# Low noise InGaAs/InP SPAD for fiber-based quantum applications


Fabio Signorelli
*Dipartimento di Elettronica, Informazione e Bioingegneria (DEIB)*
*Politecnico di Milano*
Milano, Italy
fabio.signorelli@polimi.it

Fabio Telesca
*Dipartimento di Elettronica, Informazione e Bioingegneria (DEIB)*
*Politecnico di Milano*
Milano, Italy
fabio.telesca@polimi.it

Adriano Della Frera
*Micro Photon Devices Srl*
Bolzano, Italy
adriano.dellafrera@micro-photon-devices.com

Alessandro Ruggeri
*Micro Photon Devices Srl*
Bolzano, Italy
alessandro.ruggeri@micro-photon-devices.com

Andrea Giudice
*Micro Photon Devices Srl*
Bolzano, Italy
andrea.giudice@micro-photon-devices.com

Alberto Tosi
*Dipartimento di Elettronica, Informazione e Bioingegneria (DEIB)*
*Politecnico di Milano*
Milano, Italy
alberto.tosi@polimi.it



***Abstract*— We present an InGaAs/InP single-photon avalanche diode (SPAD) with 10 µm-diameter active area, designed for fiber-based quantum applications. Improved design and fabrication lead to low dark count rate (1000 cps at 225 K), 25% photon detection efficiency and 100 ps (FWHM) timing jitter.**



***Keywords*— *Single-photon avalanche diode, SPAD, InGaAs/InP, quantum communications, QKD, photon-counting.***


## I. Introduction

Near-infrared (NIR) single-photon detection is receiving more and more interest, especially for quantum communication applications, such as quantum key distribution (QKD) [1] and quantum optics experiments, including quantum computers [2]. Among the available single-photon detectors, InGaAs/InP single-photon avalanche diodes (SPADs) are often the first practical choice, thanks to the typical advantages of solid-state detectors (such as high reliability, ease of use, compactness, and low cost, together with good overall performance). However, performance of InGaAs/InP SPADs need to be improved, by lowering their noise and increasing their detection efficiency, for competing with superconducting detectors.

Here we present a new InGaAs/InP SPAD with an active area diameter of 10 µm, designed for being pigtailed with single-mode fiber (SMF28) with high coupling efficiency via a single-lens focusing system. At 225 K, a typical operating temperature achievable with a triple-stage thermo-electric cooler mounted inside a TO-8 package, our InGaAs/InP SPAD shows a low dark count rate (DCR) and good photon detection efficiency (PDE).

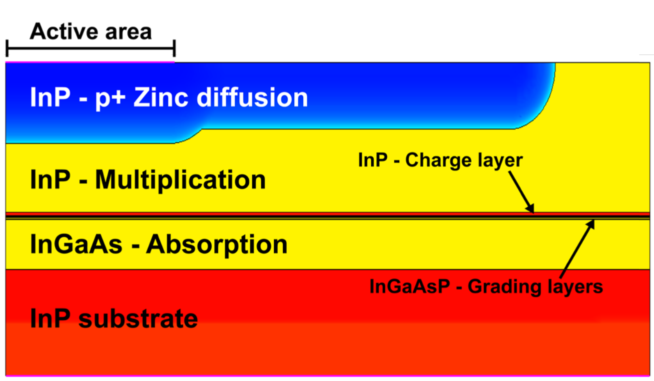


Fig. 1. Structure of our front-illuminated InGaAs/InP SPAD (just half of the cross-section is here reported). The main regions of the SPAD are labeled in the figure. Blue represents the p-doped Zinc diffusion, red is used for n-doped InP regions, while yellow indicates non-intentionally doped layers.

