



# **Increasing Dynamic Range in CMOS image sensors**

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# Outline

- Dynamic range
  - Definition
  - Limitations
- 8 different methods to increase dynamic range
- Conclusions

# Definition

$$\text{Dynamic range} = \frac{\text{Saturated signal}}{\text{Dark Temporal noise (rms)}}$$

## Logarithmic scales

$$\text{Dynamic range (dB)} = 20 \cdot \log \left( \frac{\text{Saturated signal}}{\text{Dark noise}} \right)$$

## Applying some sensor units

$$\text{Dynamic range (dB)} = 20 \cdot \log \left( \frac{\text{full well charge}}{\text{\# noise electrons}} \right) = 20 \cdot \log \left( \frac{V_{sat}}{v_{rms}} \right)$$

# Limitations

- Human observer
  - 100 dB or more : inside vs. outside
  - Logarithmic response of the eye ↔ linear response of (most) sensors and displays
  - Human can distinguish approx. 64 gray levels on a display or print
- Display or print technology
  - 256 gray levels (= 48 dB)



# Technological limitations:

## Dark current

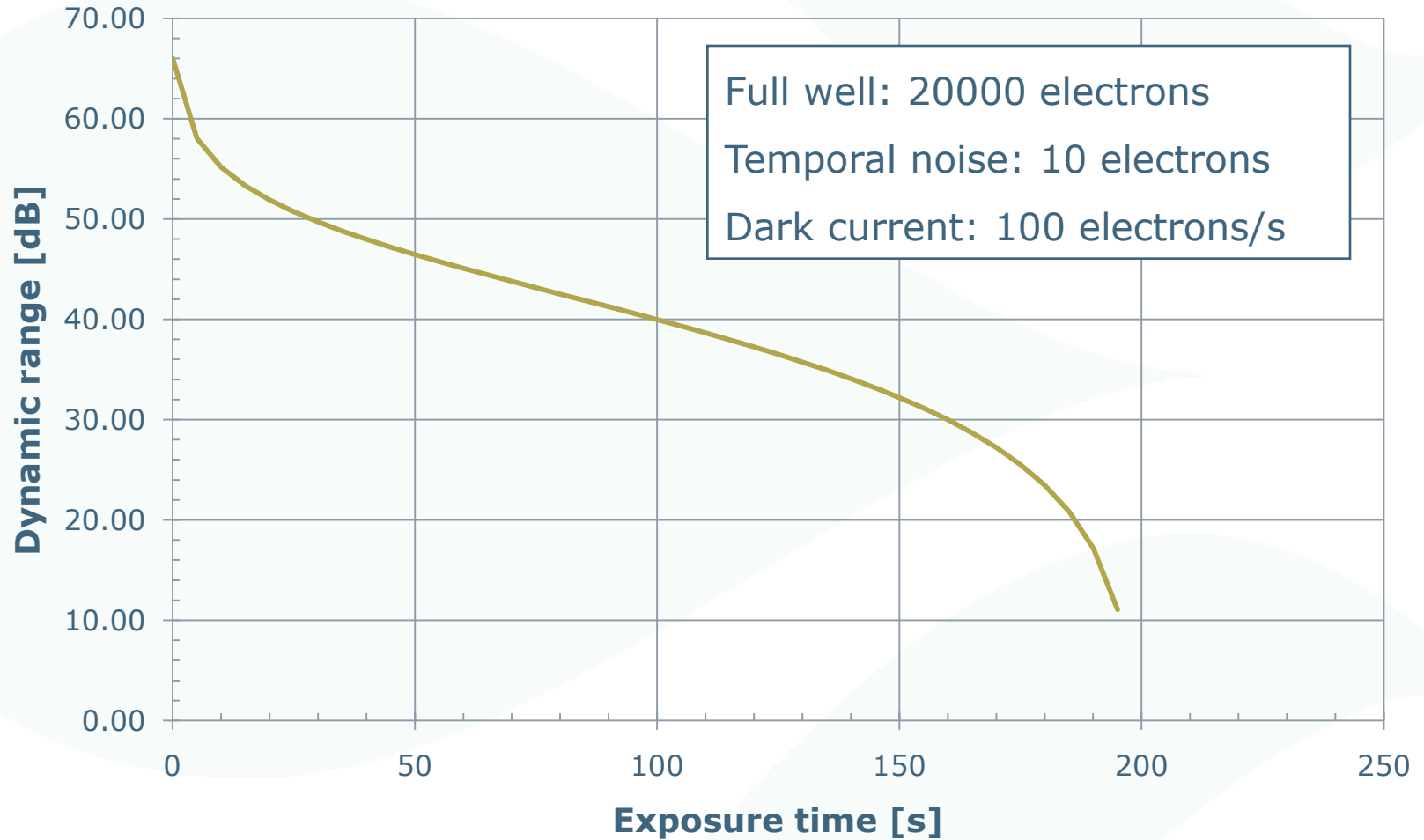
- Long exposure times : dark current
  - Dark current shot noise  $\sqrt{e_{dark}}$  increases temporal noise
  - Dark current consumes part of saturated signal

- Must be taken into account

$$\text{Dynamic range} = 20 \cdot \log \left( \frac{\text{full well} - e_{dark}}{\sqrt{e_{rms}^2 + e_{dark}}} \right)$$

- Considerable at
  - Higher temperatures
  - Long exposure times
  - Technologies with high dark currents

