High Dynamic Range Image Sensors

Abbas El Gamal

Department of Electrical Engineering

Stanford University

Motivation

- Some scenes contain very wide range of illumination with intensities varying over 100dB range or more
- Biological vision systems and silver halide film can image such *high dynamic range* scenes with little loss of contrast information
- Dynamic range of solid-state image sensors varies over wide range:

high end CCDs	> 78dB
consumer grade CCDs	66dB
consumer grade CMOS imagers	54dB

- So, except for high end CCDs, image sensor dynamic range is not high enough to capture high dynamic range scenes

Imaging High Dynamic Range Scene – The problem

HDR Scene

Short Exposure-time Image

Medium Exposure-time Image

Long Exposure-time Image

Extending Sensor Dynamic Range

- Several techniques and architectures have been proposed for extending image sensor dynamic range – many questions:
- What exactly is sensor dynamic range, what does it depend on, and how should it be quantified (100dB, 12 bits, $\ldots$)?
- In what sense do these techniques extend dynamic range?
- How well do they work (*e.g.*, accuracy of capturing scene information and/ or image quality)?
- How should their performance be compared?
  - Are all 100dB sensors equivalent?
  - Is a 120dB sensor better than a 100dB one?

Tutorial Objectives

- To provide quantitative understanding of sensor DR and SNR and their dependencies on key sensor parameters
- To describe some of the popular techniques for extending image sensor dynamic range
- To provide a framework for comparing the performance of these techniques:
  - Quantitatively based on DR and SNR
  - Qualitatively based on other criteria, *e.g.*, linearity, complexity . . .

Outline

- **Background**
  - Introduction to Image Sensors
  - Image Sensor Model
  - Sensor Dynamic Range (DR) and SNR
- **Description/ Analysis of HDR Schemes**
- **Other HDR Image Sensors**
- **Conclusion**
- **References**

Image Sensors

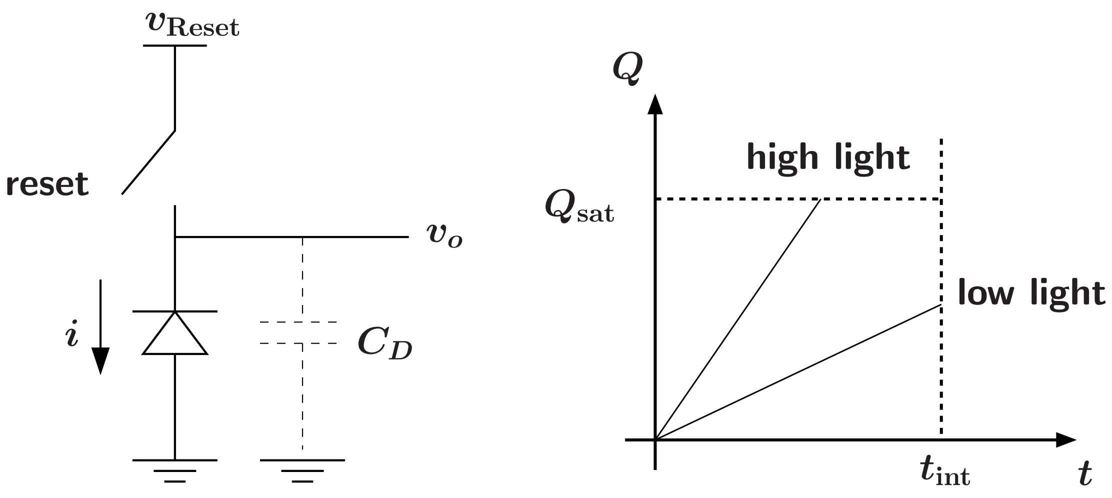
- Area image sensor consists of:
  - 2-D array of pixels, each containing a photodetector that converts light into photocurrent and readout devices
  - Circuits at periphery for readout, ...
- Since photocurrent is very small (10s – 100s of fA), it is difficult to read out directly
- Conventional sensors (CCDs, CMOS APS) operate in *direct integration* – photocurrent is integrated during exposure into charge, read out as voltage
- In some high dynamic range sensors photocurrent is directly converted to output voltage

Signal Path for Single Pixel

Photons	→	**Photocurrent**	→	**Charge**	→	**Voltage**
ph/s		Amp		Col		V

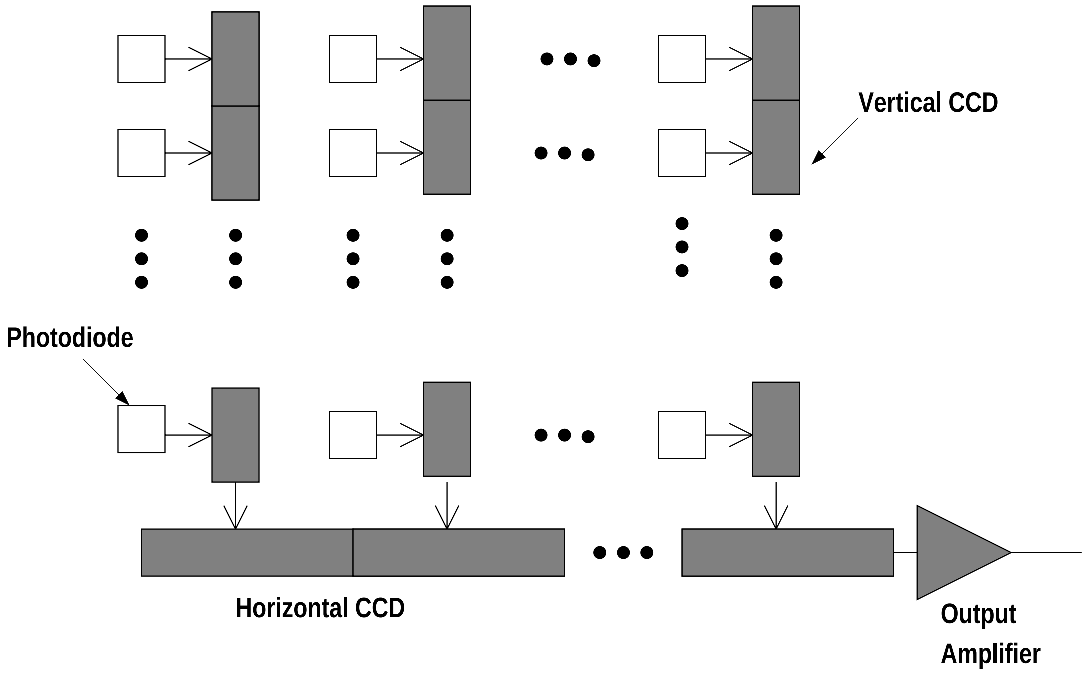
- Photon flux conversion to photocurrent is *linear* (for fixed irradiance spectral distribution) – governed by *quantum efficiency*
- Photocurrent is integrated into charge during exposure
- In most sensors, charge to voltage conversion is performed using linear amplifier(s)

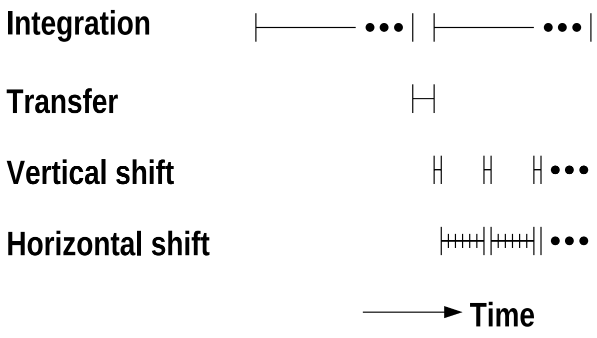
Direct Integration



- Direct integration:
  - The photodetector is reset to v_{Reset}
  - Photocurrent discharges C_D during *integration time* or exposure time, t_{int}
  - At the end of integration, the accumulated (negative) charge $Q(t_{\mathrm{int}})$ (or voltage $v_o(t_{\mathrm{int}})$) is read out
- Saturation charge Q_{sat} is called *well capacity*

Interline Transfer CCD Image Sensor

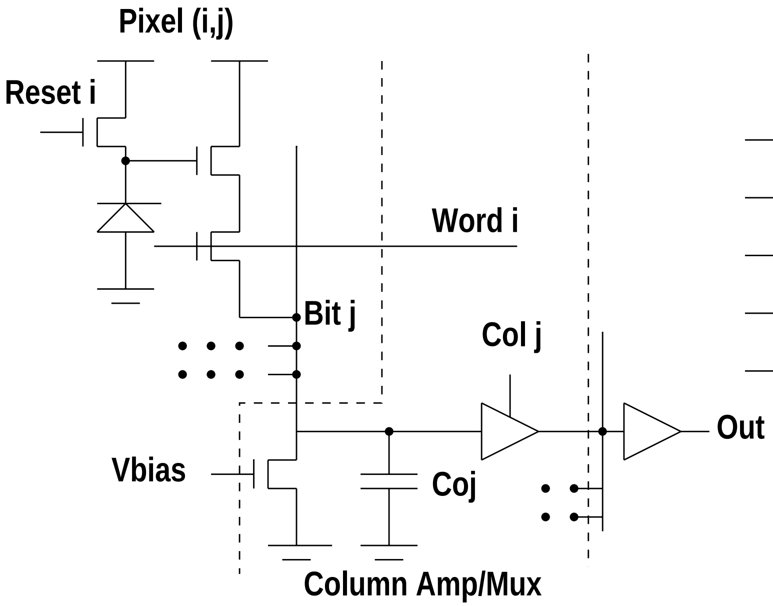


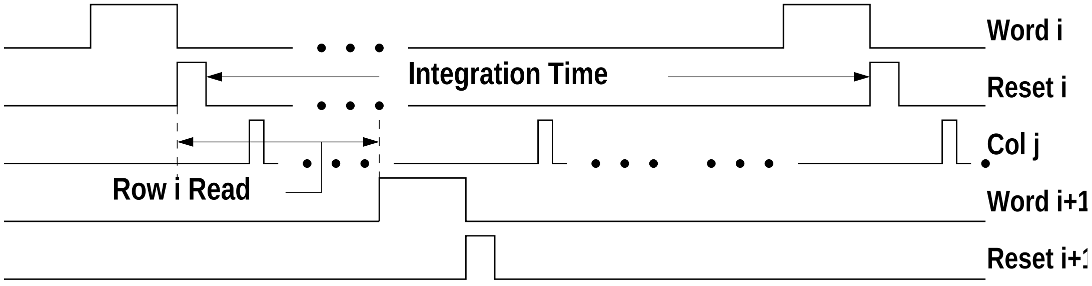


Operation

- Collected charge is *simultaneously* transferred to the vertical CCDs at the end of integration time (a new integration period can begin right after the transfer) and then shifted out
- Charge transfer to vertical CCDs simultaneously *resets* the photodiodes – shuttering done electronically (see [2])

CMOS Active Pixel Sensor (APS)





Operation

- Pixel voltage is read out one row at a time to column storage capacitors, then read out using the column decoder and multiplexer
- Row integration times are *staggered* by row/column readout time

