Geiger-Mode Avalanche Photodiodes for Near-Infrared Photon Counting

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Presentation outline

- Motivation for single photon detectors
- Overview of Geiger-mode avalanche photodiodes
- Geiger-mode operation
- Present performance and challenges
  - Dark count rate
  - Afterpulsing effects
- Conclusions

Motivation for single photon detectors

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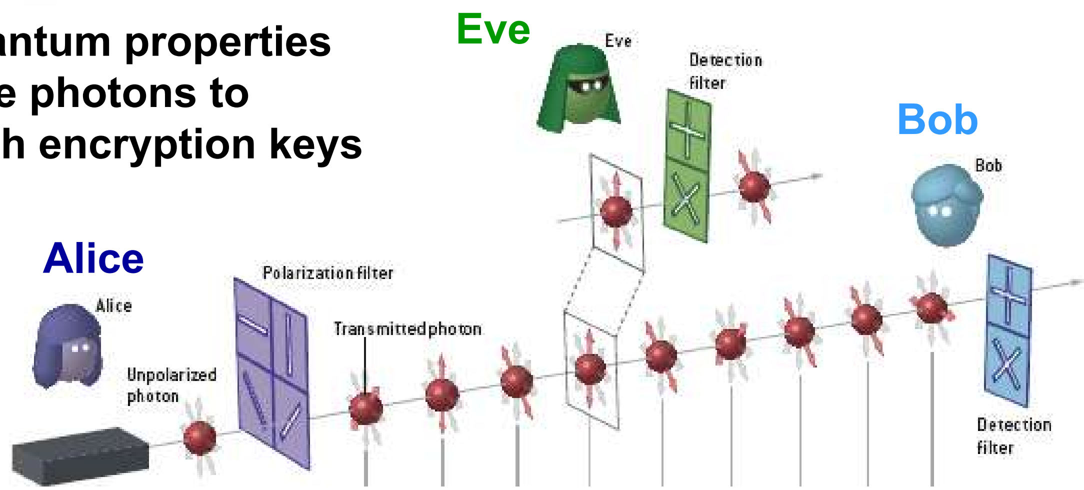
Examples of photon counting applications for λ > 1.0 – 1.7 µm:

- **Communications**
  - Secure communications (e.g., quantum key distribution)
  - Free space optical communication in photon-starved applications
- **Remote sensing**
  - 3-D Imaging
  - Lidar / atmospheric sensing
- **Industrial and Biomedical**
  - Semiconductor diagnostics
  - Single photon fluorescence (e.g., quantum dot markers)

SPC Application: Next-gen Communications

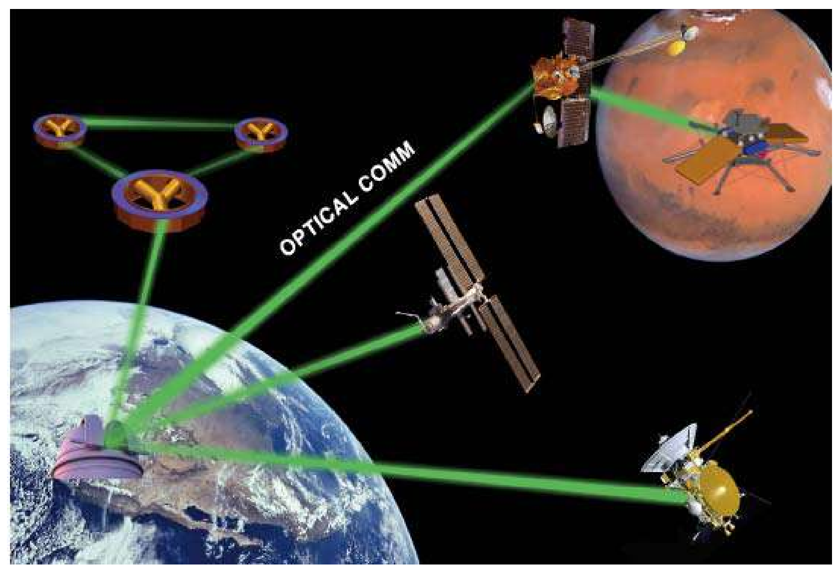
➢ Secure Communications through Quantum Key Distribution

- **Use quantum properties of single photons to establish encryption keys**



➢ Long-range Free Space Communications

- Single photon sensivity for photon-starved communication links
- “N bits per photon” protocols

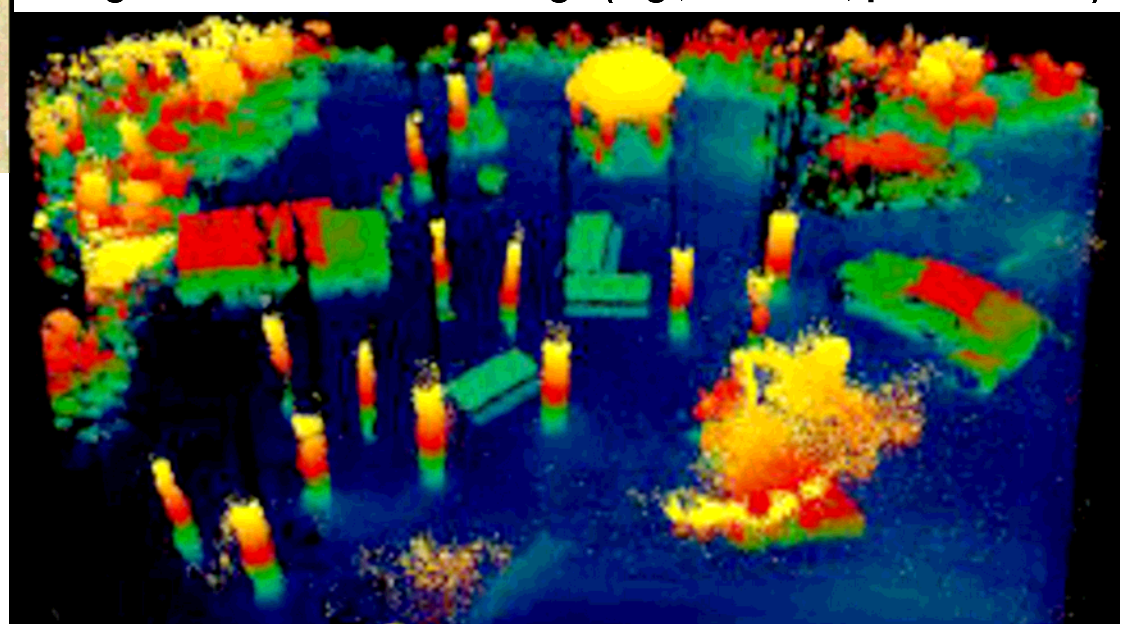


JPL Optical Communications Group – vision of free space comm

SPC Application: 3-D Imaging

- **Perform ladar ("laser radar") measurement at every pixel of array**
  - Obtain time-of-flight information at every pixel to calculate "depth"
  - Allows imaging through obscuring elements (e.g., foliage, netting, etc.)

Image of scene beneath foliage (e.g., vehicles, picnic tables)

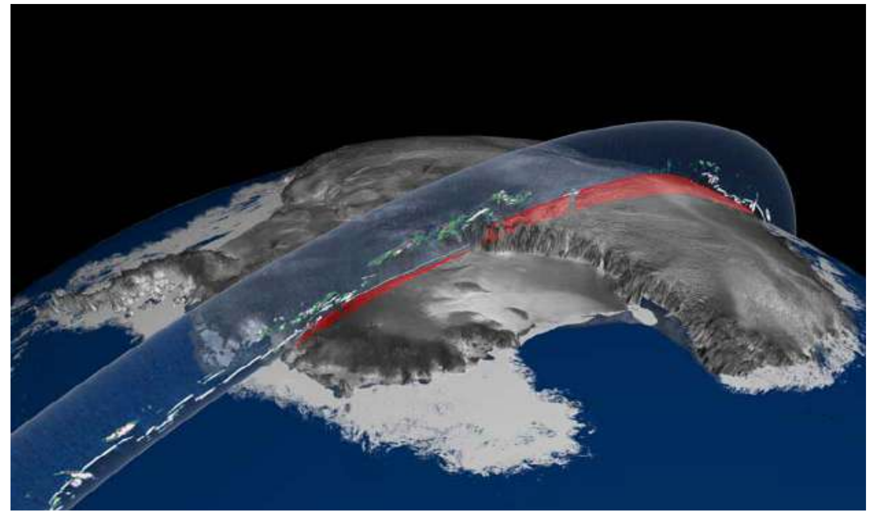


B. Aull, et al., SPIE <u>5353</u>, p. 105 (2004)

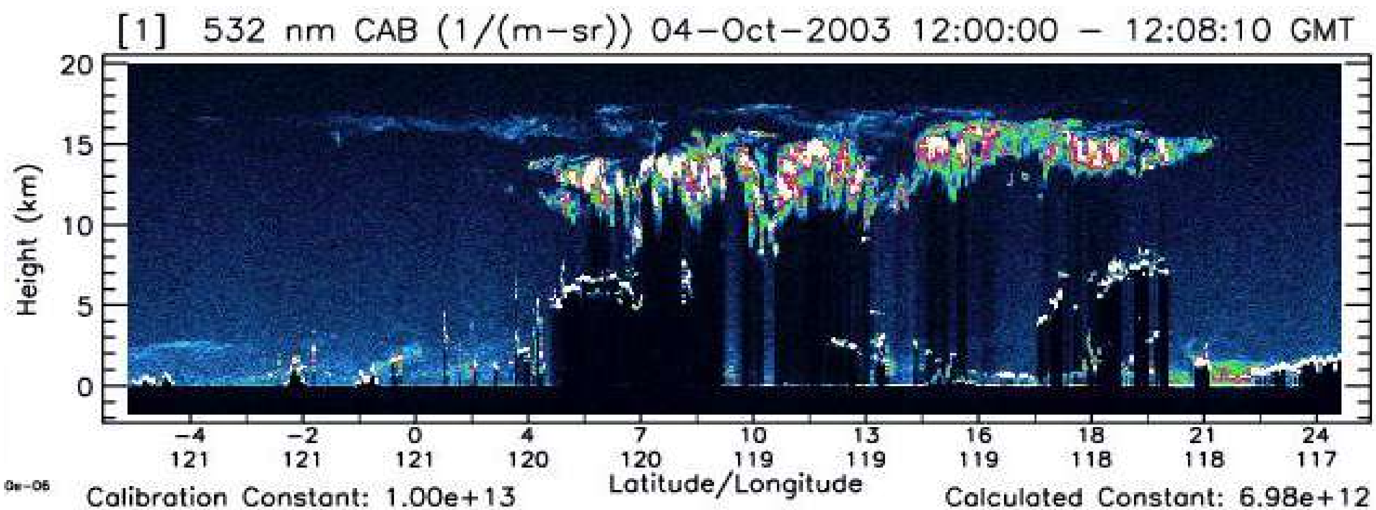
SPC Application: Atmospheric Lidar

- NASA ICESat/GLAS

Ice, Cloud, and land Elevation Satellite
on the
Geoscience Laser Altimeter System