# Example



# Technological limitations:

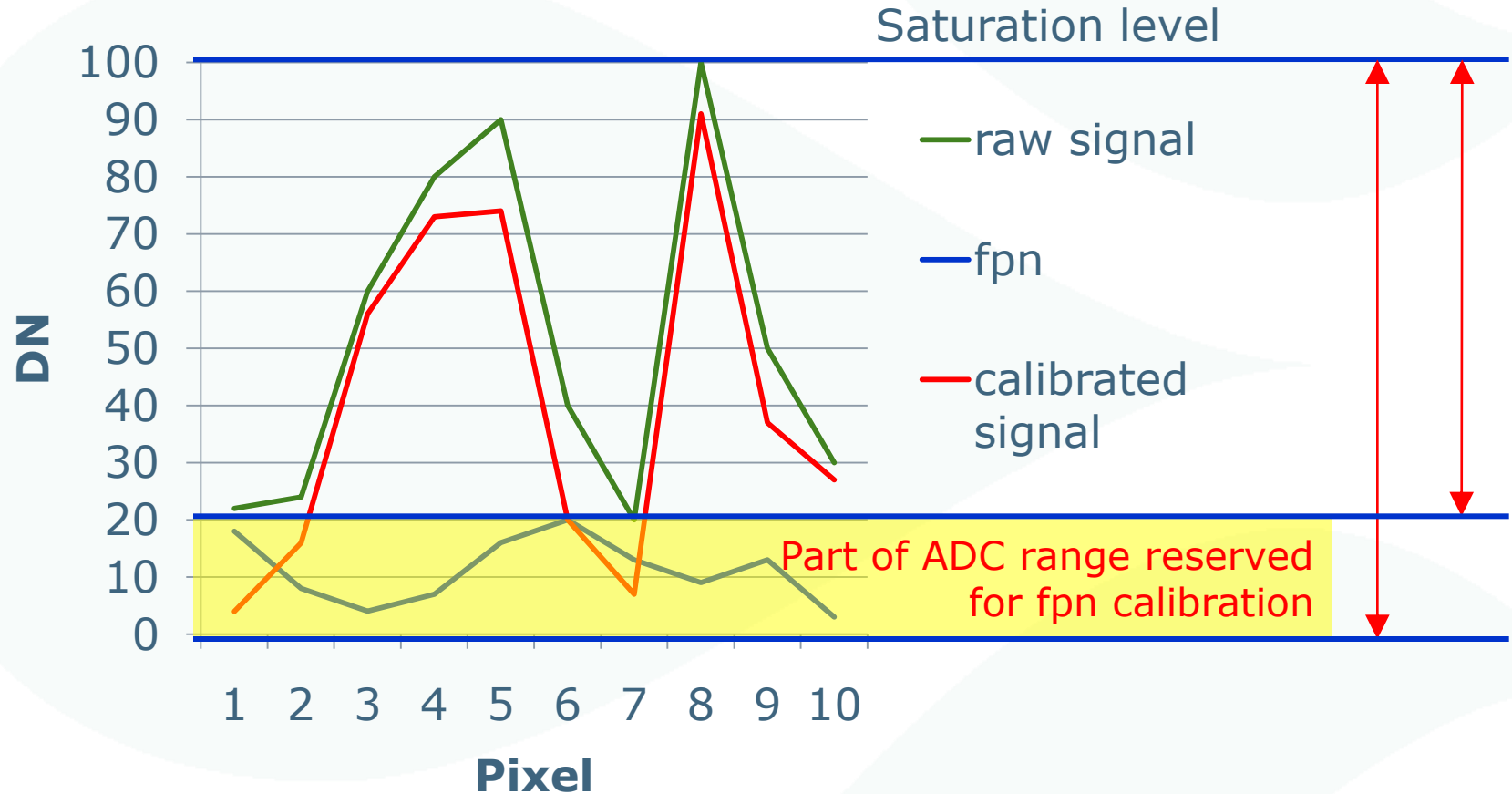
## Dark non-uniformity

- Dark non-uniformity
  - Fixed pattern noise (FPN)
  - Dark current non-uniformity (DSNU)
- Correction: subtract dark reference frame (= dark frame or better: averaged dark frame)
- Reserve # codes in your ADC to ensure that the dark signal doesn't clip
- Consumes dynamic range

$$\text{Dynamic range} = 20 \cdot \log \left( \frac{V_{sat} - V_{pTp,fpn}}{v_{rms}} \right)$$

- Can be considerable at low light levels or at high gain and with certain pixel types
    - Example:
      - Average signal: 200 mV
      - Dark non-uniformity 50 mV peak-to-peak
- 50 mV signal consumed after subtraction

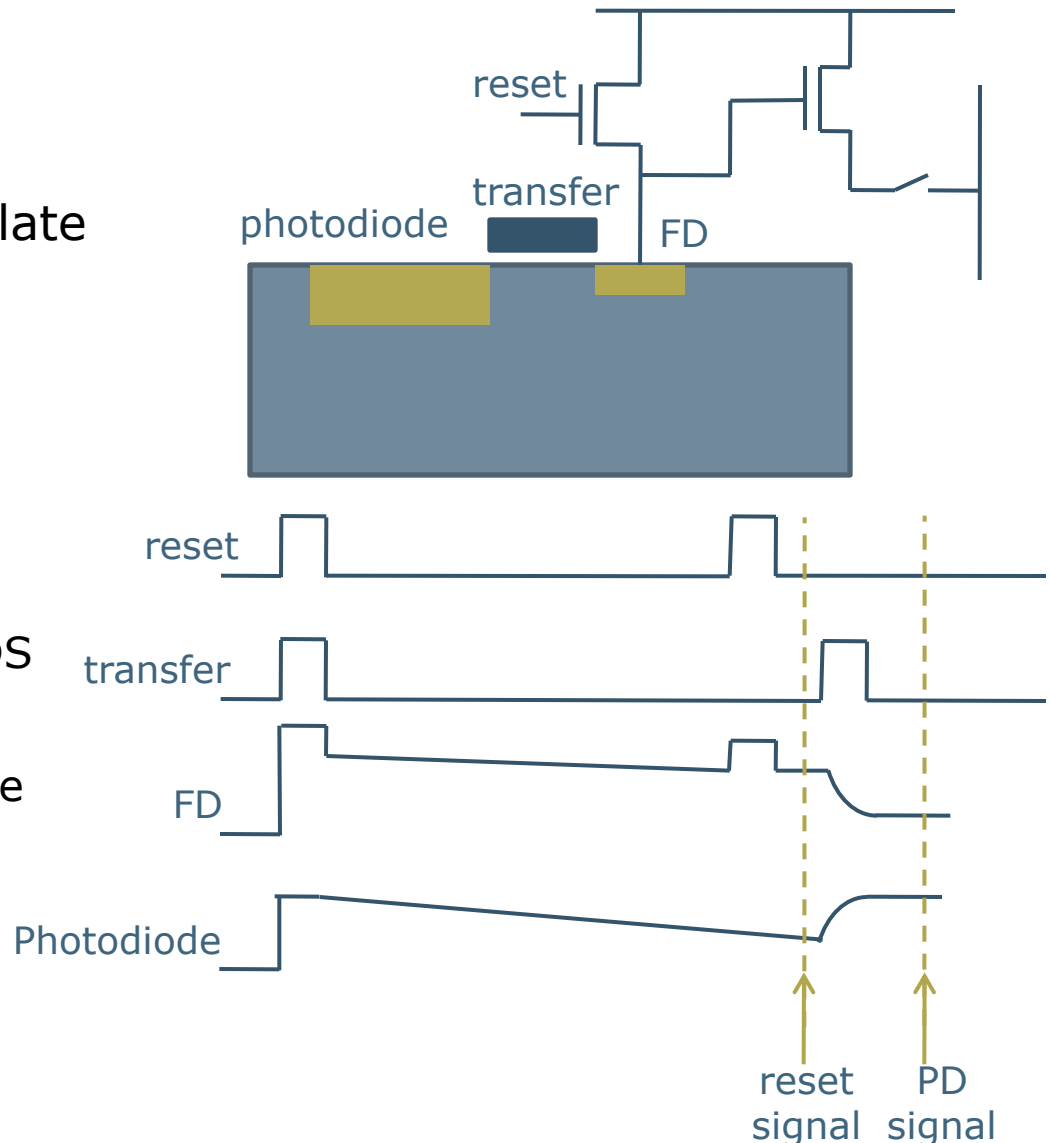
# Dark frame subtraction



# Technological limitations:

## Read noise

- Read noise = temporal variation on pixel sample
- Acquire 100 frames, calculate RMS variation of a pixel
- Sources:
  - CMOS "3T" active pixels: kTC noise (3T pixels) ~ 30-50 electrons
  - Drastically improved in CMOS with 4T pixels : CDS ~5-10 electrons
  - 1/f or RTS noise on source follower (limitation in 4T pixels)
  - Dark current shot noise



