Quantitative Study of High Dynamic Range Image Sensor Architectures

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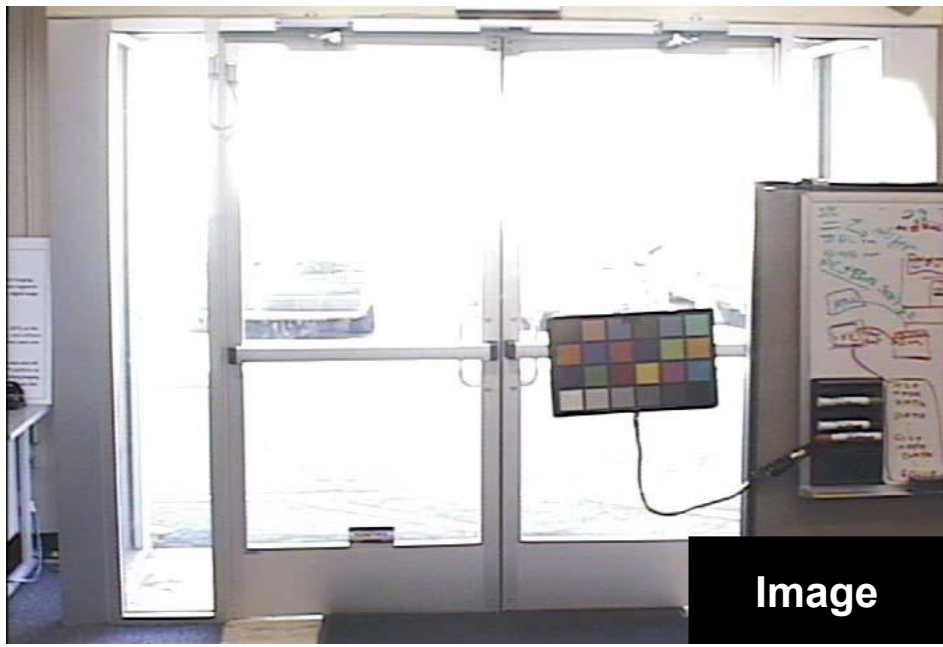
Scene DR > Image Sensor DR



Courtesy Pixim Corporation

DR Extension Methods

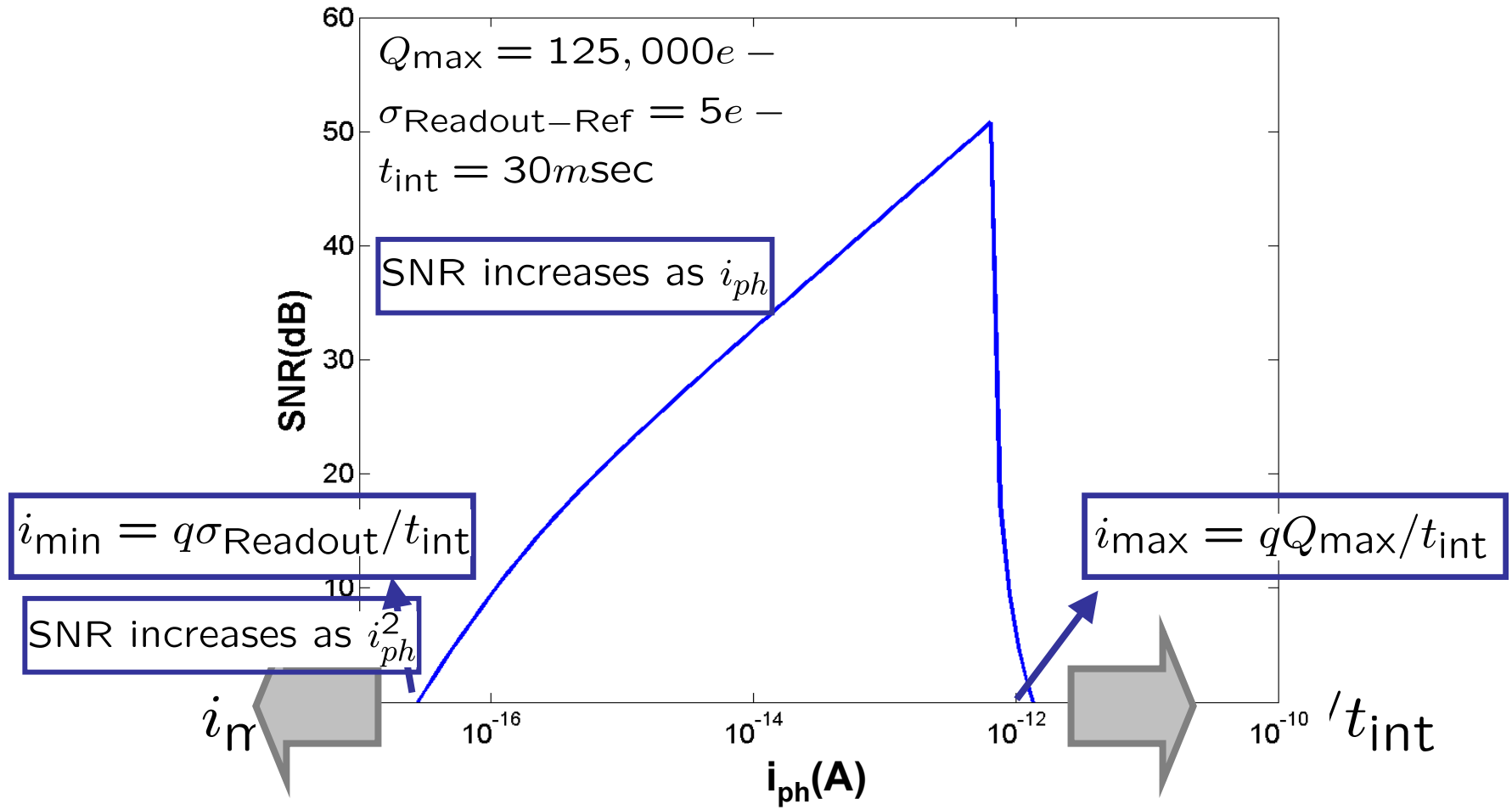
- Several methods have been developed to extend image sensor DR
- Deep submicron CMOS image sensor processes [Wuu '01] and vertical integration [Kozlowski '02] enable implementation of high DR, high fidelity methods
- This work studies four such schemes:
  - Time-to-saturation [Lule '99, Stoppa '02]
  - Multiple-capture [Yang '99, Kleinfelder '01, Bidermann '03]
  - Asynchronous self-reset with multiple capture [Liu '03]
  - Synchronous self-reset with residue readout [Bermak '02, Rhee '03]

SNR as Fidelity Measure

- How should these methods be compared?
- Methods can be partially compared based on their SNR [Yang '99, El Gamal '02]:
  - Some schemes extend DR but at expense of SNR
- This work:
  - Quantify SNR for the four schemes
  - Consider non-idealities due to implementation, especially due to pixel area constraint