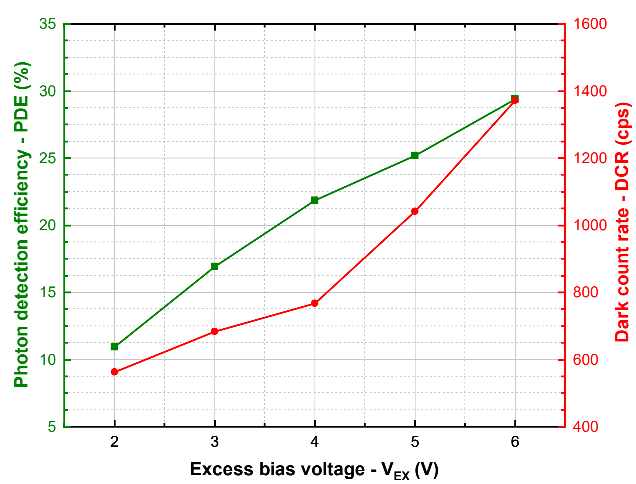


Fig. 2. Photon detection efficiency (PDE) at 1550 nm and dark count rate (DCR) as a function of excess bias voltage ($V_{EX}$). The detector is biased with $V_{EX}$ = 5 V, 100 ns ON-time and 10 kHz repetition rate. Temperature is 225 K.

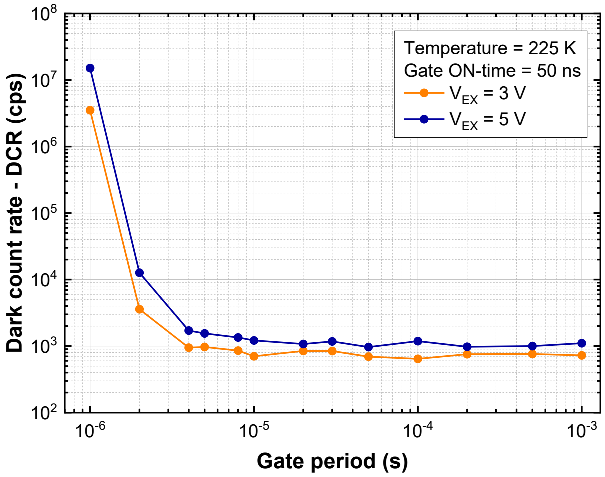


Fig. 3. DCR as a funcion of the gate period. The smaller the period, the smaller the OFF-time, so afterpulsing becomes more and more dominant over primary DCR. Temperature is 225 K, while ON-time is set to 50 ns.

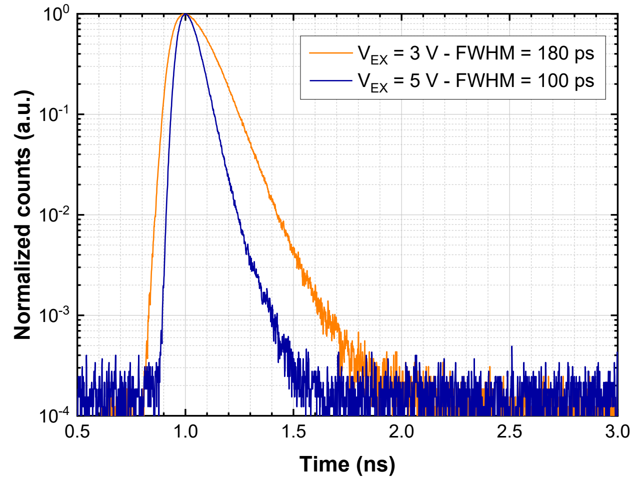


Fig. 4. Temporal response measured with a standard TCSPC setup. The response is very clean and FWHM is 180 ps and 100 ps at 3 V and 5 V excess bias voltage, respectively.

## II. Device Structure

Starting from the promising detectors reported in [3], our main goal was to design a new SPAD with reduced dark count rate, without impairing PDE and timing response. To this aim, aided by TCAD simulations and custom models, we optimized the internal structure design (see Fig. 1) by modifying the Zinc diffusion shape and position, and by tuning the charge layer dose. We obtained a lower electric field, with respect to previous-generation devices, both in the multiplication and in the absorption regions [4]. This, together with improved Zn diffusion conditions, resulted in lower DCR at typical operating temperatures. Finally, we increased the number of quaternary grading layers from 3 to 5, which helped reducing the charge persistence effect [5].

