Noise issue of SPADs in standard silicon-based technologies

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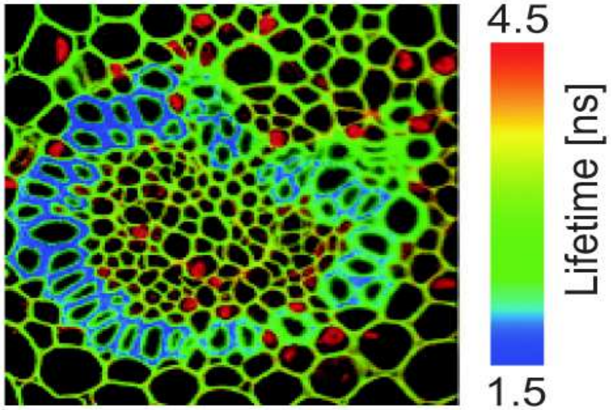
Background

High-Performance Imaging Applications

(ToF) PET

https://www.iibi.uiowa.edu/pet-center

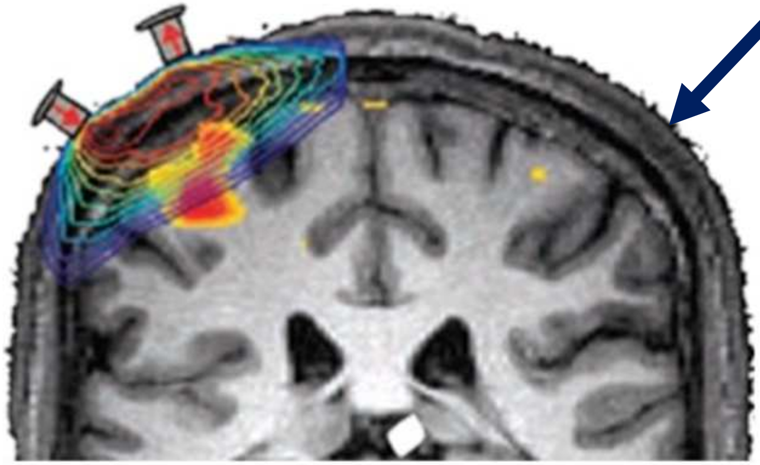
FLIM



https://www.picoquant.com/applications/category/life-science/fluorescence-lifetime-imaging-flim

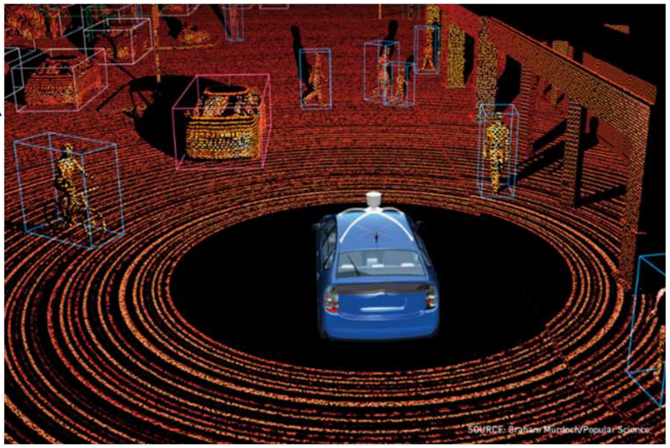
Ultimate sensitivity down to single photons & Photon timing capabilities

NIRS



http://www.researchimaging.pitt.edu/content/near-infrared-spectroscopy-nirs-brain-imaging-laboratory#

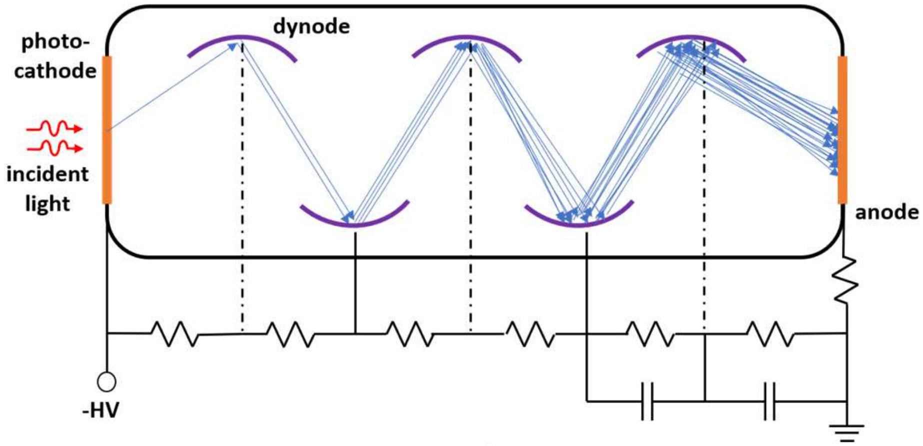
LiDAR

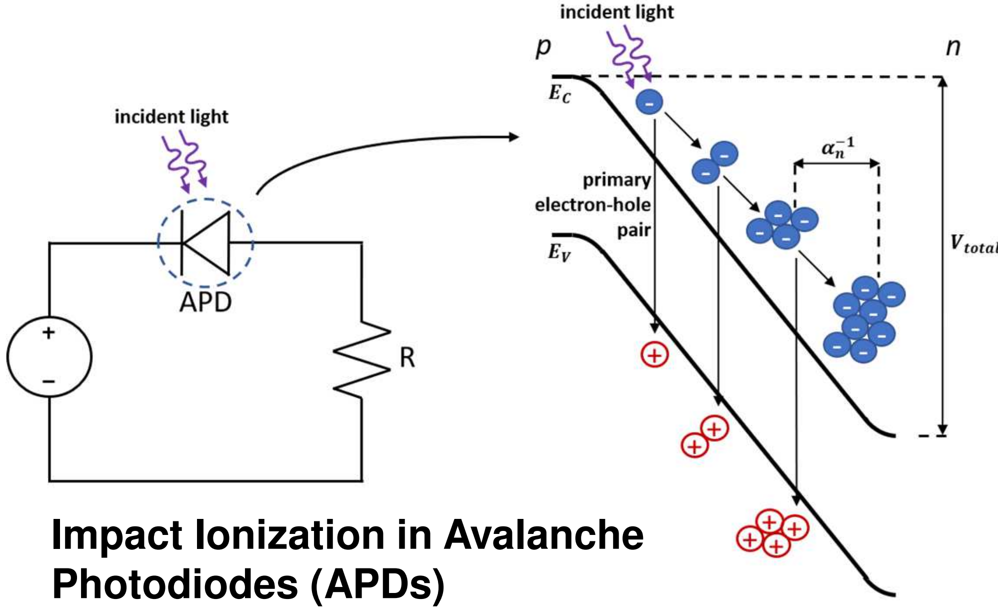


https://www.clearpathrobotics.com/blog/2017/01/3d-lidar-true-3d-sensing-spinning-2d-alternatives/

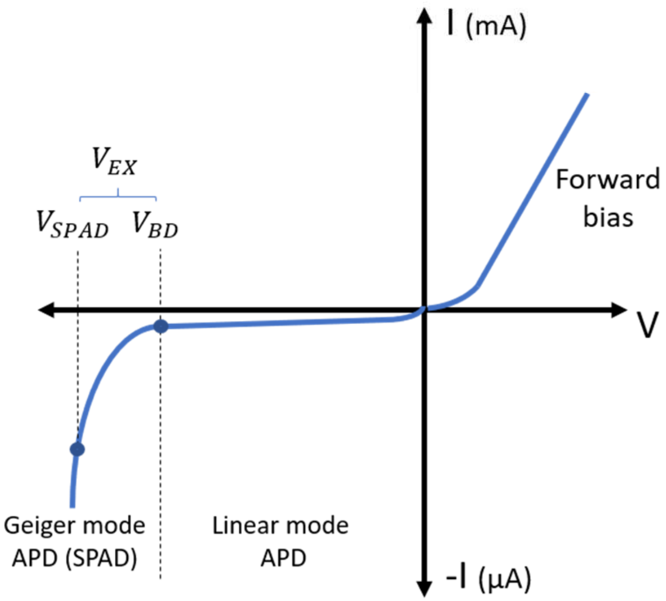
Evolution of Prominent Photodetectors

Photomultiplier Tubes (PMTs)





Impact Ionization in Avalanche Photodiodes (APDs)

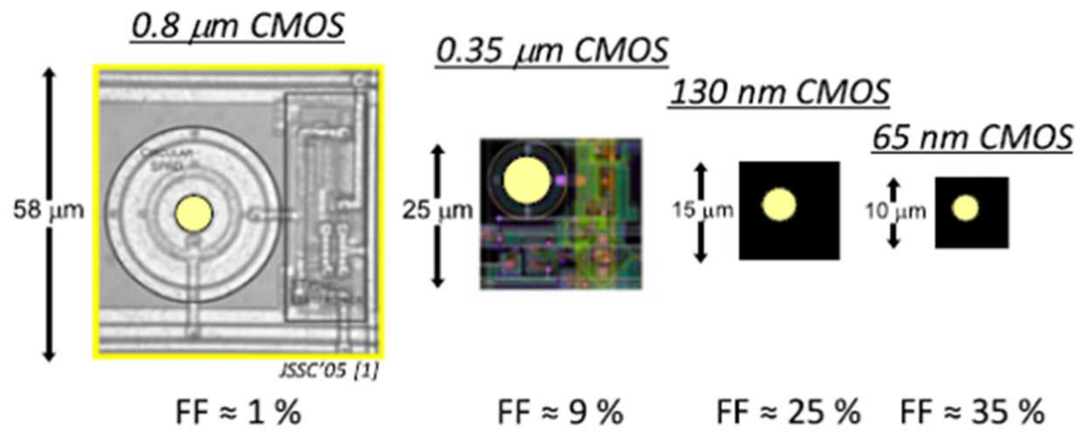


Single-Photon Avalanche Diodes (SPADs) are reverse biased above breakdown

	PMT	APD	SPAD
Gain	10^6	50-1000	~10^6
Bias (V)	>1000 V	300-1000	~15-80
QE @ 420 nm (%)	~25	~70	>50% (PDE)
Magnetic Field Compatibility	No	Yes	Yes
ToF Capability	Limited	No	Yes
Signal/Readout	Analog/Complex	Analog/Complex	Digital/Simple
Price/channel ($)	>200	~100	~50

