MICRO-523: Optical Detectors

Week Twelve: Advanced SPAD cameras – Solutions

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Based on MICRO-523, P.-A. Besse, 2025

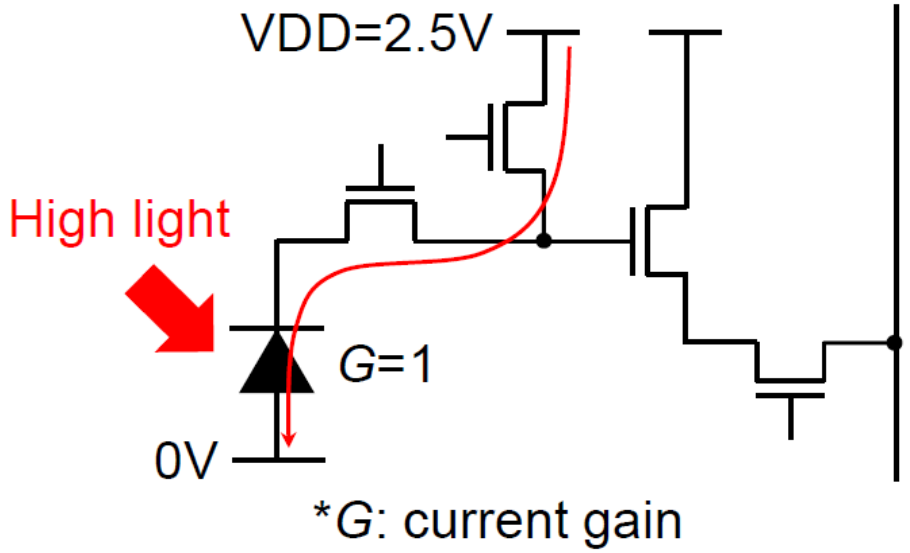
TAs: Samuele Bisi, Kodai Kaneyasu

Reminder: Exercise 11.2: SPAD camera power consumption

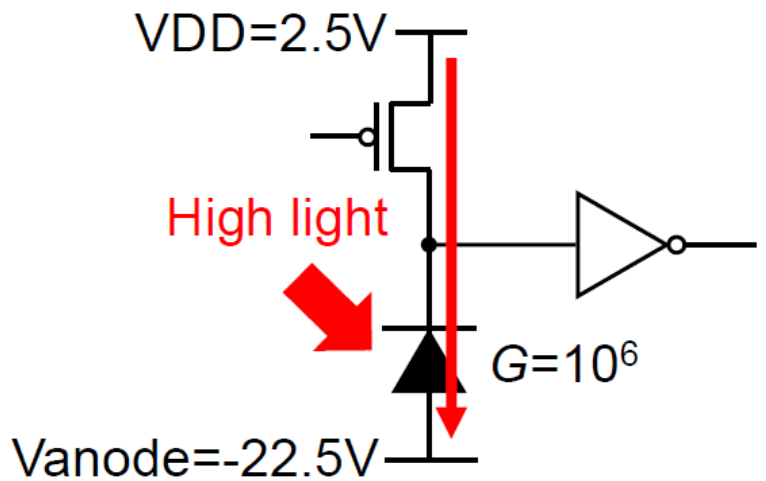
K. Morimoto, Image Sensors Europe 2024

- **Assumption: N_{pix}=3Mpixel, Q_{sat}=20k, Frame rate=60fps**

CMOS imager (4T pixel)



SPAD imager (passive recharging)



How can the power consumption of a SPAD-based camera operating at high illumination be reduced from the architectural point of view?

Reminder: Exercise 11.2: SPAD camera power consumption

K. Morimoto, Image Sensors Europe 2024

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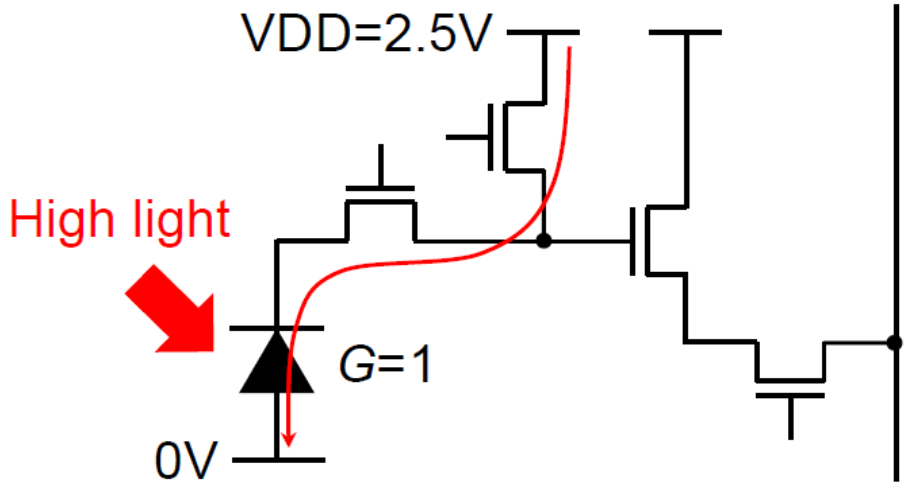
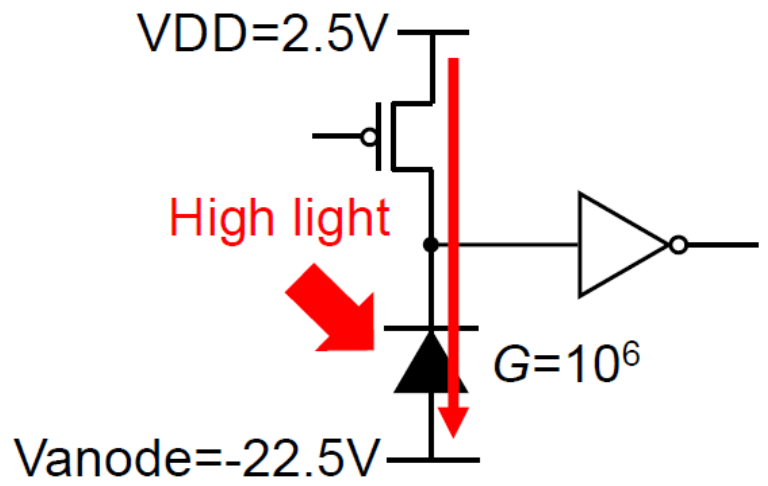


