Lecture Notes 8

SNR and Dynamic Range

- Image Sensor Model
- SNR
- Dynamic Range
- High Dynamic Range Extension Schemes
  - Well Capacity Adjusting
  - Multiple Capture
  - Time-to-Saturation
  - Synchronous Self-Reset

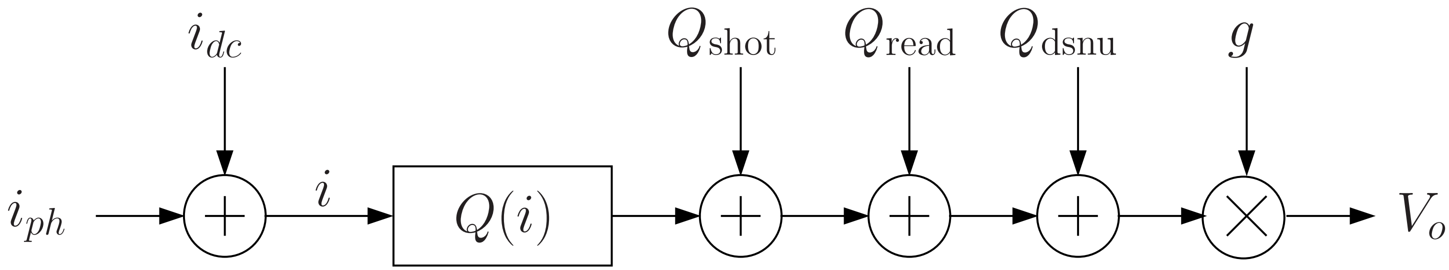
Introduction

- SNR and dynamic range are very important figures of merit for image sensors – highly related to image quality
- Image sensor dynamic range (especially CMOS) is not high enough to achieve film quality
- Several schemes have been proposed to extend dynamic range
- The plan is to:
  - Use the signal and noise models we developed to define SNR and dynamic range
  - Discuss the dependency of SNR and dynamic range on various sensor parameters
  - Describe several image sensor dynamic extension schemes
  - Show how these schemes can be compared based on their SNR

Image Sensor Signal and Noise Model

- We treat i_{ph} as the input *signal* and assume that it doesn't change during integration (due to change in QE or image blur)

- The sensor model assuming CDS is performed and ignoring PRNU is as follows:



- The *current to charge transfer function* Q is given by

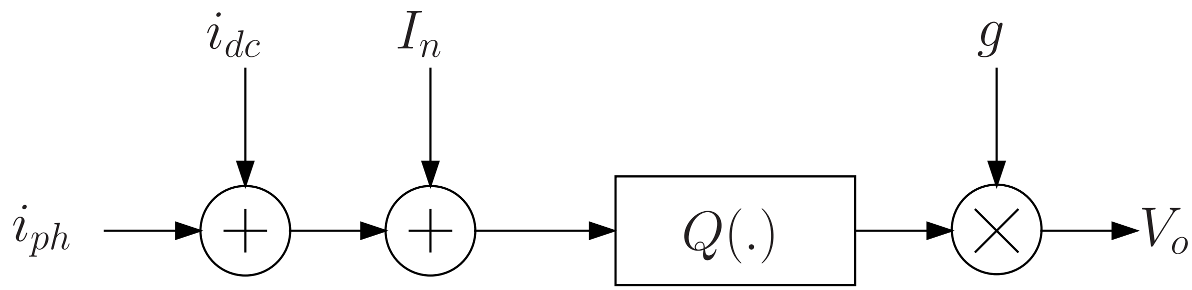
$$Q(i) = \begin{cases} \frac{1}{q}(it_{int}) \text{ electrons}, & \text{for } 0 < i < \frac{qQ_{max}}{t_{int}} \\ Q_{max} \text{ electrons}, & \text{for } i \geq \frac{qQ_{max}}{t_{int}} \end{cases}$$

So, it is *linear* up to saturation

- Q_{shot} is the r.v. representing the noise charge due to integration (photodetector shot noise) and is Gaussian with zero mean and variance $\frac{1}{q}(i_{ph} + i_{dc})t_{int}$ electrons^2
- Q_{read} is the r.v. representing the read noise (noise due to reset, readout circuits and quantization) and has zero mean and standard deviation σ_{read} electrons
- Q_{dsnu} is the r.v. representing dsnu and is assumed to have zero mean and standard deviation $\sigma_{\text{dsnu}} = \sigma_{i_{dc}} t_{int}/q$ electrons
- Q_{shot}, Q_{read}, and Q_{dsnu} are independent.
- g is the sensor conversion gain in V/electron

Equivalent Input Referred Noise

- In some of the high dynamic range schemes, the photocurrent to charge is nonlinear
- So, to calculate SNR and dynamic range, we must use the input referred noise current (gain determined by the slope of the current to charge transfer function at the final output charge)



- I_n is zero mean and since $Q(.)$ is linear, the average power of the equivalent input referred noise r.v. I_n is given by

$$\sigma^2_{I_n} = \frac{q^2}{t^2_{int}} \left(\frac{1}{q}(i_{ph} + i_{dc})t_{int} + \sigma^2_{\text{read}} + \sigma^2_{\text{dsnu}} \right) \ \text{A}^2$$

Note that since $\sigma_{\text{dsnu}} = \frac{1}{q} t_{int} \sigma_{i_{dc}}$, the contribution of DSNU is simply $\sigma^2_{i_{dc}}$

Signal to Noise Ratio (SNR)

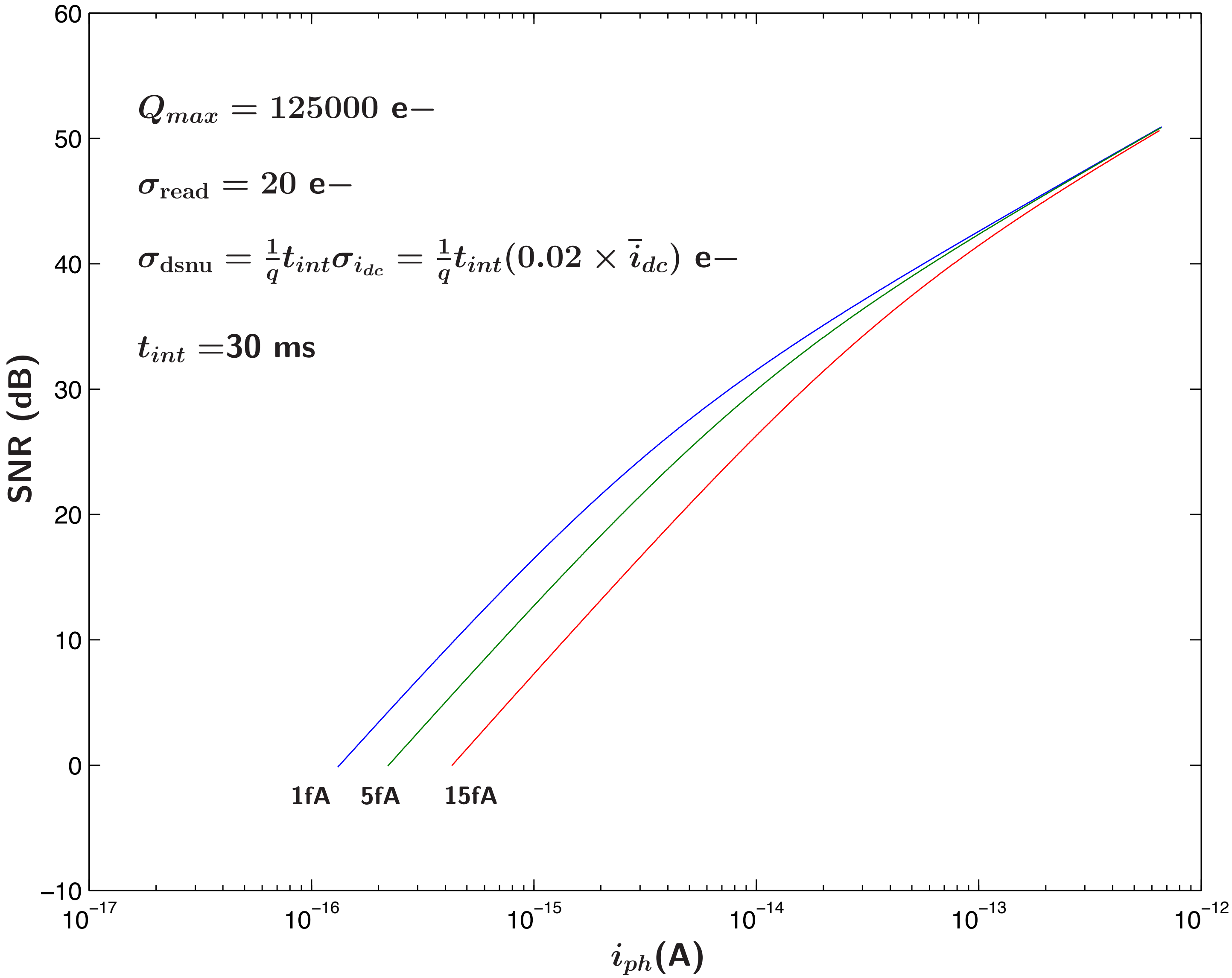
- SNR is a measure of the pixel signal fidelity. It tells us how small of a signal difference (spatially or temporally) we can distinguish
- It is defined as the ratio of the input signal power to the input referred noise power, and is a function of input signal i_{ph}

$$\text{SNR}(i_{ph}) = \frac{i_{ph}^2}{\frac{q^2}{t_{int}^2}\left(\frac{1}{q}(i_{ph}+i_{dc})t_{int} + \sigma^2_{\text{read}} + \sigma^2_{\text{dsnu}}\right)}$$

  It is typically measured in dBs
- SNR first increases with i_{ph} at 20dB per decade when read noise, dark current shot noise, and DSNU dominate, then at 10dB per decade when signal shot noise dominates
- SNR increases with t_{int} (increase limited by saturation and image blur)
- Dark current is detrimental to SNR at the low end
- Peak SNR occurs near saturation (i.e., when $i_{ph} \approx qQ_{max}/t_{int}$), thus

