10-µm InGaAsP/InP SPADs for 1064 nm detection with 36% PDP and 118 ps timing jitter

Utku Karaca[1], Ekin Kizilkan[1], Claudio Bruschini[1], and Edoardo Charbon[1]
[1]École Polytechnique Fédérale de Lausanne (EPFL), Neuchâtel, Switzerland
emails: utku.karaca@epfl.ch, ekin.kizilkan@epfl.ch, claudio.bruschini@epfl.ch, and edoardo.charbon@epfl.ch

***Abstract*—**In this work, we present a family of planar InGaAsP/InP SPADs with a diameter of 10 µm targeting 1064 nm wavelength detection. TCAD simulations enabled the determination of Zn diffusion depths, thereby achieving low noise and uniform photoresponse. Devices with 1.5-µm, 1.3-µm, and 0.75-µm multiplication region thicknesses were fabricated. The device with a 1.5-µm multiplication region demonstrated 53 kcps DCR, 118 ps timing jitter at 5 V_{ex}, and 36% PDP at 9 V_{ex}. The measurements were done from the backside without a metal reflector, all at 300K. The DCR was reduced to 14.1 kcps at 273K, 5.5 kcps at 253K, and 2.75 kcps at 225K at 5 V_{ex}. The operating frequency can be increased up to 500 kHz with only 11.8% and to 200 kHz with 5.8% afterpulsing at 300K. The active area scanning results indicated that the photoresponse is almost flat at and above 5 V_{ex}. Thinner multiplication regions showed higher PDPs and lower jitter, at a cost of higher noise.

I. Introduction

Single-photon detection at 1064 nm wavelength is useful in long-haul light detection and ranging (LiDAR) and in free-space communications [1]. Medical applications, such as time-gated diffuse correlation spectroscopy for blood flow measurements can also make use of such a detector [2]. High-power 1064 nm Nd:YAG lasers enable a variety of similar experiments and are appealing to diversify the applications. Since the photon detection probability (PDP) of CMOS-based SPADs reduces towards near-infrared (NIR) due to the low silicon absorption coefficient, superconducting nanowire single-photon detectors (SNSPDs) and InGaAsP/InP single-photon avalanche diodes (SPADs) have emerged as the best alternatives to develop single-photon cameras operating at 1064 nm. However, InGaAsP/InP SPADs perform well at much higher temperatures than SNSPDs, and even at room temperature, enabling scalable and compact solutions that are cost-effective as well.

II. Results

SPADs utilize a separate absorption-charge-multiplication (SACM) structure and the double zinc (Zn) diffusion technique to form the multiplication and guard ring (GR) regions (Fig. 1). The n-contact was carried to the top surface, allowing to illuminate SPADs from the backside. The absorber thickness is 1 µm, and the charge layer doping is larger than 2×10^{17} cm^{-3} to keep the electric field sufficient to deplete the absorber before breakdown is reached (Fig. 2). We designed, fabricated, and fully characterized 10-µm diameter SPADs with 1.5-µm, 1.3-µm, and 0.75-µm multiplication region thickness. According to avalanche breakdown probability simulations in TCAD, a 0.5-µm depth difference between shallow and deep Zn diffusions was the preferred solution. This could potentially provide lower noise at the cost of a less uniform photoresponse over the active area (Fig. 3). The SEM image of the fabricated device with a 1.3-µm multiplication region prove that the Zn diffusion depths are close to the planned values (Fig. 4). The measured I-V curves at 300K indicate the avalanche breakdown and punch-through voltages for each device (Fig. 5). In the remaining measurements, the SPADs were operated in time-gating mode with 50 kΩ ballast resistor and a 100 ns gate-on time. The gating frequency sweep of each device showed that devices can be operated up to 500 kHz with low afterpulsing probability (APP) at 300K (Fig. 6). With 10 kHz gating, a median DCR of 53 kcps was obtained with a multiplication region thickness of 1.5-µm, 302 kcps with 1.3 µm, and 2130 kcps with 0.75 µm, where the DCR was normalized with gate-on time. The median DCR was reduced to 14.1 kcps at 273K, 5.5 kcps at 253K, and 2.75 kcps at 225K, for a 1.5-µm multiplication region at 5 V_{ex} (Fig. 7). Active area scanning was performed with a 1060 nm pulsed laser, demonstrating that the response difference between the edge and center of the active region becomes smaller when increasing V_{ex}, and that a uniform response can be achieved at and above 5 V_{ex} (Fig. 8). The PDP obtained with a monochromator and wide-spectrum lamp at 1060 nm and 5 V_{ex} was 19.5% for 1.5-µm multiplication region thickness, 20.4% for 1.3 µm, and 21.5% for 0.75 µm (Fig. 9). A high PDP of 36% at 9 V_{ex} was achieved with a 1.5-µm multiplication. Inter-arrival avalanche histograms indicated that APPs of only 11.1% and 5.8% can be achieved at 500 kHz and 200 kHz gating and 300K, respectively (Fig. 10). The timing jitter was acquired via time-correlated single-photon counting (TCSPC), yielding as 118.4 ps, 110 ps, and 84 ps (FWHM) after deconvolution (Fig. 11). The comparison with state-of-the-art InGaAsP SPADs shows that fabricated devices achieved the smallest sizes, with high PDP, and low timing jitter (Fig. 12), while further optimization is to be expected.