SPAD imager (passive recharging)



*G: current gain

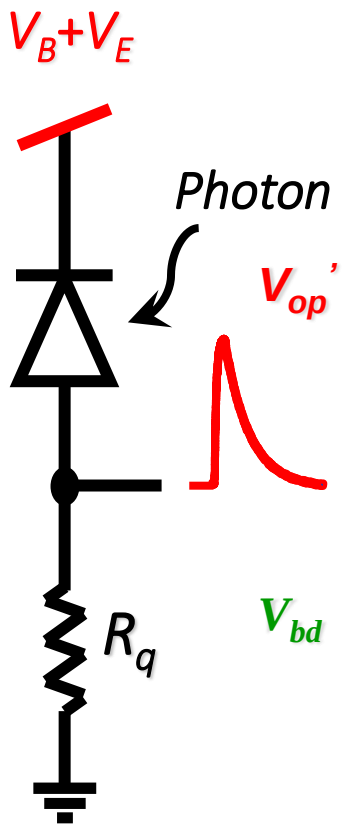
- **V = 2.5V**
- **$I = N_{pix} \times Q_{sat} \times G \times 60fps$ = 0.58µA**
- **$P = VI$ = 1.4µW**

- **V = 25V**
- **$I = N_{pix} \times Q_{sat} \times G \times 60fps$ = 0.58A**
- **$P = VI$ = 14W**

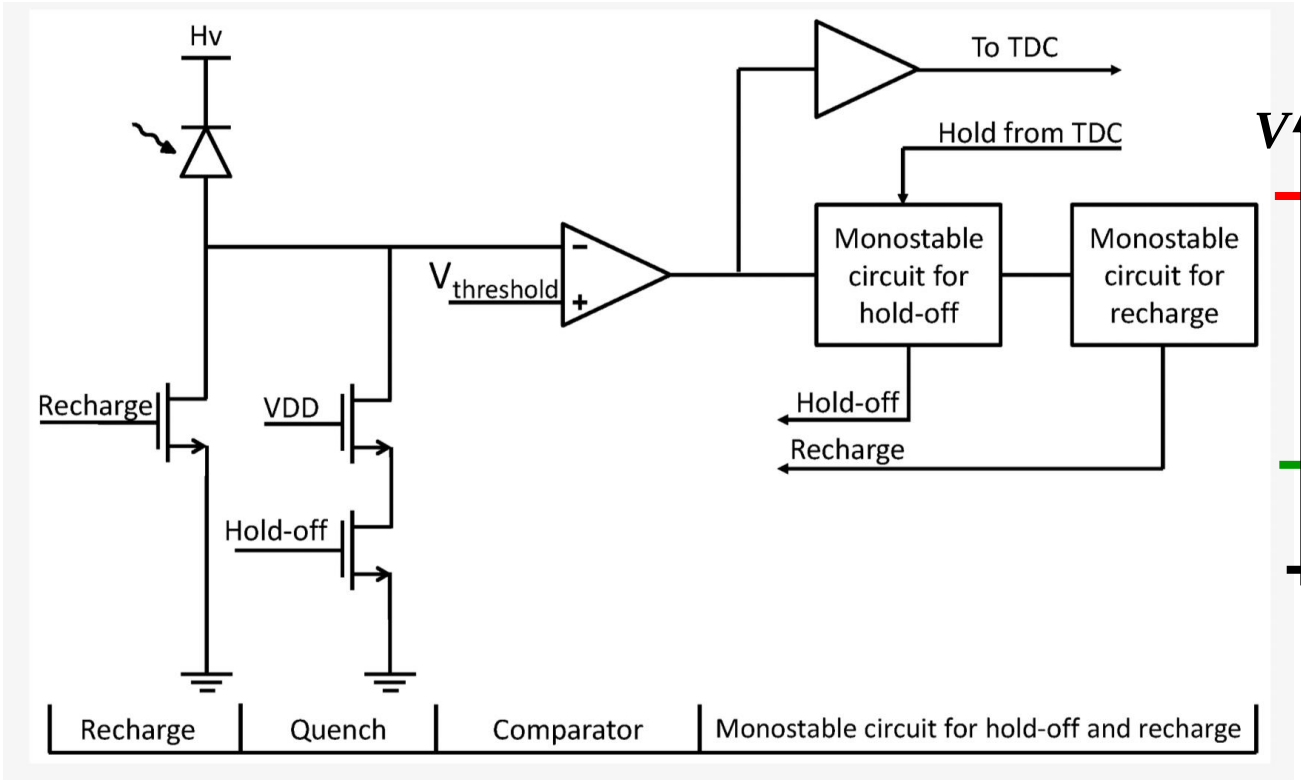
$10^7\times$ higher power!