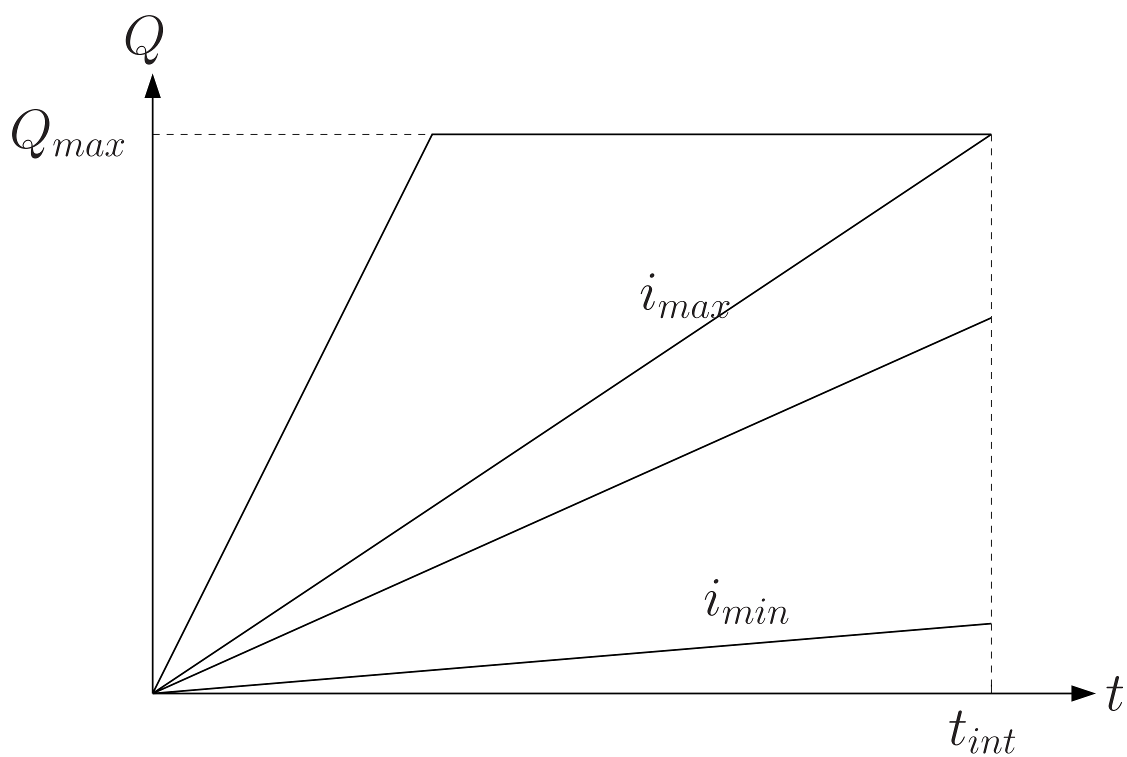
$$\text{SNR}_{peak} \approx Q_{max}$$

SNR Versus i_{ph} (for three i_{dc} values)



Dynamic Range (DR)

- Sensor dynamic range quantifies the ability of a sensor to adequately image both high lights and dark shadows in a scene
- It is defined as the ratio of the largest nonsaturating input signal (photocurrent) i_{max} to the smallest detectable input signal i_{min}



- The largest nonsaturating signal is given by

$$i_{max} = \frac{qQ_{max}}{t_{int}} - i_{dc} \approx \frac{qQ_{max}}{t_{int}},$$

  where Q_{max} is the (effective) well capacity

- The smallest detectable input signal is typically defined as the standard deviation of the input referred noise under dark conditions $\sigma_{I_n}(0)$ (the zero here refers to $i_{ph} = 0$), which gives

$$i_{min} = \frac{q}{t_{int}} \sqrt{\frac{1}{q} i_{dc} t_{int} + \sigma^2_{\text{read}} + \sigma^2_{\text{dsnu}}}$$

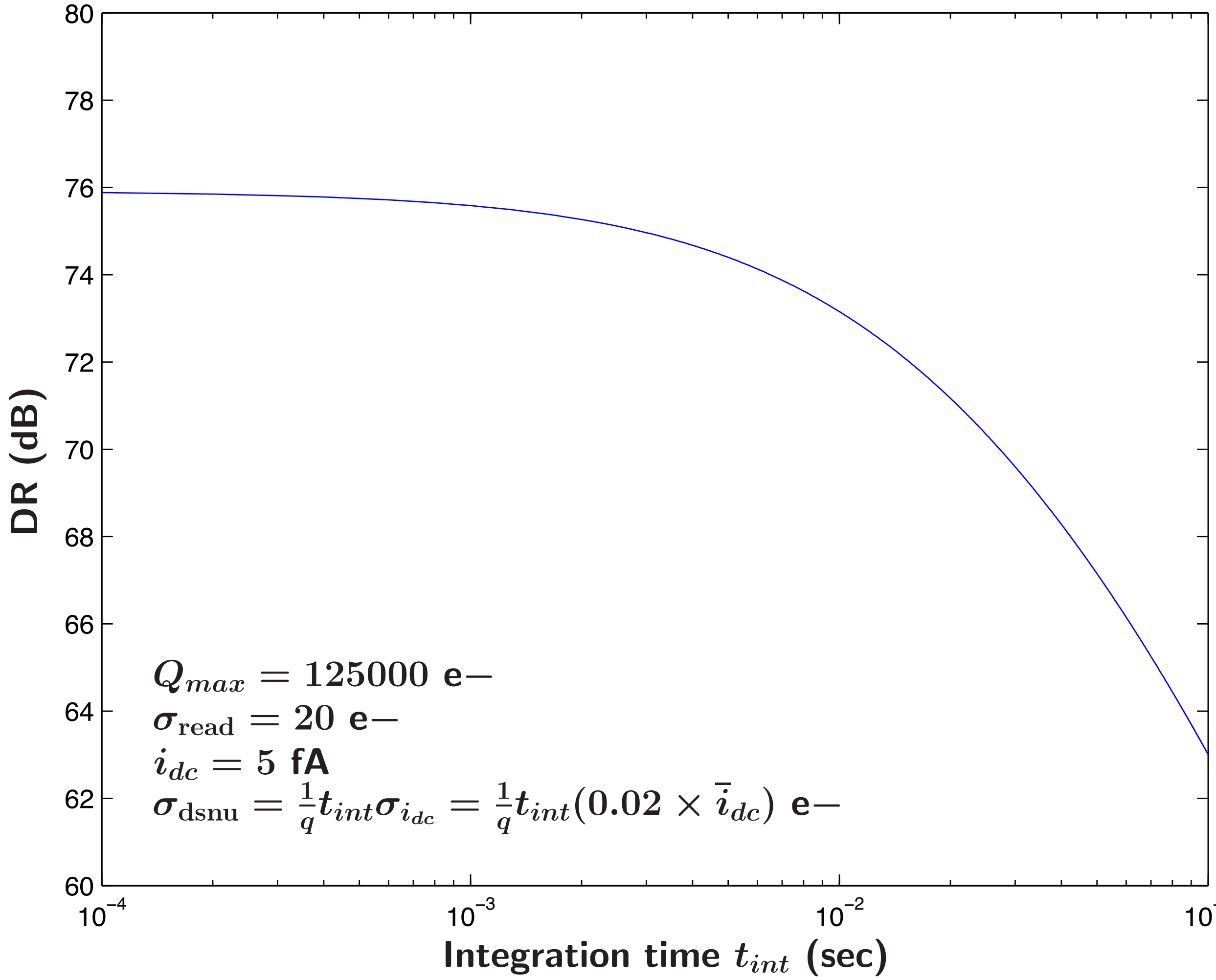
- Thus the dynamic range is given by

$$\text{DR} = \frac{i_{max}}{i_{min}} = \frac{\frac{qQ_{max}}{t_{int}} - i_{dc}}{\frac{q}{t_{int}} \sqrt{\frac{1}{q} i_{dc} t_{int} + \sigma^2_{\text{read}} + \sigma^2_{\text{dsnu}}}}$$

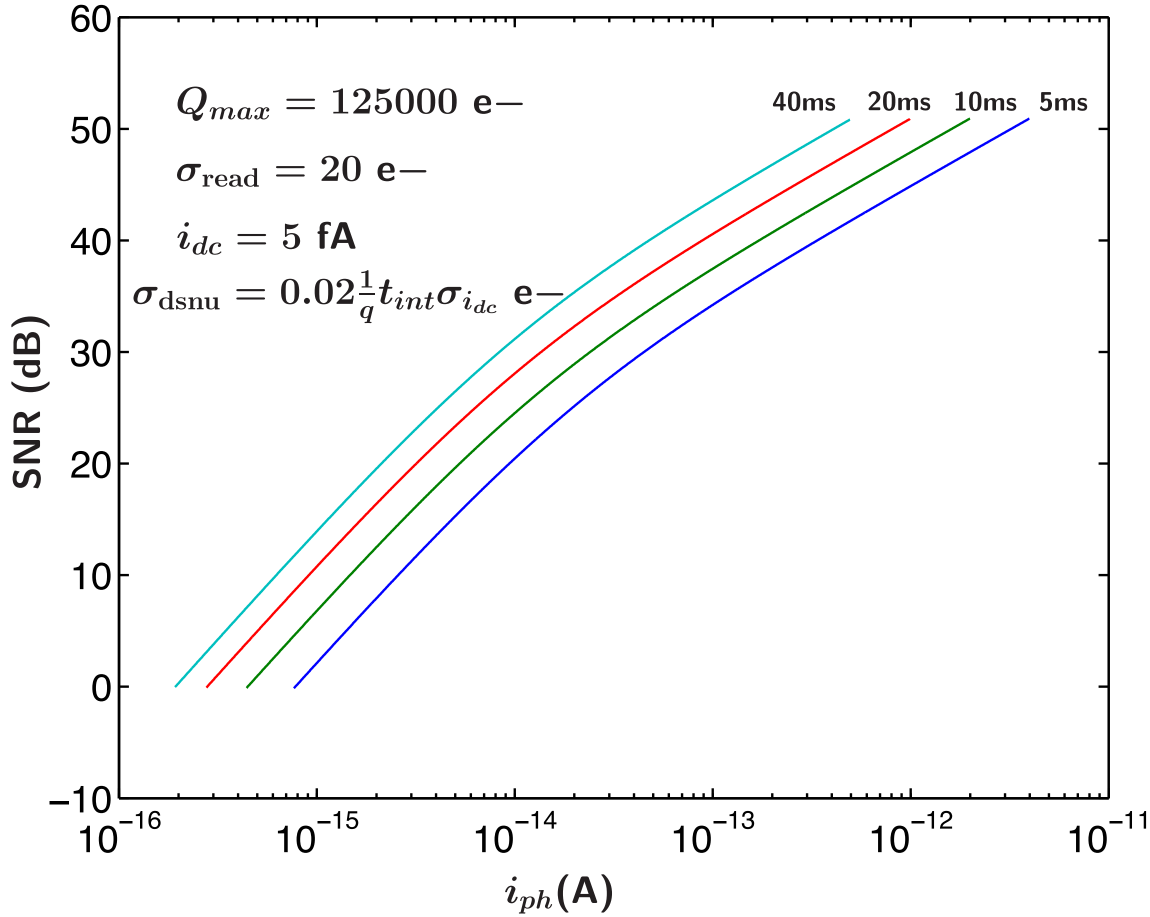
  It is measured in dBs ($20 \log_{10}(i_{max}/i_{min})$) and sometimes in bits