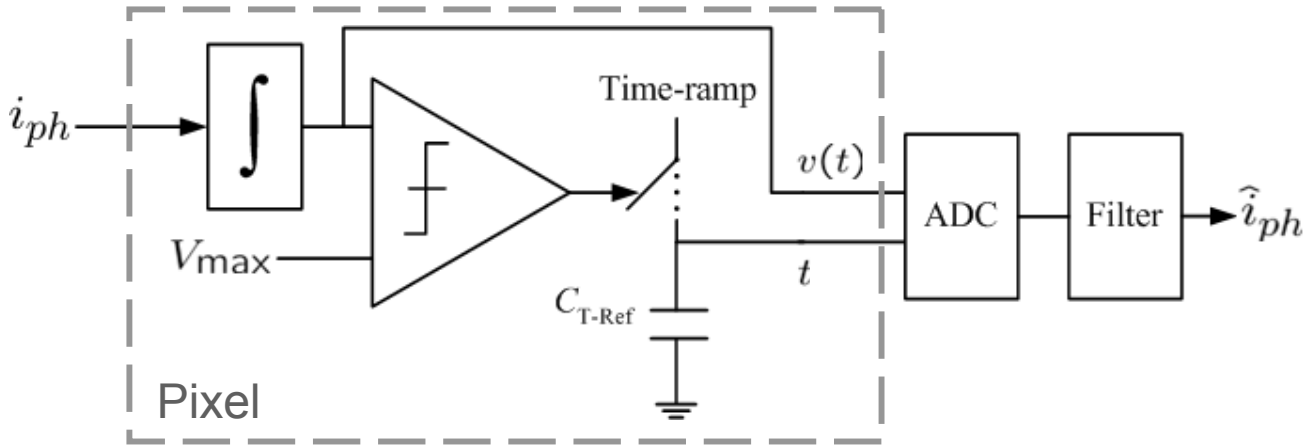
Conventional (Reference) Sensor

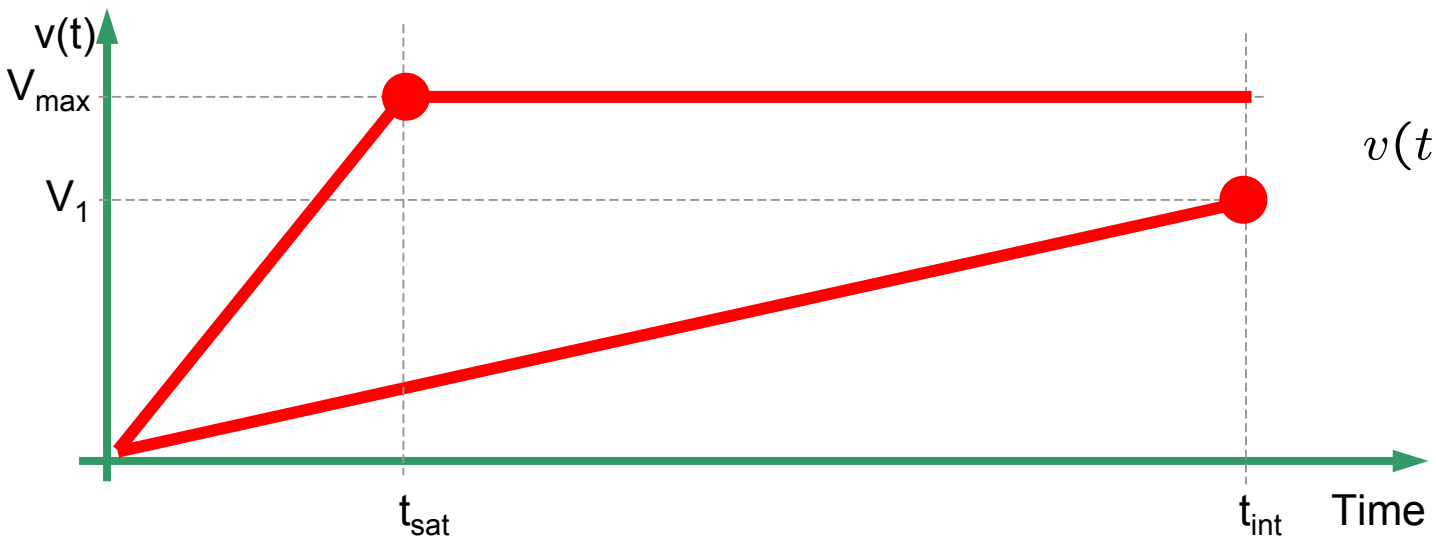
- CCD, APS, CTIA



Time-to-Saturation

[Lule '99, Stoppa '02]

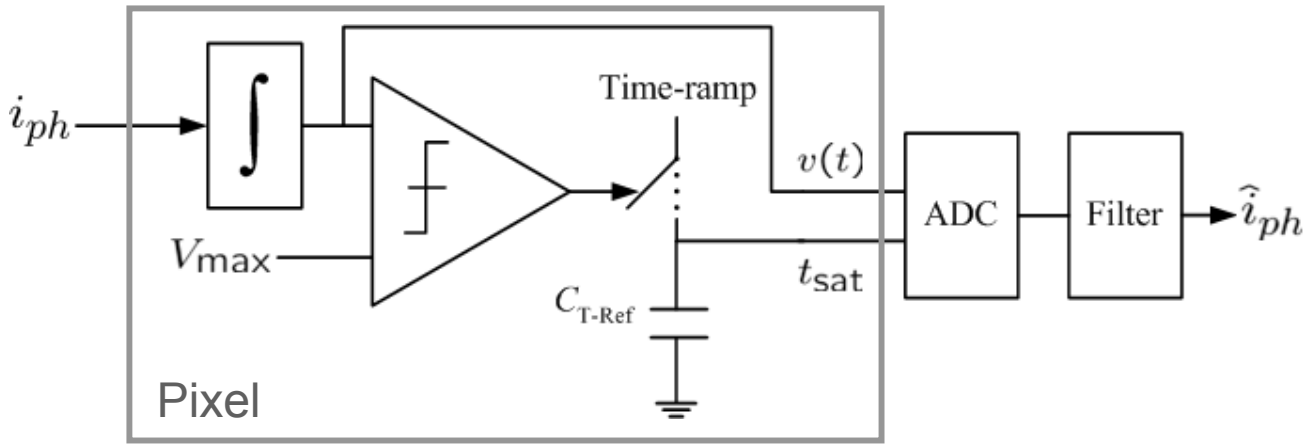




$$v(t_{int}) = V_{max}$$
$$t = t_{sat}$$
$$\widehat{i}_{ph} \propto V_{max}/t_{sat}$$