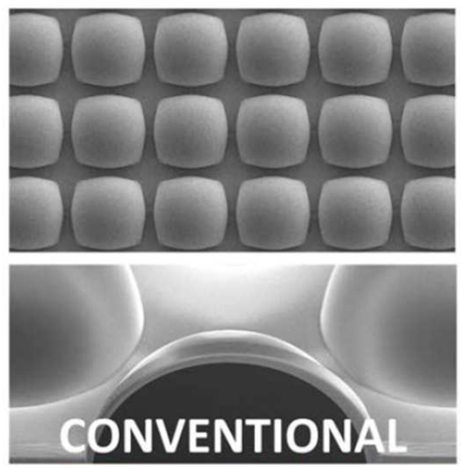
SPAD Research Challenges

- Implementation - more advanced CMOS technologies
  - ↳ ⇧ FF
  - ↳ ⇩ V_{BD}
  - ↳ ⇧ DCR
- SPADs - custom/3D tech + post-processing
  - ↳ ⇧ Overall performance
  - ↳ ⇧ Cost and complexity
- SPADs in standard CMOS
  - ↳ ⇧ Integration
  - ↳ ⇩ Cost
  - ↳ ⇩ PDE
  - ↳ ⇧ DCR

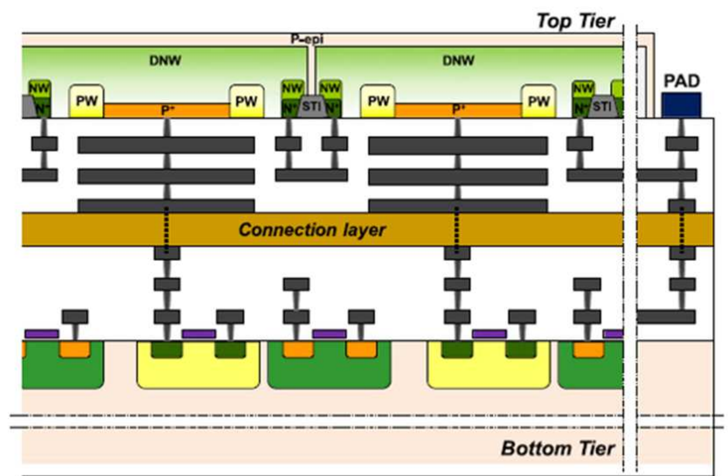


M.-J. Lee *et al.*, "High-Performance Back-Illuminated Three-Dimensional Stacked Single-Photon Avalanche Diode Implemented in 45-nm CMOS Technology," *IEEE J. Sel. Top. Quantum Electron.*, vol. 24, no. 6, pp. 1–9, Nov. 2018

A. R. Ximenes, *et al.*, "A 256×256 45/65nm 3D-stacked SPAD-based direct TOF image sensor for LiDAR applications with optical polar modulation for up to 18.6dB interference suppression," in *2018 IEEE International Solid - State Circuits Conference - (ISSCC)*, 2018, pp. 96–98



Microlenses

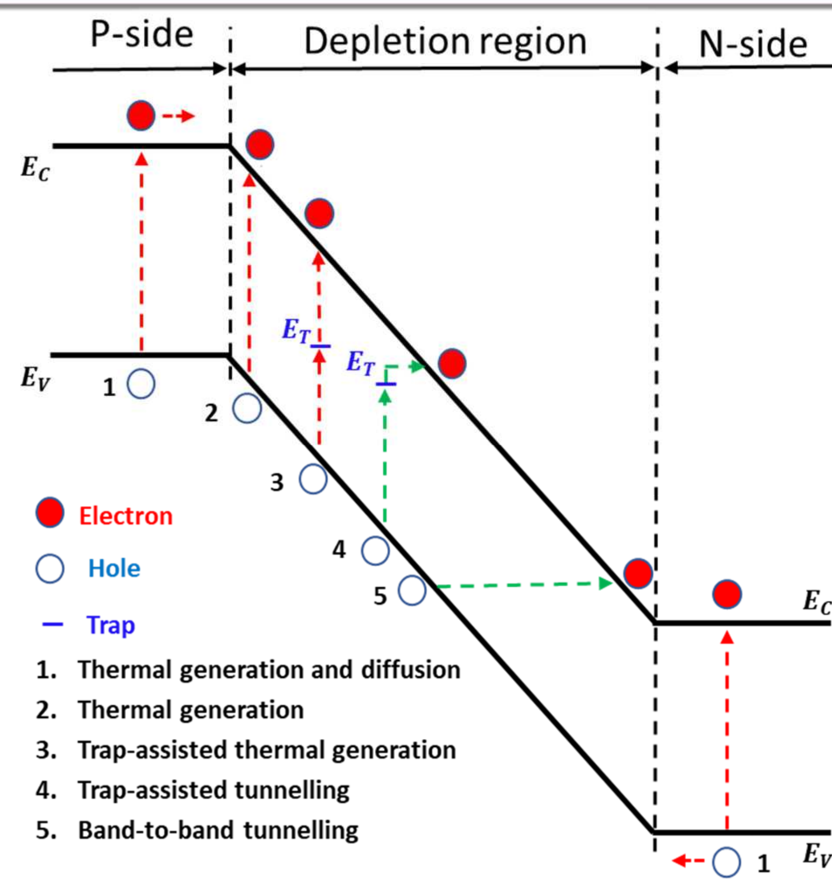


3D stacking

Noises in CMOS SPAD

❑ Dark count rate (DCR)

- Thermal generation-recombination
- Trap-assisted tunneling
- Band-to-band tunneling



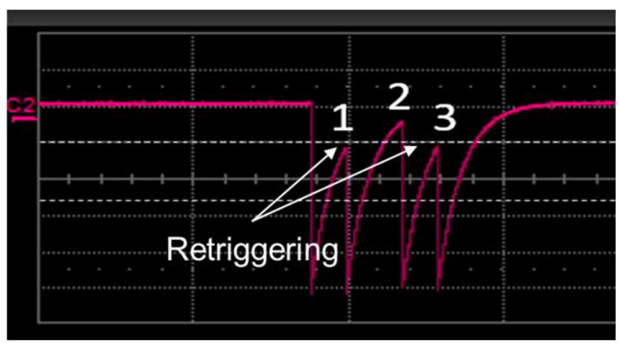
❑ Afterpulsing (AP)

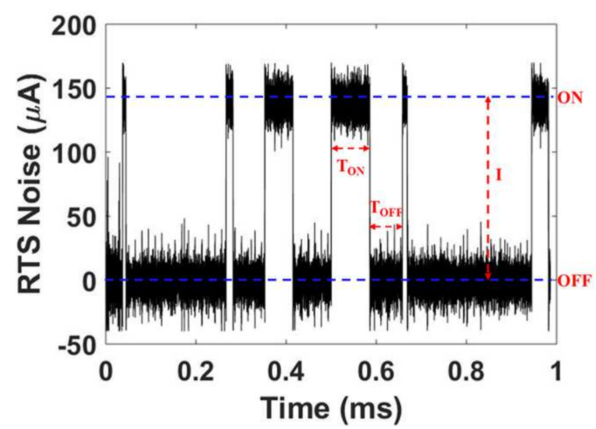
- Carriers captured by the trap center
- Secondary avalanche triggered by released carriers

❑ Random Telegraph Signal (RTS) Noise

- DCR varies with time
- Avalanche on & off

  @ breakdown point





SPAD Noise Modeling

Z Cheng, X Zheng, D Palubiak, MJ Deen, and H Peng, "*A Comprehensive and Accurate Analytical SPAD Model for Circuit Simulation*," **IEEE Transactions on Electron Devices**, Vol. 63(5), pp. 1940-1948, May 2016.

SPAD Modeling in Verilog-A

❑ SPAD's behavior with circuits

- SPAD is coupled with quenching, reset, readout circuits
- Circuits determined by SPAD's parameters/behavior
- SPAD model integrated with EDA tools

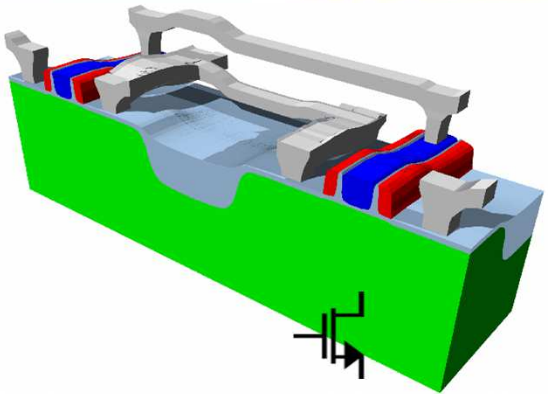
❑ SPAD noise with medical imaging systems

- Determines the system energy resolution

$$R_{energy} = \sqrt{R_{\text{intrinsic}}^{2} + R_{noise}^{2}}$$

❑ Requirement for SPAD model

- Accurate and comprehensive of SPAD's behavior
- Integrate well with EDA tools *(synthesizable design)*
- Efficient in simulation

