QUANTUM TECHNOLOGIES

Dual Anode Single Photon Avalanche Diodes for High-Speed Applications

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FACULTÉ DES SCIENCES

Motivation

→ More compact and easier to use single photon detectors;

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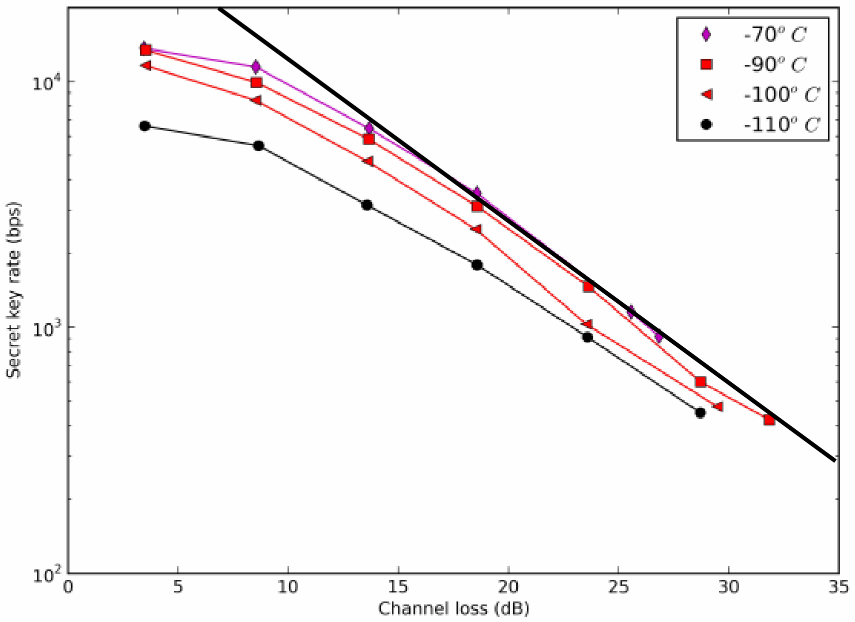
→ Improving Secret Key Rate (SKR) in Quantum Key Distribution (QKD) systems

SKR vs Channel Loss (distance) for COW Protcol



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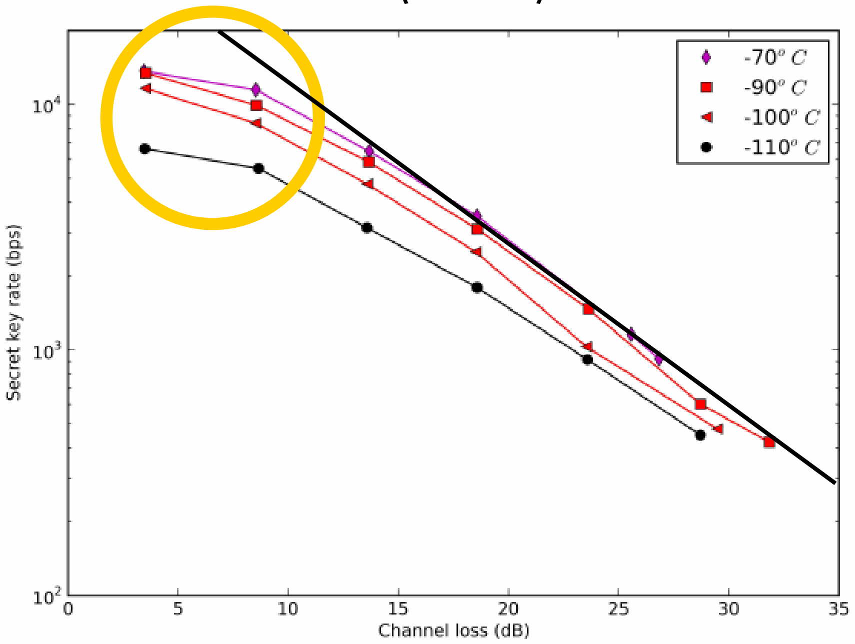

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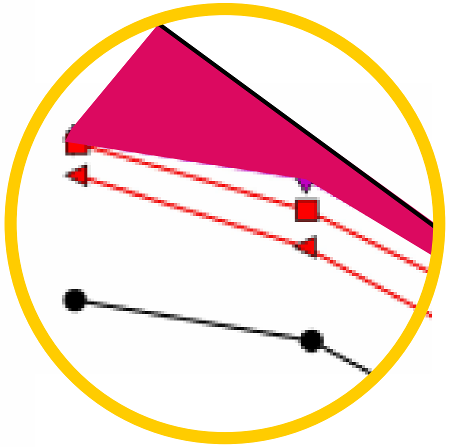

Afterpulsing effect is a cirtical problem in high speed low noise single photon avalanche diodes (SPADs)

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Limits performance of QKD protocols

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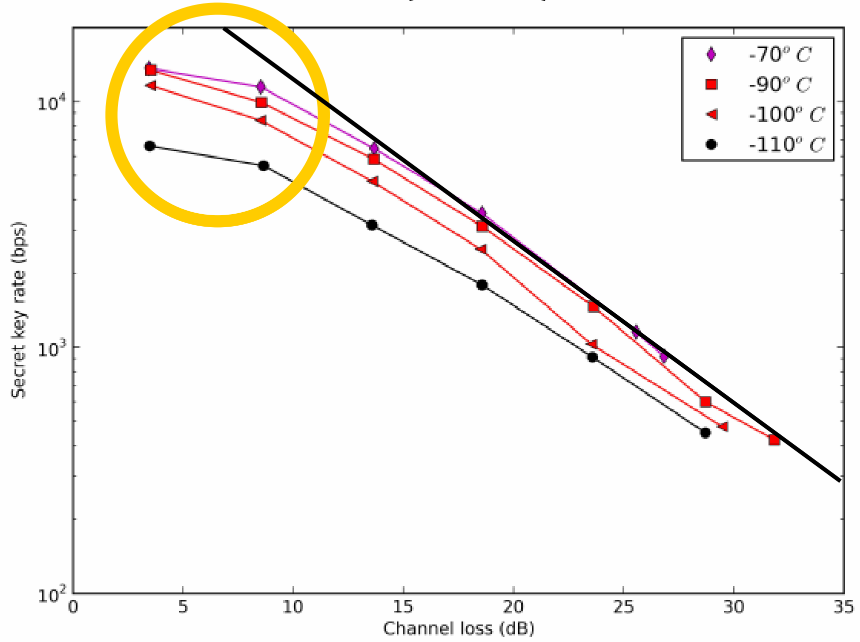

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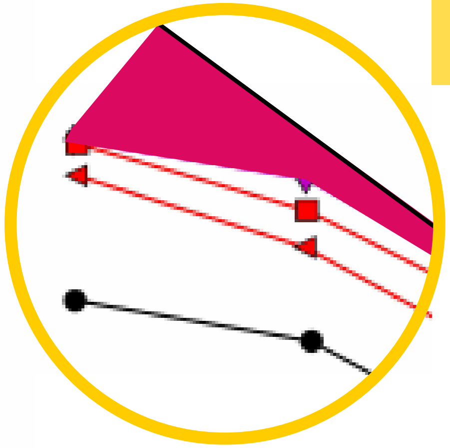


A detection is registered as a result of a previous detection, even if no ligth arrives.

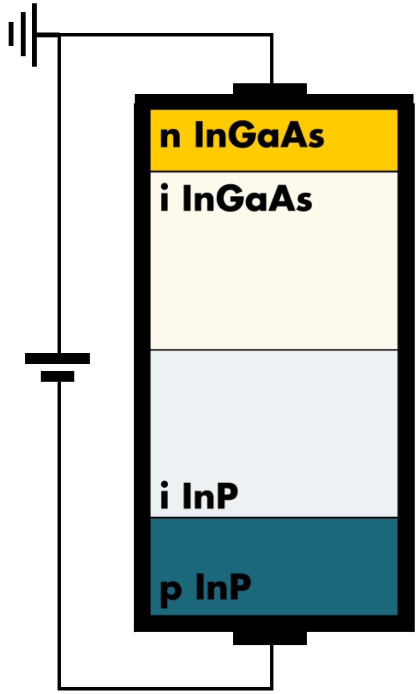
Afterpulsing effect is a cirtical problem in high speed low noise single photon avalanche diodes (SPADs)

↓

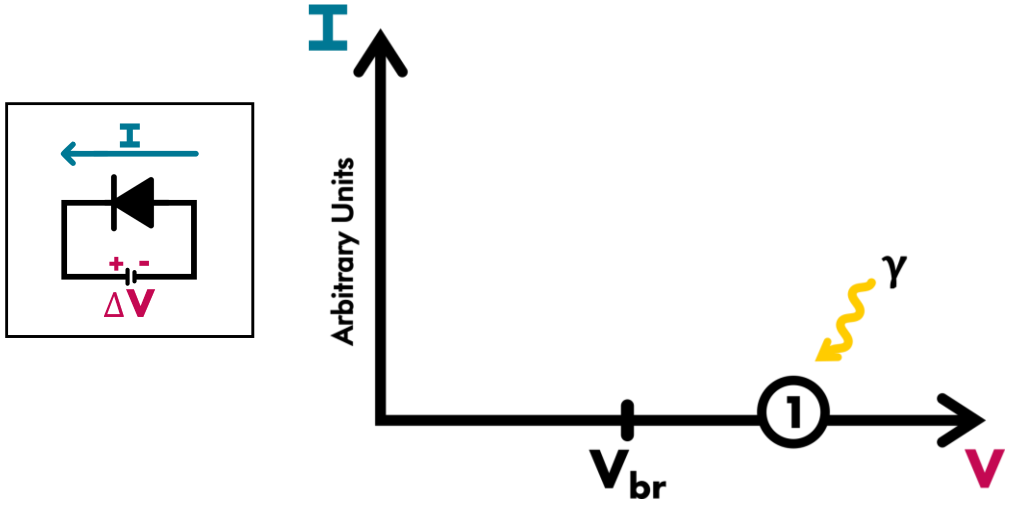
Limits performance of QKD protocols

What is a SPAD?

