UiO : Department of Informatics
University of Oslo

IN5350 – CMOS image sensor design

Lecture 7 – High Dynamic Range CIS

29-September-2020

Agenda

- Project milestone status
- Takeaways from previous lecture&exercises
- HDR image capture

Project schedule

	Task/milestone	Start	Finish
✓	Chose topic/scope	1-Sep	8-Sep
✓	Create project plan (tasks, milestones, schedule)	8-Sep	15-Sep
✓	**MS1 – project plan approved by Johannes**	15-Sep	22-Sep
✓	Study literature on the topic	22-Sep	29-Sep
	Design/simulation	**29-Sep**	**13-Oct**
	Write up prelim report (inc references, design, results)	13-Oct	20-Oct
	MS2 – submit preliminary report to Johannes	20-Oct	20-Oct
	Design/simulation	20-Oct	27-Oct
	Write up final report (incl references, design, results)	27-Oct	3-Nov
	MS3 – submit final report to Johannes & presentation	3-Nov	3-Nov
	MS4 – grading (pass/fail) by Johannes & Tohid	10-Nov	10-Nov
	Exam	18-Nov 2020	

Lecture 7 – High dynamic range capture techniques overview

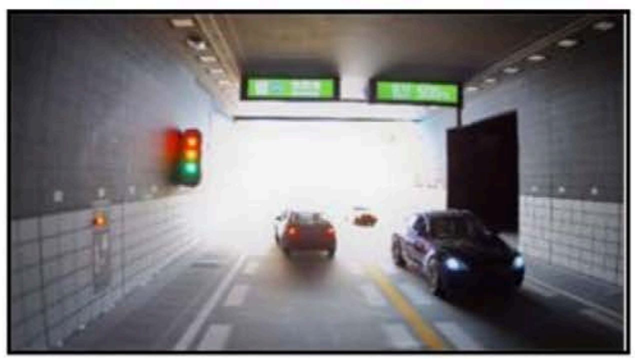
- Motivation
- Define DR
- Dual exposure HDR
- Skimming HDR (a.k.a. Lateral-Overflow HDR)
- Down sampling HDR
- Split-diode pixel HDR
- Dual conversion gain HDR (a.k.a. DCG HDR)

HDR in automotive

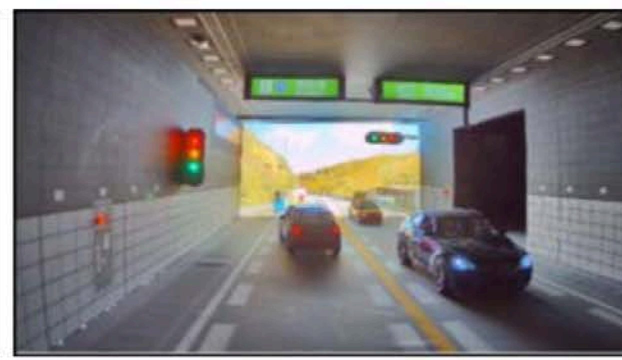
- Imaging terminology
  - *Linear sensor*: 8b to 12b output from single capture
  - *HDR sensor*: up to 24b output from multiple captures

Linear (Tint short)

Linear (Tint long)



