Development of SPADs for NIR light detection

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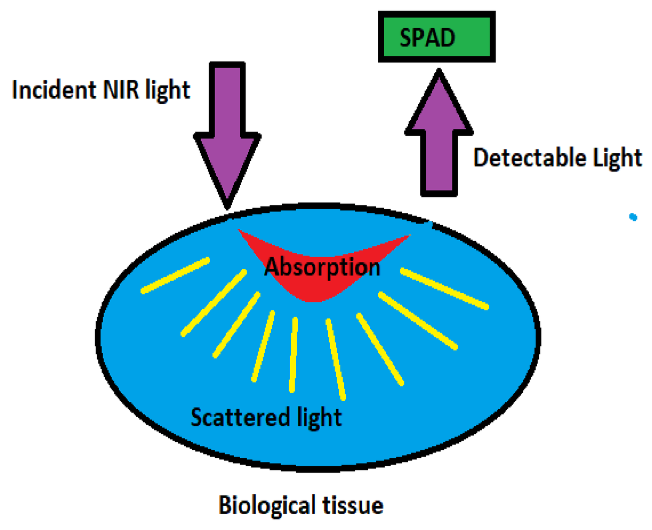
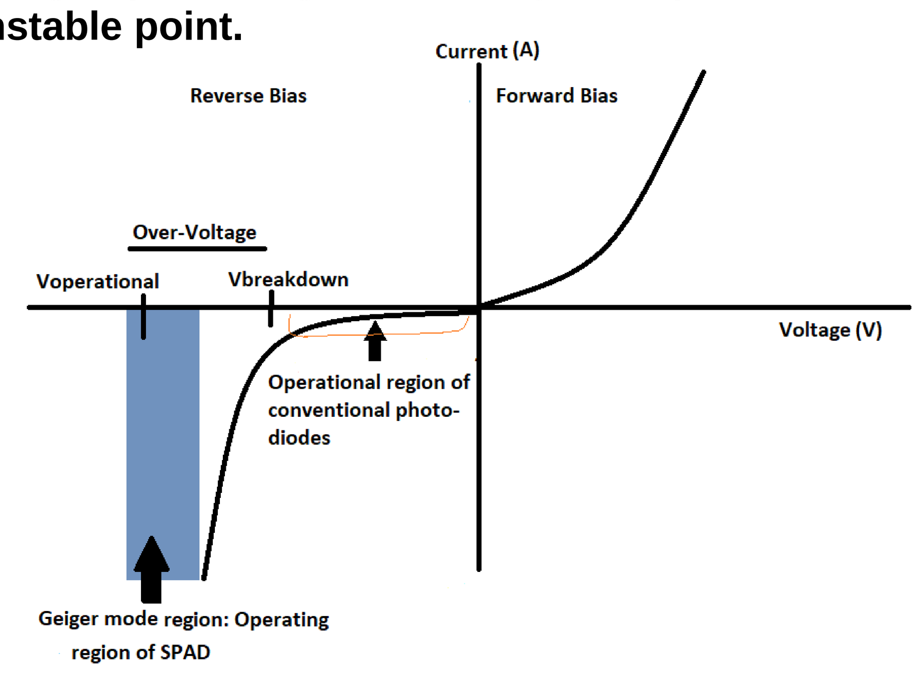
Abstract