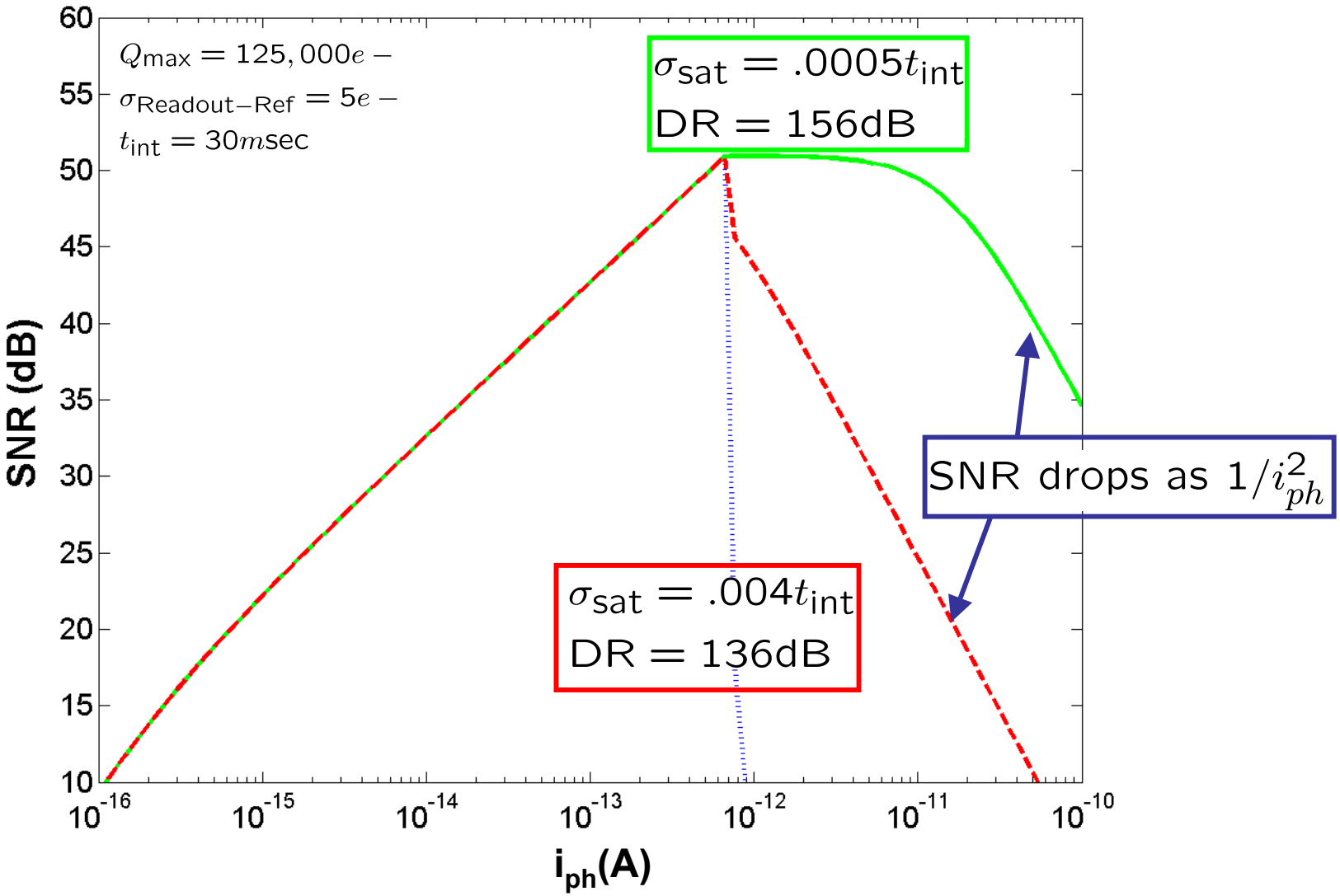
Time-to-Saturation

[Lule '99, Stoppa '02]



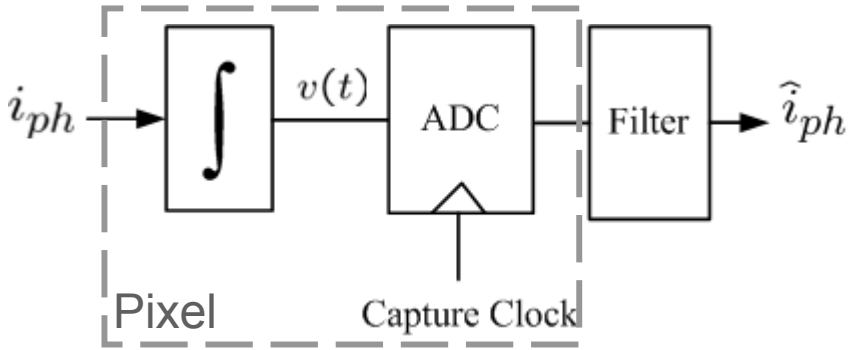
- $i_{min} = q\sigma_{Readout}/t_{int}$
  - ✓ Similar to reference sensor
- i_{max} and SNR limited by:
  - ✘ t_{sat} inaccuracy due to comparator noise/delay, time-ramp inaccuracy, kTC of $C_{T\text{-}Ref}$ (inaccuracy in t_{sat} measured by σ_{sat})
- $i_{max} = qQ_{max}/\sigma_{sat}$