HDR capture

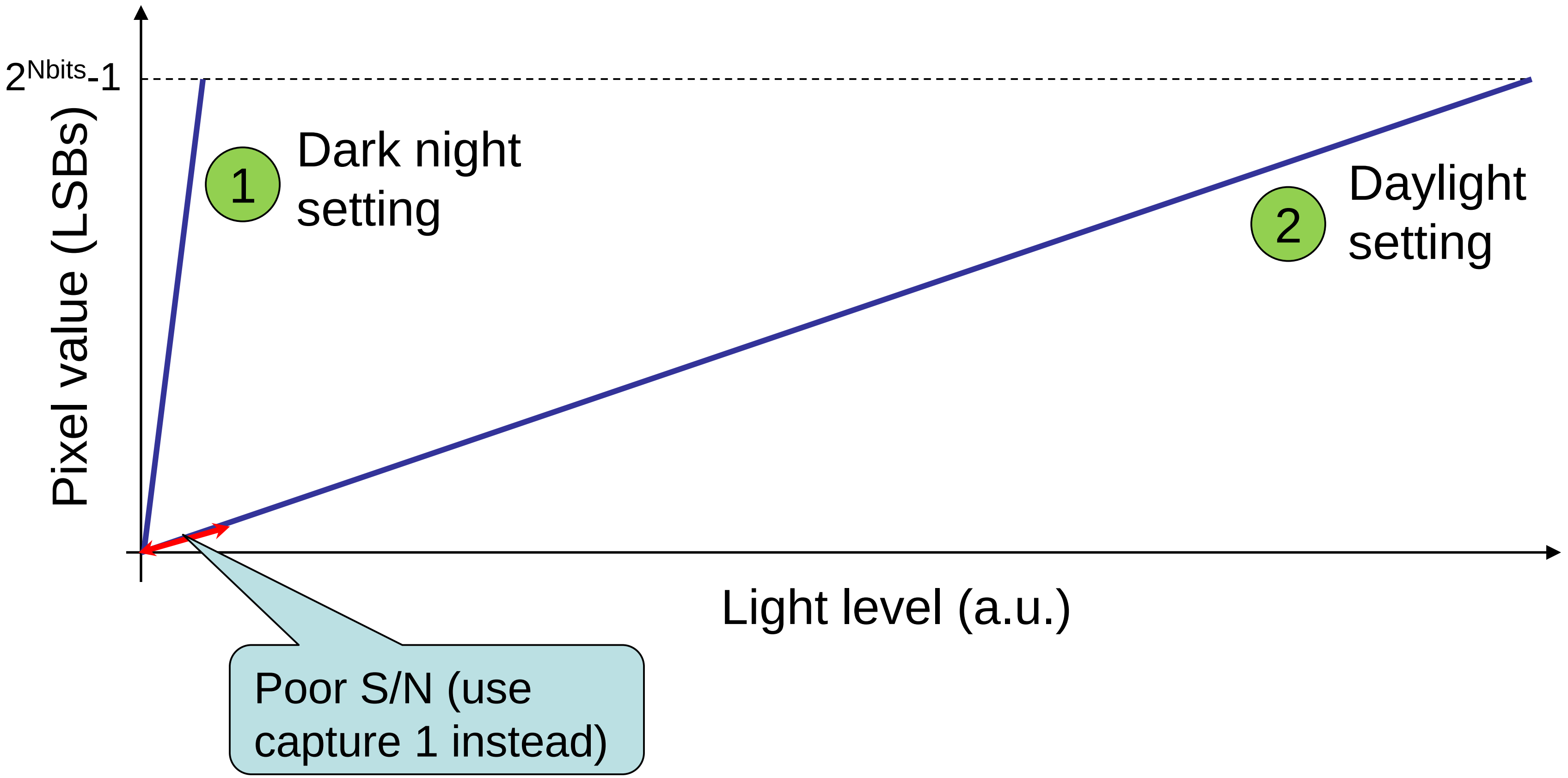


Source: Sony, IISW'19

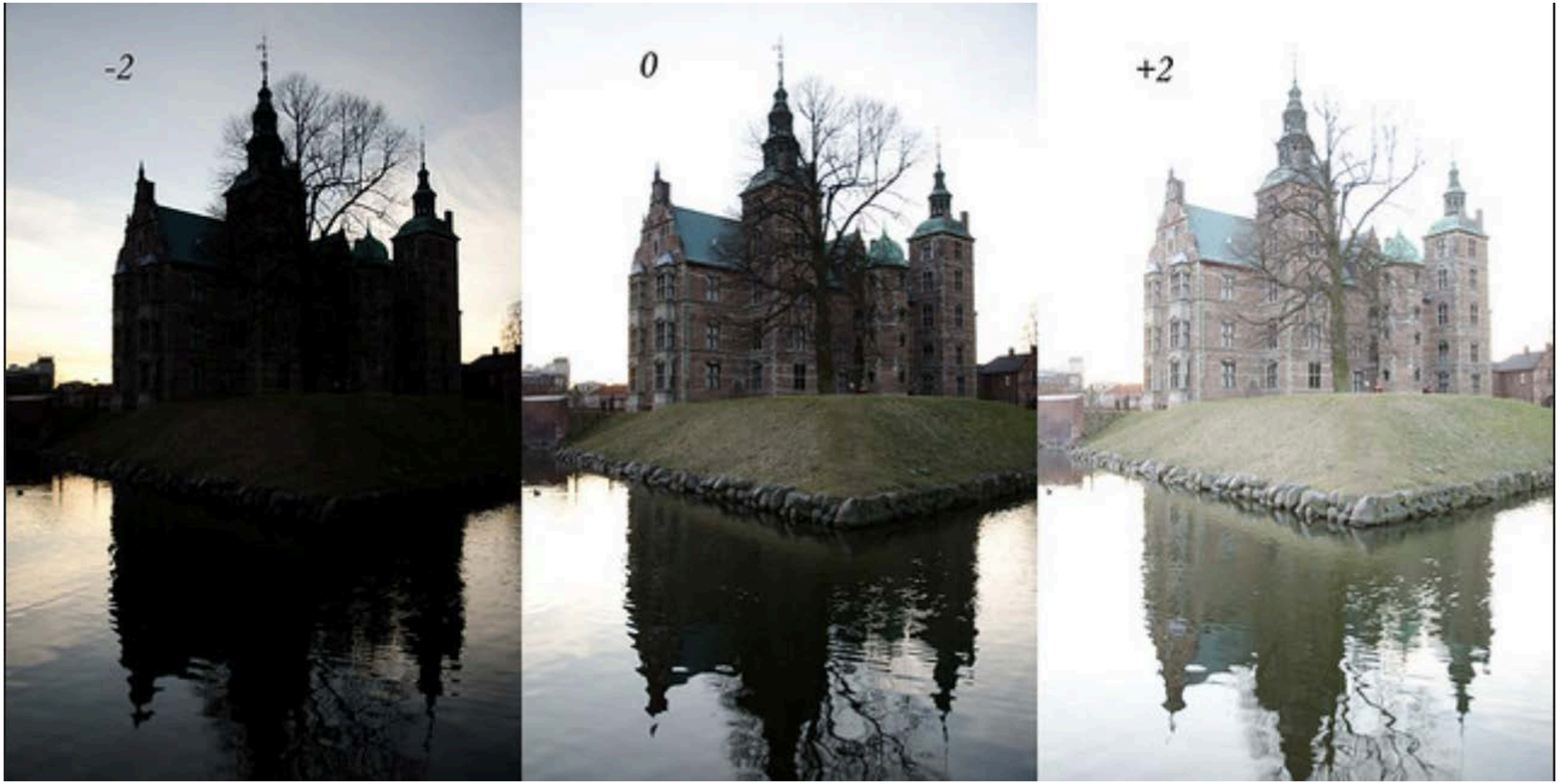

SDR
HDR

Linear sensor

