Photocurrent Estimation for a Self-Reset CMOS Digital Pixel Sensor

Xinqiao Liu and Abbas El Gamal

Department of Electrical Engineering
Stanford University

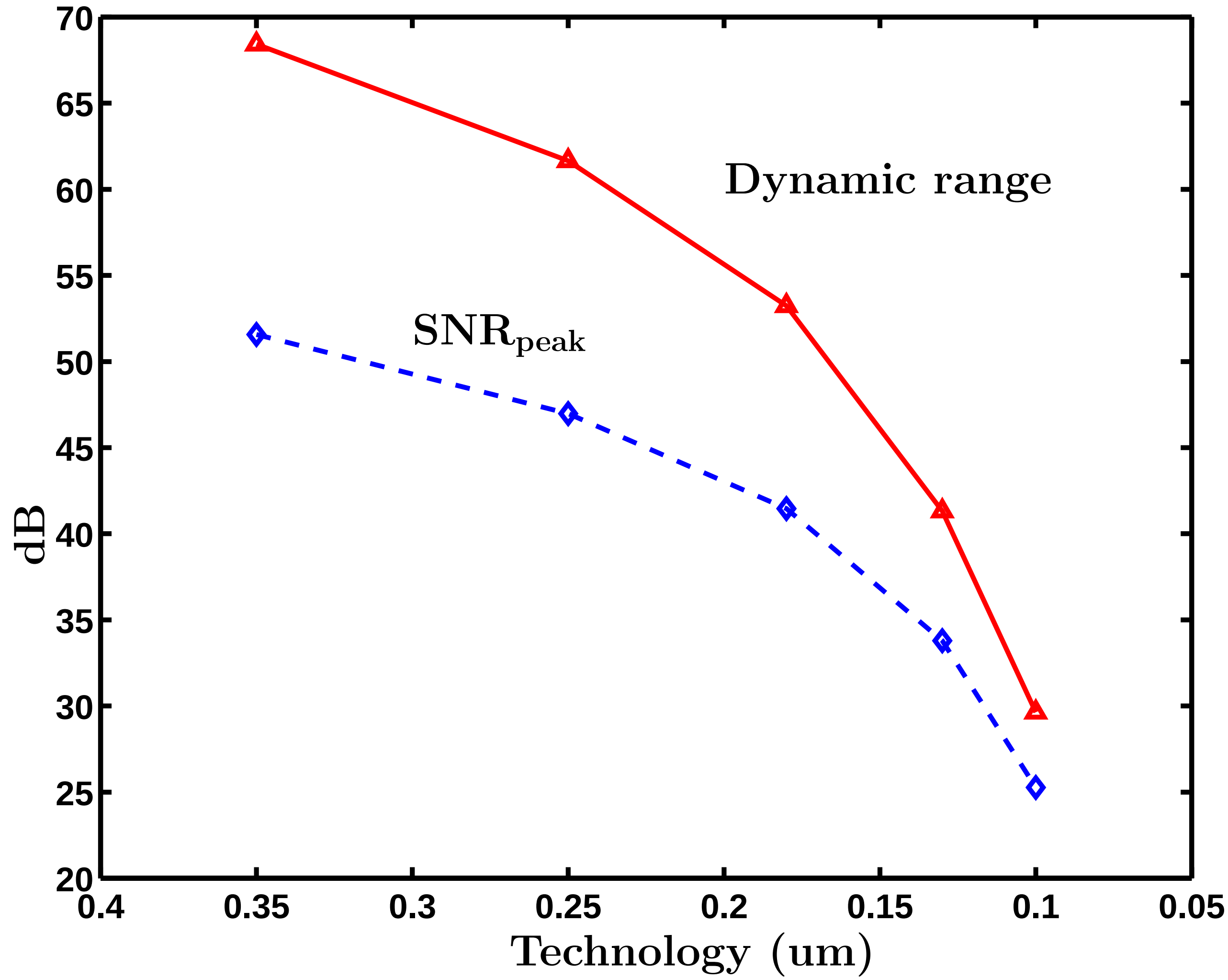
Motivation

- **CMOS imagers benefit from technology scaling**
  - Smaller pixel
  - Lower power consumption
  - More integration
- **However, well capacity decreases with scaling**

$$Q_{\text{well}} = V_{\text{swing}} \times C_{\text{sense}}$$

- **Dynamic range and peak SNR ($\approx Q_{\text{well}}/q$) becomes inadequate as technology scales**