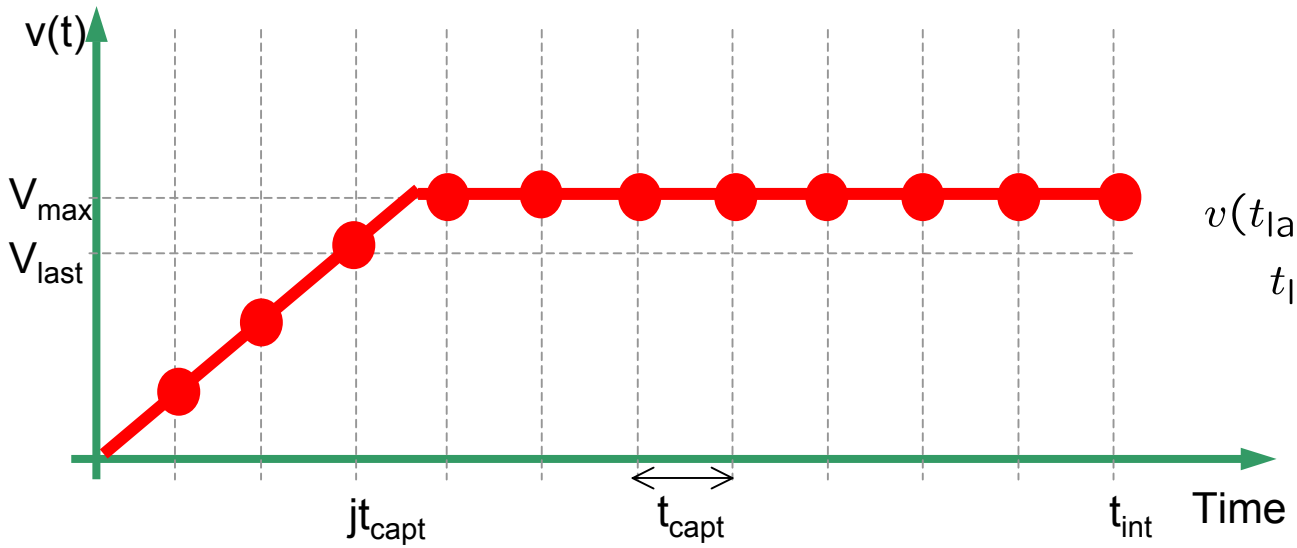
SNR


$Q_{\max} = 125,000e-$
$\sigma_{\text{Readout-Ref}} = 5e-$
$t_{\text{int}} = 30m\text{sec}$
$\sigma_{\text{sat}} = .0005t_{\text{int}}$
DR = 156dB
$\sigma_{\text{sat}} = .004t_{\text{int}}$
DR = 136dB
SNR drops as $1/i_{ph}^2$
SNR (dB)
i_{ph}(A)
60
55
50
45
40
35
30
25
20
15
10
10^{-16}
10^{-15}
10^{-14}
10^{-13}
10^{-12}
10^{-11}
10^{-10}

Multiple-Capture

[Yang '99, Kleinfelder '01, Bidermann '03]

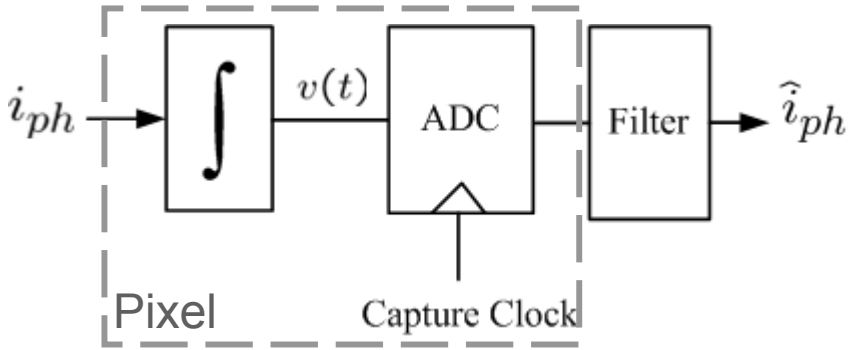


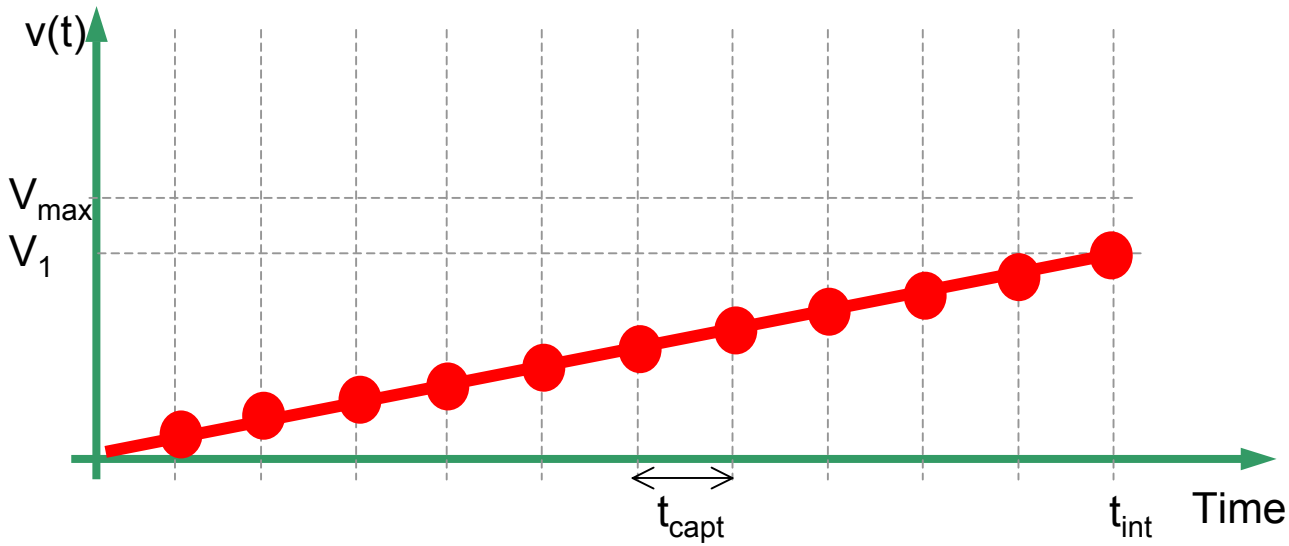


$$v(t_{\text{last-sample}}) = V_{\text{last}}$$
$$t_{\text{last-sample}} = jt_{\text{capt}}$$
$$\widehat{i}_{ph} \propto V_{last}/(jt_{\text{capt}})$$

Multiple-Capture

[Yang '99, Kleinfelder '01, Bidermann '03]

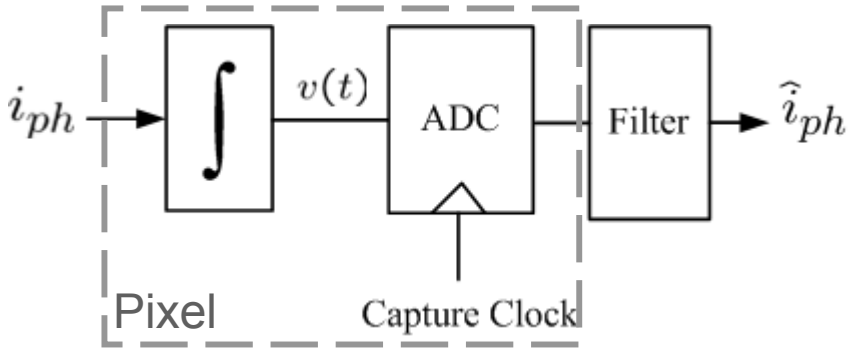




$$v(t_{\text{last-sample}}) = V_1$$
$$t_{\text{last-sample}} = t_{\text{int}}$$
$$\hat{i}_{ph} \propto V_1/t_{\text{int}}$$