- 8b to 12b output from single capture



Linear sensor



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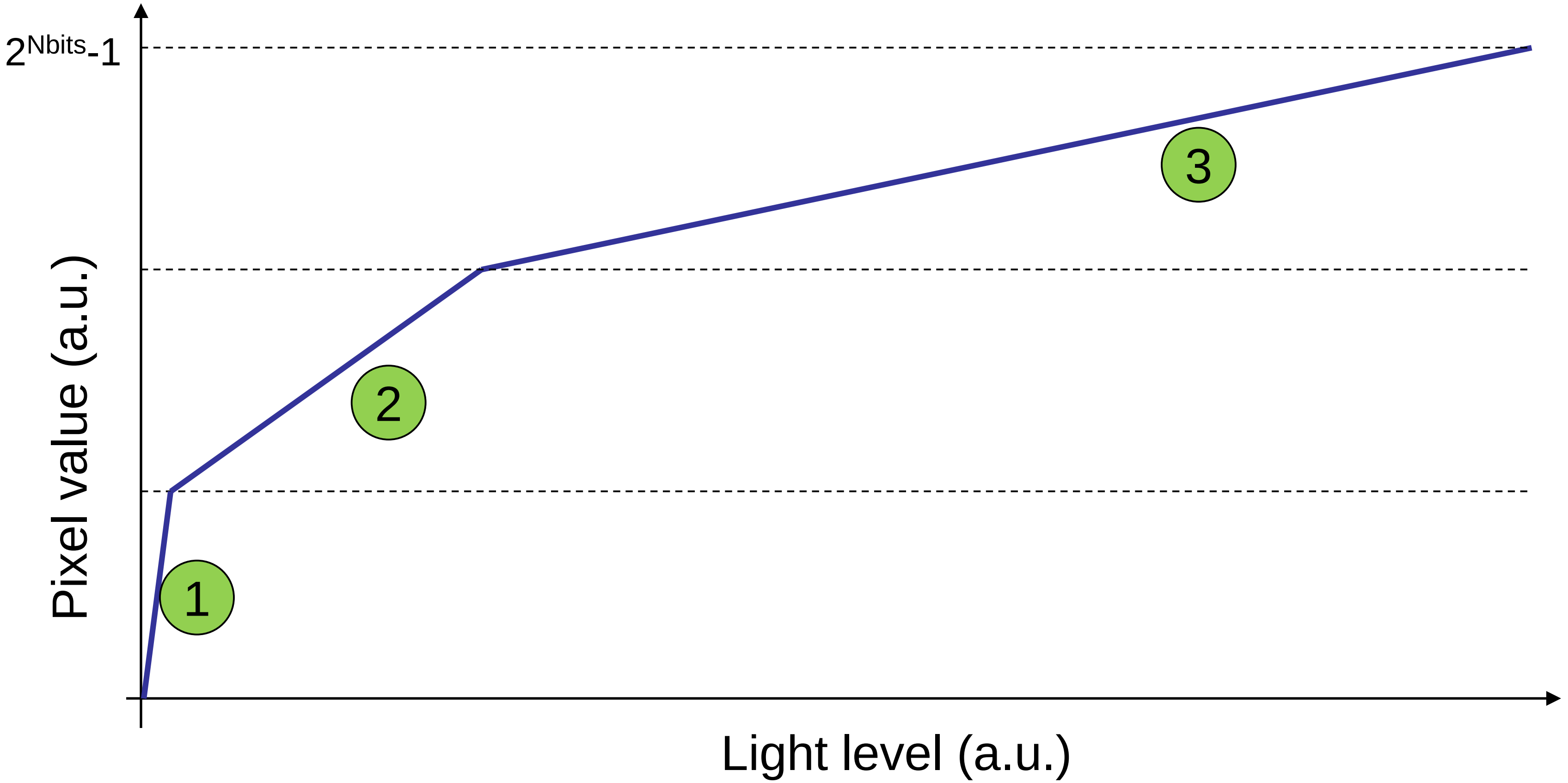
HDR sensor