Image Sensor Non-idealities

- Temporal noise
- Fixed pattern noise (FPN)
- Dark current
- Spatial sampling and low pass filtering

Temporal Noise

- Caused by photodetector and MOS transistor thermal, shot, and 1/f noise
- Can be lumped into three additive components:
  - Integration noise (due to photodetector shot noise)
  - Reset noise
  - Readout noise
- Noise increases with signal, but so does the signal-to-noise ratio (SNR)
- Noise under dark conditions presents a fundamental limit on sensor dynamic range (DR)

Fixed Pattern Noise (FPN)

- FPN is the spatial variation in pixel outputs under uniform illumination due to device and interconnect mismatches over the sensor
- Two FPN components: offset and gain
- Most visible at low illumination (offset FPN more important than gain FPN)
- Worse for CMOS image sensors than for CCDs due to multiple levels of amplification
    - **FPN due to column amplifier mismatches major problem**
- Offset FPN can be reduced using *correlated double sampling* (CDS)

Dark current

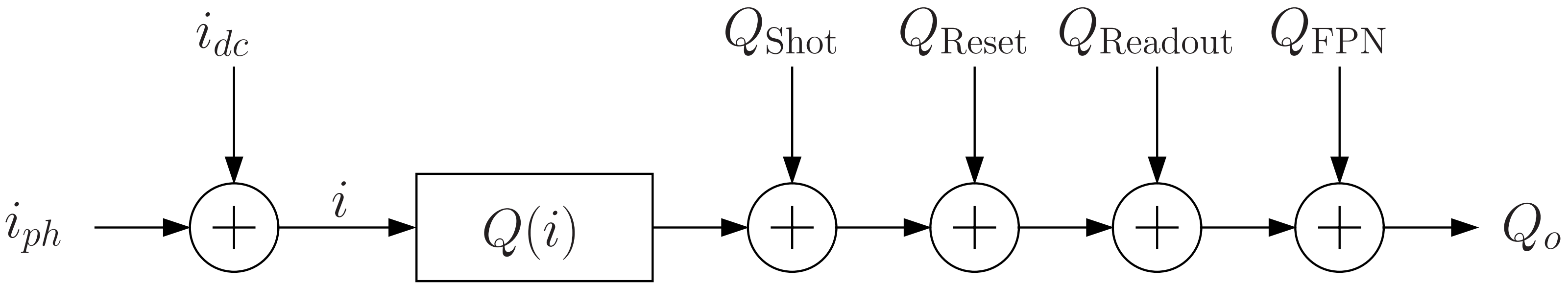
- Dark current is the leakage current at the integration node, *i.e.*, current not induced by photogeneration, due to junction (and transistor) leakages
- It limits the image sensor dynamic range by
  - introducing dark integration noise (due to shot noise)
  - varying widely across the image sensor array causing fixed pattern noise (FPN) that cannot be easily removed
  - reducing signal swing

Sampling and Low Pass Filtering

- The image sensor is a spatial (as well as temporal) sampling device — frequency components above the Nyquist frequency cause aliasing
- It is not a point sampling device — signal low pass filtered before sampling by
  - spatial integration (of current density over photodetector area)
  - crosstalk between pixels
- Resolution below the Nyquist frequency measured by Modulation Transfer Function (MTF)
- Imaging optics also limit spatial resolution (due to diffraction)

Image Sensor Model

- Photocurrent to output charge model:



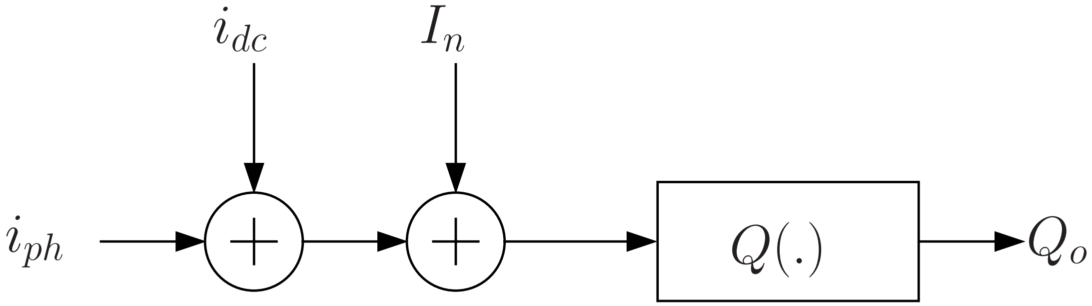
  - $Q(i)$ is the sensor transfer function and is given by:

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

  - Q_{Shot} is the noise charge due to integration (shot noise) and has average power $\frac{1}{q}(i_{ph} + i_{dc})t_{int}$ electrons^2
  - Q_{Reset} is the reset noise (KTC noise)
  - Q_{Readout} is the readout circuit noise
  - Q_{FPN} is the offset FPN (we ignore gain FPN)
- All noise components are independent

Input Referred Noise Power

- To calculate SNR and dynamic range we use the model with equivalent input referred noise current



- Since $Q(.)$ is linear we can readily find the average power of the equivalent input referred noise r.v. I_n, *i.e.*, average input referred noise power, to be

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

where

$$\sigma^2_r = \sigma^2_{\text{Reset}} + \sigma^2_{\text{Readout}} + \sigma^2_{\text{FPN}} \ \text{electron}^2,$$

is the *read noise* power

Correlated Double Sampling (CDS)

- The output of the sensor is sampled twice; once right after reset and the second time with the signal present
  - Sample without signal:

$$Q_o^{\text{Reset}} = Q'_{\text{Reset}} + Q'_{\text{Readout}} + Q_{\text{FPN}}$$

  - Sample with signal:

$$Q_o = \frac{1}{q}(i_{ph} + i_{dc})t_{\text{int}} + Q_{\text{Shot}} + Q_{\text{Reset}} + Q_{\text{Readout}} + Q_{\text{FPN}}$$

  - The difference is:

$$Q_o - Q_o^{\text{Reset}} = \frac{1}{q}(i_{ph} + i_{dc})t_{\text{int}} + Q_{\text{Shot}} + (Q - Q')_{\text{Reset}} + (Q - Q')_{\text{Readout}}$$

    offset FPN is eliminated, readout noise power is doubled, and reset noise is either eliminated (CCDs, photogate APS) or doubled (photodiode APS)

- WARNING: If sensor transfer function $Q(.)$ is not linear, CDS DOES NOT WORK

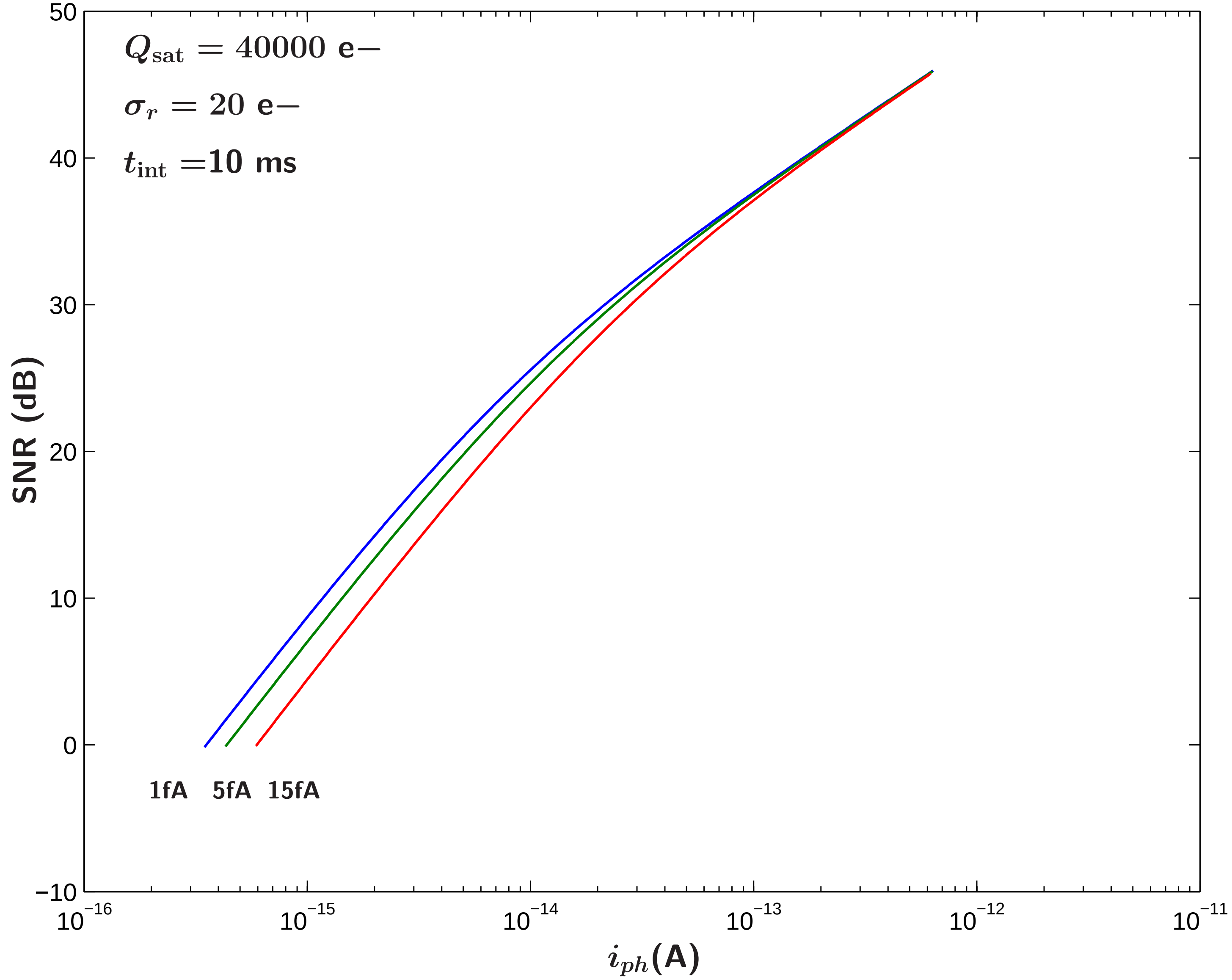
Signal to Noise Ratio (SNR)

- SNR is the ratio of the input signal power to the average input referred noise power, and is typically measured in dBs
- Using the average input referred noise power expression, we get

$$\text{SNR}(i_{ph}) = 10\log_{10} \frac{i_{ph}^2}{\frac{q^2}{t_{\text{int}}^2}\left(\frac{1}{q}(i_{ph}+i_{dc})t_{\text{int}}+\sigma_r^2\right)} \text{ dB}$$

- SNR increases with the input signal i_{ph}, first (for small i_{ph}) at 20dB per decade since read noise dominates, then at 10dB per decade when shot noise (due to photodetector) dominates