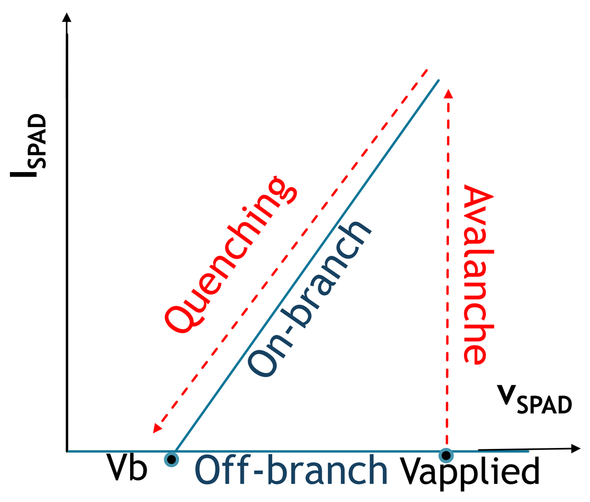
In this work, we target the development and characterisation of Single photon Avalanche Diodes (SPADs) with high Photon Detection Efficiency (PDE) in the Near-infrared (NIR) range, low Dark Count Rate (DCR) and fast timing. As a first stage, SPADs with multiplication layers buried at different depths have been designed at IFAE and produced in 150nm CMOS technology. CMOS has the advantage of being cost-effective for production of large matrices which allows to build very compact devices thanks to the capability of integrating the quenching mechanism and readout electronics on chip. In this study, we present results of the characterization of SPAD devices with an active area of 50×50 μm^2 operated with an external passive quenching circuit. We compared properties, such as DCR and PDE of the different SPAD designs and their dependence on temperature.

Motivation

- ✓ Near-infrared (NIR) light is used in non-invasive biomedical techniques to measure blood flow in deep tissues.
- ✓ Scattered photons from injected NIR laser in tissue are detected using Single Photon Avalanche Diodes (SPADs).
- ✓ From the SPAD signals, the local blood flow can be inferred.
- ✓ SPAD are Avalanche Photo-Diodes (APD) operated in Geiger mode to achieve single photon sensitivity.
- ✓ SPADs are operated above breakdown voltage to create a high electric field region.
- ✓ Using a quenching circuit, they can operate in an unstable point.