Atmospheric mapping by lidar along Earth's circumference



SPC Application: Semiconductor diagnostics

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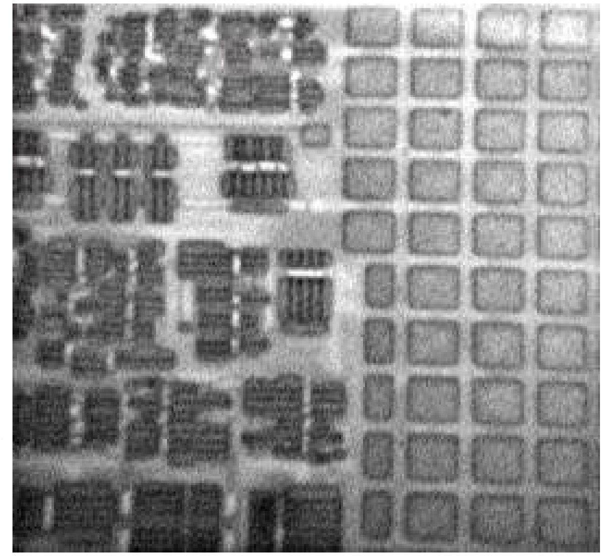
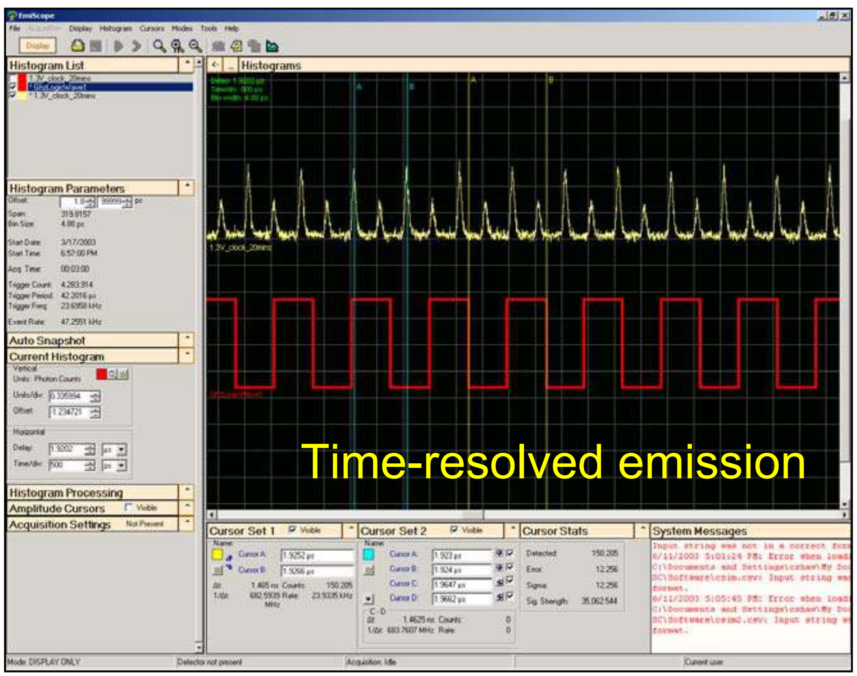
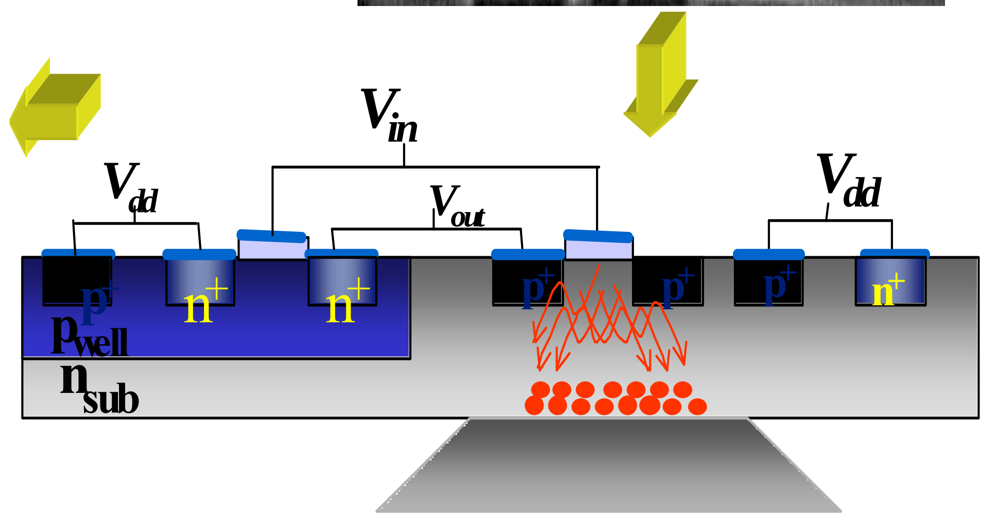
- **Time-resolved photon counting to measure CMOS hot carrier luminescence**
  - circuit design and debugging
  - circuit failure analysis



credence





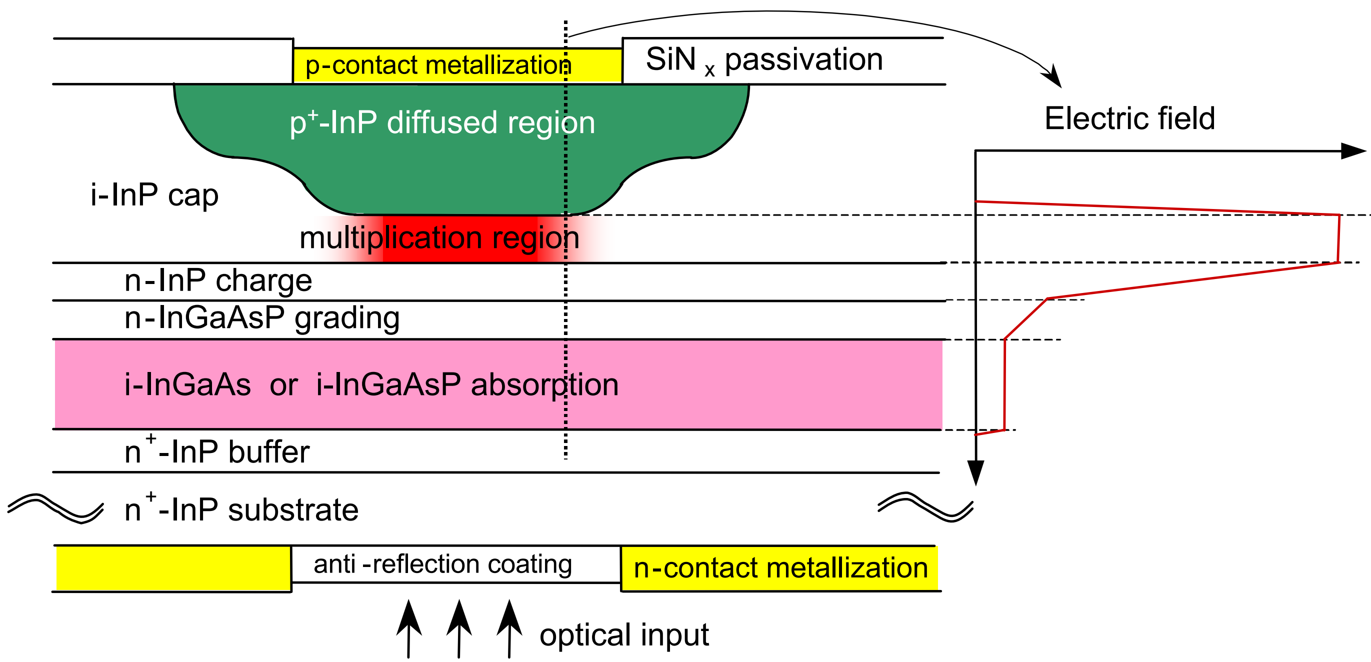
Collection (optics & detector)

Presentation outline

- Motivation for single photon detectors
- **Overview of avalanche photodiode structure**
- Geiger-mode operation
- Present performance and challenges
  - Dark count rate
  - Afterpulsing effects
- Conclusions

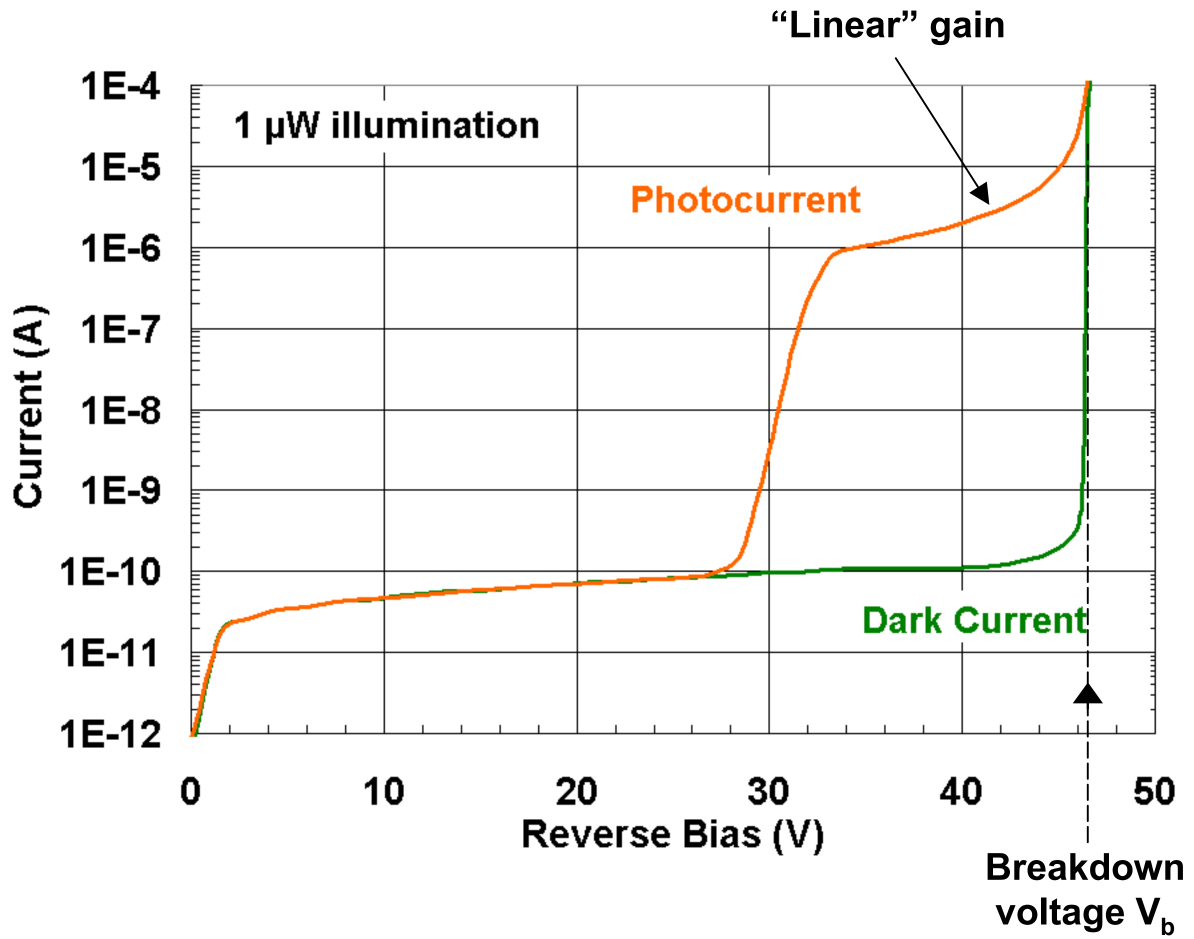
InGaAsP/InP avalanche diode design platform

- **Separate Absorption, Charge, and Multiplication (SACM) structure**
  - High E-field in multiplication region → induce avalanching
  - Low E-field in absorption region → suppress tunneling
- **Planar passivated, dopant diffused device structure**
  - Stable and reliable buried p-n junction
  - Widespread deployment of device platform in telecom Rx



