Fundamentals and Applications of Modern Single-Photon Detector Circuits and Processing Systems

Part 1: Fundamentals

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For tutorial materials:

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Notes about our Tutorial

- Scope:
  - Design and applications of single-photon detectors
  - We'll cover one particular type: single-photon avalanche diodes (SPADs)
  - Three parts:
    - **Part 1:** The fundamentals
    - **Part 2:** Applications
    - **Part 3:** Intro to Intellectual Property (offline)

https://www.icbiolab.org/data/

Prof. Dandin: Parts 1 & 3

Prof. McFarlane: Part 2

Part 1: Outline

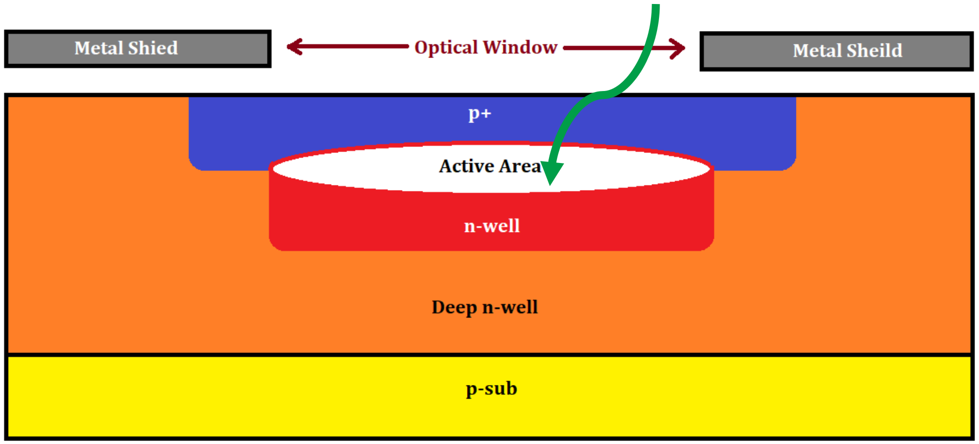
- What are single-photon avalanche diodes (SPADS)?
  - Semiconductor structure
  - CMOS implementations
    - Premature edge breakdown
  - Spectral Responsivity Measurements
  - Passive imaging

Learning Outcomes:

1. Basic SPAD structure and operation
2. Measurement techniques for spectral response characterization
3. Imager design and characterization

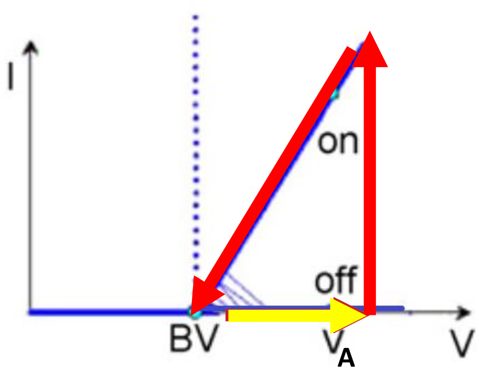
Semiconductor Structure and Device Operation

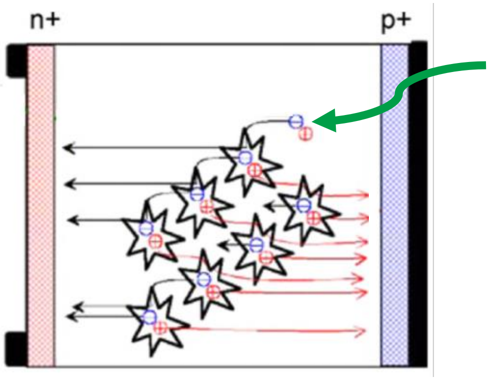
What are SPADs?



Single-Photon Avalanche Diode (SPAD)

- Reversed biased p-n junction in **Geiger mode** ($V_{AC} > V_B$)
- Sensitive to a single photon
- Fast quenching and reset enables photon counting

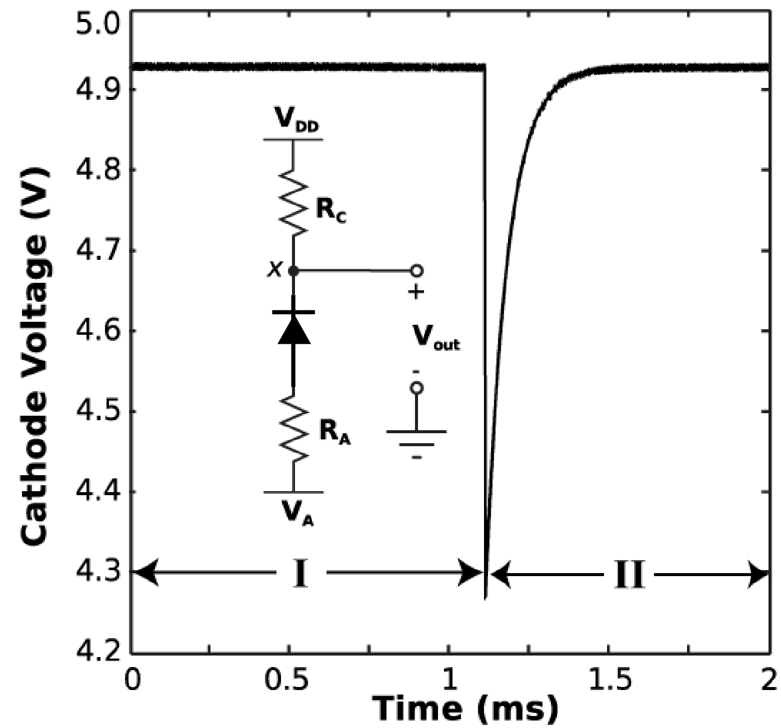




F. Zappa et.al., "Principles and features of single-photon avalanche diode arrays", Sensors and Actuators A: Physical, 140, 1, 2007.

Typical Geiger Mode Pulse

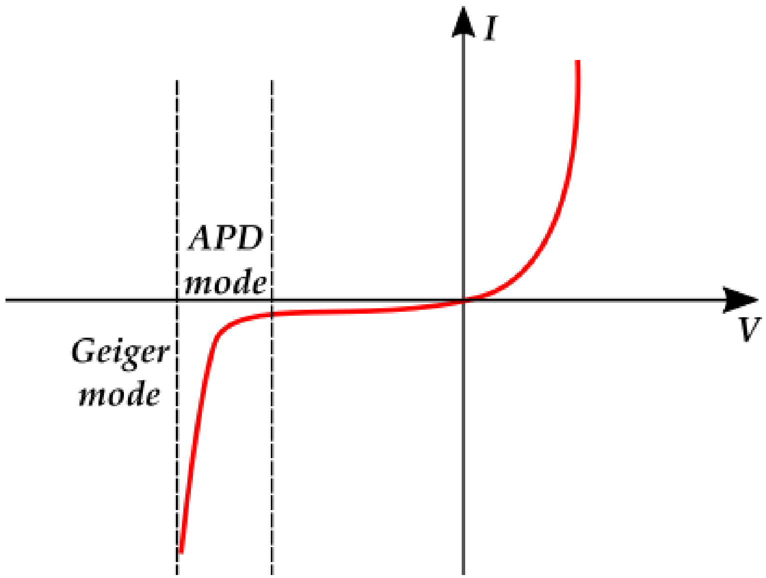
- The device is biased in the Geiger mode ($V_{AC} > V_B$)
- The avalanche is quenched, then the applied voltage is reset
- The onset of avalanche corresponds to photon arrival

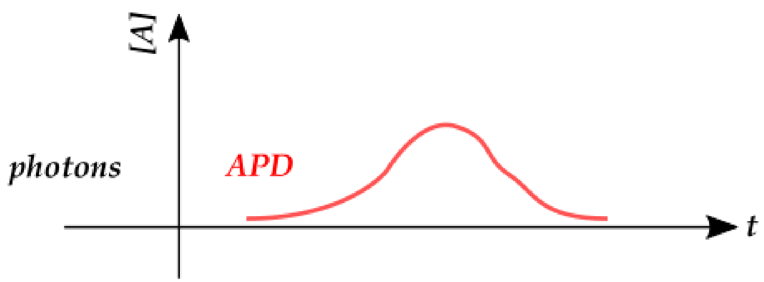


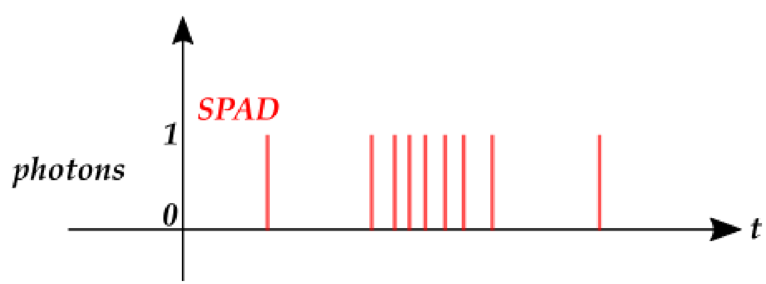
Note: a pulse can be a "dark" count…

SPAD vs. APD

- The semiconductor structure *can* be the same
- In APD mode, the device operates with gain in *linear* mode
- In SPAD mode the onset of avalanche corresponds to photon arrival, so the device *counts*
- The gain doesn't matter in Geiger mode!







SPADs in CMOS

Advantages of CMOS SPADS

- cost-effective alternative to photomultiplier tubes (PMTs)
- large arrays possible
- interfacing with other mixed-signal circuits possible

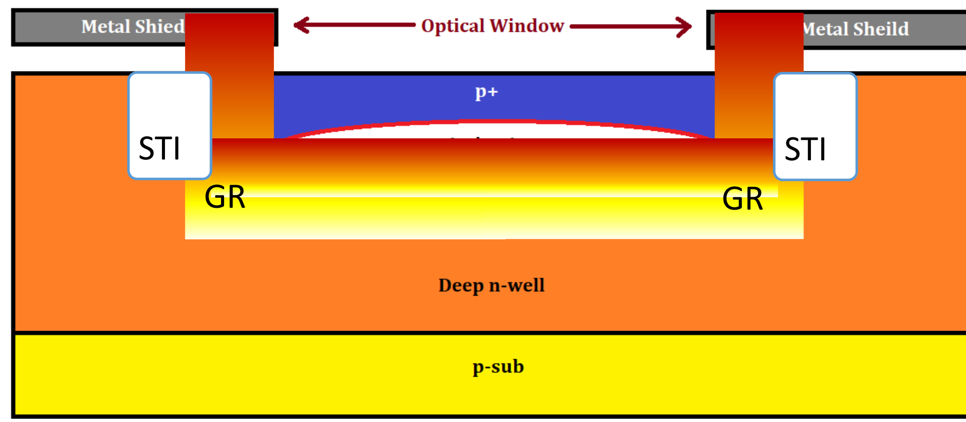
Challenges

- design parameters fixed in standard CMOS processes
- **dark count rate** can be a major issue!
- *perimeter breakdown* due to planar nature of the junctions

PEB Mitigation Strategies (1)

The issues:

- Fields are strongest at the edges of the diode
- Avalanche capability is thus constrained there in a planar diode
- Typical methods to reduce field strength: guard ring (GR), shallow trench isolation, retrograde well (RW)



PEB → Higher dark count → Lower sensitivity

Technology dependent!

PEB Mitigation Strategies (2)

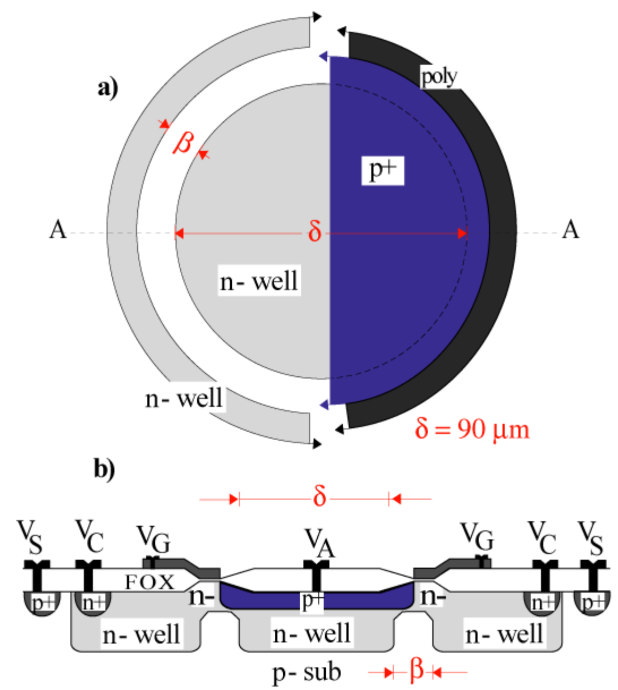
Perimeter gating is technology agnostic!

