Triple-mesa InGaAs/InP SPAD for heterogenous integration with InP waveguides

Davide Orlandelli
Dipartimento di Elettronica, Informazione e Bioingegneria
Politecnico di Milano
Milano, Italy
*davide.orlandelli@polimi.it

Simona Sorrentino
Dipartimento di Elettronica, Informazione e Bioingegneria
Politecnico di Milano
Milano, Italy
simona.sorrentino@polimi.it

Lorenzo Finazzi
Dipartimento di Elettronica, Informazione e Bioingegneria
Politecnico di Milano
Milano, Italy
lorenzo.finazzi@polimi.it

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

Alberto Tosi, *Member, IEEE*
Dipartimento di Elettronica, Informazione e Bioingegneria
Politecnico di Milano
Milano, Italy
*alberto.tosi@polimi.it

***Abstract*— We present the design of a novel triple mesa InGaAs/InP SPAD and compare it with a well-developed planar version. The mesa detector is considered as an easier path towards its heterogenous integration with InP waveguides for quantum photonic applications. Electrical and optical parameters of both the mesa and planar SPADs were investigated, at the typical temperature of 225 K for such devices. Despite the different geometries and approaches for electric field control and confinement, similar results can be obtained thanks to proper design and sizing. In particular, high photon detection efficiency (PDE) at 1550 nm wavelength was achieved (30% for the planar, 29% for the mesa), with front-side illumination.**

Keywords—InGaAs/InP, single-photon avalanche diode (SPAD), mesa, avalanche photodiode (APD), TCAD simulations, photon detection efficiency, quantum communication, photonic integrated circuit (PIC)

I. Introduction

Single-photon detectors working in the short-wavelength infrared (SWIR) are a topic of great interest in many applications, such as quantum communications [1] and eye-safe light detection and ranging (LIDAR) [2]. Among SWIR single-photon detectors, InGaAs/InP SPADs are widely employed due to their good performance, low cost and compactness. The most widespread InGaAs/InP SPAD structure is planar, where a double zinc diffusion defines the detector active area. In applications like heterogenous integration with Photonic Integrated Circuits (PICs) the SPAD active area must be defined after the integration due to alignment between waveguide and detector active area. However, the temperature at which the double zinc diffusion is performed can severely damage the bonding of the detector wafer to that of the waveguides. Additionally, the zinc diffusion is not a widespread process and not all the III-V fabs have an established recipe. For these reasons, a new SPAD structure is here presented.

In this paper, we present the design of a novel triple mesa SPAD, which can solve the above-mentioned issues. The key parameters of SPAD detectors were simulated at the typical operating temperature of 225 K, and we provide a direct comparison with planar SPADs.

II. Device structure

The planar SPAD architecture is described in detail in [3] and it is shown in Fig. 1(a). The design of the mesa SPAD started from the core of the planar one, since the goal

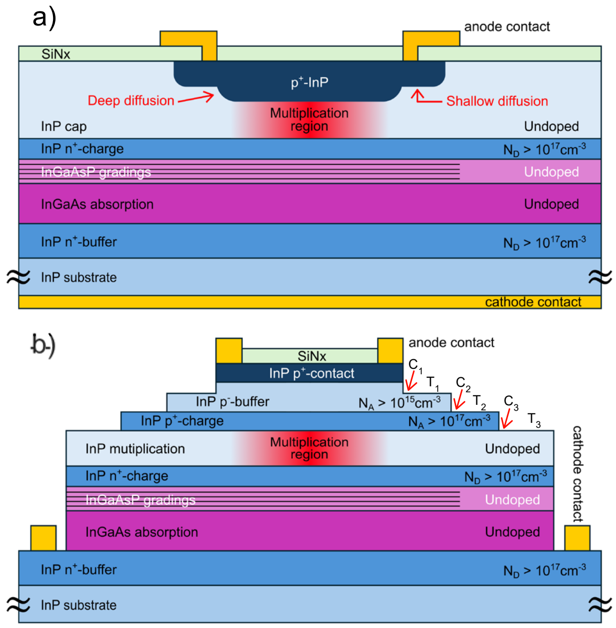

Fig. 1. a) Schematic layer stack of planar InGaAs/InP SPAD, with its typical separate absorption, grading, charge and multiplication (SAGCM) heterostructure. b) Schematic layer stack of mesa InGaAs/InP SPAD: bottom layers are as in the planar one, while additional layers are present in the top region.