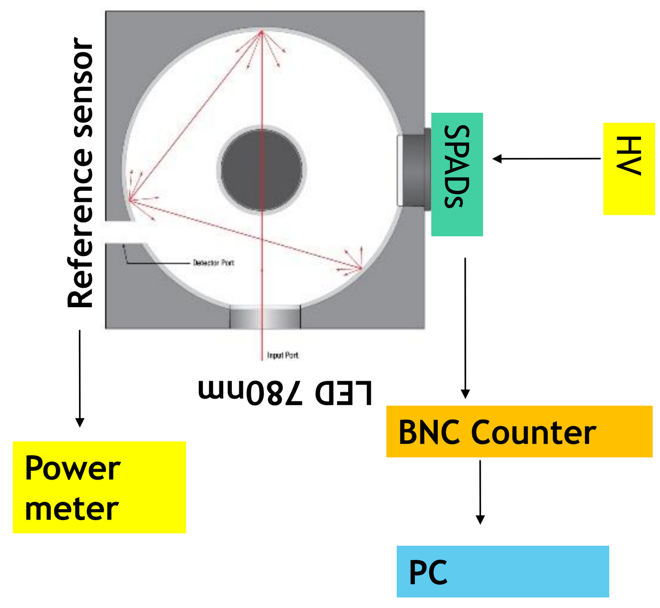






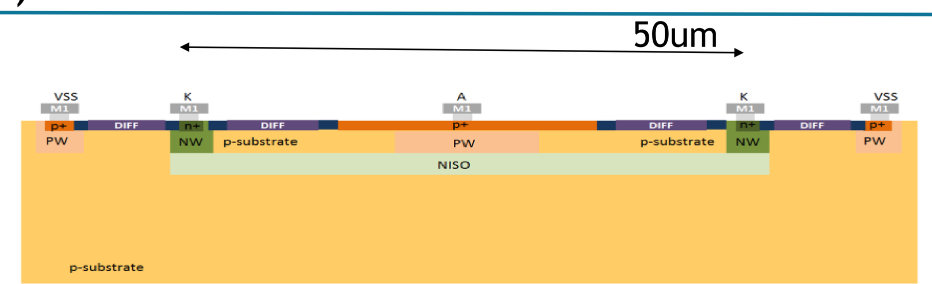
Experimental Setup

- ✓ SPAD biased up to Over-Voltage of 3 V with a quenching resistance of 200 kΩ.
- ✓ LED of 780 nm placed at input port of integrating sphere.
- ✓ Light is reflected and diffused uniformly inside the integrating sphere before reaching the SPADs.
- ✓ Reference sensor: Thor labs slim Si sensor (400 nm-1100 nm) with PM130-D power meter with ± 0.1 nW error.
- ✓ The whole setup is kept in dark inside a climate chamber at 15°C±0.1°C.
- ✓ A counter is used to count pulses crossing a threshold of about 95% of signal height.



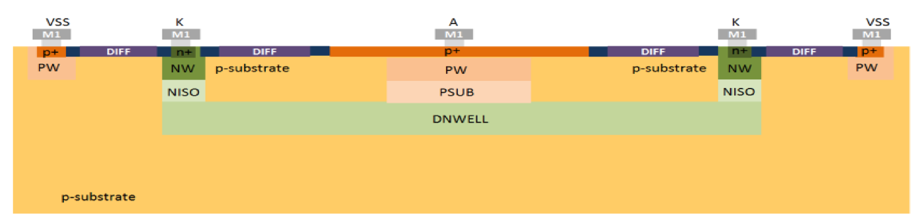
Prototype Design Specification

SPADs fabricated in LFoundary CMOS 150nm process on high resistivity substrates (~1.9kΩ-cm).



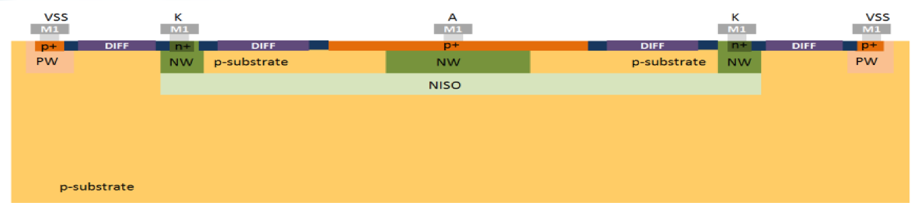
D3 specifications

- ✓ p+ electrode , PWELL layer
- ✓ N isolation layer.



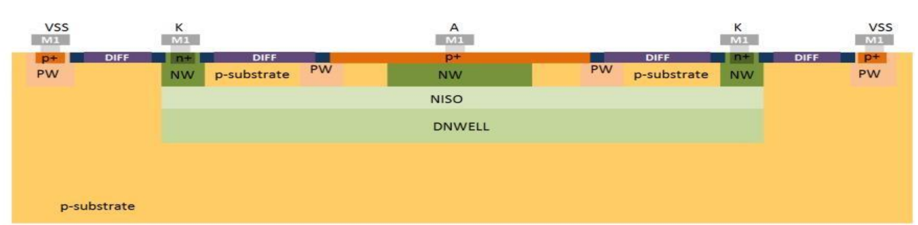
D5 specifications

- ✓ p+ electrode , PWELL layer
- ✓ DNWELL layer.