Structural Features

- p+/n-well junction in a p-sub
- n-well lateral diffusion
- *perimeter* field gate

Key Advantages

- *controllable* breakdown voltage
- *controllable* SNR
- suppresses perimeter breakdown
- portable to virtually all CMOS processes



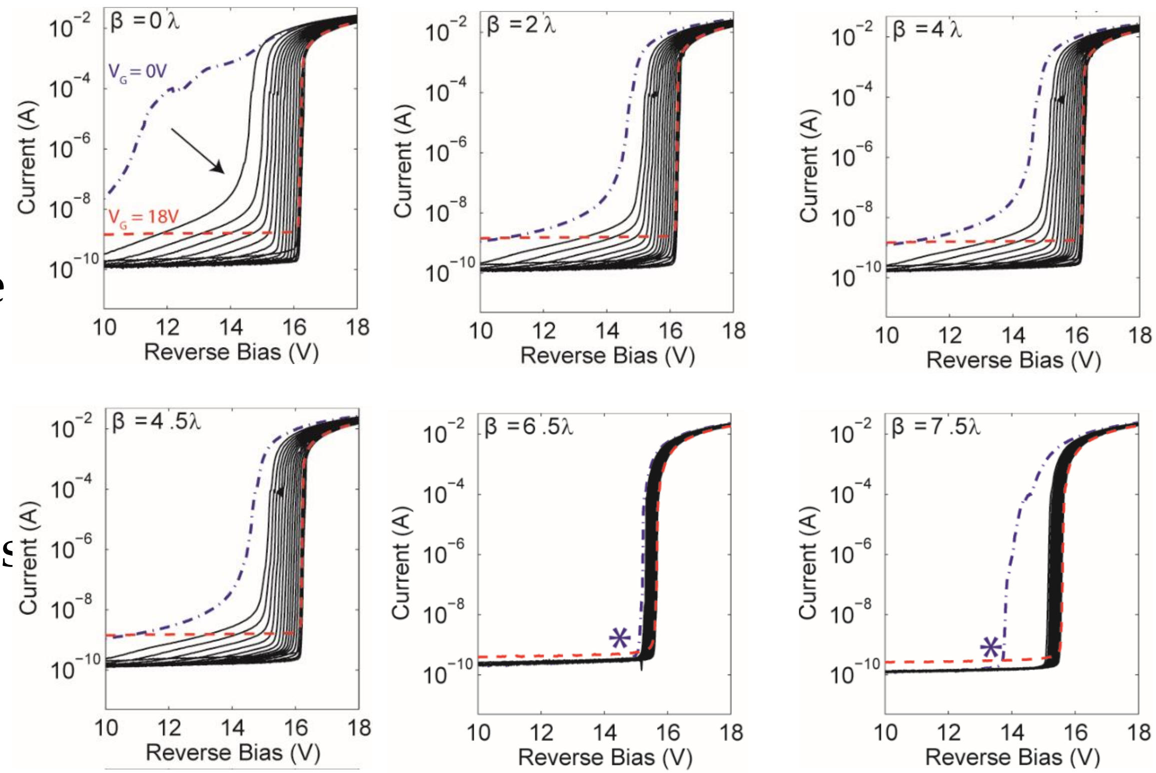
I-V Characteristics

Key Observations

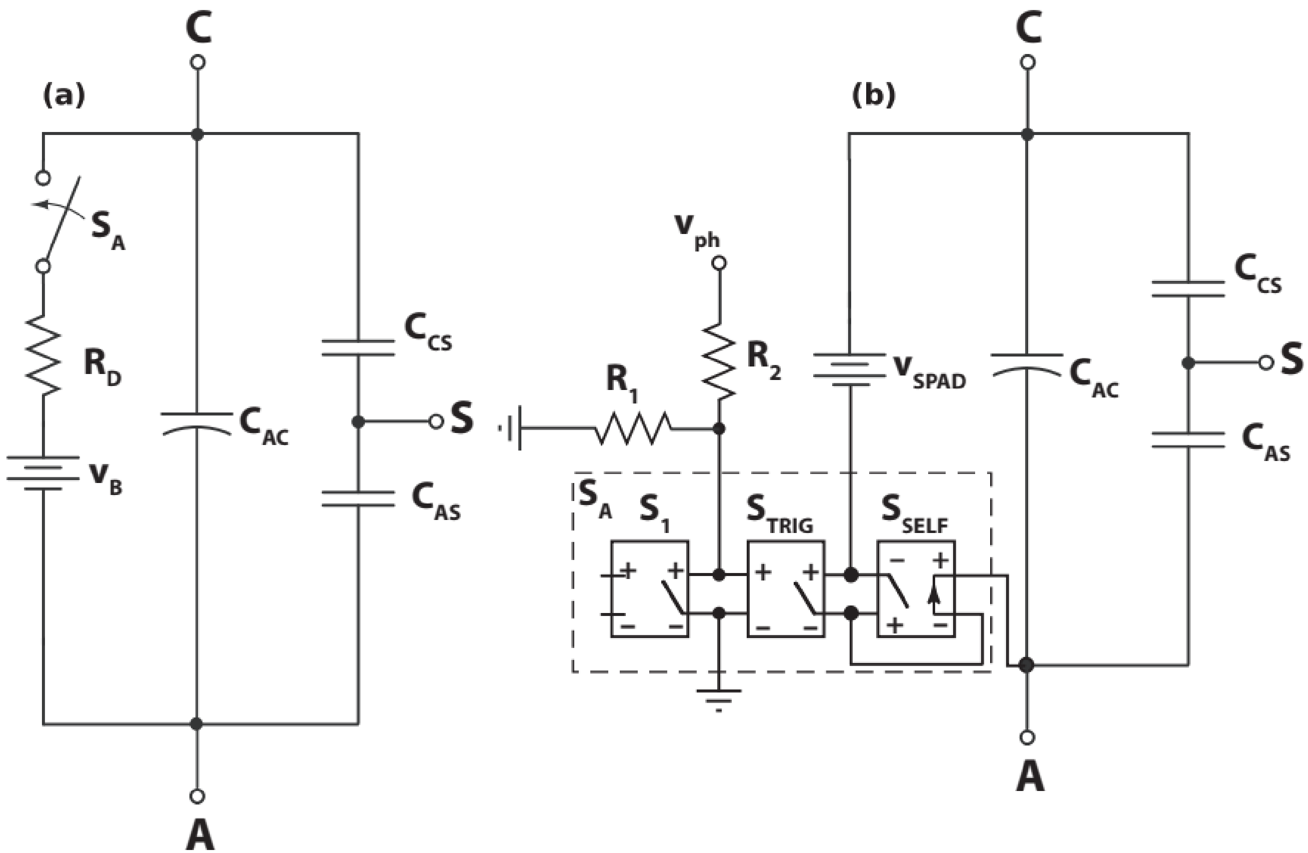
- V_G changes dark current
- V_G changes V_B
- β influences zero-gate bias V_B

Design Features

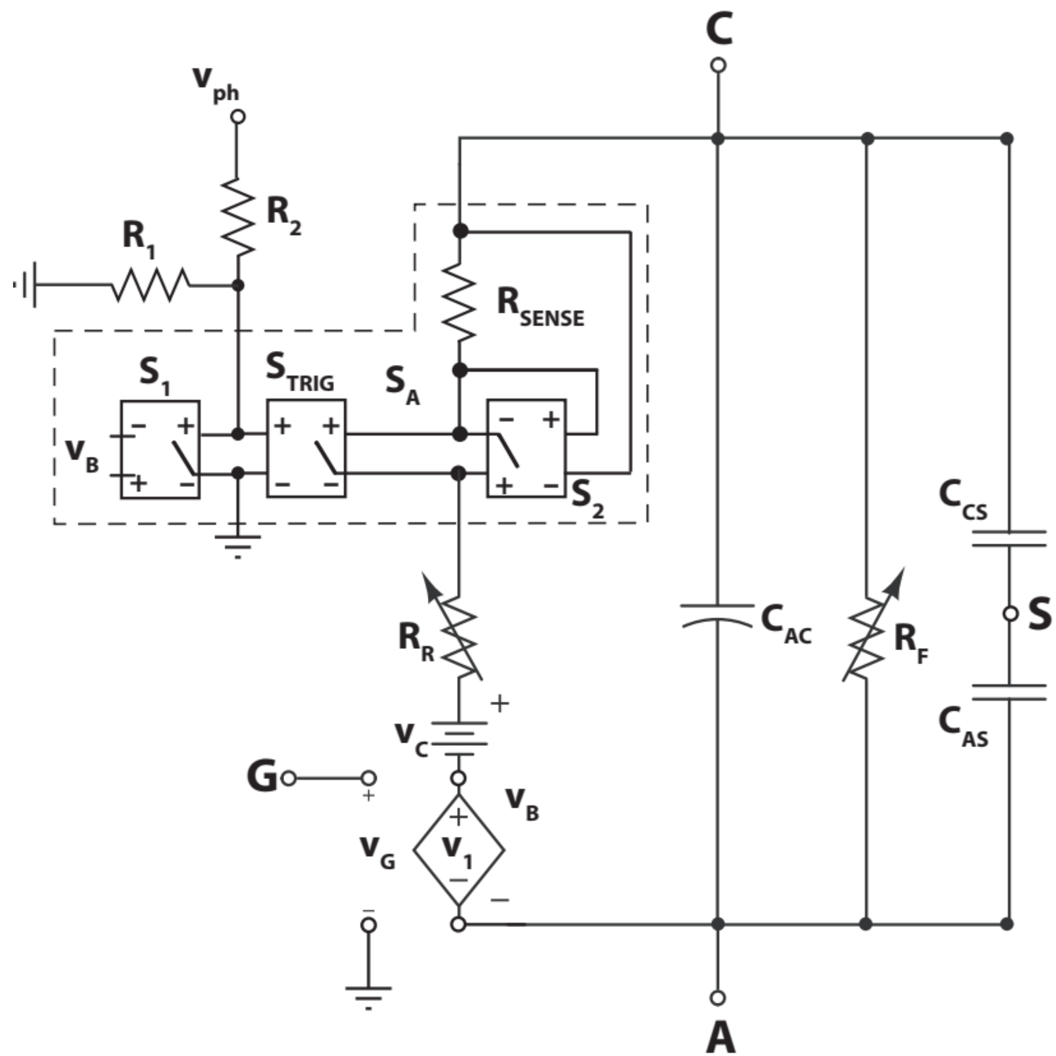
- β = 0λ for compactness
- shape need not be circular



SPAD Equivalent Circuit Models



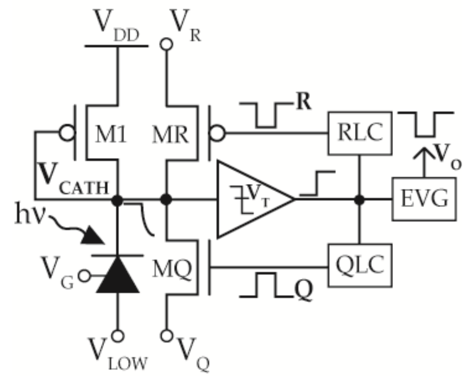
Pg-SPAD Equivalent Circuit Model



Temporal Characteristics (w/ AQAR)