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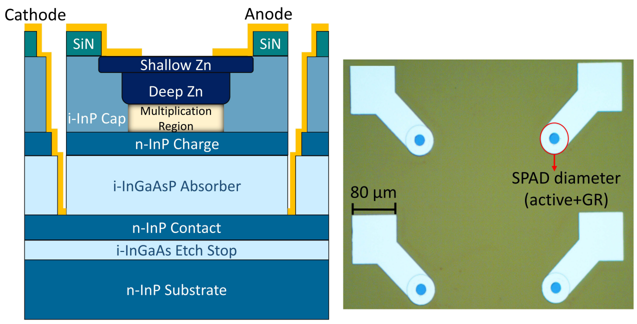

Fig. 1: The cross-section and an optical image of fabricated SPADs.

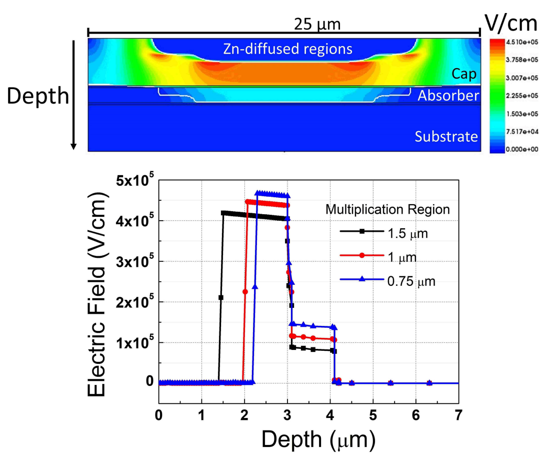

Fig. 2: Electric field simulations in TCAD at 300K.

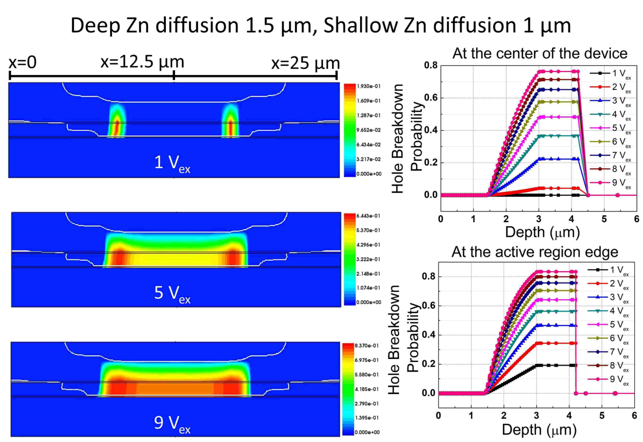

Fig. 3: Avalanche breakdown probability simulations for devices with a 0.5-µm Zn diffusion depth difference at 300K.

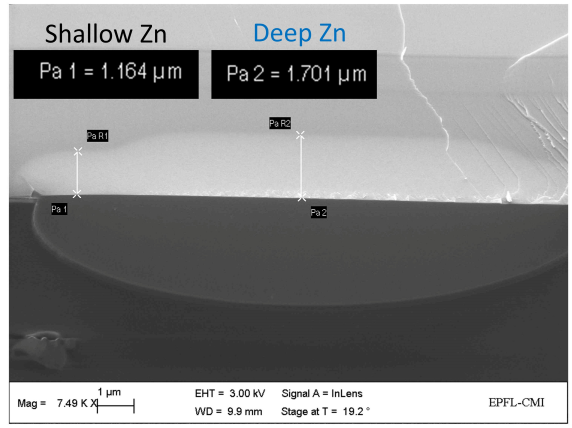

Fig. 4: SEM image belonging to a device with a 1.3-µm multiplication region.

