MICRO-523: Optical Detectors

Week Eleven: SPAD Fundamentals – Solutions

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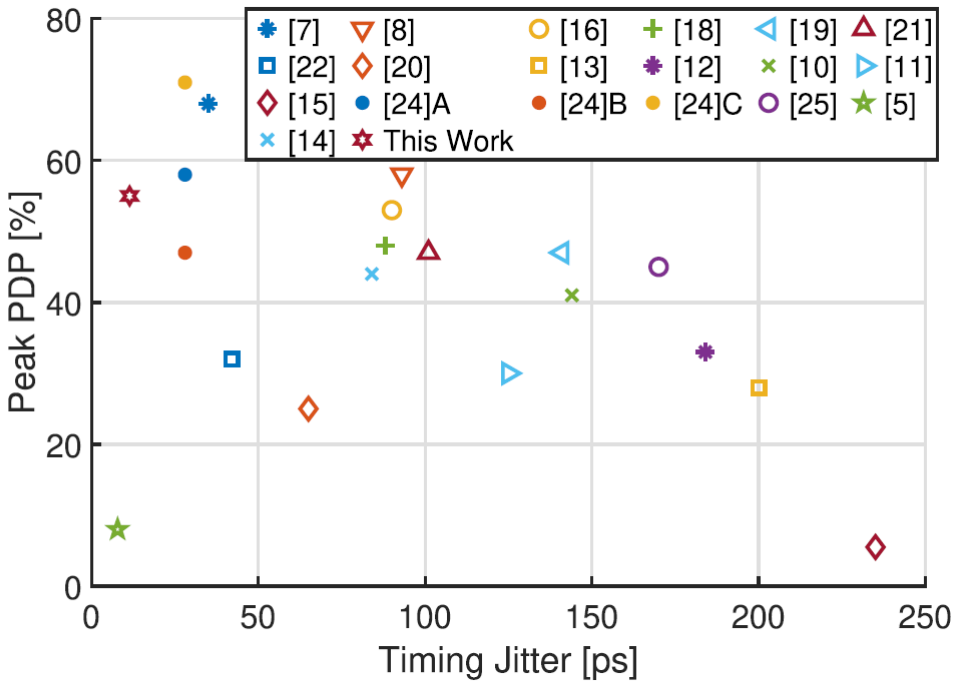
Based on MICRO-523, P.-A. Besse, 2023

TAs: Samuele Bisi, Yazan Lampert

Exercise 11.2: Key SPAD metrics

- Dead time (1-100 ns) *vs. Dynamic range -> spatial/temporal oversampling*
- Dark counts (cps-kcps) vs. *Sensitivity -> refined processes, gating, coincidence detection*
- Sensitivity (PDE = PDP × FF)
  - Photon Detection Probability (PDP) (up to 80%)
  - Fill-factor (1-80%) -> microlenses
- Timing precision (jitter) (~7.5-100 ps) *vs. Wavelength*
- Afterpulsing (0.1-10%)
- Pixel pitch (10-50 μm, lately down to a few μm!)