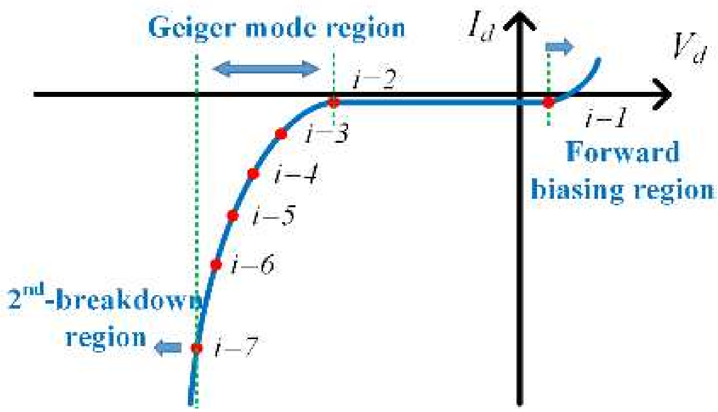


SPAD Modeling in Verilog-A

Proposed SPAD model

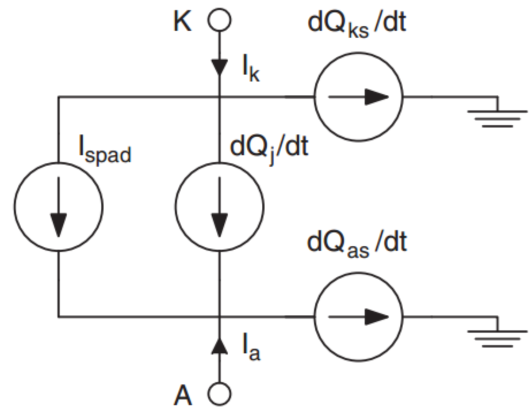
1. Static behavior

❖ Current-voltage relationship



2. Dynamic behavior

❖ Capacitor charging/ discharging



3. Noise behavior

❖ ***Primary*** **dark noise:**

- ➢ Thermal generation, band-to-band tunneling

❖ ***Secondary*** **dark noise:**

- ➢ After-pulsing phenomenon

4. Temperature dependence

❖ Si bandgap energy, intrinsic concentration, SPAD V_{brk}

$$E_g = E_{G0} + E_{G1}T + E_{G2}T^2 + E_{G3}T^3 + E_{G4}T^4$$

$$n_i = \sqrt{N_C N_V}\, e^{\frac{-E_g}{2kT}}$$

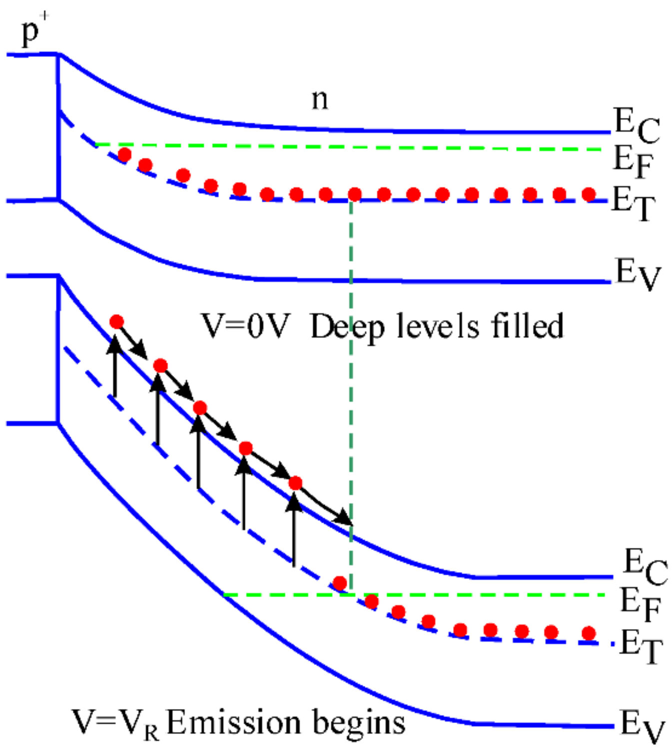
$$V_{brk} = V_{brk0}\left[1 + \beta(T - T_0)\right]$$

Q. He, *et. al.*, *J. Semicond.*, 34 (10), pp. 104007–1–6, 2013.
G. Giustolisi, *et. al.*, *Int. J. Circuit Theory Appl.*, 40 (7), pp. 661–679, 2012.
CLF Ma, *IEEE Trans El Dev*, vol. 42 (5), pp. 810-818, 1995.

SPAD Modeling in Verilog-A

❑ SPAD *primary* dark noise

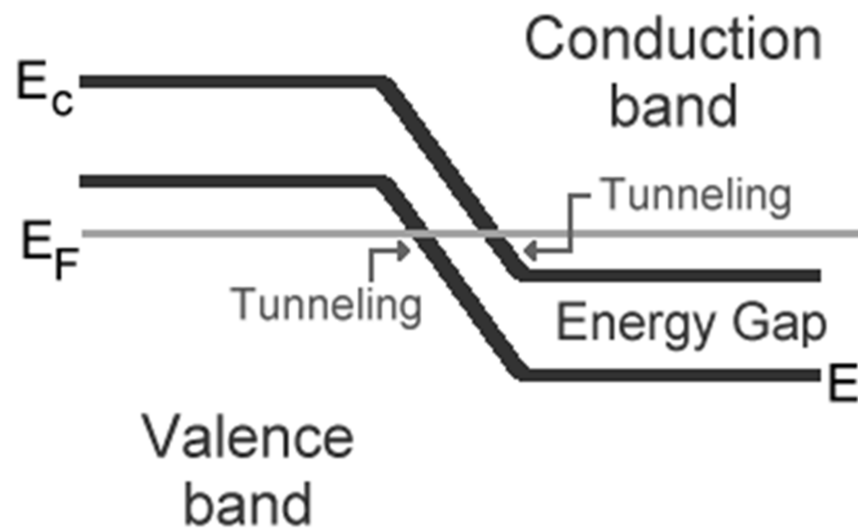
Thermal generation



- Using Shockley-Read-Hall theory to determine carrier generation rate

$$CGR_{Therm} \approx \frac{n_i \sigma_0 N_t}{2} \sqrt{\frac{3kT}{m^*}} A_D W_D$$

Band-to-band tunneling



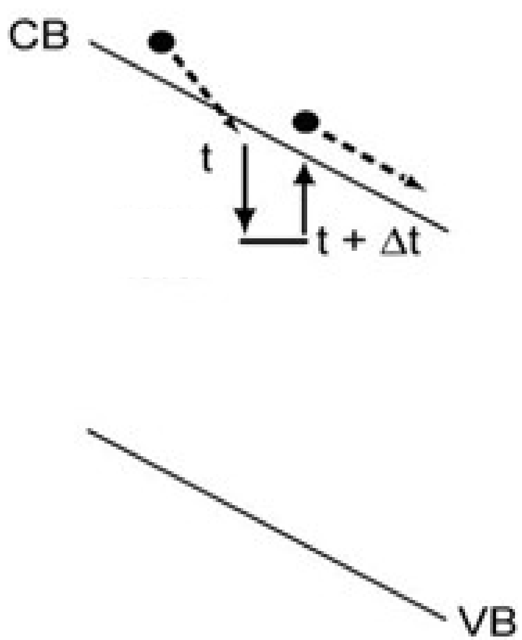
- **Significant - advanced CMOS process**
- **N ↑ ⇨SCR↓ and E ↑**

$$CGR_{Tunn} = \frac{\sqrt{2m^*} q^2 F V_R}{h^2 \sqrt{E_g}} A_D \times \exp\left(-\frac{8\pi \sqrt{2m^*} E_g^{3/2}}{3qFh} \right)$$

SPAD Modeling in Verilog-A

❑ SPAD *secondary* dark noise

- After-pulsing phenomenon
- Carrier trapping and releasing in bandgap shallow-traps

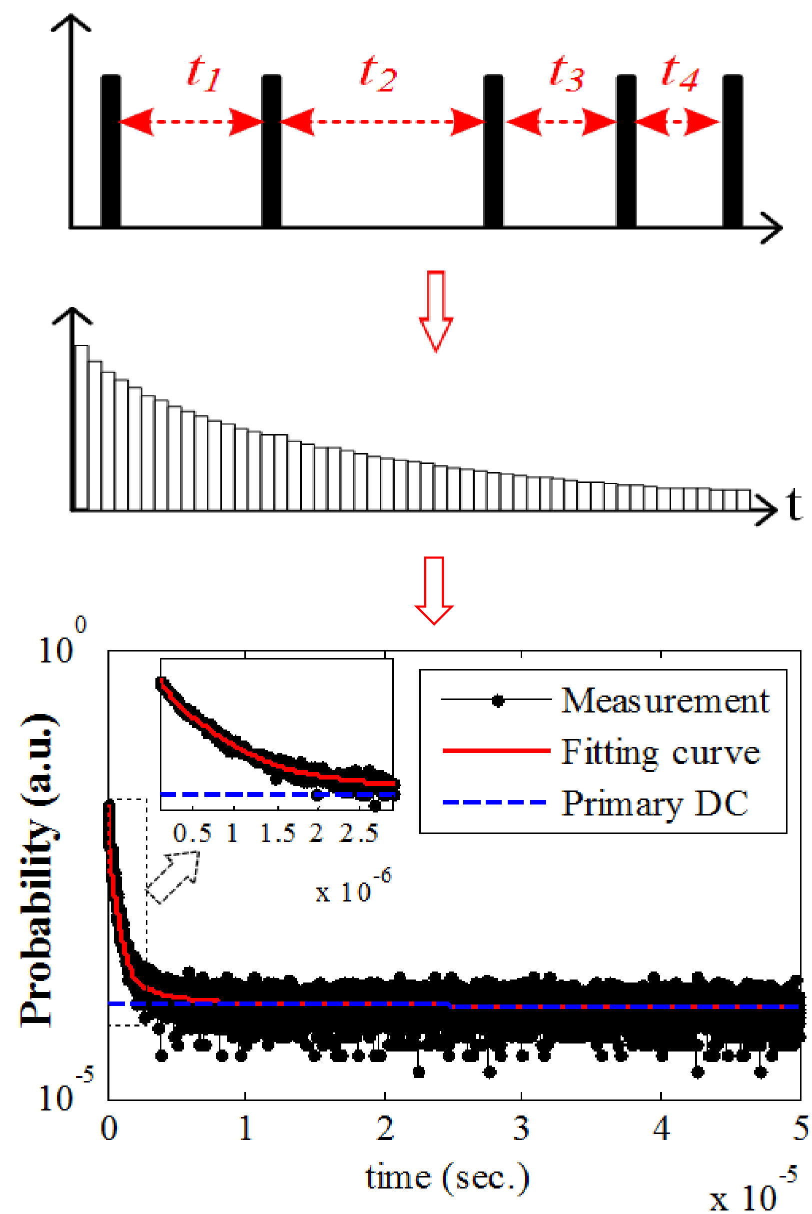


Trap's lifetime

$$\tau = \tau_0 e^{E_A/kT}$$

After-pulsing probability

$$P_{ap}(t) = \sum_{i=1}^{N} A_i \frac{1}{\tau_i} e^{-t/\tau_i}$$



[http://mxp.physics.umn.edu/s98/projects/menz/poster.htm]