SPAD –**S**ingle **P**hoton **A**valanche **D**iode → p – n / p – i – n Junction



How does a SPAD work?



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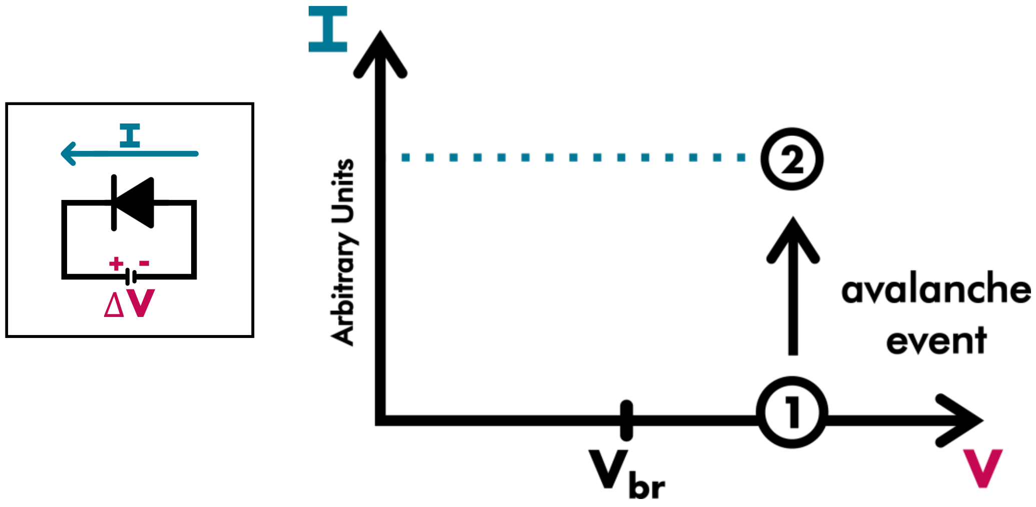

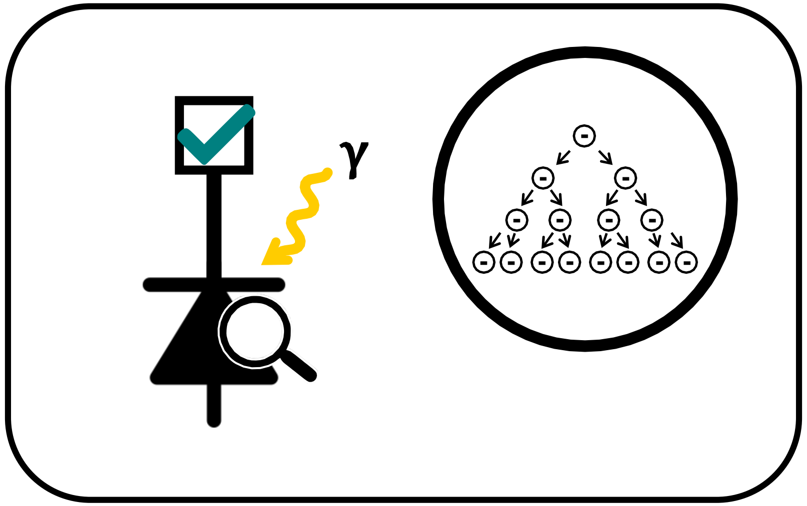

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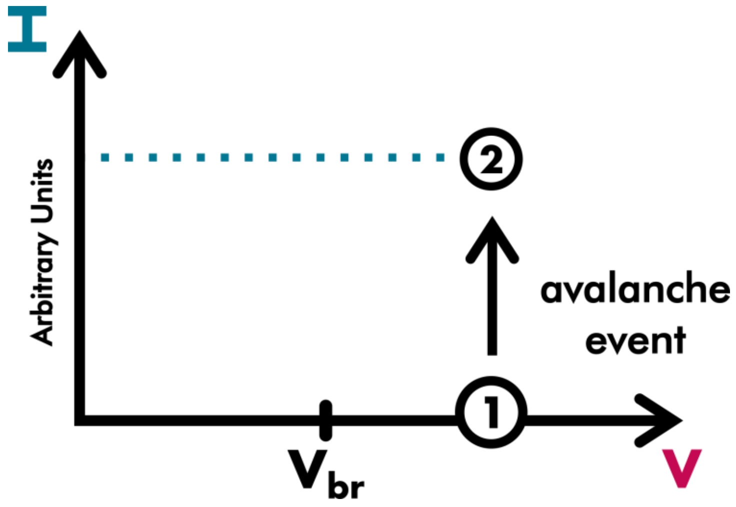

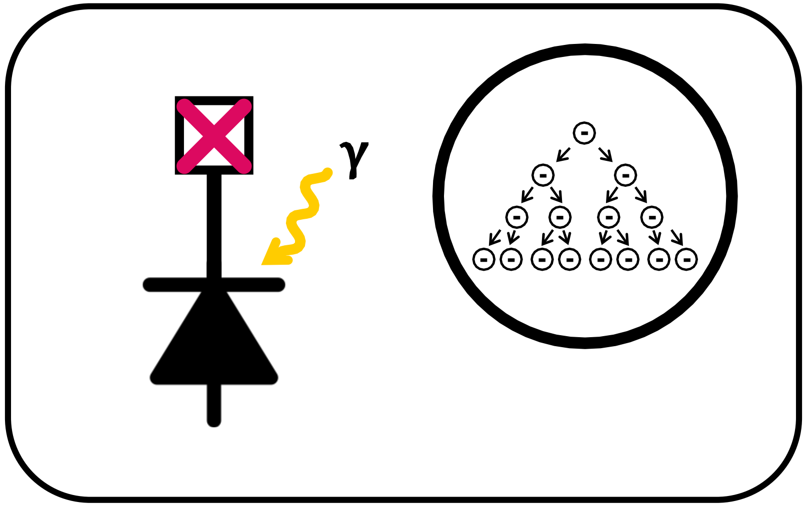

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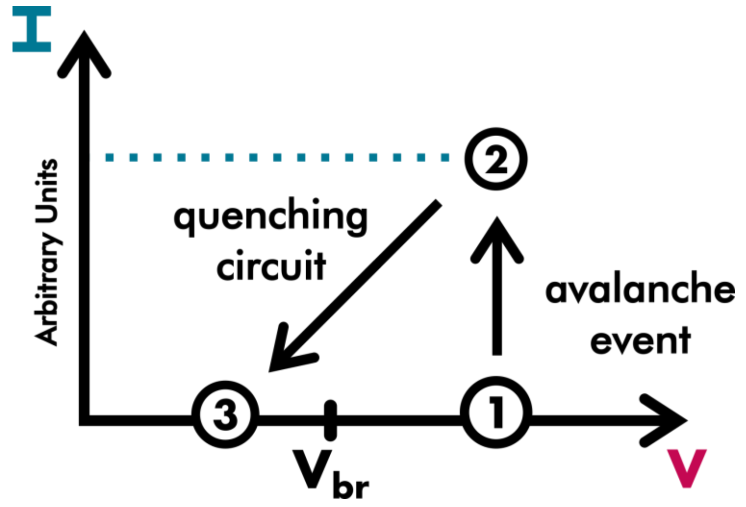

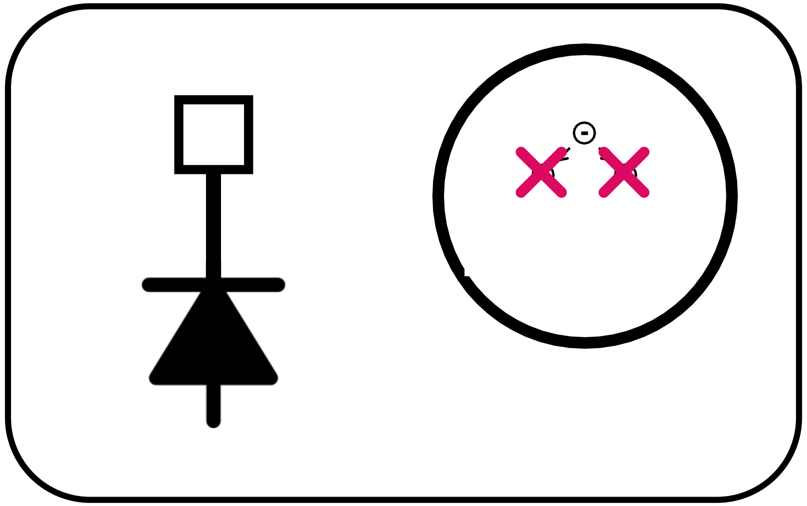

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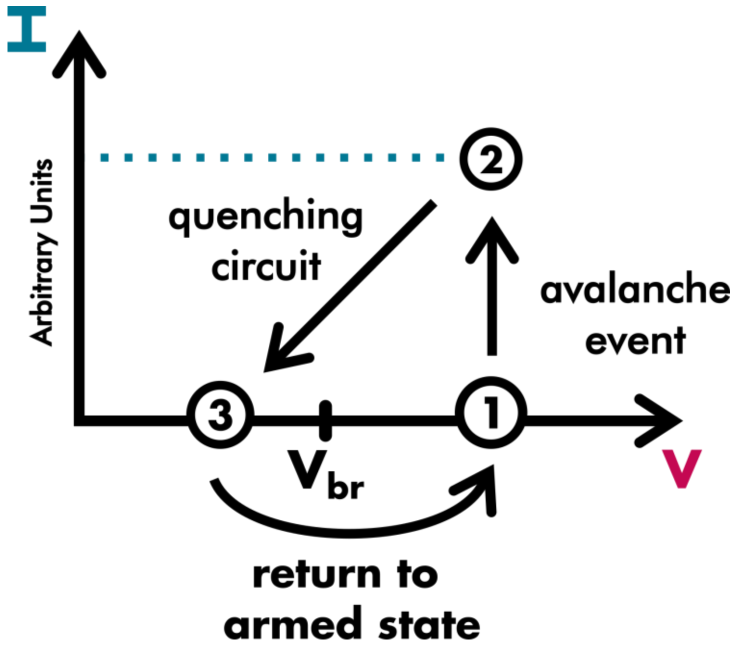

