A Geiger Mode Avalanche Photodiode

Fabricated in a Conventional CMOS Technology

A. Rochas, P.A. Besse, R.S. Popovic
Swiss Federal Institute of Technology, Lausanne
Alexis.Rochas@epfl.ch

Abstract

A Geiger mode avalanche photodiode with outstanding characteristics is fully fabricated in a conventional CMOS process. The 80µm² active area photodiode for blue detection contains an efficient guard-ring structure to prevent edge breakdown. The selectivity for blue is obtained using a P+/Nwell/Psubstrate dual junction structure. The first junction close to the surface is biased above the breakdown voltage, the second junction is short-circuited. A characterization using a passive quenching method is done. A value of the dark count rate of only 220 c.p.s. is obtained for an excess bias voltage of -2.85V, at room temperature. The maximum Geiger mode quantum efficiency for this excess bias voltage is about 20% at λ=460nm. The fabrication in a CMOS process opens the way to the co-integration of passive quenching or active quenching depending on applications and read-out electronics.

1. Introduction

Silicon avalanche photodiodes biased above breakdown voltage allow single photon detection. The so-called Geiger mode is a very attractive working principle for high-sensitivity, low-light level applications. We recently demonstrated low-noise CMOS silicon avalanche photodiodes suitable for UV-blue detection applications[1]. However, such devices have to be combined with amplification electronics that deteriorate the signal to noise ratio of the sensor. Therefore, for many applications, like in flame detection, scintillation detection, or as night vision detectors, the photomultipliers tubes or gas discharge tubes remain the most suitable detectors. But they are large in size, easily damaged, expensive, susceptible to magnetic fields, the linear range is limited and a high voltage supply is required.

Kindt demonstrated [2] high quality pixels for a Geiger mode avalanche silicon photodiode array but with a dedicated fabrication process.

In this paper, we present a Geiger mode avalanche photodiode (GAPD) fabricated in a conventional CMOS technology that approaches the characteristics of a photomultiplier tube without its drawbacks. The fabrication in a CMOS process offers additional advantages: possibility to integrate passive or active quenching and read-out electronics on the same chip, low-cost fabri-
cation, reproducibility of the dark count rate and gain characteristics, and potentially very low dark count rate due to the maturity of the CMOS process.

2. Fabrication

We recently presented a new design idea to fabricate avalanche photodiode in a conventional CMOS process[1]. The lateral diffusion of two nwell regions during the drive-in step of the process is used to create a guard ring at the edge of the p+ anode [Fig.1]. Its lower doping concentration prevents an edge breakdown.

![Figure 1. CMOS GAPD’s cross section](image1)

Fig.2 presents a full scan of a 80µm in diameter photodiode with a 2µm blue LED spot. The mean gain is plotted as a function of the spot position on the diode. The non-uniformity of the gain is less than 7% and no detrimental prebreakdown at the junction periphery can be seen.

![Figure 2. Mean gain <G> as a function of X_position[µm] and Y_position[µm]](image2)

Similar design rules have been used to fabricate 80µm² active area photodiodes for Geiger mode operation in an industrial 0.8µm CMOS process.

3. Geiger mode characterization

3.1. Experimental set-up for characterization

In the Geiger mode, a single photon can initiate avalanche breakdown. A quenching circuit is needed to generate single pulses by ending the avalanche event. A load resistor $R_q$ is introduced between the voltage source and the photodiode [Fig.3]. The bias voltage corresponds to the sum of the breakdown voltage $V_{bd}$ and an excess voltage $V_e$. The photocurrent induces a voltage drop over $R_q$, quenching the avalanche process. $N_{well}$ and $P_{substrate}$ are shortcircuited to ground to ensure selectivity for blue radiations[1,9].

![Figure 3. Experimental set-up](image3)

Geiger pulses generated across a 50Ω resistor are amplified and counted using a programmable threshold level counter. After quenching, the voltage across the GAPD slowly increases from $V_{bd}$ to $V_{bd}+V_e$. The corresponding dead time is determined by the value of $R_q$ and the capacitance of the GAPD (including parasitic capacitances).

