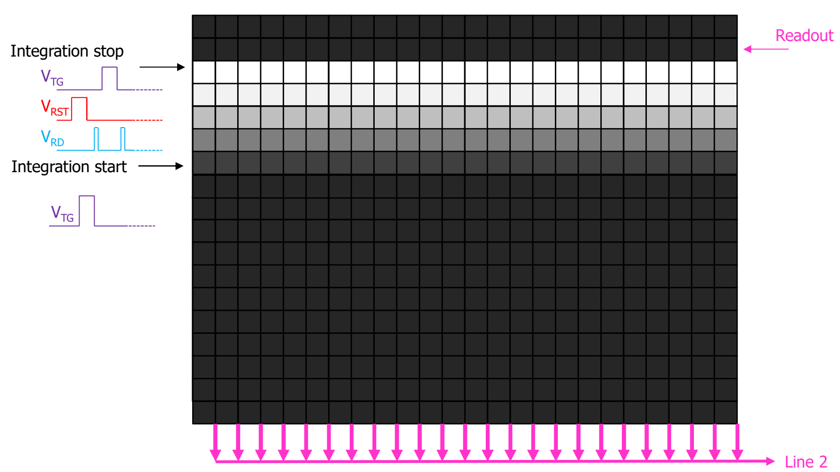

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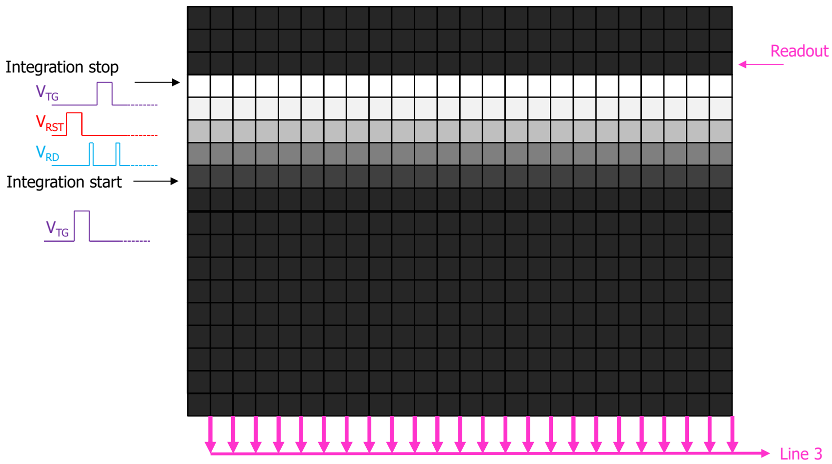
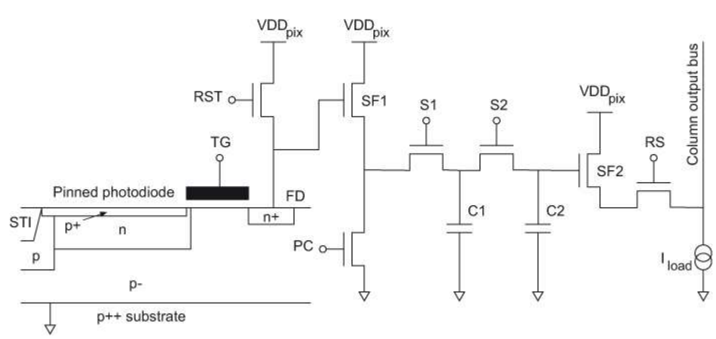


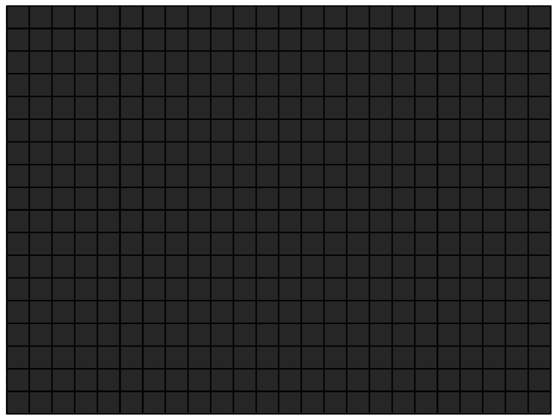
Two main architectures

- Two types of sensor depending on their integration strategy
  - Rolling Shutter
  - **Global Shutter**
    - More complex design: lower fill factor / larger pixel