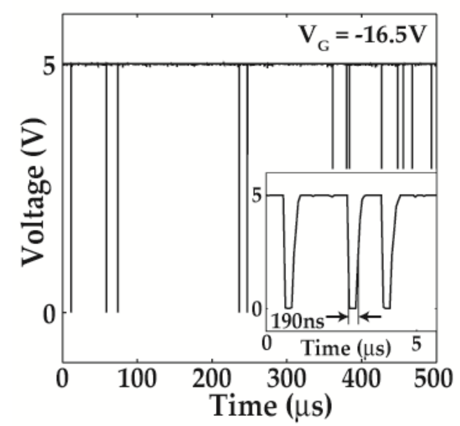
Active Quenching and Active Reset

- fast quenching with transistor MQ
- fast reset with transistor MR
- digital events with EVG



Additional Features

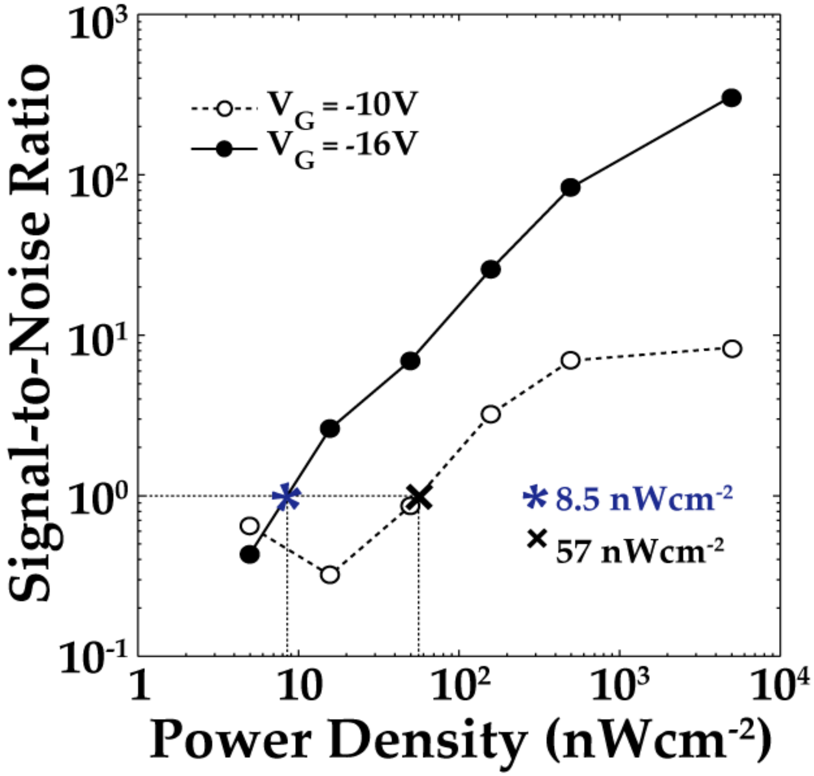
- reset duration control
- quenching duration control
- avalanche current mirroring



Signal-to-Noise Ratio (w/ AQAR)

SNR Performance

- high V_G increases SNR
- high V_G increases dynamic range
- high Vg reduces NEP by a factor of 6.7



Spectral Characterization Techniques

Near Breakdown Spectral Responsivity

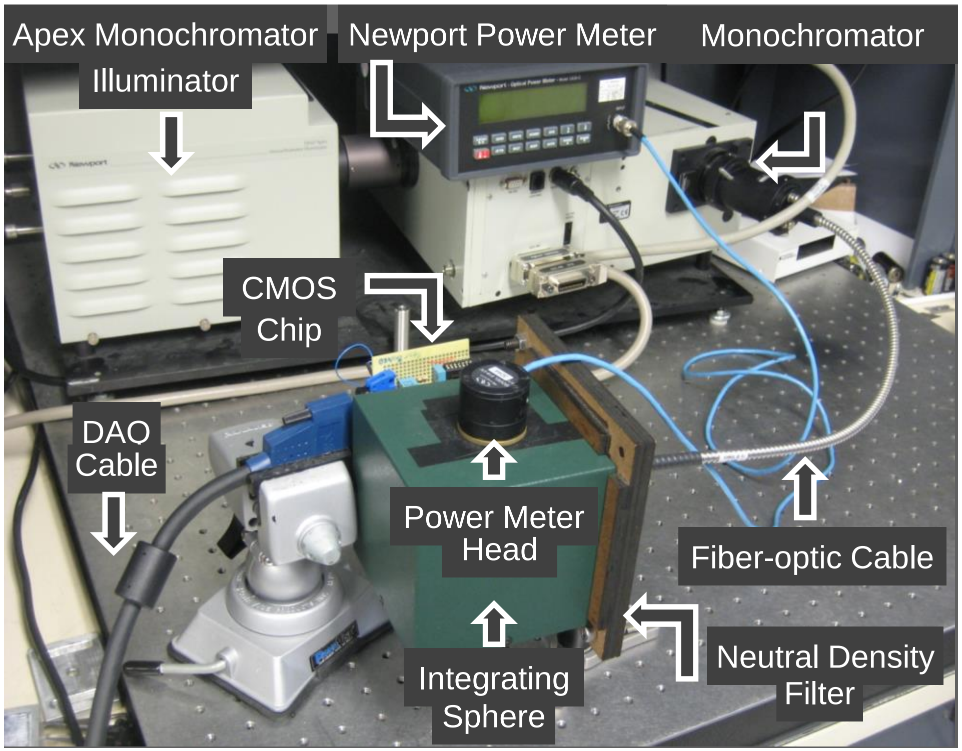
in Geiger Mode

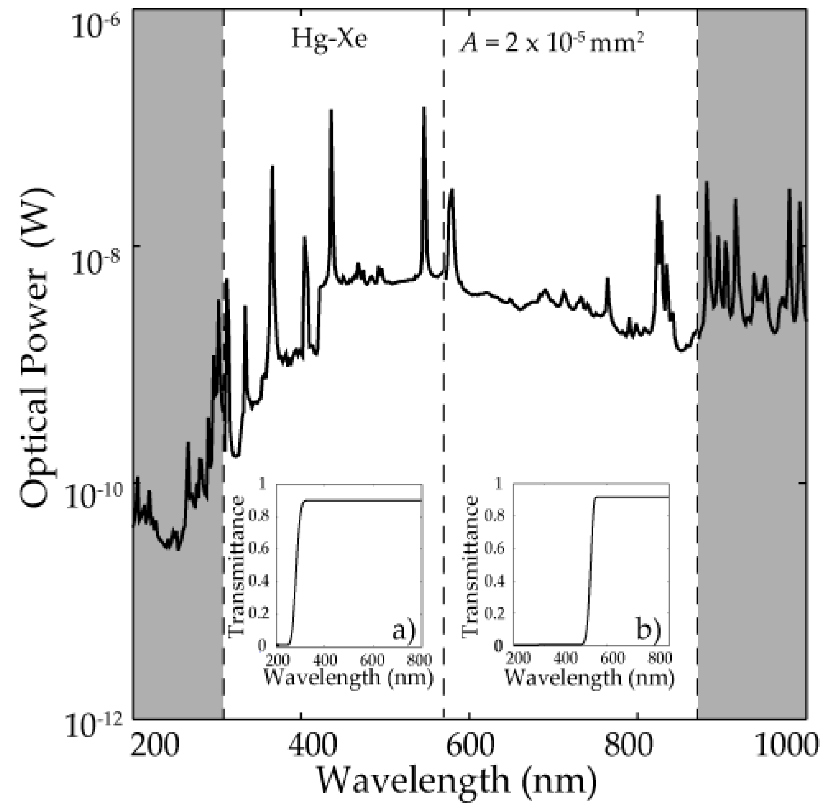
- PDE(λ) ~ $P_{avalanche}$ * R(λ)
- R(λ) can be determined empirically in Amps/Watts

Approach

- for a SPAD, the responsivity does not vary *spectrally* in the near breakdown region
- for a pg-SPAD, in contrast, gate field effects cause significant spectral variation

Responsivity Measurement Setup





Estimating Responsivity

Near-breakdown Responsivity

$$R|_{\alpha V_B} = \begin{cases} \frac{|I_M - I_D|}{P_M}\left(\frac{A_P}{A_D}\right), & for\ |I_M - I_D| > \delta \\ \epsilon\ , & for\ |I_M - I_D| \leq \delta \end{cases}$$

- I_M : photocurrent
- I_D: dark current
- P_M: optical power
- $\alpha \longrightarrow 0.99$
- $\delta \longrightarrow 3$ *std of I_D
- $\varepsilon \longrightarrow 0$

set sweep ranges

perform V_A and λ sweep

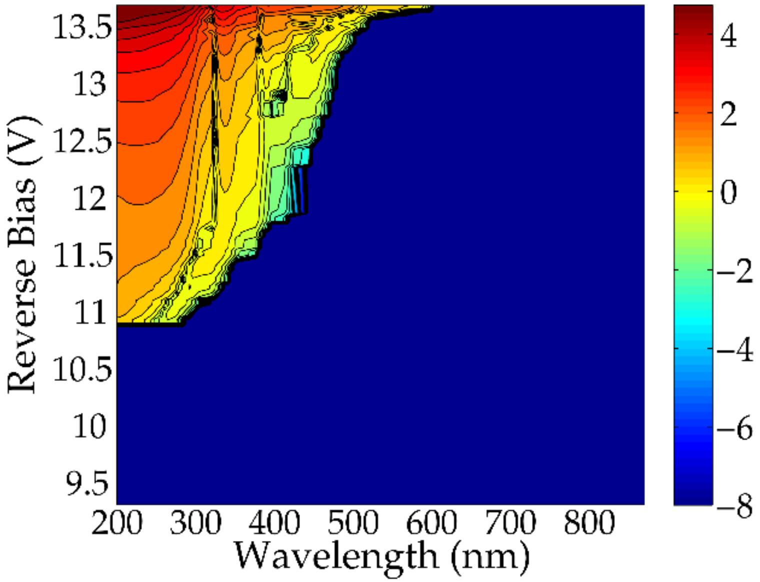
perform V_G sweep

return responsivity spectra

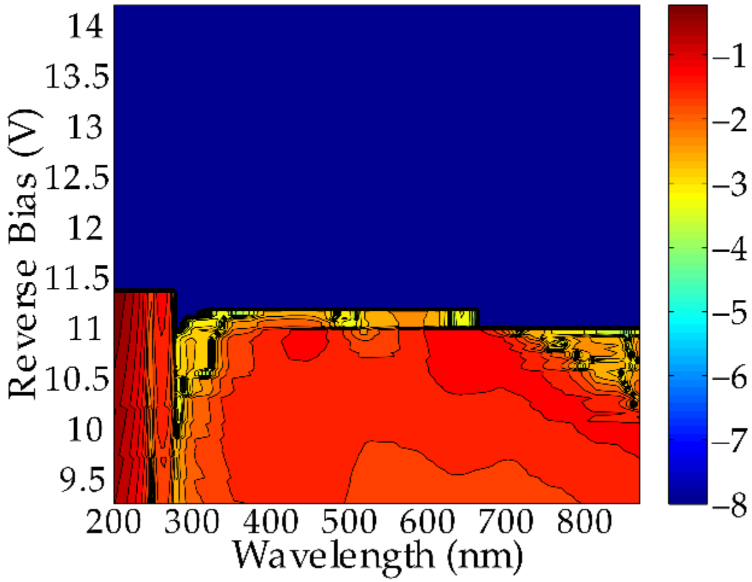
Algorithm 1 Responsivity Measurement Algorithm

procedure ESTIMATE $R|_{V_G}(I_M, I_D, P_M(\lambda))$
    $V_{app} \leftarrow V_{A1} : step : V_{Am}$
    $V_G \leftarrow V_{G1} : step : V_{Gn}$
    $\lambda \leftarrow \lambda_1 : step : \lambda_j$
    for $i = 1 : n$ **do**
        close shutter
        source $V_G(i)$
        sweep V_{app}, measure I_D
        compute V_B ▷ See ref. [10]
        $V_{A_{m-k}} \approx \alpha V_B$, $\alpha = 0.99$ and $k < m$
        $V_A^* \leftarrow V_{A1} : step : V_{A_{m-k}}$
        $I_D^* \leftarrow I_D(V_A^*)$
        open shutter
        for $r = 1 : j$ **do**
            source $V_G(i)$
            sweep V_A^*, measure I_M
            compute $R|_{V_G(i)}(I_M, I_D^*, P_M(\lambda_r))$
        end for r
    end for i
    return R
    close shutter
end procedure

pg-SPAD Responsivity Spectra (1)