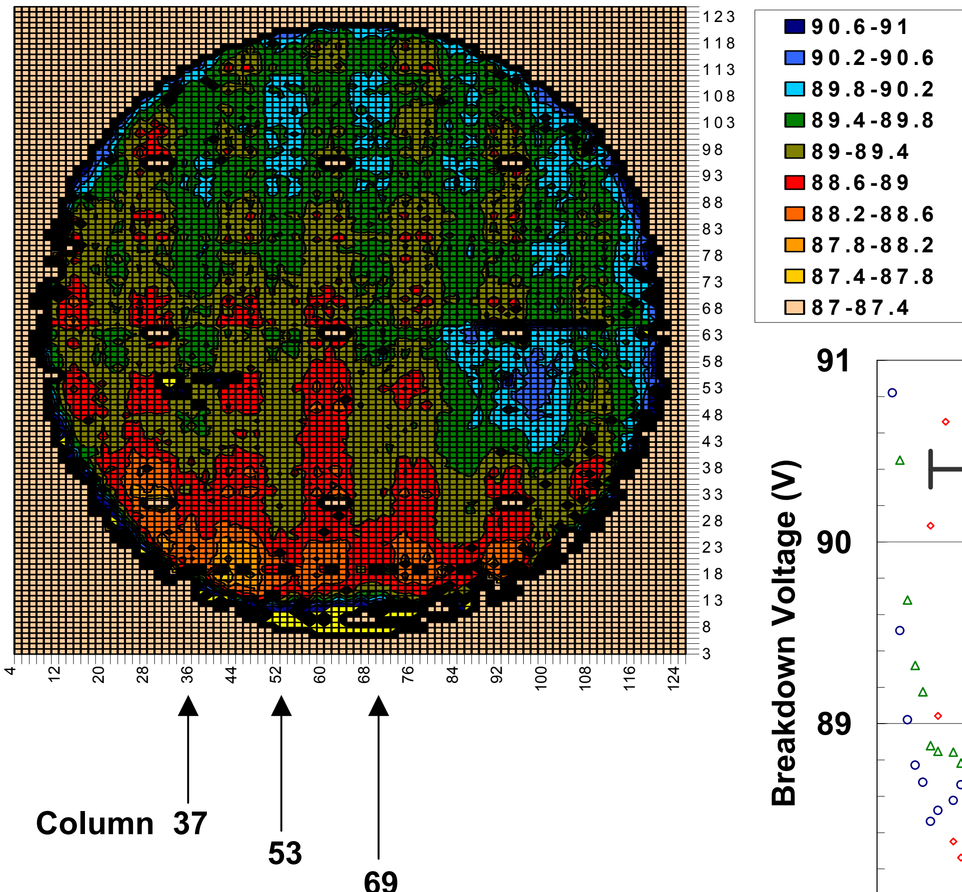
APD Current-Voltage Characteristics

- Linear mode performance is behavior below breakdown voltage V_b
  - Output photocurrent below V_b is linearly proportional to input optical power

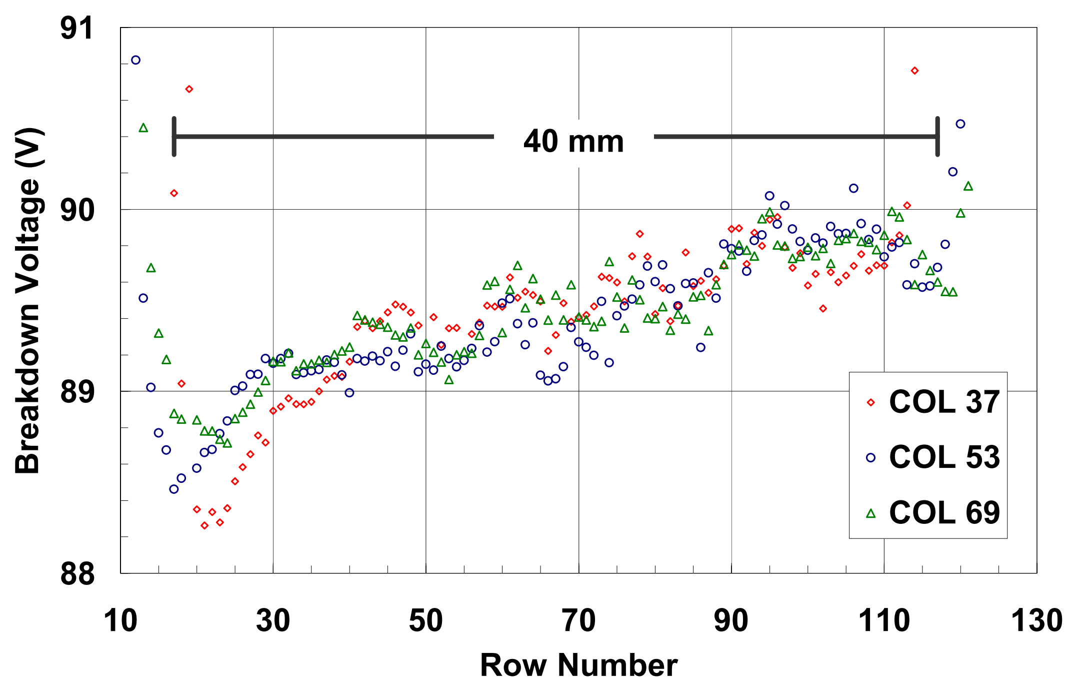


Performance uniformity at wafer level

- Breakdown voltage is very sensitive to structural details
  - Provides good measure for consistency of many device attributes



- Ex.: 1.06 μm SPAD wafer
- Intentional systematic variation to confirm diffusion control process
- **V_b variation: ~ 0.03 V per mm**



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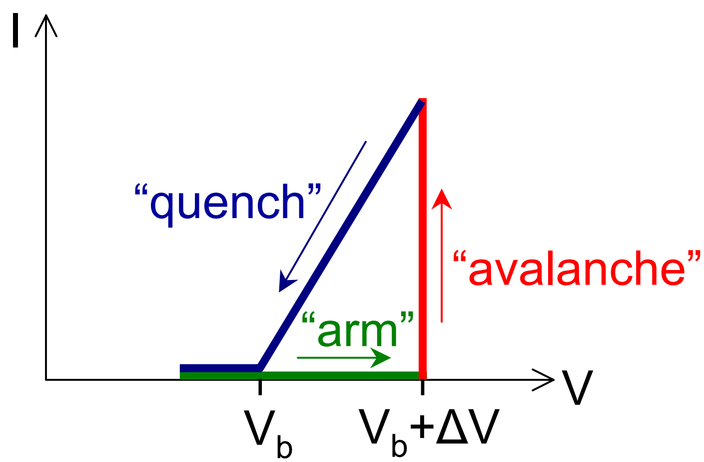
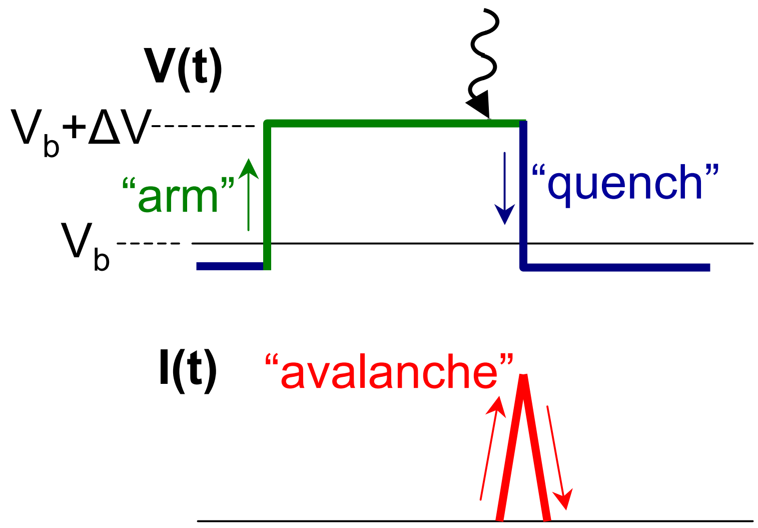
Geiger mode operation

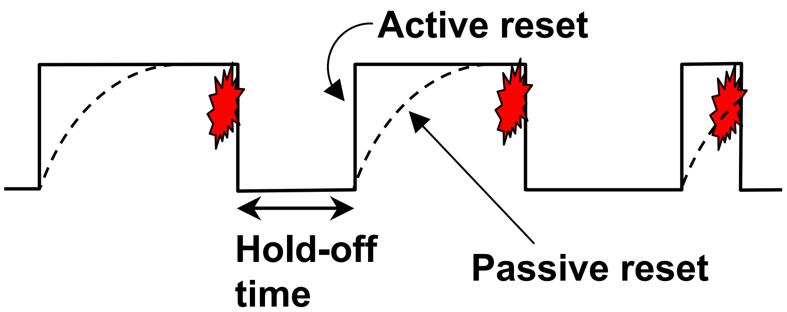
- **Single photon avalanche diodes (SPADs) operate in "Geiger mode"**
  - Bias above breakdown voltage V_b by overbias ΔV
  - Single photon induces avalanche leading to macroscopic current pulse
    - Avalanche detected using threshold detection circuit
  - Used as a photon-activated switch with purely digital output
  - Avalanche must be quenched after detection by lowering bias below V_b



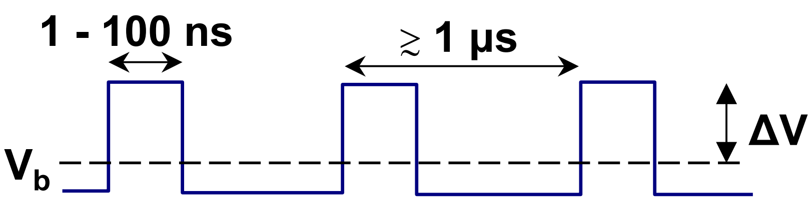


Geiger mode quenching schemes

- **Free-running operation**
  - **SPAD is "armed" (biased above breakdown) until avalanche occurs**



- **Gated-mode operation**
  - **Most relevant operation for InP-based SPADs**
  - **Periodic arming and disarming of the SPAD**



  - Short gates (~1 ns) are ideal if photon arrival is deterministic (e.g., communications)

SPAD performance parameters

- **Detection efficiency (DE):** probability of detecting incident photon
- **Dark count rate (DCR):** probability of "false" detection (no incident photon)
- **Afterpulsing (AP):** increase in dark count rate following previous detection
  - Mitigated only by limiting repetition rate
- **Timing jitter (TJ):** randomness in detection timing

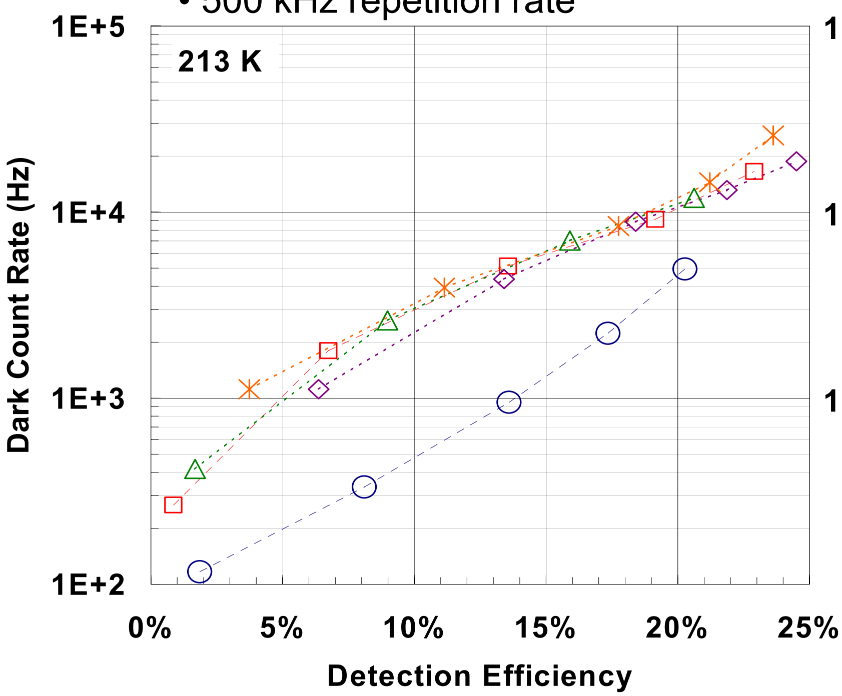
- **Important performance trade-offs to be managed**
  - **Increase overbias: DE ☺ , TJ ☺ , DCR ☹**
  - **Decrease temperature: DCR ☺ , AP ☹**