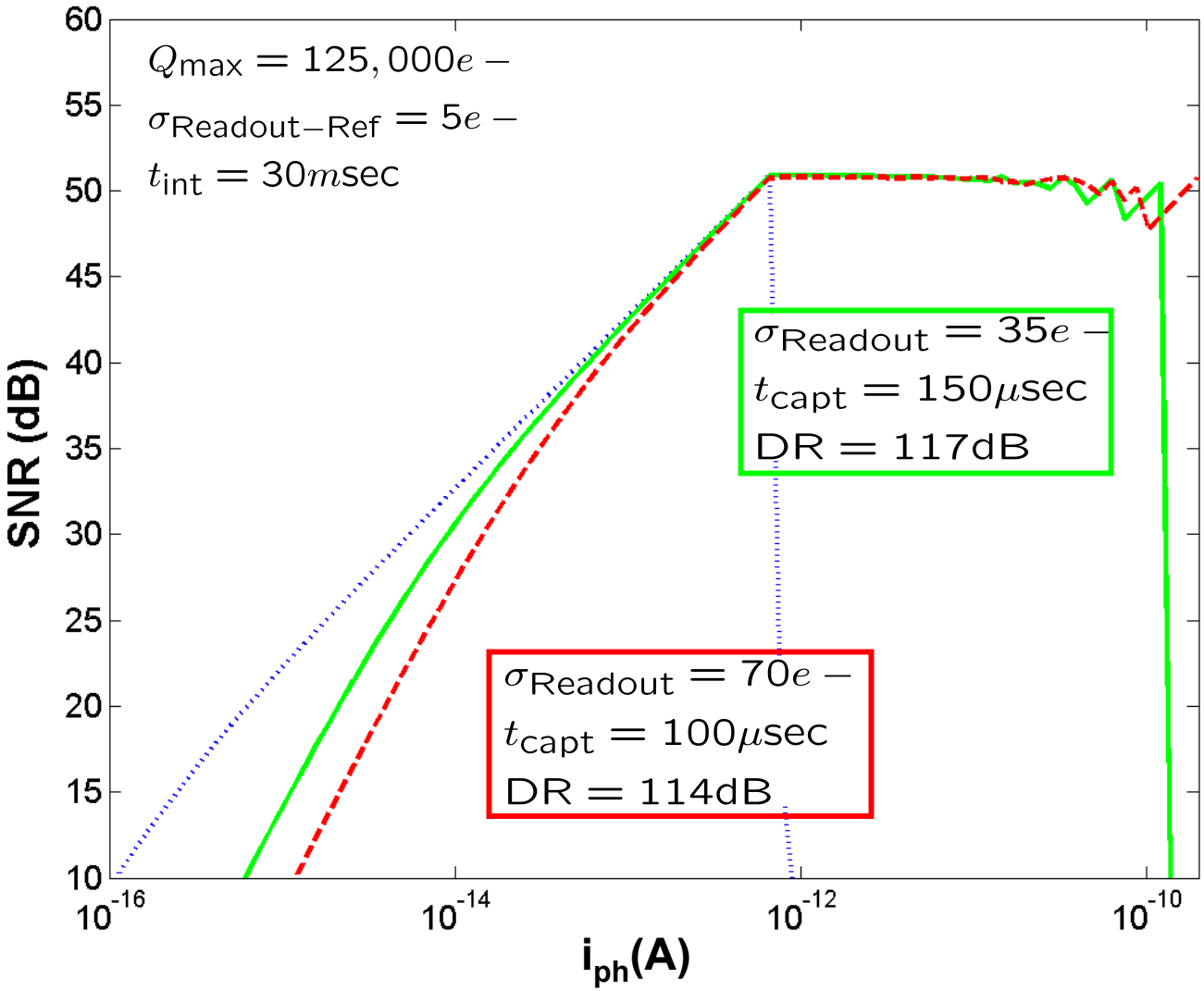
Multiple-Capture

[Yang '99, Kleinfelder '01, Bidermann '03]



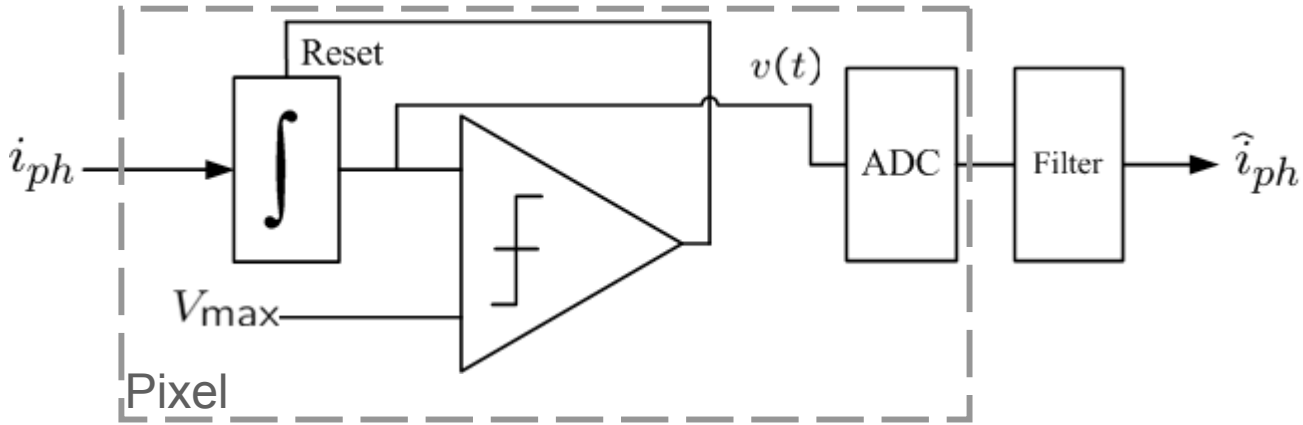
- $i_{\text{min}} = q\sigma_{\text{Readout}}/t_{\text{int}}$
  - ✘ Pixel-level ADC resolution limited (ADC-ramp, speed/resolution trade-off)
  - ✓ Digital weighted averaging is possible [Liu '03]
  - ✓ Increasing t_{int} is possible by motion blur prevention [Liu '03]
- $i_{\text{max}} = qQ_{\text{max}}/t_{\text{capt}}$
  - ✓ Capture time is very accurate