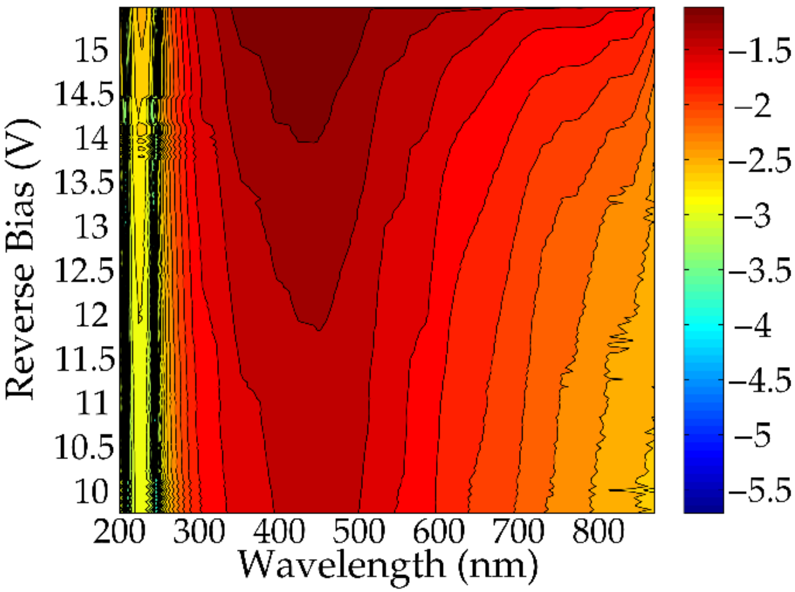


(a) V_G= 0V

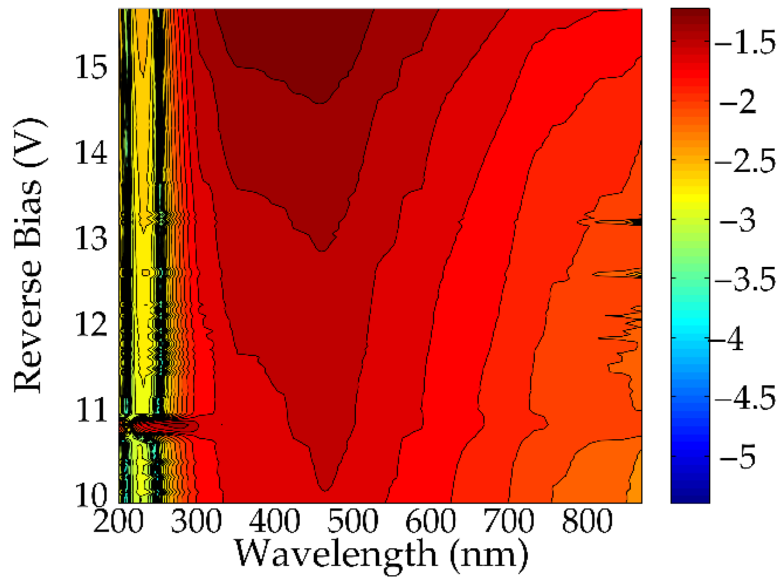


(b) V_G= 2V

pg-SPAD Responsivity Spectra (2)

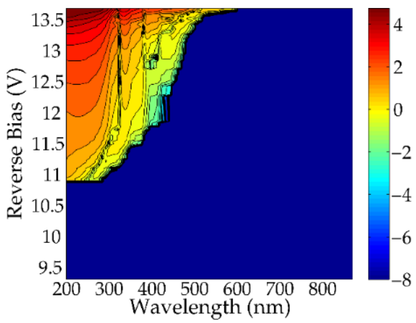


(g) V_G= 12V

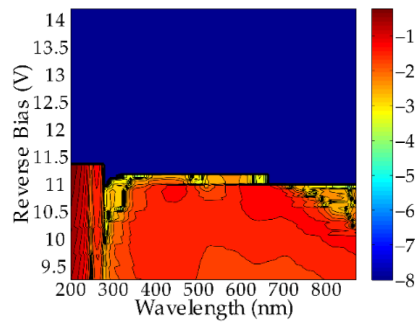


(h) V_G= 14V

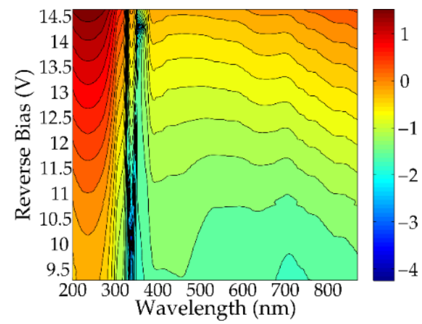
pg-SPAD Responsivity Spectra (3)



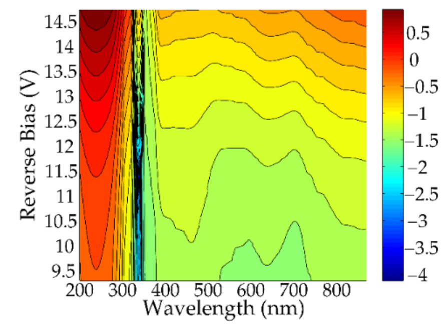
(a) V_G= 0V



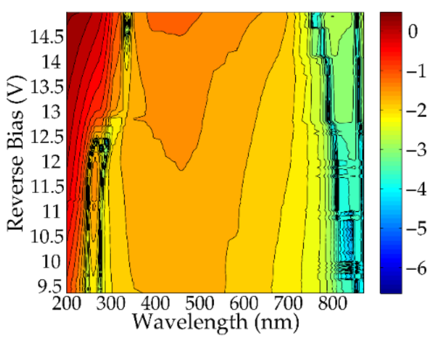
(b) V_G= 2V



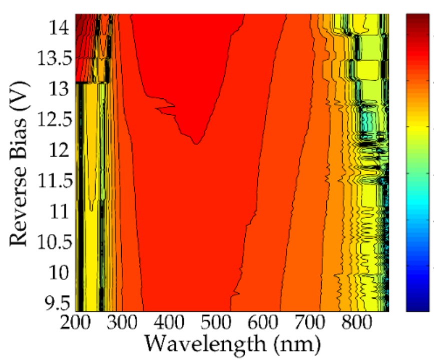
(c) V_G= 4V



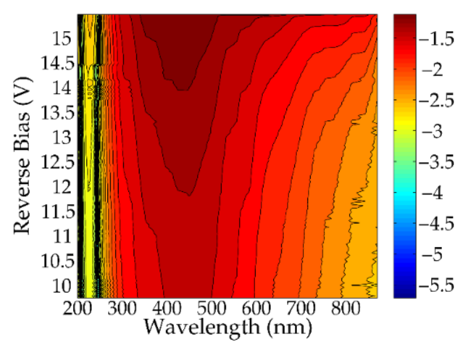
(d) V_G= 6V



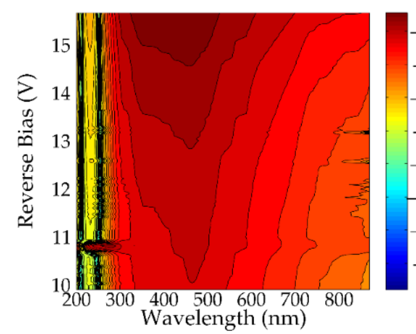
(e) V_G= 8V



(f) V_G= 10V



(g) V_G= 12V

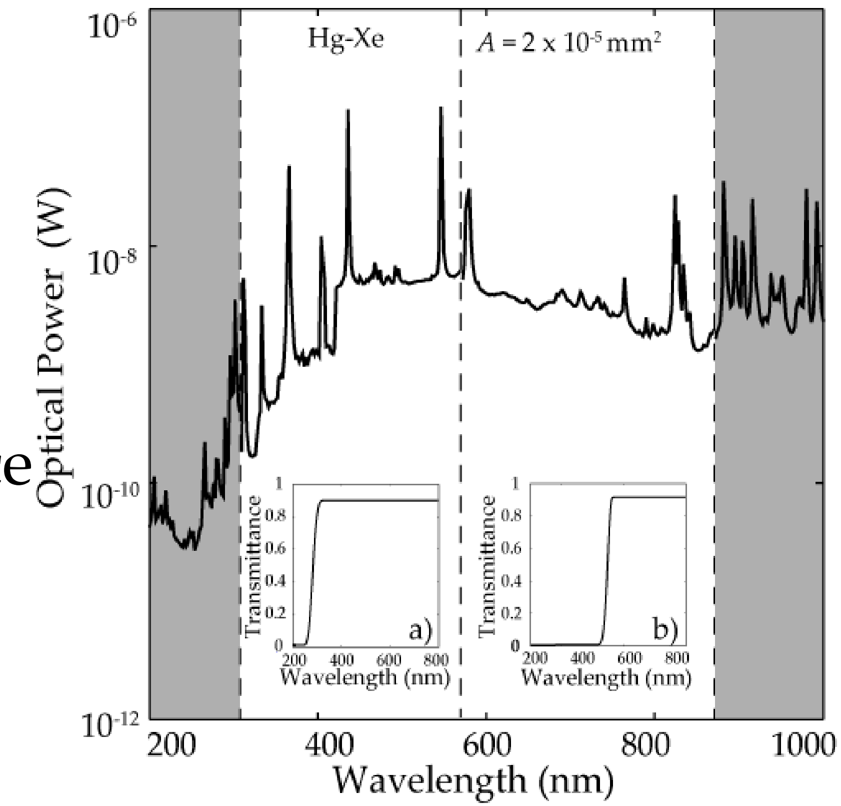


(h) V_G= 14V

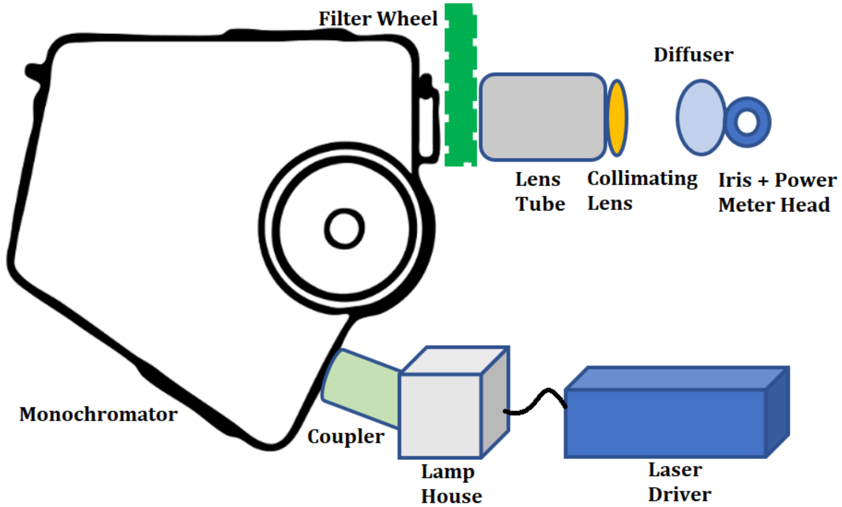
Potential Issues with this Measurement

SNR Performance

- Hg-Xe has lots of peaks
- Light intensity at high peaks can saturate sensor
- Dynamic range of light source over sweep region can introduce
  errors in the estimation