- DR increases with Q_{max}, and decreases with i_{dc}, read noise, and DSNU

Dynamic Range Versus Integration Time



SNR vs. i_{ph} for Different Integration Times



Conclusion: shuttering attempts to match the sensor dynamic range to the scene range of illumination

Image Sensor Dynamic Range is Not Wide Enough

- Natural scenes can have dynamic range $> 10^5$ (100dB)
- Scenes with even higher DR can be encountered in industrial and tactical applications
- Dynamic range of image capture devices:

Human eye dynamic range	around 90dB
Film	80dB
High end CCDs	> 78dB
Consumer grade CCD	66dB
Consumer grade CMOS sensors	54dB

- So except for high end CCDs, image sensors have lower dynamic range than film and the human eye
- Many scenes have higher DR than conventional image sensors

Scene DR > Image Sensor DR

78dB scene

image using DR=48dB sensor at $t_{int}/16$

Image using DR=48dB sensor at $t_{int}/4$

Image using DR=48dB sensor at t_{int}

Extending Image Sensor Dynamic Range

- To increase dynamic range we need to increase i_{max} and/or decrease i_{min}
- $i_{max} \approx \frac{qQ_{max}}{t_{int}}$, so it can be increased by shortening integration time and/or increasing well capacity
  - Shortening integration time of all pixels, however, only shifts DR to the right
  - Increasing Q_{max} requires larger capacitance/voltage swing
- $i_{min} = \sqrt{\frac{q}{t_{int}} i_{dc} + \left(\frac{q\sigma_{\text{read}}}{t_{int}}\right)^2 + \left(\frac{q\sigma_{\text{dsnu}}}{t_{int}}\right)^2}$, so it can be decreased by lengthening integration time, decreasing DSNU, and/or decreasing read noise
  - Lengthening integration time of all pixels only shifts DR to the left
  - Decreasing DSNU and read noise require improvements in fabrication technology and more careful circuit design

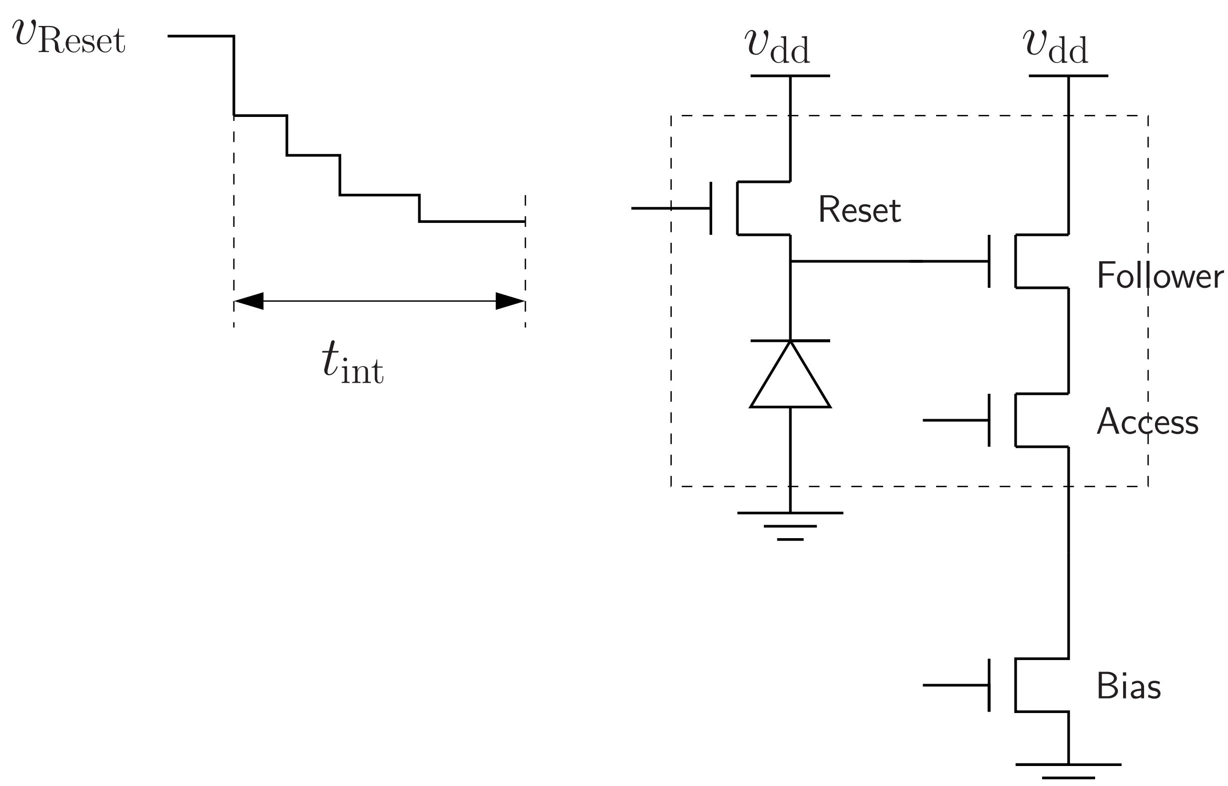
- Several schemes have been developed to extend DR
- Most of these schemes extend DR only at the high end, i.e., increase i_{max}:
  - By spatially 'adapting' pixel integration times to illumination; shorter integration times for pixels with high illumination and longer integration times for pixels with low illumination
  - Or, by increasing the effective well capacity through well recycling, i.e., resetting the well and keeping track of the number of resets
- Most of these schemes require per pixel processing, e.g., more complex analog front end or ADC
- Deep submicron technology and 3D intergation through wafer stacking is make these schemes more practical

Outline

- We first discuss two schemes that increase dynamic range by spatially 'adapting' pixel integration times
  - Well-capacity adjusting
  - Multiple capture
- We evaluate SNR over their extended DR and discuss each scheme's pros and cons
- We then briefly discuss two other schemes:
  - Time-to-saturation, where again DR is extending by adapting integration time to signal values, and
  - Synchronous self-reset with residue readout, where DR is extended by increasing the effective well capacity through well recycling
- More details and discussion of these schemes and others can be found in [1-3]

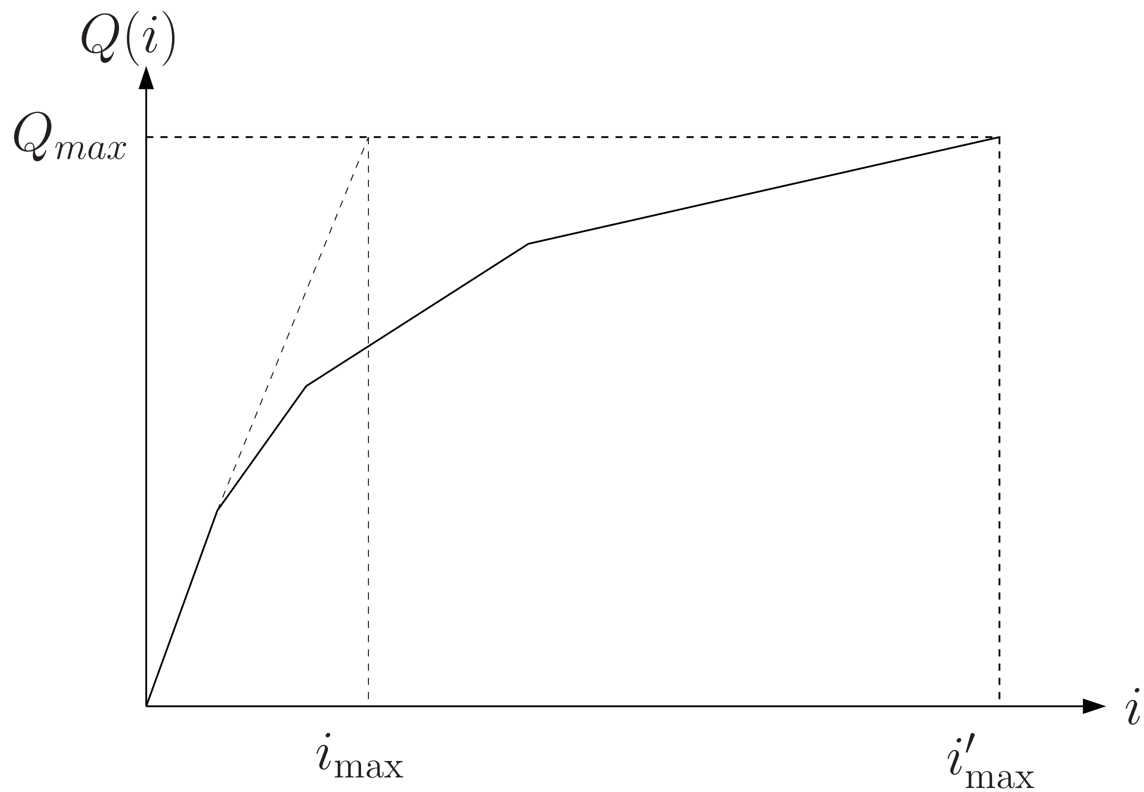
Well Capacity Adjusting

- Available well capacity is increased one or more times during integration (idea initially applied to CCDs [4,5] using Lateral Overflow Gate)
- For APS this is done by adjusting the reset signal one or more times during integration [6]:



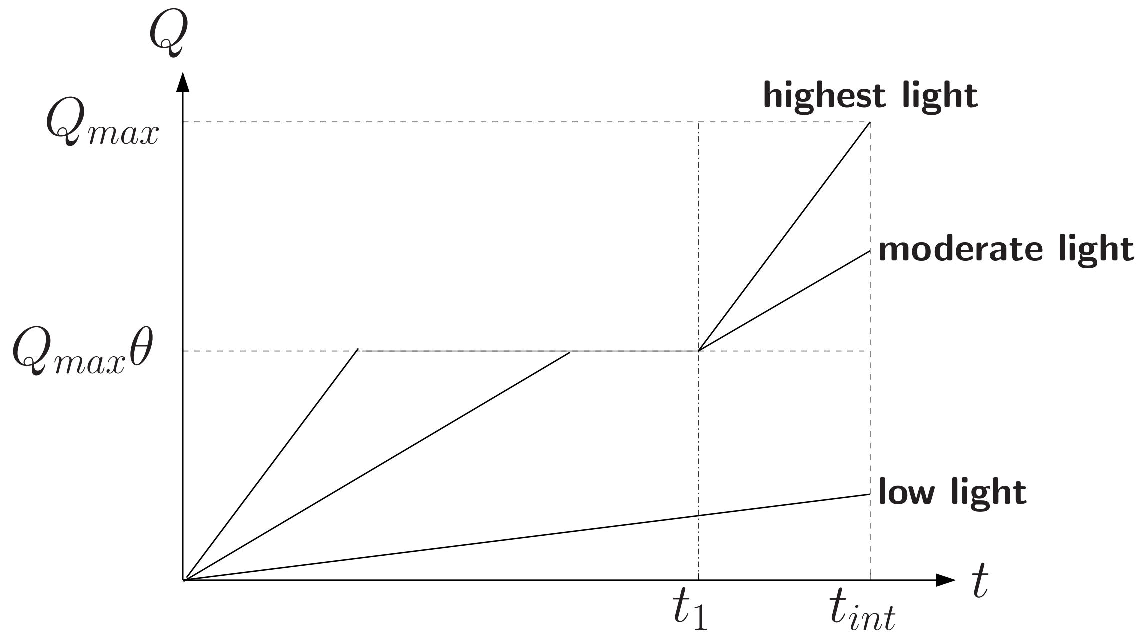
Sensor Transfer Function

- The current to charge transfer function is compressed resulting in higher maximum nonsaturating current i'_{max}:



DR for Well Capacity Adjusting

- We only discuss the case of a single well capacity adjustment. Here well capacity is first set to $Q_{max}\theta$, where $0 < \theta < 1$ from $t = 0$ to $t = t_1$, and then increased to Q_{max} for the rest of the integration time



- The largest nonsaturating current (ignoring dark current) is now given by

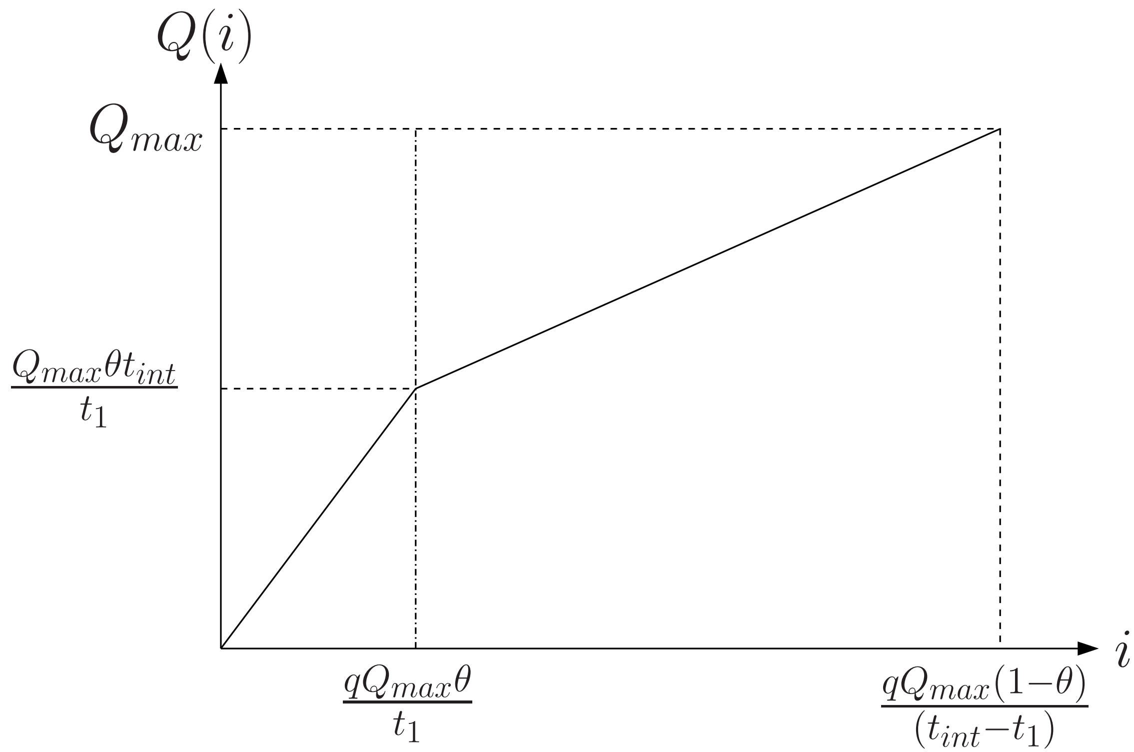
$$i_{max} = \frac{(1-\theta)qQ_{max}}{t_{int} - t_1}$$

- The smallest detectable signal does not change, so dynamic range is increased by a factor

$$\text{DRF} = \frac{(1-\theta)}{(1-\frac{t_1}{t_{int}})}$$

So $\theta << \frac{t_1}{t_{int}}$ is needed to achieve significant increase in dynamic range

- The current to charge response is as follows:



SNR for Well Capacity Adjusting Scheme

- Again we only consider the single well capacity adjusting case
- For $0 \leq i_{ph} < \frac{qQ_{max}\theta}{t_1}$, SNR is the same as for the normal sensor operation, and we obtain

$$\text{SNR}(i_{ph}) = \frac{i_{ph}^2}{\frac{q^2}{t_{int}^2}\left(\frac{1}{q}(i_{ph}+i_{dc})t_{int} + \sigma_{\text{read}}^2 + \sigma_{\text{dsnu}}^2\right)}$$

For $\frac{qQ_{max}\theta}{t_1} \leq i_{ph} < \frac{qQ_{max}(1-\theta)}{(t_{int}-t_1)}$, the average power of the noise charge is

$$\frac{1}{q}(i_{ph}+i_{dc})(t_{int}-t_1) + \sigma_{\text{read}}^2 + \sigma_{\text{dsnu}}^2 \text{ electrons}^2$$

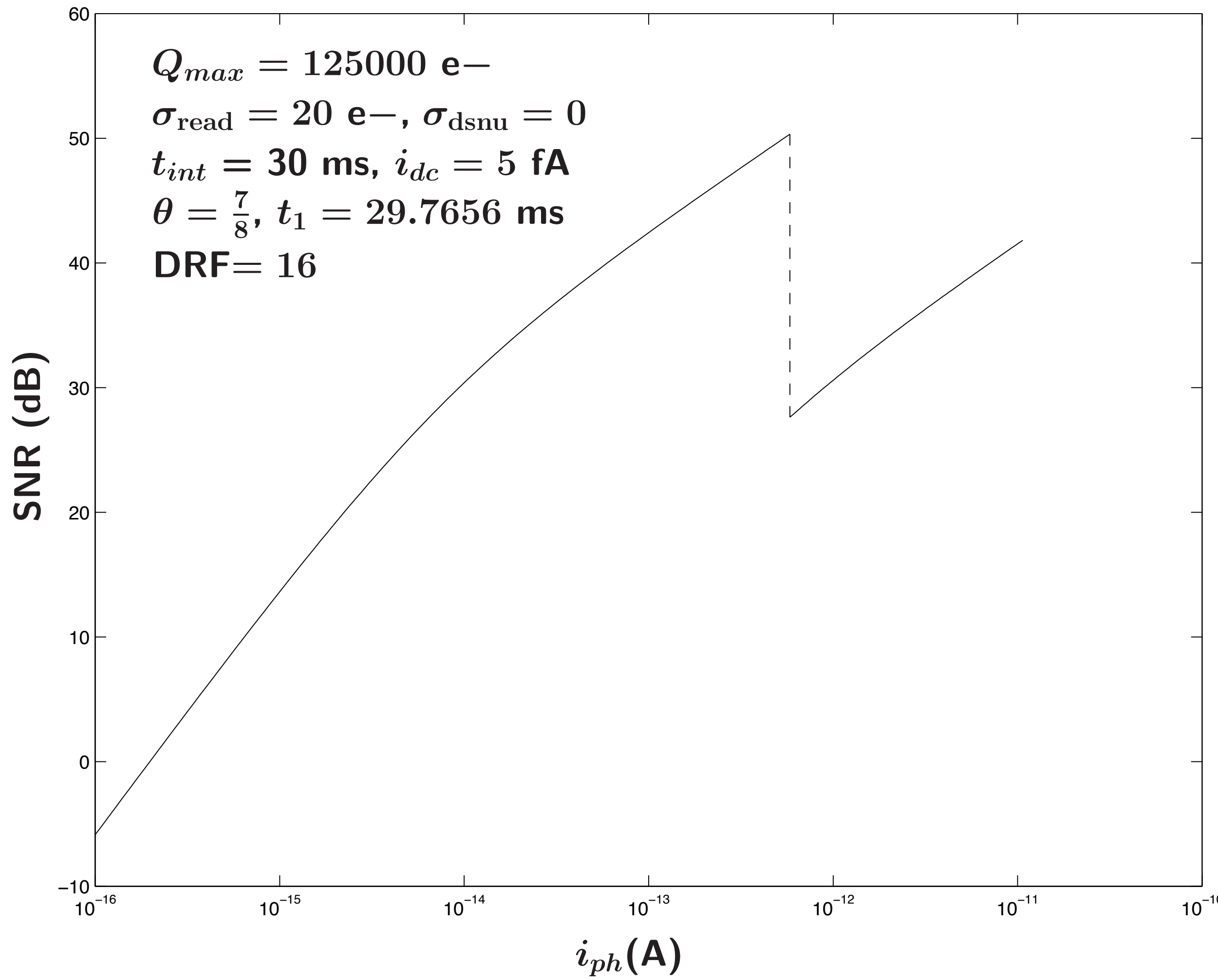
Thus, the average power of the equivalent input referred noise current is

$$\sigma_{I_n}^2 = \frac{q^2}{(t_{int}-t_1)^2}\left(\frac{1}{q}(i_{ph}+i_{dc})(t_{int}-t_1) + \sigma_{\text{read}}^2 + \sigma_{\text{dsnu}}^2\right) \text{ A}^2,$$