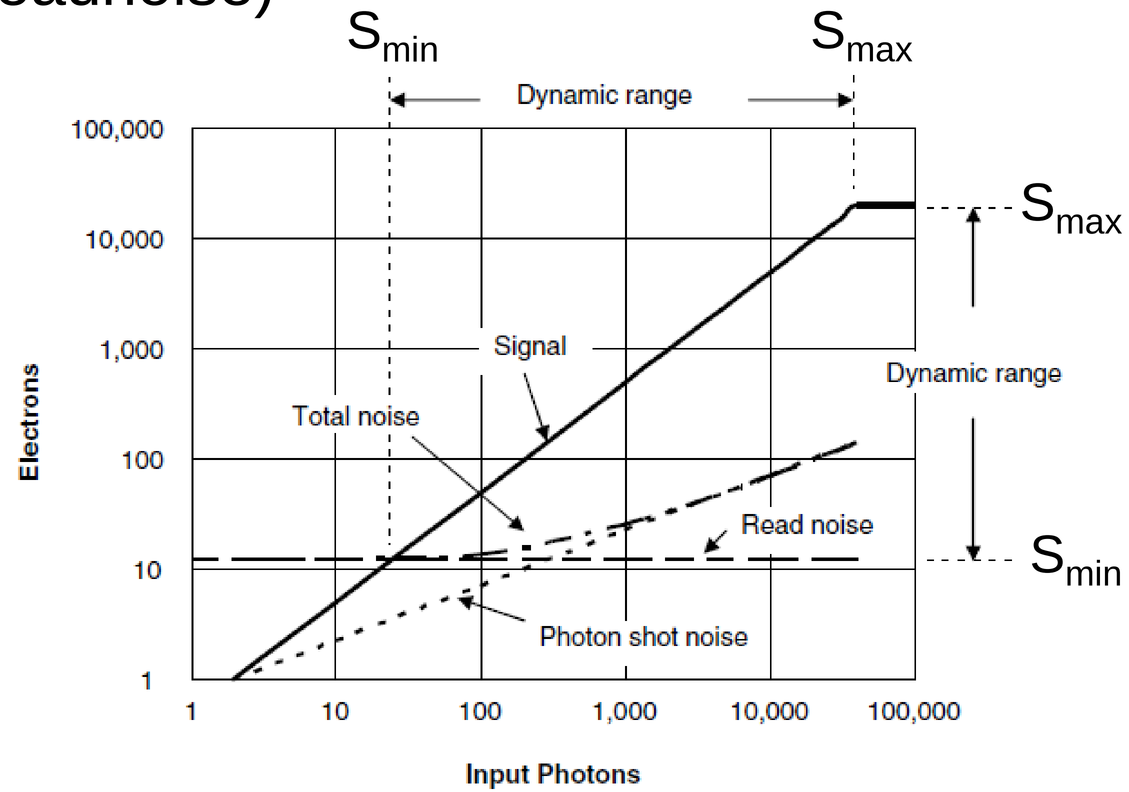
- Up to 24b output from multiple captures combined



HDR sensor after combine&processing

Dynamic Range for Image Sensors

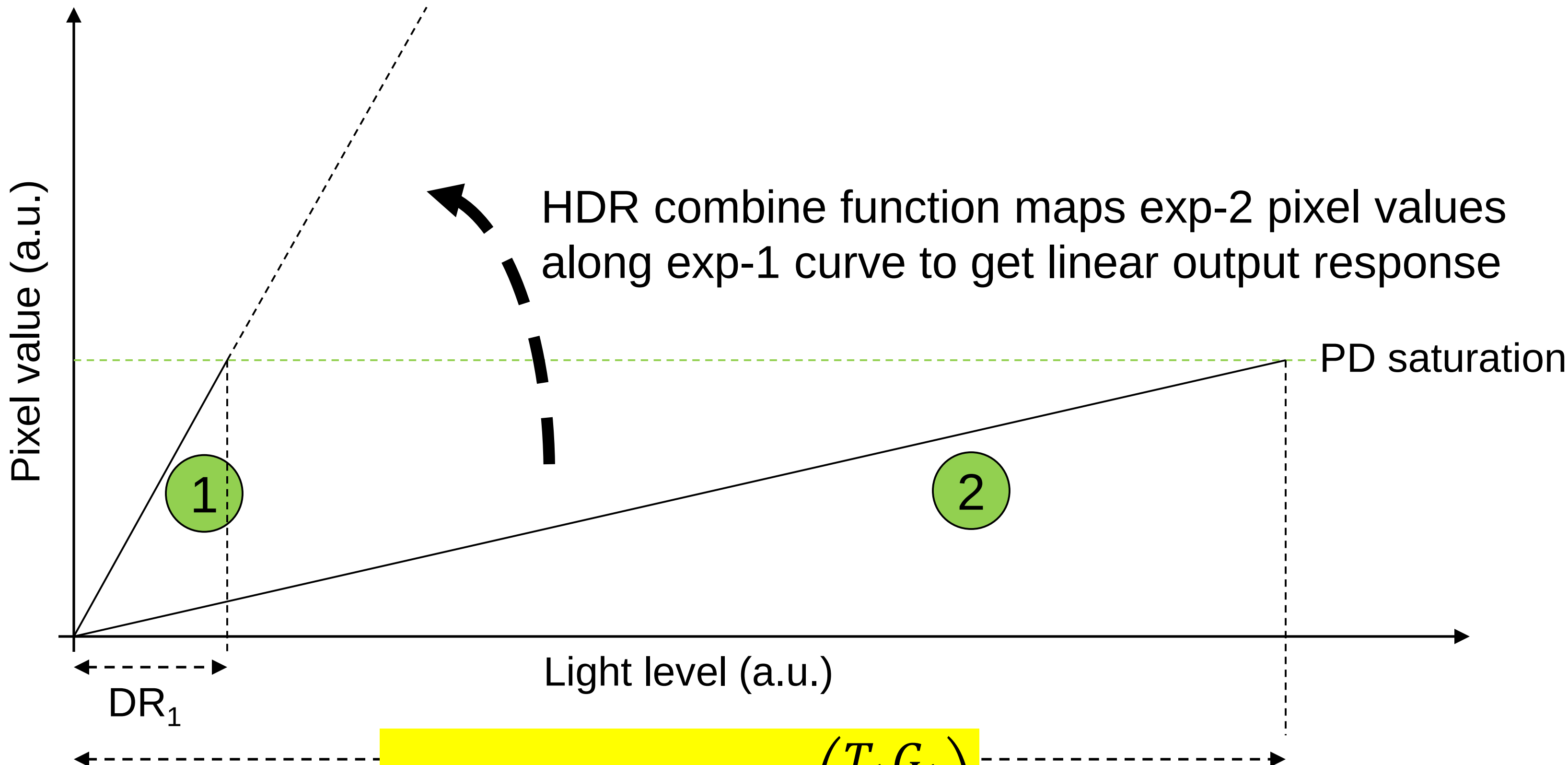
- $DR \stackrel{\text{def}}{=} 20log\left({}^{S_{max}}/_{S_{min}}\right)$
- S_{min} defined to be equal to the noise floor at zero light (a.k.a. readnoise)