DCR vs. DE trade-off

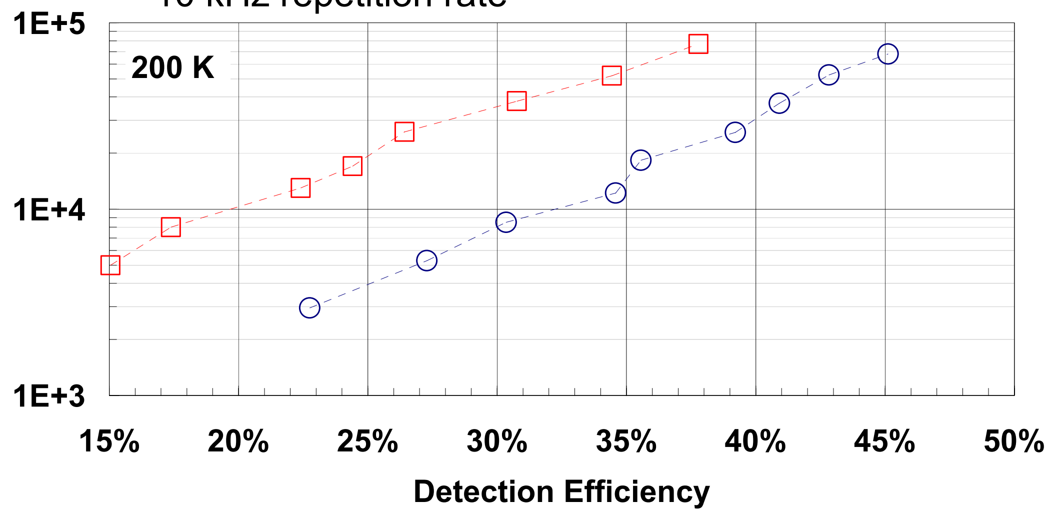
- **Most important SPAD performance tradeoff: DCR vs. DE**
- Typical performance: 10 kHz DCR at 20% DE, 100 kHz at 40% DE

Data for 25 μm diameter InGaAs/InP SPADs for 1.5 μm

• 1 ns gating
• 500 kHz repetition rate



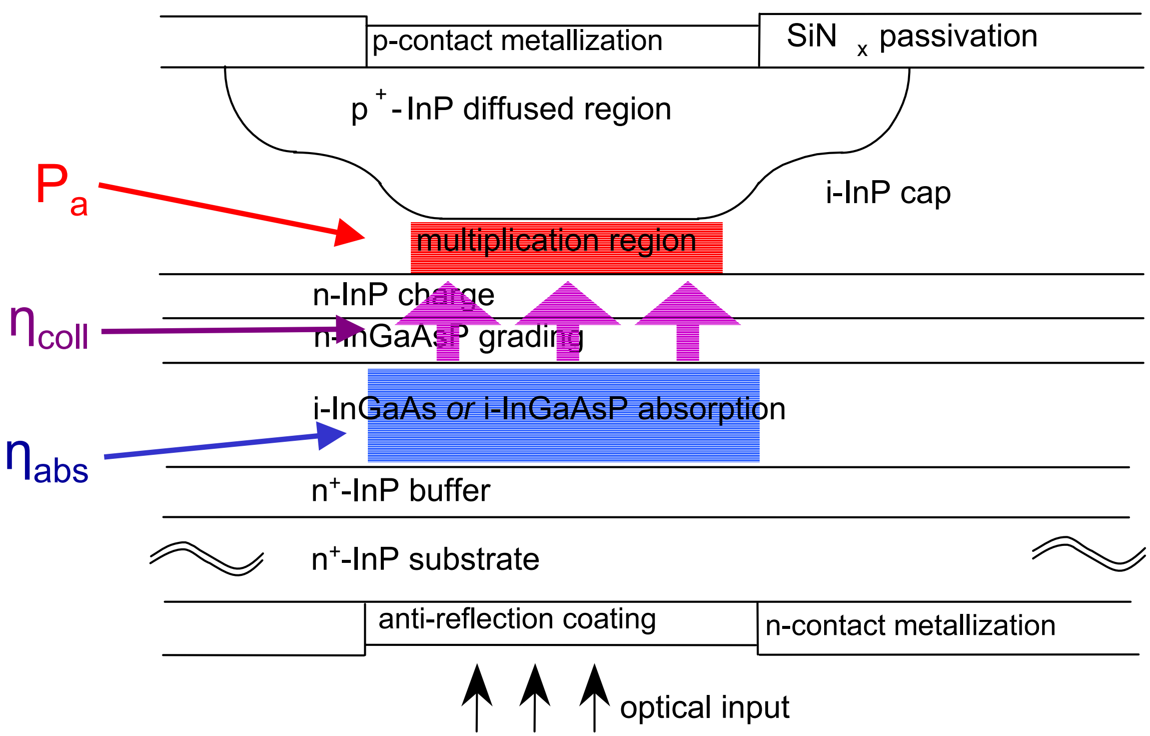
• 200 ns gating with active quenching
• 10 kHz repetition rate



--⊖-- "hero" devices

Photon Detection Efficiency

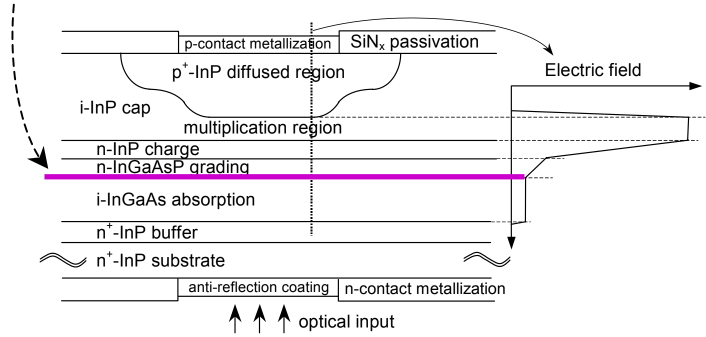
- **Detection efficiency: DE = $\eta_{abs} \times \eta_{coll} \times P_a$**
  - η_{abs} : probability of photon absorption (i.e., quantum efficiency)
  - η_{coll} : probability of carrier injection to multiplication region
  - P_a : probability that injected carrier initiates self-sustaining avalanche

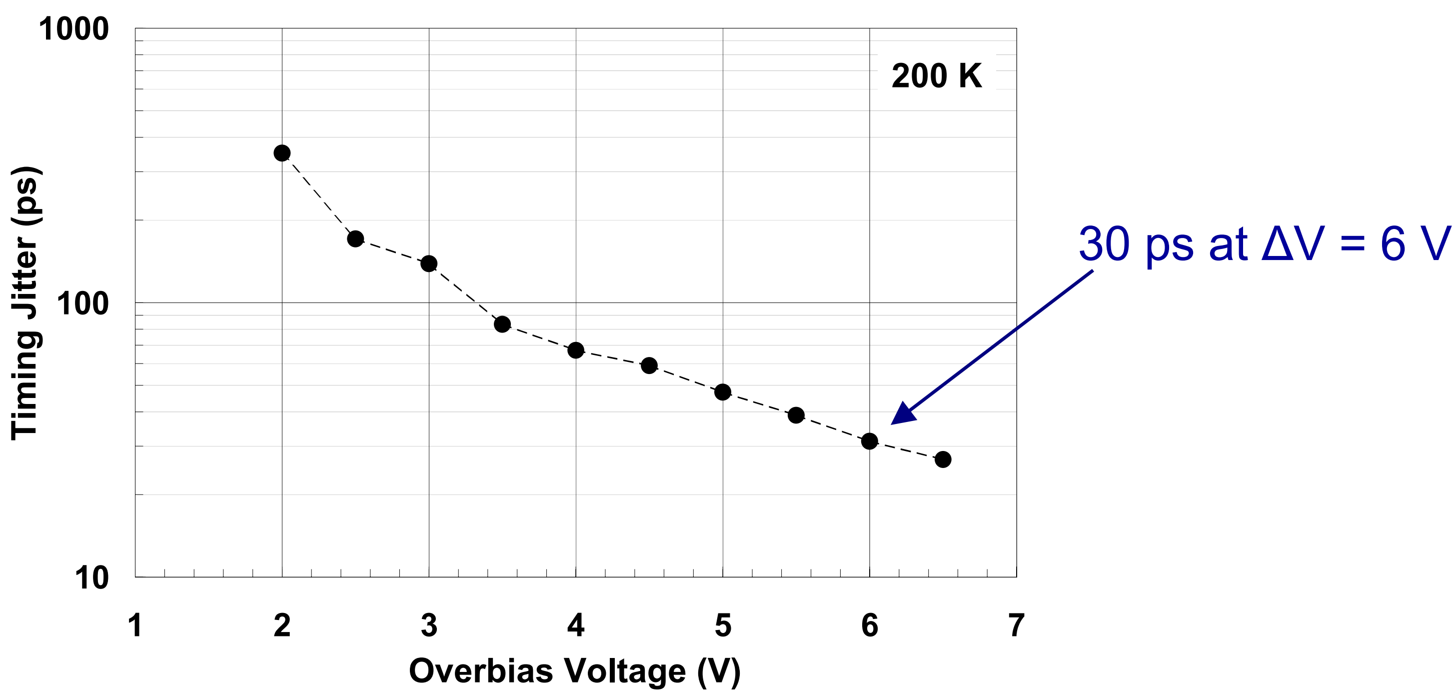


Timing Jitter

- Factors contributing to timing jitter:
  - Absorption location (through varying transit time)
  - **Carrier propagation delay at interfaces**
  - Avalanche build-up time (vertical and lateral)
- SPAD capability generally < 100 ps
  - Electronics design is critical to TJ performance

Critical interface for primary hole trapping





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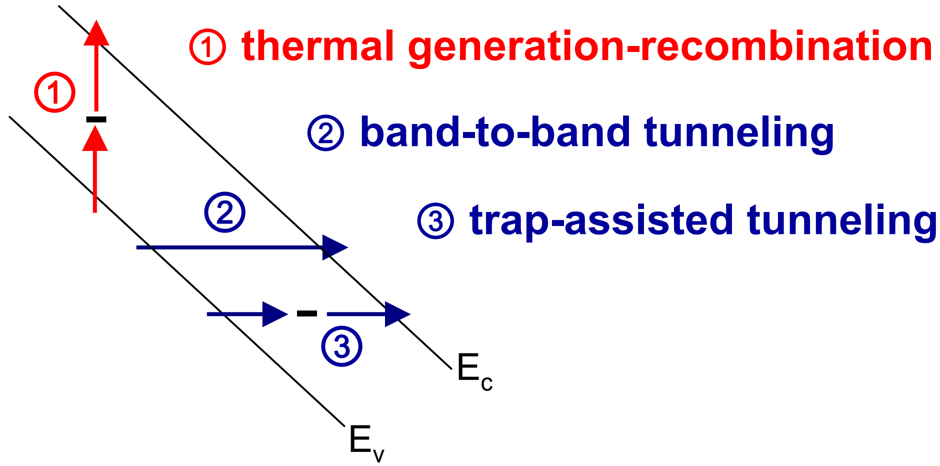
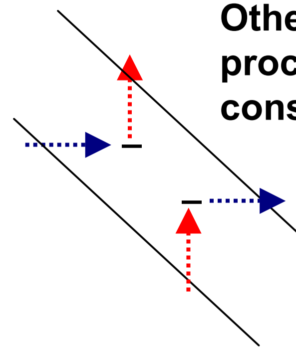
Dark count rate behavior and mechanisms