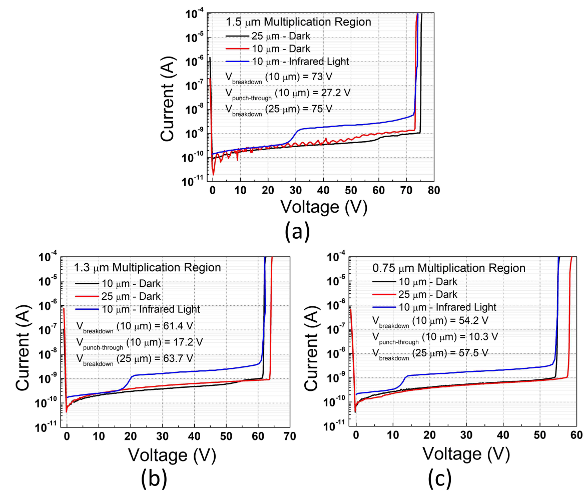

Fig. 5: I-V characteristics of the devices with (a) 1.5-µm, (b) 1.3-µm, and (c) 0.75-µm multiplication regions at 300K.

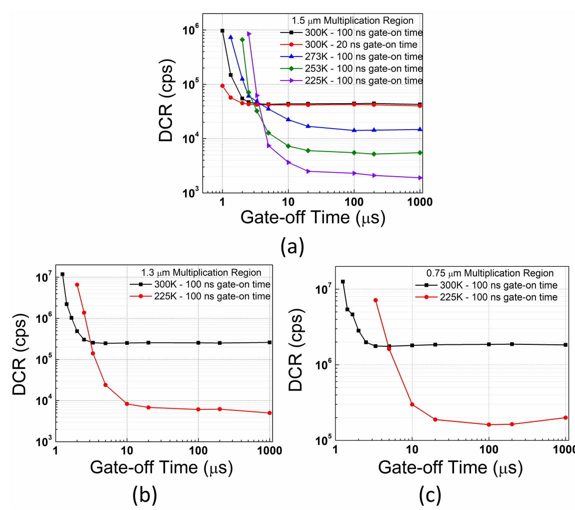

Fig. 6: Gating frequency sweep of the devices with (a) 1.5-µm, (b) 1.3-µm, and (c) 0.75-µm multiplication regions.

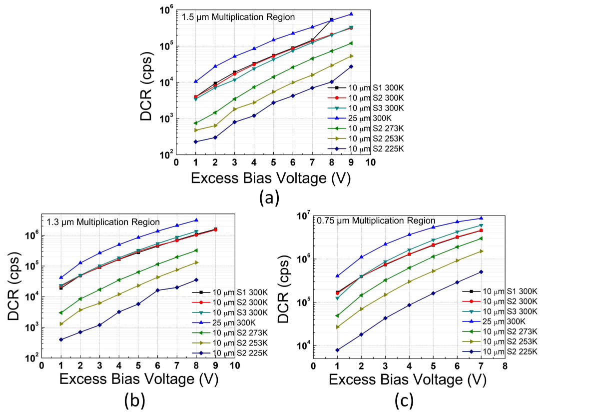

Fig. 7: DCR measurements of the devices with (a) 1.5-µm, (b) 1.3-µm, and (c) 0.75-µm multiplication regions with 10 kHz gating and 100 ns gate-on time. Note: Three devices (S1, S2, and S3) were characterized with a 10-µm diameter. S2 corresponds to the median device.

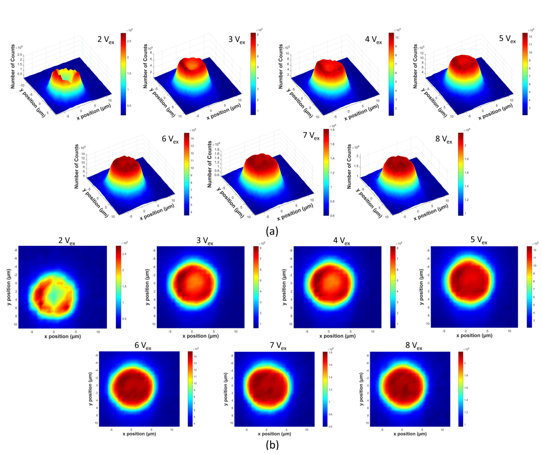

Fig. 8: Active area scanning of the SPAD with a 1.3-µm multiplication region from the (a) side and (b) top view by utilizing a 1060 nm pulsed laser at 300K.