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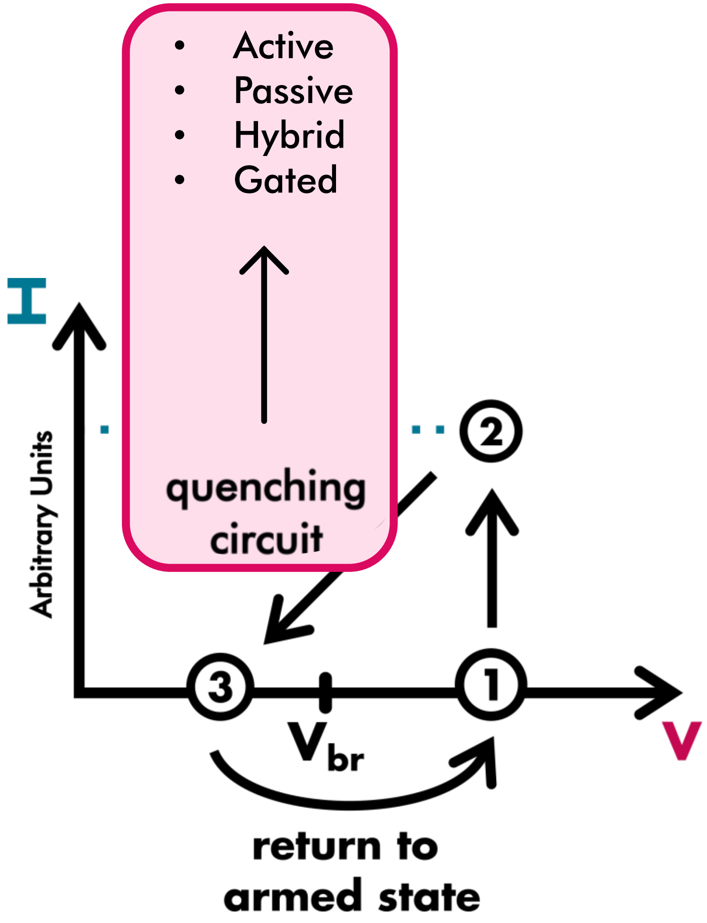

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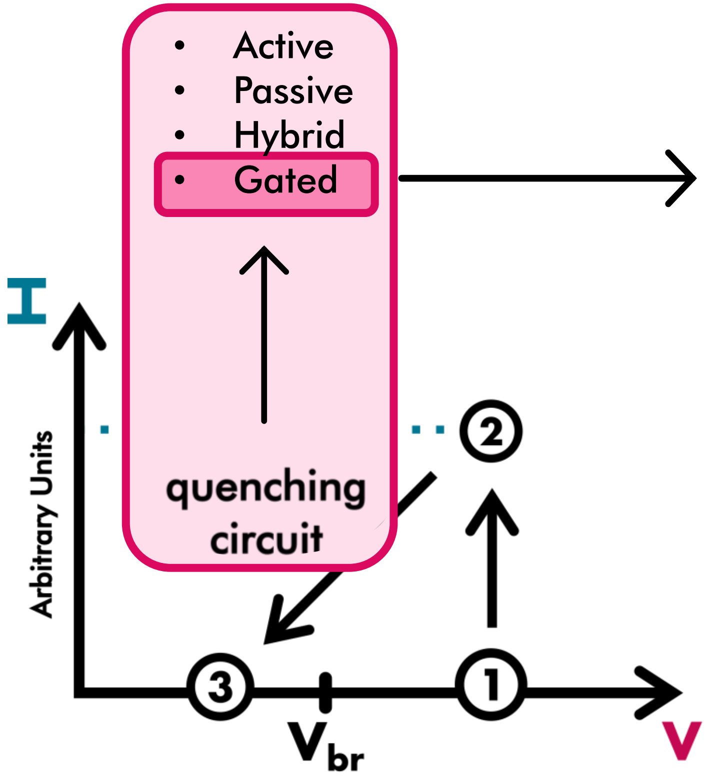

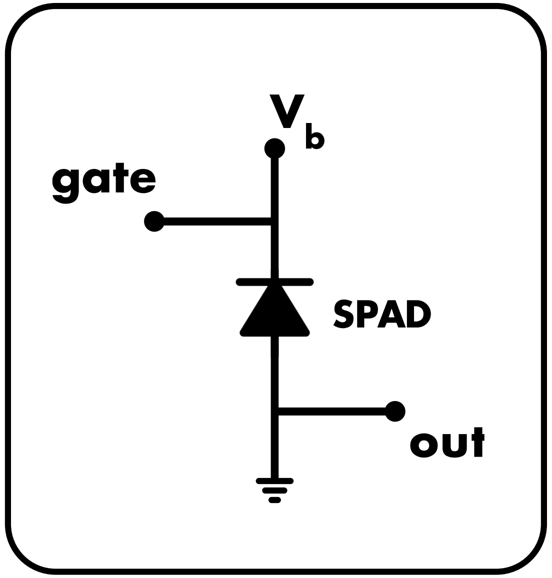

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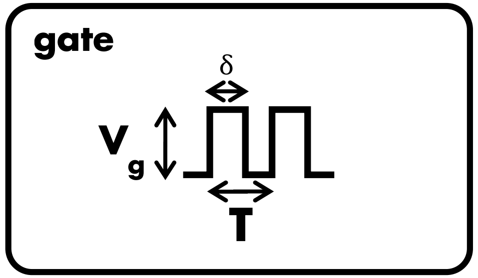