12.1 Active vs Passive Recharge

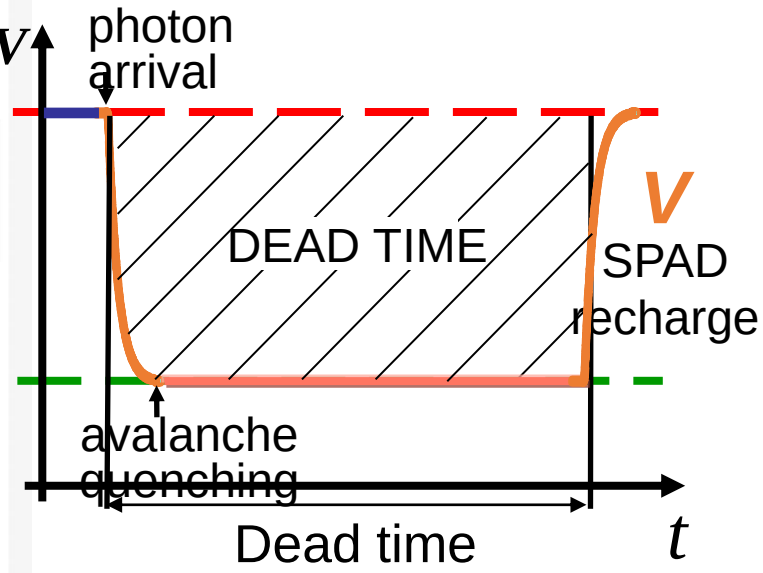
Passive Recharge



Active Recharge

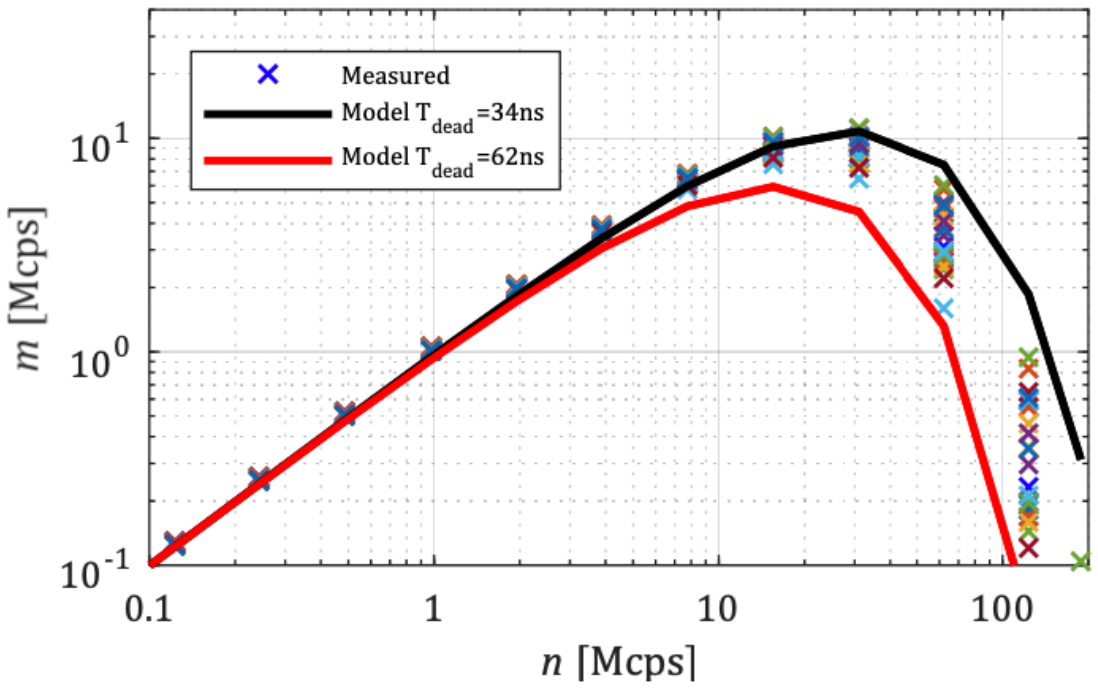


Dead time control (hold-off)