As Technology Scales



Well Capacity Recycling

- **Idea: each pixel resets its photodiode one or more times during exposure**
  - **Reset is self-triggered and asynchronous**
  - **Depends on its illumination level**

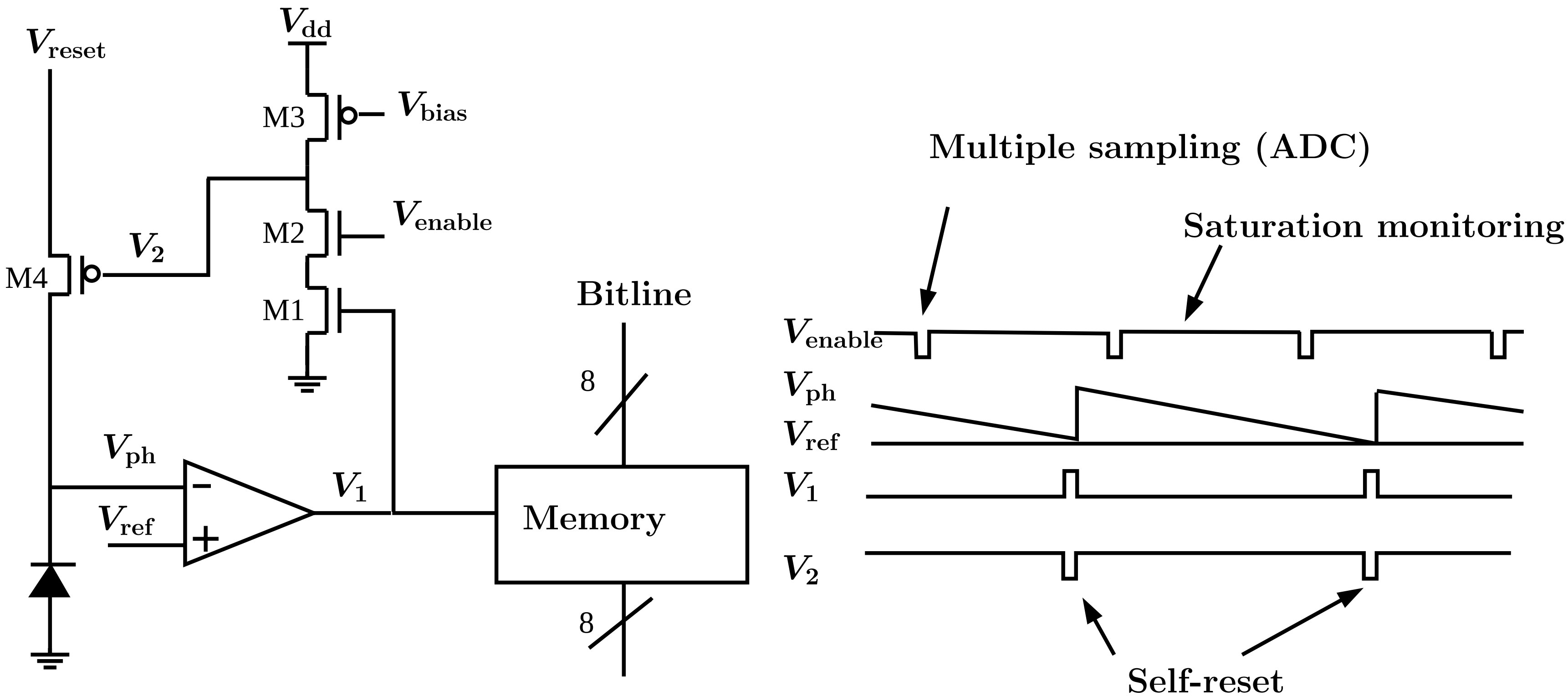
- **Each reset "recycles" the well, resulting in higher effective well capacity**