Remark about DR for image sensors

- $S_{min} \stackrel{\text{def}}{=}$ signal level at which S/N=1
  - Common to ignore photon shot noise and simply set S_{min}=RN
  - Strictly speaking this is only true for large RN. Here is why:
  - SNR=1 when S_{min}=rms noise value
  - In electron domain this means $S_{min} = \sqrt{(S_{min} + RN^2)}$
  - Solving for S_{min} gives $S_{min} = \frac{1+\sqrt{1+4RN^2}}{2}$
  - Hence, S_{min}=RN for large RN (ie above 2e- rms)
  - Rem: modern image sensors have RN≅1e- rms..

Dual exposure HDR concept



$$DR = DR_1 + 20log\left(\frac{T_1G_1}{T_2G_2}\right)$$

T_1, T_2: integration time (T_1 is long, T_2 is short)
G_1, G_2: total gain in readout chain (LSBs per electron)

Dual exposure with Staggered readout

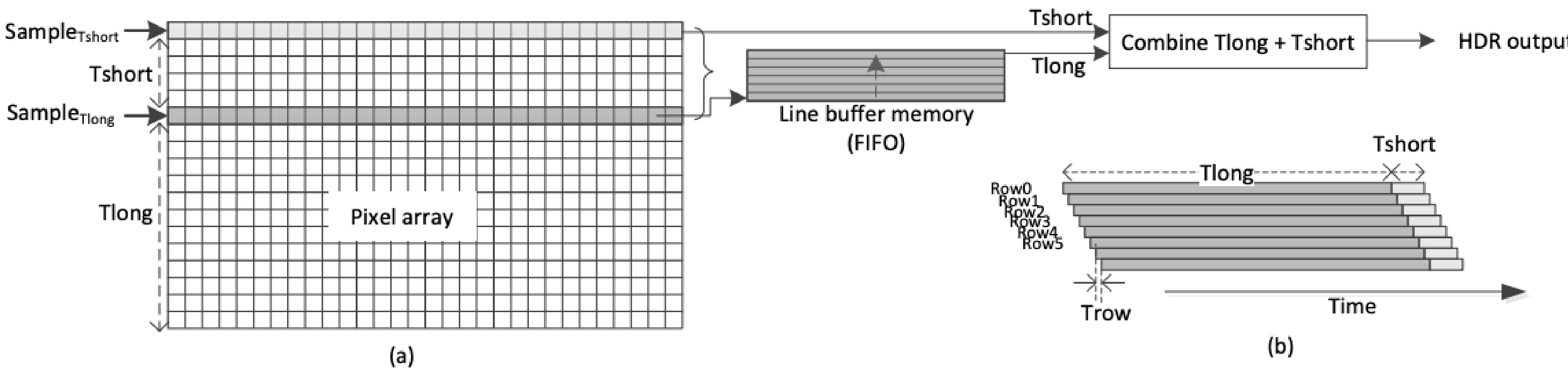


Fig. 2 Illustration of (a) staggered HDR concept and (b) timing diagram of each rows exposure periods