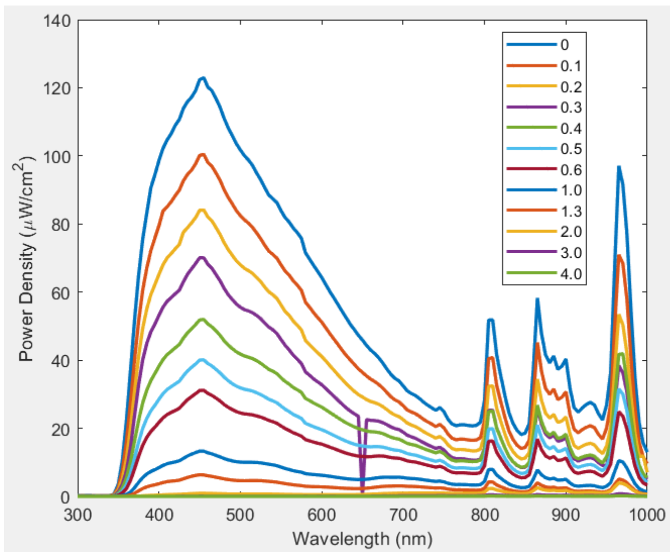


Improved Measurement Setup

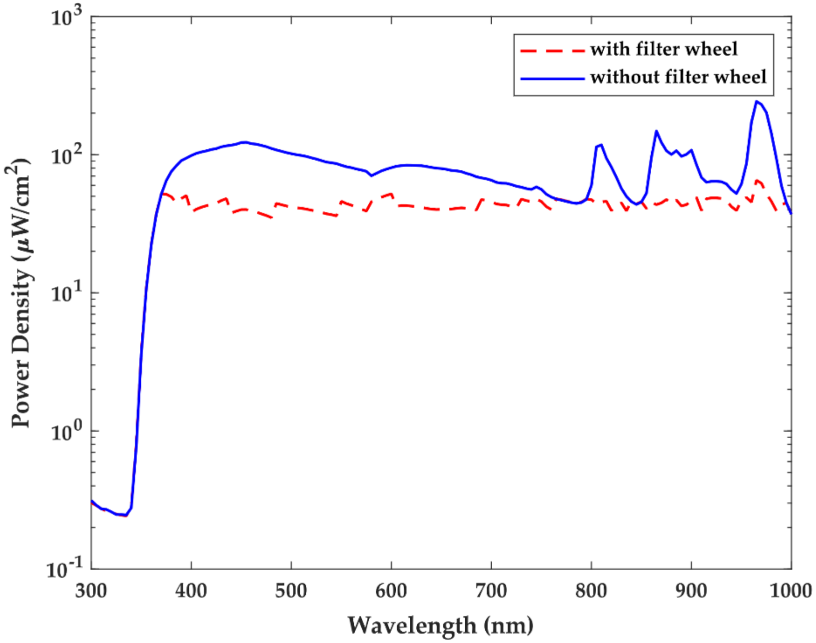


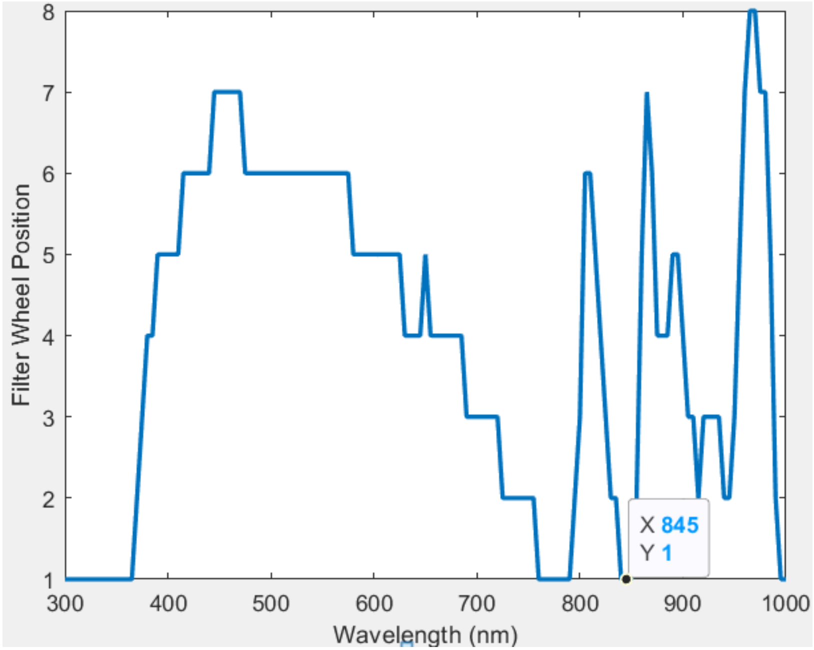
Towards a flat spectrum

- Get a better source!
- Filter wheel provides different attenuation level
- Programmability offers control on the fly during sweeps
- Can equalize on the basis of power density or photon arrival rate



Solution: Custom Filter Wheel Control Program Based on Acquired Spectrum





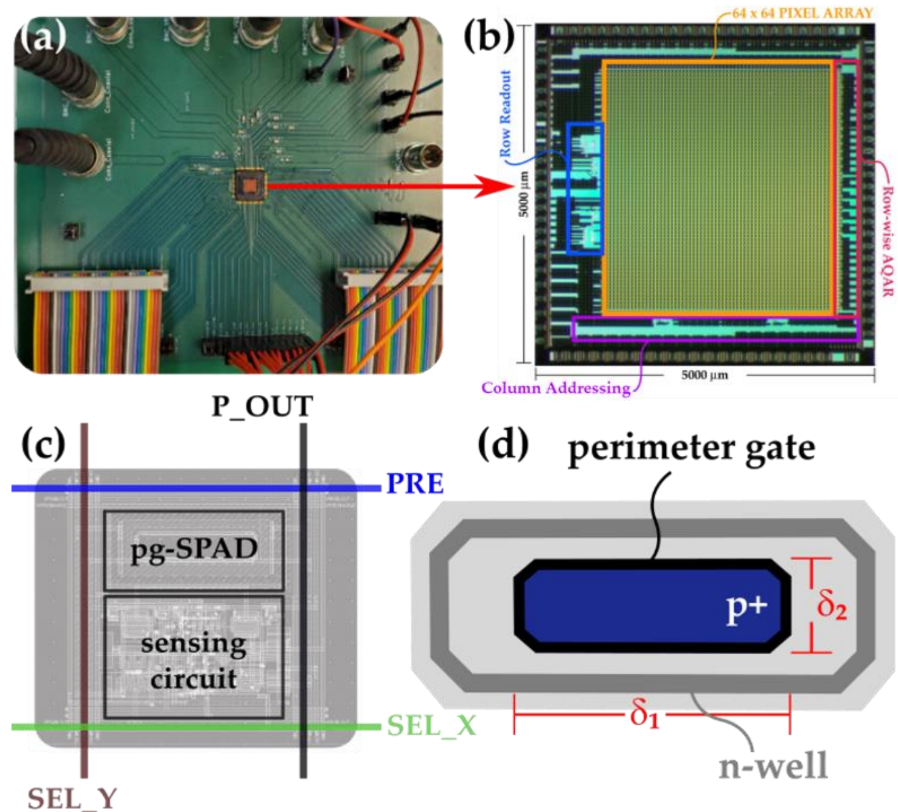
The light intensity is substantially constant across the spectrum of interest (350 nm – 800 nm)

Imaging

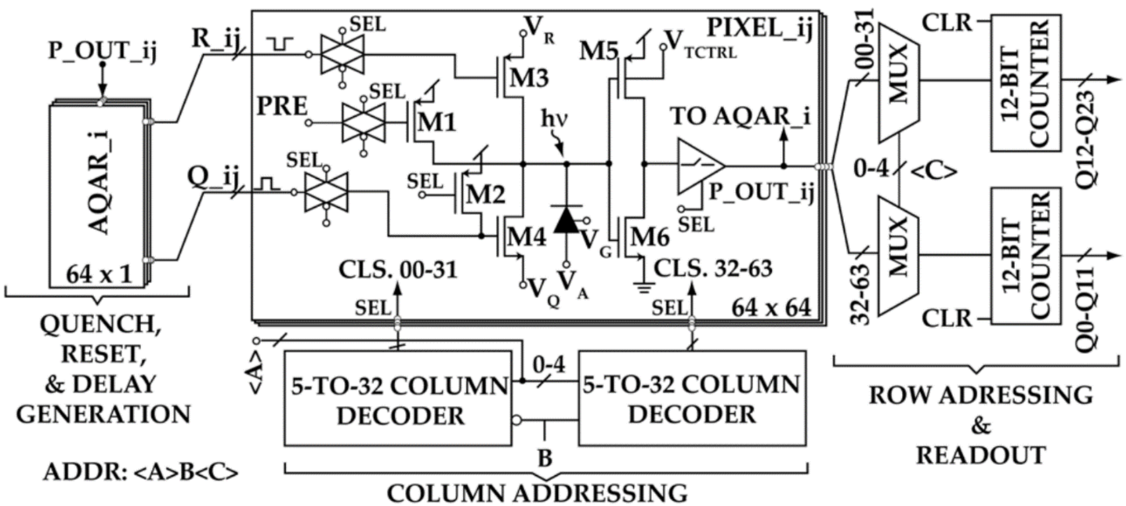
Passive Imaging w/ pg-SPADs

Chip characteristics

- Chip-on board
- Encapsulated wire bonds
- Pixels 10 x 30 μm
- Fill factor is small (~6%)
  - too many things in-pixel
- 5 x 5 mm die
- On-board TDC
- All digital readout



Imager Architecture & Operation

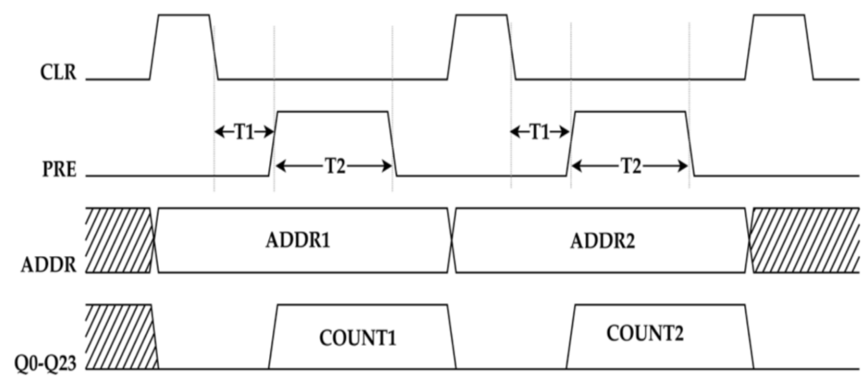


Design Features

- Large quench and reset transistors are in pixel
- Encapsulated wire bonds
- Pixels 10 x 30 µm
- Fill factor is small (~6%)
  - too many things in-pixel
- 5 x 5 mm die
- On-chip TDC
- All digital readout

Operation

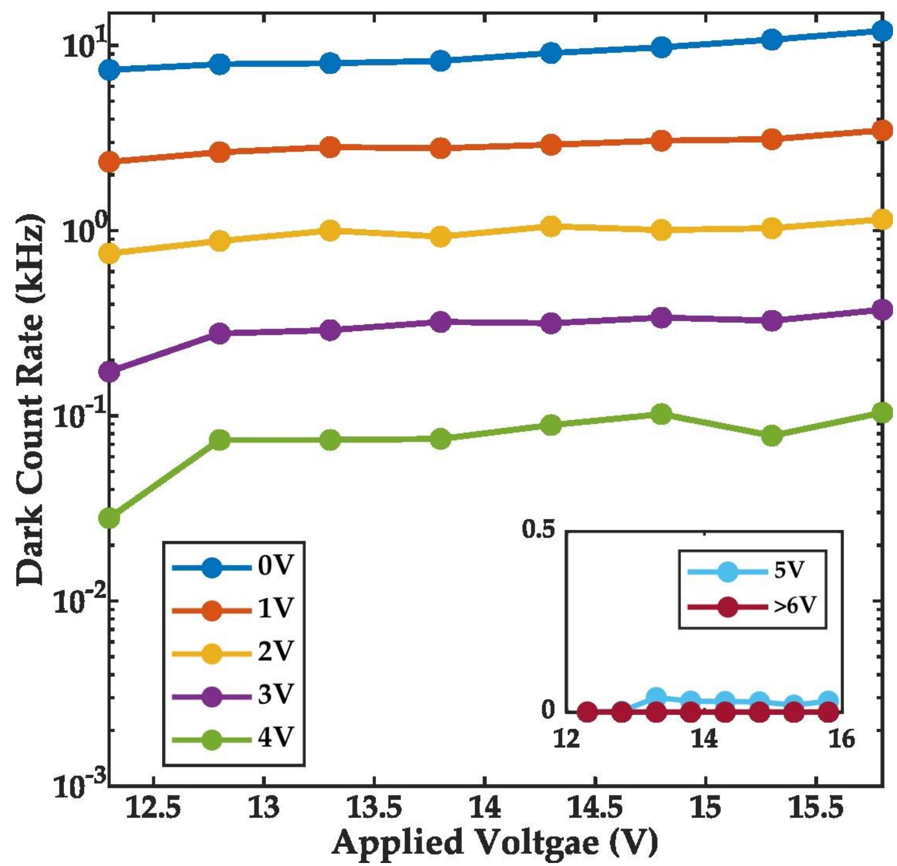
- Two-pixels are read at a time (not a fast imager, although with small integration time, we reach about 1000 fps)
- Pixel output signal *travels* to a row-wise AQAR circuit
- Column counters are cleared (CLR)
- Pixels are pre-charged with a hard reset
- Addressed is passed via I/O pads
- Counters are read after integration time elapses