SPAD Modeling in Verilog-A

❑ Method & Simulation

Fabricated device measurement

↓

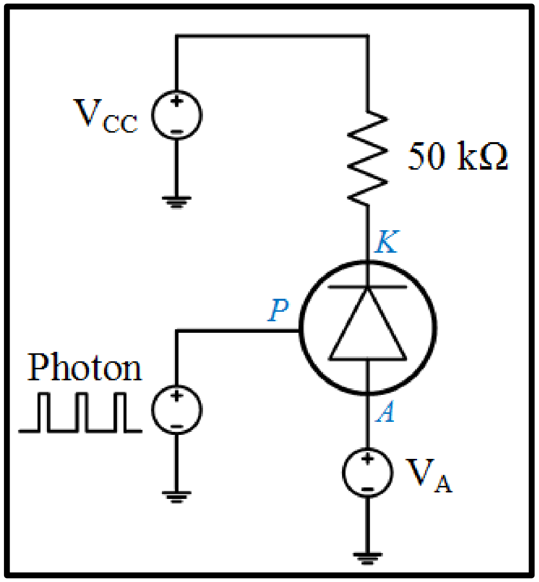
Physical parameter extraction

↓

Analytical modeling

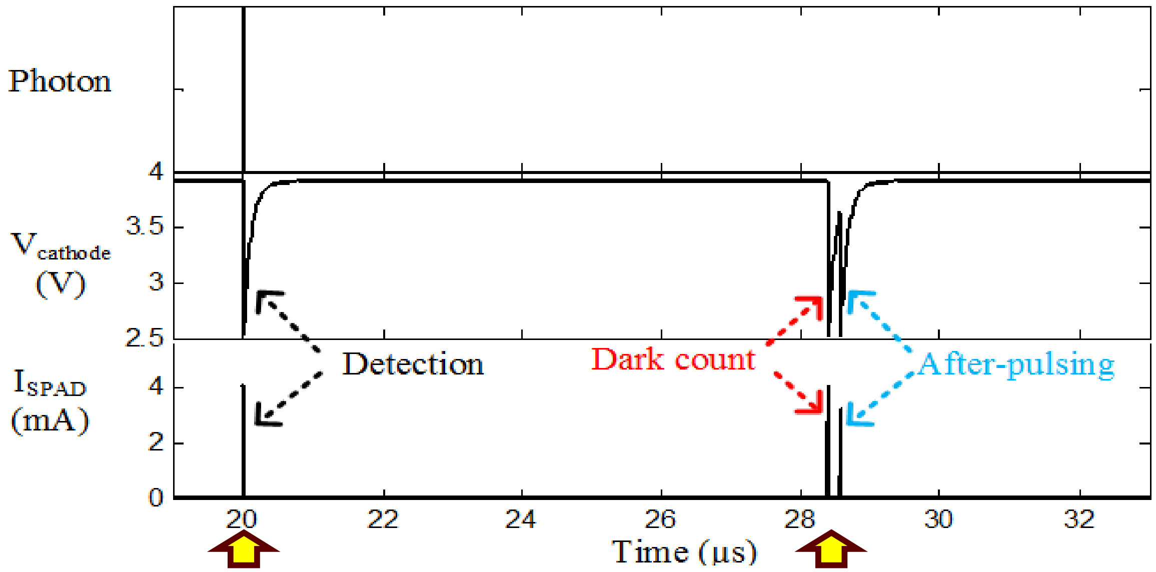
↓

Validation



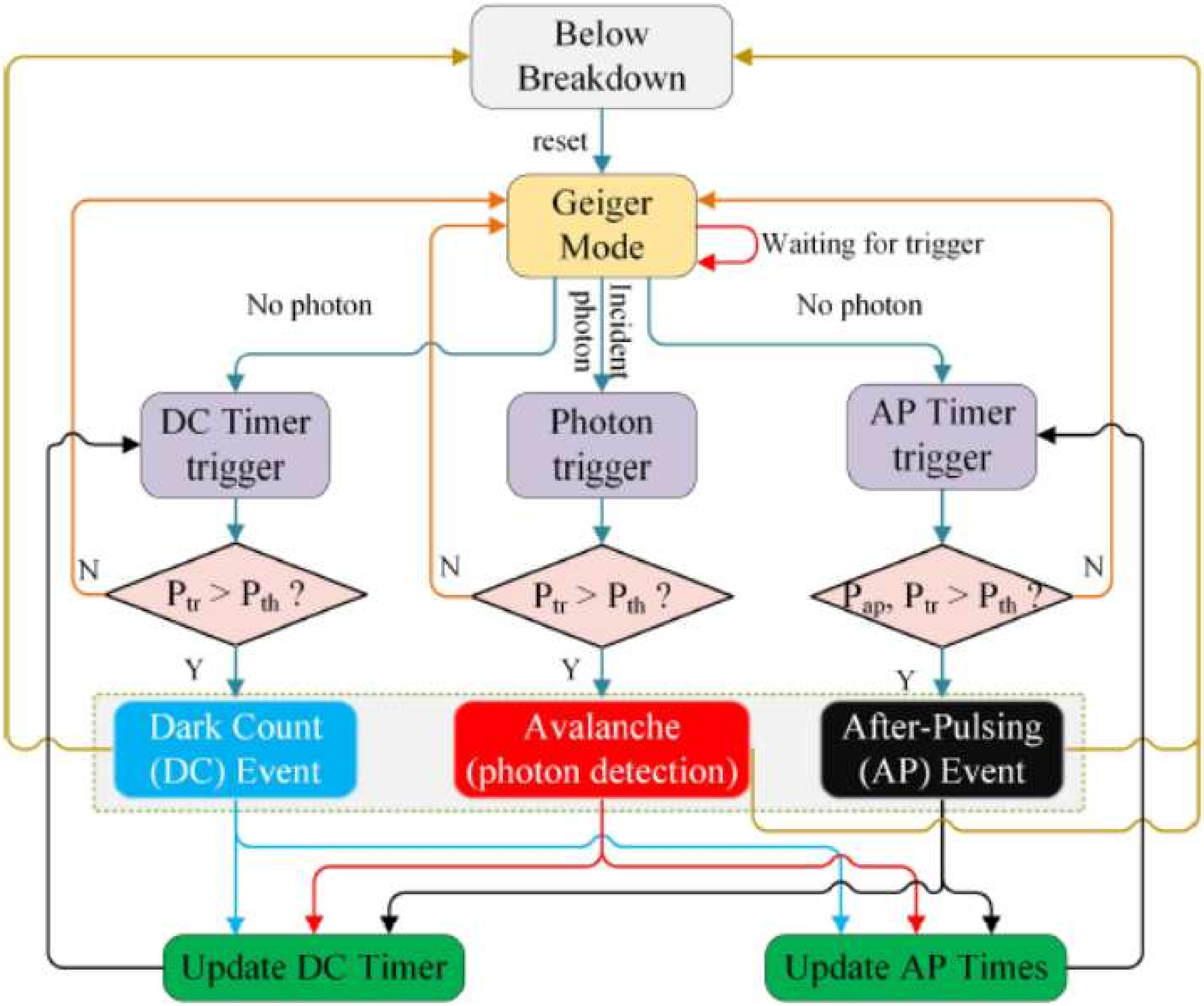
SPAD in Verilog-A

Simulation validated in Cadence Spectre, HSPICE



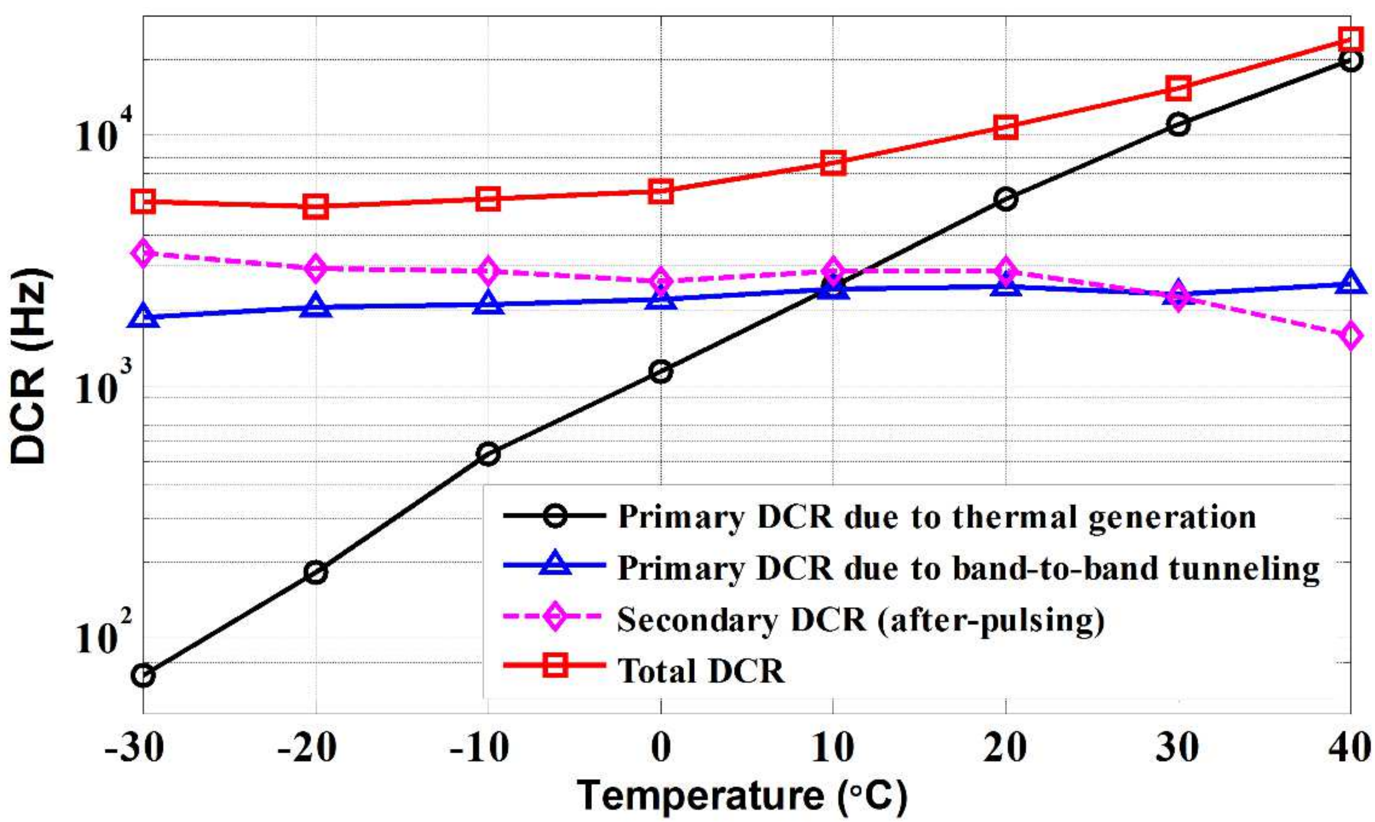
SPAD Noise model

❑ Single-Photon Avalanche Diode (SPAD)



SPAD Modeling in Verilog-A

❑ Simulation result example



1. Band-to-band tunneling shows least temperature dependence
2. Thermal generation is dominant noise source at high temperatures
3. After-pulsing effect reduces with temperature
4. Total DCR reduces when temperature decreases