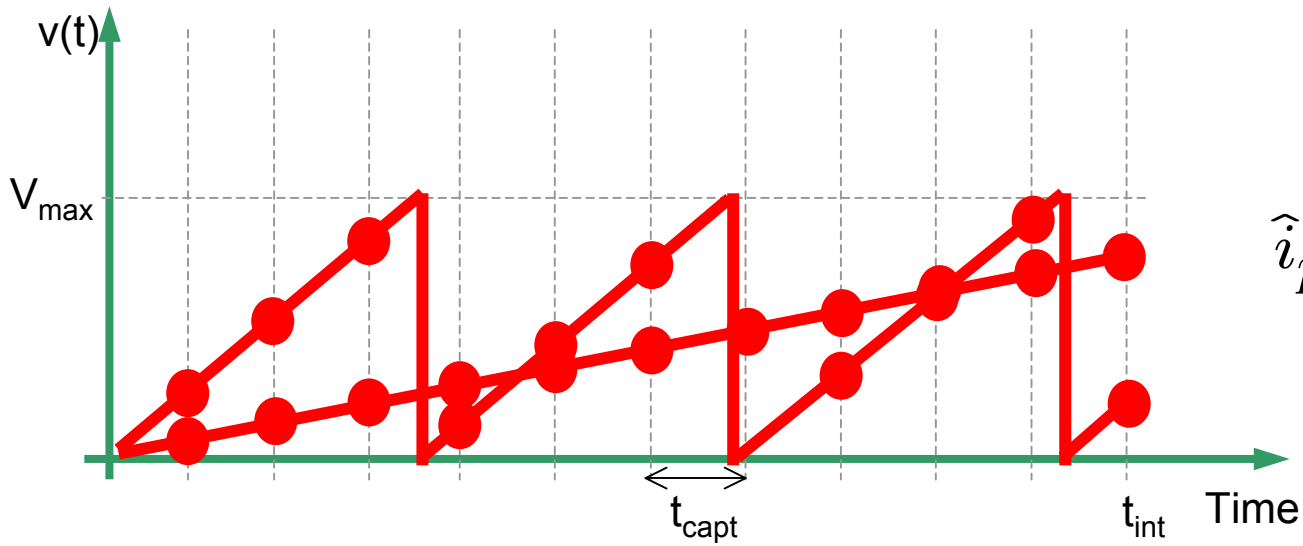
SNR


$Q_{\max} = 125,000e-$
$\sigma_{\text{Readout-Ref}} = 5e-$
$t_{\text{int}} = 30m\text{sec}$
$\sigma_{\text{Readout}} = 35e-$
$t_{\text{capt}} = 150\mu\text{sec}$
DR = 117dB
$\sigma_{\text{Readout}} = 70e-$
$t_{\text{capt}} = 100\mu\text{sec}$
DR = 114dB
SNR (dB)
60
55
50
45
40
35
30
25
20
15
10
10^{-16}
10^{-14}
10^{-12}
10^{-10}
i_{ph}(A)

Asynchronous Self-Reset

[Liu '02]

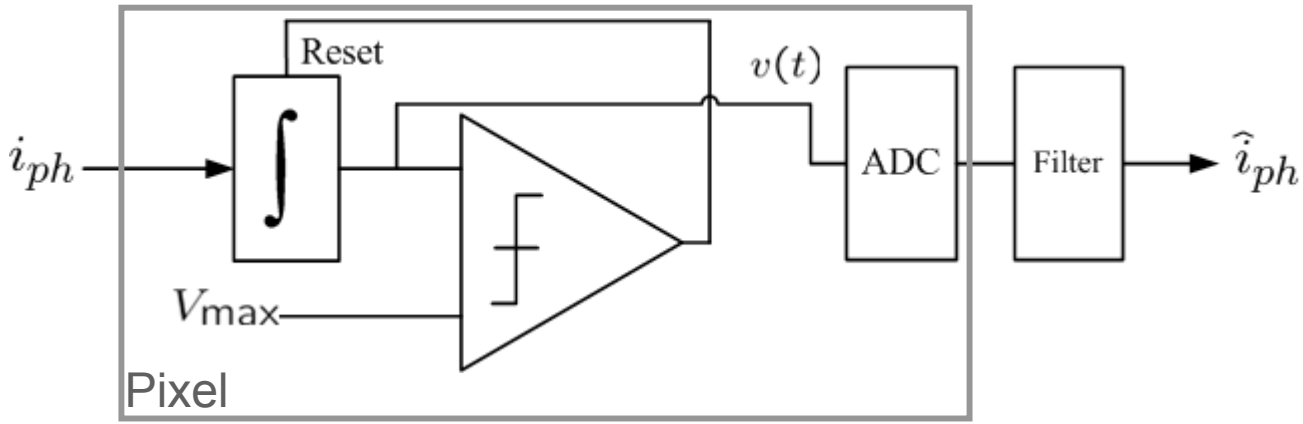




$$\widehat{i}_{ph} \propto v'(t)$$

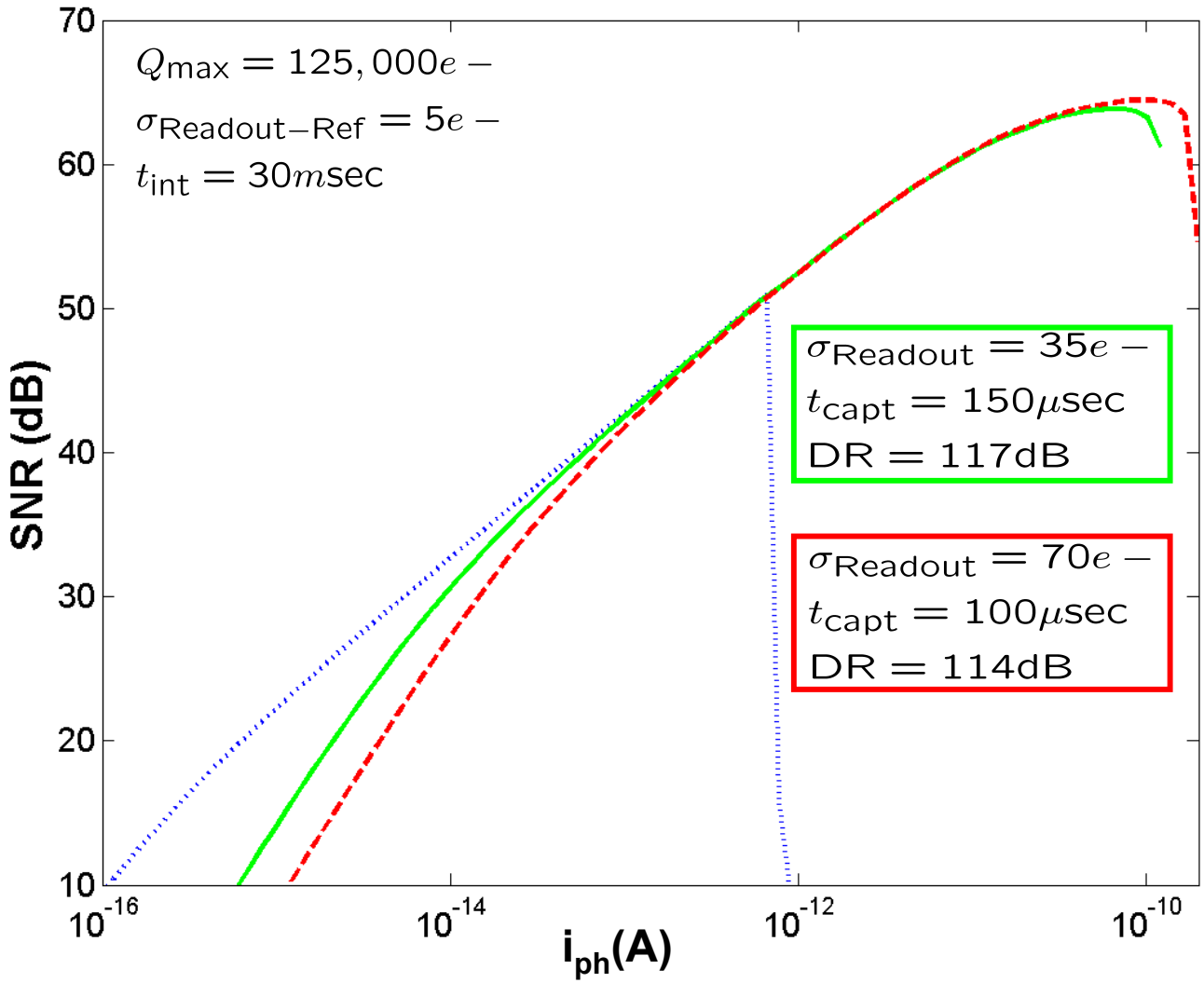
Asynchronous Self-Reset

[Liu '02]