Single Pixel DCR

Results

- DCR increases with V_A
- DCR decreases with PG
- **No DCs observed at high perimeter gate voltages!**

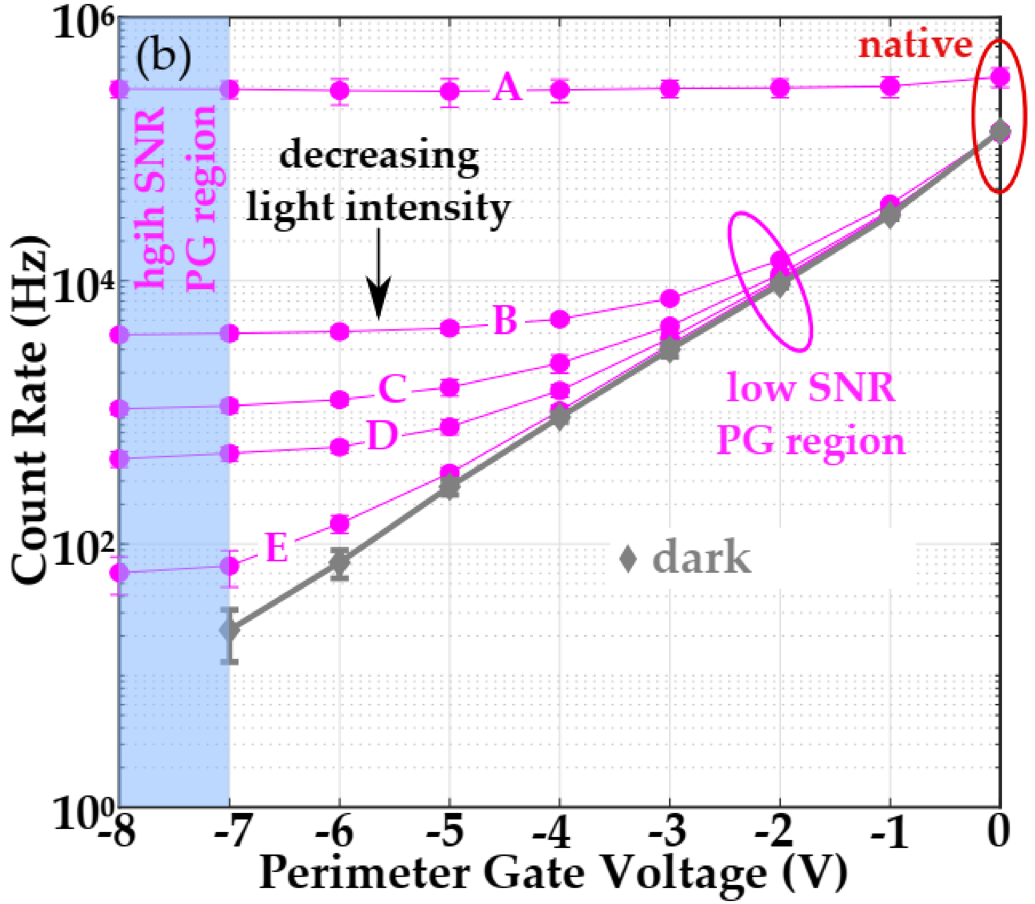


But zero DCR is associated with a probability!

High-SNR Operation at High Magnitude PG Voltages

Effects of PG on Photodetection

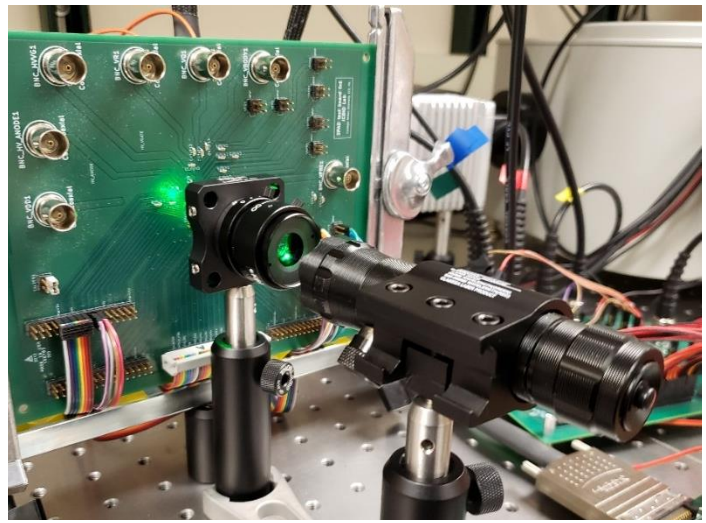
- PG eliminates the DCR and enhances SNR
- Lower photon fluxes can be detected with *zero* DCR

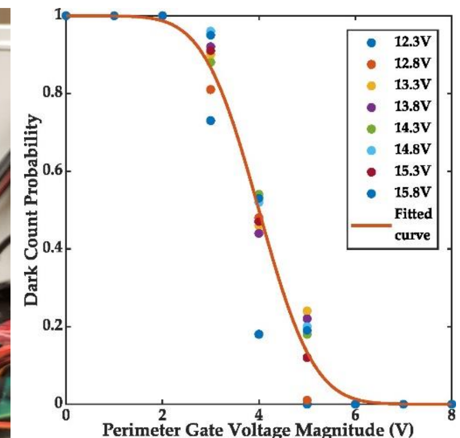


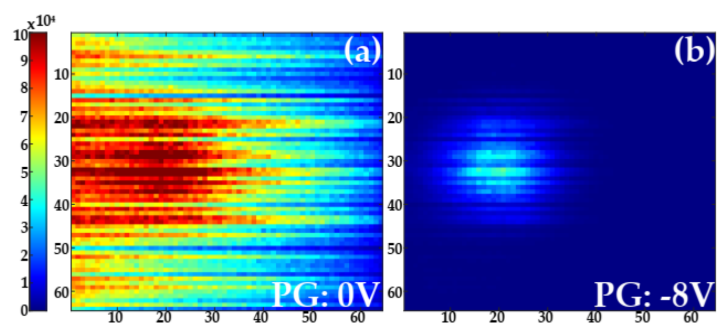
Probability of Observing a DC in any one of *n* Pixels

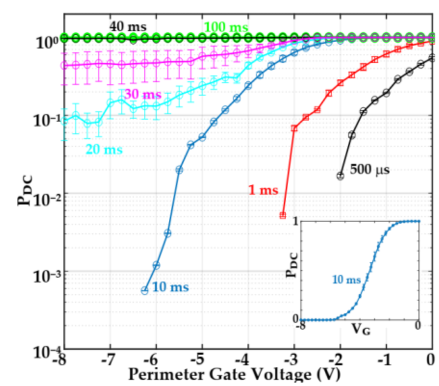
Conclusions

- Zero DCR operation is possible
- Probability of zero DCR depends on Integration time
- **Perimeter gating provides high-SNR operation**