## III. Experimental Results

We characterized our InGaAs/InP SPAD in gated mode with a passive quenching circuit and a gate ON-time of tens of nanoseconds. When OFF, the SPAD is kept 0.5 V below its breakdown voltage, while an excess bias voltage $V_{EX}$ of few volts above breakdown is applied during the ON-time. Fig. 2 shows the dark count rate at different excess bias voltages. The detector is operated with 100 ns ON-time and 10 kHz repetition rate, which is low enough to rule out any afterpulsing contribution. DCR is quite low, being below 1000 cps with $V_{EX} < 5$ V, and it is still below 1.5 kcps with $V_{EX} = 6$ V. Concerning afterpulsing, Fig. 3 shows the dark count rate as a function of the square wave period, with a fixed gate ON-time of 50 ns. DCR starts to increase when the gate period (which is almost equal to the OFF time after each avalanche) is set to few microseconds. This is a first simple measurement of the contribution of afterpulsing, which can be effectively reduced by swiftly quenching the avalanche with dedicated front-end circuits. We measured the photon detection efficiency at 225 K by focusing a 1550 nm continuous wave LASER on the SPAD active area, with a spot size of 6 µm, which is comparable to that of the fiber pigtailing mounting system. As shown in Fig. 2, PDE is 25% at $V_{EX} = 5$ V and reaches almost 30% at $V_{EX} = 6$ V, while it is still above 10% at $V_{EX} = 2$ V, where DCR is below 600 cps. We also measured that PDE at 1310 nm and 1064 nm is 31% and 33%, respectively, at $V_{EX} = 5$ V. In Fig. 4, we reported the instrument response function of our device, measured with a 1550 nm pulsed LASER (20 ps FWHM) focused within a 6 µm spot inside the active area. The measured response is very clean, with FWHM of 180 ps and 100 ps at 3 V and 5 V excess bias, respectively.

## IV. Conclusions

We designed and characterized a new InGaAs/InP SPAD for optical fiber-based quantum applications. Thanks to the small size, the optimized Zinc diffusion conditions, and a new design of the structure, DCR is as low as 1000 cps when the PDE is 25% at 1550 nm and timing jitter is 100 ps (FWHM). So, this makes our SPAD a good candidate for quantum experiments via optical fibers.

## Acknowledgment

This work was partially funded by the Autonomous Province of Bozen/Bolzano with the SPIR project (Bando Innovazione 2016).

## References

[1] N. Gisin, G. Ribordy, W. Tittel, and H. Zbinden, "Quantum cryptography," *Rev. Mod. Phys.*, vol. 74, no. 1, pp. 145–195, Mar. 2002.

[2] R. H. Hadfield, "Single-photon detectors for optical quantum information applications," Nat. Photonics, vol. 3, no. 12, pp. 696–705, Dec. 2009.

[3] A. Tosi, N. Calandri, M. Sanzaro, and F. Acerbi, "Low-noise, low-jitter, high detection efficiency InGaAs/InP single-photon avalanche diode," *IEEE J. Sel. Top. Quantum Electron.*, vol. 20, no. 6, pp. 192–197, Nov. 2014.

[4] F. Acerbi, M. Anti, A. Tosi, and F. Zappa, "Design criteria for InGaAs/InP single-photon avalanche diode," *IEEE Photonics J.*, vol. 5, no. 2, 2013.

[5] N. Calandri, M. Sanzaro, A. Tosi, and F. Zappa, "Charge Persistence in InGaAs/InP Single-Photon Avalanche Diodes," *IEEE J. Quantum Electron.*, vol. 52, no. 3, Mar. 2016.