$$Q_{\text{max}} = m \times Q_{\text{well}}$$

where m is the maximum number of self-resets

- **Peak SNR is extended to** mQ_{well}/q

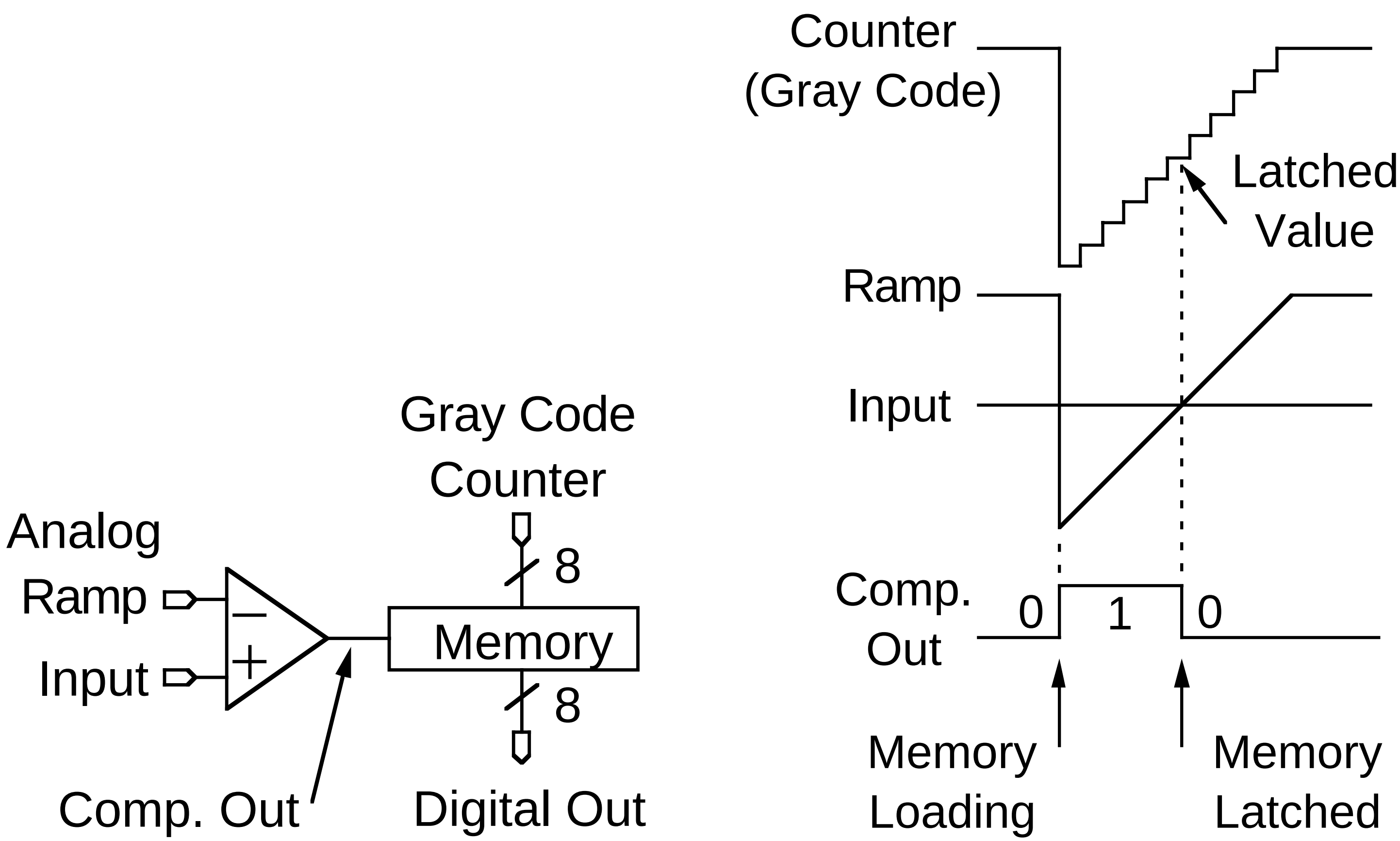
A Self-Reset Digital Pixel Sensor (DPS)