# Technological limitations: Signal swing

## We benefit from semiconductor scaling

- Allows to make smaller pixels
  - Feature size of routing, vias, transistors scales
- Allows pixels with more transistors on the same pitch
  - Snapshot shutter
  - “smart” pixels

## We suffer from semiconductor scaling

- Lower supply voltages limit signal swing

<b>0.35</b>	<b>0.25</b>	<b>0.18</b>	<b>0.13</b>	<b>0.09</b>
3.3 V	2.5 V	1.8 V	1.3 V	1 V

- “Solution”
  - high volt devices  
(= 0.35  $\mu\text{m}$  or 0.25  $\mu\text{m}$  transistor)
- Transistor leakage
  - Subthreshold leakage
  - Gate leakage (65 nm & beyond)
- Technology changes
  - Copper : SiN intermediate layers

# Technological limitations: motion blur

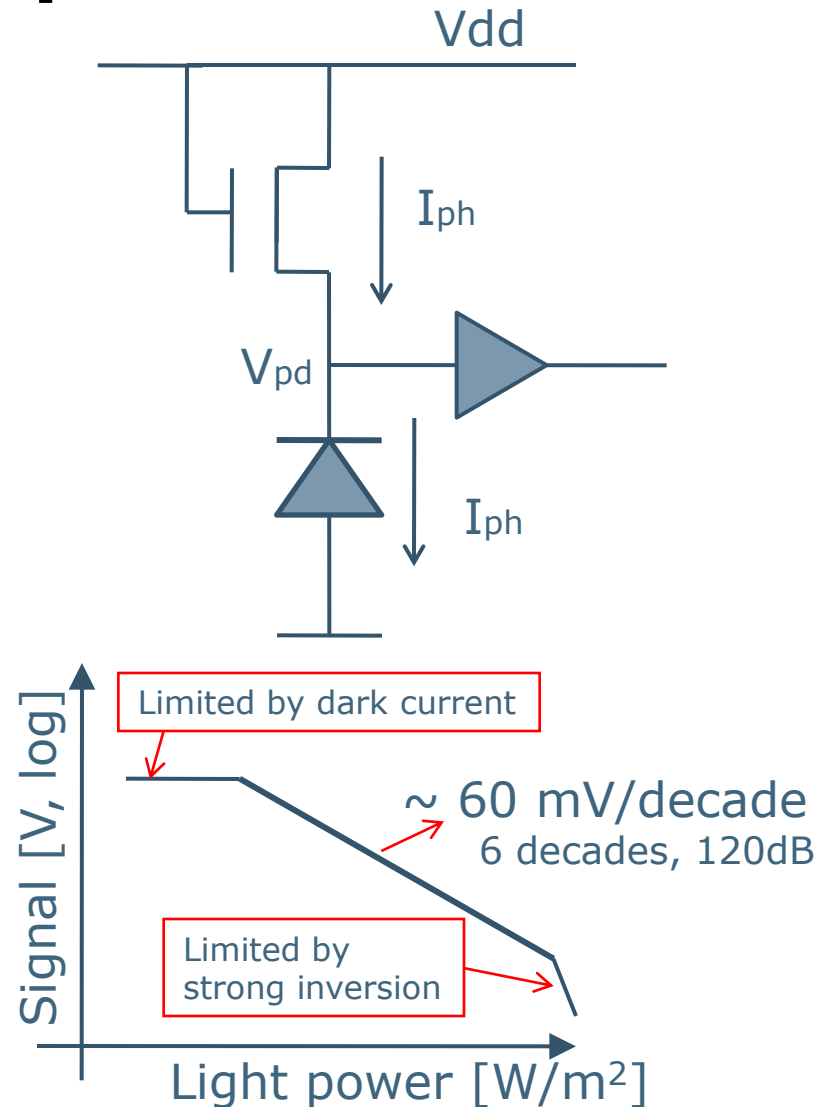
- Motion blur limits longest exposure time
  - An old photography rule
- Methods to increase dynamic range use longer exposure times to extend sensitivity near dark
  - If read noise is fixed and certain dynamic range must be reached, the only way to do it is increasing exposure time

# Techniques to increase dynamic range

- Non-linear compression
  - Logarithmic response
  - Piece-wise linear response
- Tricks in 4T pixels
- Multiple non-destructive readings
- Smart reset pixels
- Pixels with feedback
- Interleaved schemes
  - Pixel sizes
  - RGBW and variants
  - Exposure time