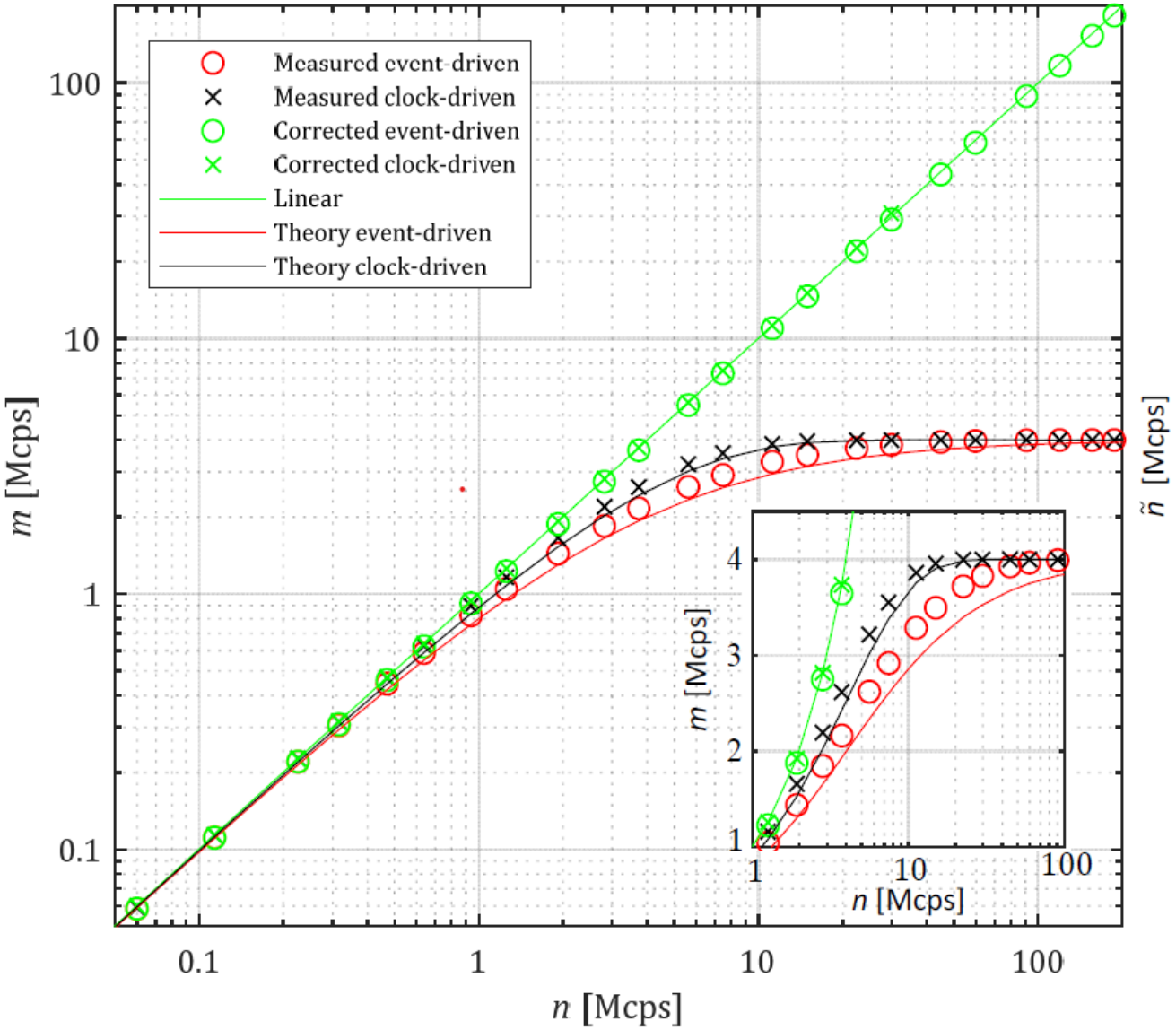


12.1 Active vs Passive Recharge

Passive Recharge

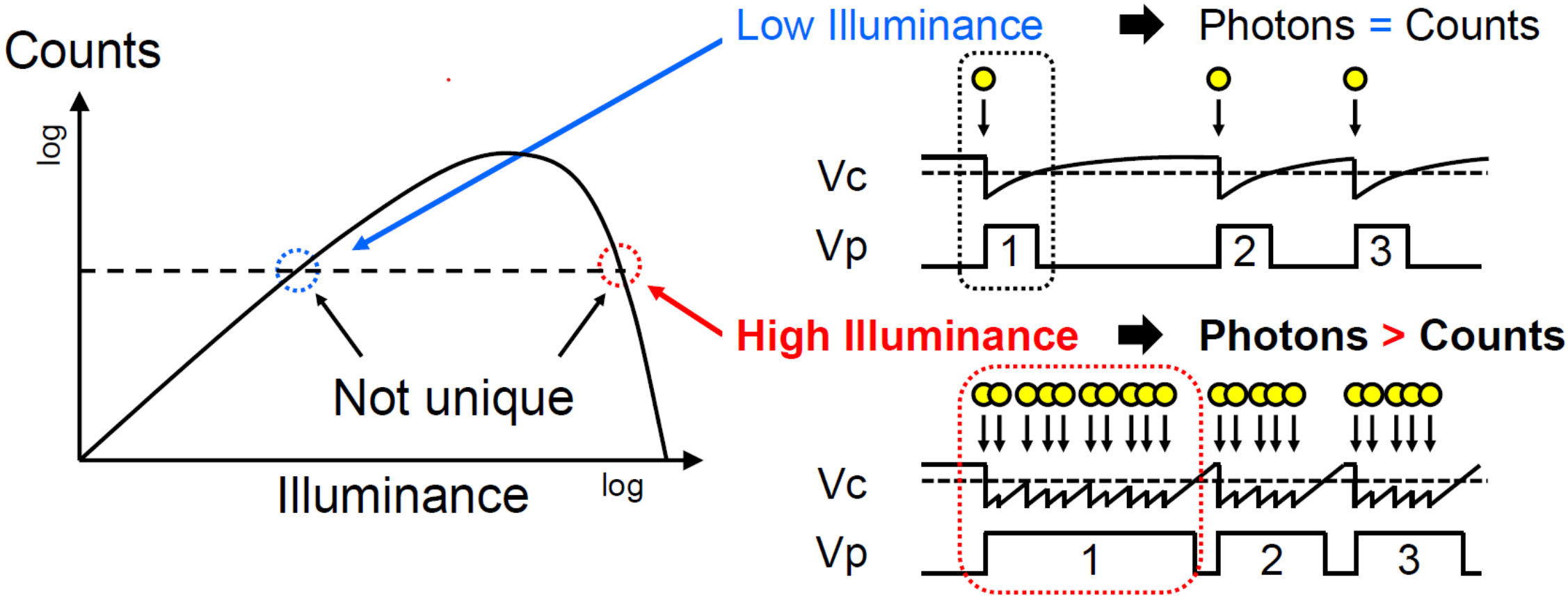


Active Recharge



Ivan M. Antolovic, *et al*, Dynamic range extension for photon (

12.1 Drawbacks of passive recharge



- Low & high illuminance could lead to the same counts

Y. Ota, et al., ISSCC 2022

5.1: A 0.37W 143dB-Dynamic-Range 1Mpixel Backside-Illuminated Charge-Focusing SPAD Image Sensor with Pixel-Wise Exposure Control and Adaptive Clocked Recharging

12.1 Power Consumption Reduction Strategies

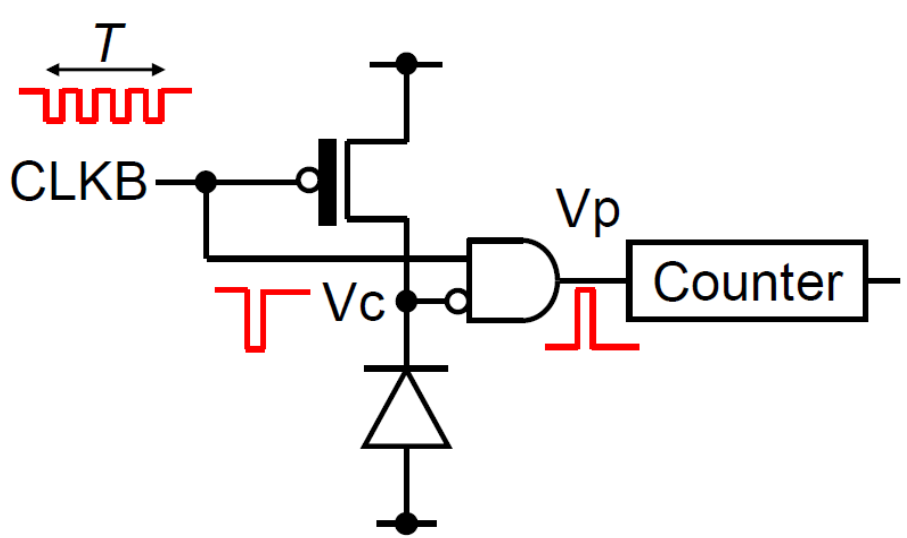
- *How can the power consumption of a SPAD-based camera operating at high illumination be reduced from the architectural point of view?*