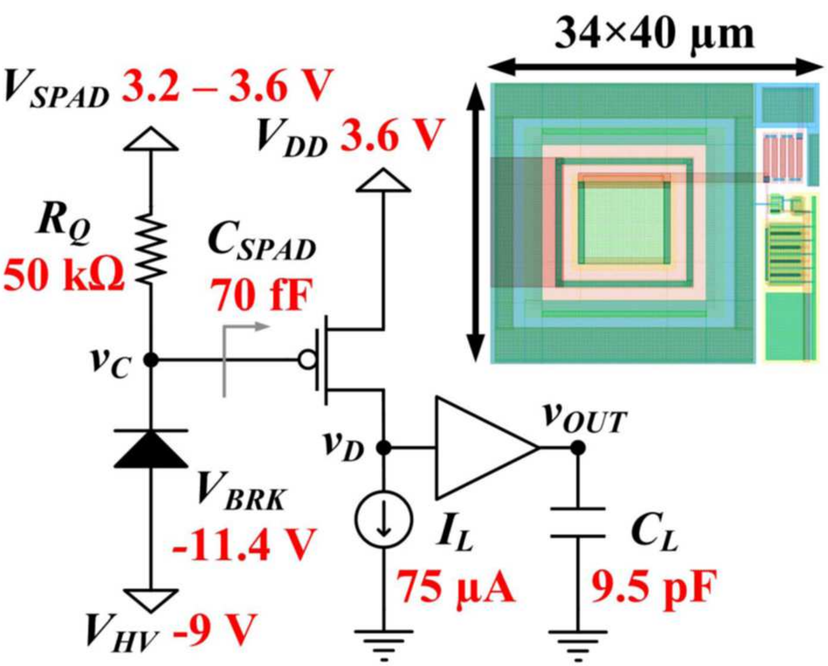
Afterpulsing in TG SPAD

DP Palubiak, Z Li and MJ Deen, "*Afterpulsing Characteristics of Free-Running and Time-Gated Single-Photon Avalanche Diodes in 130-nm CMOS*," **IEEE Transactions on Electron Devices**, Vol. 62(11), pp. 3727-3733, 2015

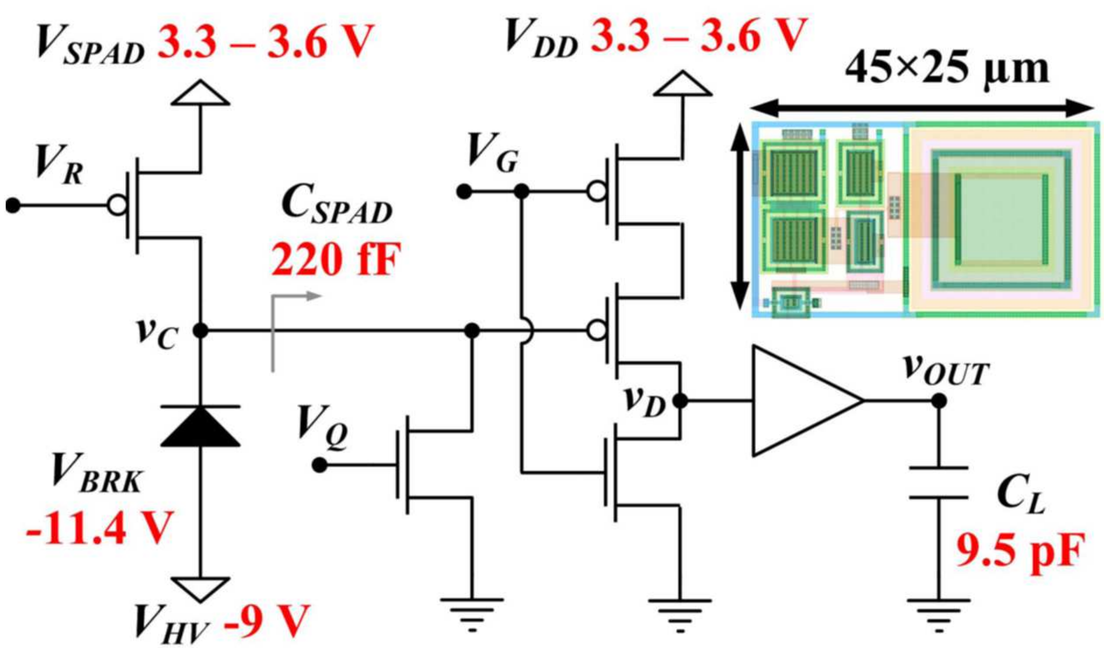
Afterpulsing in Time-gated SPAD

❑ Two operational modes

↳ Free-running SPAD



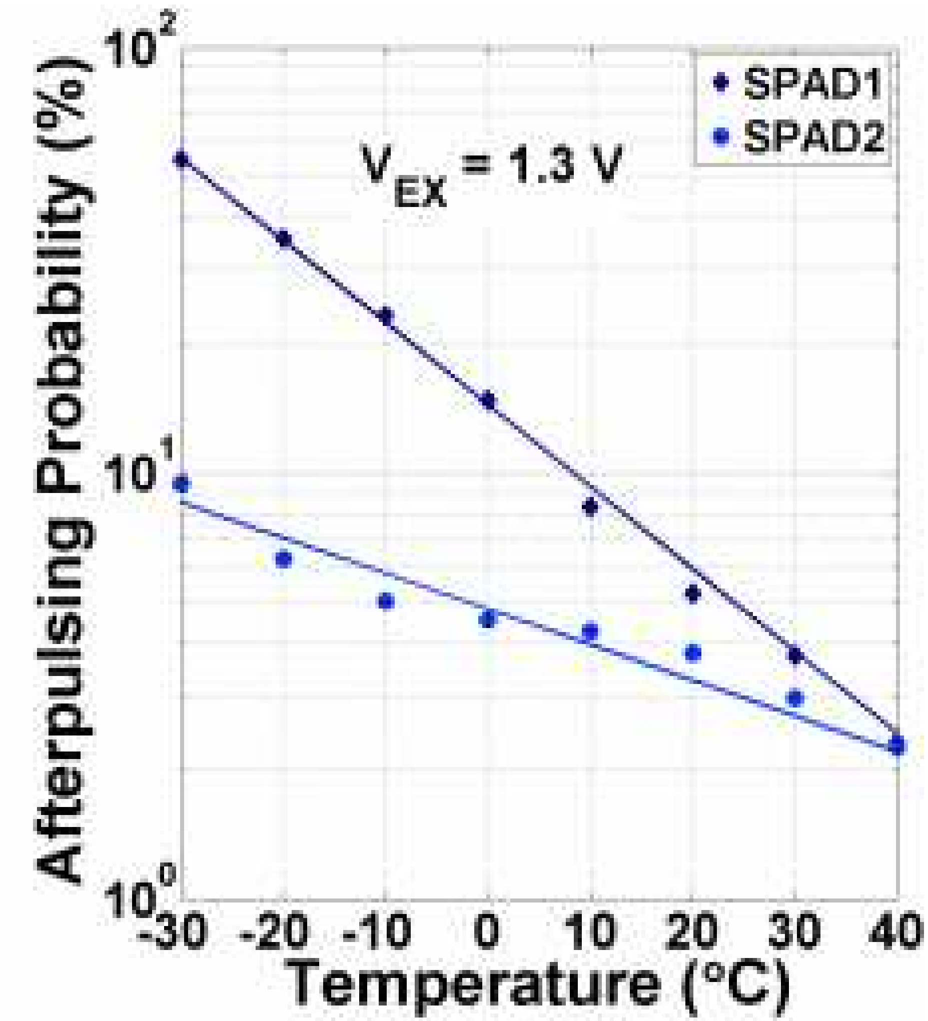
↳ Time-gated SPAD

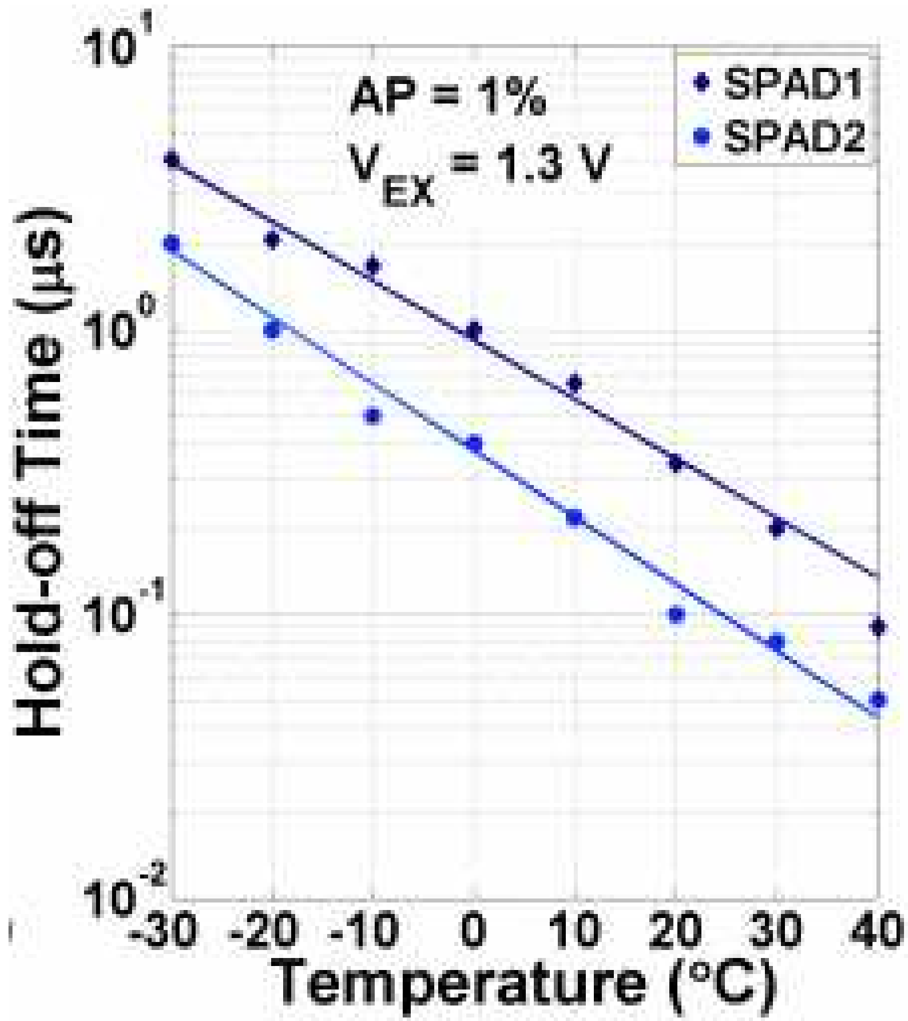


DP Palubiak, Z Li, MJ Deen, "Afterpulsing characteristics of free-running and time-gated single-photon avalanche diodes in 130-nm CMOS," **IEEE Transactions on Electron Devices**, vol. 62 (11), pp. 3727-3733, 2015