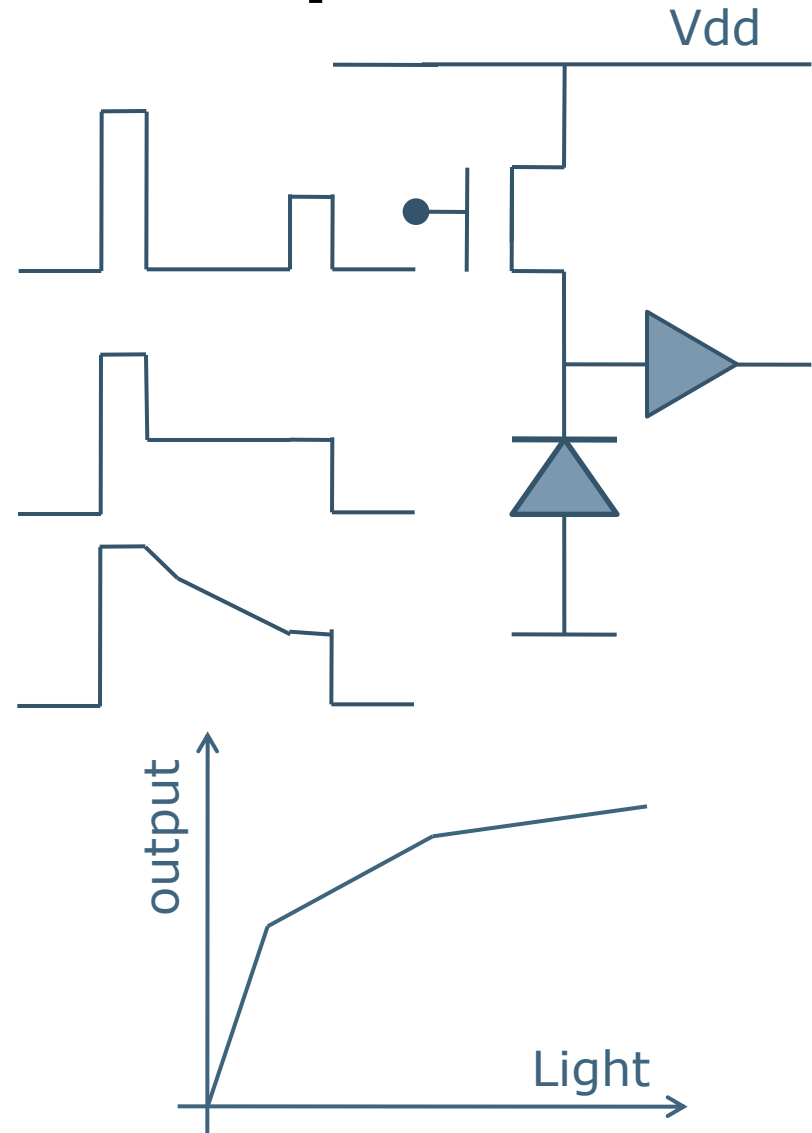
# Logarithmic sensor response

- Load mosfet in weak inversion
- $V_{pd} \sim \ln(I_{ph})$
- Can be combined with linear response (integration during exposure time, logarithmic for highlights)
- Direct photocurrent measurement
- Lag ( $\tau \sim C_{pd}/I$ ): high in dark
- Fixed pattern noise (no dark reference available)

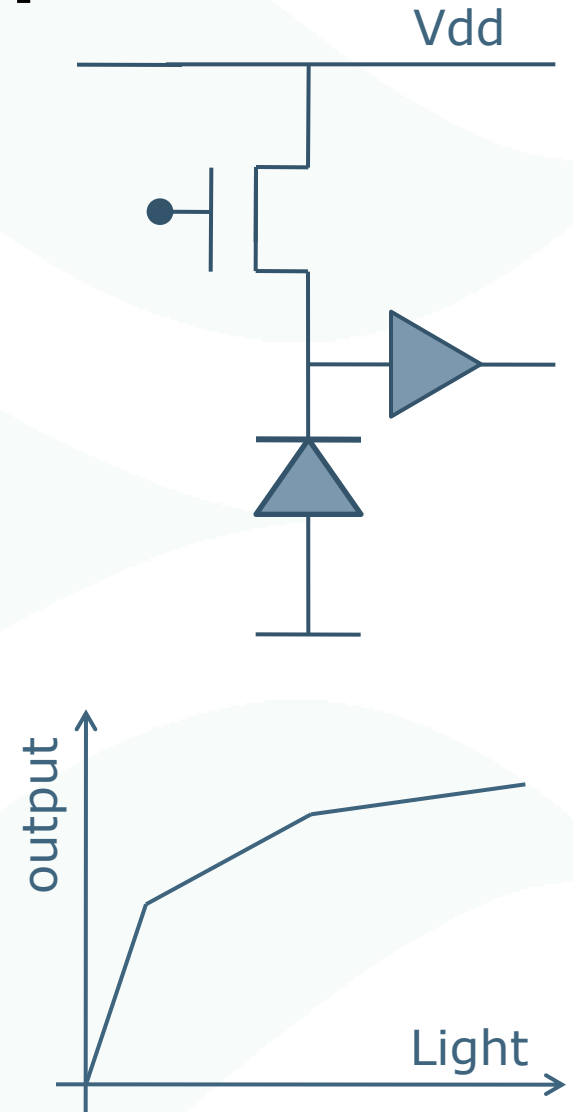
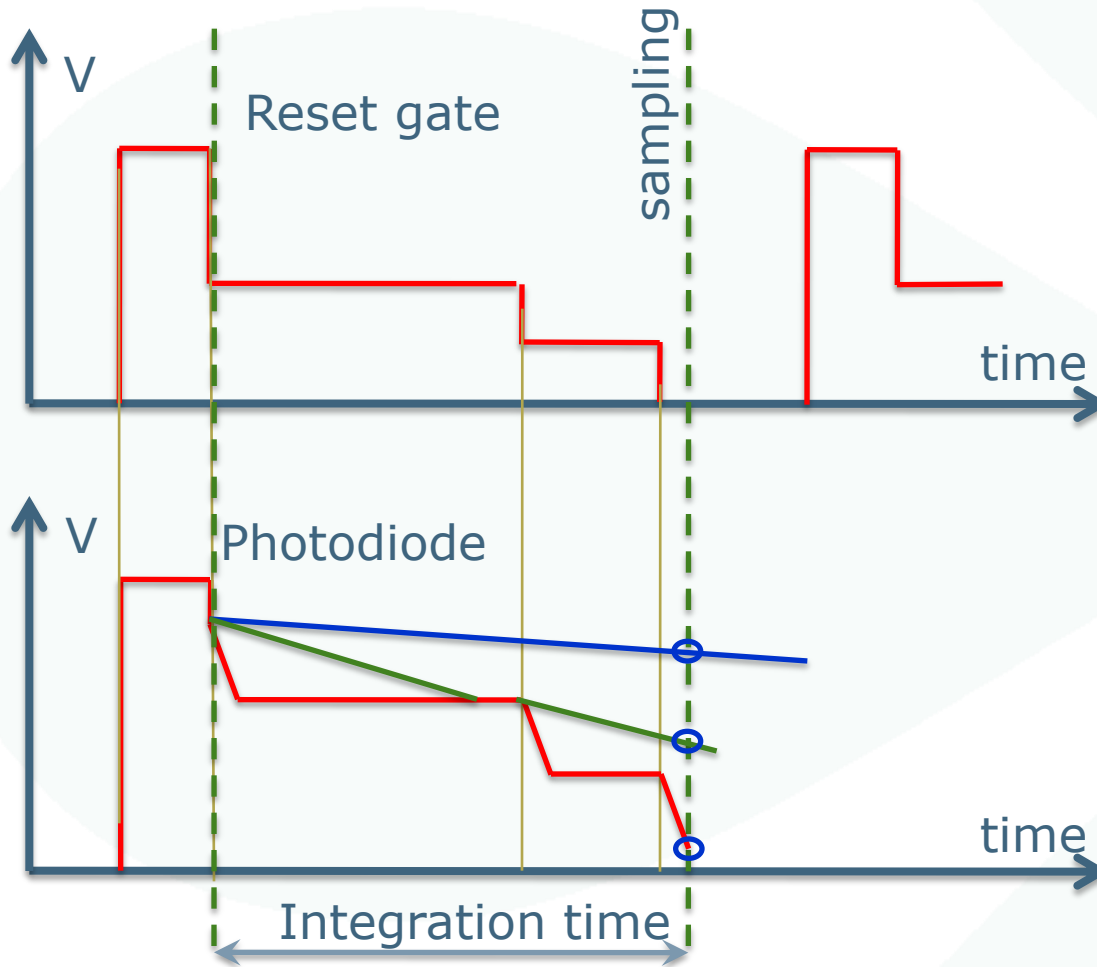