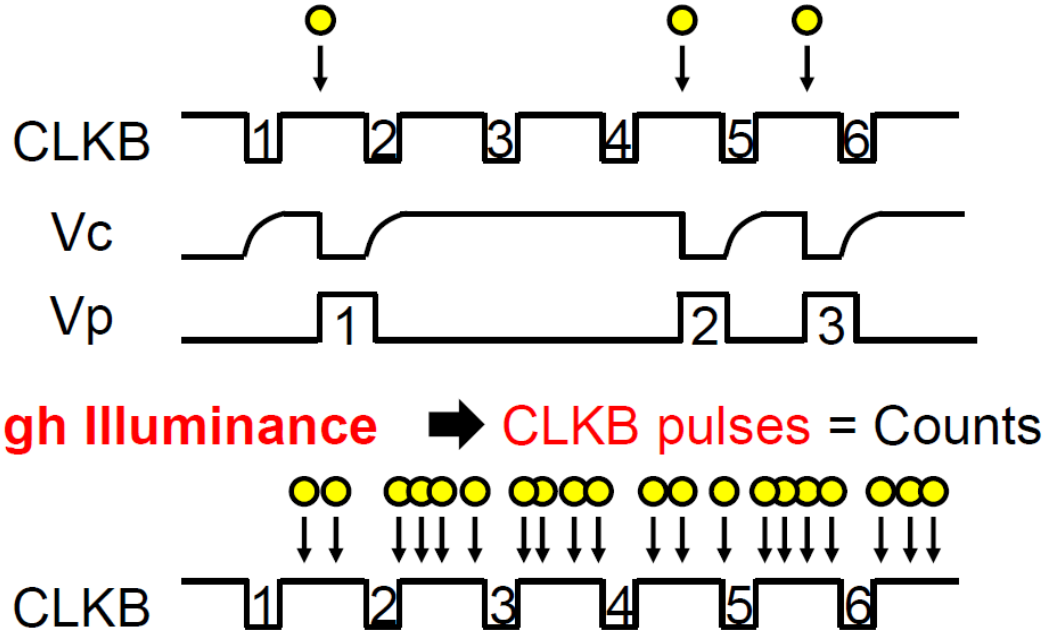
- *Hints for possible strategies:*

  - Reduce count for high illuminance. Example: employ active recharge.

  - Shut pixels off – how, when? Example: time to saturation.