was to replicate the state-of-the-art performance of the latter one. Indeed, the two approaches present the same active area size (25 µm diameter) and the same layer stack, up to the InP n^+-charge, in order to obtain similar photon absorption probability and temporal response. Additionally, the InP multiplication layer of the mesa SPAD was sized to match the multiplication region thickness of the planar SPAD. The fundamental difference between the two structures is how the detector active area is defined. The planar SPAD presents a double zinc diffusion, while the mesa one relies on a series of etching steps. Indeed, the newly added layers (InP p^+-charge, InP p^--buffer and InP p^+-contact) are all etched, as they show mesa terraces (i.e., the stepped surface regions left after etching, called T_i in Fig. 1). The main cause of failures in the mesa SPAD is related to the critical corners (i.e., the corners at the end of the terraces, called C_i in Fig. 1) where the electric field reaches very large values. The InP p^--buffer is thus introduced to place the first critical corner (C_1) in a low electric field region. The mesa etch must be close enough to the InP p^+-contact to confine the electric field following the latter, but it also needs to be far enough

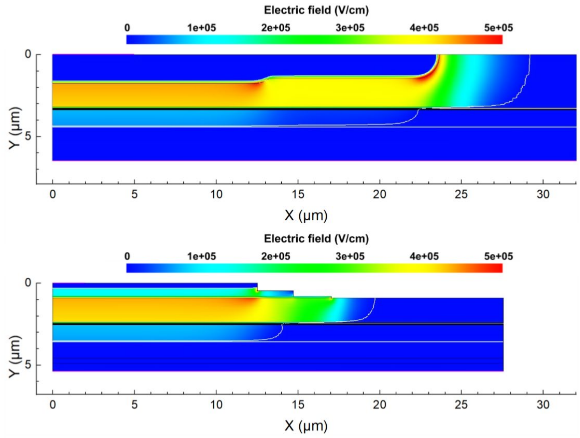

Fig. 2. Electric field distribution at 225 K for planar (top) and mesa (bottom) SPADs, both biased 5 V beyond their breakdown voltages. Thin white line represents depletion region.

from the contact/buffer and the charge/buffer interfaces to avoid premature breakdown. The InP p$^+$-charge layer accommodates the electric field difference with the high field InP multiplication layer: it must be thin and highly doped and it contributes to the horizontal electric field confinement, preventing the depletion region from reaching the edges of the device. Finally, the introduction of two additional corners (C_2 and C_3) is beneficial in avoiding failures of the mesa SPAD because the high electric field results to be distributed over more angular points.

The width of the mesa terraces is another critical design parameter, since a proper balance must be found: terraces horizontally confine the electric field, thus they have to be long enough to avoid high electric field peaks at the critical corners. However, they must be limited to achieve better field confinement and to reduce the expected detector noise.

III. Simulation Results

Electrical and optical simulations were performed using a technology computer-aided design (TCAD) simulator (Synopsys Sentaurus) to investigate the breakdown voltage, the electric field distribution, the avalanche triggering probability and the absorbed photon density. The simulations were then processed using MATLAB to derive an estimation of the detector PDE. The simulation parameters, such as ionization coefficients and complex refractive indexes, were calculated at 225 K following [4], and employing the datasets there reported.