- $i_{min} = q\sigma_{Readout}/t_{int}$
- $i_{max} = qQ_{max}/t_{capt}$
- SNR better than MC but with higher DSP cost:
  - ✘ ADC resolution limited (ADC-ramp, speed/resolution trade-off)
  - ✓ Digital weighted averaging can compensate for it
  - ✓ Increasing t_{int} is possible by motion blur prevention [Liu '03]
  - ✓ Self-reset accuracy is relaxed
- SNR increasing but limited by gain FPN

SNR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$t_{\text{capt}} = 150\mu\text{sec}$
DR = 117dB
$\sigma_{\text{Readout}} = 70e-$
$t_{\text{capt}} = 100\mu\text{sec}$
DR = 114dB
SNR (dB)
70
60
50
40
30
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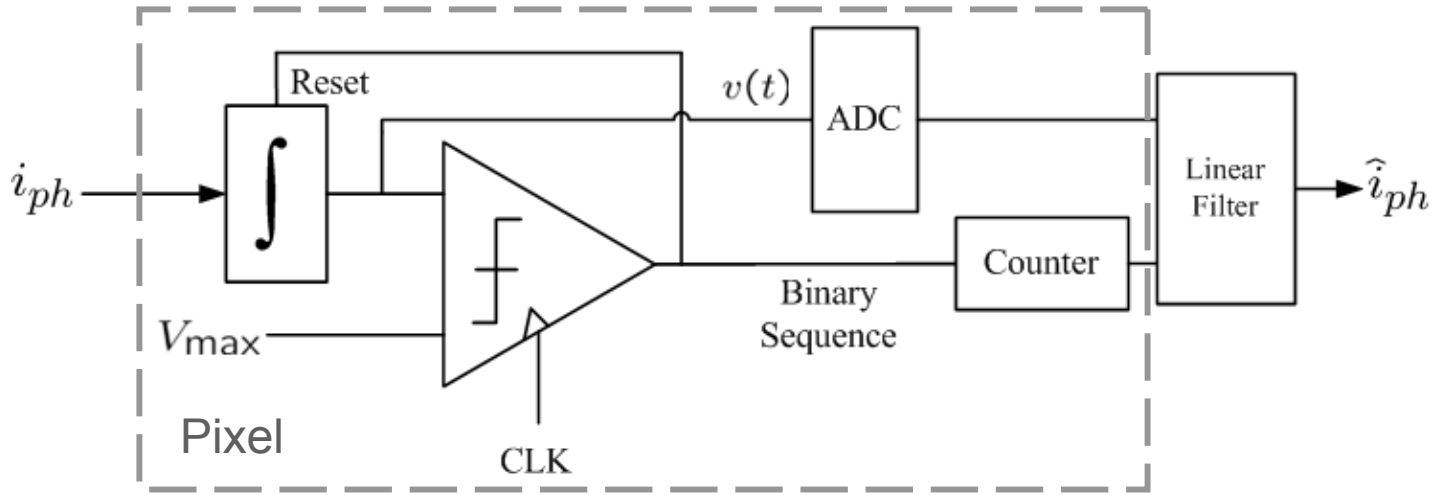
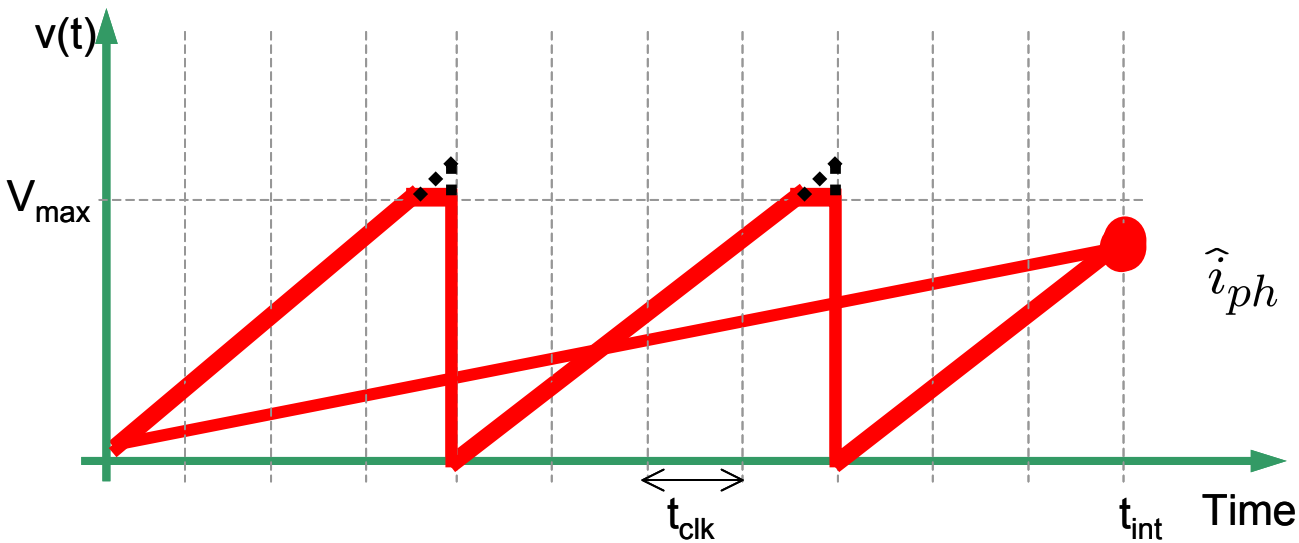
10^{-16}
10^{-14}
10^{-12}
10^{-10}
i_{ph}(A)

Synchronous Self-Reset with Residue Readout

[Bermak '02, Rhee '03]