D7 specifications

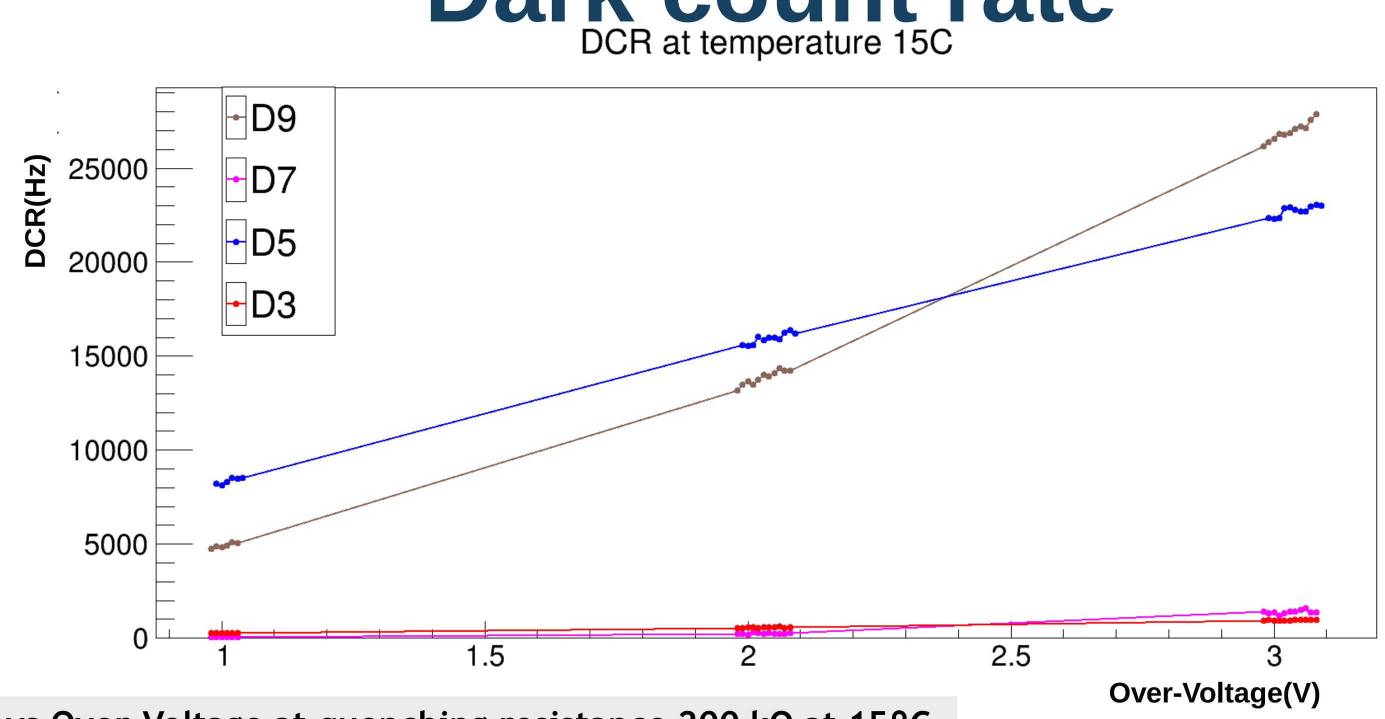
- ✓ p+ electrode , NWELL layer
- ✓ N isolation layer.