- Dark carriers can be generated by a number of mechanisms





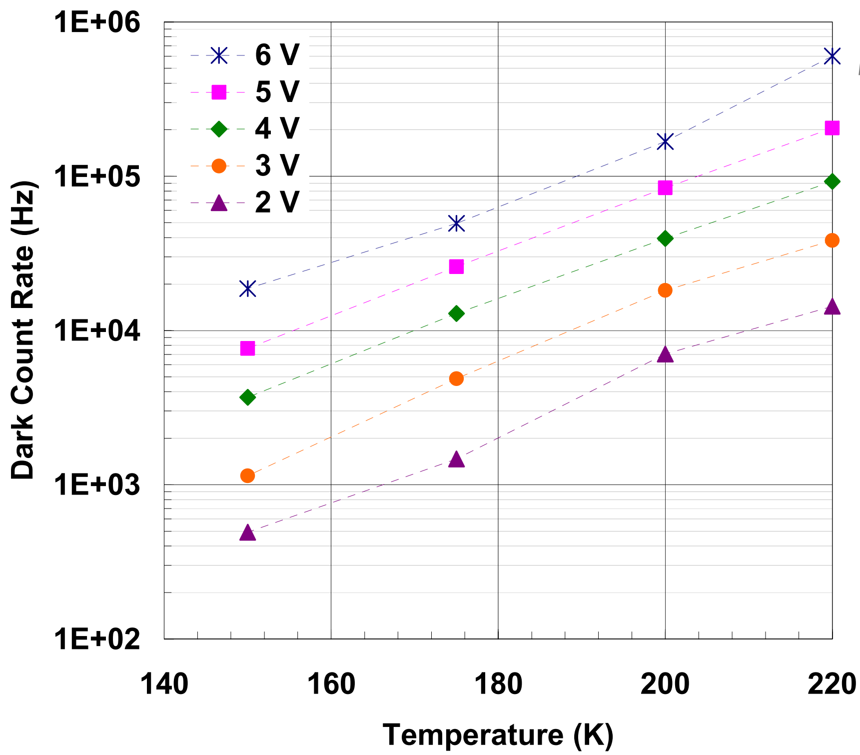
Other "combined" processes not considered

- Sample properties will have a large impact on DCR
  - Bandgap (InP vs. InGaAs vs. InGaAsP)
  - Defects

- Study DCR dependence on temperature and bias for clues
  - **Extract activation energies** to help identify dominant DCR mechanisms

Dark count rate behavior and mechanisms

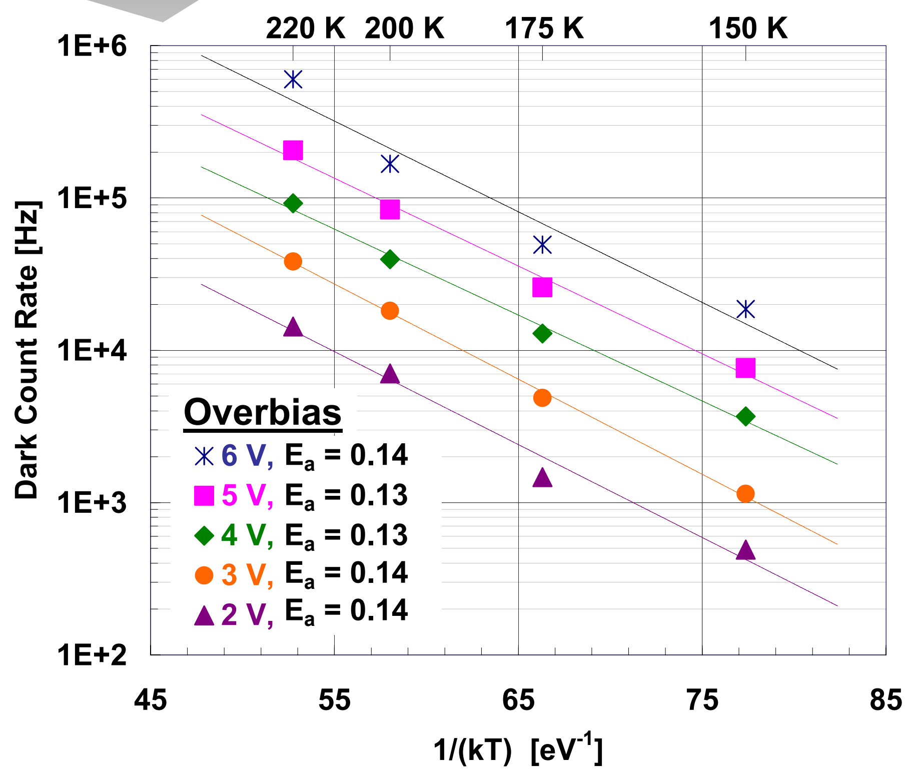
- **Characterize DCR vs. temperature at different overbias for T < 220 K**
  - Assume DCR ~ exp($-E_a/kT$) to extract activation energy E_a



Itzler *et al*., J. Mod. Opt. 54, p 283 (2007)

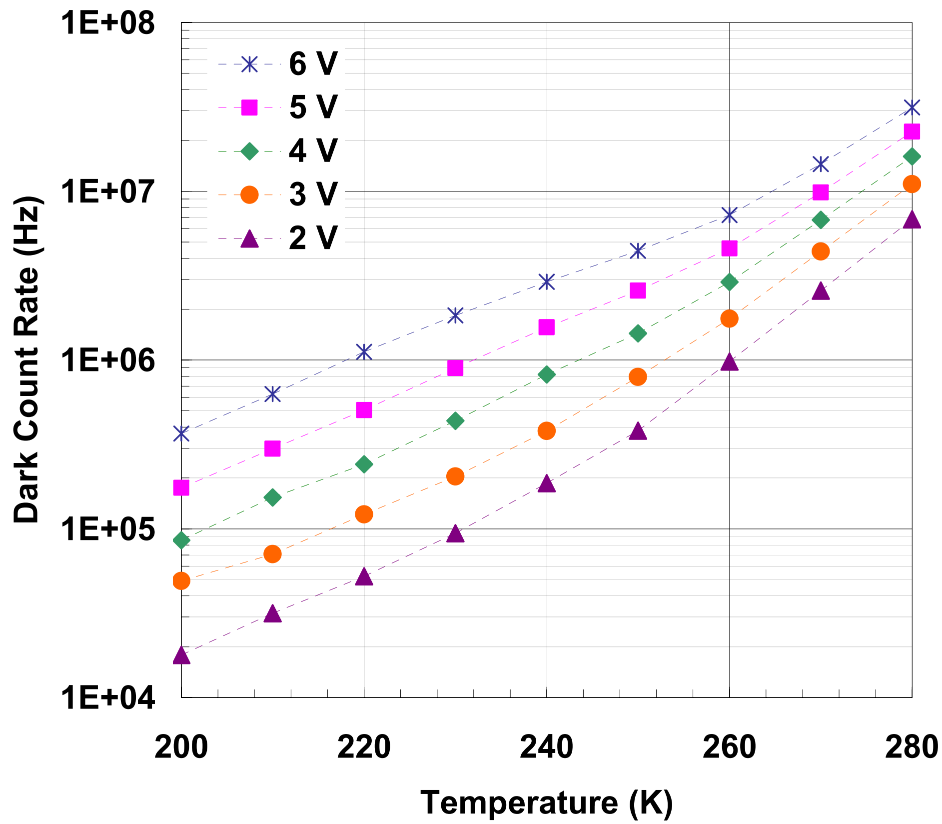
Plot DCR vs $(kT)^{-1}$

$\langle E_a \rangle$ ~ 0.14 eV



Dark count rate behavior and mechanisms

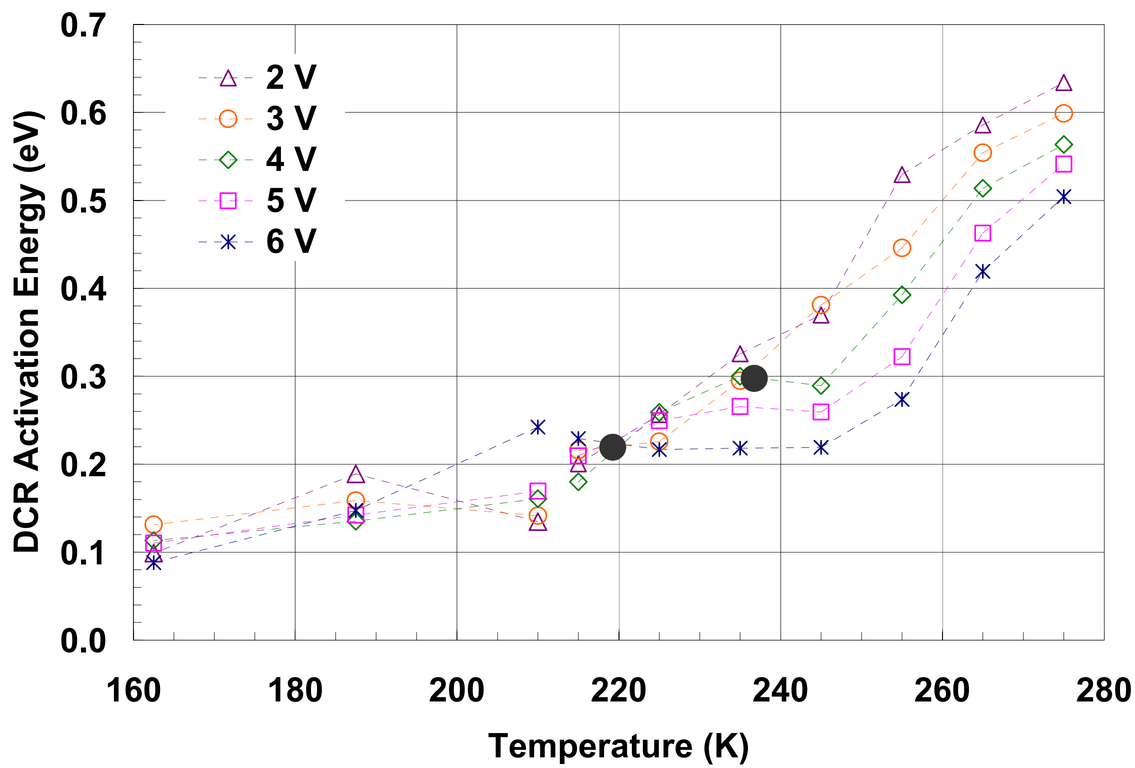
- **DCR vs. temperature at different overbias for T > 200 K**
  - Can not fit with fixed E_a for T $\gtrsim$ 220 K



Need to consider E_a(T):
change in E_a → change in dark carrier generation mechanism