A. *Electrical simulations*

Firstly, I-V curves were simulated at 225 K for both structures. The punch-trough voltages for the planar and mesa SPADs are 53.7 V and 55 V, while the breakdown voltages are 67.5 V and 73.4 V, respectively. The higher breakdown voltage of the mesa is a consequence of the newly added layers in the detector layer stack.

Then, the electric field was simulated with the SPADs biased 5 V beyond their respective breakdown voltages. The results are shown in Fig. 2. The electric field distributions are quite comparable inside the active area of both detectors, but the two confinement approaches define a different profile outside of the central region. The most critical region in the planar SPAD is represented by the edges of the double zinc diffusion, while the highest electric field value in the mesa structure is reached at the critical corners.

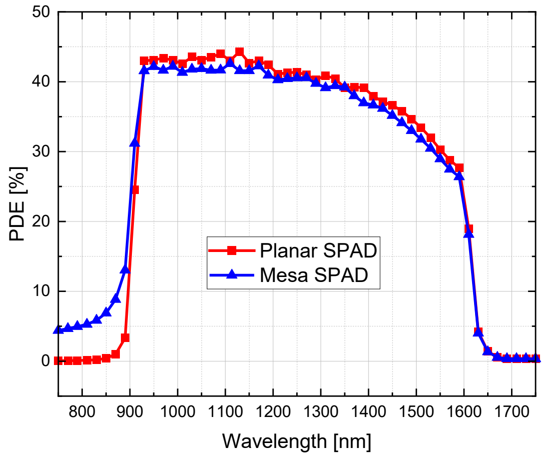

Fig. 3. Simulated PDE at 225 K for planar (red with squares) and mesa (blue with triangles) SPADs, both biased 5 V beyond their breakdown. At 1550 nm (our wavelength of interest) the PDE is 30% and 29% for planar and mesa respectively.

B. *Optical simulations*

By combining avalanche triggering probability simulations with finite-difference-time-domain (FDTD) optical absorption simulations, we compared the PDE of the two SPADs. Fig. 3 presents the PDE spectrum calculated from 750 nm to 1750 nm illuminating both detectors from the front side with a plane wave. The simulations show a good agreement between PDE values for the planar and for the mesa SPADs. In particular, at 1550 nm, the simulated PDE is 30% for the planar SPAD and 29% for the mesa SPAD.

IV. Conclusions

We presented a comparison between models of a well-developed planar SPAD and a novel triple-mesa SPAD. The main performance parameters are comparable, opening the possibility of employing mesa SPADs in quantum photonic applications, with the advantage of easier fabrication and integration processes with waveguides.

Acknowledgment

This work was partially supported by European Union's Horizon Europe program under Grant Agreement no. 101135785 (QPIC1550 project). Views and opinions expressed are, however, those of the authors only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the granting authority can be held responsible for them.

References

[1] N. Gisin e R. Thew, «Quantum communication», *Nature Photon*, vol. 1, fasc. 3, pp. 165–171, mar. 2007, doi: 10.1038/nphoton.2007.22.

[2] C. Yu, M. Shangguan, H. Xia, J. Zhang, X. Dou, e J.-W. Pan, «Fully integrated free-running InGaAs/InP single-photon detector for accurate lidar applications», *Opt. Express, OE*, vol. 25, fasc. 13, pp. 14611–14620, giu. 2017, doi: 10.1364/OE.25.014611.

[3] F. Signorelli *et al.*, «Low-Noise InGaAs/InP Single-Photon Avalanche Diodes for Fiber-Based and Free-Space Applications», *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 28, fasc. 2: Optical Detectors, pp. 1–10, mar. 2022, doi: 10.1109/JSTQE.2021.3104962.

[4] F. Telesca, F. Signorelli, e A. Tosi, «Temperature-dependent photon detection efficiency model for InGaAs/InP SPADs», *Opt. Express, OE*, vol. 30, fasc. 3, pp. 4504–4514, gen. 2022, doi: 10.1364/OE.444536.