D9 specifications

- ✓ p+ electrode , NWELL layer
- ✓ N isolation layer + DNWELL

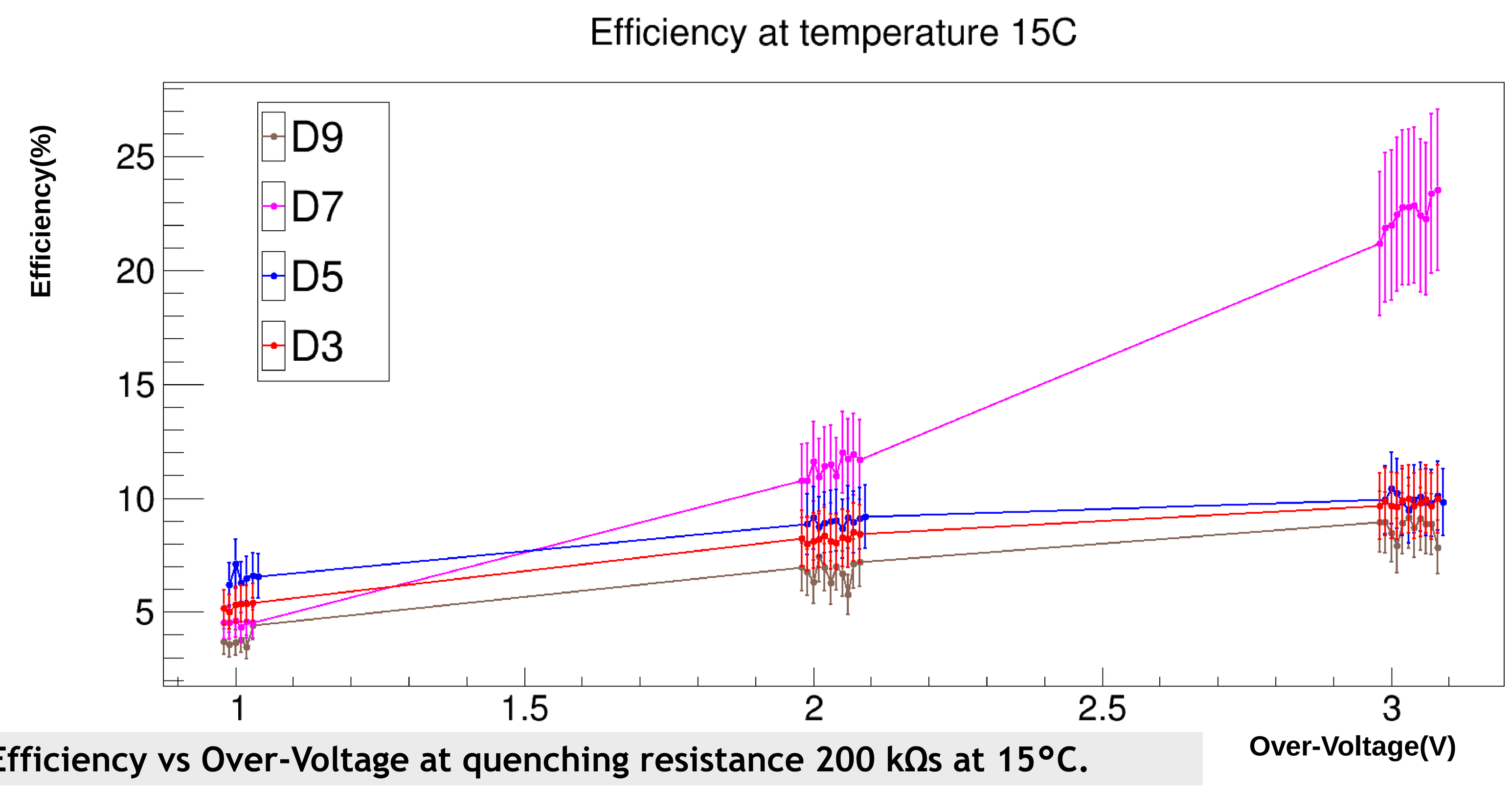
Dark count rate



DCR vs Over-Voltage at quenching resistance 200 kΩ at 15°C.

- ✓ Structures with DNWELL (D5 and D9) have a larger DCR, around 15 kHz at over-voltage 2 V and 20kHz at over-voltage 3 V.
- ✓ D3 and D7 have the lowest DCR (< 1 kHz) followed by D9 and D5.