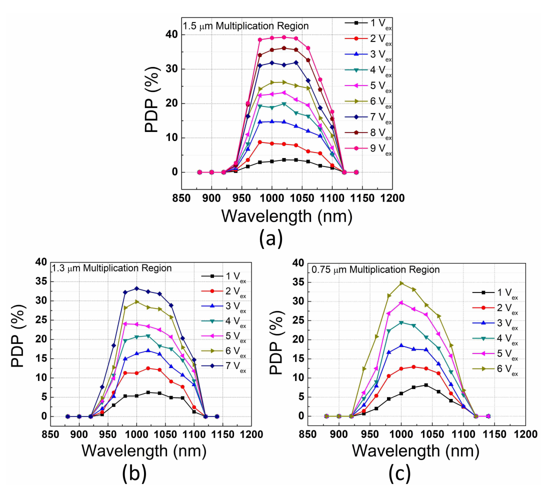

Fig. 9: PDP measurements of the devices with (a) 1.5-µm, (b) 1.3-µm, and (c) 0.75-µm multiplication regions at 300K and with 10 kHz gating and 100 ns gate-on time.

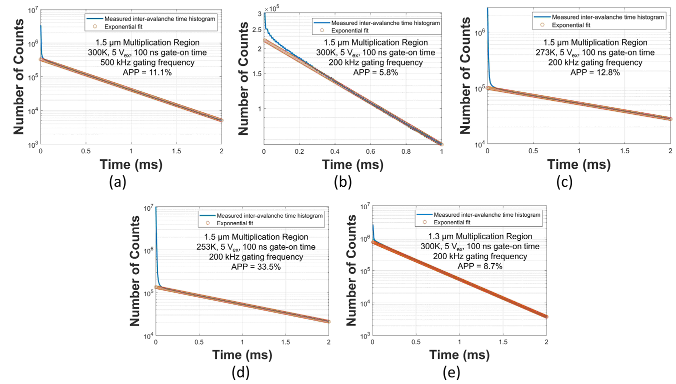

Fig. 10: Inter-arrival avalanche pulse histograms of the devices at various temperatures and gating frequencies with 100 ns gate-on time.

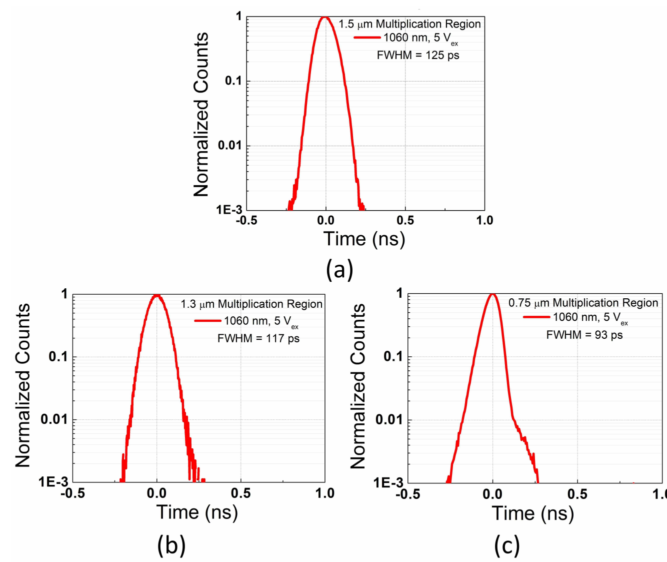

Fig. 11: Timing jitter measurements of the devices with (a) 1.5-µm, (b) 1.3-µm, and (c) 0.75-µm multiplication regions at 300K.

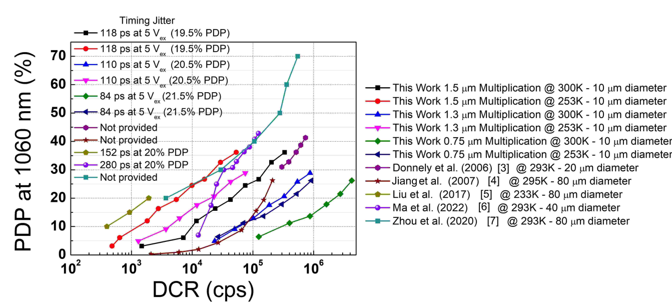

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Fig. 12: Comparison of the developed SPADs with the state-of-the-art InGaAsP SPADs targeting 1064 nm detection.