Thus for $\frac{qQ_{max}\theta}{t_1} \leq i_{ph} < \frac{qQ_{max}(1-\theta)}{(t_{int}-t_1)}$, SNR is given by

$$\text{SNR}(i_{ph}) = \frac{i_{ph}^2}{\frac{q^2}{(t_{int}-t_1)^2}\left(\frac{1}{q}(i_{ph}+i_{dc})(t_{int}-t_1) + \sigma_{\text{read}}^2 + \sigma_{\text{dsnu}}^2\right)}$$

- Example:



- Notice the 22dB dip in SNR at the transition point

$$i_{ph} = \frac{qQ_{max}\theta}{t_1} = 583 \text{ fA}$$

- The dip in general is given by

$$\begin{aligned}\text{DIP} &\approx \frac{t_{int}^2}{(t_{int}-t_1)^2}\cdot\frac{(Q_{max}\theta\frac{(t_{int}-t_1)}{t_1})}{(Q_{max}\theta\frac{t_{int}}{t_1})}\\ &= \frac{1}{1-\frac{t_1}{t_{int}}}\\ &= \frac{\text{DRF}}{(1-\theta)}\end{aligned}$$

- Thus it increases with DRF, but also as θ increases

- Note: Our analysis ignored reset transistor subthreshold current for signals that are close to saturation before well adjustment
  Including the subthreshold current smoothes out the transfer function around the $qQ_{max}\theta/t_1$, which smoothes out the dip
  However, this smoothing and the shot noise due to the reset transistor subthreshold current reduce SNR before the dip

Well Capacity Adjusting Pros and Cons

- Implementation is very simple; no additional circuits required in APS
- Increasing DR directly lowers SNR
- Sensor response is nonlinear
  - Higher quantization noise for large signals
  - Color processing is a problem

Example Using Well Capacity Adjusting

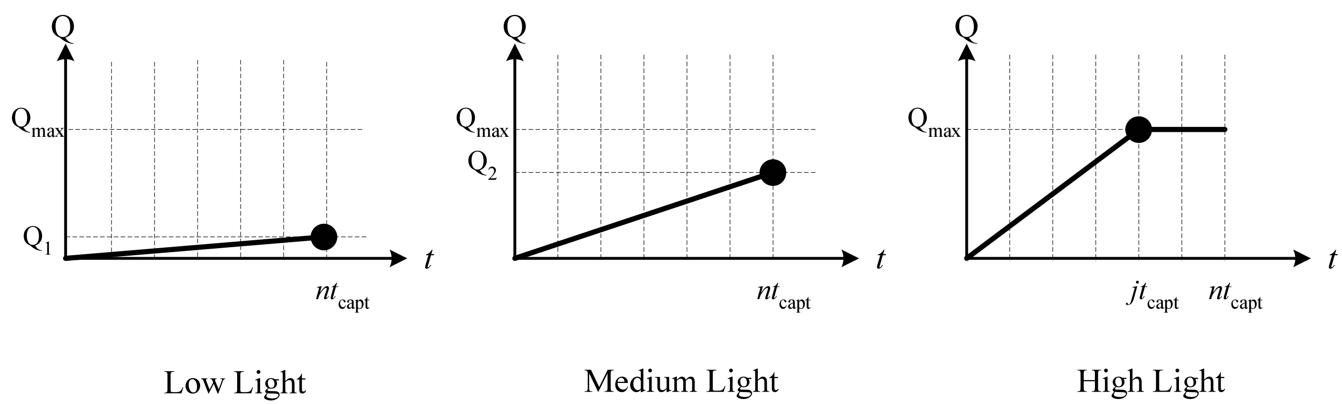
78dB scene

using single well capacity adjusting, $\theta = \frac{7}{8}$, $t_1 = \frac{127}{128} t_{int}$, DRF=16

Note the high quantization noise in the high light region on the right

Multiple Capture

- Idea: Capture several images within normal exposure time
  - short integration time images capture high light regions
  - long integration time images capture low light regions



- Form a HDR image out of the multiple captures, e.g., by using each pixel's last sample before it saturates
- Implementation of 2 captures demonstrated for CCDs and CMOS APS [7]
- Implementing many captures requires very high speed non-destructive readout – have been demonstrated using DPS [8,9] and APS with per-column ADC [15]

Multiple Capture Example

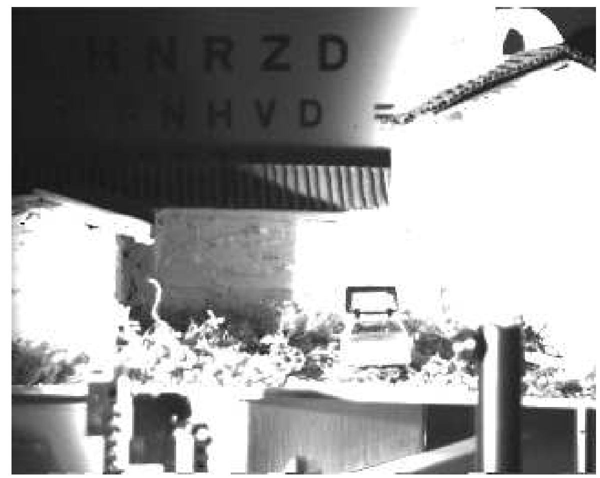
T

$2T$

$4T$

$8T$

$16T$



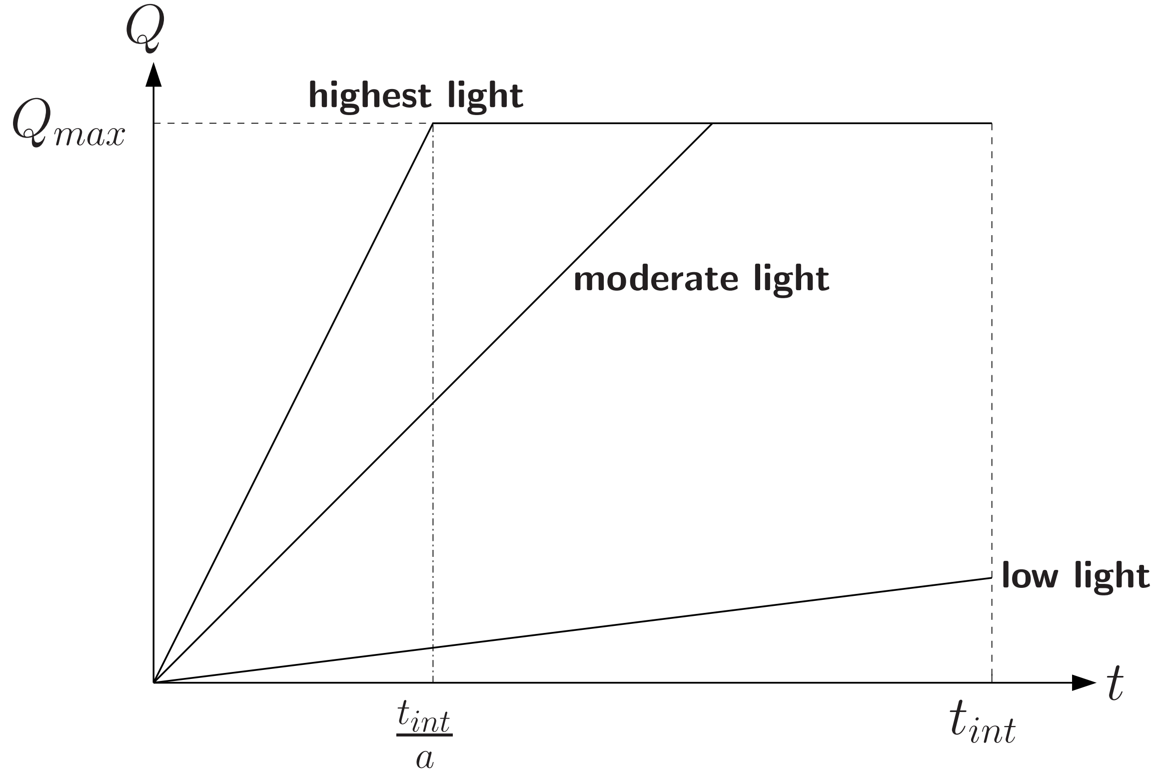
$32T$

HDR Image

- Using last pixel sample before saturation, we obtain the HDR image

DR for Multiple Capture

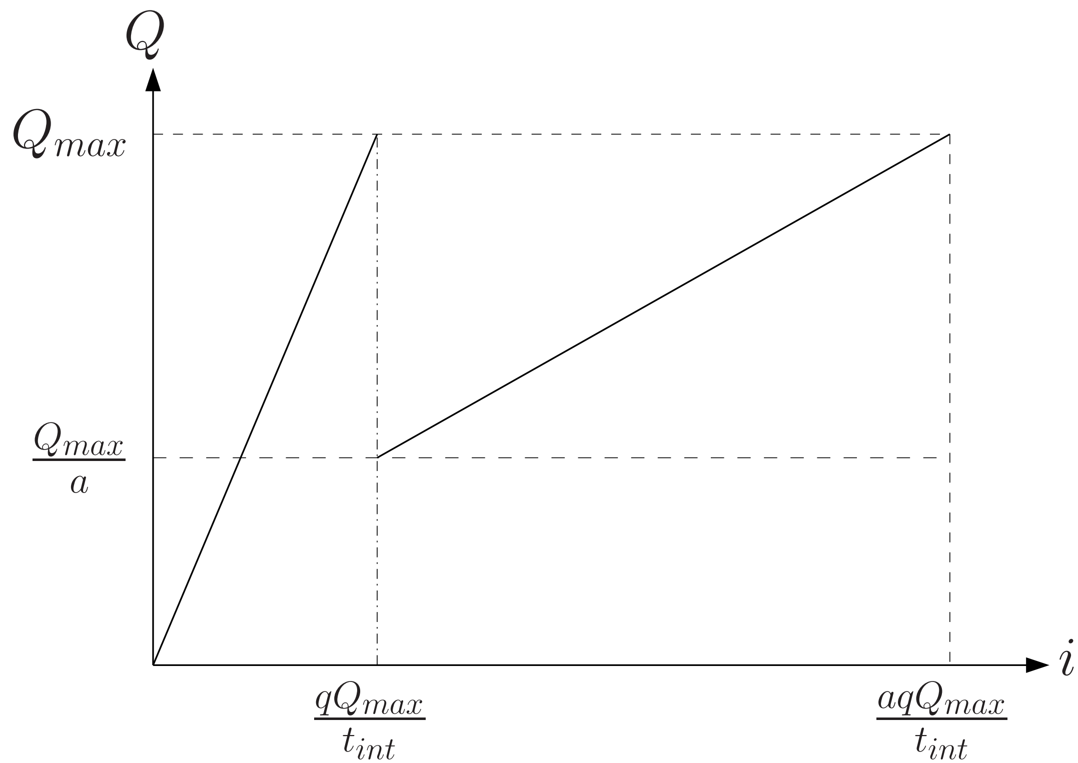
- We only consider the case of two captures, one at a short integration time $\frac{t_{int}}{a}$, $a > 1$, and one at a longer integration time t_{int}