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

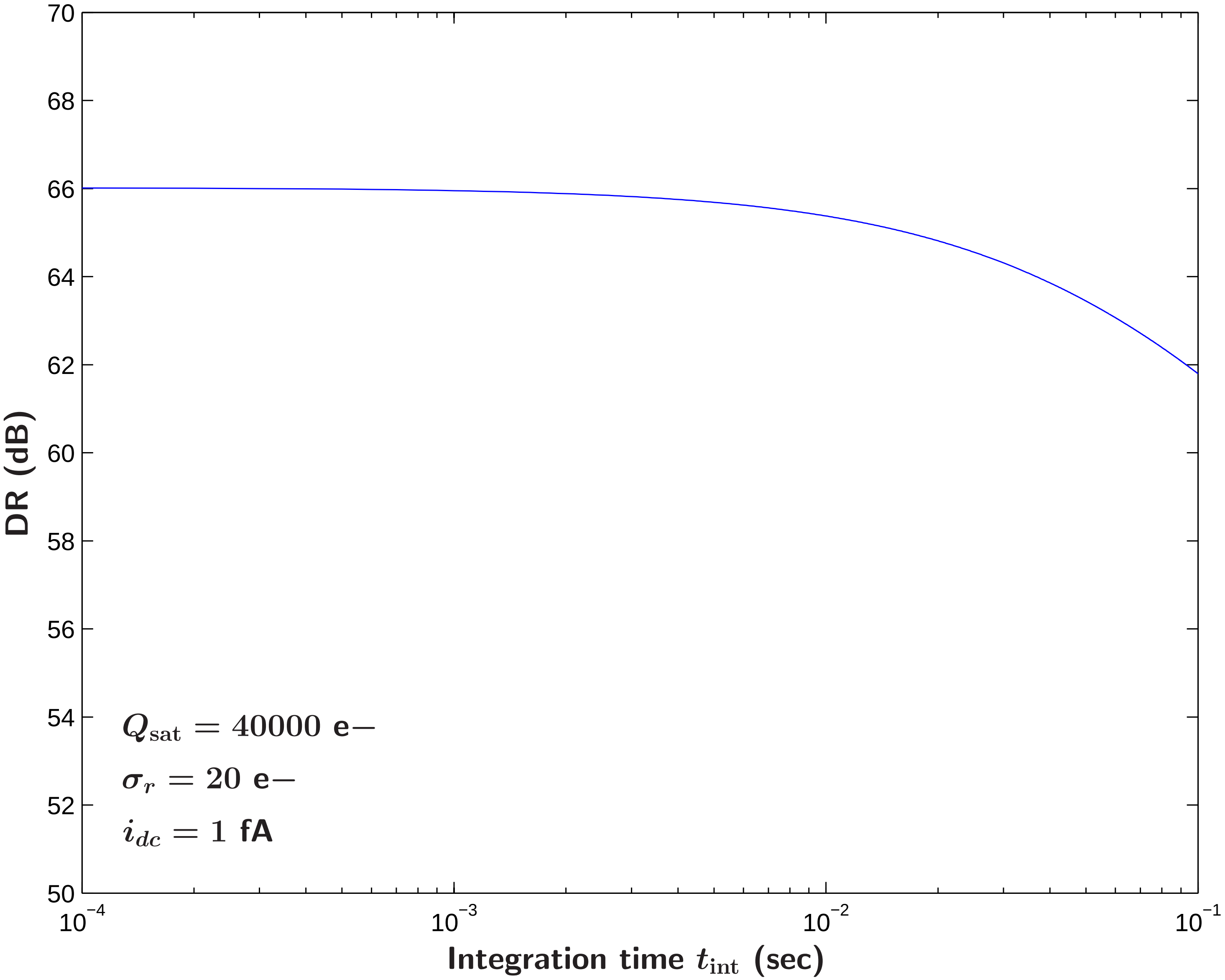


Dynamic Range

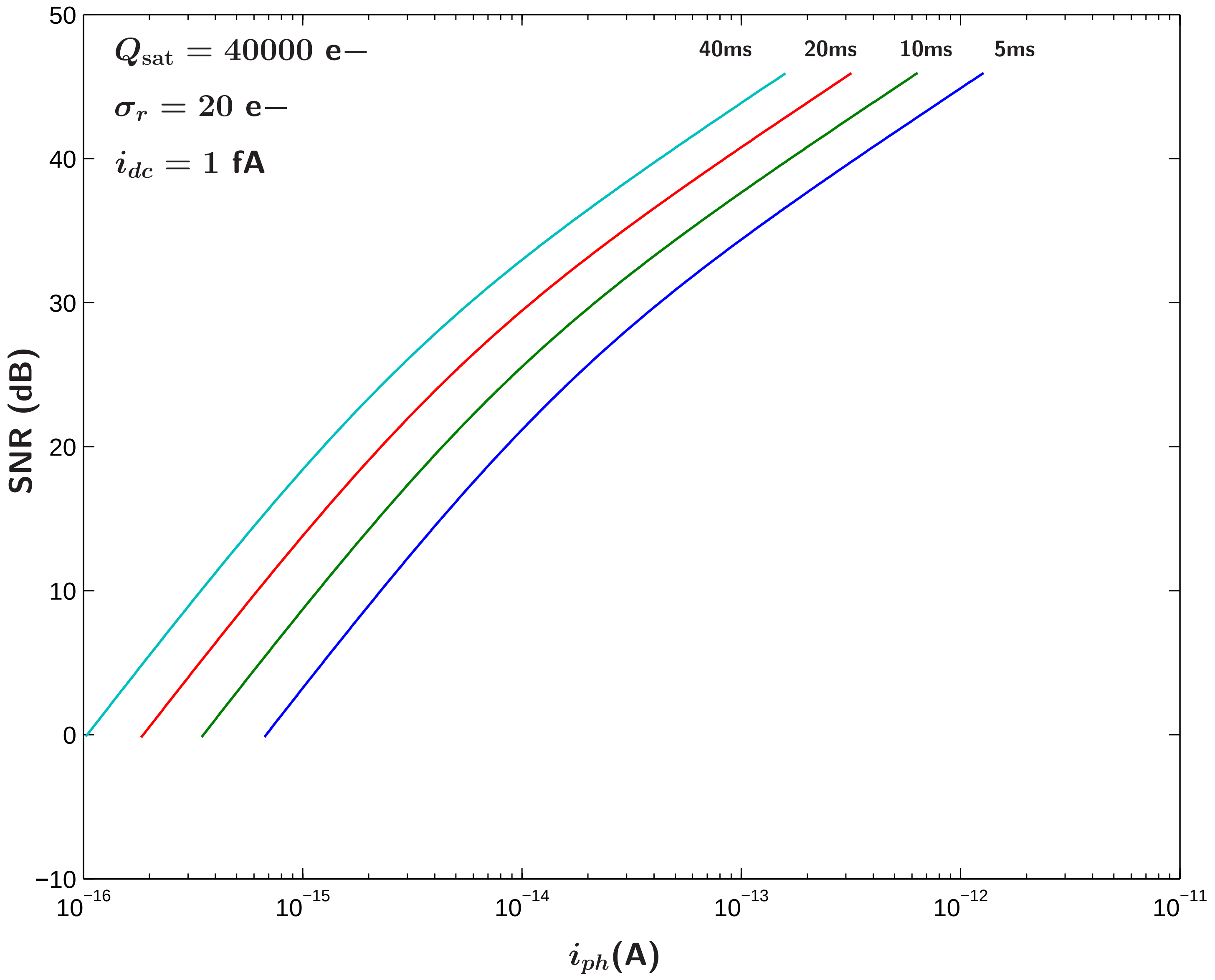
- Dynamic range quantifies the ability of a sensor to adequately image both high lights and dark shadows in a scene
- It is defined as the ratio of the largest nonsaturating input signal to the smallest detectable input signal
  - largest nonsaturating signal given by $i_{\max} = \frac{qQ_{\text{sat}}}{t_{\text{int}}} - i_{dc}$, where Q_{sat} is the well capacity
  - smallest detectable input signal defined as standard deviation of input referred noise under dark conditions $\sigma_{I_n}(0)$ (the zero here refers to $i_{ph} = 0$), which gives $i_{\min} = \frac{q}{t_{\text{int}}}\sqrt{\frac{1}{q} i_{dc} t_{\text{int}} + \sigma_r^2}$
- Thus dynamic range

$$\text{DR} = 20\log_{10}\frac{i_{\max}}{i_{\min}} = 20\log_{10}\frac{\frac{qQ_{\text{sat}}}{t_{\text{int}}} - i_{dc}}{\frac{q}{t_{\text{int}}}\sqrt{\frac{1}{q} i_{dc} t_{\text{int}} + \sigma_r^2}}$$

Dynamic Range Versus Integration Time



SNR vs. i_{ph} for Different Integration Times



Summary

- Presented brief tutorial on image sensor operation and nonidealities
- Described sensor signal and noise model
- Used the model to quantify sensor SNR and DR
- Discussed dependencies of SNR and DR on sensor parameters

Outline

- Background
- **Description/ Analysis of High DR Schemes**
  - Well Capacity Adjusting
  - Multiple Capture
  - Spatially Varying Exposure
  - Time to Saturation
- **Other HDR Image Sensors**
  - Logarithmic Sensor
  - Local Adaptation
- **Conclusion**
- **References**

Extending Dynamic Range

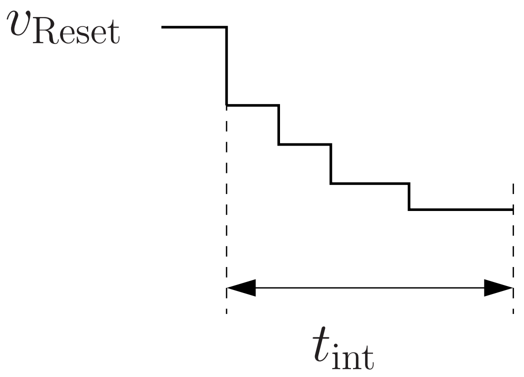
- To increase dynamic range we need to increase $i_{\max}$ and/or decrease $i_{\min}$
    - $i_{\max} \approx \frac{qQ_{\text{sat}}}{t_{\text{int}}}$, **increases as integration time is decreased**
    - $i_{\min} = \sqrt{\frac{q}{t_{\text{int}}} i_{dc} + (\frac{q\sigma_r}{t_{\text{int}}})^2}$, **decreases as integration time is increased**
- To increase dynamic range need to spatially 'adapt' pixel integration times to illumination
    - **short integration times for pixels with high illumination**
    - **long integration times for pixels with low illumination**
- Integration time can't be made too long due to saturation and motion
- The HDR techniques only increase $i_{\max}$ (for a given maximum integration time)
- Recent work [3] shows how $i_{\min}$ can be reduced by lowering read noise and preventing motion blur