Dark count rate behavior and mechanisms

- **Consider temperature dependence of DCR activation energy $E_{a,DCR}$**



Open symbols, T ≲ 210 K:
20 ns gating

Open symbols, T ≳ 215 K:
100 ns gating

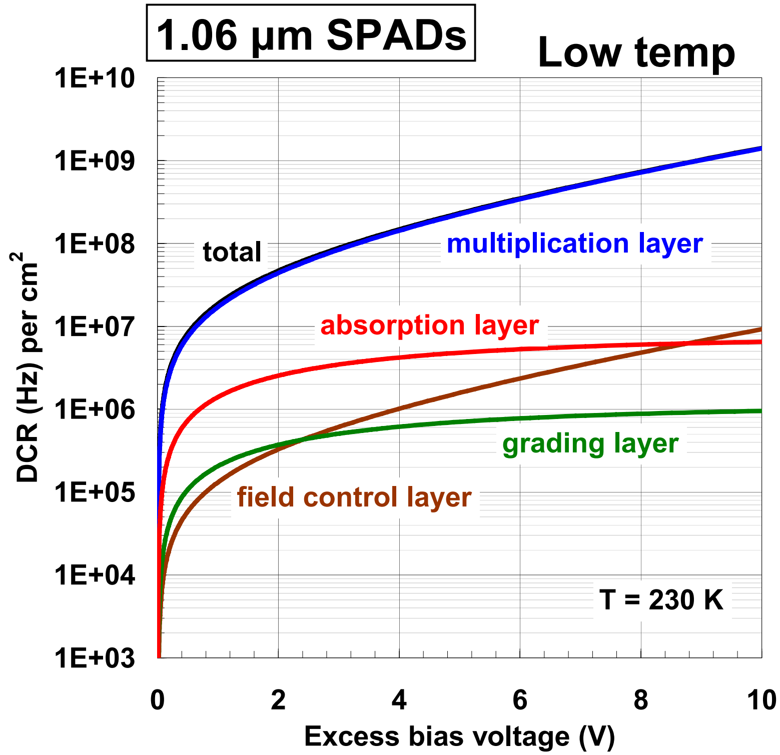
"●" : 1 ns gating, ~3 V

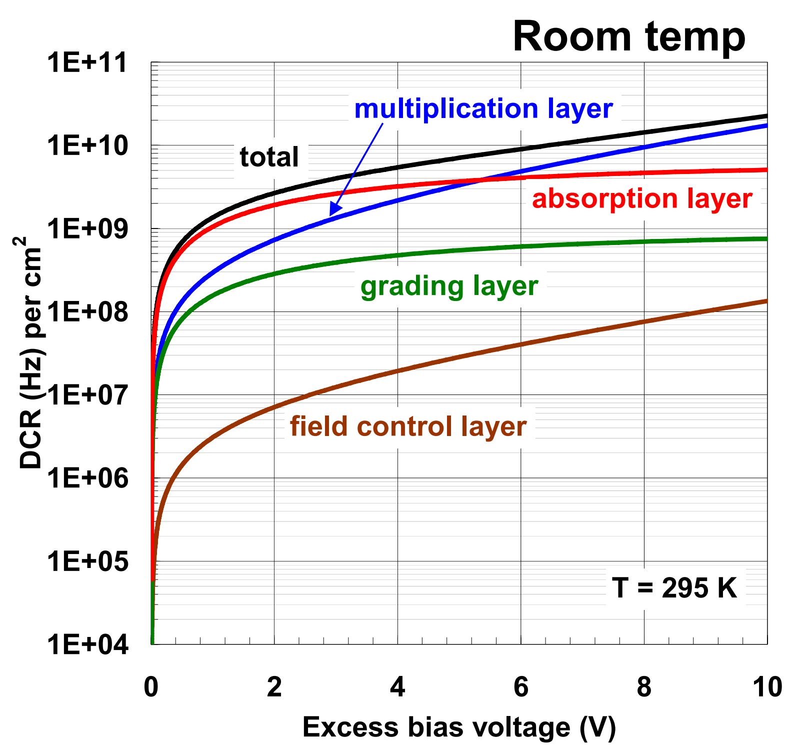
- **For T ≲ 230, low $E_{a,\,DCR}$ → tunneling mechanisms**
- **For T ≳ 230, increasing $E_{a,\,DCR}$ → thermal generation becomes important**
  - thermal generation more significant at low overbias

DCR mechanisms for 1.06 μm SPADs

- Simulations give insight into dominant DCR mechanisms
  - following formalism of Donnelly *et al.* [JQE 42, p. 797 (2006)]
- At low temp, multiplication region trap-assisted tunneling dominates
- At room temp, two mechanisms compete
  - absorption region thermal generation dominates at low bias
  - multiplication region trap-assisted tunneling dominates at high bias

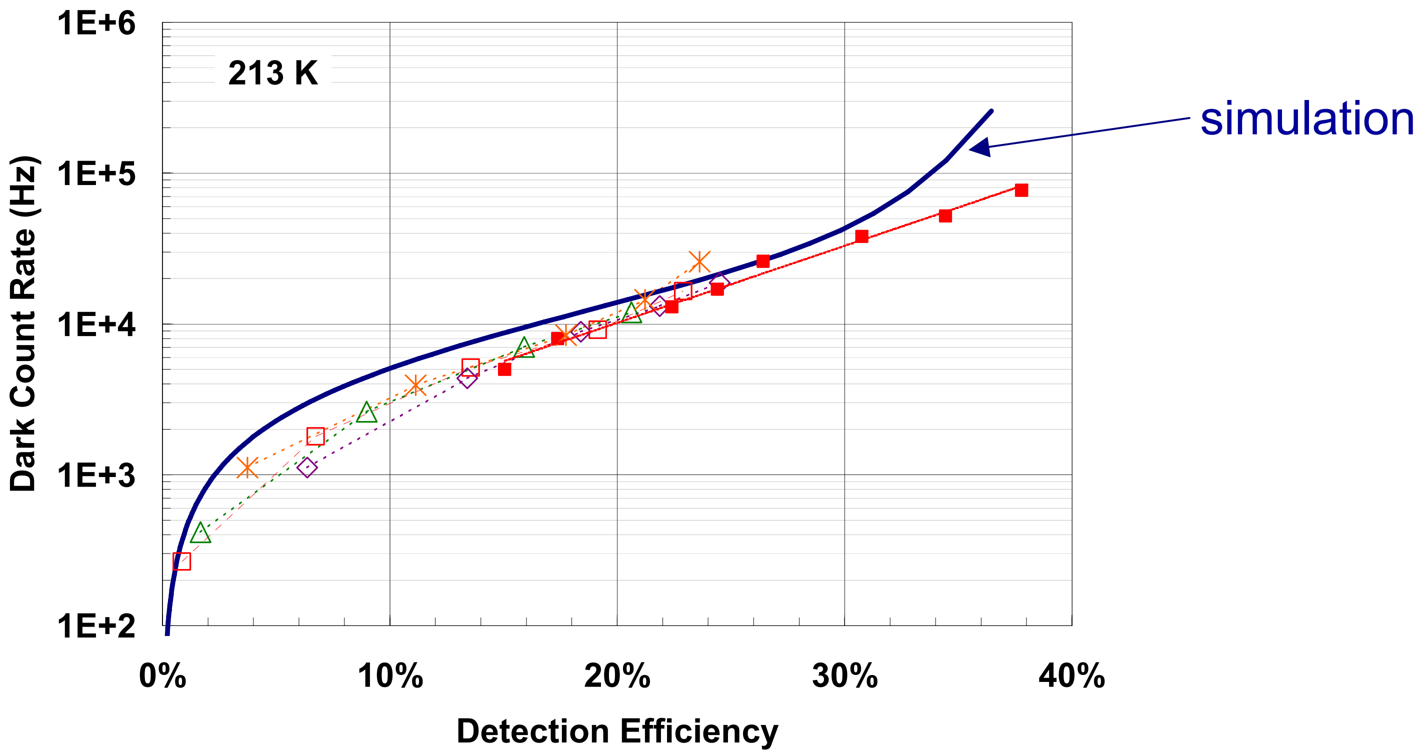
1.06 μm SPADs





Dark count rate modeling for 1.5 μm SPADs

- **DCR modeling is more complicated for 1.5 μm SPADs**
- **First attempts at fitting DCR vs. DE at 1.5 μm are encouraging**
  - Fit parameters are similar to those used for 1.06 μm SPADs
  - For 1.5 μm, thermal and tunneling contributions are comparable even at low temp



- Simulations very sensitive to defect attributes
- Need appropriate materials analysis (e.g., DLTS/capacitive spectroscopy)

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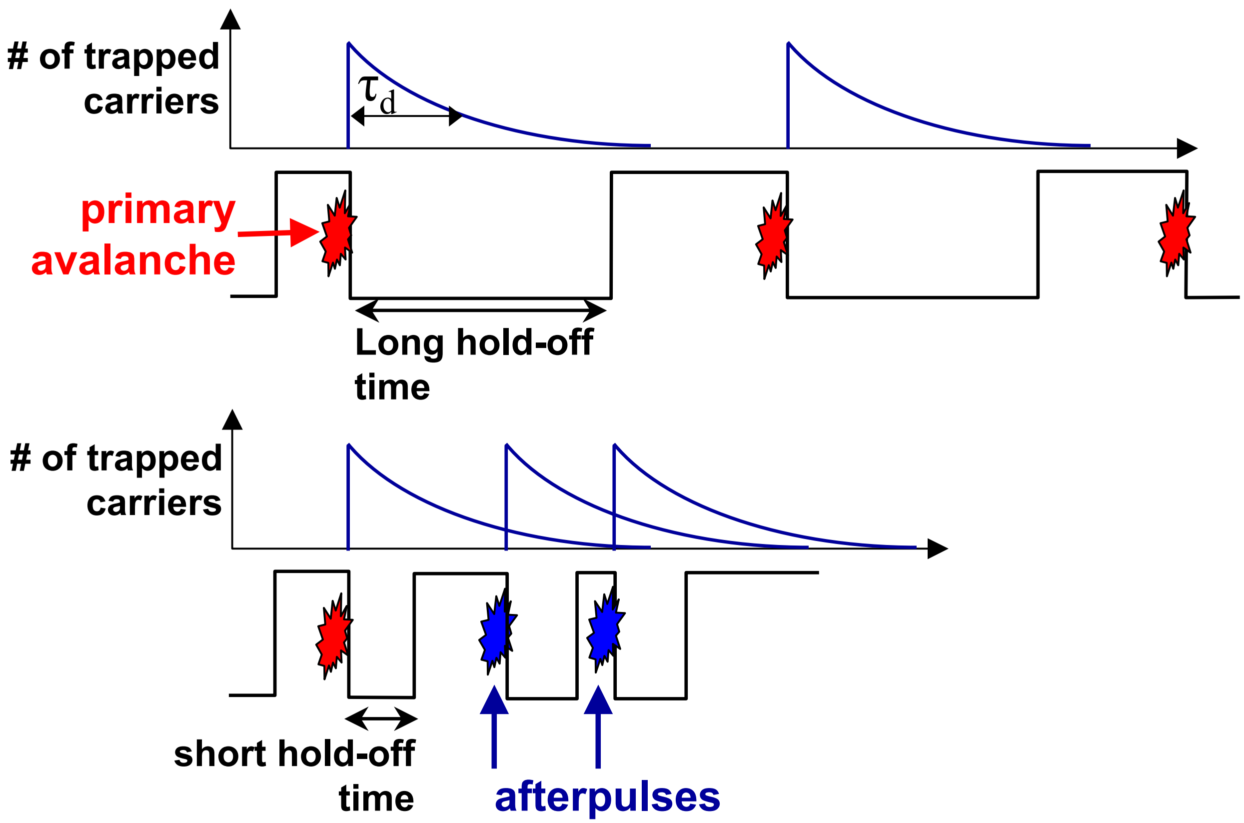
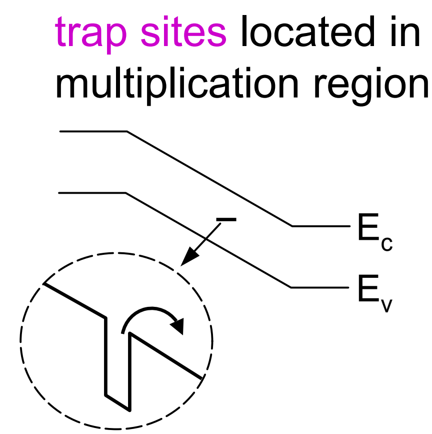
Description of afterpulsing