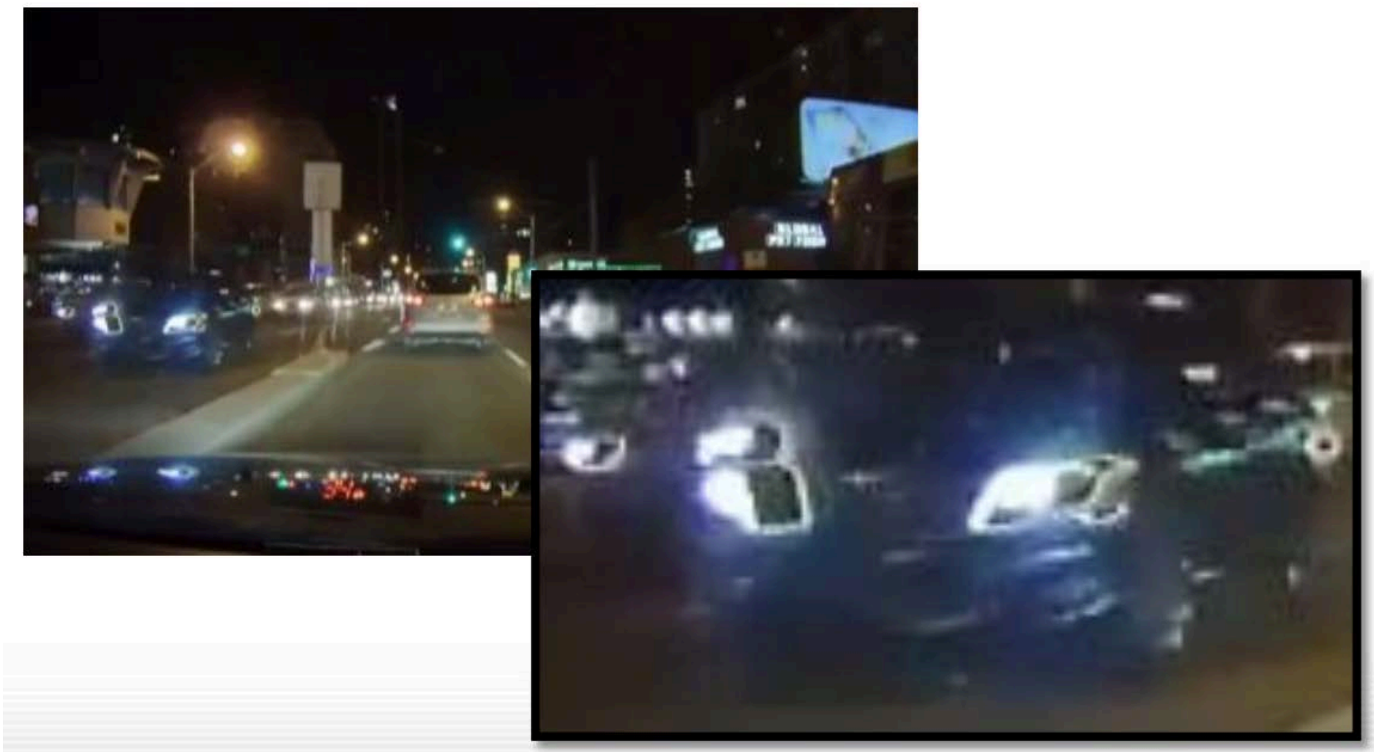
- Two readout pointers running in parallel (Tlong and Tshort)
- Line memory used as FIFO to delay processing of Tlong pixel values until they can be combined with Tshort values from same pixel row and produce linear HDR value
- Delay between Tlong and Tshort => motion artifacts
  - More details here: Solhusvik, IISW'13

Staggered dual exposure remarks

- If analogue gain is applied in the readout chain, then the full DR of the photodiode is not utilized
- For instance, 8x analog gain reduces full-well capacity (FWC) by 8x
- Therefore, Tshort capture is usually with 1x gain and Tlong with 2x-16x depending on application
- Significant SNR drop at the Tlong/Tshort transition point (a.k.a. knee-point), especially at large exposure ratios

HDR motion artefact

- Time-multiplexed staggered HDR scheme introduces motion artifacts (“ghosting”) due to motion in scene, as objects are in different position for each capture



