



Article Current-Assisted Single Photon Avalanche Diode (CASPAD) Fabricated in 350 nm Conventional CMOS

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Received: 3 March 2020; Accepted: 15 March 2020; Published: 22 March 2020



Featured Application: Single photon counting, LIDAR, FLI, Low light imaging.

Abstract: A current-assisted single-photon avalanche diode (CASPAD) is presented with a large and deep absorption volume combined with a small p-n junction in its middle to perform avalanche trigger detection. The absorption volume has a drift field that serves as a guiding mechanism to the photo-generated minority carriers by directing them toward the avalanche breakdown region of the p-n junction. This drift field is created by a majority current distribution in the thick (highly-resistive) epi-layer that is present because of an applied voltage bias between the p-anode of the avalanching region and the perimeter of the detector. A first CASPAD device fabricated in 350-nm CMOS shows functional operation for NIR (785-nm) photons; absorbed in a volume of $40 \times 40 \times 14 \ \mu m^3$. The CASPAD is characterized for its photon-detection probability (PDP), timing jitter, dark-count rate (DCR), and after pulsing.

Keywords: single photon detector; avalanche breakdown; current-assistance

1. Introduction

Single-photon avalanche diodes (SPADs) become an integral part of applications which require high photon sensitivity, and/or accurate photon arrival timing. SPAD versions based on complementary metal-oxide semiconductor (CMOS) technology have the advantage of low production cost and the ability to monolithically integrate them with electronic circuitry for read-out and signal processing. They are employed in various applications such as 3D time-of-flight (TOF) and fluorescence-lifetime imaging (FLI) [1–5].

A SPAD is a p-n junction biased above its reverse breakdown voltage. At this bias, the SPAD operates in a meta-stable Geiger regime where a single electron/hole can generate impact ionization and the resulting electrons/holes also generate impact ionization and so on and therefore a large reverse current flows, which is self-sustaining. Therefore, the gain for this mode of operation is virtually infinite. The reverse current needs to be quenched to protect the p-n junction from overheating and physical damage. Quenching is also necessary to restore the SPAD to detect further photons. Quenching [6] is done by using a load resistor (passive quenching) or an active circuit of transistors (active quenching). In a conventional SPAD, the incoming light generates photo-carriers inside or near the depletion region of a horizontal p-n junction where the multiplication is expected to happen. Photo-carriers that are generated farther from the depletion region slowly diffuse and can potentially also cause avalanche breakdown. Increasing the detection area is not very straight-forward because that increases the active area where the multiplication is expected, and this puts more emphasis on careful design to have uniform field all over the active area. Increasing the detection area also increases the diode capacitance which in turn leads to a larger dead time of the detector. Another important concern is

that a larger detection area increases the number of traps in the active area where the multiplication occurs and thereby increasing the probability of afterpulsing [7]. Further, sensitivity in near infrared (NIR) wavelengths, so important to many applications, is also posing problems, because the associated large photon penetration ($10 \mu m$ – $20 \mu m$) depth is difficult to match with the limited thickness of the horizontal depletion region of the avalanching junction (several microns). Retrograde wells with variable doping profile for generating a built-in electric field have been introduced improving the NIR sensitivity of SPADs [8].

In this work, we present the current-assisted single-photon avalanche diode (CASPAD) that has a small p-n junction located in the center for avalanche breakdown and a large detection volume around it for photon absorption. The photo-electrons in the detection volume are guided using a drift field toward the central "SPAD" where they initiate an avalanche breakdown and can be subsequently detected by attached circuitry. Separate absorption and multiplication region avalanche photodiodes (SAM APDs [9]) in III-V semiconductors exist also having infrared sensitivity, but these are not in CMOS and thus require 3D hybrid stacking for read-out and signal-processing circuitry.

2. Detector Design

This first CASPAD is fabricated in a standard 350-nm CMOS process, making only use of the standard doping profiles for transistor fabrication like p⁺ and n⁺ zones for source and drain and Pand N-wells as local substrate. This limits quite much the number of options for the topological design, but it is good enough to show basic functionality of the CASPAD.

The cross section of the proposed CASPAD detector is shown in Figure 1. When there is a voltage difference between two highly doped p^+ regions in a p^- epilayer, there is a majority current which flows between the two p^+ regions, in this case a hole current. This current has an associated drift field and when there is an electron generated in this drift field region, it is quickly guided toward the p^+ region with the higher voltage. This "current assistance" detection principle has been used in photodetectors to improve device speed while having a larger detection volume [10]. A modulated hole current and drift field have been used in photonics demodulators for time-of-flight [11,12], and fast gated detectors for fluorescence lifetime imaging [13]. More recently, using the same structure as in this letter, linear gain mode avalanche photodiode operation [14] has been characterized below the breakdown voltage.