12.1 Possible strategy 1: Clocked Recharging



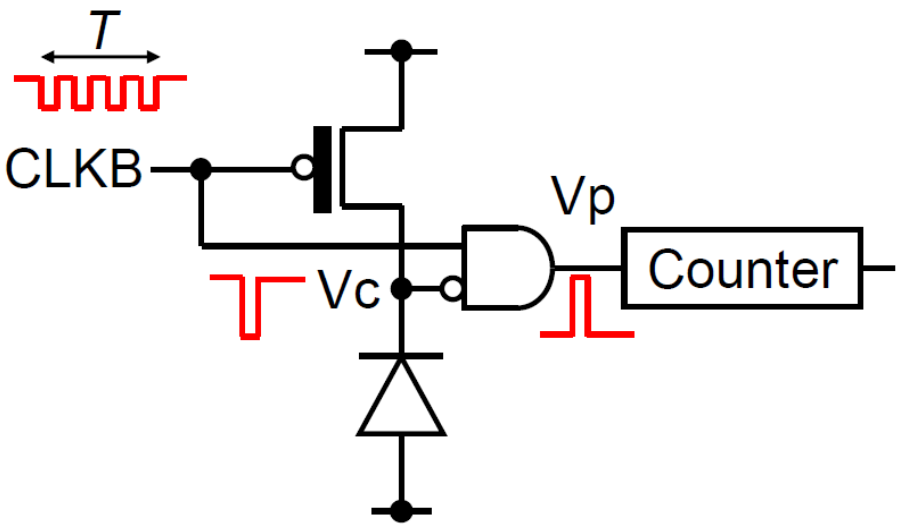


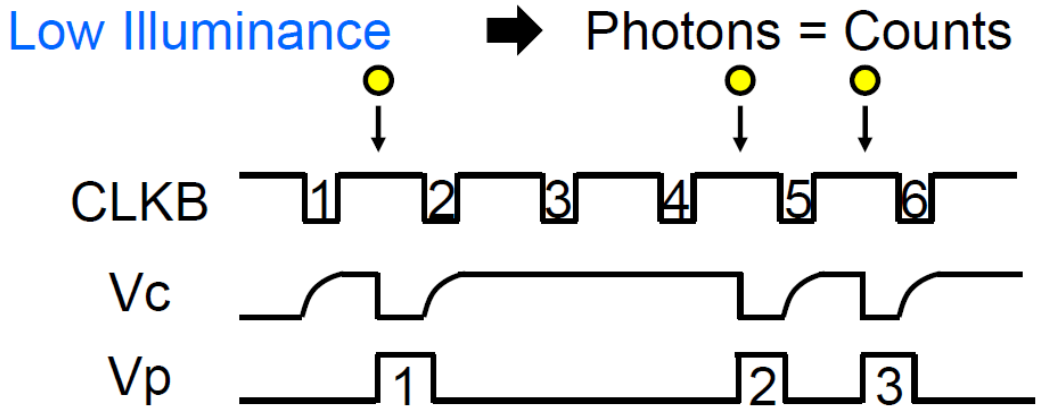
High Illuminance ➡ CLKB pulses = Counts

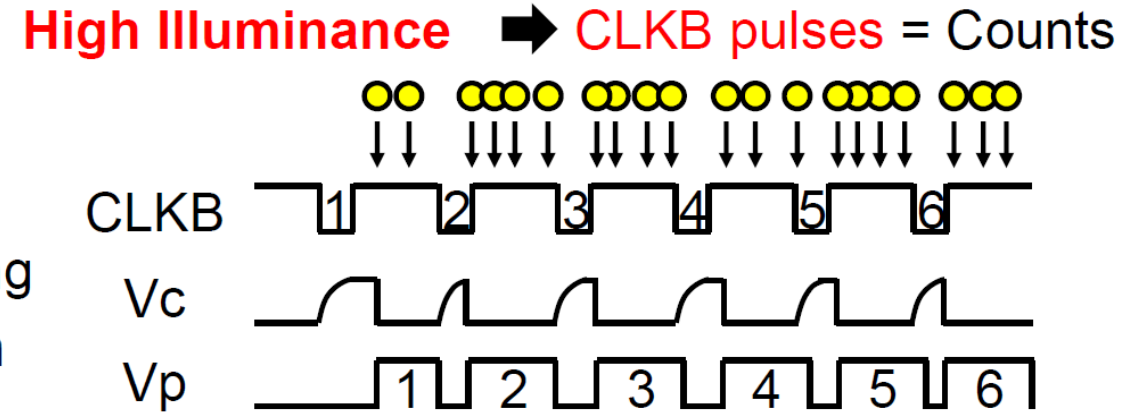
Draw a graph with illumination (horizontal axis) vs Counts (vertical axis).

Y. Ota, et al., ISSCC 2022

12.2 Architecture 1: Clocked Recharging







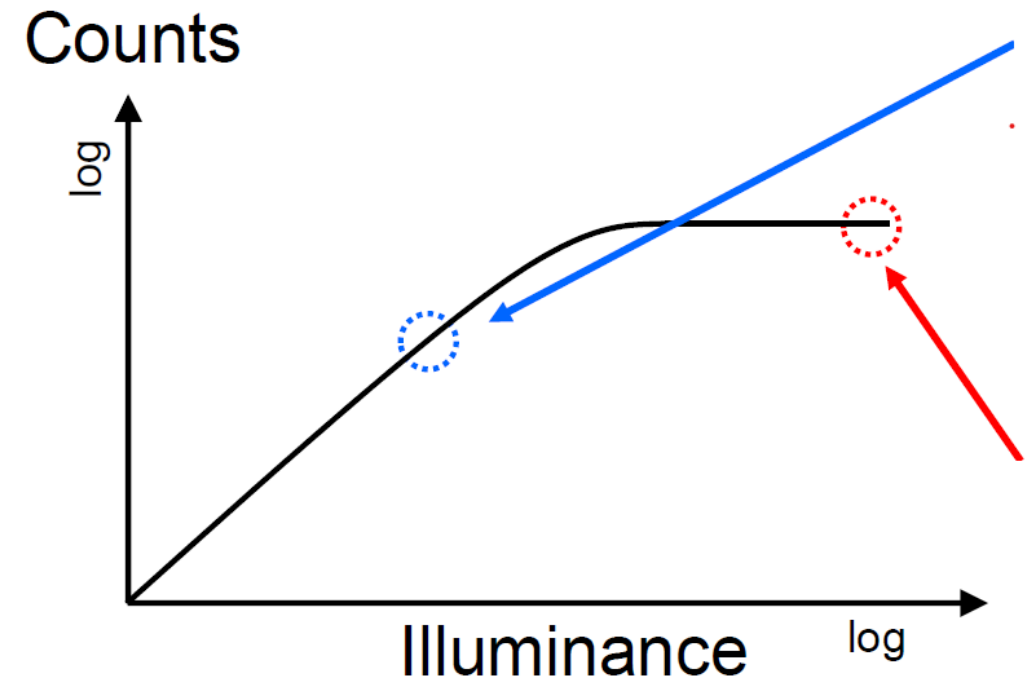
- CLKB controls number of recharging
- CLKB pulses = counts at saturation