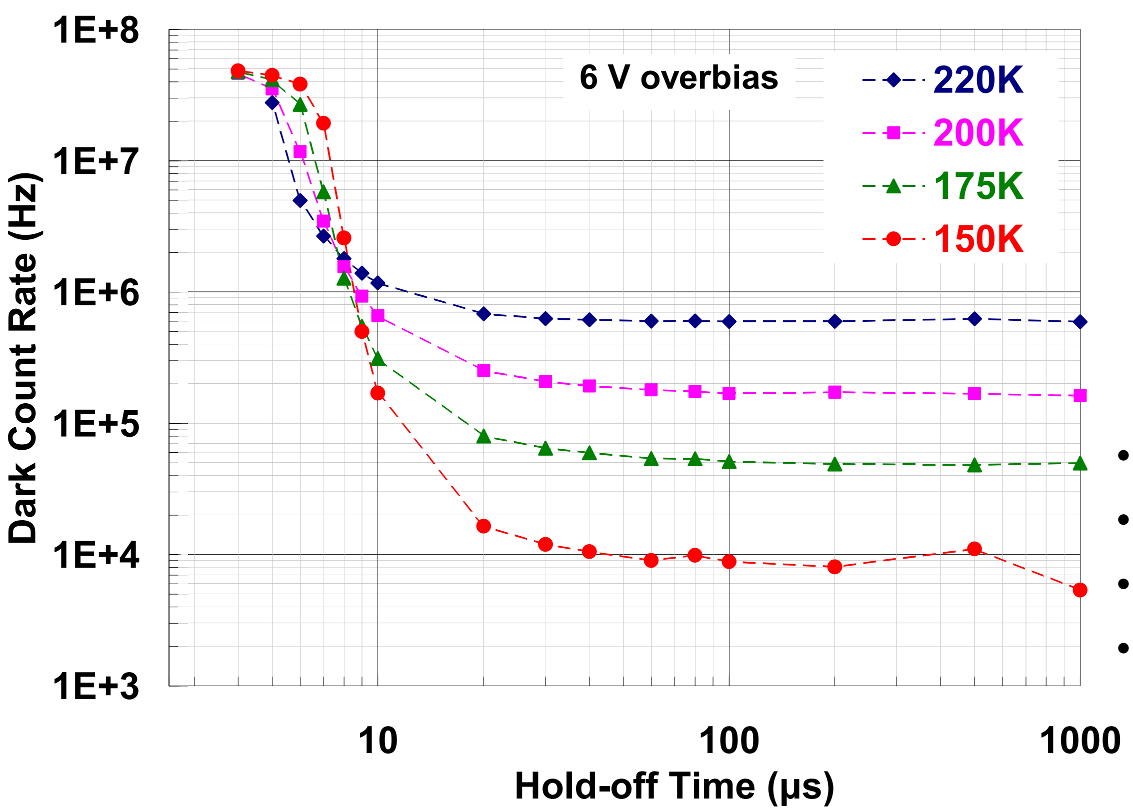
- **Afterpulsing is most serious limitation of InP SPADs; limits repetition rate**
- Avalanche carriers temporarily trapped at defects in InP multiplication region
- Carrier de-trapping at later times can initiate “afterpulse” avalanches
  - **Afterpulsing likely if “hold-off” times $T_{h\text{-}o} \lesssim$ detrapping time τ_d**

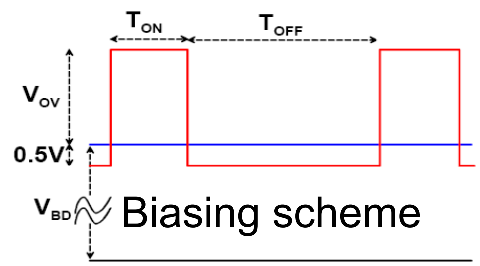




Impact of afterpulsing on count rates

- **Assess impact of afterpulsing through DCR dependence on hold-off time**
  - Looking at afterpulses induced by dark counts only
  - Sharp rise in DCR at short $T_{h\text{-}o}$ due to afterpulsing



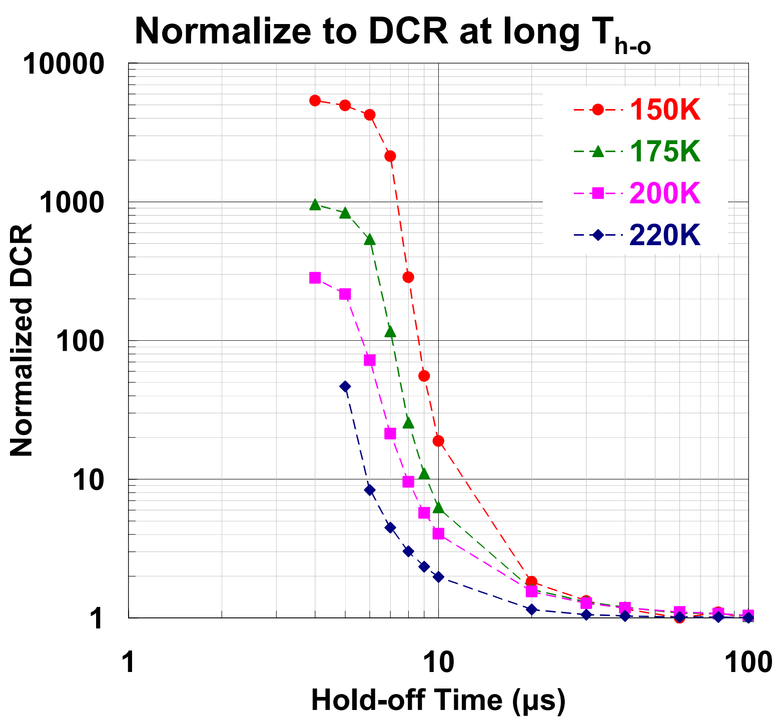


Biasing scheme

- **40 µm diameter SPADs**
- **periodic gated operation**
- **20 ns gates**
- **6 V overbias**

Universal scaling of afterpulse behavior

- Normalize to background DCR
- DCR vs. $T_{h\text{-}o}$ curves collapse to a single curve with correct rescaling
  - Same curve shape up to temperature-dependence scale factor for $T_{h\text{-}o}$



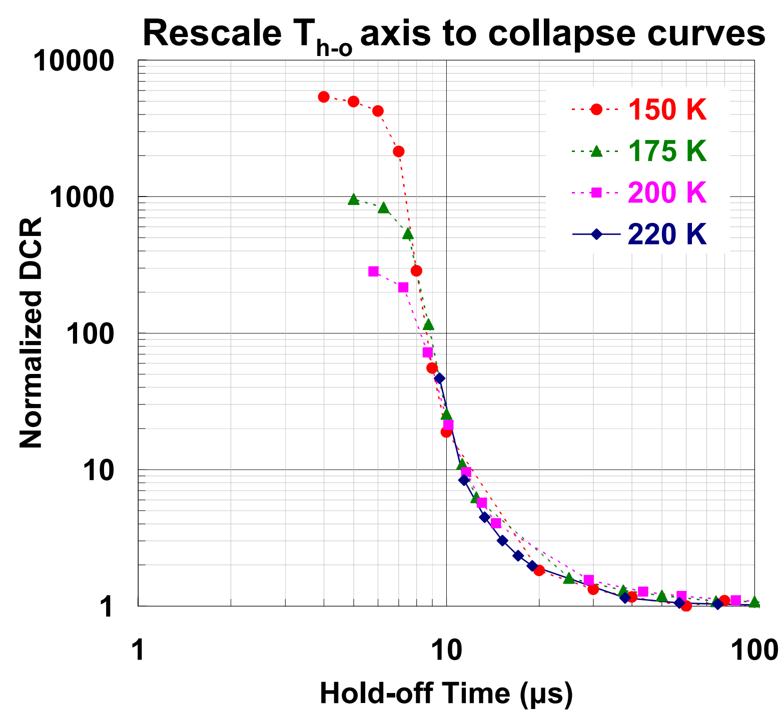
Scale factors

150 K: 1

175 K: 1.25

200 K: 1.45

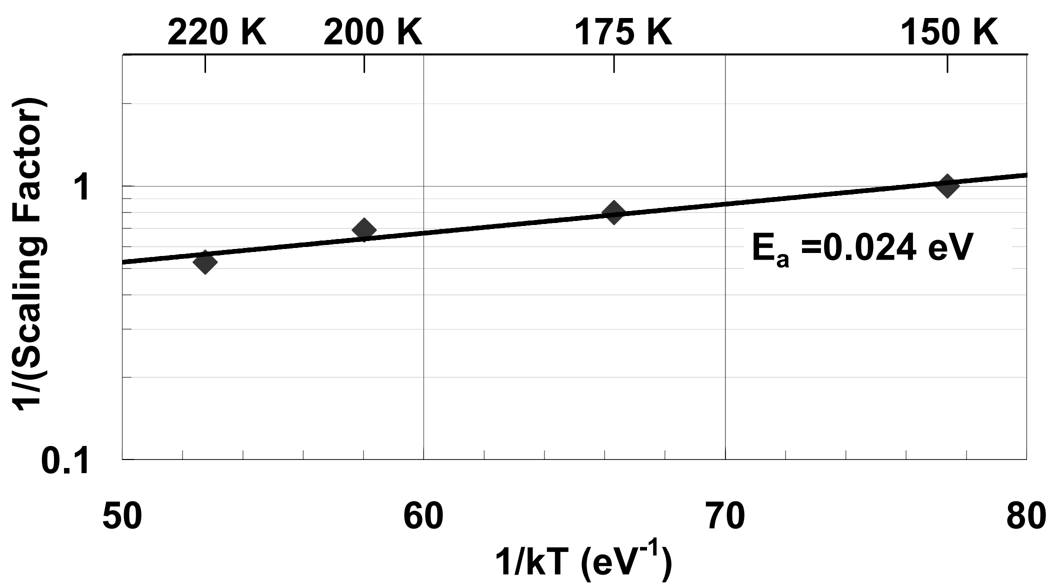
220 K: 1.90



Collapse allows extraction of afterpulsing activation energy

Afterpulsing activation energy $E_{a,AP}$

- Use DCR vs $T_{h\text{-}o}$ curve collapse to find afterpulse activation energy
  - Assuming single detrapping time τ_d , inverse of scale factor $\propto \tau_d$
  - Plot against 1/kT to extract activation energy $E_{a,AP}$

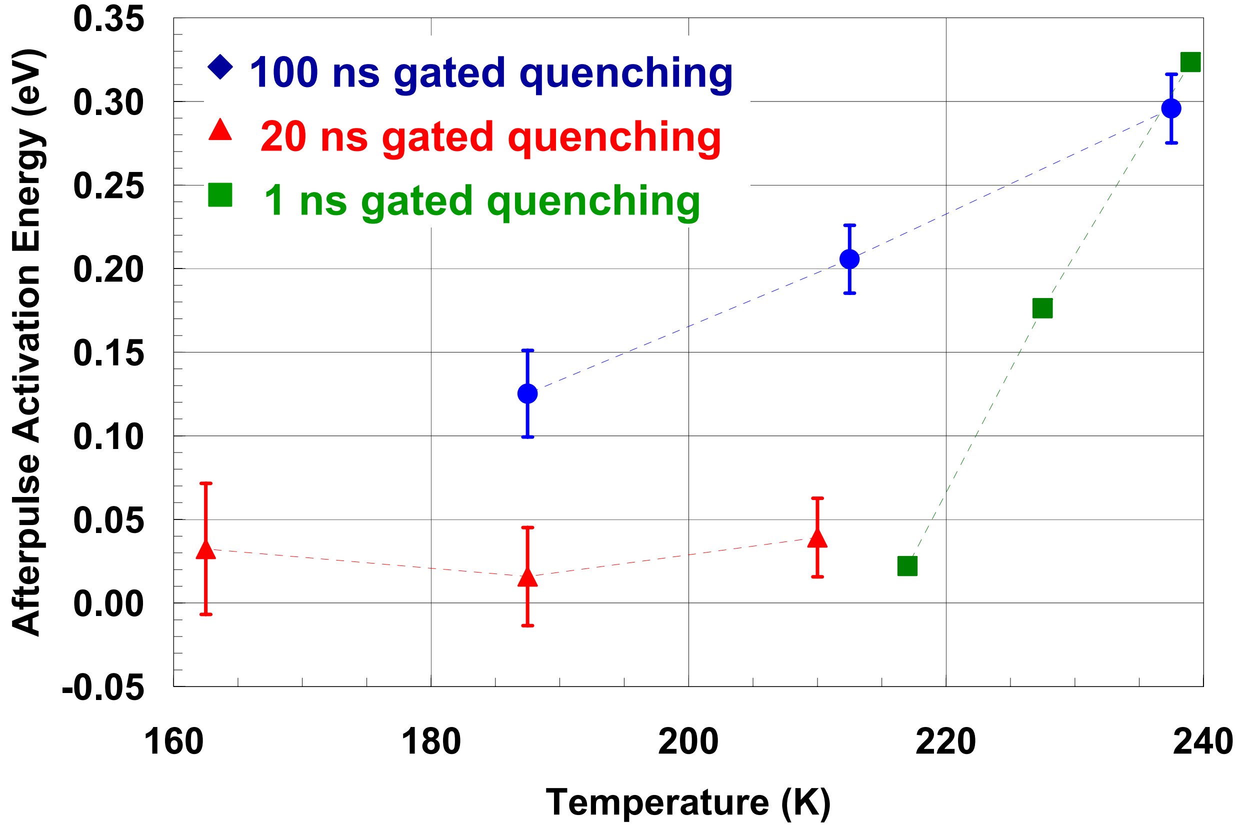


Scale factors	
150 K:	1
175 K:	1.25
200 K:	1.45
220 K:	1.90

- As with DCR, see if $E_{a,AP}$ depends on temperature
- Consider data from additional measurements