- … and in SPAD matrices: Crosstalk, PDP/DCR Uniformity



Explain all the parameters, the underlying physics and their relevance

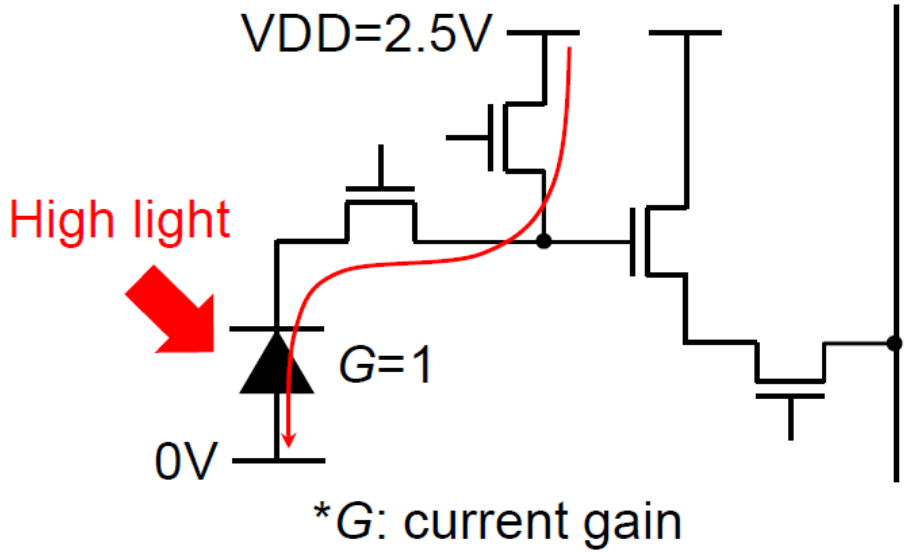
F. Gramuglia, et al., JSTQE (28), 2022

Exercise 11.2: SPAD camera power consumption

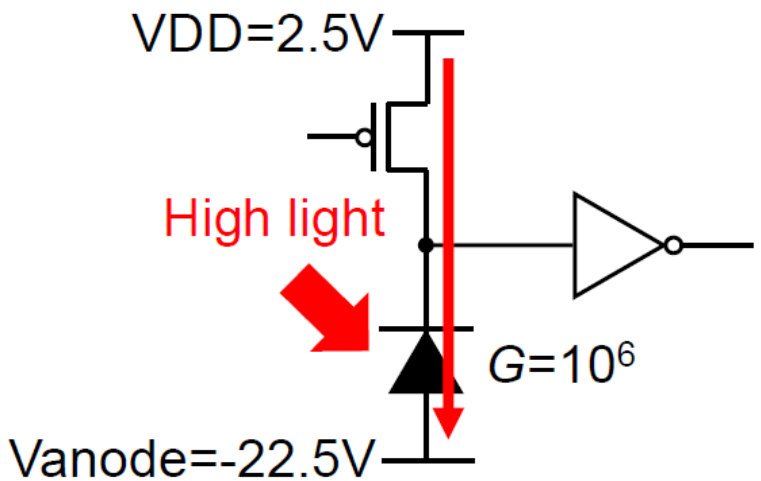
K. Morimoto, Image Sensors Europe 2024

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

CMOS imager (4T pixel)



SPAD imager (passive recharging)



How does the power consumption of the two cameras compare?

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

Exercise 11.2: SPAD camera power consumption

K. Morimoto, Image Sensors Europe 2024

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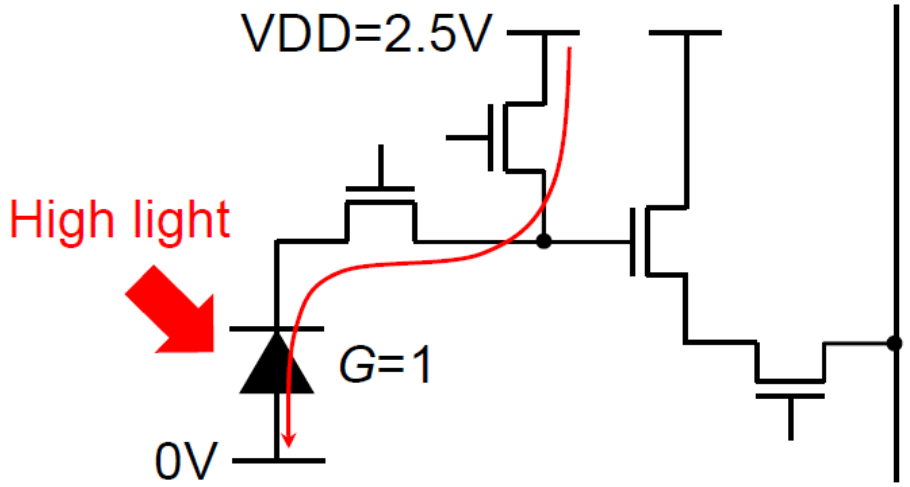
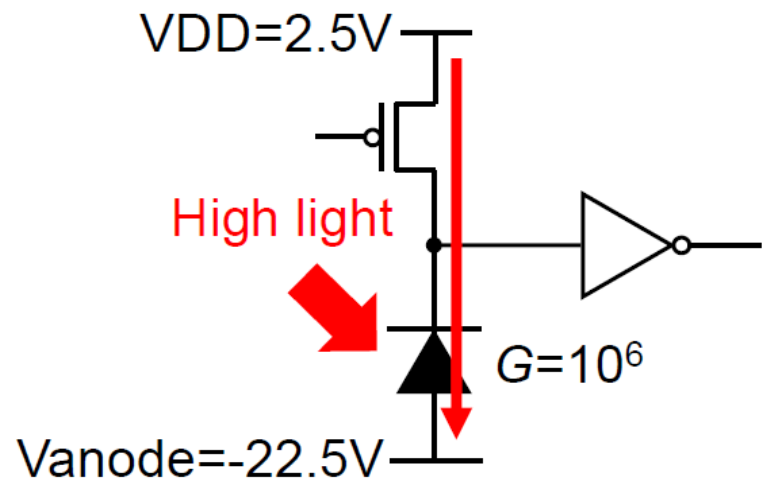
CMOS imager (4T pixel)