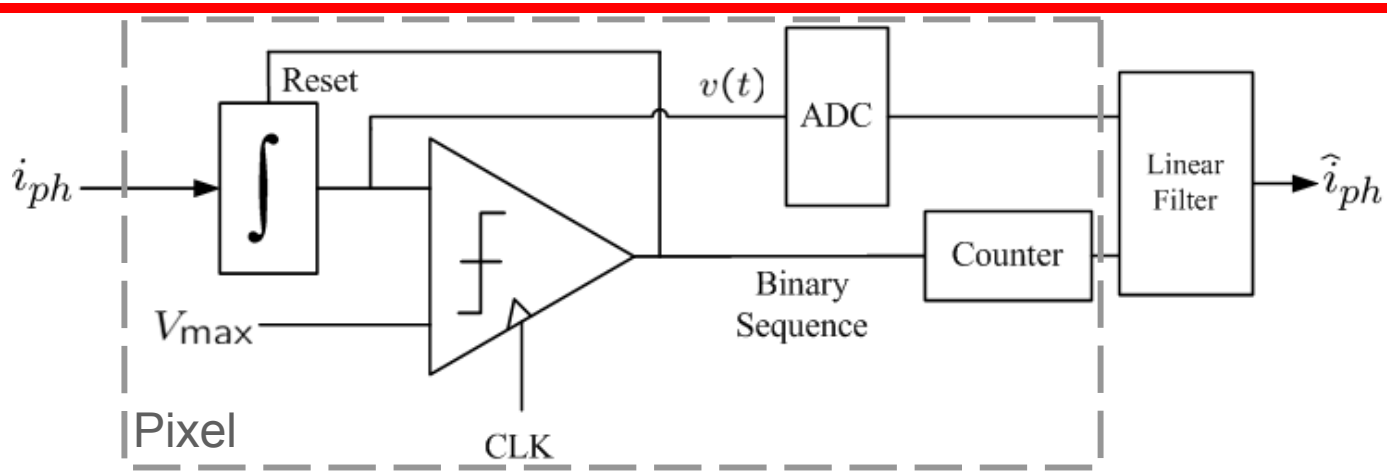




$$\hat{i}_{ph} \propto n_{\text{Reset}} + \frac{v(t_{\text{int}})}{V_{\text{max}}}$$

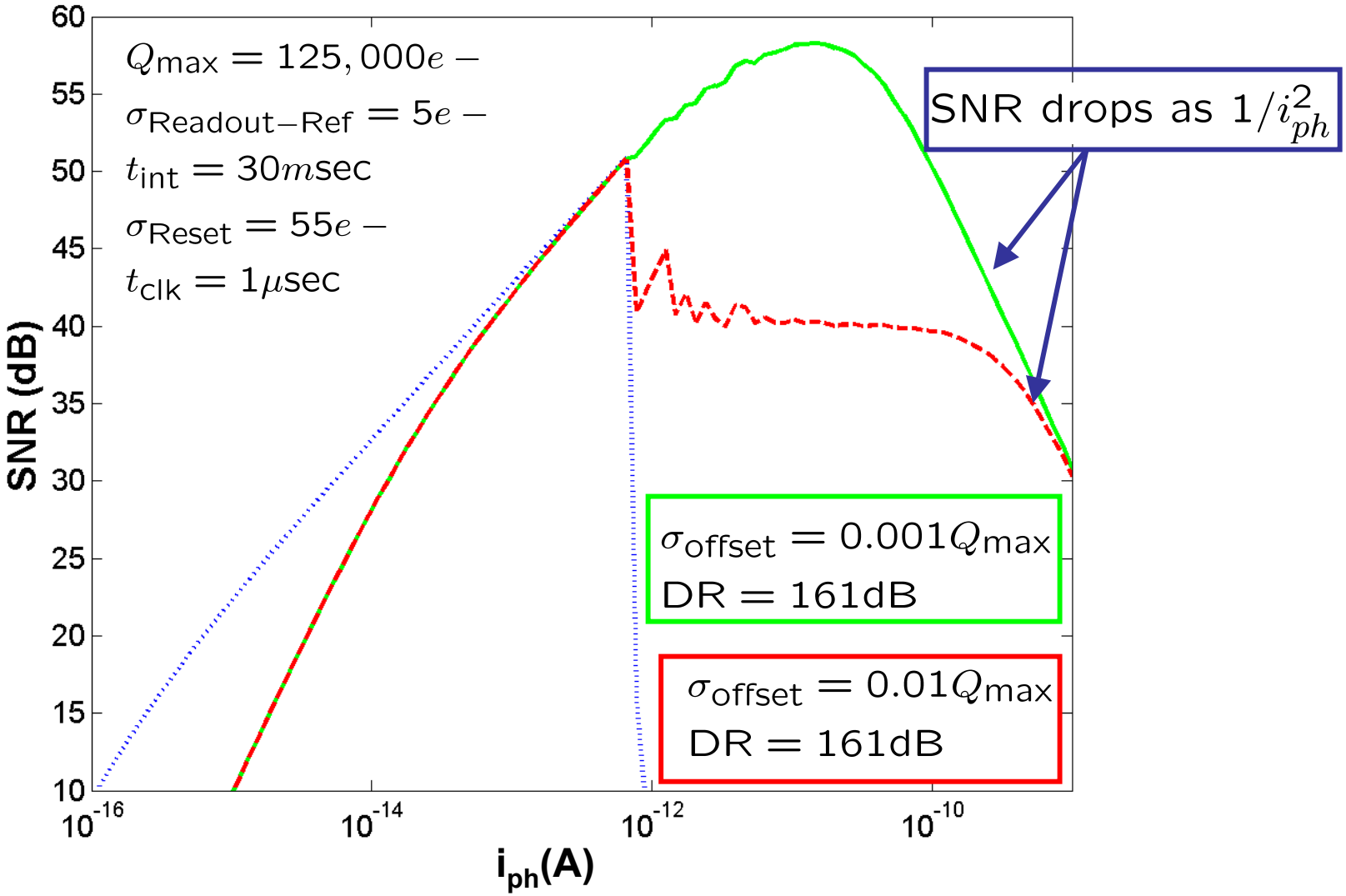
Synchronous Self-Reset with Residue Readout

[Bermak '02, Rhee '03]



- $i_{min} = q\sqrt{\sigma^2_{Readout} + \sigma^2_{Reset}}/t_{int}$
  - ✘ Reset noise and ADC resolution
- i_{max} and SNR at high end limited by:
  - ✘ Comparator and self-reset offset accumulation resulting in gain FPN (inaccuracy measured by σ_{offset})
  - ✘ Underestimation of i_{ph} due to signal saturation
- $i_{max} = \sqrt{3}qQ_{max}/t_{clk}$

SNR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$\sigma_{\text{Readout-Ref}} = 5e-$
$t_{\text{int}} = 30m\text{sec}$
$\sigma_{\text{Reset}} = 55e-$
$t_{\text{clk}} = 1\mu\text{sec}$
SNR drops as $1/i_{ph}^2$
$\sigma_{\text{offset}} = 0.001Q_{\max}$
DR = 161dB
$\sigma_{\text{offset}} = 0.01Q_{\max}$
DR = 161dB
SNR (dB)
i_{ph}(A)
60
55
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10^{-12}
10^{-10}

Summary

Method	i_{min}	i_{max}	SNR	Pixel Mismatches Effect	DSP	Power
TTS	=	++	–	High	Low	Comparator
MC	– /=	+	+	Moderate	Moderate	Readout/DSP
Async	– /=	+	++	Moderate	High	Readout/DSP
Sync	– –	+++	– –	High	Moderate	Comparator/digital circuits