Clocked recharging reduces max power consumption by 1/10x-1/100x

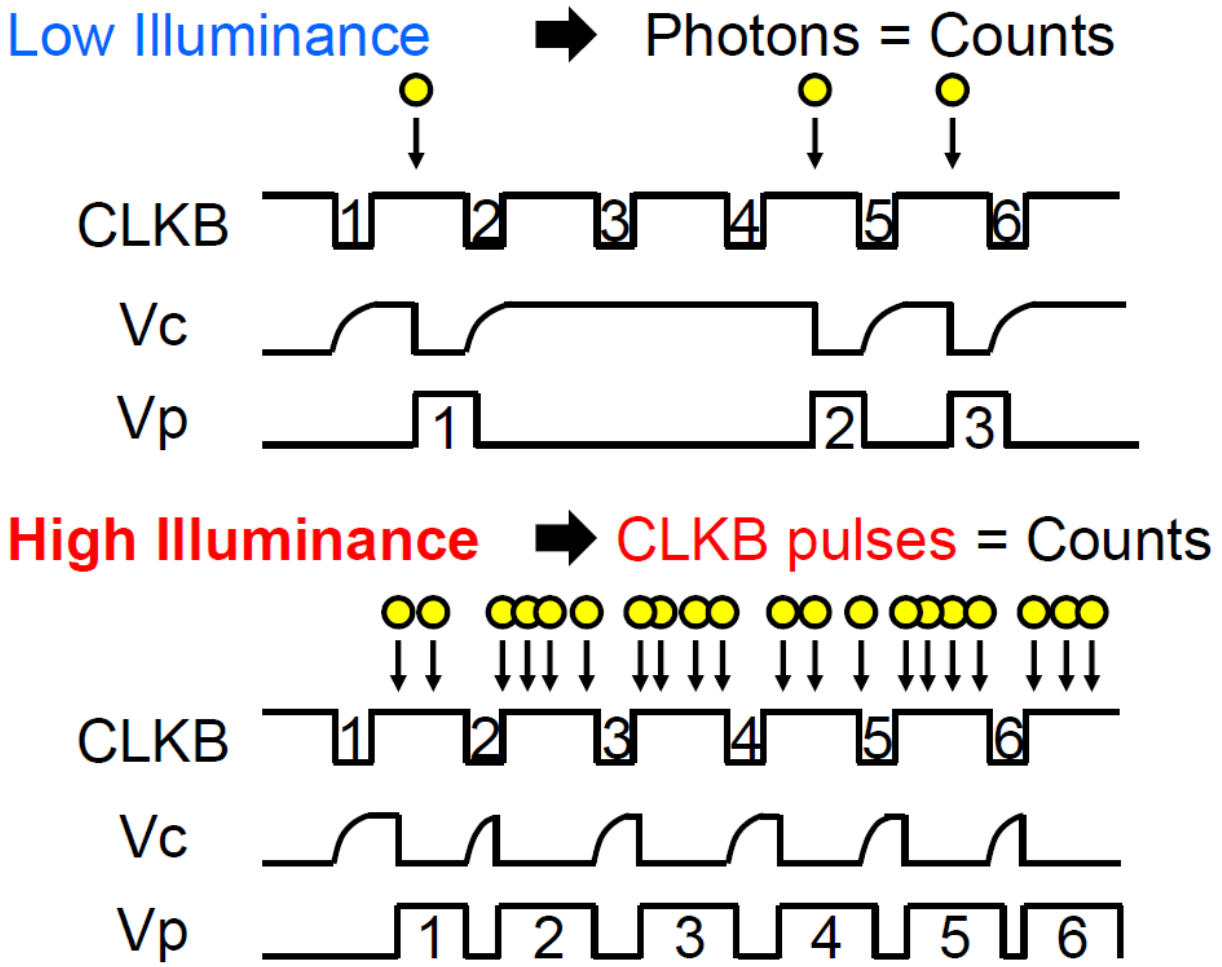
Y. Ota, et al., ISSCC 2022

15

12.2 Architecture 1: Clocked Recharging - Advantages



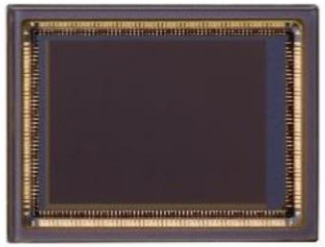
Monotonic increase towards saturation



Y. Ota, et al., ISSCC 2022

5.1: A 0.37W 143dB-Dynamic-Range 1Mpixel Backside-Illuminated Charge-Focusing SPAD Image Sensor with Pixel-Wise Exposure Control and Adaptive Clocked Recharging

12.2 Architecture 1: Clocked Recharging - Implementation



SPAD SENSOR

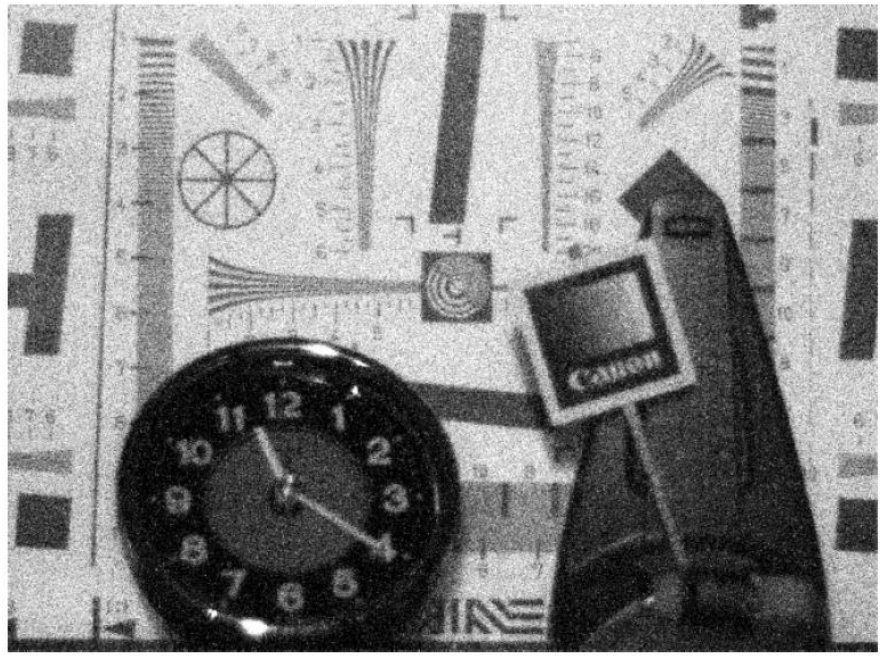
*Zoomed image of ship at 5km distance, captured at midnight

Power consumption at high illuminance!
Here: clocked recharging

Canon MS-500 Backside Illuminated 3.2 Mpx

Each SPAD in top tier is connected to a quenching circuit and an 11-bit digital counter in bottom tier → pixel-parallel photon counting.