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× higher power!

Device level improvement

How can we improve the power consumption from a device-level perspective?

- SPAD Power Consumption is calculated from:

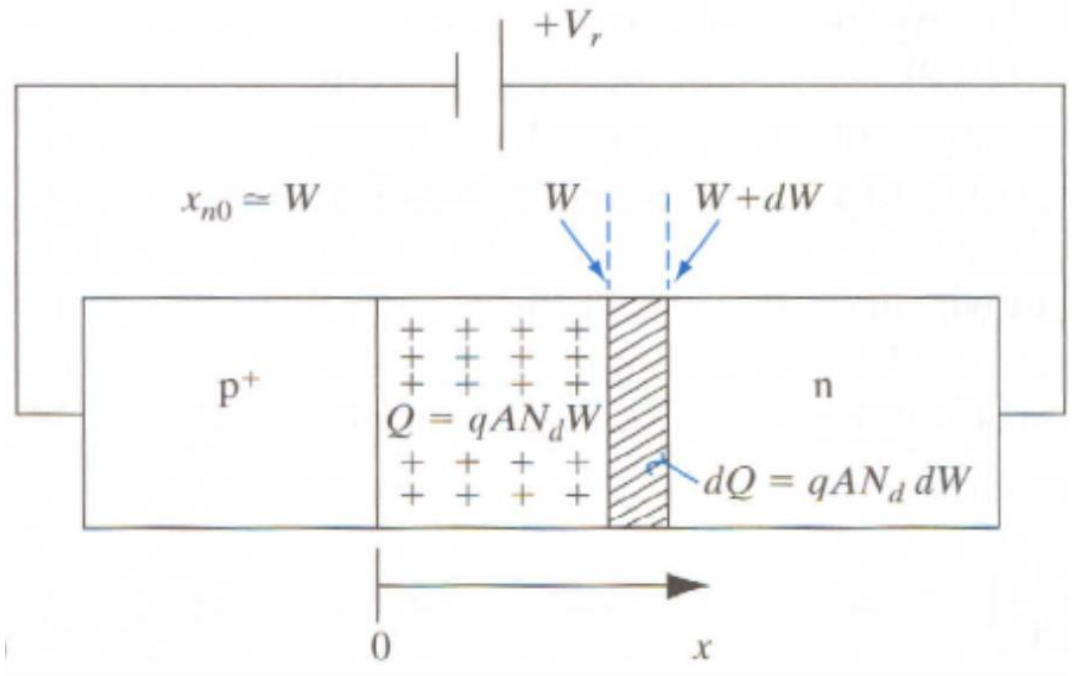
$$P = fCV_{excess}(V_{BD} + V_{excess})$$

Where f is average triggering rate, C is SPAD capacitance V_{excess} is excess bias voltage and V_{BD} is the breakdown voltage.

- To reduce **peak** power we can:
  1. Reduce the triggering rate by employing optical filters, choice of lens f#, aperture over detector.
  2. Reduce the SPAD capacitance and hence charge per pulse $Q=CV_{excess}$ by suitable device engineering
  3. Reduce the breakdown voltage of the SPAD by device engineering
- To reduce **average** power SPADs should be operated with the minimum duty cycle for the required SNR and gated below V_{BD} when not in use.

Robert K. Henderson, ESSxxRC 2022

Junction depletion capacitance



$$W = \left[\frac{2\epsilon(V_0 - V)}{q}\left(\frac{N_a + N_d}{N_a N_d}\right)\right]^{1/2}$$

$$C_j = \epsilon A\left[\frac{q}{2\epsilon(V_0 - V)}\frac{N_d N_a}{N_d + N_a}\right]^{1/2} = \frac{\epsilon A}{W}$$