Global shutter

- Integration start / stop send to all pixels at a time



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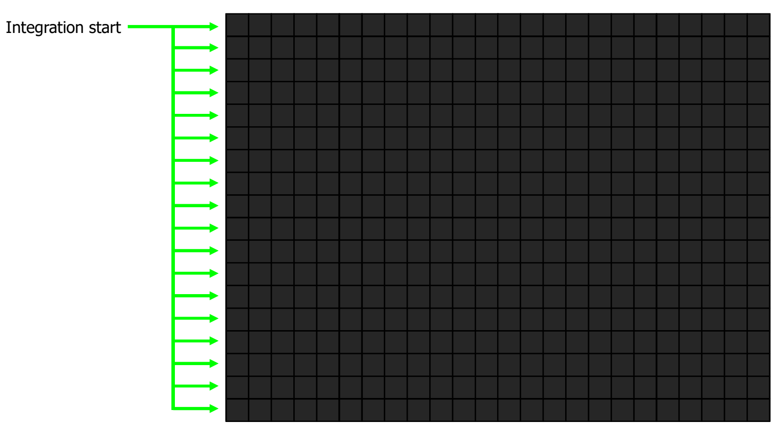

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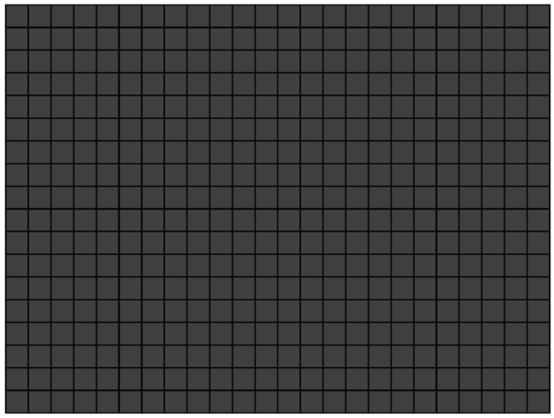

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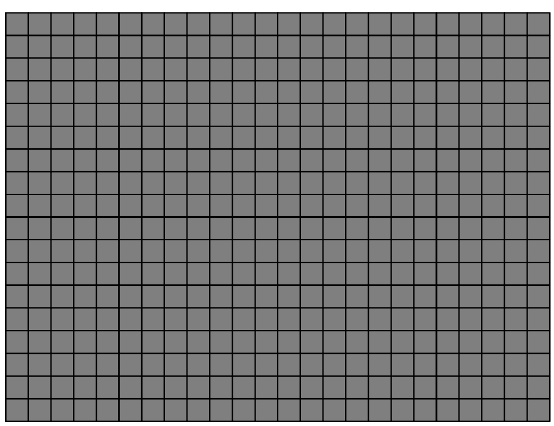

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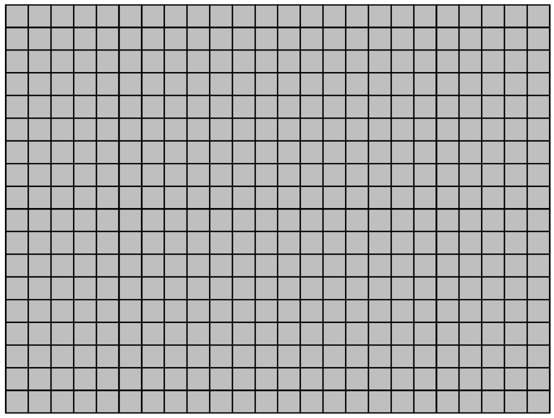