- The largest nonsaturating current is now

$$i_{max} \approx \frac{aqQ_{max}}{t_{int}}$$

- The smallest detectable signal does not change, so dynamic range is increased by a factor DRF $\approx a$
- To form a HDR image, use all nonsaturated pixel values from the long integration time and replace each saturated pixel value by a scaled value (multiplied by a) of its short integration time value
- The current to charge response using this algorithm (before normalization) is as follows



- After normalization, the resulting transfer function becomes linear

SNR for Multiple Capture Scheme

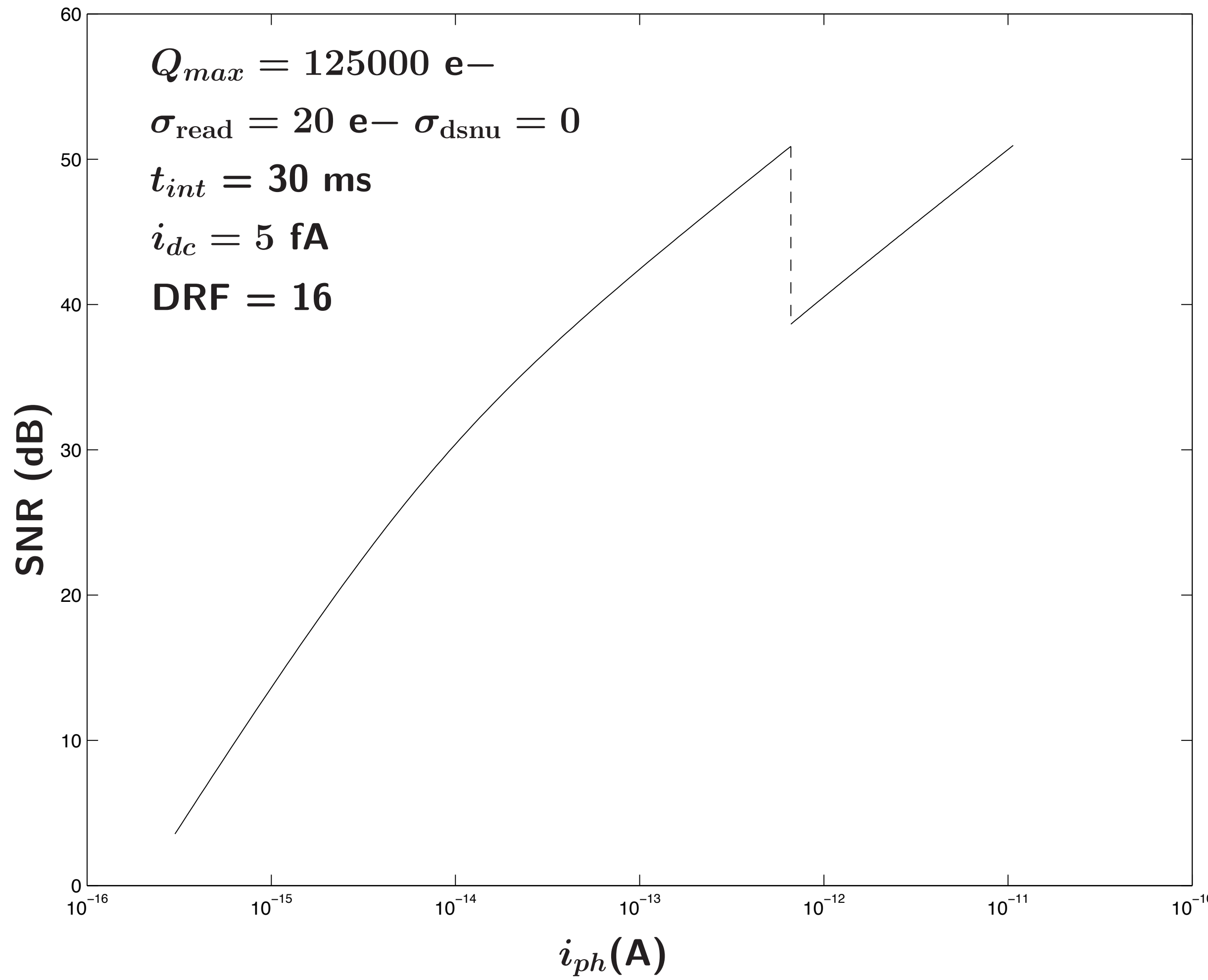
- We consider the case of two captures and the last-sample-before saturation algorithm
- For $0 \le i_{ph} < \frac{qQ_{max}}{t_{int}}$, SNR is the same as for the normal operation, and we obtain

$$\text{SNR}(i_{ph}) = \frac{i_{ph}^2}{\frac{q^2}{t_{int}^2}\left(\frac{1}{q}(i_{ph}+i_{dc})t_{int} + \sigma_{\text{read}}^2 + \sigma_{\text{dsnu}}^2\right)}$$

- For $\frac{qQ_{max}}{t_{int}} \le i_{ph} < \frac{aqQ_{max}}{t_{int}}$, SNR is the same as normal operation with t_{int} replaced by $\frac{t_{int}}{a}$, and we obtain

$$\text{SNR}(i_{ph}) = \frac{i_{ph}^2}{\frac{a^2q^2}{t_{int}^2}\left(\frac{1}{q}(i_{ph}+i_{dc})\frac{t_{int}}{a} + \sigma_{\text{read}}^2 + \sigma_{\text{dsnu}}^2\right)}$$

• Example:



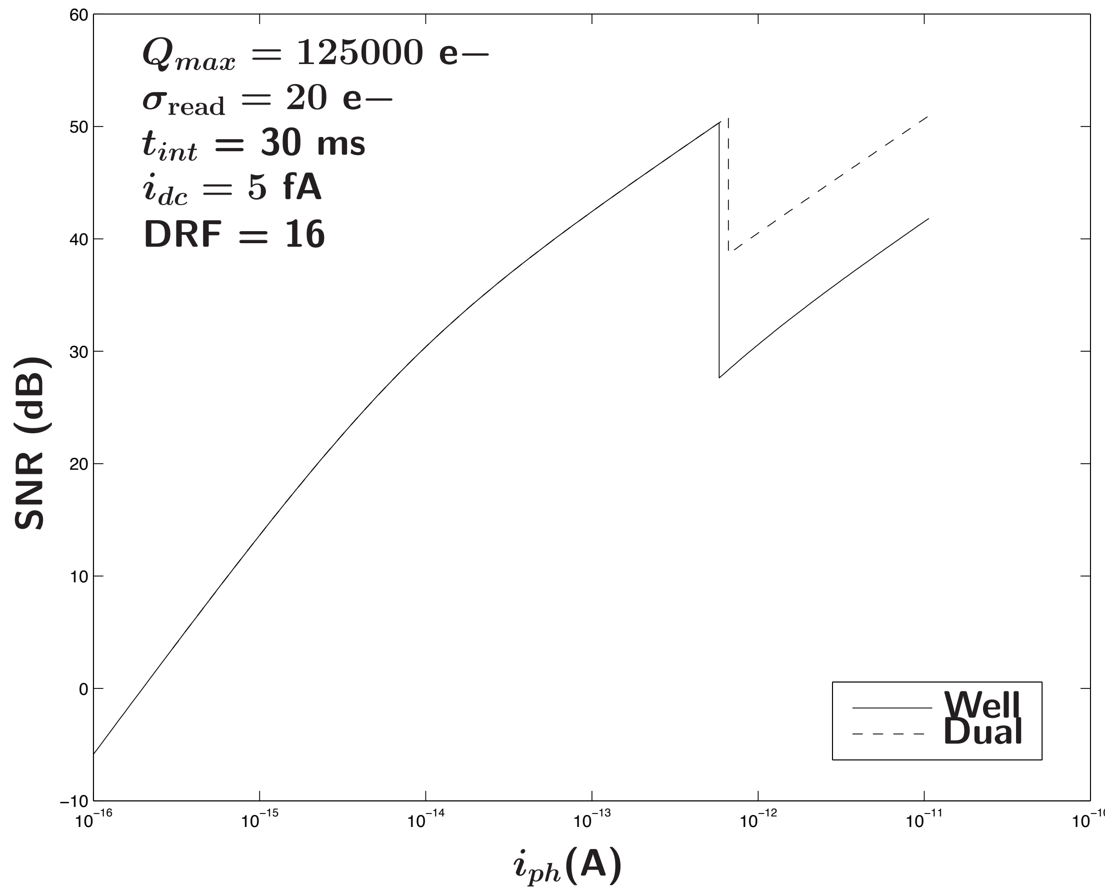
• Notice that SNR dips by 12.2 dB at the transition current $i_{ph} = \frac{qQ_{max}}{t_{int}} = 662$ fA

- In general

$$\text{DIP} \approx \frac{a^2\left(\frac{Q_{max}}{a}\right)}{Q_{max}} \approx \text{DRF},$$

which is smaller than the DIP for well adjusting for the same DRF and can be reduced by using more than two captures

- Combining the SNR curves of the two schemes:



Multiple Capture Pros and Cons

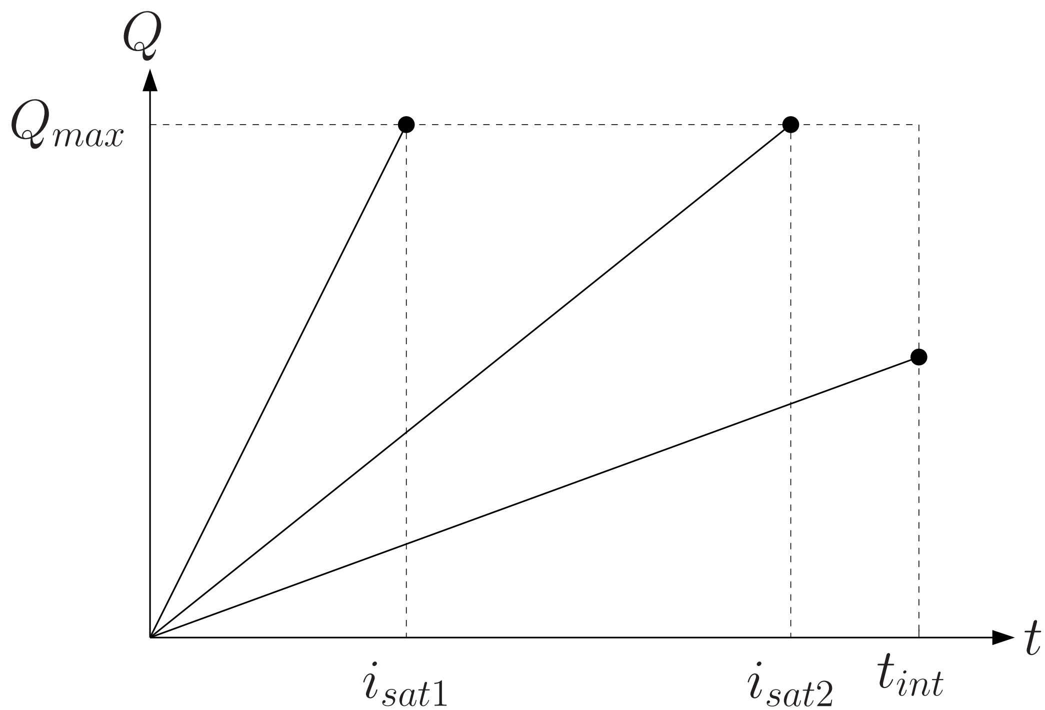
- High SNR maintained over extended dynamic range
- Response is linear – can perform conventional color processing and CDS
- Dynamic range can also be extended at low illumination by appropriately "averaging" the captured images to reduce read noise [10]
- Dual capture implementation not too difficult (plenty of time between the two captures to readout the first capture)
  - High SNR dip for regions of moderate light and
- Implementing many captures requires high speed non-destructive readout:
  - APS with per-column ADC [15]: High ADC resolution but scrolling shutter and limited speed
  - Per-pixel ADC (Digital Pixel Sensor) [9,11]: High speed readout, but limited ADC resolution
- To reduce output data rate, on-chip memory and processing are needed to perform reconstruction of HDR image during capture [9]

Time-to-Saturation [12,13]

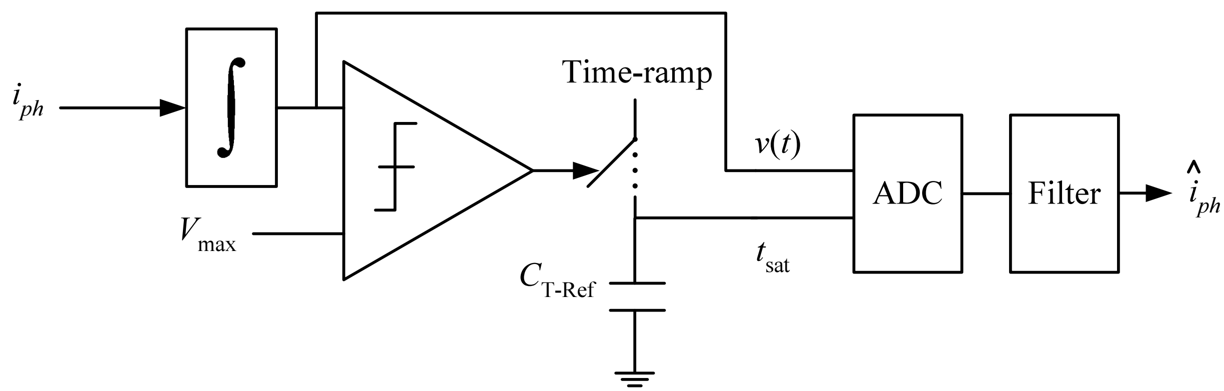
- Idea: For $i_{ph} > qQ_{max}/t_{int}$, measure the integration time required to saturate each pixel, the photocurrent is estimated by

$$i_{ph} = \frac{qQ_{max}}{t_{\text{sat}}}$$

For $i_{ph} < qQ_{max}/t_{int}$, read out the sample at t_{int}



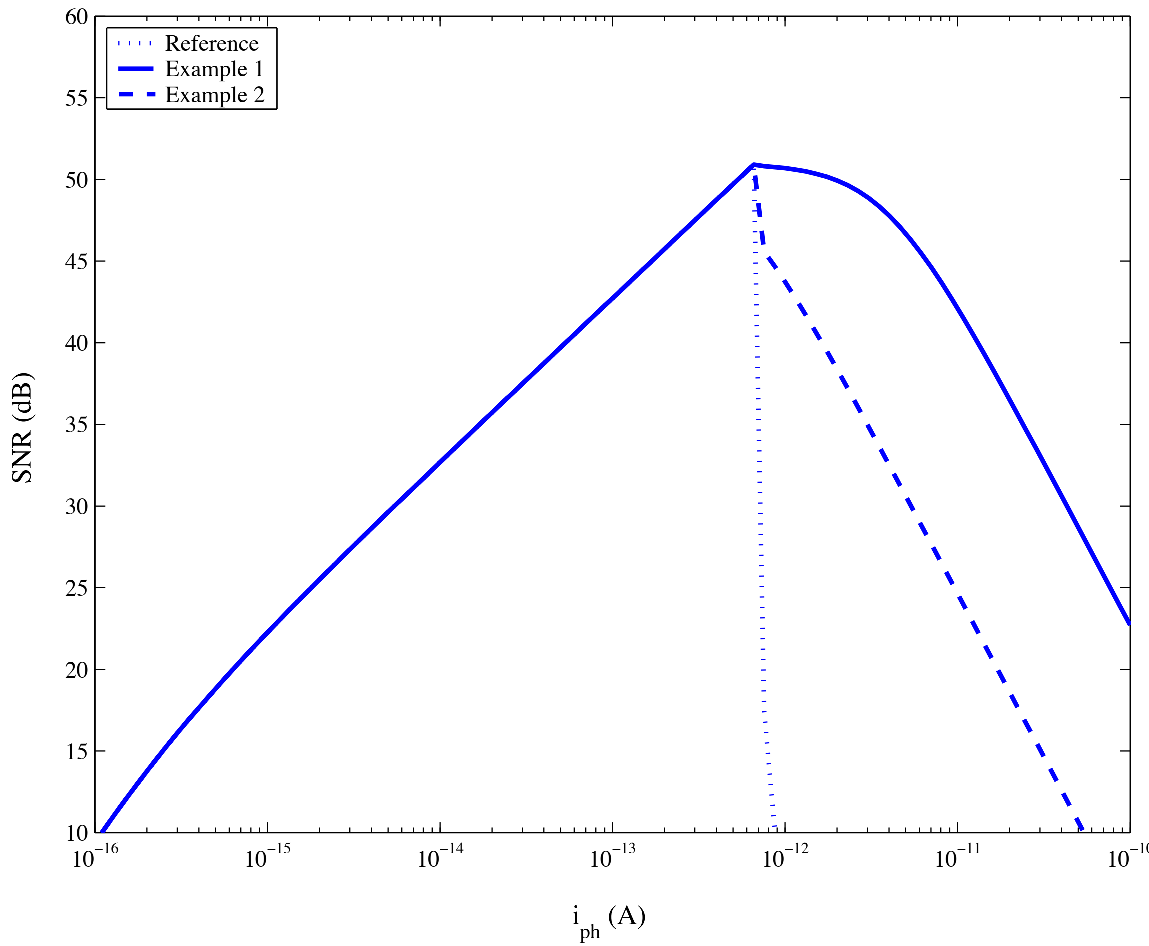
- Each pixel comprises a photodetector, a comparator, and a capacitor for storing the time-stamp



- Note that the current to output transfer function is linear up to $i_{ph} = qQ_{max}/t_{int}$ but nonlinear thereafter
- The minimum detectable signal is the same as for a conventional sensor
- The maximum non-saturating signal depends on comparator delay and offset, and noise associated with time-stamp readout. Let's denote the standard deviation of this noise by σ_{sat} in seconds, then

$$i_{max} = \frac{qQ_{max}}{\sigma_{sat}}$$

- SNR for this scheme is limited at the high end by σ_{sat} [2]



Assumtions: $Q_{max} = 125,000e-$, $\sigma_{\text{read}} = 5e-$, $\sigma_{\text{dsnu}} = 0$, $t_{\text{int}} = 30$msec

Example 1 assumes $\sigma_{\text{sat}} = 0.0005t_{\text{int}}$, DR$= 156$dB

Example 2 assumes $\sigma_{\text{sat}} = 0.004t_{\text{int}}$, achieves DR$= 136$dB

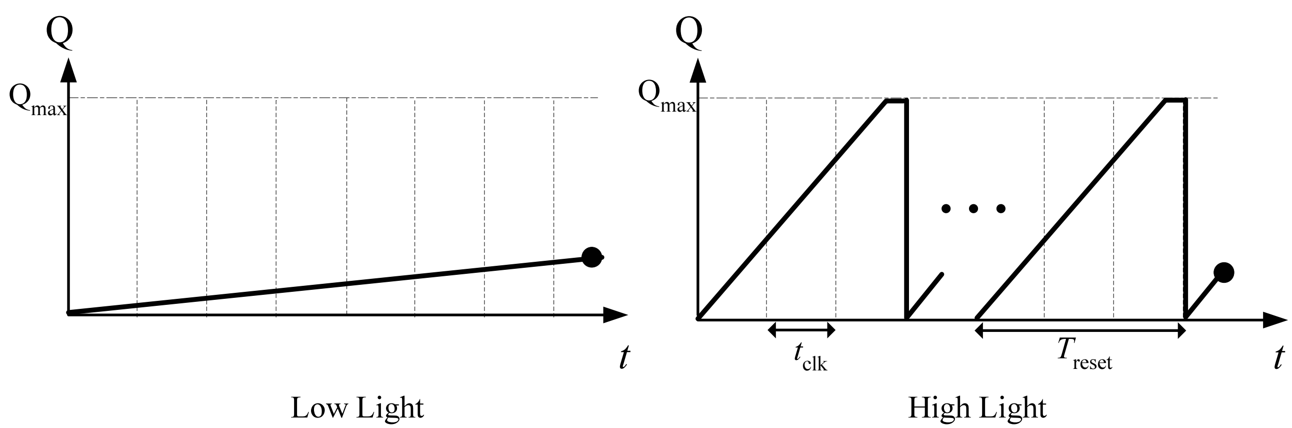
Reference is SNR for normal operation

Time-to-Saturation Pros and Cons

- SNR is maximized for part of the extended range
- Reducing σ_{sat} requires reducing comparator offset and delay and improving time-stamp accuracy. This would require larger pixel area and higher power consumption
- Implementation is quite complex requiring significant per-pixel circuitry
- Power consumption is high due to the fact that the comparator is always on