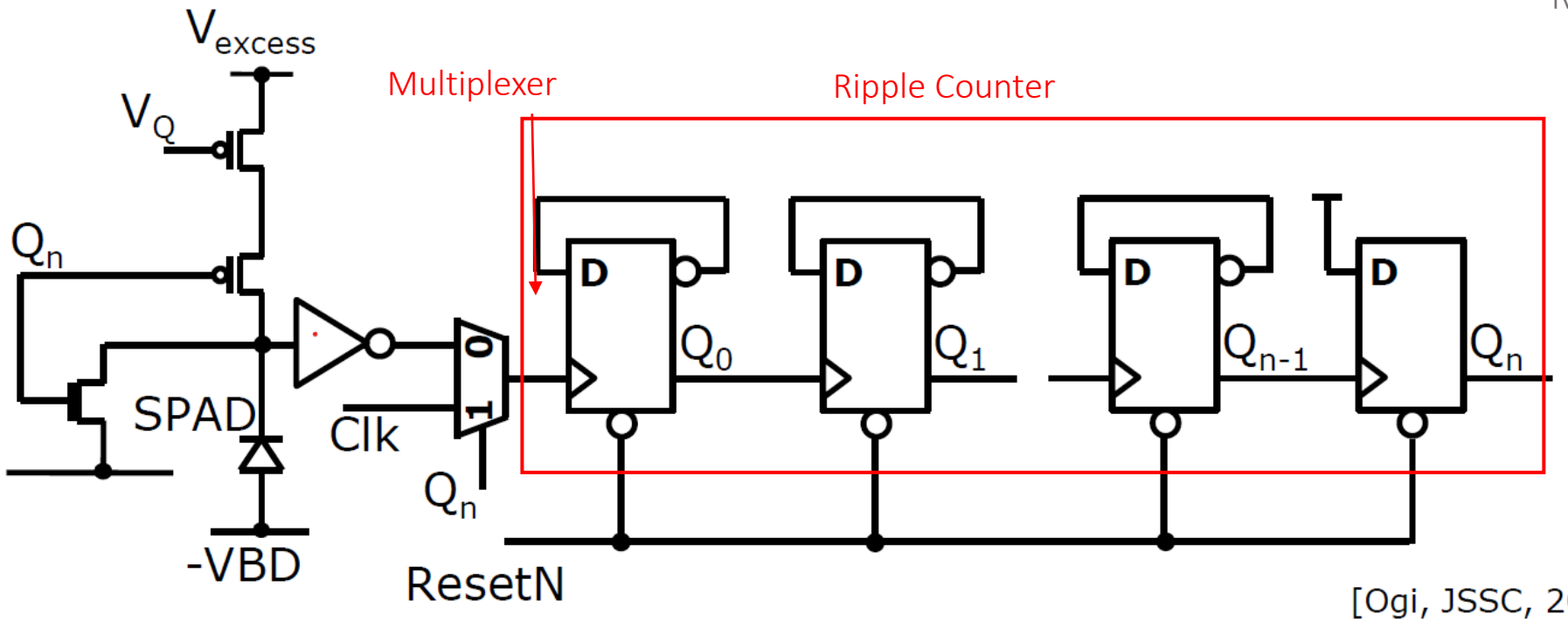
2 mLux

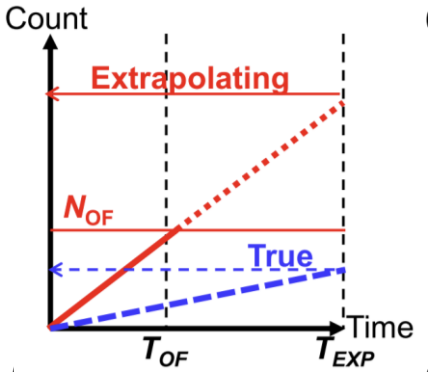


- [K. Morimoto, IEDM 2021]

12.1 Possible strategy 2: Time to saturation HDR

Robert K. Henderson, ESSxxRC 2022

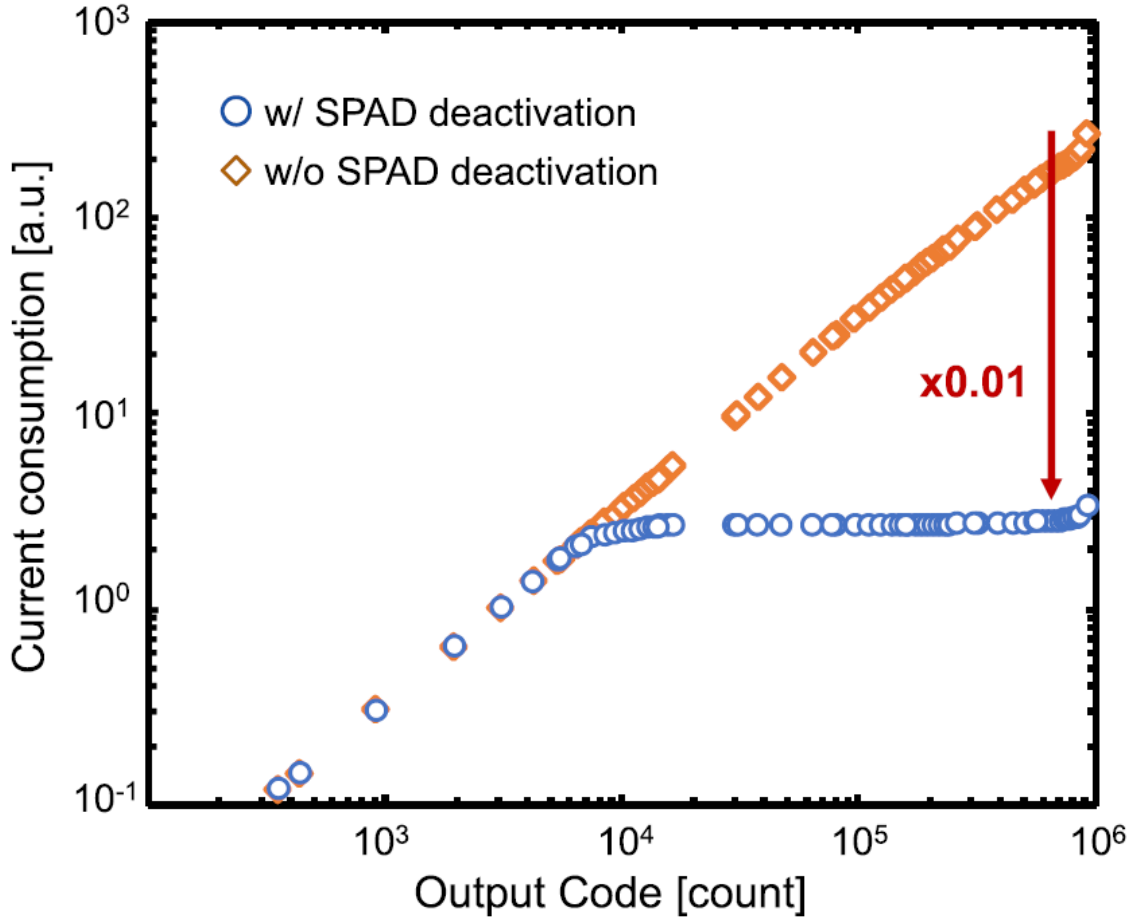




- All pixels initially count SPAD events
- When Q_n=1 representing saturation the counter switches over to Clk AND the SPAD is inhibited saving power for the most active SPADs.
- If Q_n=1 the $Q_{n:0}$ count represents time from saturation allowing DR extension

Draw a graph with SPAD Counts (horizontal axis) vs Power consumption (vertical axis).

12.2 Architecture 2: Time to saturation HDR



J. Ogi, et al., JSSC(56), 2022

Measurement results of current consumption at V_{ANODE}. Open circles are current consumption with SPAD deactivation after counter overflow with extrapolating count. Open rhombuses are those without SPAD deactivation after the counter overflow.