Afterpulsing in Time-gated SPAD

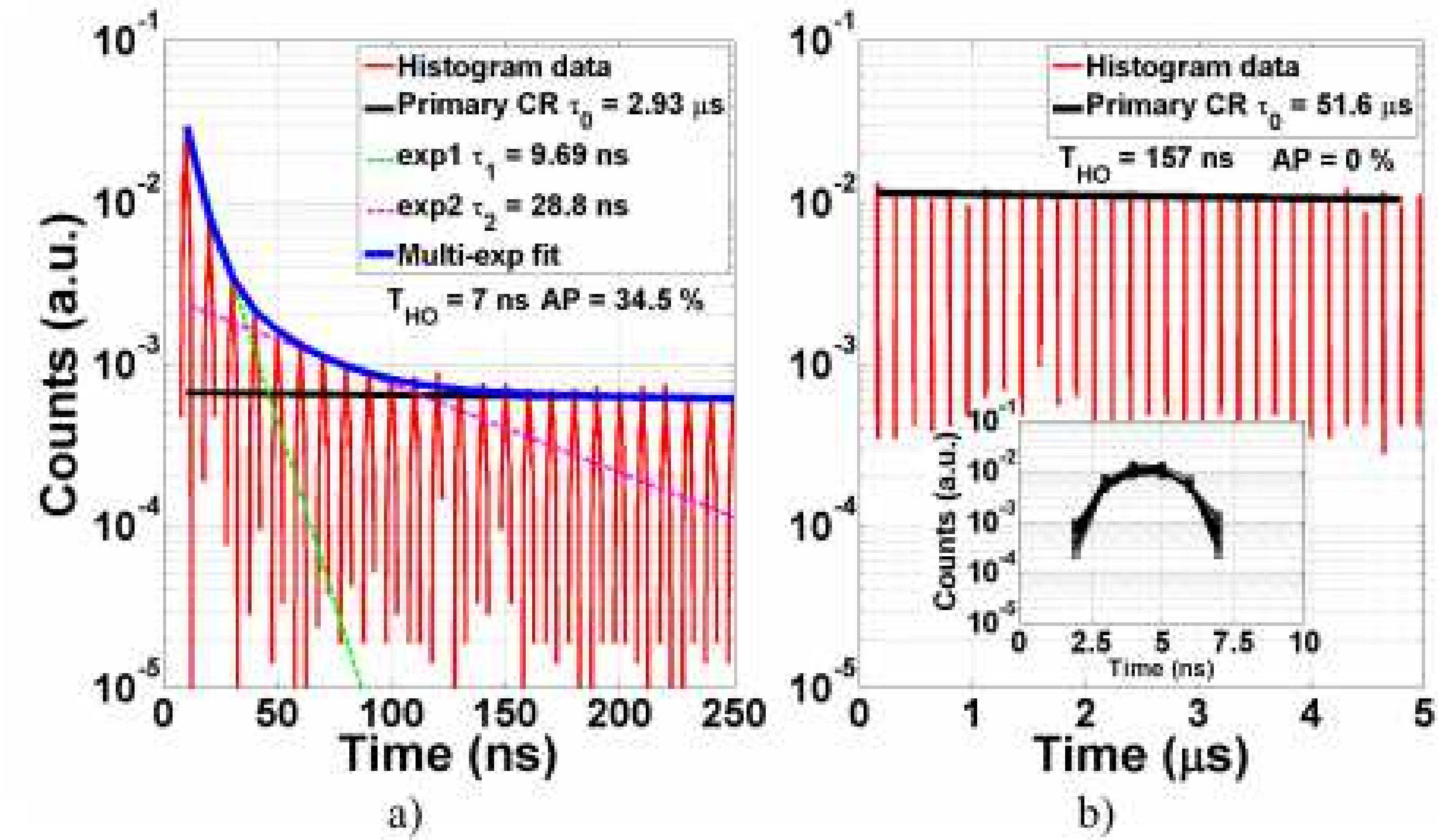
- Afterpulsing for free-running SPAD





Afterpulsing in Time-gated SPAD

❑ Afterpulsing for time-gated SPAD



A strong reduction in AP was evident in the TG mode compared with the FR SPAD pixels

RTS Noise

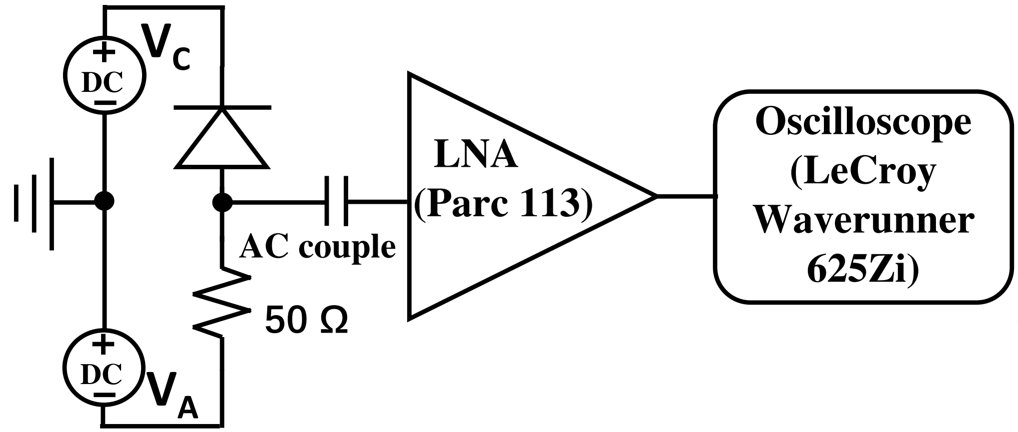
W Jiang and MJ Deen, "*Random Telegraph Signal in n^+/p-Well CMOS Single-Photon Avalanche Diodes*," **IEEE Transactions on Electron Devices**, vol. 60, 6 pages (On-line 12 April 2021).

W Jiang, R Scott and MJ Deen, "*Differential Quench and Reset Circuit for Single-Photon Avalanche Diodes*," **IEEE/OSA Journal of Lightwave Technology** Vol. 39(22), pp. 7334-7342 (15 November 2021).

Random Telegraph Signal (RTS)

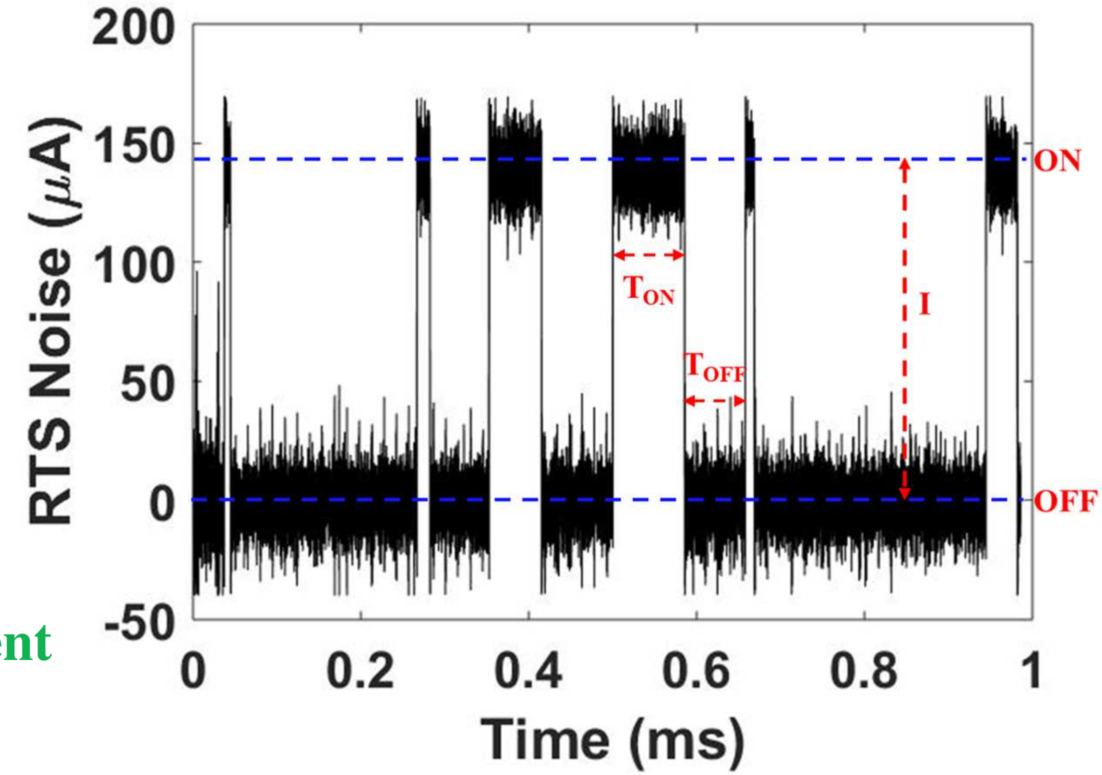
❑ What is RTS noise?

- Known as burst noise, popcorn noise, impulse noise, bi-stable noise
- Looks like square wave with several levels of amplitude & random pulse width
- Originate from defects

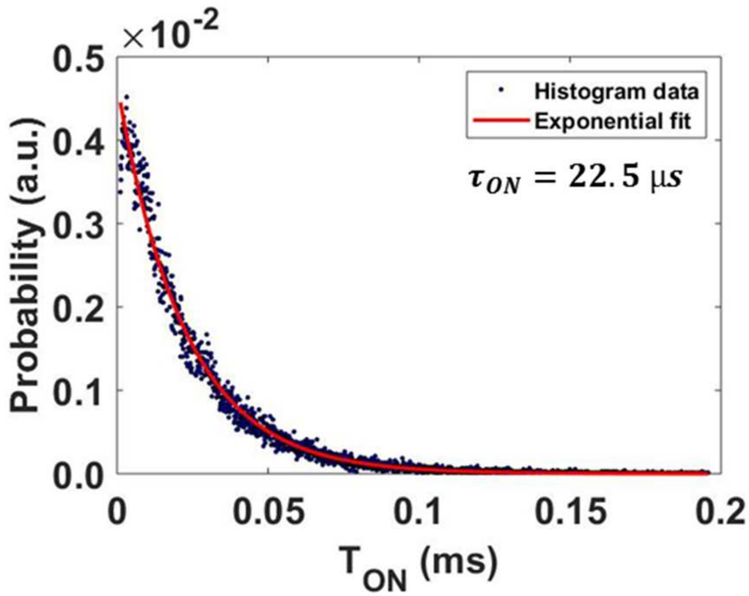


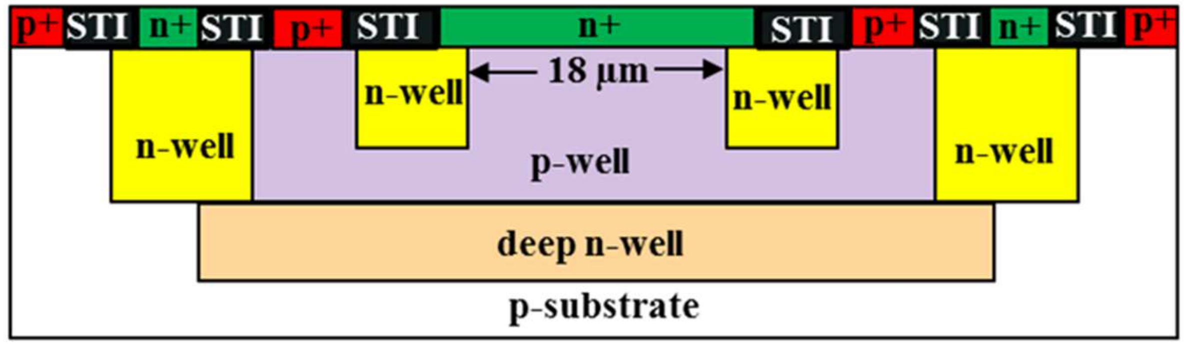
❑ Typical waveform

- T_{ON} - time spent in "on" state of the avalanche
- T_{OFF} - time spent in "off" state of the avalanche
- I - Amplitude of RTS noise current