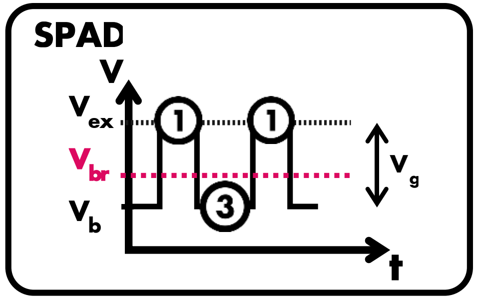

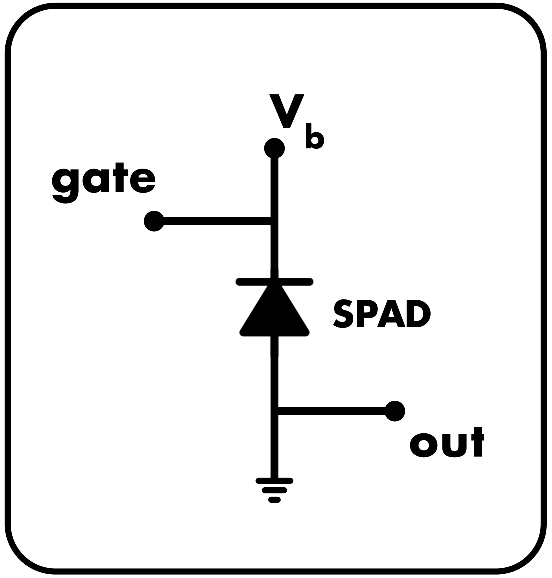

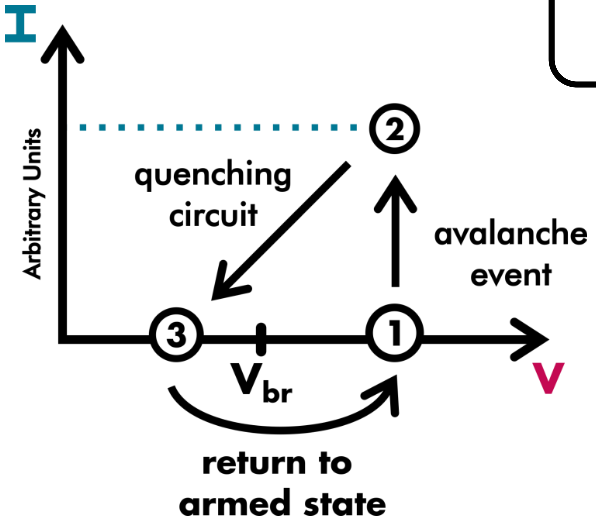

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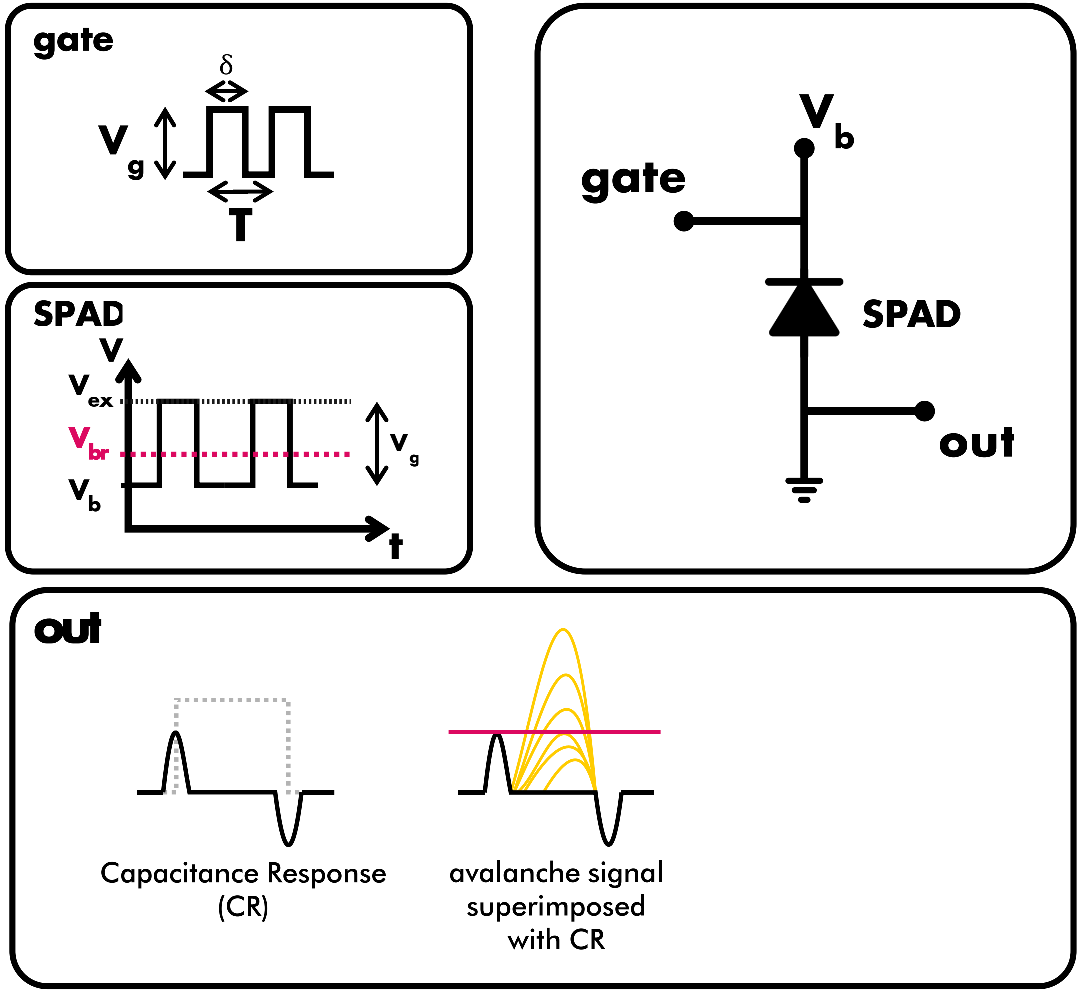
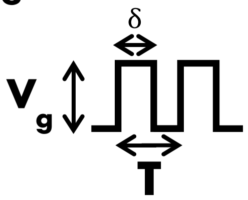
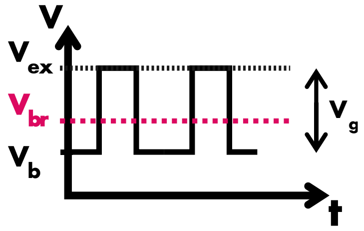


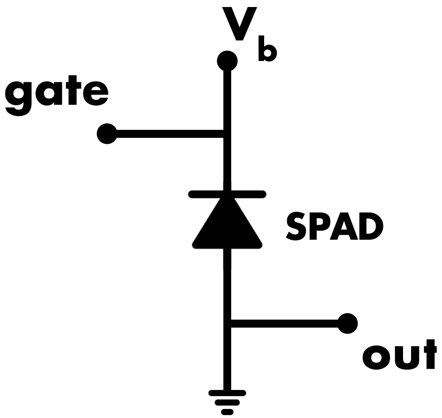
How does a SPAD work?

gate

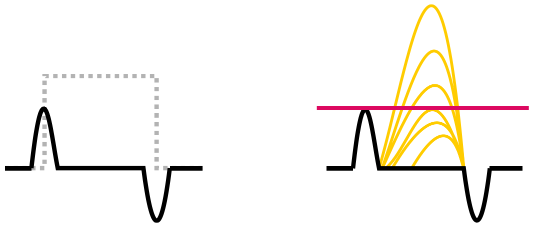


SPAD





out



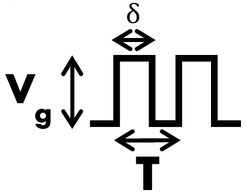
Capacitance Response (CR)

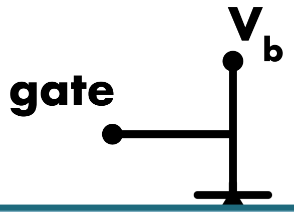
avalanche signal superimposed with CR

Afterpulsing effect is worse for bigger avalanches.

How does a SPAD work?

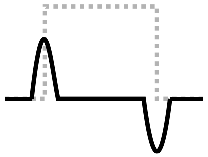
gate





Goal: minimize CR to allow the discrimination of the smallest possible avalanche events, **to improve count rate.**

out



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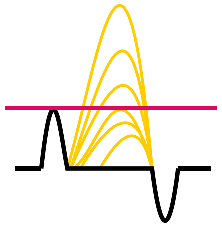

avalanche signal superimposed with CR

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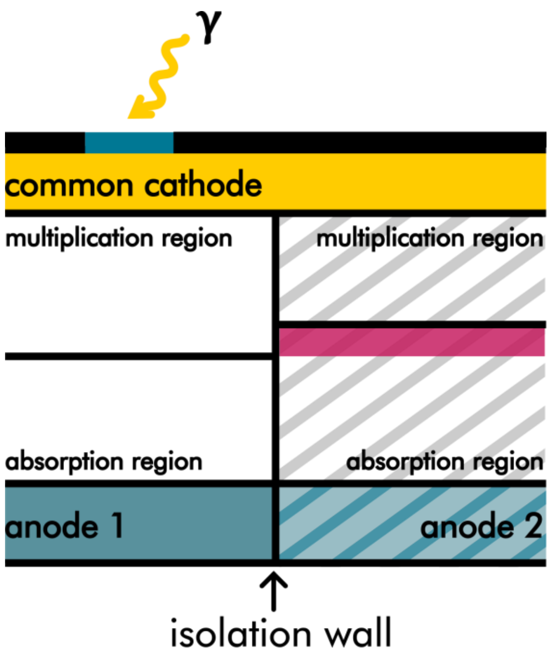
Dual-Anode SPAD (DA-SPAD)



} Difference in V_{br} ~4V

Chulwoo Park, Seok-Beom Cho, Chan-Yong Park, Soohyun Baek, and Sang-Kook Han, "Dual anode single-photon avalanche diode for high-speed and low-noise Geiger-mode operation," Opt. Express 27, 18201-18209 (2019)

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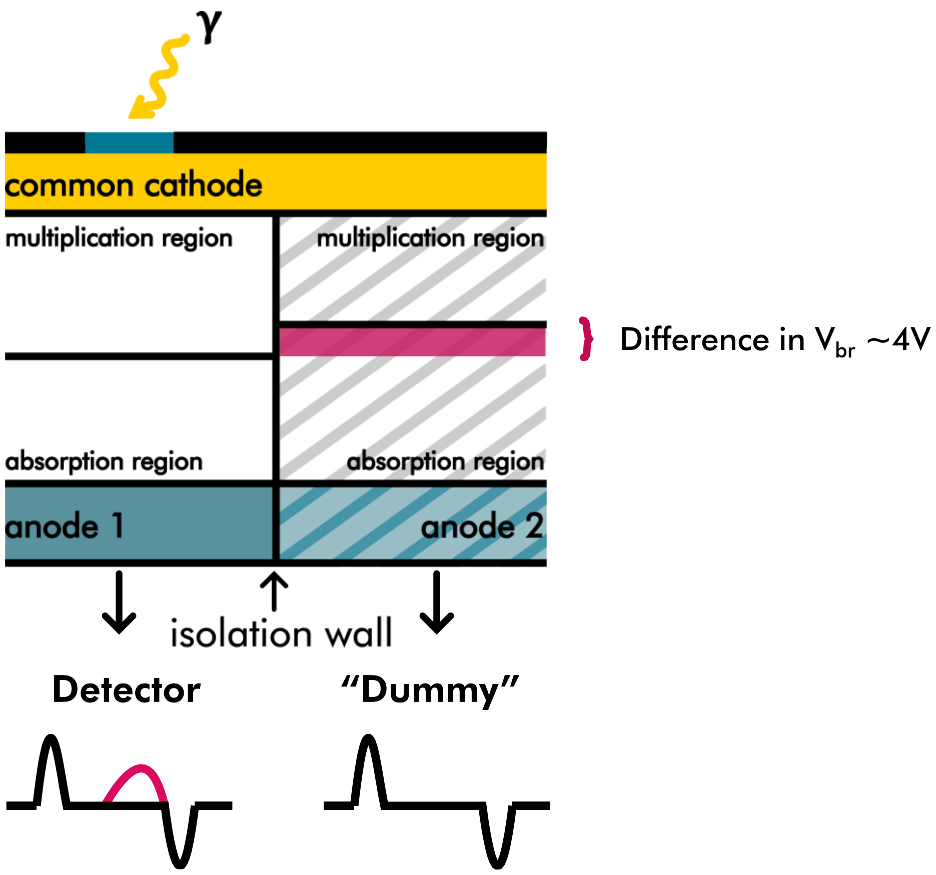