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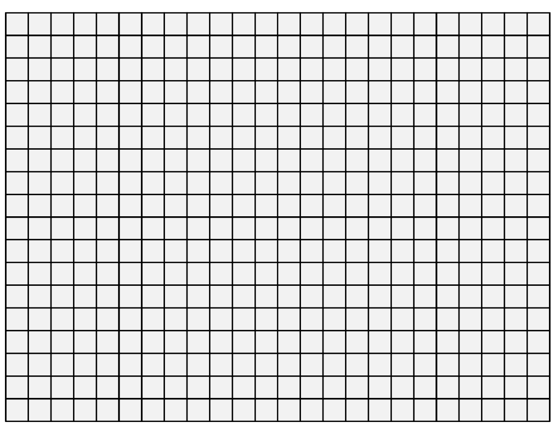

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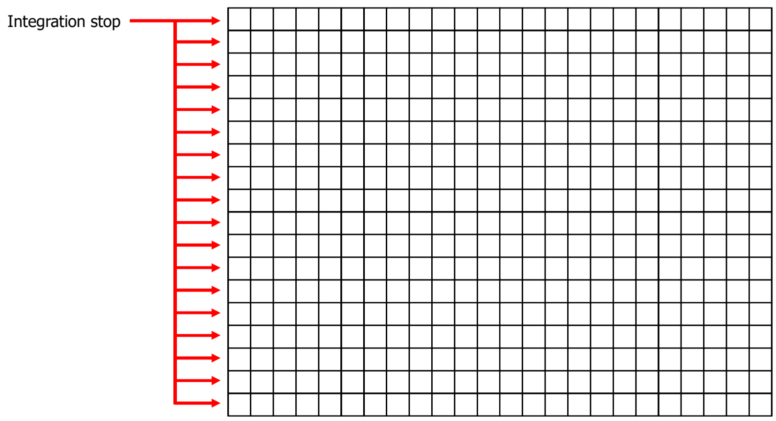
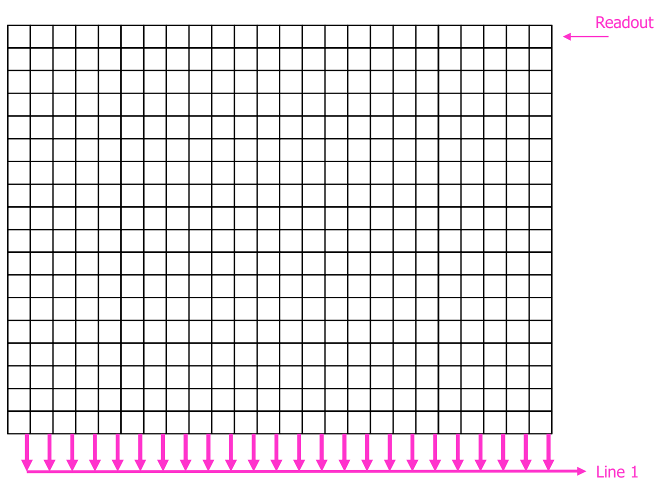


Global shutter

- Then, readout is done line by line via the shift register (i.e. in a rolling mode)