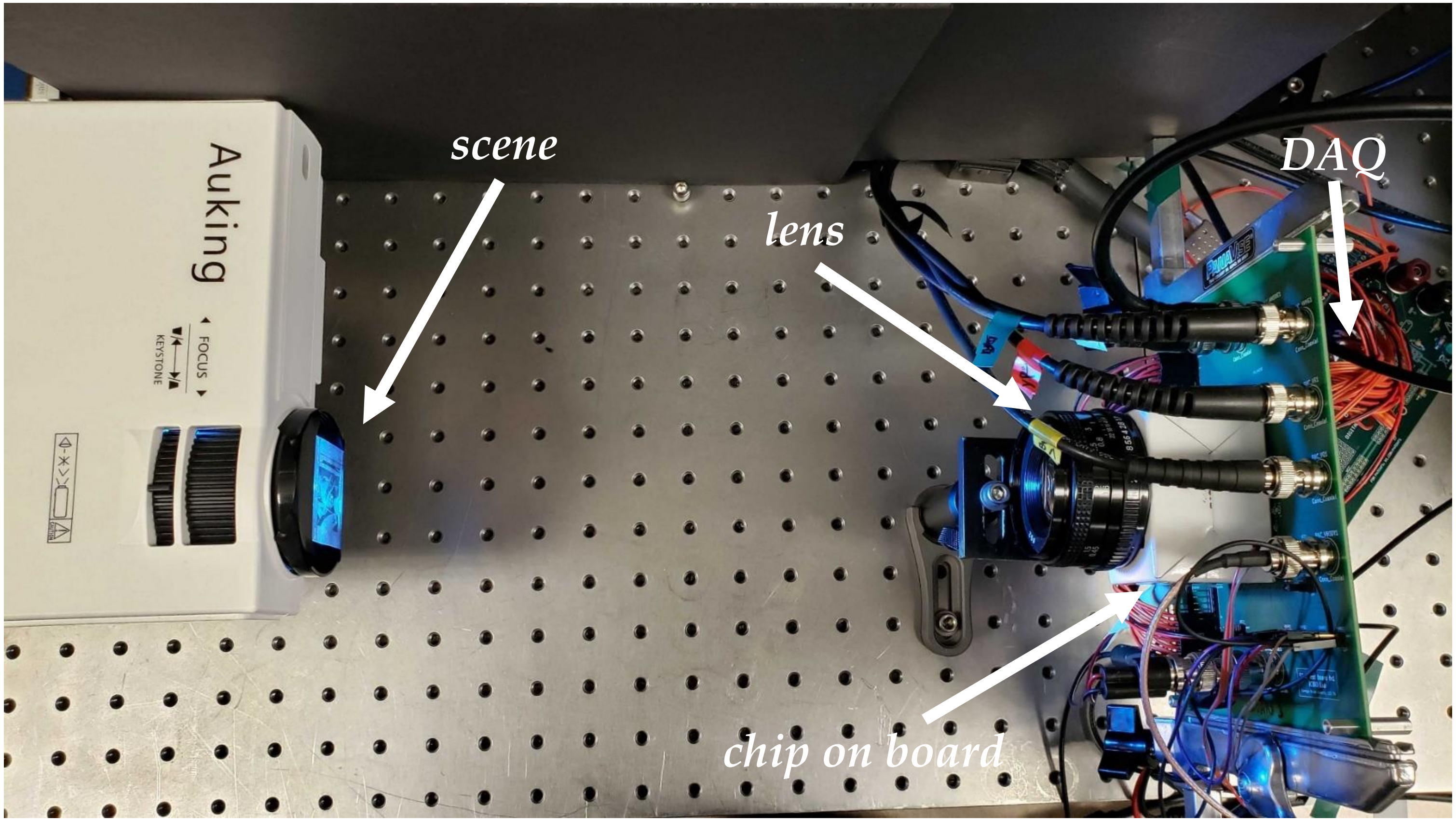




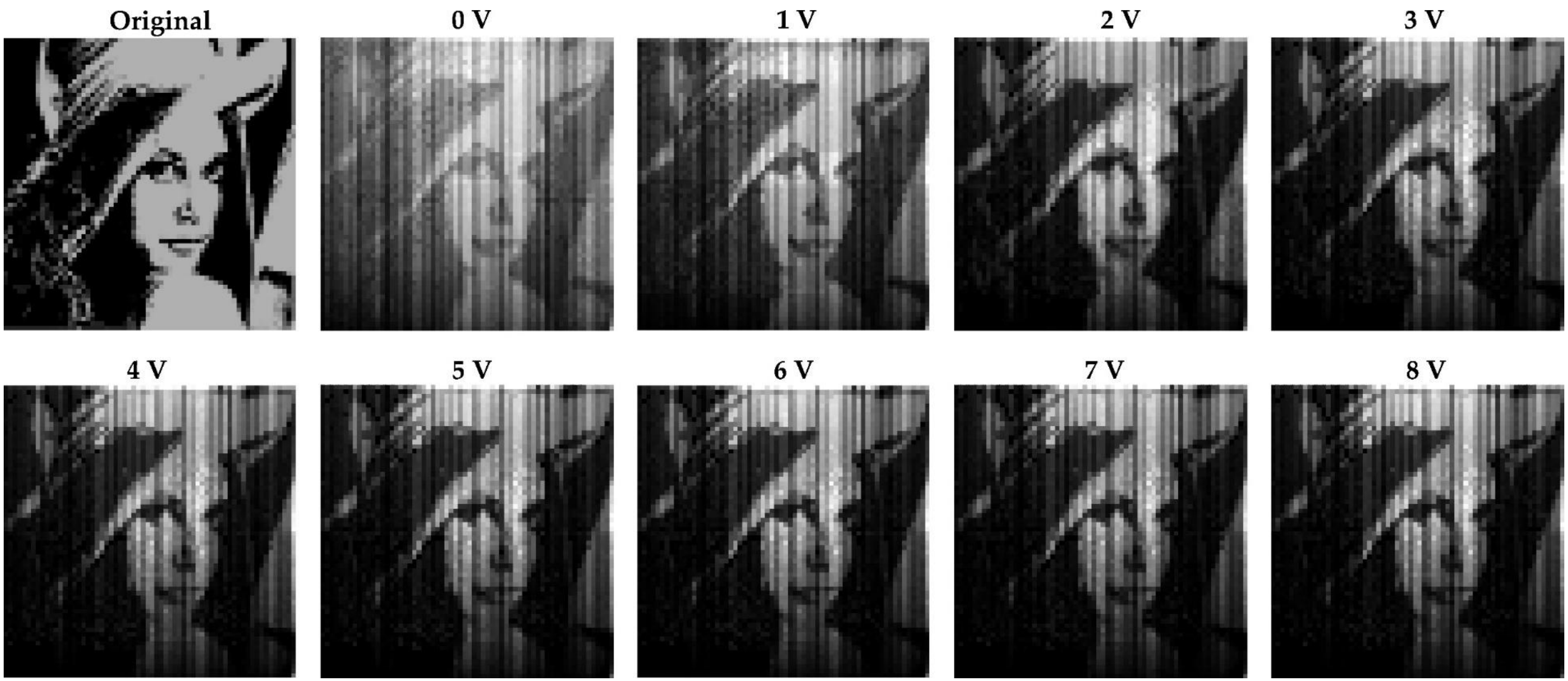




Can we image with this *imager* ?



Imaging *Lena* at Low Resolution

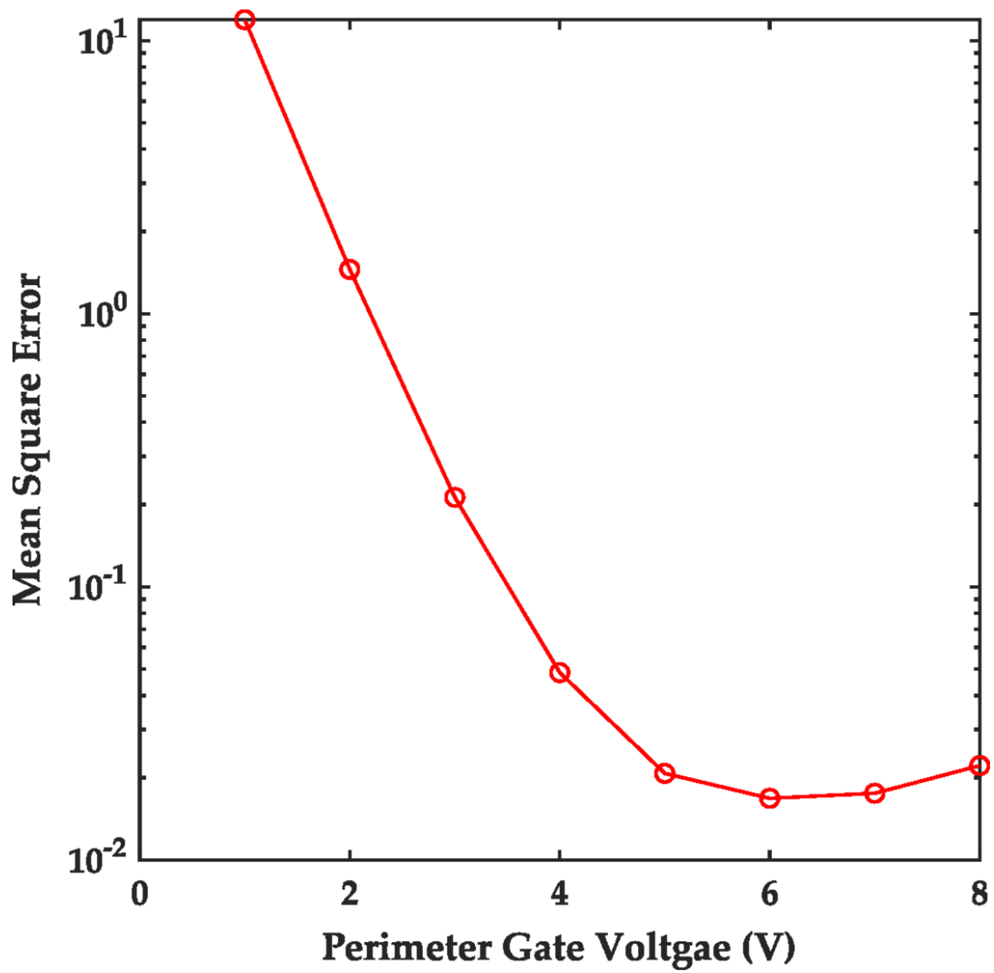


we can see *Lena* but there's a strong fixed pattern noise component likely due unequal delays in the readout paths from each pixel

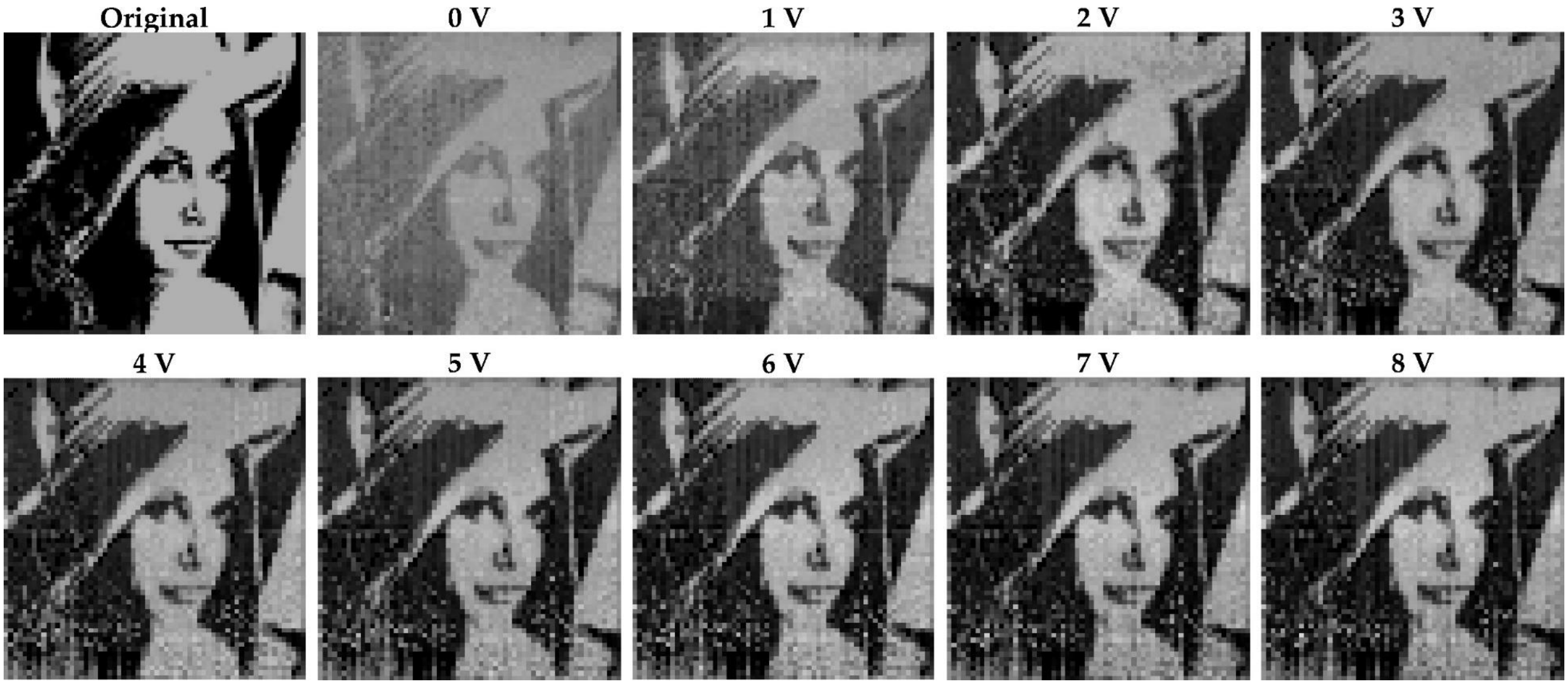
How Different are the Images for Each PG Voltage?

Effects of PG on Image Acquisition

- PG removes the DCR components and enhances images
- MSQE reveals a diminishing return region in terms of image quality
- Images beyond PG = 6V are essentially the same



Correct for Readout Fixed Pattern Noise in Software

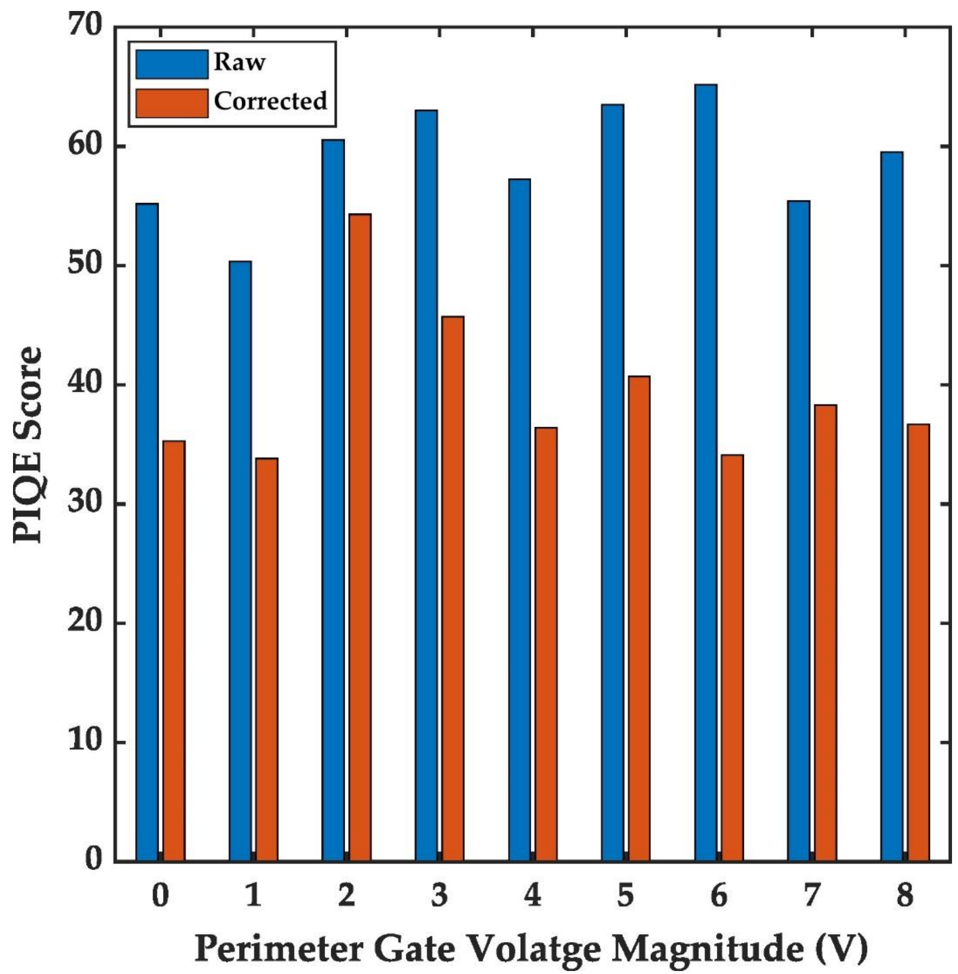


images are corrected in software to remove readout fixed pattern noise

Picture Quality after Readout Fixed-Pattern Noise Correction

Readout fixed pattern noise removal improves picture quality

- The PIQE score is a no-reference image quality score
- The lower the PIQE the better the perception of the image