Skimming (lateral overflow) HDR concept

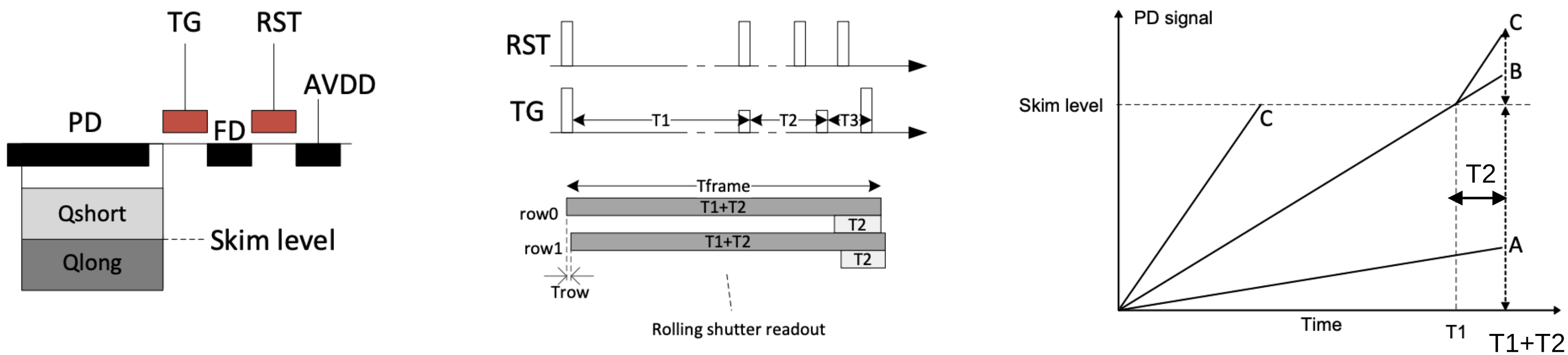


Fig. 1 Illustration of Skimming HDR (Lateral-Overflow) approach

- At T1, TG is pulsed with reduced amplitude to 'skim' (remove) any charge above 50% of FWC
- DR = DR_1 + 20log((T1+T2)/T2), where DR_1 is for capture A
  - Assumes same gain in both captures
- No need for line memory (smaller chip, lower power)
  - More details here: Solhusvik, IISW'13

Skimming (Lateral-Ovflw) HDR remarks

- Sensitive to Vth variations on TG device
  - Leads to pixel-to-pixel variations of skimming level (source of FPN)
  - Possible to measure and compensate for Vth spread by ‘flushing’ PD with electrons, then skimming pulse, then reading out the remaining charge which equals the skimming level

Down sampling HDR

- Trade off optical (array) resolution to achieve HDR
- Combine neighbouring pixels with different Tint
  - T1/T2 represent long/short integration times

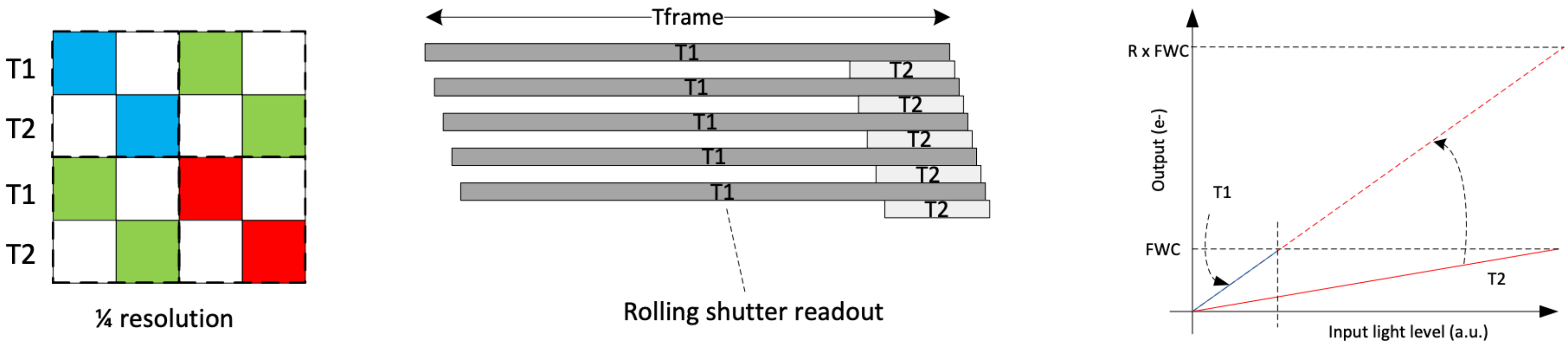
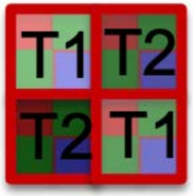


Fig. 3 Down-sampling HDR concept with RGBC CFA pattern for increased sensitivity

- Above example uses RGBC CFA for improved sensitivity
  - RGBC is not unique for down-sampling HDR sensors
  - Equally applicable to other sensors for improved sensitivity

Down sampling HDR remarks



- Similar to staggered HDR, but only requires one line buffer (small chip size, low power)
- Trade off on resolution often not observable since even HDTV monitors (2Mpixels) have much lower resolution than most consumer imagers (8-80Mpixels)
- Possible to further increase DR with for instance T1, T2, T3, T4 of four neighbouring pixels

Split-diode pixel HDR

- One small PD (SPD) and one large PD (LPD) in each pixel
- SPD used to capture bright parts of the scene