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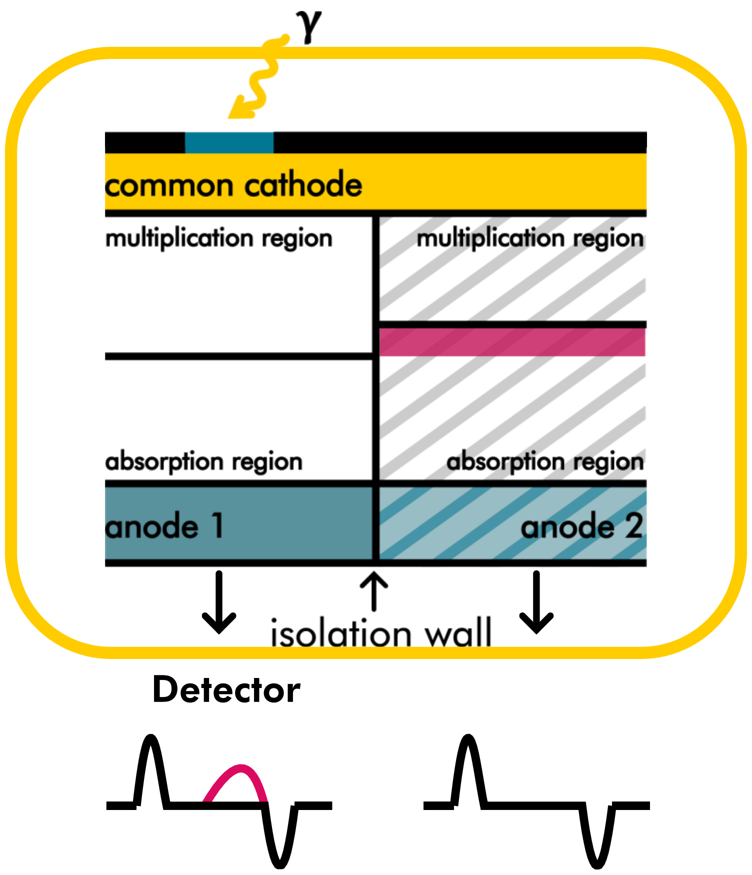

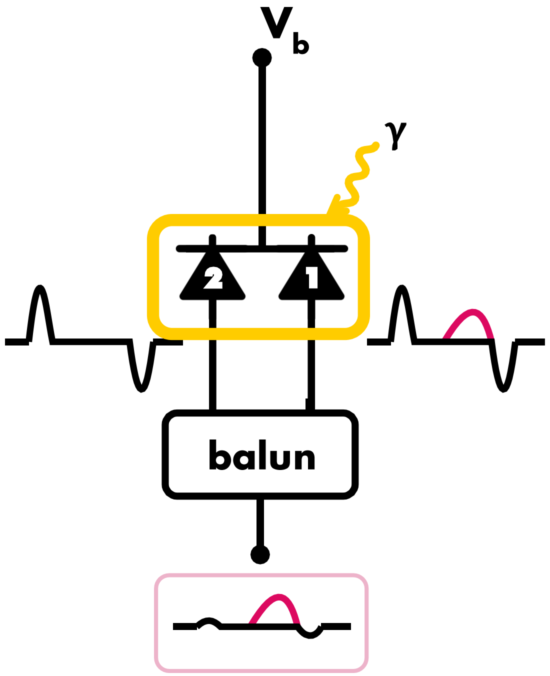

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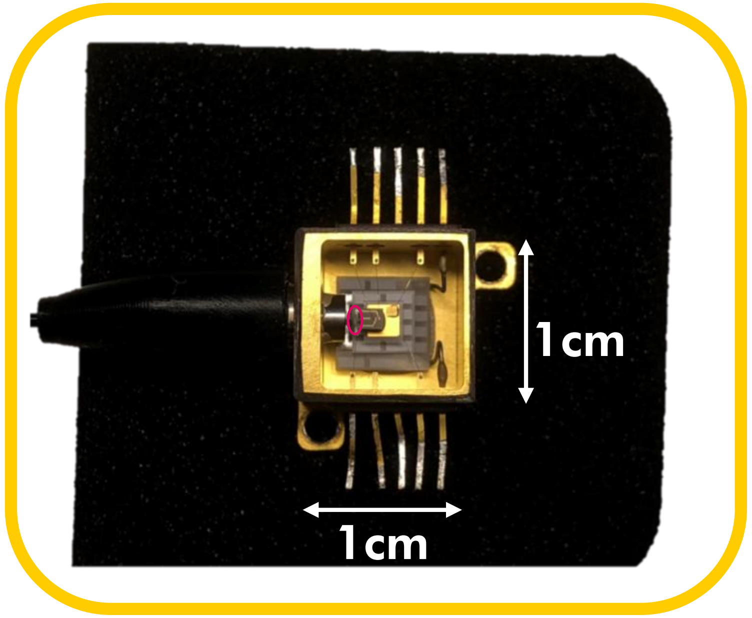
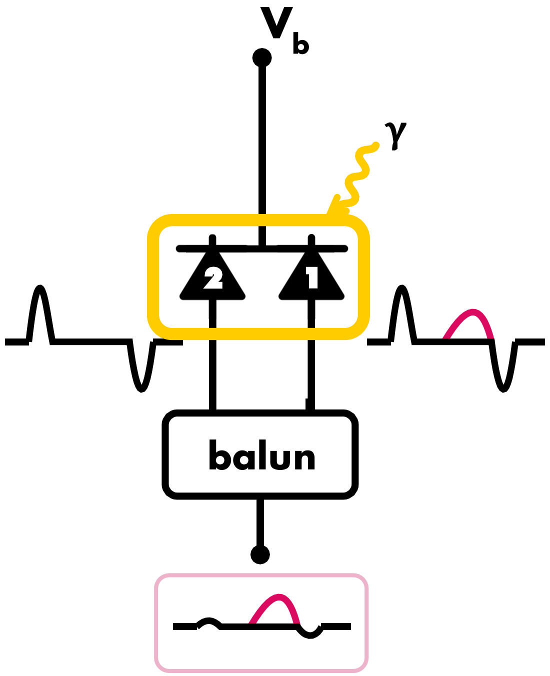
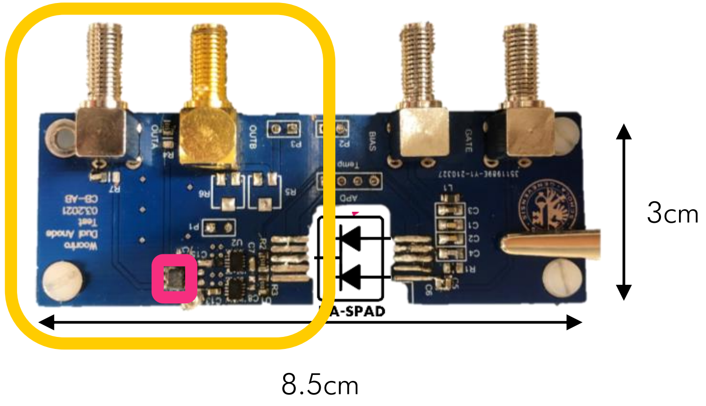
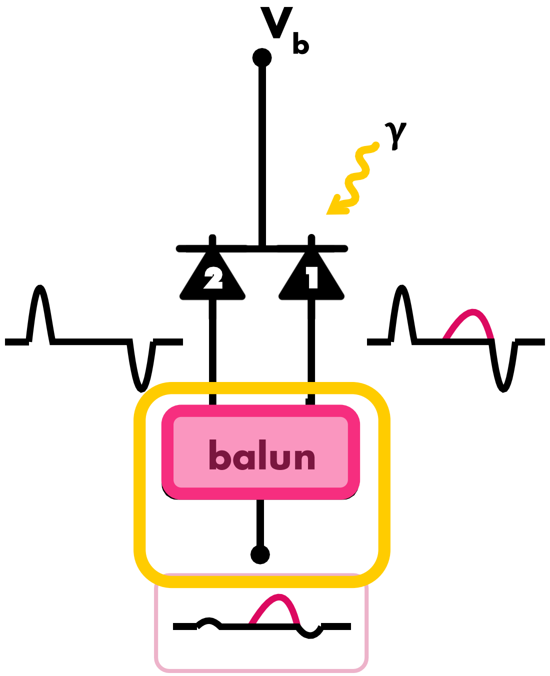




My Goal?





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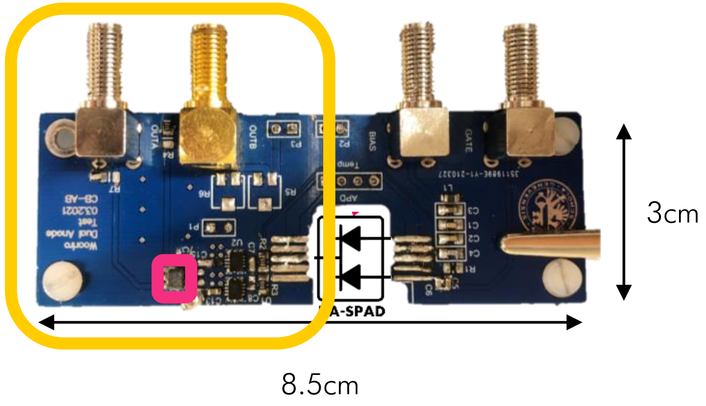

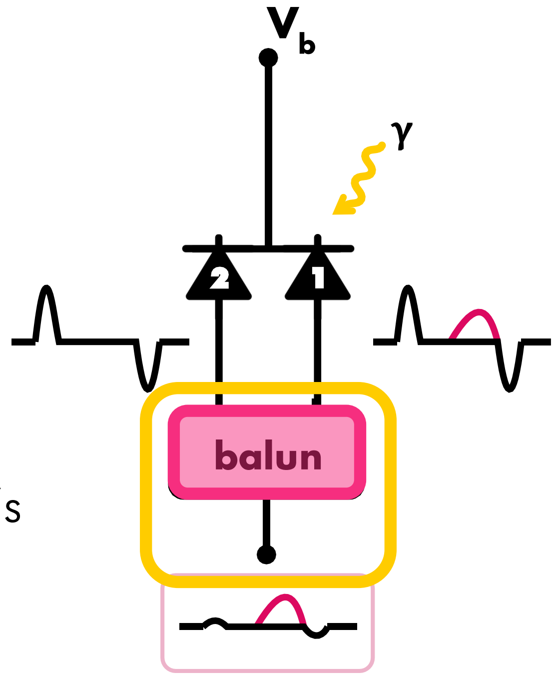

- **Reduce mismatch** between the "dummy"'s and detector's **CR** with appropriate **electronics**.
- **Optimize** set up to be used in **QKD scenario**.