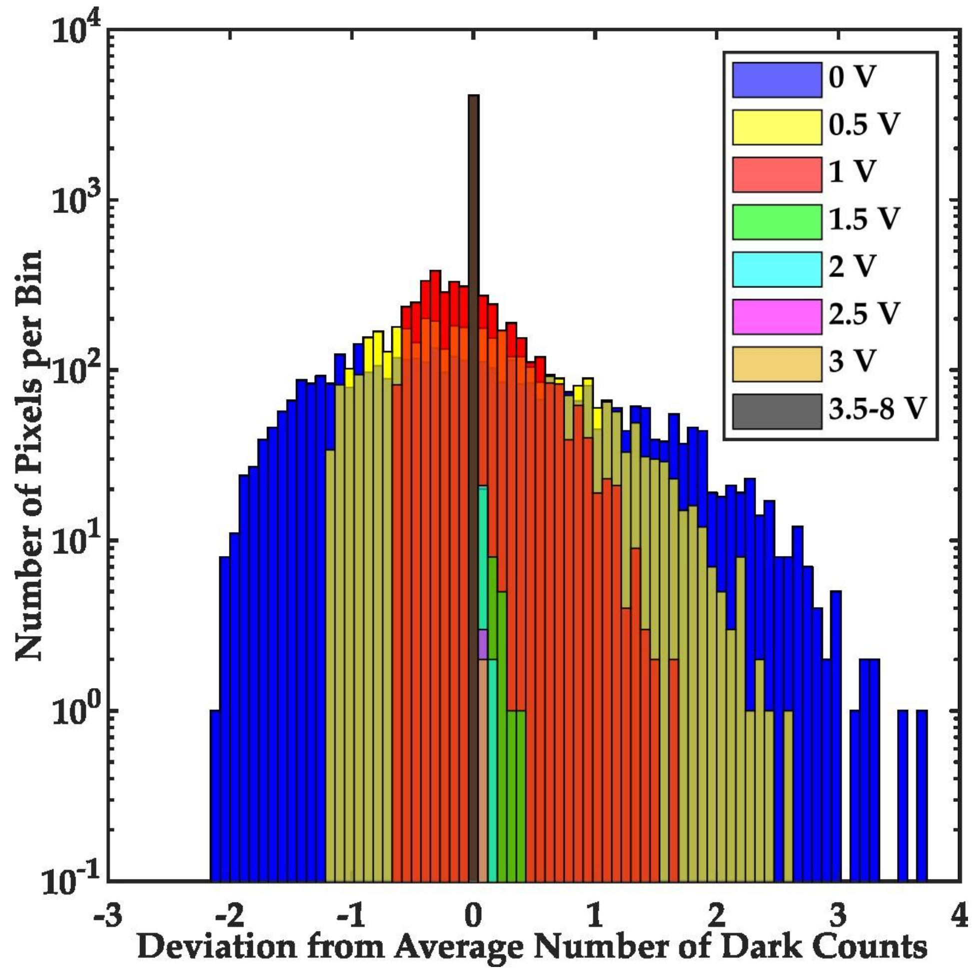
DSNU Characterization

The fixed pattern noise includes:

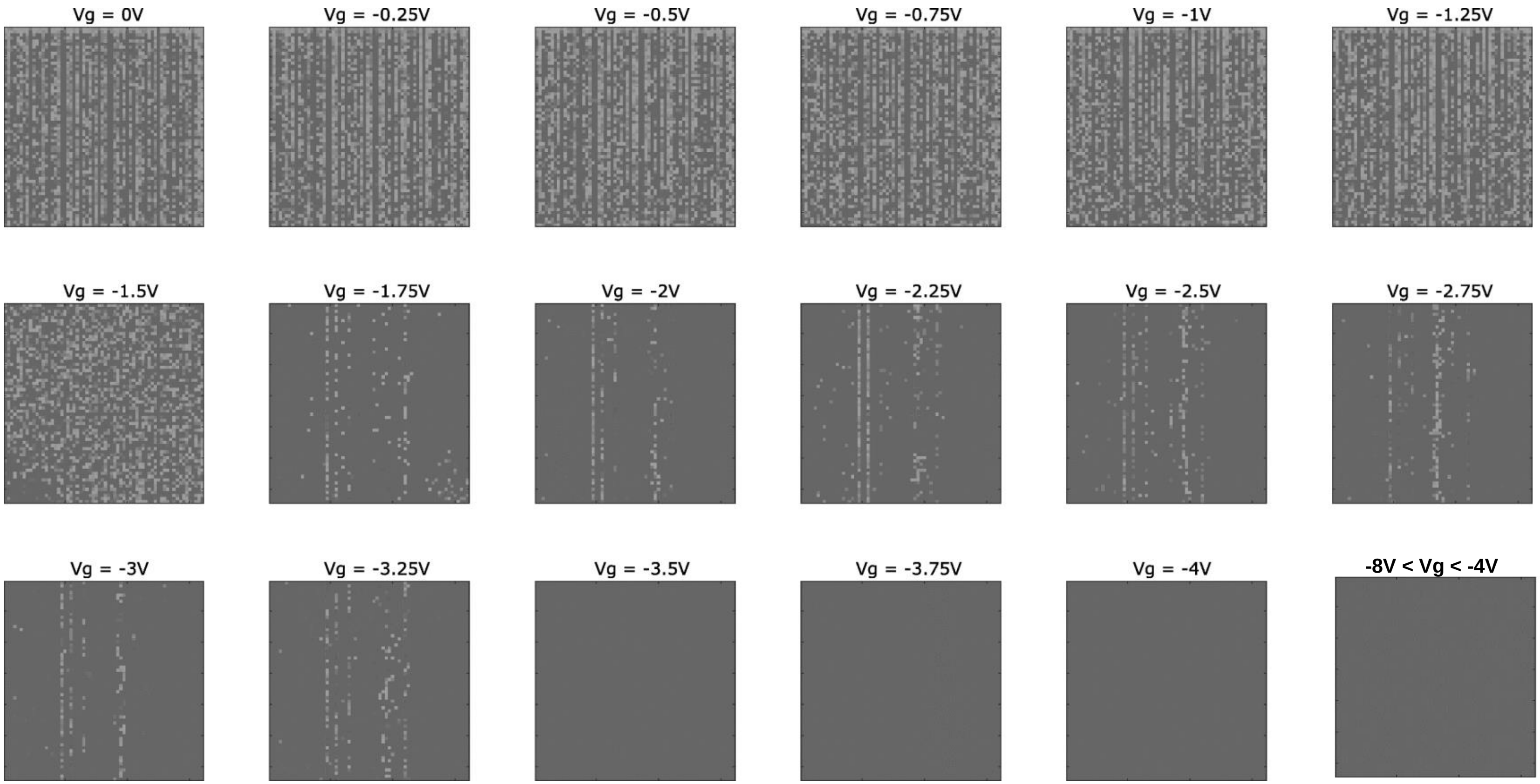
- a dark signal non-uniformity (DSNU) component
- a readout component

Perimeter gating removes the DSNU

- DSNU histogram narrows with increasing PG voltage magnitude



Effects of Perimeter Gating on DSNU

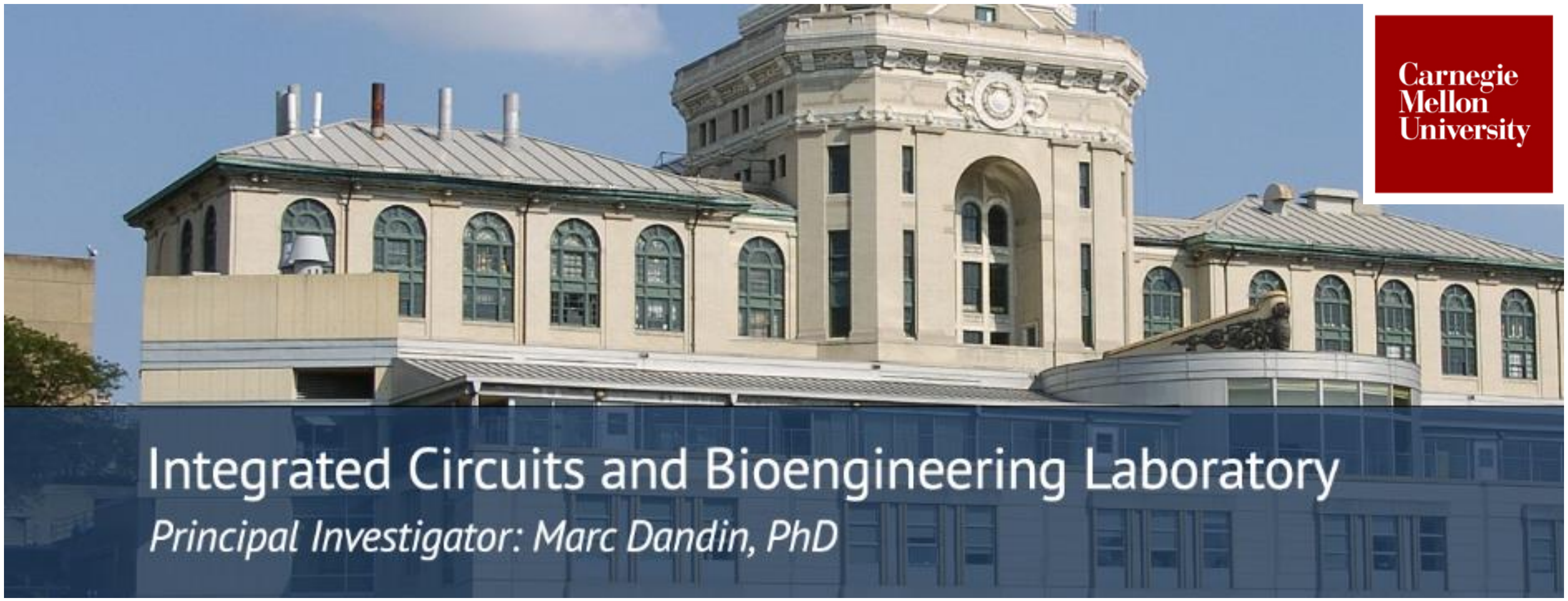


DSNU can be eliminated with PG

Part 1 Conclusions

- We’ve covered:
  1. Basic SPAD structure and operation
     - premature edge breakdown
     - pg-SPAD structure and operation
     - equivalent circuits
  2. Measurement techniques
     - bench setup for spectral response measurement
  3. Imager design & characterization
     - readout strategies
     - image acquisition
     - fixed patter noise

Acknowledgements



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