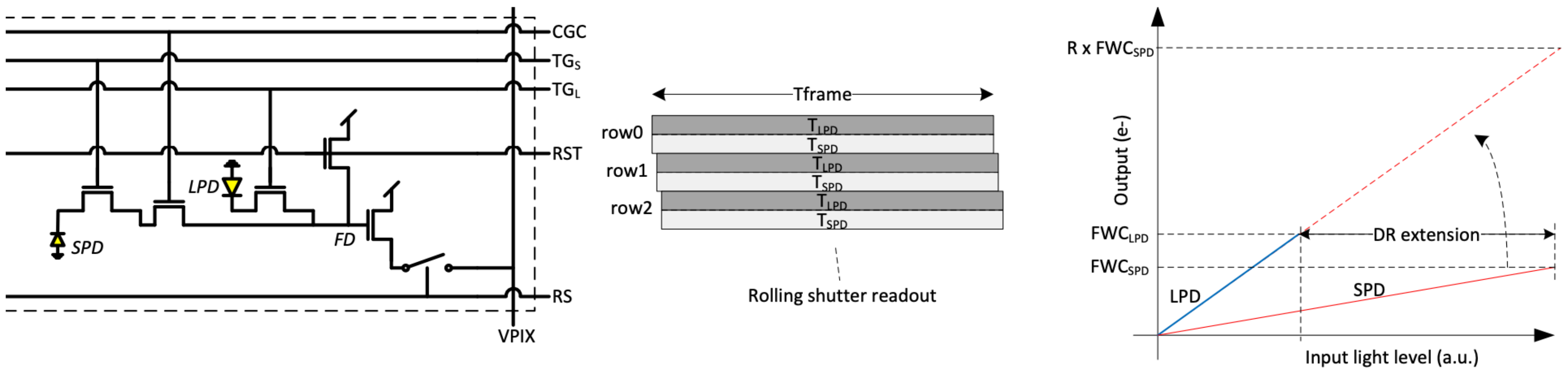
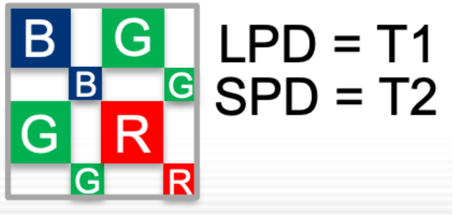


Fig. 4 Example of split-diode pixel architecture and timing

- If $T_{LPD}=T_{SPD}$ then motion artefacts if mitigated (ref: the other HDR methods)

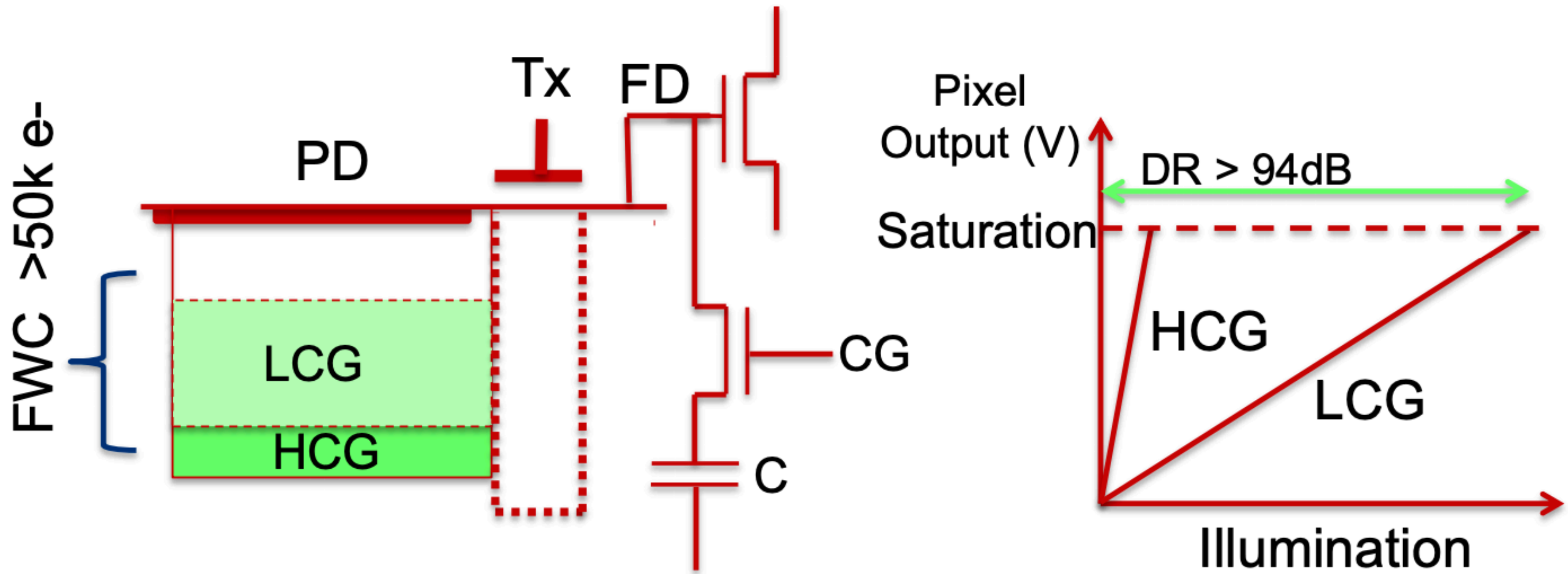
Split-diode HDR remarks



- Trades off pixel sensitivity to get HDR with minimum motion artifacts
- Complex architecture, difficult to scale below say 2um
- Challenging to obtain identical QE curve for both LPD and SPD
- Alternative approach, use 2x2 pixel cluster and reduce sensitivity of one of them, and combine the other there together into one large PD

Dual conversion gain HDR

- One single capture (Tint). Read out PD charge with high CG (low light) and low CG (high light).



- DR = 20log(FWC_{LCG} / RN_{HCG})

DCG HDR remarks

- One single integration => no motion artifacts
- DR limited to about 96dB (60ke-/1e-) which is smaller than Tlong/Tshort HDR schemes
- Often combined with other HDR schemes such as split-diode, multi-exposure, etc
- Requires pixels with large FWC which is challenging w.r.t. dark current and charge lag from PD to FD node

Thanks!