# Piece-wise linear sensor response

- Partial reset of photodiode
  - Extra pulses with lower amplitude on reset gate
  - Piece-wise linear or other pulse shape on reset gate
- Simple to integrate in 3T pixels
- Adjustable response curve
  - Kneepoints
  - Slope
- 4T pixels:
  - more difficult to implement
  - Charge must be evacuated via transfer gate + reset
- Difficult to know in which part (with which slope) the response sample was taken (color reconstruction)
- Non-uniformity in kneepoints

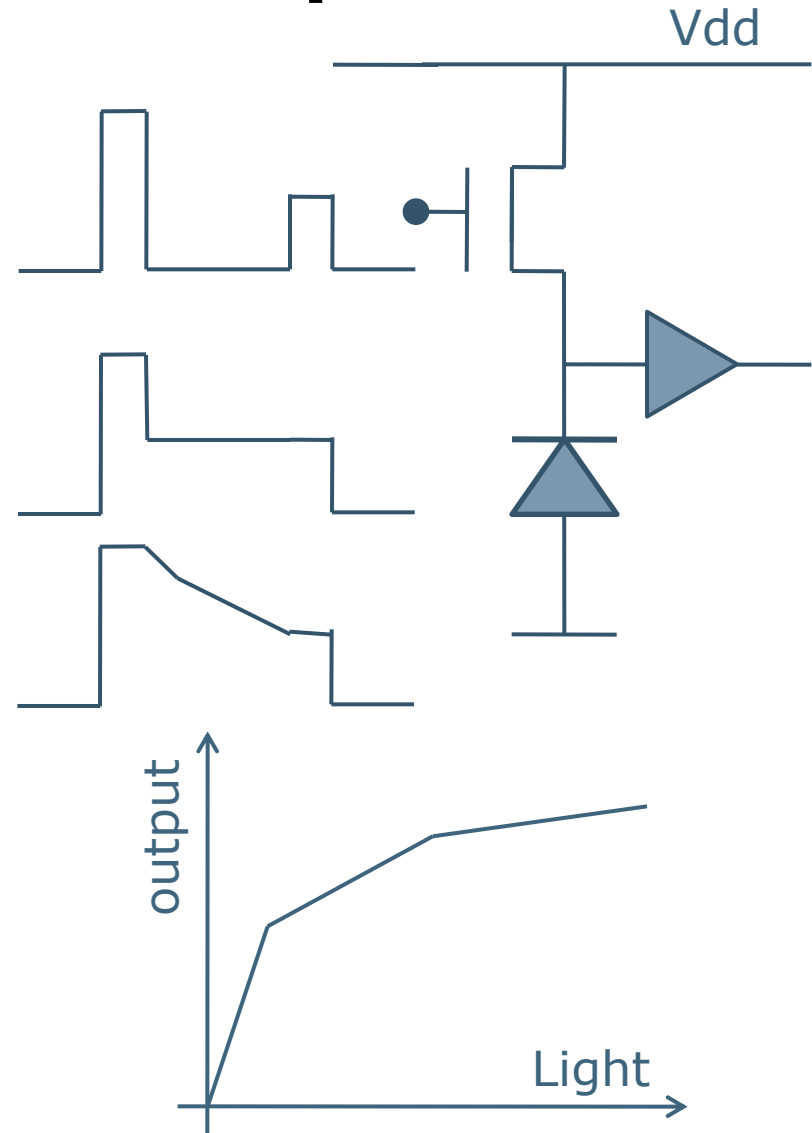


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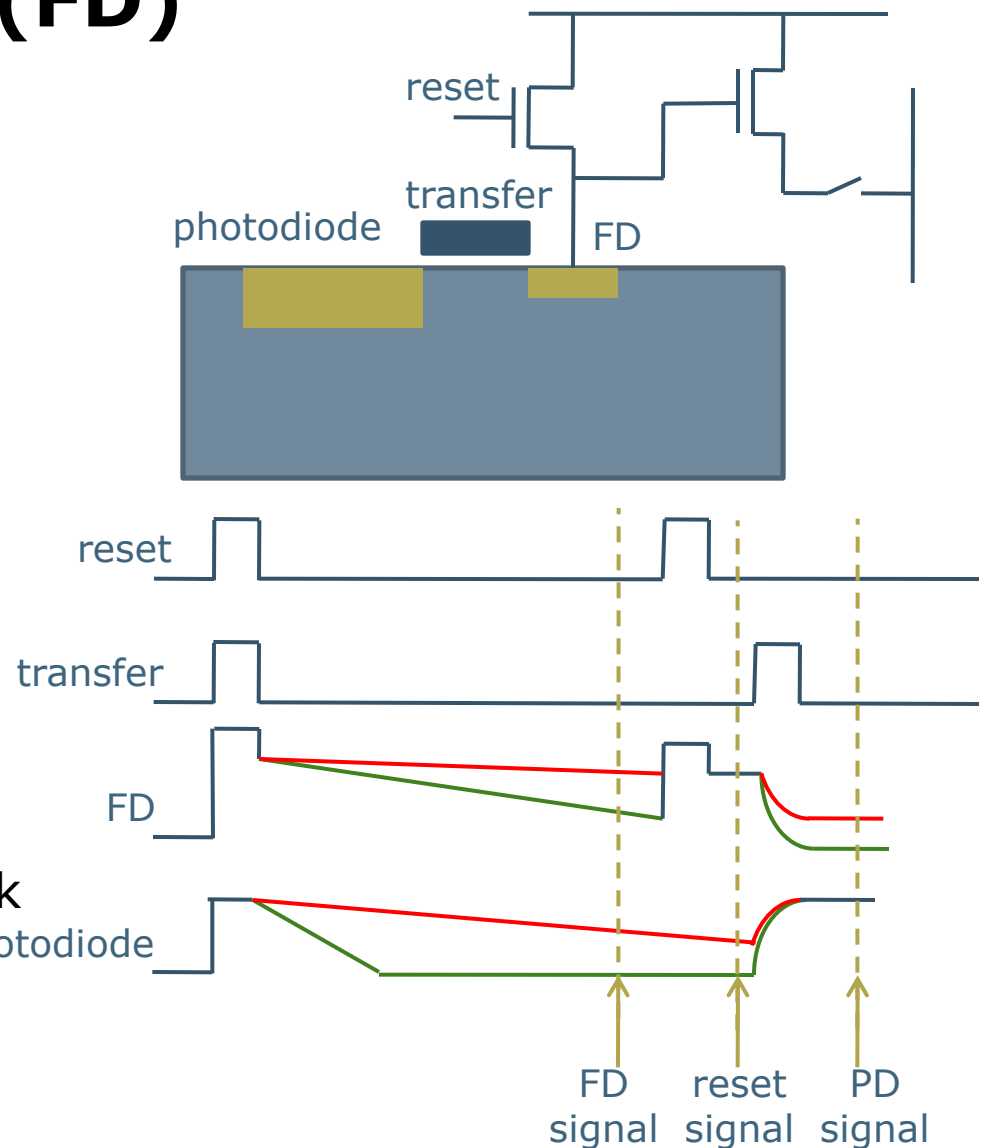
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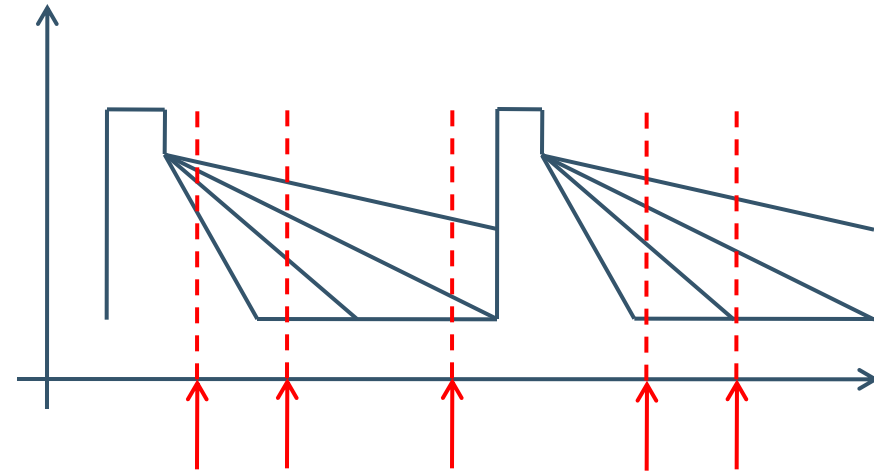
# 4T pixel : integration on floating diffusion (FD)