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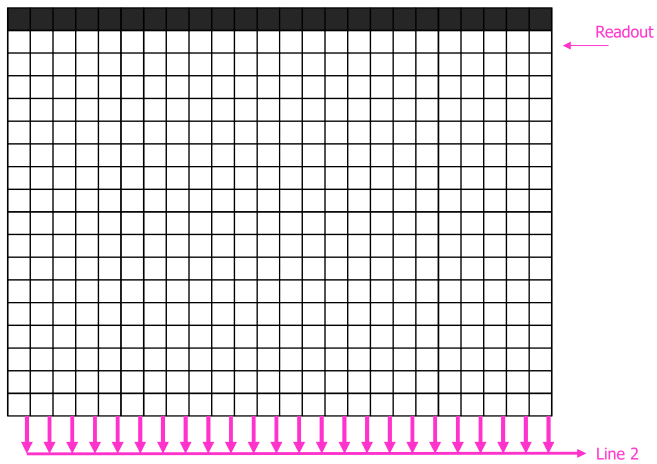
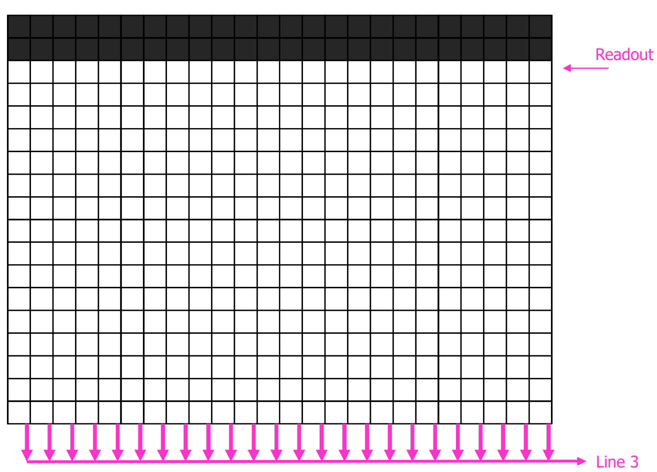


Global shutter

- Then, readout is done line by line via the shift register (i.e. in a rolling mode)



Two main architectures

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Rolling vs Global shutter

Rolling Shutter		Global Shutter	
Small pixel	Rolling shutter effect	No rolling shutter effect “Freeze the scene”	Larger pixel
Charge domain (4T pixels) No reset noise			Voltage domain used to reduce pixel pitch, but at the cost of reset noise
			Impact of light during readout time (Parasitic Light Sensitivity, PLS)

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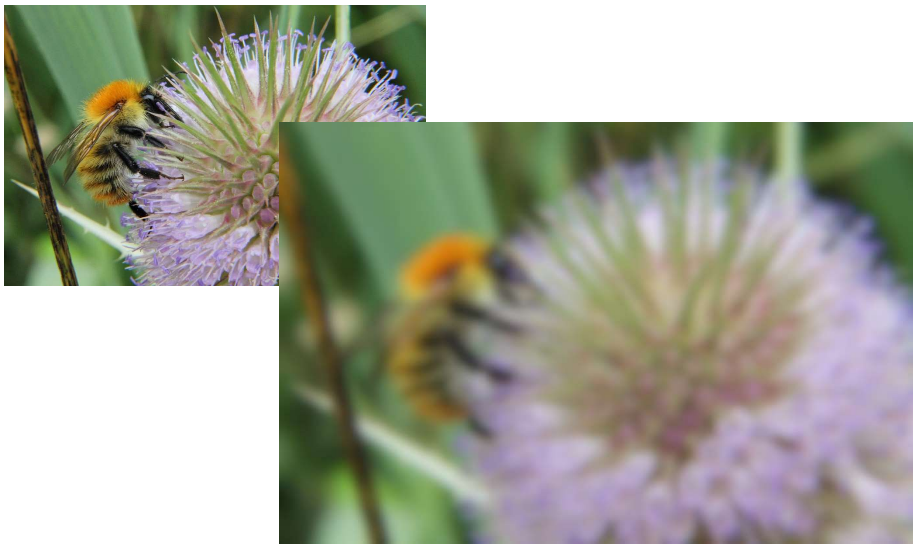
Noises / Performances

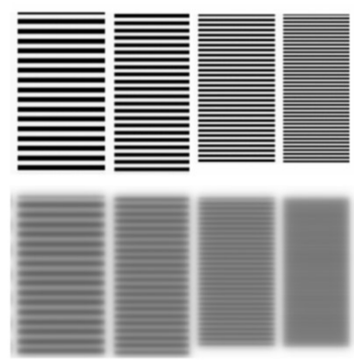
- Performances ↔ SNR
  - What we define as signal?
  - Noise?