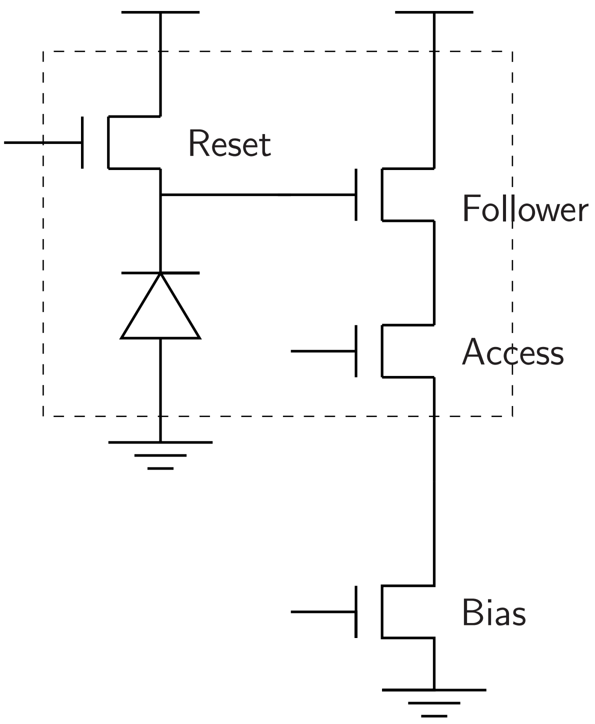
The Plan

- To describe Well Capacity Adjusting and Multiple Capture
- To analyze their SNR and show that the increase in dynamic range comes at the expense of decrease in SNR
  - **Multiple Capture achieves higher SNR than Well Capacity Adjusting for the same increase in dynamic range (see [4])**
- To describe two other techniques: Spatially Varying Exposure and Time-to-Saturation
- To briefly describe two other types of sensors that do not use direct integration: Logarithmic Sensor and Local Adaptation
- To qualitatively compare these six HDR techniques

Well Capacity Adjusting

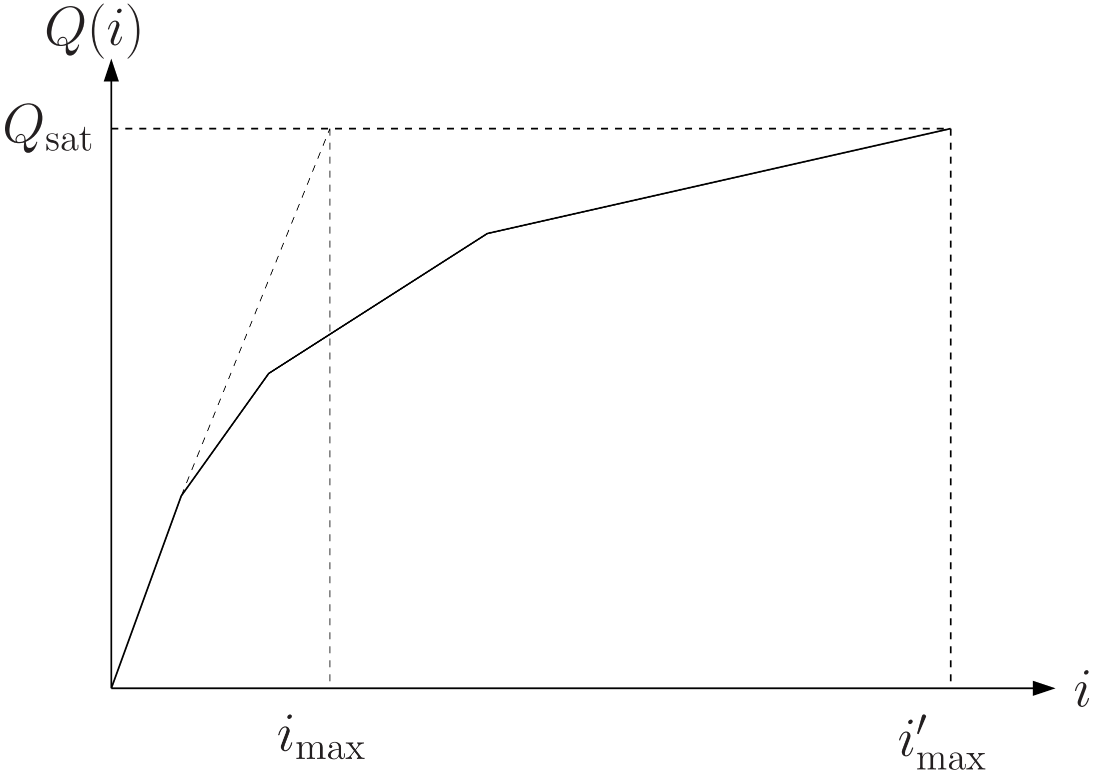
- Available well capacity is increased one or more times during integration (idea initially applied to CCDs [5,6])
- For APS this is done by adjusting the reset signal one or more times during integration [7]:





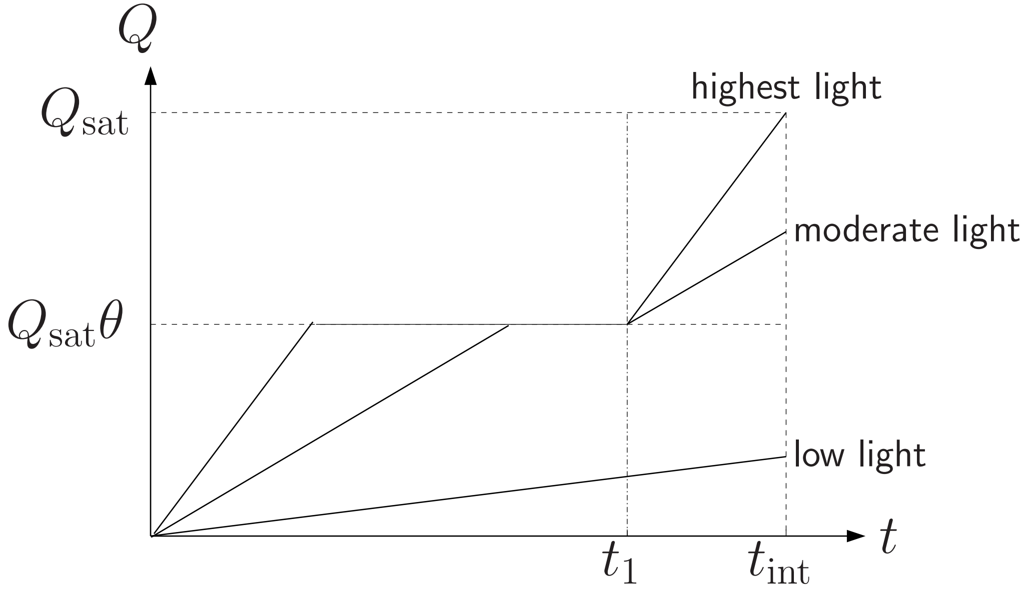
Sensor Transfer Function

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



Analysis of Well Capacity Adjusting

- Consider the case of a single well capacity adjustment:



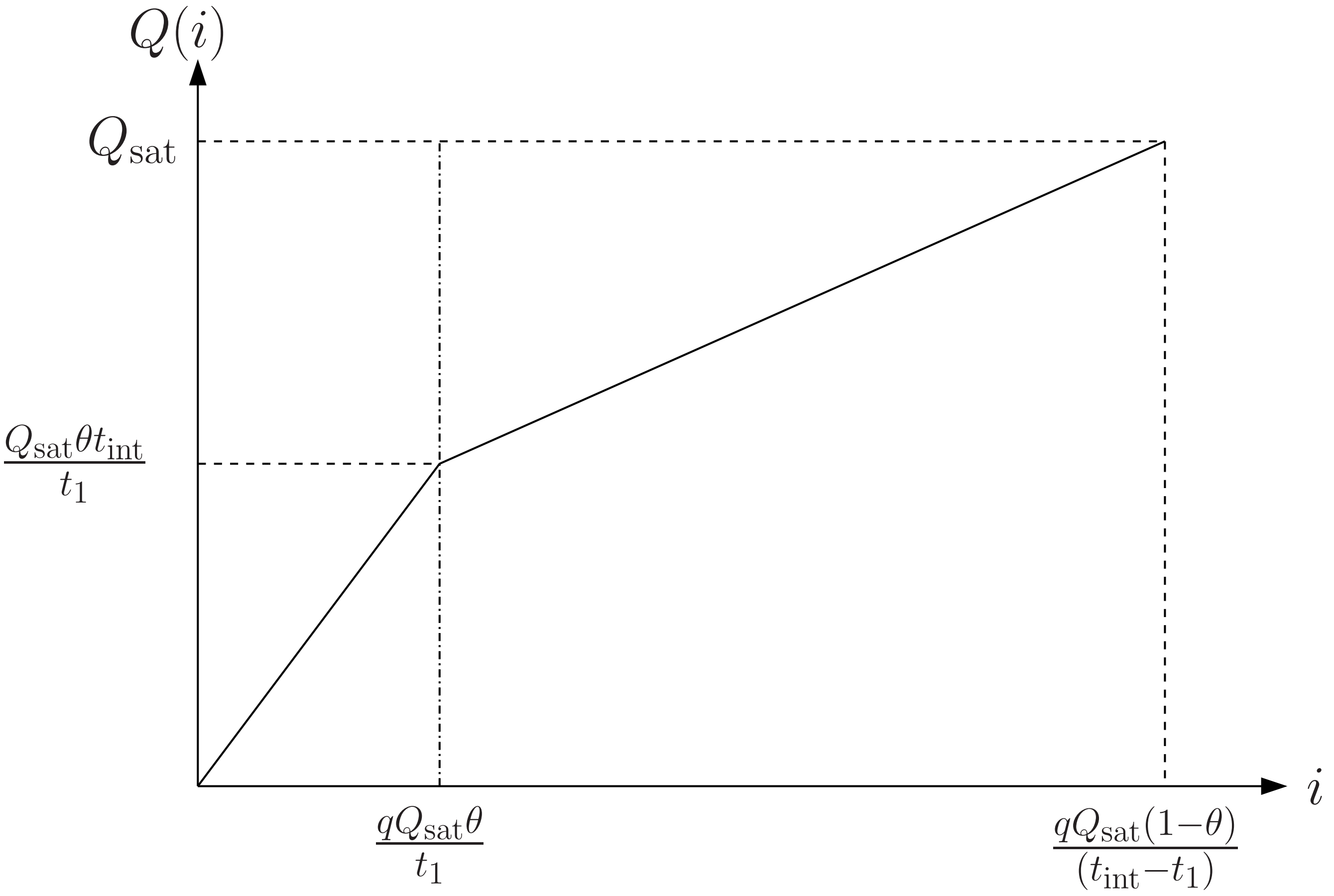
- Largest nonsaturating current is now given by

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

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

$$\mathsf{DRF} \approx \frac{(1-\theta)}{(1-\frac{t_1}{t_{\mathrm{int}}})}$$

Sensor Transfer Function



Well Capacity Adjusting Example

78**dB Scene**

Using Well Capacity Adjusting (DRF=16)