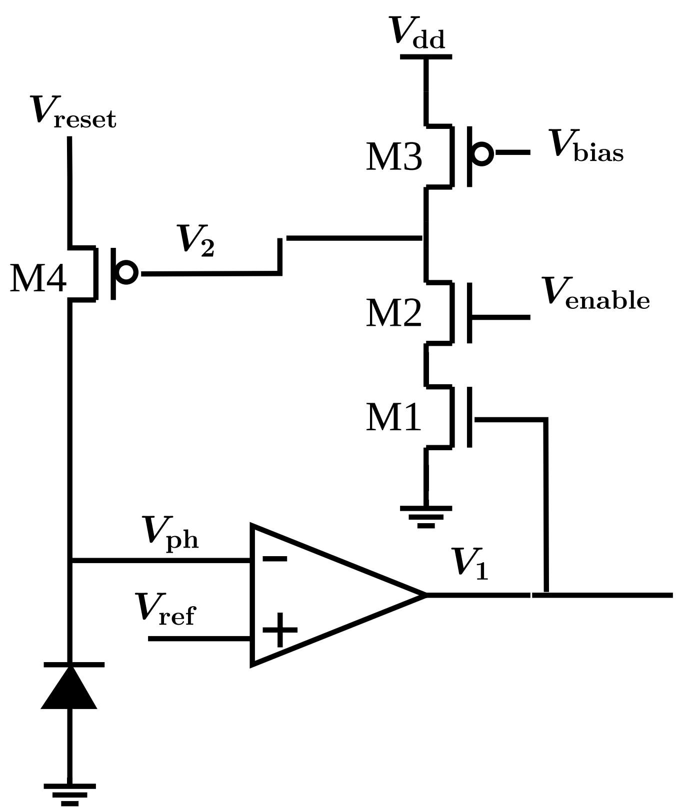
- Based on latest DPS design (ISSCC'01)
- Two modes of operation alternate during exposure
  - Multiple non-destructive sampling (ADC)
  - Saturation monitoring