Thank you!

----- QUESTION SLIDES -----

Photon Detection Efficiency

Probability that a photon impinging on the active area of the detector succeeds in triggering an avalanche current that can be detected by the electronics.

$$PDE = \int_0^{x_{end}} (1 - R)\, \eta_{abs}(x)\, P_{col}(x)\, P_{trig}(x)\, dx$$

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Reflection Coefficient   Collection Probability

$$PDE = \int_0^{x_{end}} \boxed{(1-R)}\,\boxed{\eta_{abs}(x)}\,\boxed{P_{col}(x)}\,\boxed{P_{trig}(x)}\,dx$$

Absorption Probability Density   Triggering Probability

Photon Detection Efficiency

$$PDE = \int_0^{x_{end}} (1-R)\,\eta_{abs}(x)\,P_{col}(x)\,P_{trig}(x)\,dx$$

Absorption Probability Density

$$\eta_{abs}(x) = \alpha e^{-\alpha x}$$

λ dependent

Photon Detection Efficiency

Collection Probability

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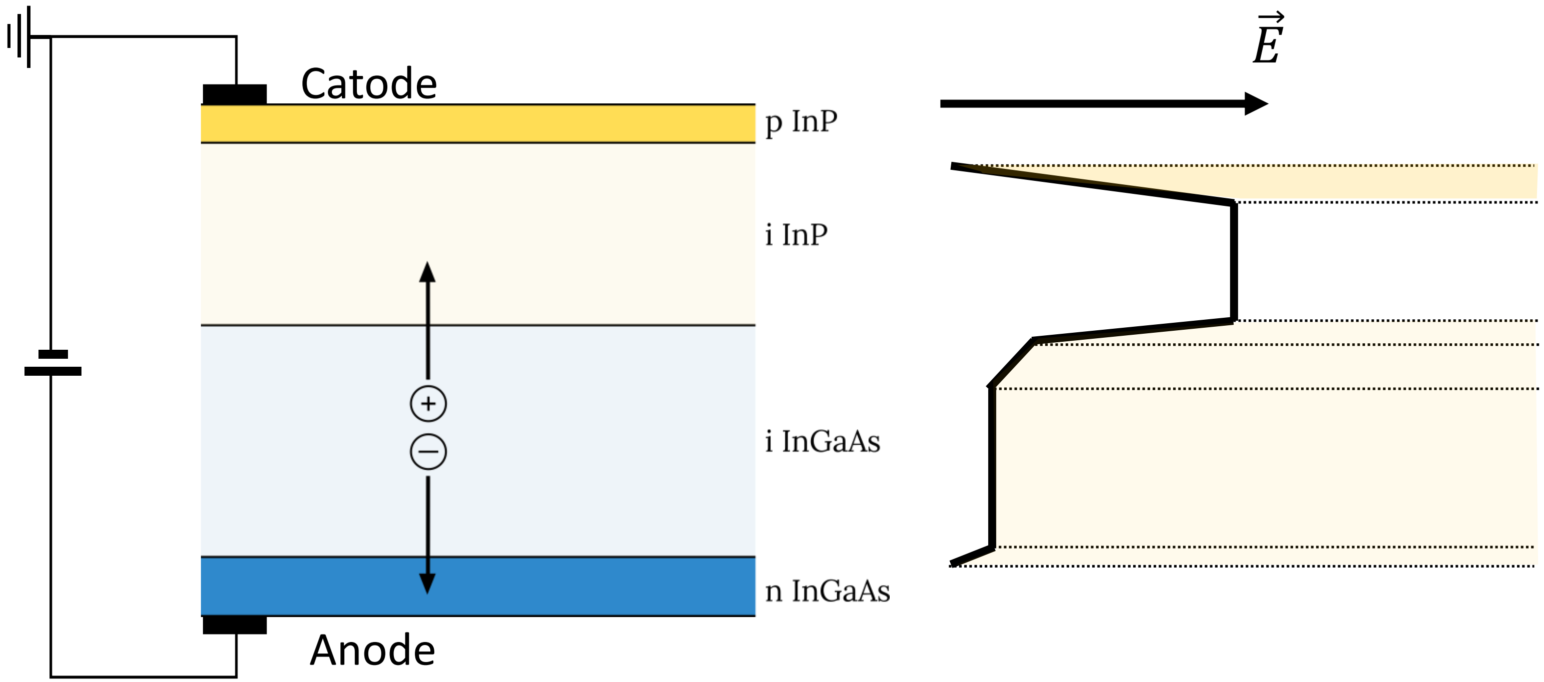

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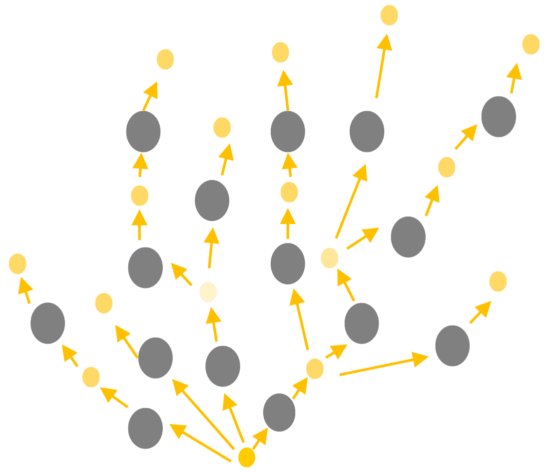

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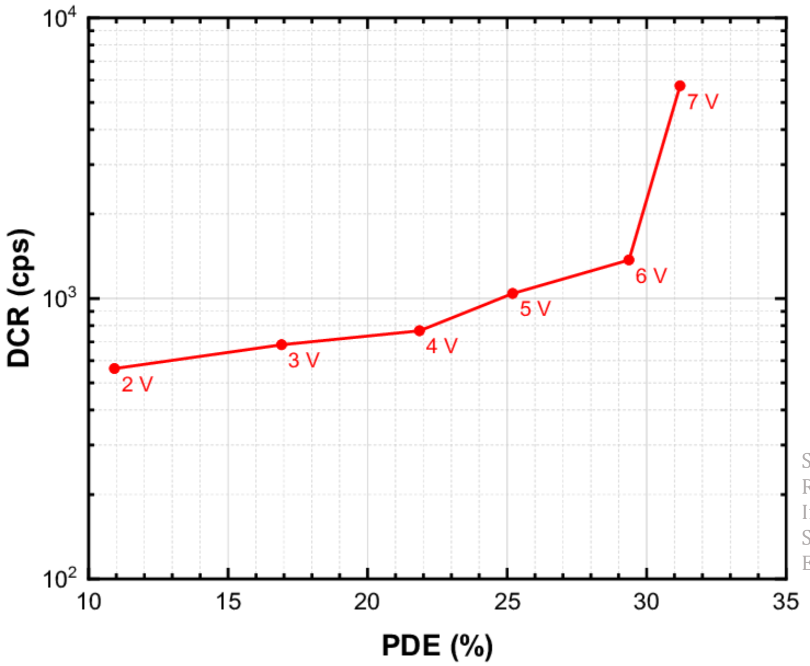


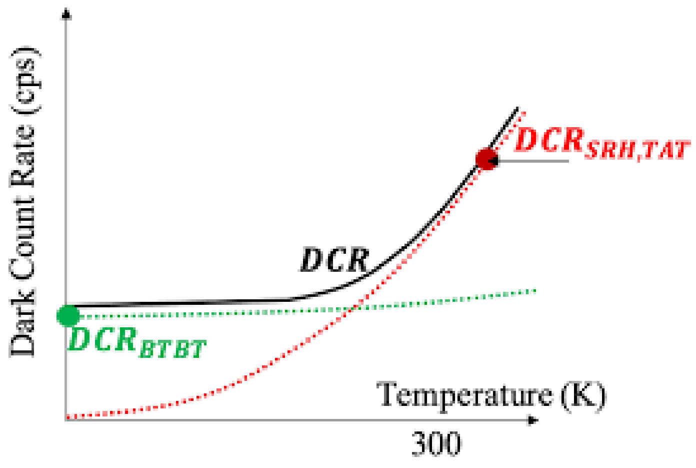
Signorelli, Fabio & Telesca, Fabio & Conca, Enrico & Frera, Adriano & Ruggeri, Alessandro & Giudice, Andrea & Tosi, Alberto. (2021). Low-Noise InGaAs/InP Single-Photon Avalanche Diodes for Fiber-Based and Free-Space Applications. IEEE Journal of Selected Topics in Quantum Electronics. PP. 1-1. 10.1109/JSTQE.2021.3104962.