SNR for Well Capacity Adjusting

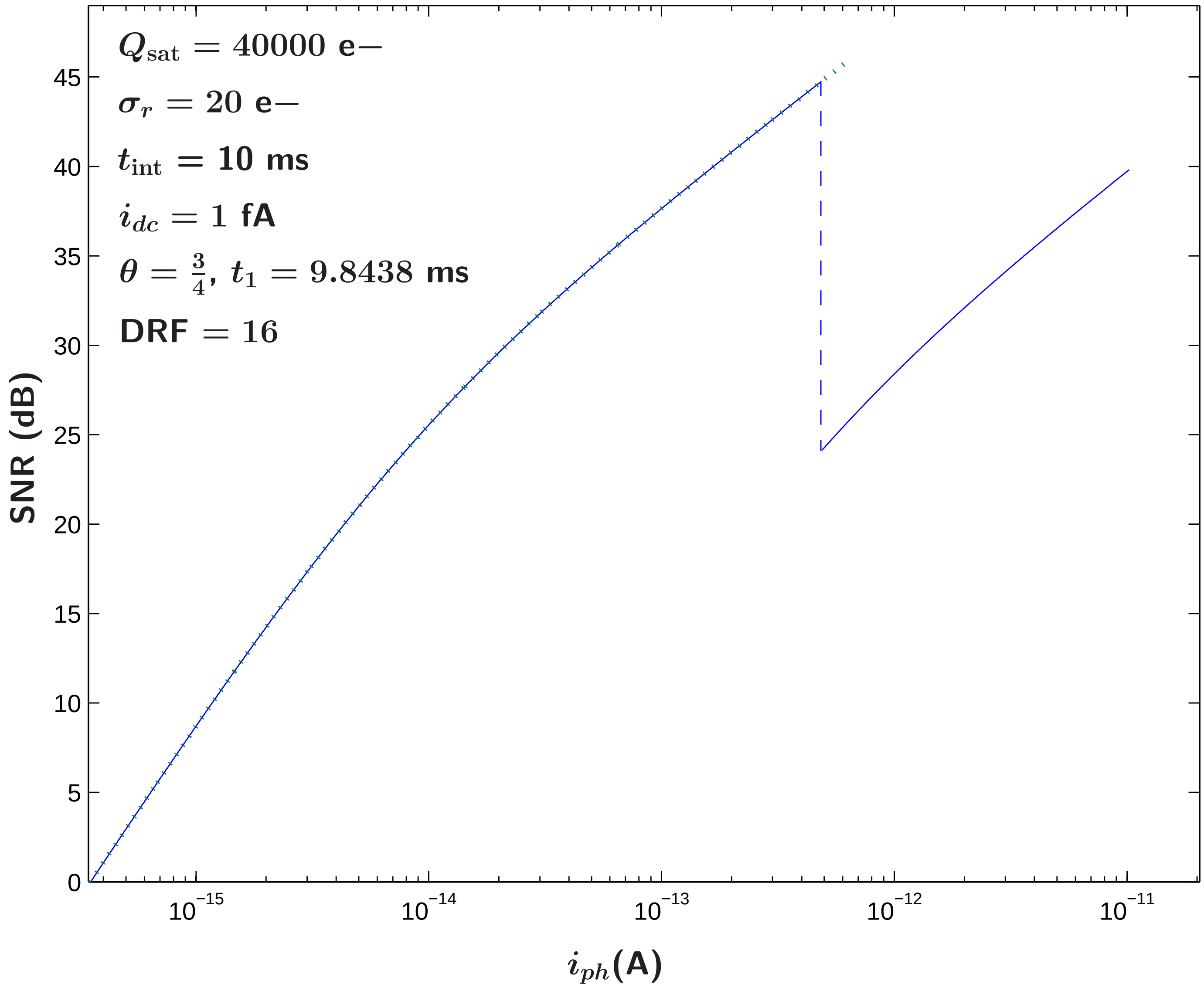
- Again consider the single well capacity adjusting case:
- For $0 \leq i_{ph} < \frac{qQ_{\text{sat}}\theta}{t_1} - i_{dc}$, the SNR is the same as for the normal sensor operation, and we get

$$\text{SNR}(i_{ph}) = 10\log_{10} \frac{i_{ph}^2}{\frac{q^2}{t_{\text{int}}^2}(\frac{1}{q}(i_{ph} + i_{dc})t_{\text{int}} + \sigma_r^2)} \text{ dB}$$

- For $\frac{qQ_{\text{sat}}\theta}{t_1} - i_{dc} \leq i_{ph} < \frac{qQ_{\text{sat}}(1-\theta)}{(t_{\text{int}}-t_1)} - i_{dc}$, the variance of the noise charge is given by $\frac{1}{q}(i_{ph} + i_{dc})(t_{\text{int}} - t_1) + \sigma_r^2$ electrons^2
- So the variance of the equivalent input referred noise current is given by $\sigma_{I_n}^2 = \frac{q^2}{(t_{\text{int}}-t_1)^2}(\frac{1}{q}(i_{ph} + i_{dc})(t_{\text{int}} - t_1) + \sigma_r^2)$ A^2
- Thus, the signal to noise ratio

$$\text{SNR}(i_{ph}) = 10\log_{10} \frac{i_{ph}^2}{\frac{q^2}{(t_{\text{int}}-t_1)^2}(\frac{1}{q}(i_{ph} + i_{dc})(t_{\text{int}} - t_1) + \sigma_r^2)} \text{ dB}$$

Example


$Q_{\text{sat}} = 40000$ e−
$\sigma_r = 20$ e−
$t_{\text{int}} = 10$ ms
$i_{dc} = 1$ fA
$\theta = \frac{3}{4}$, $t_1 = 9.8438$ ms
DRF $= 16$
SNR (dB)
45
40
35
30
25
20
15
10
5
0
10^{-15}
10^{-14}
10^{-13}
10^{-12}
10^{-11}
i_{ph}(A)

SNR DIP

- Notice the 21dB dip in the SNR example at the transition point:

$$i_{ph} = \frac{qQ_{\text{sat}}\theta}{t_1} - i_{dc} = 487 \text{ fA}$$

- In general, the DIP is given by

$$\begin{aligned}
\text{DIP} &= 10\log_{10} \frac{t_{\text{int}}^2}{(t_{\text{int}} - t_1)^2} \frac{(Q_{\text{sat}}\theta \frac{(t_{\text{int}} - t_1)}{t_1} + \sigma_r^2)}{(Q_{\text{sat}}\theta \frac{t_{\text{int}}}{t_1} + \sigma_r^2)} \\
&\approx 10\log_{10} \frac{1}{1 - \frac{t_1}{t_{\text{int}}}} \\
&= 10\log_{10} \frac{\text{DRF}}{(1 - \theta)}
\end{aligned}$$

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

Well-Adjusting Issues

- Increasing DR directly lowers SNR
- Implementation is straightforward – well adjusting causes more noise and FPN (not accounted for in analysis)
- Sensor response is nonlinear
    - CDS only effective at low illumination
    - Color processing ?

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**
- Combine images into HDR image, *e.g.*, using Last Sample Before Saturation algorithm:
  - **Only extends dynamic range at high illumination end**
- Implementation of 2 captures demonstrated for CCDs and CMOS APS [8]
- Implementing many captures requires very high speed non-destructive readout – 9 captures demonstrated using DPS [9]
- Recent work [3] shows that dynamic range can also be extended at the low illumination by appropriately "averaging" the captured images to reduce read noise

Multiple Capture Example

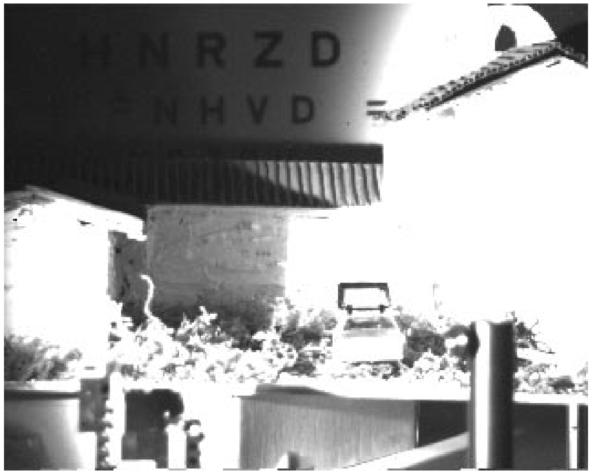
T

$2T$

$4T$

$8T$

$16T$

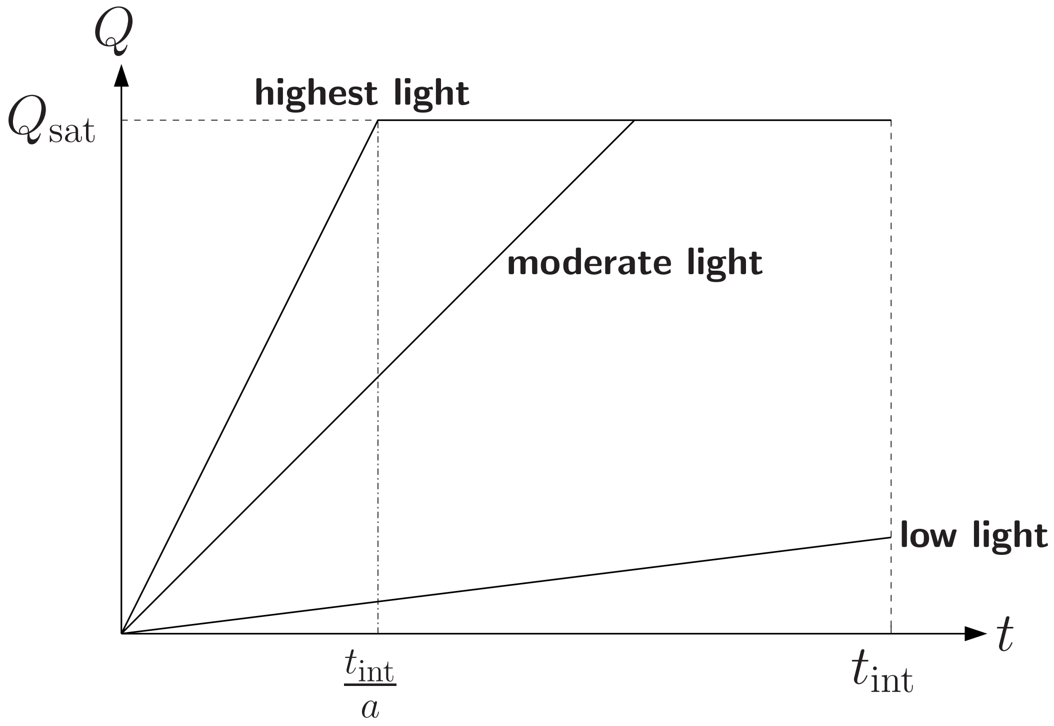


$32T$

High Dynamic Range Image

Analysis of Multiple Capture

- Consider the case of two captures:



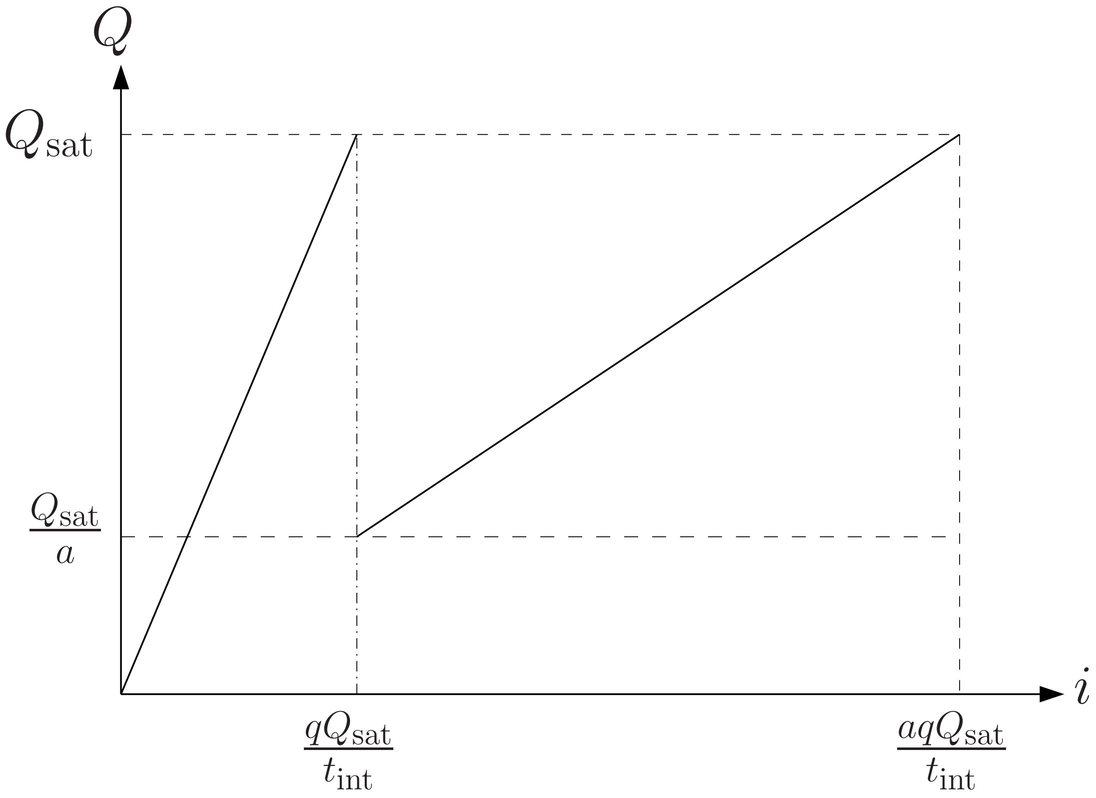
- The largest nonsaturating current is now

$$i_{\max} = \frac{aqQ_{\text{sat}}}{t_{\text{int}}} - i_{dc}$$

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

Sensor Transfer Function

- The current to charge response using the Last Sample Before Saturation algorithm



SNR for Multiple Capture

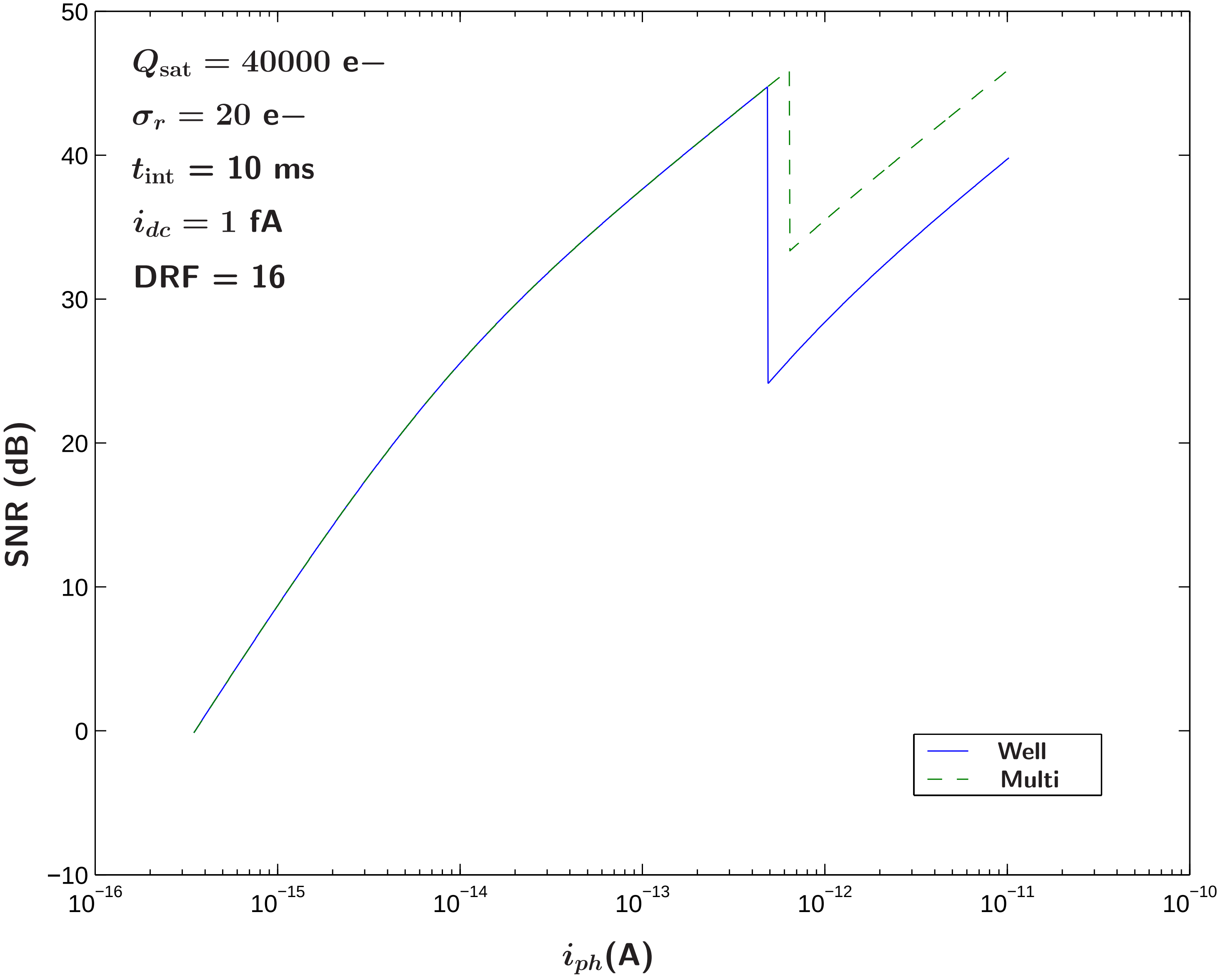
- Consider the case of two captures and the Last Sample Before Saturation algorithm
- For $0 \leq i_{ph} < \frac{qQ_{\text{sat}}}{t_{\text{int}}} - i_{dc}$, the SNR is the same as for the normal operation, and we get

$$\text{SNR}(i_{ph}) = 10 \log_{10} \frac{i_{ph}^2}{\frac{q^2}{t_{\text{int}}^2}(\frac{1}{q}(i_{ph} + i_{dc})t_{\text{int}} + \sigma_r^2)} \text{ dB}$$

- For $\frac{qQ_{\text{sat}}}{t_{\text{int}}} - i_{dc} \leq i_{ph} < \frac{aqQ_{\text{sat}}}{t_{\text{int}}} - i_{dc}$, the SNR is the same as normal operation with t_{int} replaced by t_{int}/a, and we get

$$\text{SNR}(i_{ph}) = 10 \log_{10} \frac{i_{ph}^2}{\frac{a^2 q^2}{t_{\text{int}}^2}(\frac{1}{q}(i_{ph} + i_{dc})\frac{t_{\text{int}}}{a} + \sigma_r^2)} \text{ dB}$$

SNR Example


$Q_{\text{sat}} = 40000$ e−
$\sigma_r = 20$ e−
$t_{\text{int}} = 10$ ms
$i_{dc} = 1$ fA
DRF = 16
50
40
30
20
10
0
−10
10^{-16}
10^{-15}
10^{-14}
10^{-13}
10^{-12}
10^{-11}
10^{-10}
SNR (dB)
i_{ph}(A)
Well
Multi

SNR DIP

- Notice that SNR dips by 12.6 dB at the transition current $i_{ph} = \frac{qQ_{\text{sat}}}{t_{\text{int}}} - i_{dc} = 640$ fA
- In general

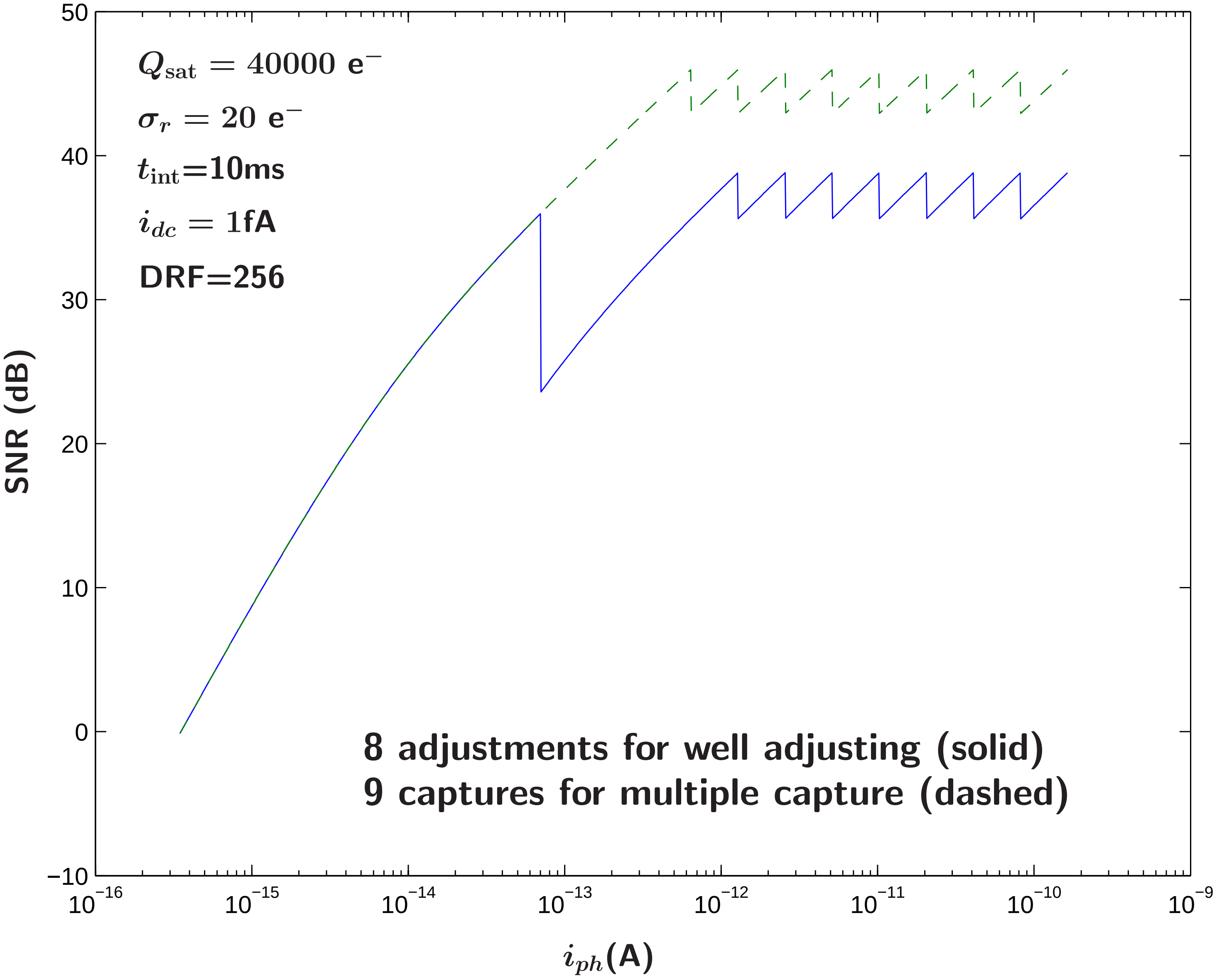
$$\text{DIP} = 10\log_{10} \frac{a^2(\frac{Q_{\text{sat}}}{a} + \sigma_r^2)}{(Q_{\text{sat}} + \sigma_r^2)} \approx 10\log_{10} \text{DRF dB}$$