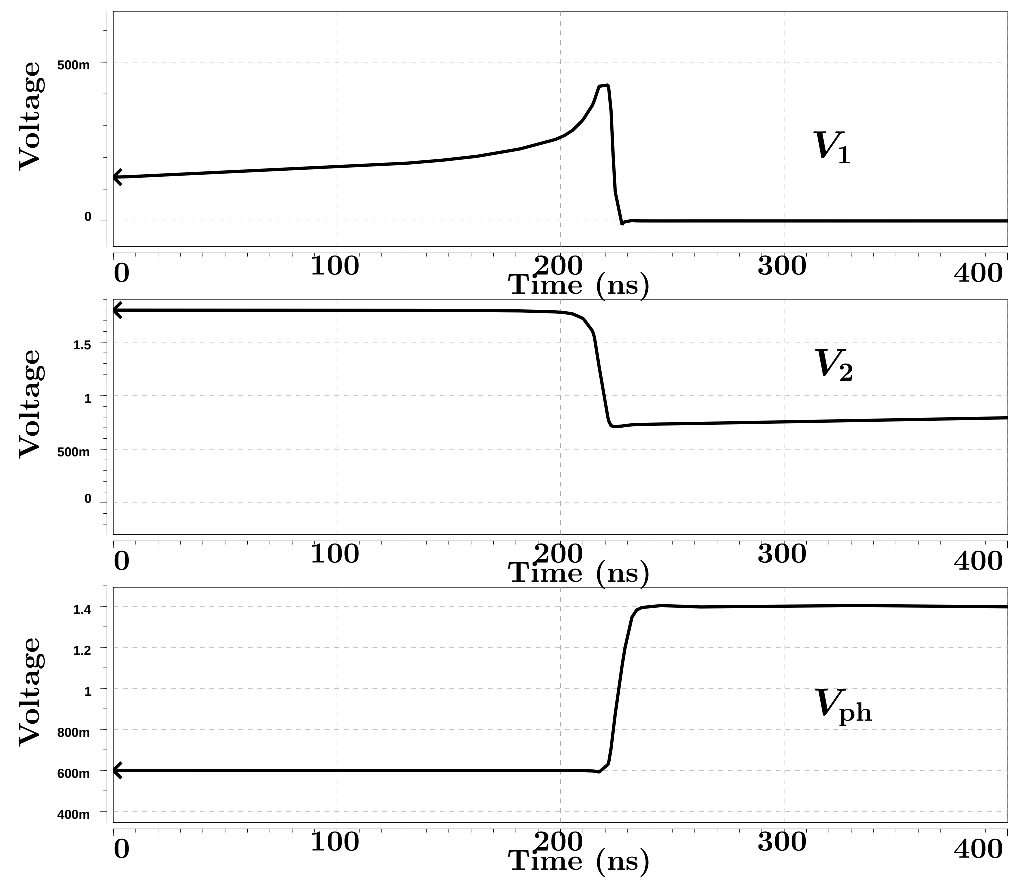
Pixel Level ADC Operation

- Single slope ADC performed at regular time interval
- Read out from digital memory performed during following saturation monitoring mode