Dark Count Rate

$$DCR = \frac{average\ number\ of\ dark\ pulses}{unit\ time}$$

<u>Shockley–Read–Hall (SRH) Mechanism</u>

<u>Band to Band Tunneling (BBT)</u>

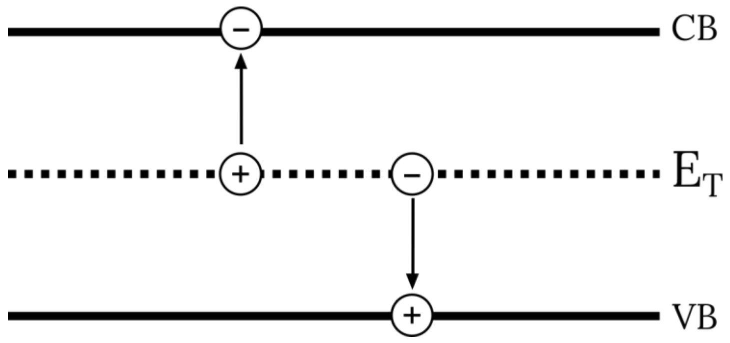


Panglosse, A., Martin-Gonthier, P., Marcelot, O., Virmontois, C., Saint-Pe, O. and Magnan, P., 2020. *IEEE Transactions on Circuits and Systems I: Regular Papers*, 67(5), pp.1507-1515.

Dark Count Rate

Shockley–Read–Hall (SRH) Mechanism

Dominant @ Room Temperature



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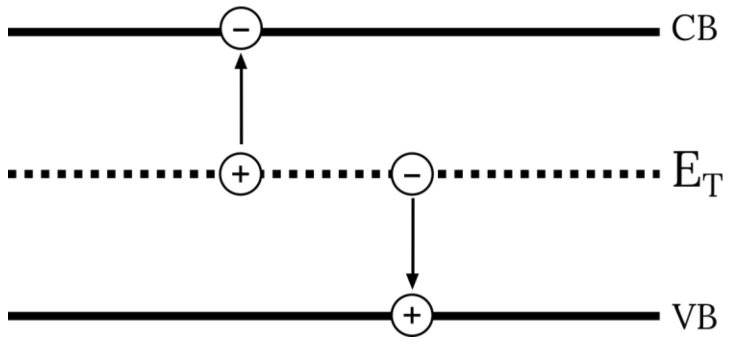


$\propto N_{trap}$

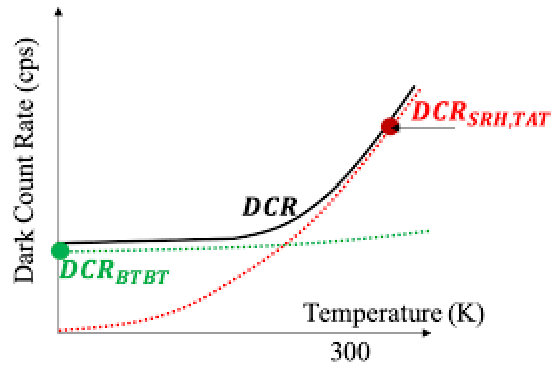
Volume Dependent

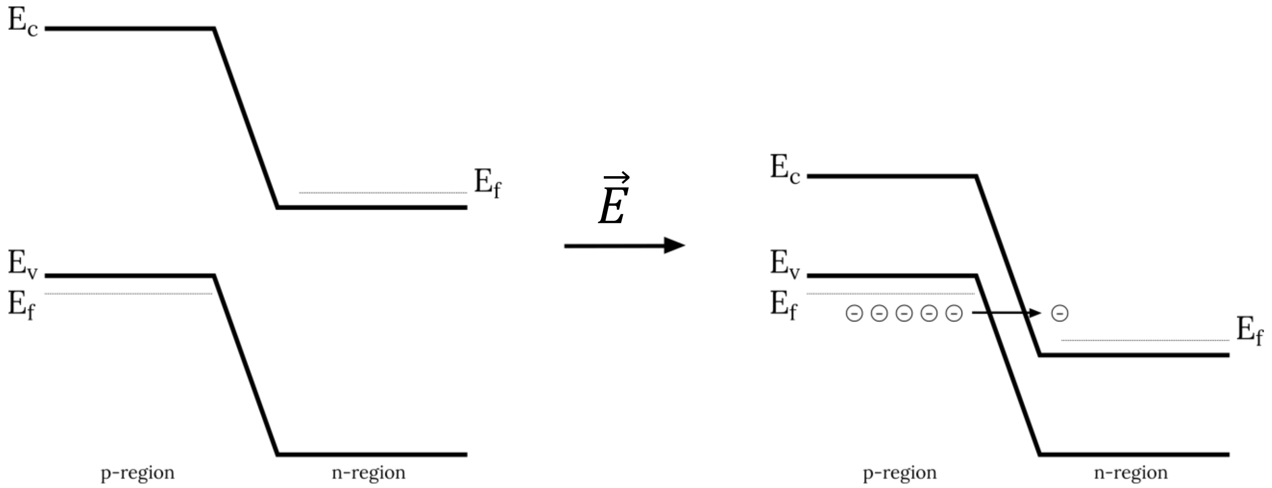
Affected by fabrication process & initial quality of the material

Dark Count Rate

Band to Band Tunneling (BBT)

Dominant @ Low Temperature





- Weak Dependence on T
- Strong Dependence on $\vec{E}$

Improved with proper design of detector

Dark Count Rate

Band to Band Tunneling (BBT)

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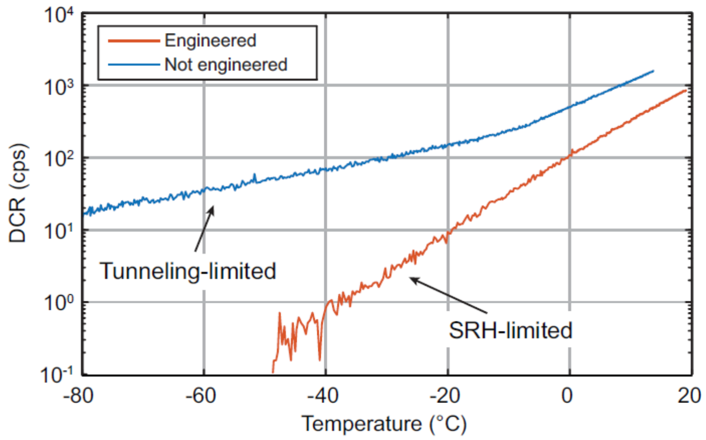