Spatial resolution



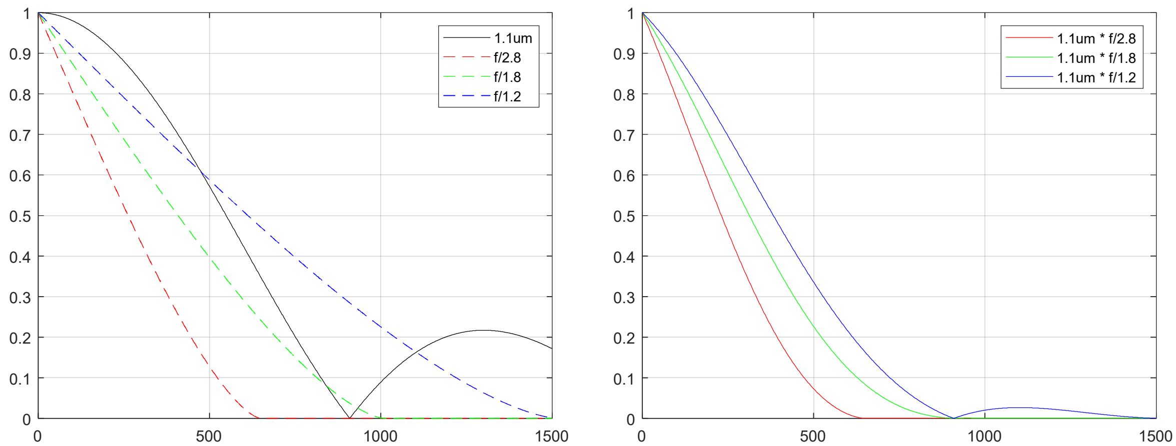
Spatial resolution

- Resolution ≠ definition
  - Resolution: ability to record spatial frequency
  - Definition: number of pixels in the image



Spatial resolution

- Pixel MTF & objective MTF



Spatial noise

Noise

- Photon shot noise
- Reset noise
- Dark current
- Readout noise
- Spatial non-uniformities

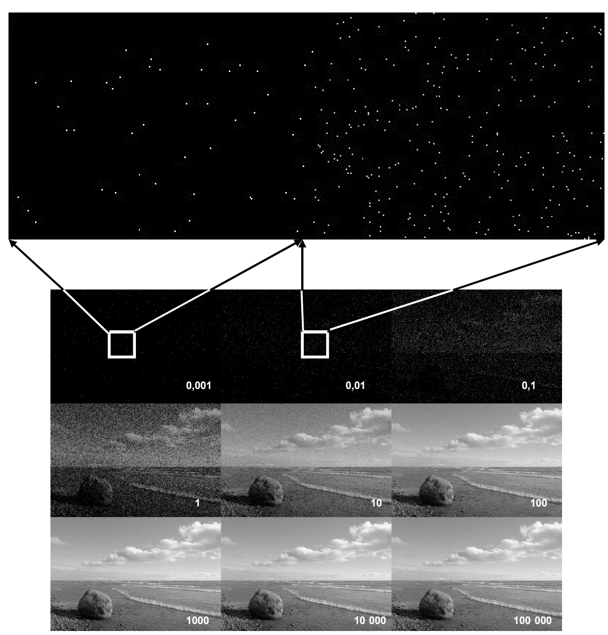
Photon shot-noise

- Due to particle nature of light
- Statistics of photon arrival – Poisson distribution:

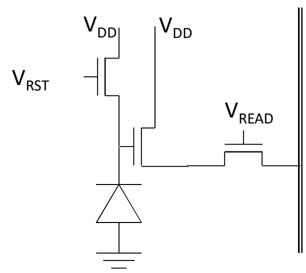
$$P(X_\lambda = k) = \frac{\lambda^k e^{-\lambda}}{k!}$$

$E(X) = \lambda$ and $Var(X) = \lambda$

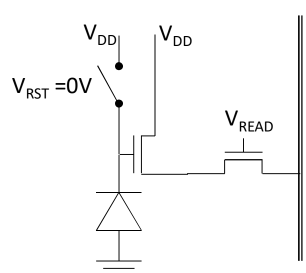
$$SNR = \frac{E(X)}{\sqrt{Var(X)}} = \frac{\lambda}{\sqrt{\lambda}} = \sqrt{\lambda}$$