- Recall that for well capacity adjusting

$$\text{DIP} \approx 10\log_{10} \frac{\text{DRF}}{(1-\theta)},$$

which is larger for the same DRF

Well Adjusting versus Multiple Capture

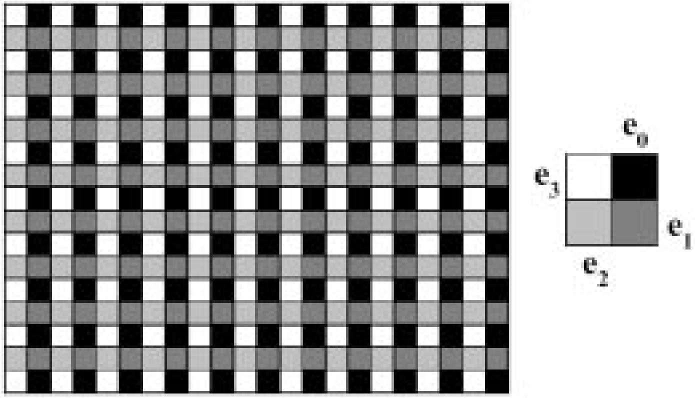


Multiple Capture Issues

- SNR for normal sensor signal range is not affected
- SNR maintained over extended dynamic range
- Response is linear – can use CDS and perform conventional color processing
- 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 – HDR image can look segmented
- Multiple capture implementation is quite difficult, needs
  - Very high speed non-destructive readout (see [10])
  - On-chip memory and some logic to perform reconstruction of HDR image during capture

Spatially Varying Exposure

- The spatially varying exposure technique [11] implements multiple capture using a conventional sensor by sacrificing spatial resolution
- The idea is to deposit an array of neutral density filters on the sensor so that in a single capture pixels with darker filters sample high lights while pixels with lighter filters sample low lights



- High dynamic range image synthesized using low pass filtering or more sophisticated techniques such as cubic interpolation

Spatially Varying Exposure Issues

- Very simple to implement and requires no change to the sensor itself
- Blocking light reduces sensor sensitivity and SNR
- Very high resolution sensor is needed, since spatial resolution is reduced
- DR is extended at the high illumination end only (same as multiple capture using the Last Sample Before Saturation algorithm)

Time-to-Saturation

- The idea is to measure the integration time required to saturate each pixel, the photocurrent is estimated by

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

  so the sensor current to time transfer function is nonlinear

- SNR is maximized for each pixel and is equal to

  $$\text{SNR} = 20\log_{10}\frac{Q_{\text{sat}}}{\sqrt{Q_{\text{sat}} + \sigma_r^2}} \approx 10\log_{10} Q_{\text{sat}}$$

- Minimum detectable current is limited by maximum allowable integration time (not zero !)

  $$i_{\min} \geq \frac{qQ_{\text{sat}}}{t_{\text{int}}}$$

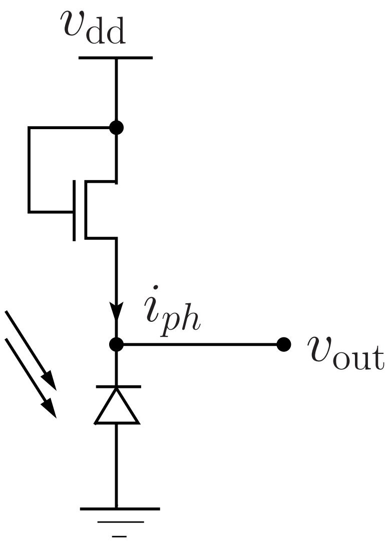
  and the maximum detectable current is limited by circuit mismatches, readout speed, and FPN (it is not infinity !) [12,13,14]

Time-to-Saturation Issues

- Implementation is quite difficult – need a way to detect saturation for each pixel, then record the time
  - If global circuits are used [13], contention can severely limit performance
  - If done at the pixel level [14], pixel size may become unacceptably large
- i_{min} can be unacceptably large (=213fA for $Q_{\text{sat}} = 40000\text{e}-$ and $t_{\text{int}} = 30\text{ms}$) unless sensor is read out at t_{int}
- No CDS support

Logarithmic Sensor

- In logarithmic sensors, photocurrent is directly converted to voltage for readout [15]

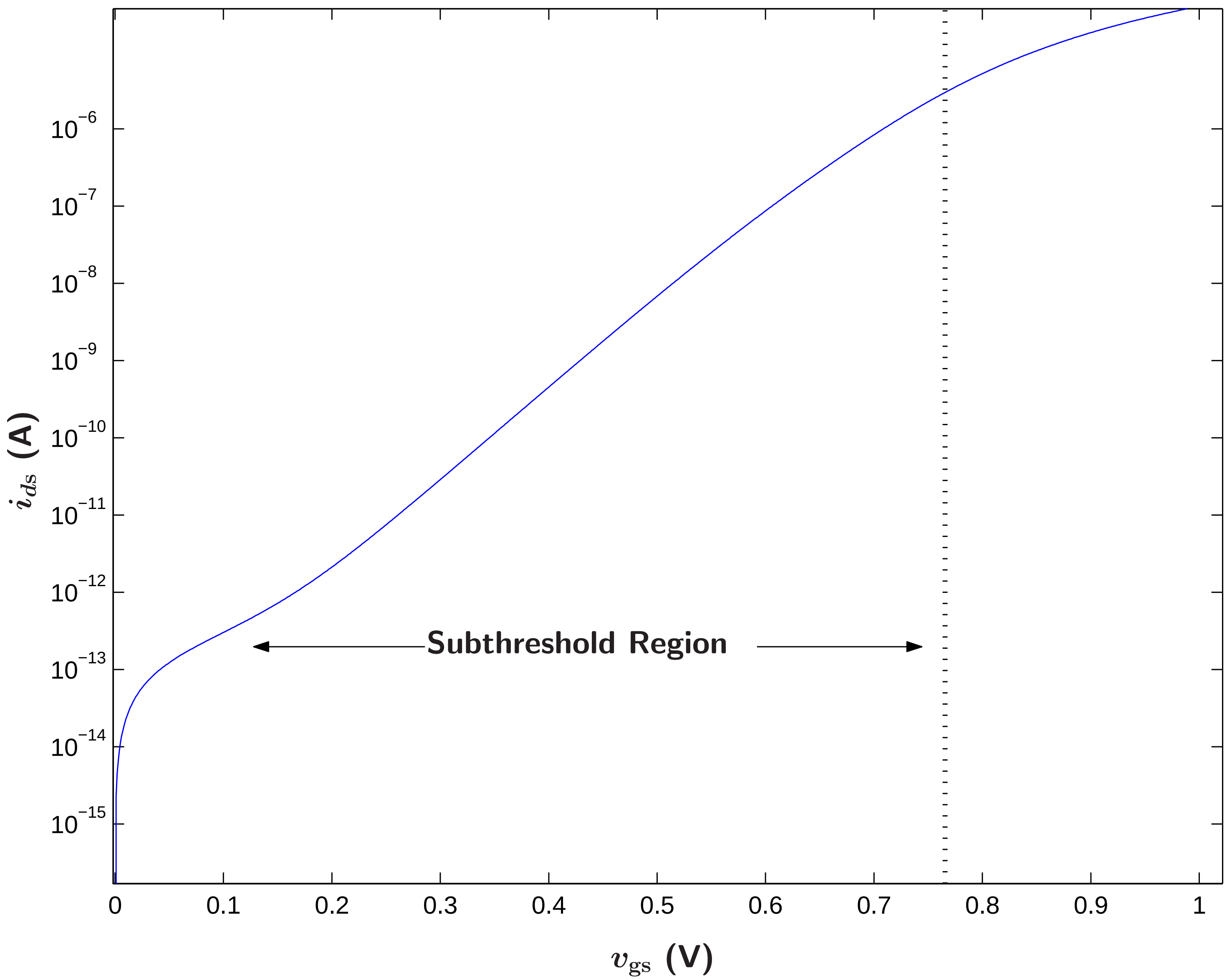


- High dynamic range achieved via *logarithmic compression* during conversion (to voltage), using exponential I–V curve of MOS transistor in subthreshold

$$v_{\mathrm{out}} = k \ln \frac{i_{ph}}{I_o}$$

- Up to 5–6 decades of dynamic range compressed into 0.5V range (depending on v_{T} and the number of series transistors)