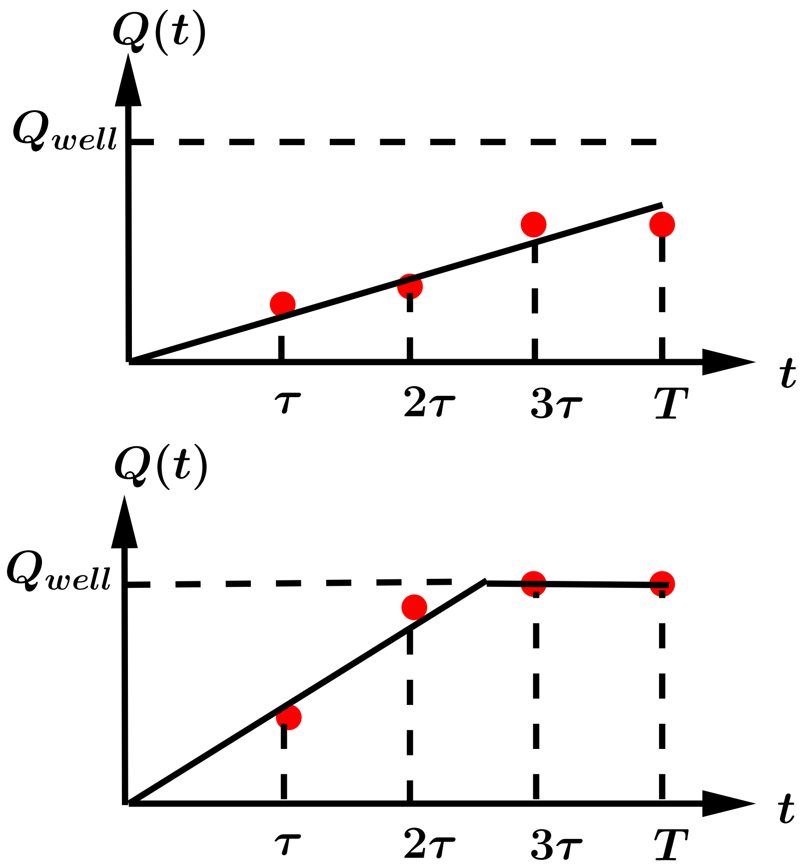


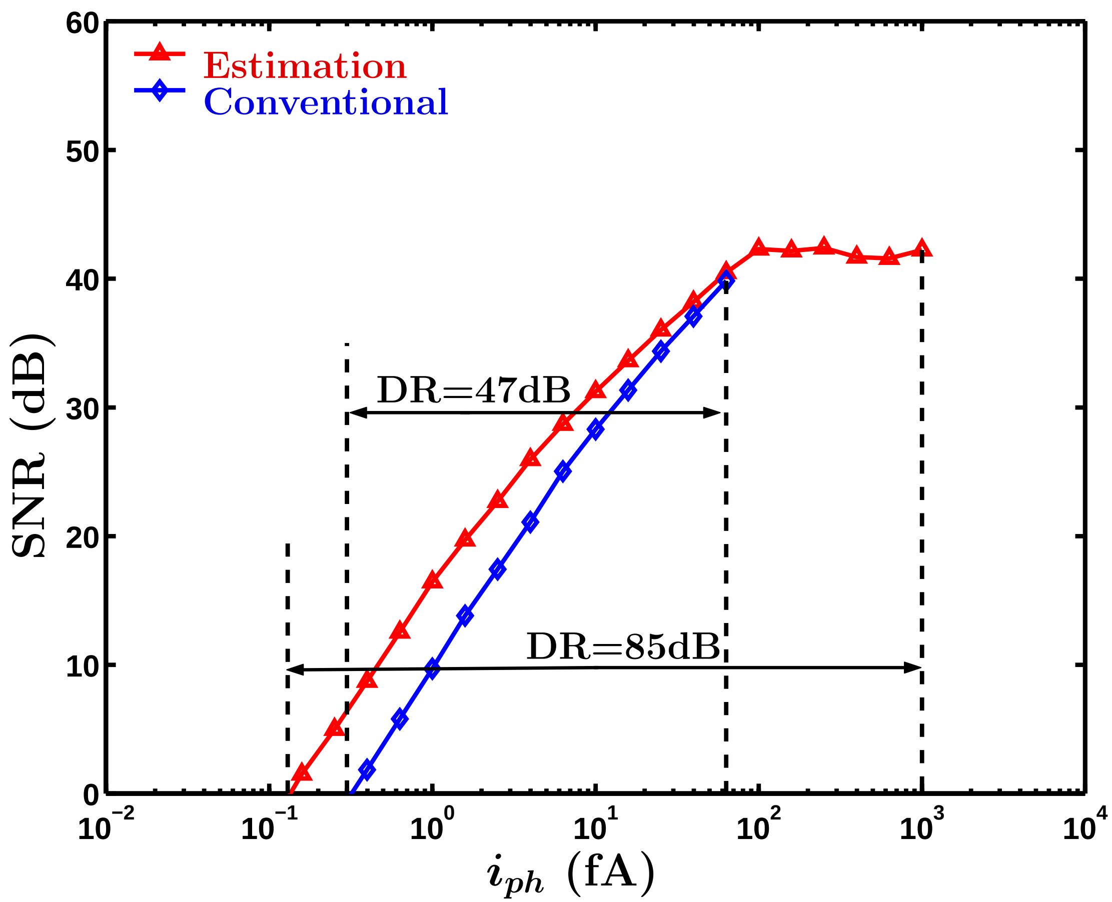
Self-Reset During Saturation Monitoring



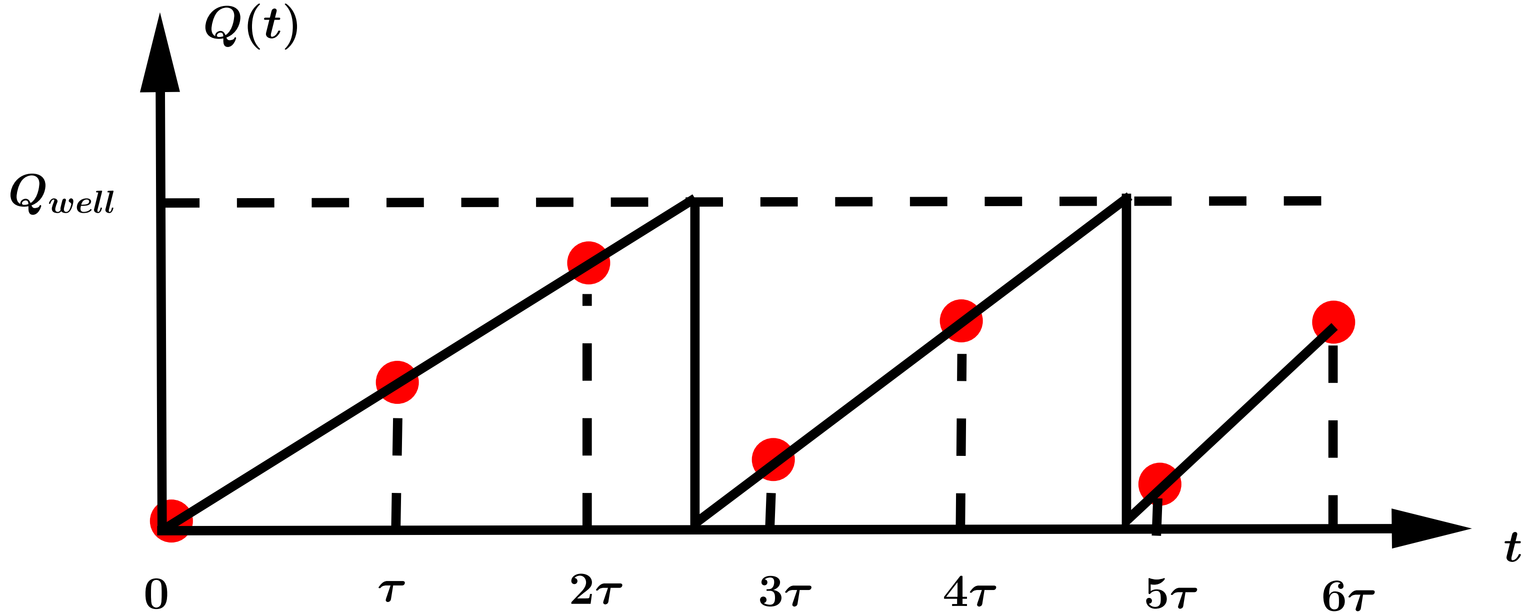


Estimation from Multiple Non-destructive Samples
(Liu and El Gamal, SPIE'01)





Photocharge with Multiple Self-Resets



- **Occurrence of self-reset can be detected so long as sampling rate is fast enough**
- **Reset noise and FPN accumulate — need to modify previous estimation algorithm**

Estimation with Multiple Self-Resets

- **The charge samples $Q_{k,m}$ at $k\tau$ with m self-resets, for $0 < k \leq n$, $m < k$**

$$Q_{k,m} = ik\tau + \sum_{j=1}^{k} U_j + V_k + \sum_{j=0}^{m} G_j + (m+1)F$$

  - U_j Shot noise
  - V_k Readout noise
  - G_j Reset noise
  - F Fixed Pattern Noise
  - Assume $F >> G_j$

- **Define photocurrent sample**

$$\tilde{I}_{k,m} = \frac{Q_{k,m} - (m+1)Q_{0,0}}{k\tau}, \text{ for } 1 \leq k \leq n$$

Problem Formulation

- **Use linear MSE estimation to estimate signal i**
- **At time $k\tau$, find the best unbiased linear estimate of the parameter i given $\{\tilde{I}_{1,0}, \tilde{I}_{2,0}, \ldots, \tilde{I}_{k,m}\}$, *i.e.*, coefficients $a_1, a_2, \ldots, a_k$ such that**