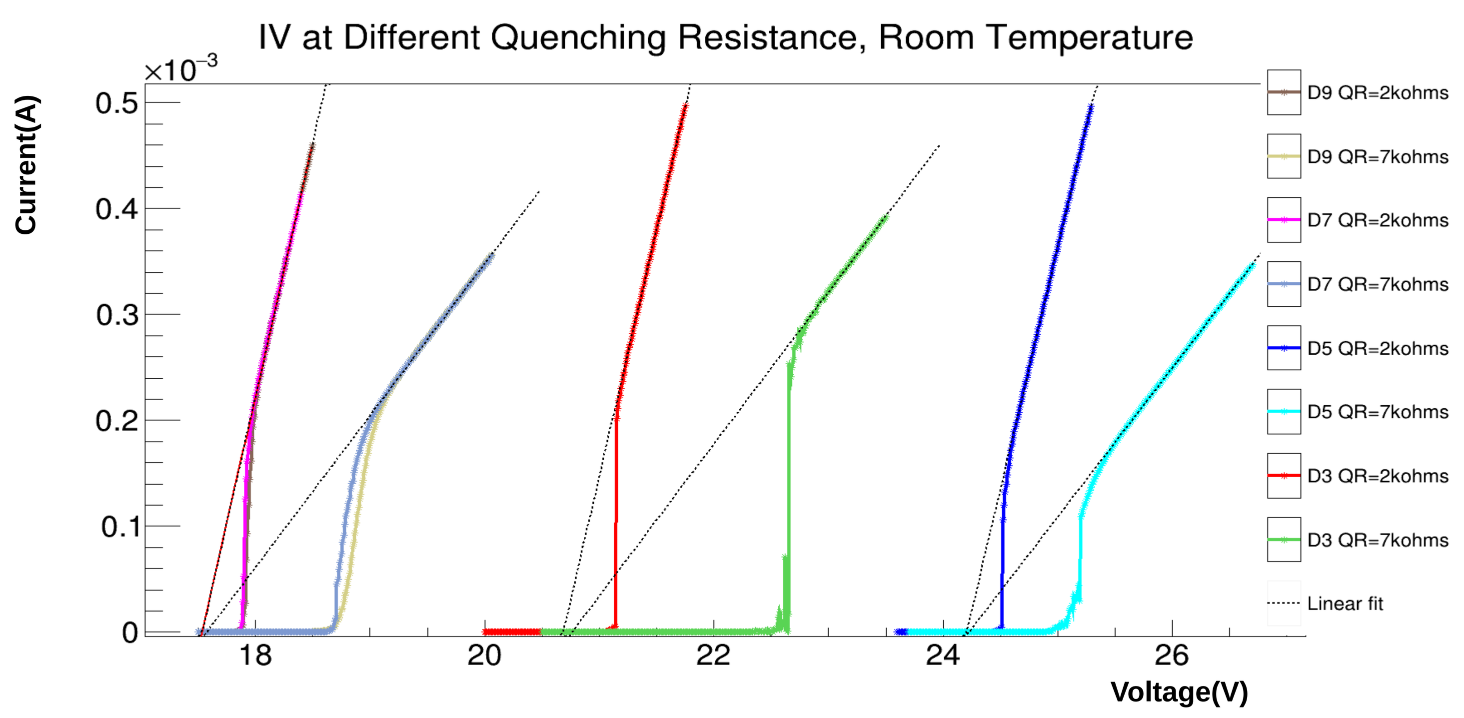
Photon Detection Efficiency



Efficiency vs Over-Voltage at quenching resistance 200 kΩs at 15°C.

- ✓ D7 design has the best efficiency at over-voltage 3 V, 20%±3% and 10%±1.5% at over-voltage 2 V.
- ✓ Structure with DNWELL (D5) has best efficiency at over-voltage 1 V, 7%±1% but has a lower efficiency (8%) than SPAD without DNWELL (D7) at over-voltage 2 V and 3 V.
- ✓ D9 and D3 have similar efficiencies (4%-5%) at over-voltage 1 V and up to 8% at over-voltage 3 V.

I-V and breakdown



- ✓ Second slope of I-V at different quenching resistances (QR) intersects at same point, defined as breakdown voltage.
- ✓ From -30°C to +30°C, breakdown voltage increases with temperature as 20mV/°C
- ✓ Breakdown voltage at 15°C for:

D9 and D7 = 17.39V
D5= 23.96V
D3= 20.48V

Conclusions

- ✓ The D7 SPAD design with the NW layer below the p+ implant and without DNWELL performs best both in terms of DCR (<1 kHz) and PDE (20%±3%) at over-voltage 3 V.
- ✓ Following the results of these first prototypes, a new generation of CMOS SPADs including arrays and devices with the quenching mechanism on-chip to improve compactness is being produced and will be studied at IFAE.

References:

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