3.2. Dead time/Afterpulsing/Dark count rate

Fig.4 shows a typical Geiger pulse observed across the 50Ω resistor without amplification. The bias voltage $V_{bd}+V_e$ is equal...
to -21V with \( V_{bd} = -19.65 \text{V} \). Using a 220kΩ quenching resistor, the pulse width (fwhm) is less than 20 ns.

Typical values of the dead time are about 2\( \mu \text{s} \) using a 220kΩ quenching resistor. Such long dead times are inherent in passive quenching. However, active quenching can be used[4] and integrated[5] to reduce the dead time in the 50ns range. In applications where a large dynamic range is not a requirement, such as flame detection, a long dead time could be used to limit afterpulsing influences. Afterpulses are due to the release of carriers trapped in the multiplication region during an avalanche process. In a first study of the afterpulsing, we noticed that at room temperature, most of the afterpulses were encountered during the first microsecond after a full discharge of the diode. Since a carrier released during the dead time exhibits a smaller gain i.e. induces a smaller pulse, a well adjustment of the counter threshold allows the excluding of afterpulses due to short lifetime traps.

Fig.5 presents the dark count rate as a function of \( V_e \), at room temperature. For a 80\( \mu \text{m}^2 \) active area element, a dark count rate of 220 c.p.s. is obtained, for \( V_e = -2.85 \text{V} \). This value is in the range of commercially available photomultipliers[6].

3.3. Avalanche breakdown probability \( P_{bd} \)

Breakdown initiation probabilities as a function of \( V_e \) in both cases of pure electrons and pure holes injection [Fig.6] in the multiplication region have been calculated for our \( \text{P+/Nwell} \) structure using the numerical calculation described by Oldham[7]. A one side abrupt junction assumption was made for this calculation. The ionization coefficients published by Van Overstraeten and de Man[8] for electrons \( \alpha_e \) and for holes \( \alpha_h \) have been used.
tral density filter. The breakdown initiation probability $P_{bd}$ is then given by:

$$P_{bd} = \frac{\alpha}{\eta}$$

where $\eta$ is the quantum efficiency of the diode ($\eta \approx 50\%$ at 420nm, [1]) and $\alpha$ is the Geiger mode quantum efficiency defines as the probability that an incident photon will be detected. One can see that $P_{bd}$ increases with $V_e$, as well as dark count rate [Fig.5] and afterpulsing probability. Since at $\lambda = 420$nm the light absorption occurs very close to the surface (i.e. above the multiplication region), the illumination results in a close to pure electrons injection.

3.4. Geiger mode quantum efficiency $\alpha$

Fig.7 shows the Geiger mode quantum efficiency $\alpha$ of the GAPD for $V_e = -0.85V$, -1.85V and -2.85V as a function of the wavelength, at room temperature.

![Figure 7. GAPD's $\alpha$ as a function of $\lambda$ for different values of $V_e$.](image)

Since $P_{bd}$ increases with $V_e$ [Fig.6], $\alpha$ also increases with $V_e$. A Geiger mode quantum efficiency of 20% , close to state-of-the-art photomultipliers[6], is obtained for $V_e = -2.85V$ and $\lambda = 460$nm.

The dual junction structure $P_{+}/N_{well}/P_{substrate}$ leads to a large selectivity for blue wavelengths without any additional interference filter. If necessary, $\alpha$ can be greatly improved in the UV range by removing the Si$_3$N$_4$ layer deposited to passivate the circuit[9]. The maximum of $\alpha$ can also be shifted towards lower wavelengths using advanced CMOS processes with ultra-shallow junctions or towards higher wavelengths using technologies with deeper junctions.

4. Conclusion

We demonstrate the outstanding potential of a $80 \mu m^2$ active area GAPD fabricated in a conventional CMOS process. Using a passive quenching, a low value of the dark count rate of 220 c.p.s. has been obtained for an excess bias voltage of -2.85V, at room temperature. The maximum Geiger mode quantum efficiency for this excess bias voltage is 20% at $\lambda = 460$nm. The fabrication in a CMOS process opens the way to the co-integration of quenching and read-out electronics.

5. References