$$\hat{I}_k = \sum_{j=1}^{k} a_j \tilde{I}_{j,m},$$

minimizes

$$\Phi_k^2 = E(\hat{I}_k - i)^2,$$

subject to

$$E(\hat{I}_k) = i$$

Recursive Solution

- Optimal estimate expressed in recursive form

$$\hat{I}_k = \hat{I}_{k-1} + a_k(\tilde{I}_{k,m} - \hat{I}_{k-1})$$

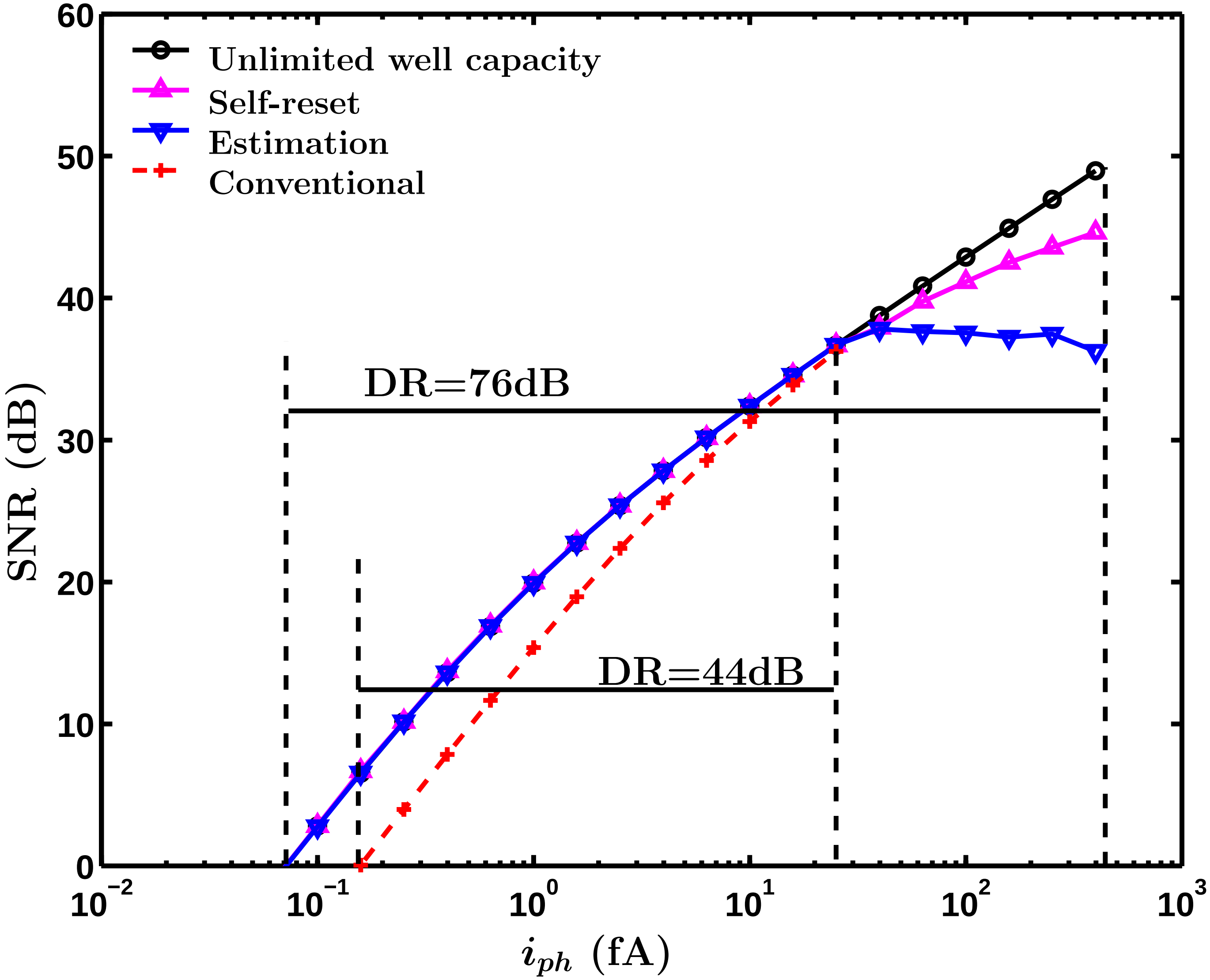
where

$$a_k = \frac{\Phi_{k-1}^2 - \Psi_k}{\Phi_{k-1}^2 + \Delta_k^2 - 2\Psi_k}$$

- Parameters $\Phi_k, \Psi_k, \Delta_k, a_k$ and estimate $\hat{I}_k$ updated at each iteration
- Small amount of memory independent number of captures — suited for camera-on-a-chip implementation

Simulation Results

- Simulated with total 32 samples, $Q_{well} = 6,250e^-$



Conclusion

- **Proposed a self-reset DPS architecture**
  - **Solve the problem of technology scaling by recycling limited well capacity multiple time during exposure**
- **A recursive estimation algorithm to enhance SNR at both low and high illumination end**
- **Other benefits:**
  - **Further reduction in pixel size**
  - **Larger effective voltage swing — relaxed ADC design**
  - **No need for anti-blooming device**