- FD is light sensitive, but
  - Lower sensitivity (area, efficiency)
  - High leakage current
- Use FD as 2<sup>nd</sup> photodiode for bright areas
- CDS for photodiode readout (dark areas)
- DS for FD readout (bright areas, so dark noise does not count)
- FD is "poor" photodiode (dark current, MTF, ...)
- Photodiode blooming into FD



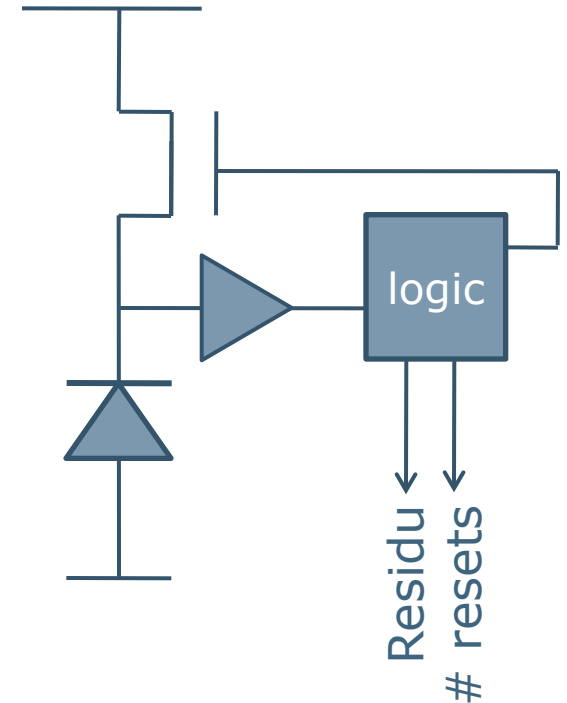
# Multiple non-destructive readings

- Multiple readouts
- Non-destructive readout
- Utilize data from non-saturated pixels
- Algorithms:
  - Last sample before saturation
  - Weighted averaging: reduce also the read noise
- + knowledge of sensitivity of sample
- + Extra data can be used to reduce read noise
- Increased data rate, signal processing. Difficult at higher frame rates



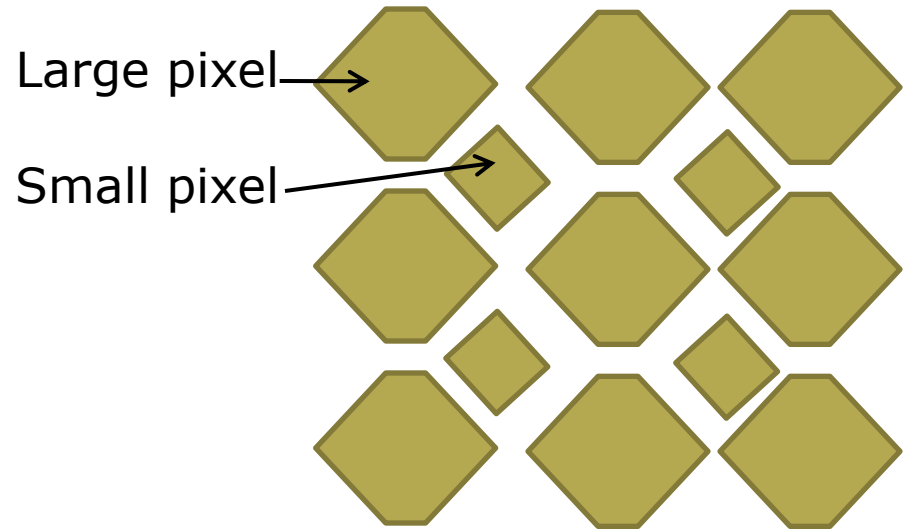
# Smart reset pixels

- In-pixel binarisation and logic
  - Feedback in the pixel
  - Count # resets
  - Readout:
    - # resets
    - Residu
- 
- + very high dynamic range
  - extra circuitry in pixel