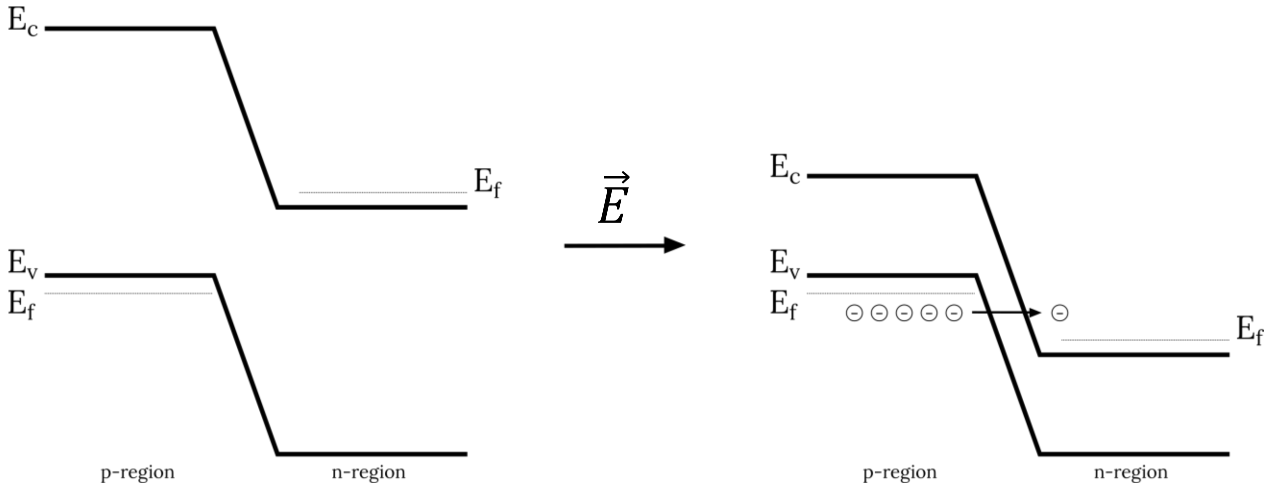

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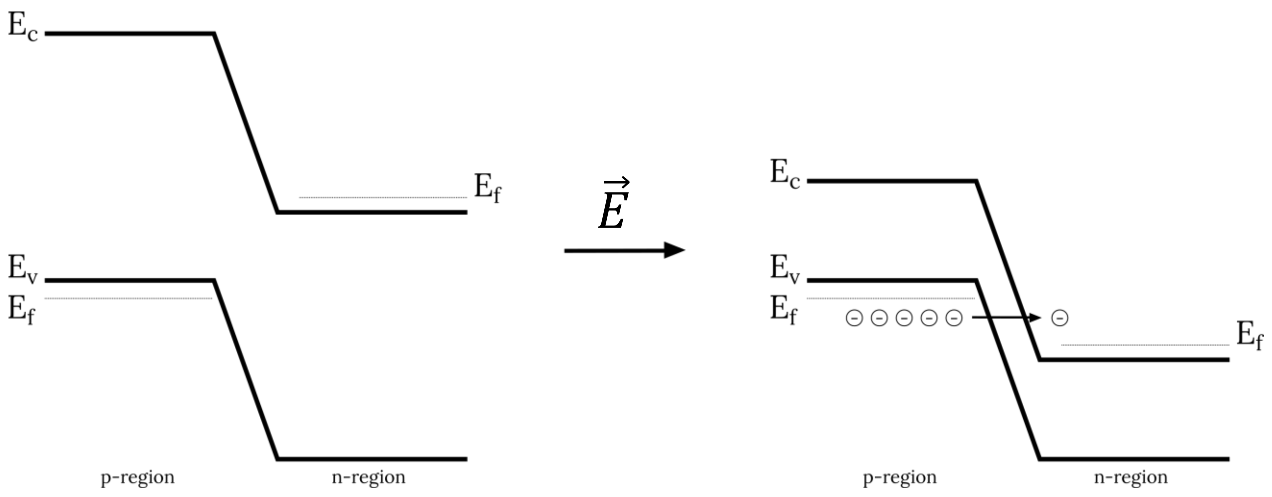
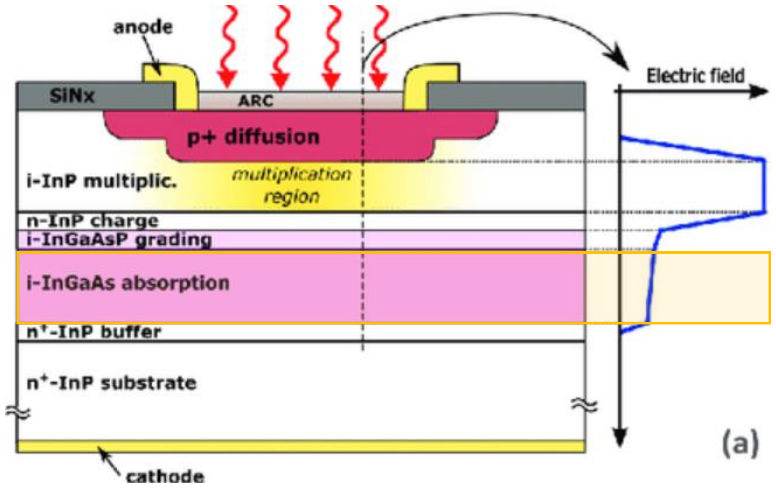




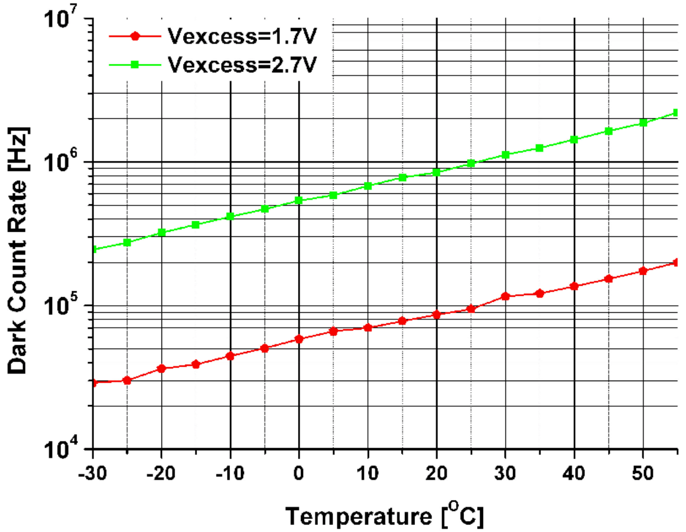
Separate Absorption, Charge, and Multiplication (SACM) structure

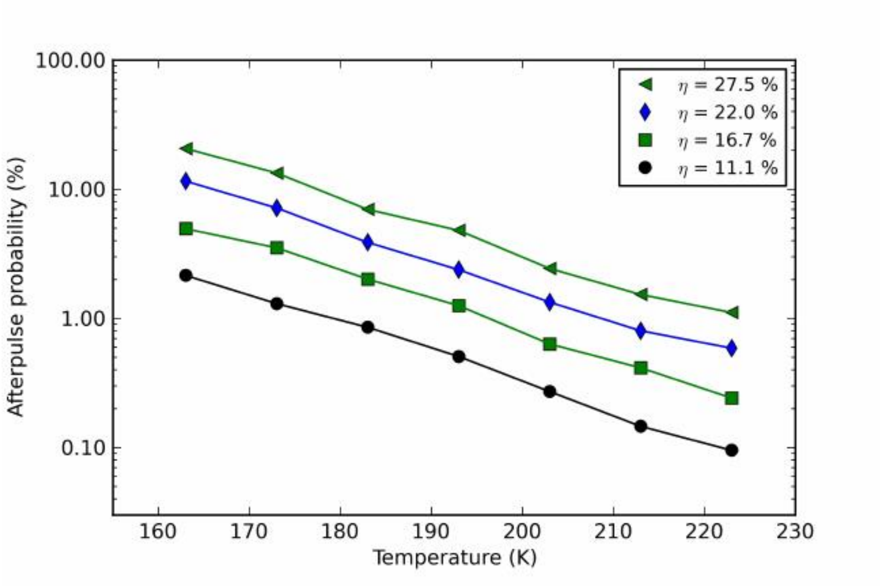
Acerbi, Fabio & Perenzoni, Matteo. (2018). High Sensitivity Photodetector for Photon-Counting Applications. 10.5772/intechopen.71940.

Reduce $\vec{E}$ on absorption layer to prevent BBT

- Weak Dependence on T
- Strong Dependence on $\vec{E}$

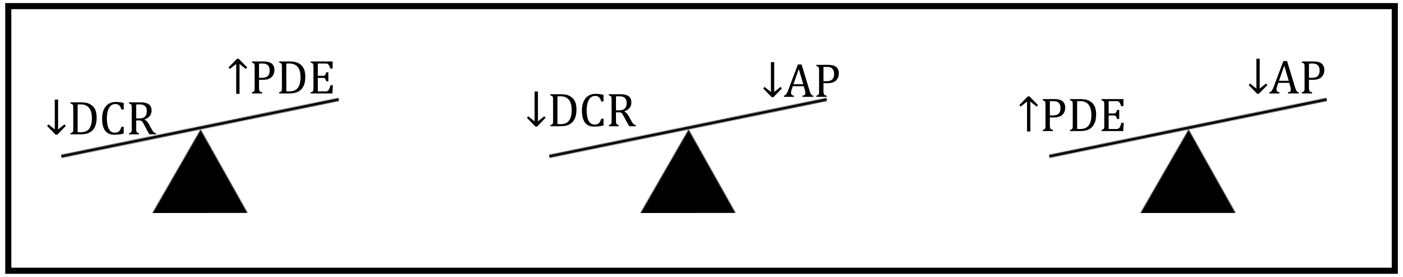
Improved with proper design of detector

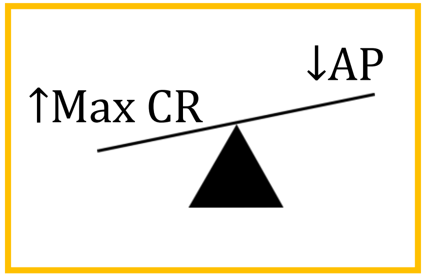




Niclass, Cristiano & Gersbach, Marek & Henderson, Robert & Grant, Lindsay & Charbon, E.. (2007). A 130-nm CMOS single-photon avalanche diode. Proceedings of SPIE - The International Society for Optical Engineering. 6766. 10.1117/12.728878.

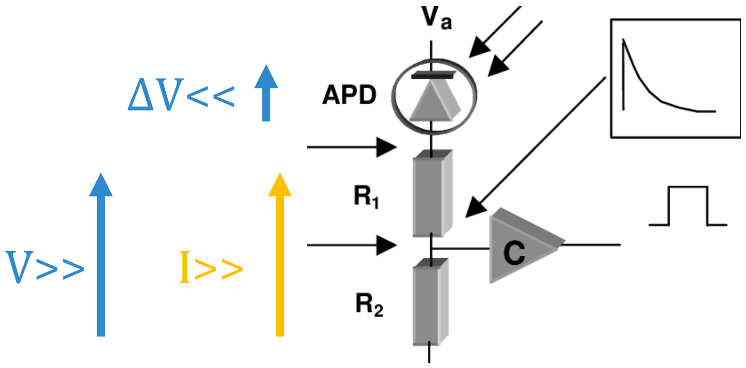
Korzh, Boris & Zbinden, Hugo. (2014). Low temperature performance of free-running InGaAs/InP single- photon negative feedback avalanche diodes. Proceedings of SPIE - The International Society for Optical Engineering. 9114. 10.1117/12.2050487.





Quenching Electronincs

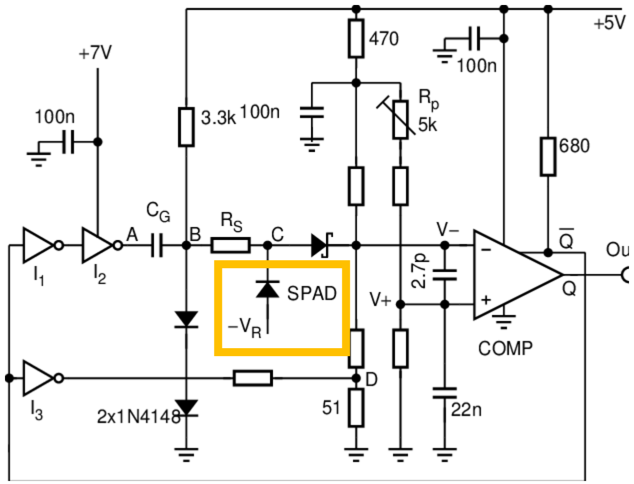
Passive Quenching Circuit.



Phelan, Don & Jackson, Carl & Redfern, R. & Morrison, Alan & Mathewson, Alan. (2002). Geiger mode avalanche photodiodes for microarray systems. Proc SPIE. 10.1117/12.472068.

Avalanche spontaneously quenched by high resistor

Active Quenching Circuit.



Stipčević, Mario. (2009). Active quenching circuit for single-photon detection with Geiger mode avalanche photodiodes. Applied optics. 48. 1705-14. 10.1364/AO.48.001705.

Fast disc. electronics detects avalanche → lowers V_b below V_{br} for a given "hold-off" time