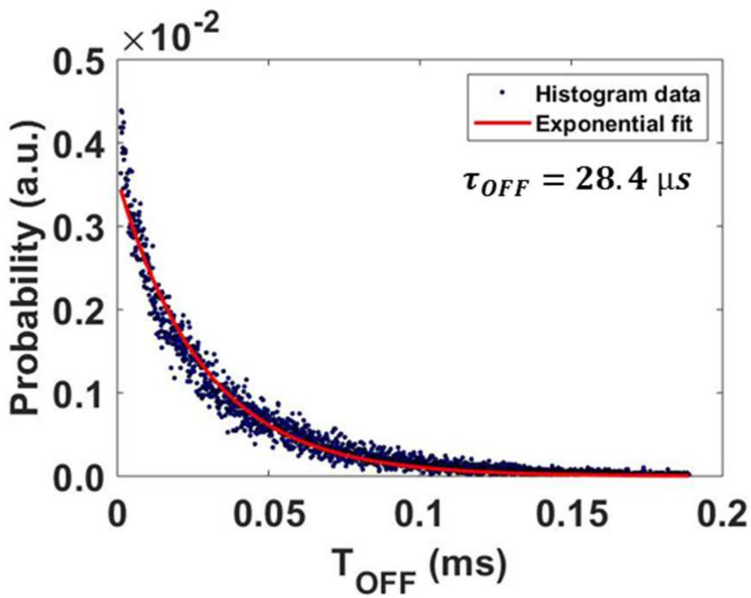


RTS Noise Parameters



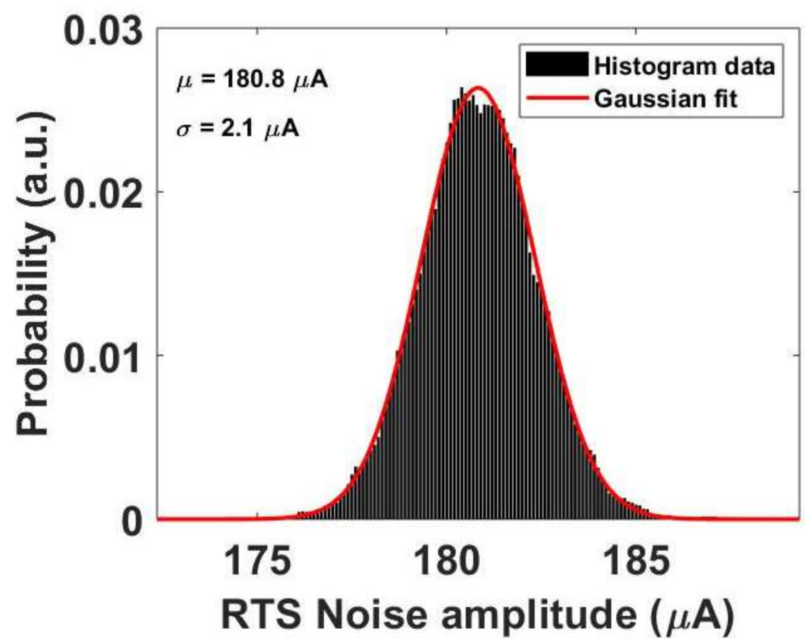


- n^+/p-well SPAD; n-well guard ring
- Square shape ~$(18\mu m)^2$



Histograms

- T_{ON} T_{OFF} with exp. fits
- RTS noise amp. - Gaussian fit



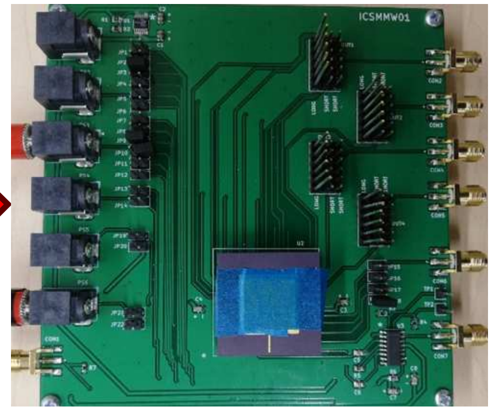
DCR and AP Measurement

❑ Setup

Agilent 66312A

Agilent E3646A

Power

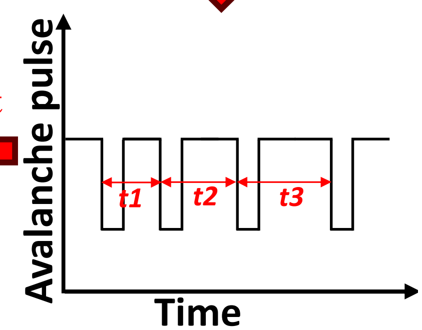


Printed circuit board

Trigger

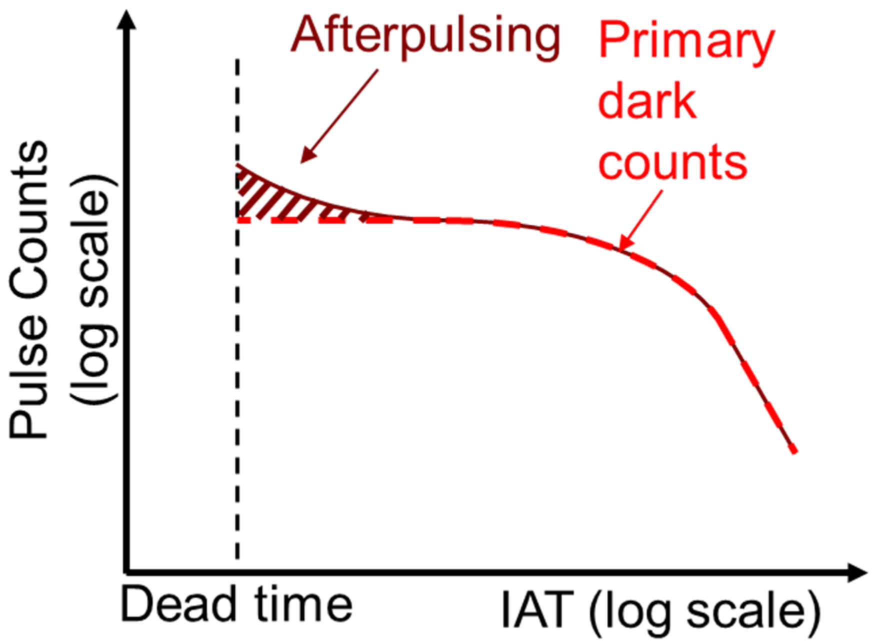
Oscilloscope
(LeCroy Waverunner 625Zi)

IAT



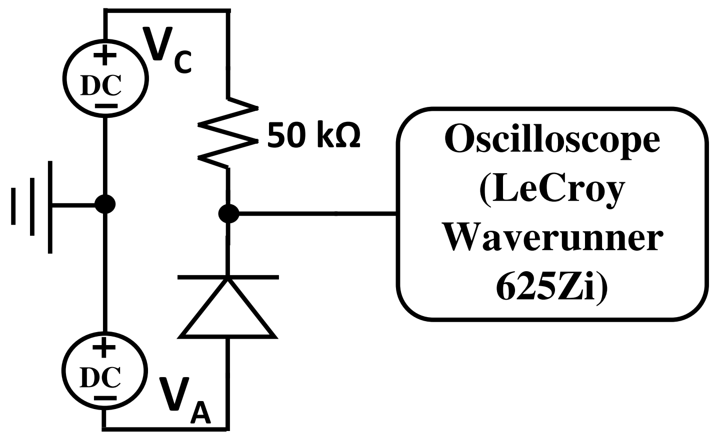
Inter-arrival time
(IAT)