Synchronous Self-Reset with Residue Readout [14]

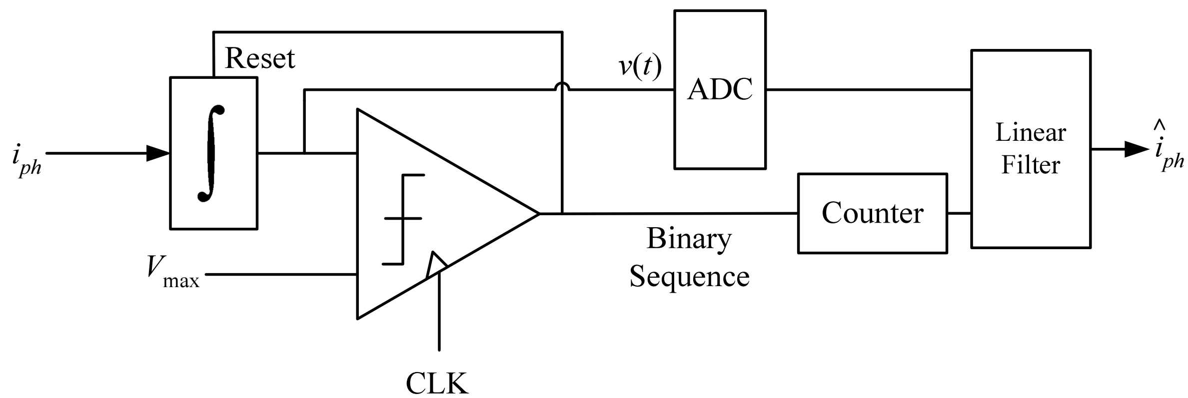
- Idea: Increase the effective well capacity by synchronously resetting each pixel depending on its illumination level one or more times during integartion, keeping count of the number of resets, and reading the residue at t_{int}



- The signal is reconstructed by multiplying the number of resets by Q_{max} and adding the charge collected during the last integration interval (residue), i.e.,

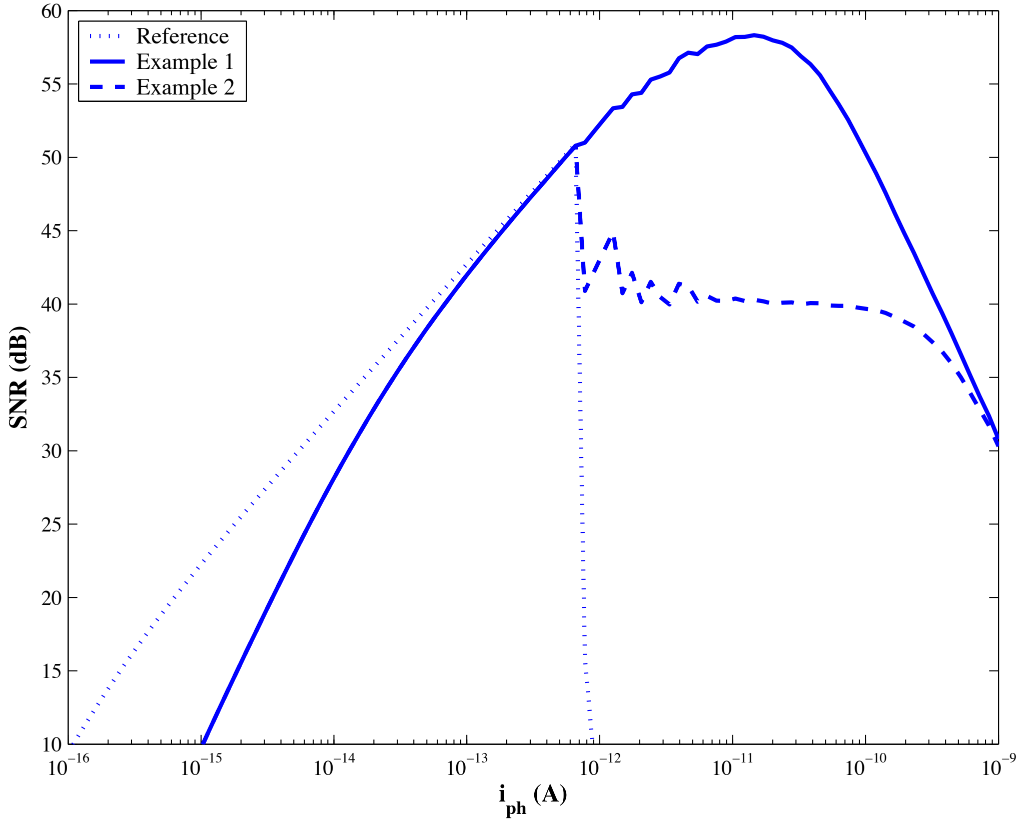
$$\hat{i}_{ph} = (Q_{max} N_{\text{reset}} + Q_{\text{residue}})/t_{int}$$

- Each pixel comprises a photodetector, a comparator, a self-reset mechanism and a digital counter (and an ADC)



- DR at the high end increases with clock rate
- SNR at the high end drops due to:
  - The error in estimating the photocurrent caused by synchronous reset
  - Accumulation of reset offset and noise
  - Comparator offset σ_{offset} (causes PRNU)

- Example:



Assumtions:

$Q_{max} = 125,000e-, \ \sigma_{\text{read}} = 35e-, \ \sigma_{\text{dsnu}} = 0, \ t_{\text{int}} = 30m\text{sec}, \ t_{\text{clk}} = 1\mu\text{sec}$

Example 1: $\sigma_{\text{offset}} = 0.001 Q_{\text{max}}$

Example 2: $\sigma_{\text{offset}} = 0.01 Q_{\text{max}}$, both achieve DR$= 161$dB

Synchronous Self-Reset Pros and Cons

- DR can be increased much more than other schemes at higher frame rate and with lower power consumption
- SNR is poor
- Implementation requires significant per pixel circuitry

References

[1] D. Yang, and A. El Gamal, "Comparative Analysis of SNR for Image Sensors with Enhanced Dynamic Range," In *Proceedings of the SPIE Electronic Imaging '99 conference*, Vol. 3649, San Jose, CA, January 1999.

[2] S. Kavusi, and A. El Gamal, "Quantitative Study of High Dynamic Range Image Sensor Architectures," in *Proceedings of the SPIE Electronic Imaging '04 conference*, Vol. 5301, San Jose, CA, January 2004.

[3] S. Kavusi and A. El Gamal, "Quantitative study of high dynamic range SD-based focal plane array architectures,"in *Proceedings of the SPIE Infrared Technology and Applications*, Vol. 5406, April 2004.

[4] T. F. Knight, *Design of an Integrated Optical Sensor with On-Chip Preprocessing*. PhD thesis, MIT, 1983.

[5] M. Sayag, "Non-linear Photosite Response in CCD Imagers." U.S Patent No. 5,055,667, 1991. Filed 1990.

[6] S. J. Decker, R. D. McGrath, K. Brehmer, and C. G. Sodini, "A 256x256 CMOS imaging array with wide dynamic range pixels and column-parallel digital output," *IEEE J. of Solid State Circuits*, Vol. 33, pp. 2081-2091, Dec. 1998.

[7] O. Yadid-Pecht and E. Fossum, "Wide intrascene dynamic range CMOS APS using dual sampling." *IEEE Trans. Electron Devices*, vol. 44, pp. 1721-1723, Oct. 1997.

[8] D. X. D. Yang, A. El Gamal, B. Fowler, and H. Tian, "A 640x512 CMOS image sensor with ultrawide dynamic range floating-point pixel level ADC," *IEEE Journal of Solid State Circuits*, vol. 34, pp. 1821-1834, Dec. 1999.

[9] W. Bidermann, A. El Gamal, S. Ewedemi, J. Reyneri, H. Tian, D. Wile, and D. Yang, "A 0.18m high dynamic range NTSC/PAL imaging system-on-chip with embedded DRAM frame buffer," *IEEE International Solid-State Circuits Conference*, pp. 212213, February 2003.

[10] X.Q. Liu and A. El Gamal, "Simultaneous Image Formation and Motion Blur Restoration via Multiple Capture," In *ICASSP'2001 conference*, Salt Lake City, Utah, May 2001.

[11] S. Kleinfelder, S.H. Lim, X.Q. Liu and A. El Gamal, "A 10,000 Frames/s 0.18 um CMOS Digital Pixel Sensor with Pixel-Level Memory," In *Proceedings of the 2001 IEEE International Solid-State Circuits Conference*, pp. 88-89, San Francisco, CA, February 2001.

[12] D. Stoppa, A. Simoni, L. Gonzo, M. Gottardi, and G. F. Dalla Betta, "Novel CMOS image sensor with a 132-dB dynamic range," *IEEE Journal of Solid-State Circuits*, vol. 37, no. 12, pp. 1846 1852, December 2002.

[13] V. Brajovic and T. Kanade, "A sorting image sensor: and example of massively parallel intensity-to-time processing for low-latency computational sensor," *Proceedings of the 1996 IEEE International Conference on Robotics and Automation*, pp. 16381643, 1996.

[14] J. Rhee and Y. Joo, "Wide dynamic range CMOS image sensor with pixel level ADC," *Electronics Letters*, vol. 39, no. 4, pp. 360 361, February 2003.

[15] M. Mase, S. Kawahito, M. Sasaki, Y. Wakamori, "A 19.5b Dynamic Range CMOS Image Sensor with 12b Column-Parallel Cyclic A/D Converters," In *Proceedings of the 2005 IEEE International Solid-State Circuits Conference*, vol. 48, pp. 350-351, February 2005.