MOSFET Subthreshold I-V Characteristic



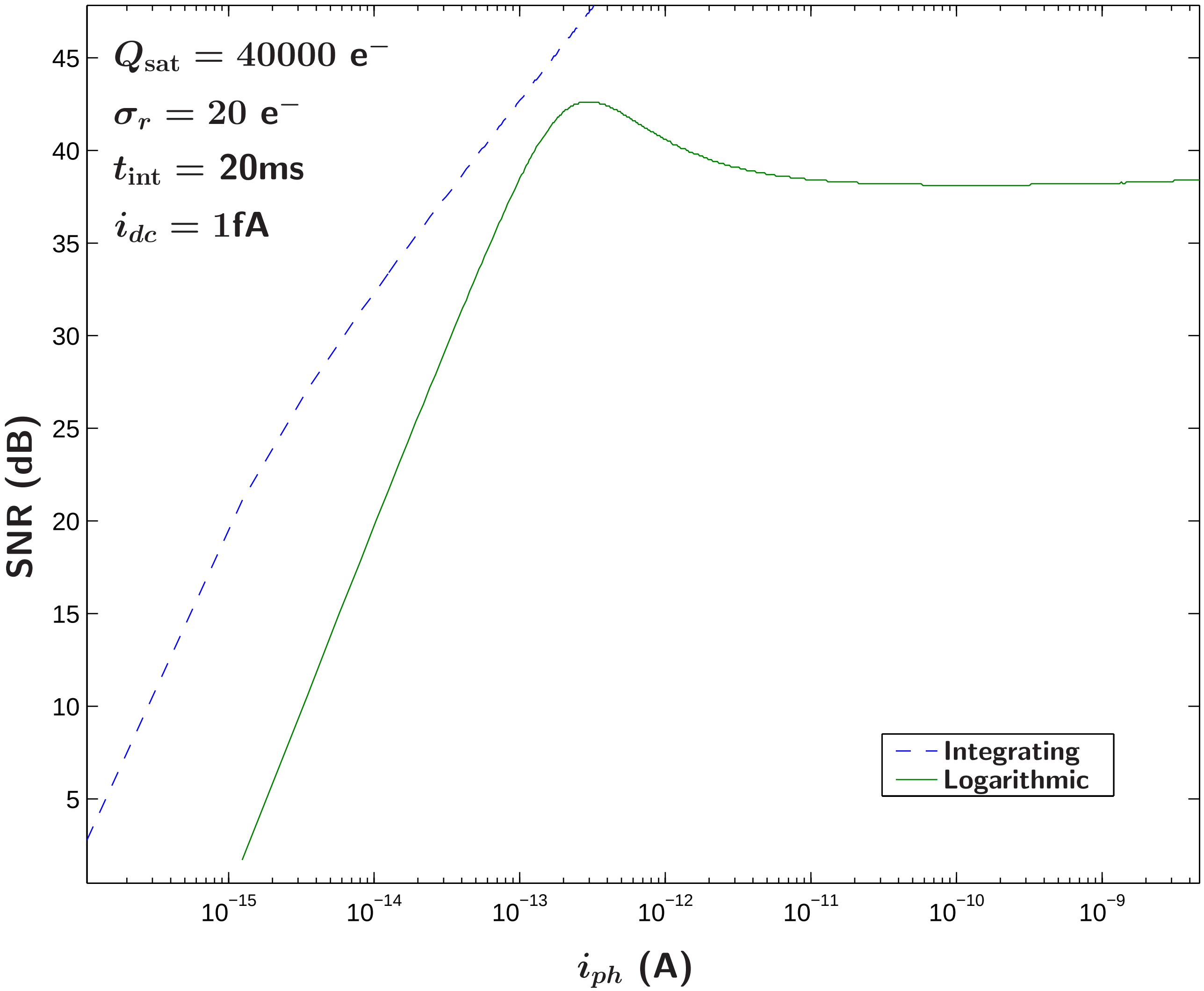
Logarithmic Compression Issues

- Large variation in subthreshold MOSFET characteristics and threshold voltage cause high FPN
  - **Offset FPN as high as 10-40% of swing reported**
  - **Since CDS cannot be used, FPN can only be corrected by storing the offsets or other techniques, which increase complexity [15]**
- Succeeding circuitry must be extremely precise to make use of the dynamic range afforded by the compressed output voltage
- Non-integrating nature limits achievable SNR even for high illumination due to exponential transconductance relationship

$$\text{SNR}(i_{ph}) = 10\log_{10}\frac{i_{ph}^2 kTC_D}{q^2(i_{ph}+i_{dc})^2} \approx 10\log_{10}\frac{kTC_D}{q^2}$$

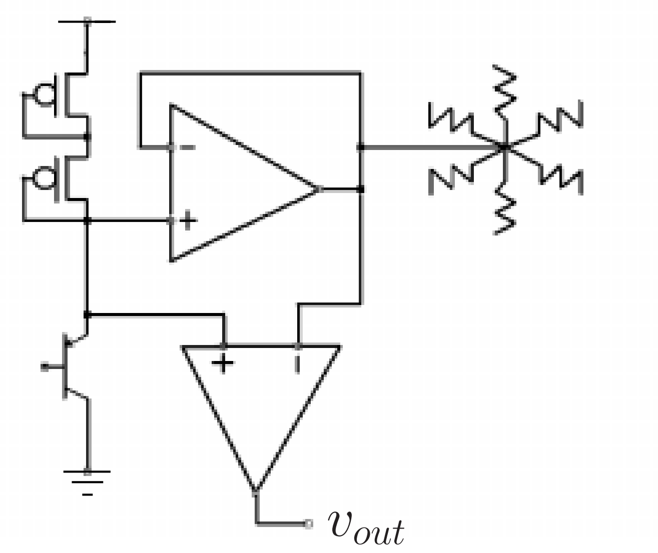
Note: Here we neglected read noise (which would make SNR even worse)

SNR for Logarithmic vs. Integrating Sensor



Local Adapatation (Artificial Retina)

- The idea is to mimic biological vision systems where local averages are subtracted off each receptor value in order to increase the contrast while maintaining wide dynamic range [16,17]
- Hexagonal *resistive network* is used to weight closer pixels exponentially higher than distant ones, thereby approximating *Gaussian smoothing*



Comparison Between HDR Schemes

	Well-Adjust	Multi-Capture	Spatial	Saturation	Log	Adapt
DR:						
i_{max}	↑	↑	↑	↑	↑	↑
i_{min}	Same	Same/ ↓	↑	↑	↑	↑
Linearity	No	Yes	Yes	No	No	No
CDS	No	Yes	Yes	No	No	No
SNR	$-$	$+$	$--$	$-$	$--$	$--$
Complexity:						
Pixel	Low	Med-High	Low	High	Med	High
External	Low	Low-Med	High	High	Low	Low

Conclusion

- Defined image sensor DR and SNR and discussed their dependencies on sensor parameters
- Described six techniques for extending DR:
  - Well Adjusting
  - Mutiple Capture
  - Spatially Varying Exposure
  - Time to saturation
  - Logarithmic
  - Local adaptation (artificial retina)
- All techniques only increase $i_{\max}$ (Multiple Capture can also decrease $i_{\min}$ by weighted averaging)
- SNR can be used to compare different HDR sensors
- Multiple Capture with weighted averaging is the most effective method but requires high speed non-destructive readout sensor and DSP hardware to implement

References

[1] A. El Gamal, *392b Lectures and Classnotes*, Stanford University, 2001.

[2] A. J. P. Theuwissen, *Solid-State Imaging with Charge-Coupled Devices*. Norwell, MA: Kluwer, 1995.

[3] 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.

[4] 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.

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

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

[7] 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.

[8] 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.

[9] 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.

[10] 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.

[11] S. K. Nayar and T. Mitsunaga, "High dynamic range imaging: Spatially varying pixel exposures." *http://www.cs.columbia.edu/CAVE/*, March 2000.

[12] V. Brajovic, T. Kanade, "A sorting image sensor: an example of massively parallel intensity-to-time processing for low-latency computational sensors." *Proceedings of the 1996 IEEE International Conference on Robotics and Automation*, Minneapolis, MN, pp. 1638-1643.

[13] E. Culurciello, R. Etienne-Cummings, and K. Boahen, "High dynamic range, arbitrated address event representation digital imager." *The 2001 IEEE International Symposium on Circuits and Systems*, Vol. 2, pp. 505-508, 2001.

[14] V. Brajovic, R. Miyagawa and T. Kanade, "Temporal photoreception for adaptive dynamic range image sensing and encoding." *Neural Networks*, Vol. 11, pp. 1149-1158, 1998.

[15] S. Kavadias, B. Dierickx, D. Scheffer, A. Alaerts, D. Uwaerts, J. Bogaerts, "A Logarithmic Response CMOS Image Sensor with On-Chip Calibration", IEEE Journal of Solid-State Circuits, Volume 35, Number 8, August 2000

[16] C. A. Mead and M. A. Mahowald, "A Silicon Model of Early Visual Processing," *Neural Networks*, vol. 1, pp. 91-97, 1988.

[17] C. A. Mead, "Adaptive Retina," *Analog VLSI Implementation of Neural Systems*, C. Mead and M. Ismail, Eds., Boston: Kluwer Academic Pub., pp. 239-246, 1989.

Supplementary References:

[18] M. Aggarwal, N. Ahuja, "High dynamic range panoramic imaging." *Proceedings of Eighth IEEE International Conference on Computer Vision*, Vol. 1, pp. 2-9, 2001.

[19] V. Brajovic, "Sensory Computing." Conference 4109: *Critical Technologies for the Future of Computing*, SPIE's 45th Annual Meeting, SPIE, 2000.

[20] S. Chen, R. Ginosar, "Adaptive sensitivity CCD image sensor." Conference C: Signal Processing, *Proceedings of the 12th IAPR International Conference on Pattern Recognition*, Vol. 3, pp. 363-365, 1994.

[21] T. Delbruck and C. A. Mead, "Analog VLSI phototransduction." California Institute of Technology, CNS Memo No. 30, May 11, 1994.

[22] T. Hamamoto, K. Aizawa, "A computational image sensor with adaptive pixel-based integration time" *IEEE Journal of Solid-State Circuits*, Vol. 36, Issue 4, pp. 580-585, April 2001.

[23] M. Loose, K. Meier, J. Schemmel, "A self-calibrating single-chip CMOS camera with logarithmic response." *IEEE Journal of Solid-State Circuits*, Vol. 36, Issue 4, pp. 586-596, April 2001.

[24] C. A. Mead, "A Sensitive Electronic Photoreceptor," In *1985 Chapel Hill Conference on VLSI*, H. Fuchs, Ed., Rockville: Computer Science Press, pp. 463-471, 1985.

[25] N. Ricquier and B. Dierickx, "Pixel structure with logarithmic response for intelligent and flexible imager architectures," *Microelectronic Eng.*, vol. 19, pp. 631-634, 1992.

[26] M. Schanz, C. Nitta, A. Bussmann, B.J. Hosticka, and R.K. Wertheimer, "A high-dynamic-range CMOS image sensor for automotive applications." *IEEE Journal of Solid-State Circuits*, Vol. 35, Issue 7, pp. 932-938, July 2000.

[27] O. Schrey, R. Hauschild, B.J. Hosticka, U. Iurgel, and M. Schwarz, "A locally adaptive CMOS image sensor with 90 dB dynamic range." *Solid-State Circuits Conference Digest of Technical Papers*, pp. 310-311, 1999.

[28] Y. Wang, S. Barna, S. Campbell, and E. Fossum, "A High Dynamic Range CMOS Image Sensor." *In Proceedings of 2001 IEEE Workshop on Charge-Coupled Devices and Advanced Image Sensors*, pp. 137-140, June 2001.

[29] O. Yadid-Pecht, "Wide dynamic range sensors." *Optical Engineering*, Vol. 38, No. 10, pp. 1650-1660, October 1999.

[30] Yadid-Pecht, O.; Belenky, A. "Autoscaling CMOS APS with customized increase of dynamic range." *Solid-State Circuits Conference: Digest of Technical Papers.* pp. 100-101, 2001.

[31] W. Yang, "A wide-dynamic-range, low power photosensor array." *IEEE ISSCC* Vol. 37, 1994.