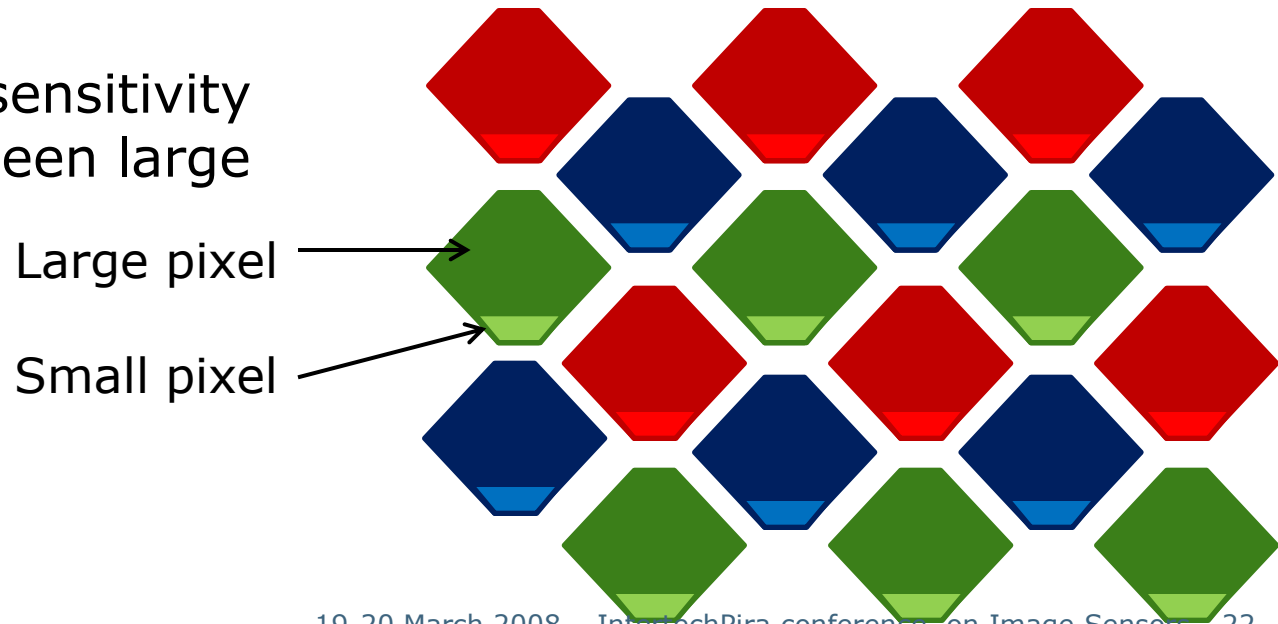


# Interleaved pixel sizes

- Small pixels for bright areas
- Large pixels for dark area
- Color : Interpolate RGB data from bright/small.
- Fuji

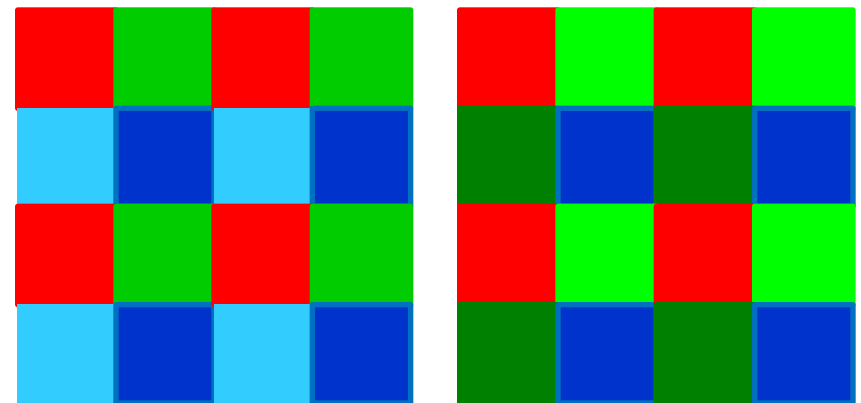
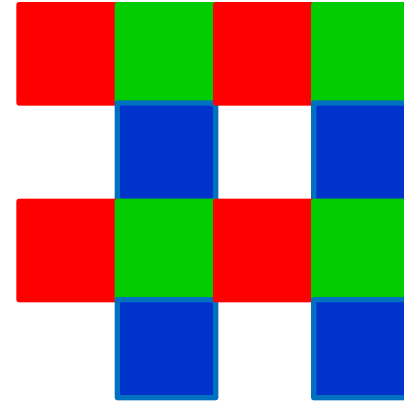


- no control over sensitivity (fixed ratio between large and small pixel)
- interpolation



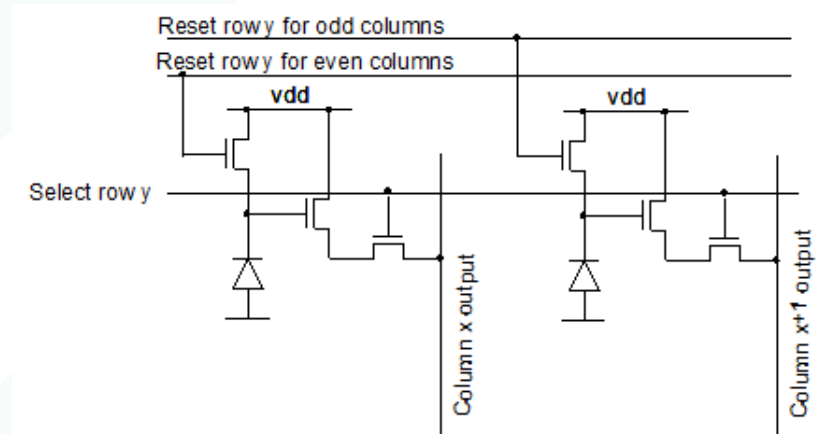
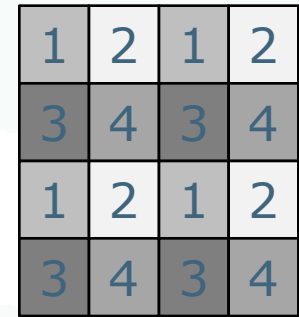
# Red-Green-Blue-White

- RGBW color filter (Kodak, Toshiba)
- White pixel:
  - 3x more light
  - Used at low light levels
- no control (fixed ratio between W &G)
- Crosstalk : more charges generated under W, part may diffuse to RGB
- Angular response effects (non-perpendicular light)
- Other alternatives
  - RGB+ "teal" (ST)
  - RG1G2B (2 green)