Figure 1. Schematic cross-section of the current-assisted single-photon avalanche diode (CASPAD) (not to scale) with the p-n junction in the middle and a current assistance "ring" to guide the photo-generated

electrons towards the middle based on the additional electric field distribution. The lines with arrows represent the inverse of the drift field indicating the guiding direction for the absorbed photo-electrons. The dotted line represents the extent of the depletion region.

The CASPAD device is embedded in a high resistive (~1000 Ω .cm) 14 µm thick p-type epilayer to limit the majority hole current level for the current assistance and its associated power dissipation. The cathode consists of an n-diffusion embedded in an N-well. The backside contact is formed of silver paste to the highly doped p-substrate which acts similarly to a metal contact. Minimum widths and spacings allowed by the CMOS process are chosen with a certain added tolerance. The dimensions of the CASPAD device are illustrated in Figure 2.



Figure 2. Dimensions of the CASPAD device.

3. Results and Discussion

3.1. Electric Field Simulation

Device physics simulations were done in Silvaco ATLAS to verify the CASPAD functionality and to determine the breakdown region. The simulated plot with electric field contours at the central "SPAD" (single-photon avalanche diode) junction can be seen in Figure 3. The electric field in the junction between the N-well and the p substrate is high enough to cause an avalanche breakdown when there is an electron. It should be noted that the vertical junction (shown in Figure 3) has lower field than the lateral junction. This is expected to not have a major effect in photon detection probability because most of the photo-electrons generated in the detection volume are guided toward the p⁺ anode region by the drift field and these photo-electrons are more likely to go to the lateral junction. The capacitance of the p-n junction is estimated to be around 1 fF from device physics simulations.



Figure 3. Simulated electric field profile at the cathode-anode junction at the central multiplication area of the CASPAD at an excess bias voltage (V_{ex}) of 2 V.

3.2. I-V Characteristics

Figure 4 shows the measured IV characteristics of the selected CASPAD. An anode-to-ring voltage of 15 V is applied in order to have a high-speed transfer of photo-electrons toward the avalanching p-n junction. Also, the backside substrate voltage is held at the same voltage as the ring voltage in order to guide the photo-electrons which are generated deeply in the epilayer (from e.g., NIR light) upwards to the lateral field between the ring and the anode. The p-n junction breaks down at a reverse voltage of 52.5 V and the associated reverse current at the onset of breakdown is ~20 pA. Hence, a high dark count rate is foreseen because most of these carriers flow through the avalanche multiplication region. The dark counts are due to contributions from the surface states, the silicide contact layer and band-to-band tunneling. The measurements in the following sections are defined in terms of excess bias voltage (V_{ex}) which is the voltage above the breakdown voltage (V_{bd}) of 52.4 V and the anode-ring voltage was maintained at +15 V was found to be the optimum voltage for fast transfer of photo-electrons [14].



Figure 4. Measured IV characteristics of the detector in the dark (with anode-ring voltage of 15 V).

3.3. Dark Count Rate

For photon-counting measurements, an external quenching resistor of 47 k Ω is used and the parasitic capacitance of the bond pad is estimated to be around 1 pF which disguises the small (~1 fF) capacitance of the p-n junction.

Figure 5a shows the dark count rate of the device with respect to the excess bias voltage (V_{ex}). As expected from the IV characteristics, the DCR is high. The main contribution to the DCR is possibly band-to-band tunneling, traps in the surface, and the silicide layer present close to the avalanching junction. Therefore, the device should be optimized in future versions to achieve a low DCR.



Figure 5. (a) Measured dark count rate with respect to the excess bias voltage. (b) Timing jitter full-width half-maximum (FWHM) = 370 ps ($V_{ex} = 0.86$ V). (c) Measured interavalanche times to characterize afterpulsing ($V_{ex} = 0.86$ V) with an exponential fit (d) Measured photon detection probability with respect to the excess bias voltage at a wavelength of 785 nm.

3.4. Timing Jitter

Timing jitter of photon-detection in a conventional SPAD is due to the statistical variation on the avalanche process and is in the order of tens to hundreds of picoseconds. However, in CASPAD, the timing jitter is due to the sum of the statistical variation in the avalanche process and the variable time it takes for the photo-generated electrons to travel to the central avalanching region. In [14], the position dependent delay has been characterized in more detail. For characterizing the timing jitter, a pulsed fiber laser, with a wavelength of 785 nm, is used which has a pulse width of ~70 ps. The laser spot is aligned on the whole device area with a custom microscope. Figure 5b shows the timing jitter of the device measured with a Becker and Hickel SPC-130 photon counting card. The timing jitter is characterized by the full-width half-maximum (FWHM) which is ~370 ps. A small diffusion tail (<1%)

can also be observed, most likely due to the slowly diffusing carriers which are generated deeply in the substrate below the epi layer.