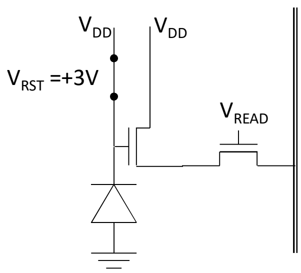
Reset noise



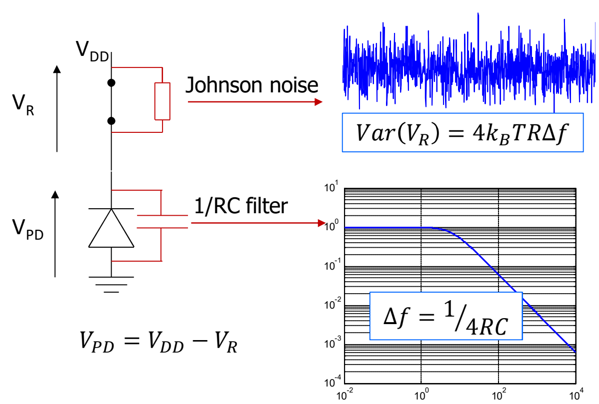
Reset noise



Reset noise



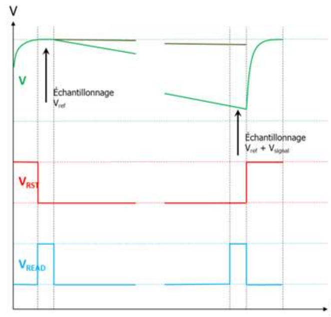
Reset noise



$$\sigma^2_{V_{PD}} = \frac{k_BT}{C}$$

Reset noise

- On 3T pixel:
  - Two uncorrelated sampling $\sigma_{e^-} = \frac{C}{q}\sqrt{\frac{2k_BT}{C}} = \frac{1}{q}\sqrt{2k_BTC} \quad [e^-]$
  - Ambiant Temp.: 300K
  - Pixel 2µm $\Rightarrow C_{pix} \simeq$ 10fF $\quad \boldsymbol{\sigma_{e^-} \simeq 60\ e^-}$
  - k_B = 1,38 x 10^{-23} J.K^{-1}



Number of photons per pixel

- Main objective with f/D=16 and a transmission of T=90%
- Macro photography, $\gamma = -1$
- Maximum sunlight illumination: E_s=10 000 lux
- Average reflectivity of the scene R=18%
- Pixel pitch 2µm
- Integration time 1/100 s

- $Ep = \frac{RT}{4\left(f/D\right)^2 \times (\gamma-1)^2} E_s \simeq 0.40\ lux$
- $N_{photons} = E_p \times p_{pixel}^2 \times \tau_{int} \simeq 160\ photons/pixel$

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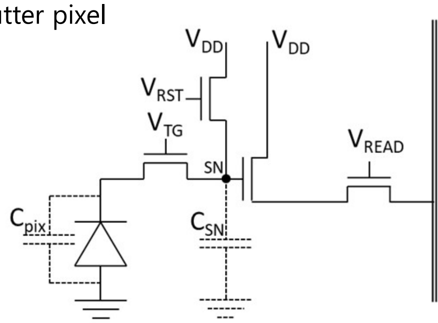
Reset noise

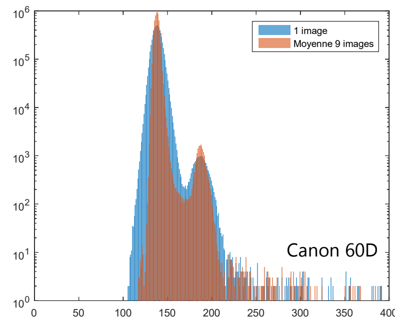
- Can be cancelled by doing Correlated Double Sampling (CDS)
  - Done inside the pixel for 4T architecture
  - Current standard architecture for CMOS rolling shutter pixel
- In datasheet:
  - Charge domain => no reset noise
  - Voltage domain => reset noise