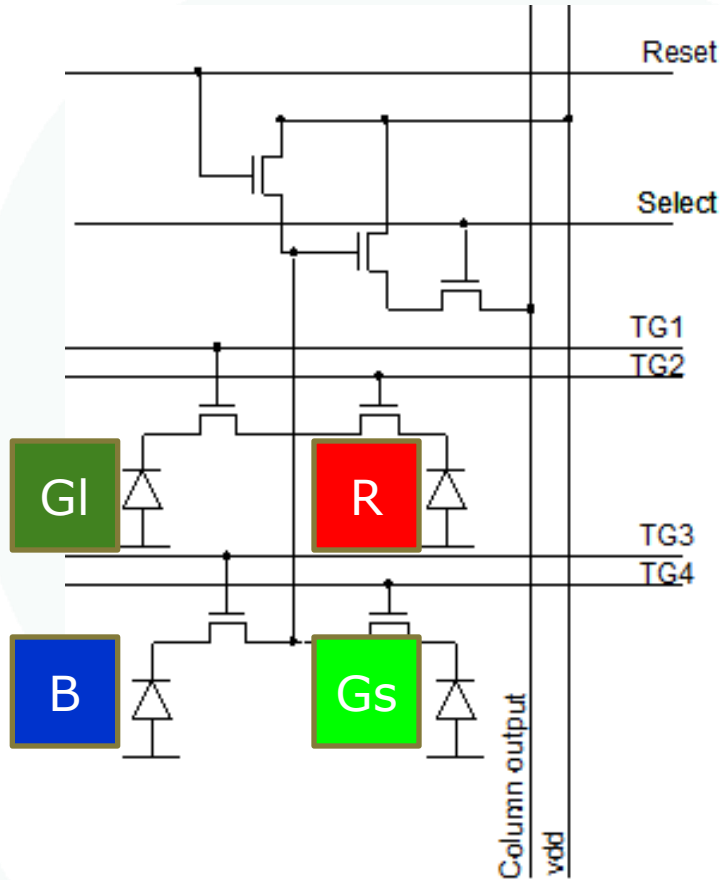


# Multiple exposure pattern

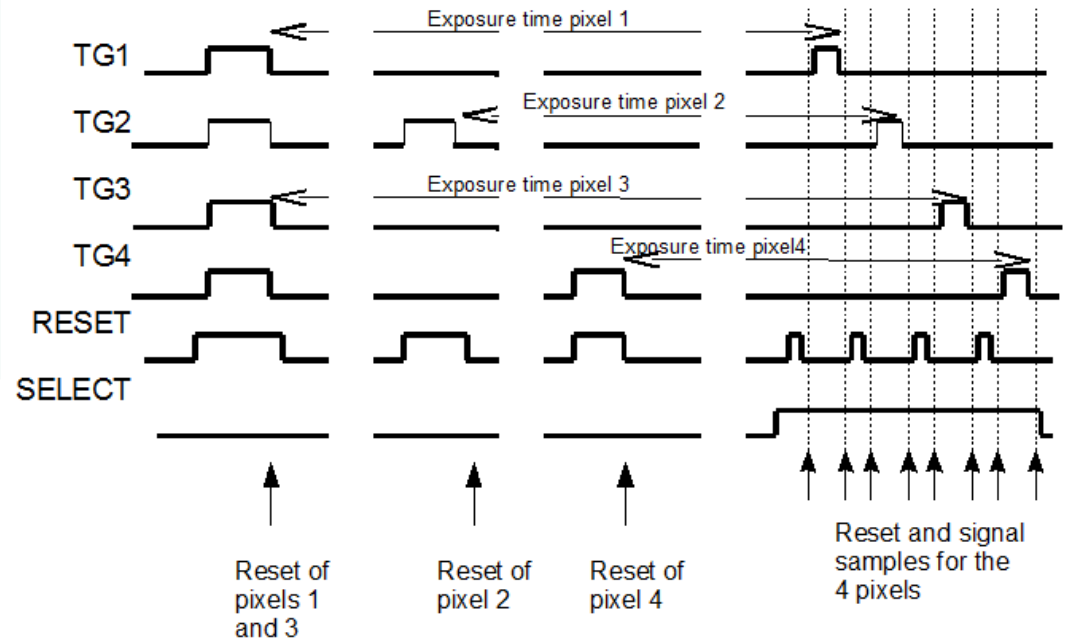
- Pattern of pixels with exposure time
- Combined with Bayer pattern:
  - Green1 : short exposure time ( $G_s$ )
  - Green2 : long exposure time ( $G_l$ )
  - Red/Blue: medium exposure time
- Examples
  - Separate reset or transfer line for odd/even columns
  - Different exposure times for odd/even rows (no extra control lines)
  - Shared 4T pixels



# Multiple exposure pattern in s4T



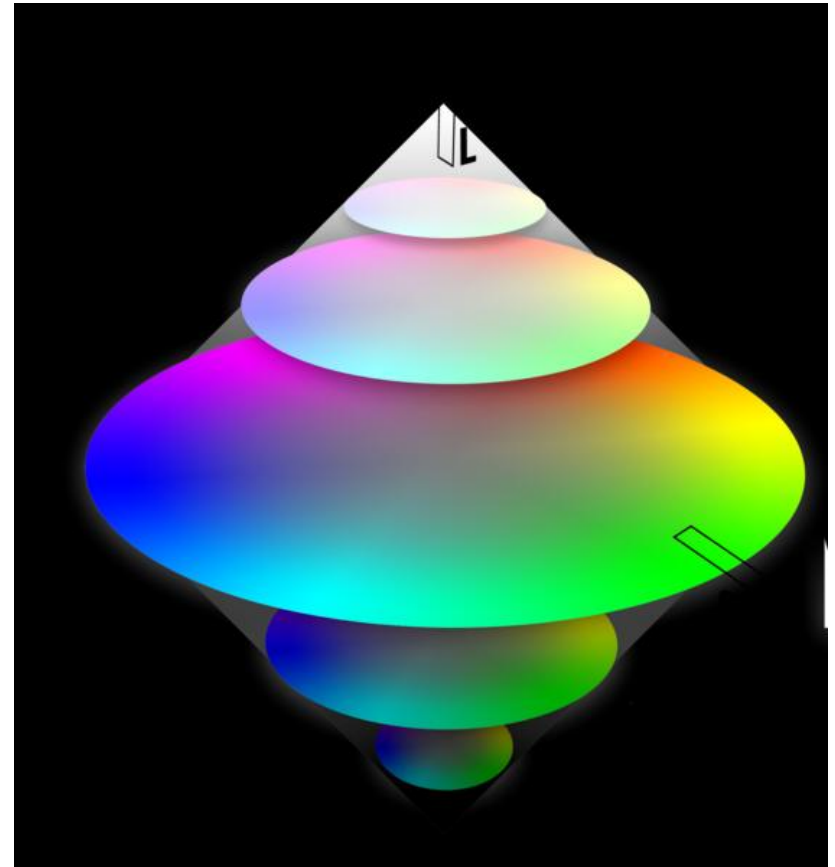
- Transfer gate control lines TG1, TG2, TG3, TG4 control exposure times individually in 2x2 block
- No extra control lines required in pixel



# Color reconstruction with $RG_1G_sB$



- In HSL space
  - Lightness -> mainly from G ( $G_1$  &  $G_s$ )
  - Hue/Saturation from R & B / G
  - For dark/bright: lower accuracy required for Hue & saturation



# Wrap up

- Dynamic range is important
  - Big consequence on imaging performance of camera
- Operating conditions must be considered
  - Dark current (-> Temperature)
  - Non-uniformity
- A whole set of methods exist to increase dynamic range
  - Each have their trade-offs
  - Choice depends on application
- Some limitations are there *in any case*
  - Motion blur
    - Limits longest exposure time
    - = limited extension of DR to the dark side for particular imaging situation.
  - Read noise
    - Improvements: pinned photodiode pixels, buried channel source followers.
    - Concerns: increased leakage in advanced CMOS.
  - Max. voltage swing
    - Which is a challenge in very advanced CMOS technologies

# Thank you

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