Temperature dependence of $E_{a,AP}$

- **Extract $E_{a,AP}(T)$ to determine trends in afterpulsing behavior**
  - Using very different gate durations, still find consistent trend
  - $E_{a,AP}$ very small ($\lesssim$ 0.1 eV) for T < 200 K), increases for T > 220 K
  - Suggests that scaling may not hold above 220 K – need confirmation



Assume trap lifetime given by:

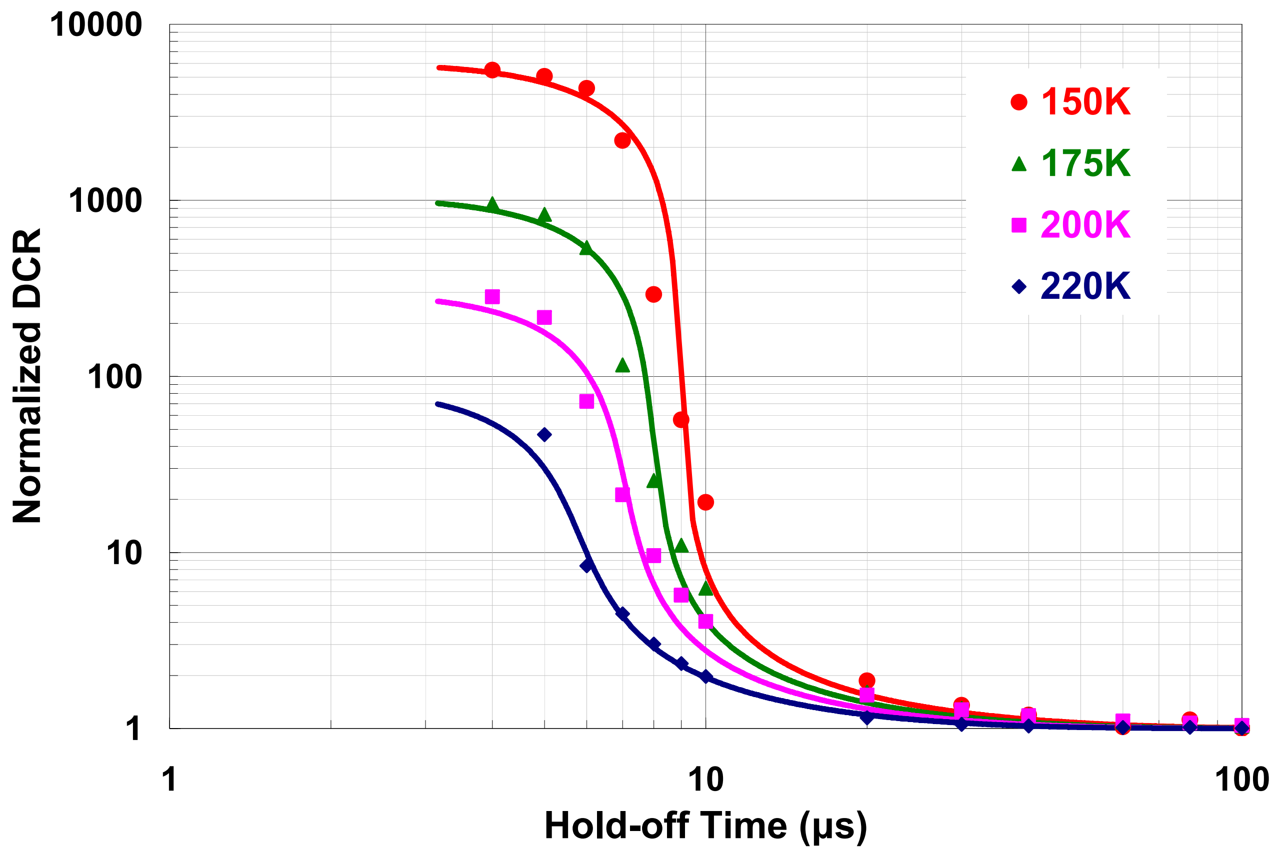
$$\tau_d = \frac{1}{\sigma \upsilon N} \exp\left(-\frac{E_{a,AP}}{kT}\right)$$

Pre-factor $\propto T^{-2}$

Afterpulsing model fit to gated operation data

- **Use model of Kang *et al.* to fit measured DCR vs. $T_{h\text{-}o}$ data**
  - Model includes probability of de-trapping from all previous gates
  - Initial model assumed single trap; we have added additional traps
  - For 220 K, **model yields τ_d ~ 15 μs** using single trap

Kang, Lu, Lo, Bethune, Risk, APL 83, p. 2955 (2003).



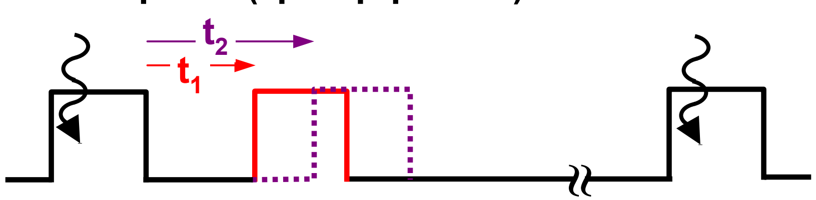
Solid curves: simulation

Problem of detrapping times

- Recent results related to de-trapping times in InP is quite varied
  - Fundamental question for modeling: single trap vs. multiple traps
    - Multiple traps: too many free parameters, or correct physics?
  - De-trapping times found will depend on range of hold-off times $T_{h\text{-}o}$ used
    - For narrow range of $T_{h\text{-}o}$ (< 10X), see just one de-trapping time from $R_{AP}(t)$

$$R_{AP}(t) = \frac{N_1}{\tau_1} e^{-t/\tau_1} + \frac{N_2}{\tau_2} e^{-t/\tau_2} + \frac{N_3}{\tau_3} e^{-t/\tau_3} + \dots$$

Double-pulse ("pump-probe") method:

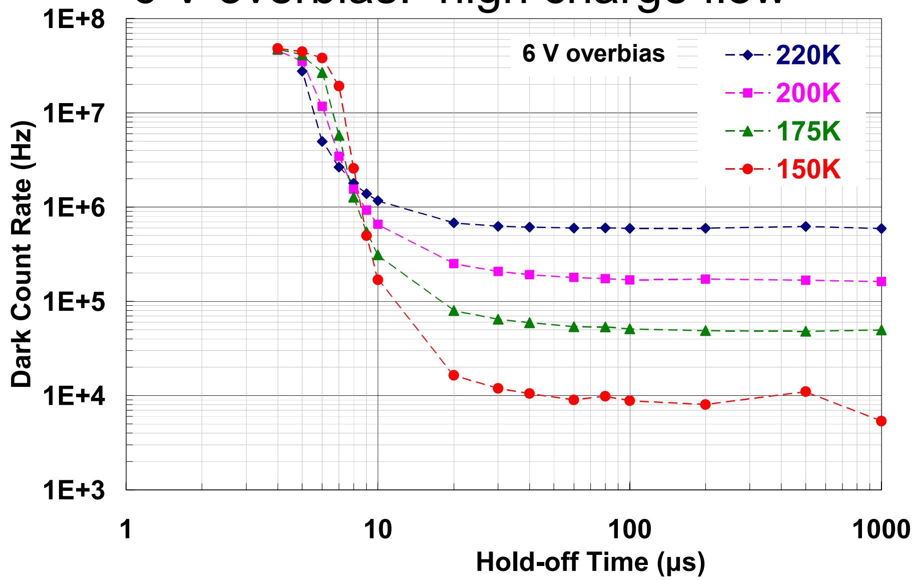


Authors	Temperature [K]	Hold-off time [μs]	Detrapping times [μs]				Technique
			τ_1	τ_2	τ_3	τ_4	
PLI/NASA	250	0.14 – 0.46	0.07				free-running
Jensen *et al.*	250	1.0 – 10		0.9			double-pulse
Liu *et al.*	220 – 240	0.02 – 50	0.15	1.0	5	45	double-pulse
Trifonov *et al.*	195 – 230	1.25 – 100		0.5	6	100	double-pulse
PLI (this work)	200 – 220	4 – 1000			~15	~150	DCR vs. $T_{h\text{-}o}$ scaling

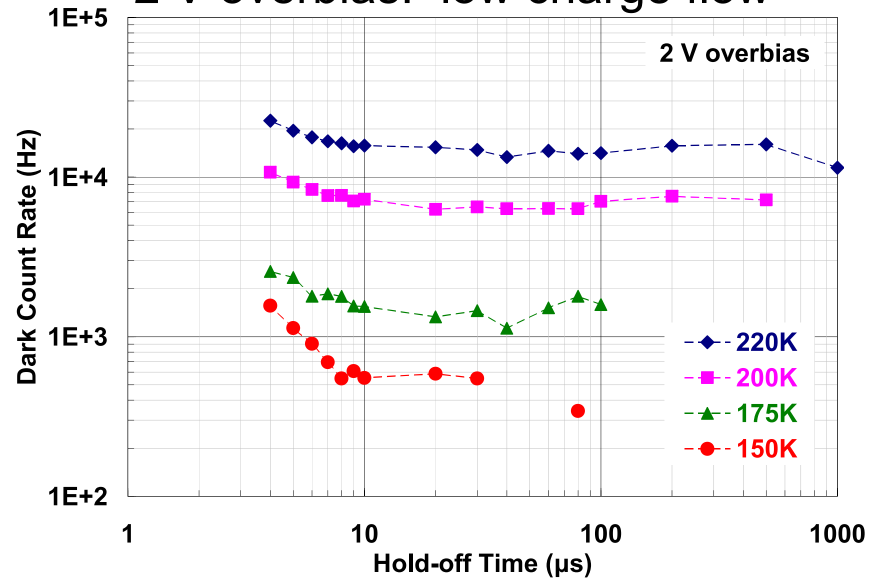
Afterpulsing and Carrier Trapping Mitigation

- Impact on afterpulsing from: **materials properties**
  - Extract basic properties (trap levels & densities) from measurable quantities (τ_d , E_a)
  - Materials improvements are challenging [ref: Si SPAD hold-off times: ~100 ns]
- Impact on afterpulsing from: **operating conditions**
  - Key factor is total charge flow through device – **reduce charge flow per avalanche**
    - Overbias, quenching conditions, short gates (where possible)
  - Higher temperature reduces afterpulsing

6 V overbias: high charge flow



2 V overbias: low charge flow



Conclusions

- **Present DCR vs. DE: ~10 kHz at 20% at 1.5 μm, T ~ 215 K, 25 μm dia.**
- **Temp-dependent DCR activation energy gives insight into mechanisms**
  - Shift from thermal processes at room temperature to tunneling for T < 220 K
  - Good simulations should reproduce $E_{a,DCR}(T)$ behavior
- **Initial simulations provide good description of DCR vs. DE behavior**
  - Valuable for understanding relative contributions of different DCR mechanisms
  - **Need better information regarding defects** and thermal+tunneling mechanisms
- **Afterpulsing is key limitation for high counting rates**
  - Activation energy is constant at low temp, changes at T > 240 K
  - Collapse of DCR vs. hold-off time curves indicates universal behavior for T < 220
  - **Determination of number of trap types and lifetimes is key** to accurate modeling
  - **Reduce charge flow per avalanche to reduce afterpulsing**