TG : Transfer Gate
SN : Sense Node

Dark current

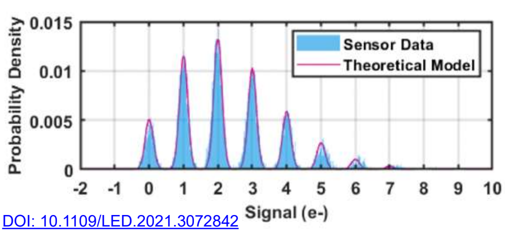
- Collected e⁻ even without illumination
  - Trap assisted thermal generation at interfaces Si/SiO2 (and in Si volume)
- Properties:
  - Strongly temperature dependent $\times \mathbf{2}$ **every** $\Delta T \simeq 8°C$
  - Can be managed by interfaces passivation.
  - Distribution over the matrix: main Gaussian distribution + secondary population + outlier
  - A given pixel follows a Poisson statistic
- Mean value (over the matrix)
  - Idark down to ~0.1 e-/s @ 25°C in 1µm and below pixels
- Spatial variation over the matrix
  - DSNU: Dark Signal Non-Uniformity
- Can be partially corrected by dark image subtraction
  - Poisson noise remains



Read noise

- Sum of all electronic noises between photodiode and output
  - 1/f noise
    - Traps in transistor channel
  - Reset noise of sampling capacitances
  - Reset noise in case of 3T pixel
  - Gaussian statistic is a reasonable assumption
- Typical value on small pixels: $\sigma_{read} \simeq 1.5 - 3\ e^-$
  - Low noise sensors recently developed (gigajot.tech)

    $\sigma_{read} = 0.19\ e^-$



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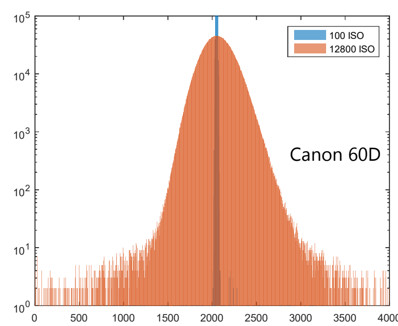
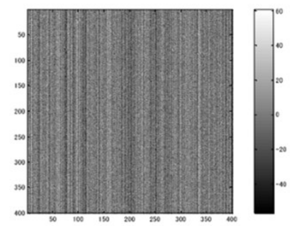


Fix Noises

- Fixed Pattern Noise (FPN)
  - Mismatch of transistor parameters
    - At pixel level (spatial high frequency)
    - In readout circuit at the bottom of the column ⇒ vertical pattern
  - Could be partially corrected by dark image subtraction
- Photon Response Non-Uniformity
  - Spatial variation of pixel sensitivity
  - Could be corrected by taking a flat field image



Fixed Pattern Noise

Quantification noise

- Due to finite number of digital levels (# of ADC bits)

$$\sigma_{quant}^2 = \frac{LSB^2}{12}$$

3 x 8bits

3 x 6bits

3 x 4bits

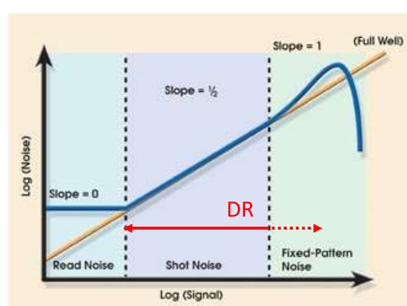
3 x 2bits

3 x 1bits

Dynamic

Dynamic Range

- Range of signal that can be captured in one single frame
  - $DR \neq SNR$ $$DR = 20 \times \log\left(\frac{Saturation}{noise\ floor}\right)\ [dB]$$
  - SNR_{max} achieved at saturation
    - Limited by photon shot-noise $SNR_{max} = \sqrt{Q_{sat}}$
  - $SNR_{min} = 1$ is noise floor



https://www.photonics.com/Article.aspx?AID=15891