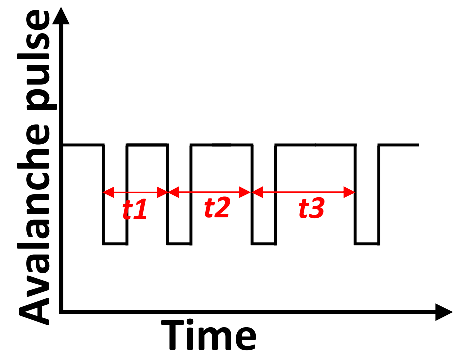
Exponential fit

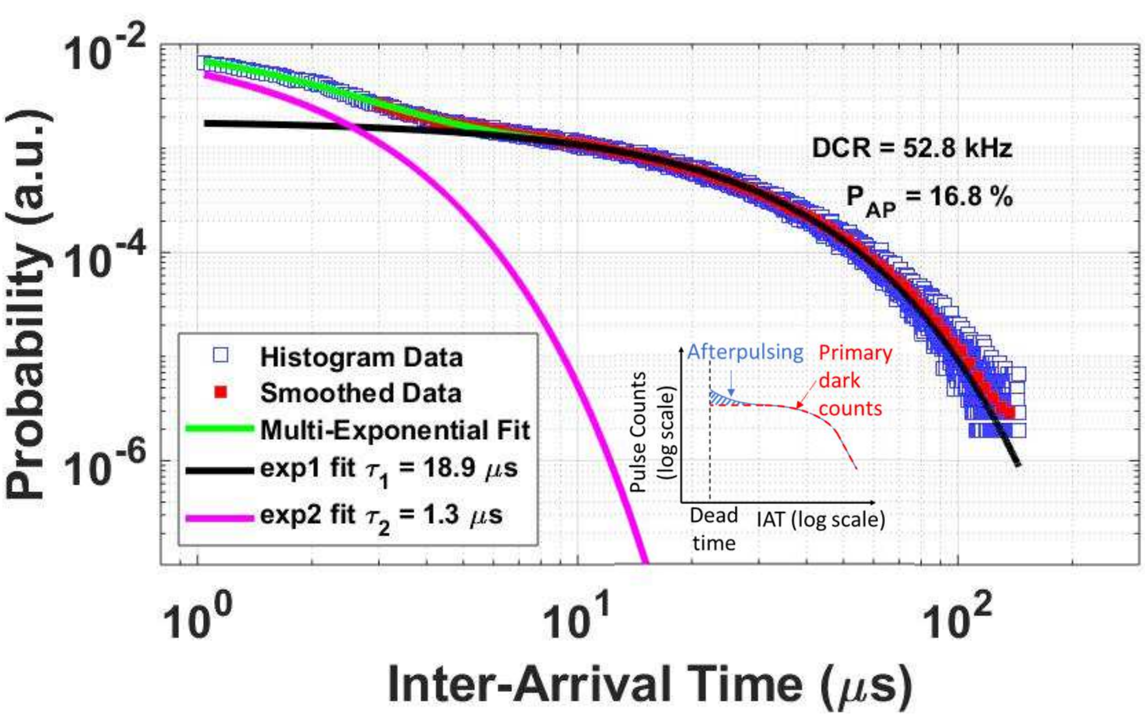


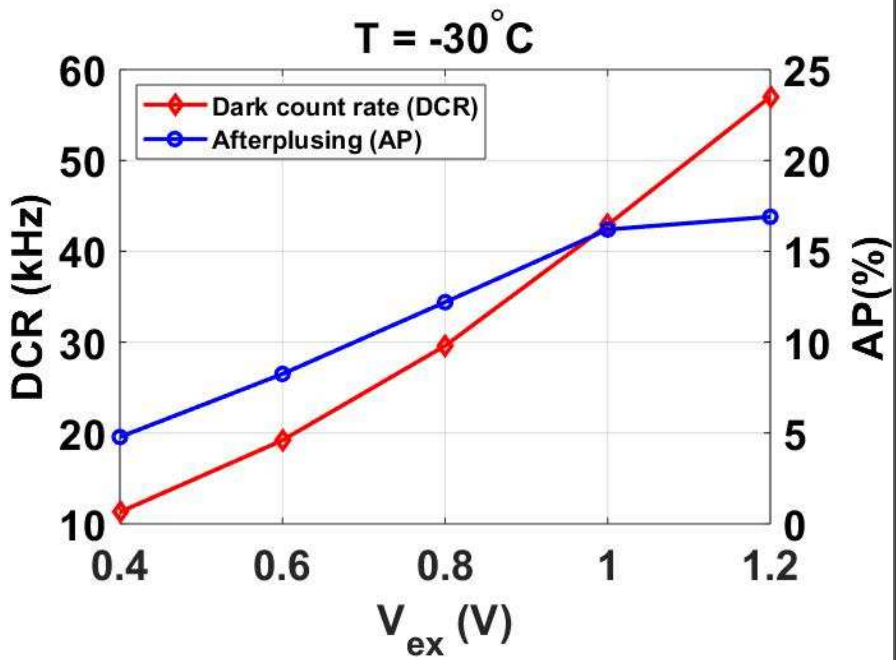
DCR and AP Measurement

- ❑ Setup
- ❑ DCR and AP (V_{ex}=1.2V, T=-30 °C)





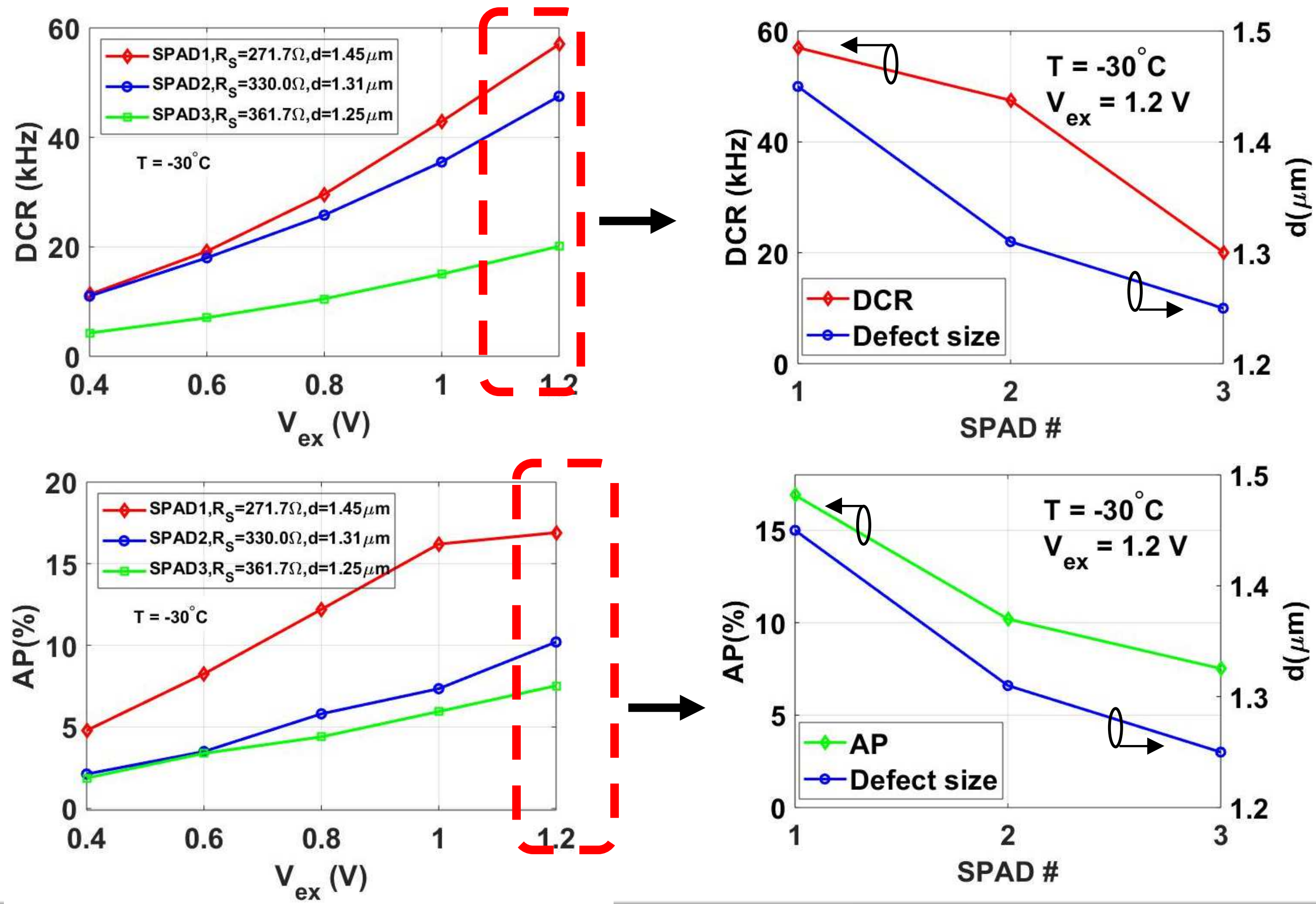




RTS noise correlates with DCR and AP

- Effective defect dimensions - 3 SPAD samples
- DCR and AP comparison

SPAD#	Slope (dI/dV_{BIAS}) (μA/V)	R_S (Ω)	d (μm)
SPAD1	3681	271.7	1.45
SPAD2	3030	330.0	1.31
SPAD3	2765	361.7	1.25



Slope (dI/dV_{BIAS}) ↑

↓

Defect dimension (d) ↑

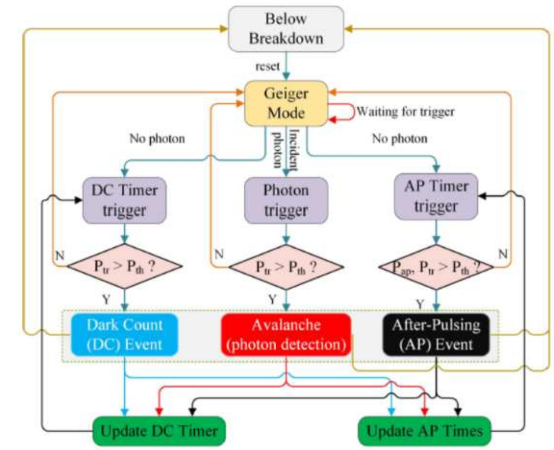
↓

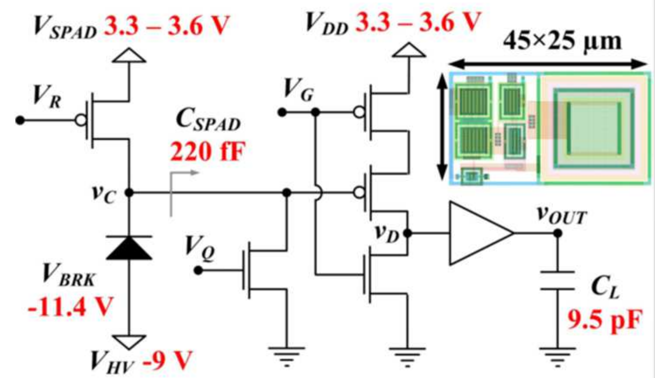
DCR↑ AP↑

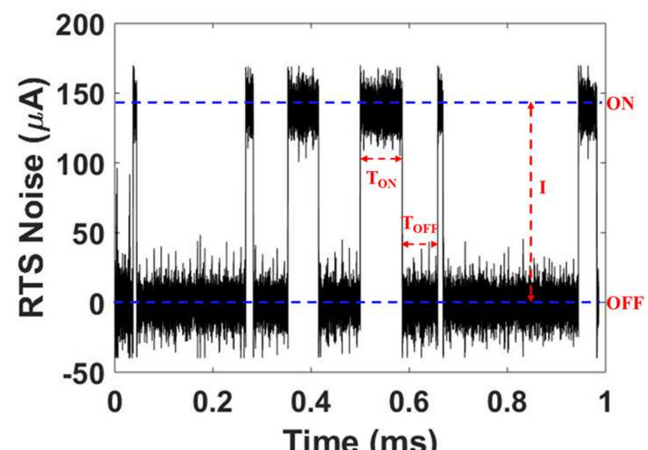
Conclusion

Conclusions

- **SPAD noise model using Verilog-A**
  - Compatible with mainstream simulators
  - Includes band-to-band tunneling mechanism & temporal dependence of afterpulsing (AP) probability
- **Afterpulsing in Time-gated (TG) SPAD**
  - Compare AP for free-running & TG SPADs
  - AP reduction in TG SPAD
- **Random Telegraph Signal (RTS) Noise in SPAD**
  - RTS noise dependence on temp & voltage
  - RTS correlates with DCR & AP







THANK YOU

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