3.5. Afterpulsing

Traps in the active area of the SPAD "trap" charges during an avalanche event and release it later. The time delay of release ranges from a few tens to hundreds of nanoseconds. This adds co-related noise to the measurement and is known as afterpulsing. Since the active area of the CASPAD is very small, low afterpulsing is expected. Figure 5c shows the interavalanche time (Δ t) histogram [15,16] of the device with an exponential fit (Δ t = 50 µs). With negligible afterpulsing, the interavalanche curve should follow an exponential distribution. The deviation from this exponential distribution is a result of correlated noise. The afterpulsing probability is calculated by dividing the number of counts above the exponential fit by the total number of counts. The afterpulsing probability is calculated to be 5.7% at an excess bias voltage of 0.86 V. Although the afterpulsing probability is not very high, it could be attenuated by using on-chip quenching with low parasitic capacitance to reduce the number of carriers per avalanche event.

3.6. Photon Detection Probability

The sensitivity of SPADs are characterized by photon detection probability (PDP). The PDP is calculated in this work by dividing the number of counts (without the dark counts) by the number of photons incident. Figure 5d shows the PDP as a function of V_{ex} . The PDP is the product of the probability of avalanche by an electron or a hole and the quantum efficiency of the device. The quantum efficiency of this CASPAD is calculated to be 47%, at a wavelength of 785 nm, from the measured responsivity (~0.3 A/W) from our previous work [14]. The low probability of avalanche breakdown by an electron (~12.2% max) for the CASPAD is primarily attributed to the square geometry of the p-n junction, the breakdown occurs at the sharp corners due to high concentration of electric field at sharp edges in a similar way to premature edge breakdown [17,18]. Further investigation by light emission tests confirms that the breakdown occurs at the sharp corners (shown in Figure 6). Light emission tests show that the light emission primarily stems from 3 out 4 corners proving that the breakdown does not occur in the entire p-n junction but only at the sharpest corners where the electric field is concentrated. Breakdown occurs much less frequently in one of the corners likely due to non-uniformity of the CMOS process. The PDP could be improved by having a circular geometry. A summary of performance parameters is listed in Table 1 and comparison is made with a few conventional SPADs fabricated in 350 nm CMOS.



Figure 6. Photomicrograph of the CASPAD device emitting light at (a) $V_{ex} = 2.1$ V and (b) $V_{ex} = 2.8$ V.

Work	This Work	[20]	[21]	[22]
Technology	350 nm	350 nm	350 nm	350 nm
Detection area (shape)	40 μm (square)	50 μm active area diameter (circular)	10 μm active area diameter (circular)	20 μm active area diameter (circular)
P-N Junction type	P+/p-epilayer/N-well	P+/n-enrichment/High Voltage-N-well/N+	P+/Deep N-well/N+	P+/N-Well/N+
Breakdown voltage	52.4 V between cathode and anode (15 V between anode and ring)	25 V	-	24 V
Afterpulsing (V _{ex})	5.7% (0.86 V)	4.5% (5 V) with minimum hold-off time of 20 ns	23% with minimum hold-off time of 40 ns	22% with a hold-off time of 100 ns
Timing jitter (V_{ex}) [λ]	370 ps (0.86 V) [785 nm]	82 ps (6 V) [780 nm]	80 ps (3.3 V) [670 nm]	39 ps (5 V) [820 nm]
PDP max (V _{ex}) @785 nm	5.74% (1.15 V)	~10% (6 V)	~3% (4 V)	~8% (5 V)
Quenching type	Passive: 47 kΩ quench resistor	Active	Active, event-driven	Variable-load quenching

Table 1. Performance parameters of the first generation of CASPAD compared with a few SPADs fabricated in 350 nm CMOS [19].

4. Conclusions

The device structure can still be improved in many ways, mainly in its center area. Layout and depth of diffusions and wells and the use of circular shapes can be further investigated. They all affect the CASPAD performance parameters like PDP, DCR, deadtime, and afterpulsing. Receiver circuitry can also be considered, thereby taking advantage of the very small detector capacitance with passive and/or active quenching. Use of enhanced CMOS technology can also improve device operation. Further, using the current assistance principle, it becomes probably feasible to make devices that mainly have only vertical current assistance (omitting the ring). In that way a thicker epi-layer of 20 μ m with a smaller CASPAD pitch (e.g., <10 μ m) could be envisaged for higher resolution, NIR-efficient, imager solutions.

In summary, a detector which combines the principles of SPAD and current assistance has been presented. The device showed relatively good timing response for its larger area. Its basic operation has been demonstrated, in terms of its photon-detection probability (PDP), timing jitter, dark-count rate (DCR), and afterpulsing. Changes at the device level and integration with circuitry can still improve general performance.

Author Contributions: Conceptualization, G.J. and M.K.; methodology, G.J.; validation, G.J., H.I., and M.K.; formal analysis, G.J.; investigation, G.J.; writing—original draft preparation, G.J.; writing—review and editing, G.J. H.I., and M.K.; supervision, M.K.; All authors have read and agreed to the published version of the manuscript.

Funding: This work was sponsored in part by Sony Depthsensing Solutions NV and in part by the Research Council of the Vrije Universiteit Brussel (SRP 19).

Conflicts of Interest: The authors declare no conflict of interest.

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