Design of CMOS Avalanche Photodiode for Embedded Laser Range Finder

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Abstract- In this paper, the design of CMOSAPD in standard 0.35 μm CMOS technology is presented; Simulation and Comparison between two CMOS avalanche photodiode (APDs) modes are performed. Electrical and Optical Simulations are carried out using SILVACO ATLAS© Suite. Two modes of Electrical Simulation have been presented. The performances of APDs in both modes have been compared in terms of responsively, noise and gain. Both structures present interesting characteristics. Monolithic integration of sensors and circuits in CMOS processes result in tremendous advantages in terms of dimensions shrink, low power consumption, low cost etc.

Keywords— CMOS APD, Range Finder, SPAD, Distance measurement, integrated Optoelectronics.

I. INTRODUCTION

Avalanche photodiodes (APDs) are very attractive devices for their high sensitivity in low light level and even high speed applications such as long distance, optical communications and optical distance measurement. APDs have been well known for decades, but high reverse voltage needed to allow avalanche mechanism in the multiplication region prevented their fabrication in standard CMOS technology.

Avalanche photodiode (APD) is the keystone of the accurate embedded system for distance measurement, thanks to a strong internal gain and a high bandwidth. However, there are two main difficulties to take into account when designing a CMOS APD. First, the realization of the APD has to be compatible with the CMOS process characteristics. Second, the APD has to operate with a sufficient voltage, allowing for avalanche mode without destroying the device, particularly at the peripheral junction. The usually used solution is the implementation of a guard ring [1] that generally consists in a slightly doped region at the peripheral junction because a slightly doped region holds tension better than a heavily doped one.

The Avalanche process occurs when the carriers in the transition region are accelerated by the electric field to energies sufficient to free e-h pairs via collisions with bond electrons. An Avalanche diode is a diode (usually made from silicon, but can be made from another semiconductor) that is designed to go through avalanche breakdown at a specified reverse bias voltage and conduct as a type of voltage reference.

Some CMOS APDs have been previously reported. Most of them are developed for photon counter applications in Geiger mode [2,3,4]. They are implemented in CMOS technologies at < 0.2 μm, and the guard rings are realized with a p-well. Some of them have a buried n-type isolation layer that prevents a punchthrough of the p-well guard ring to the P-substrate. Moreover, CMOS APDs working as an optoelectronic mixer have been also reported for fiber-supported wireless systems [5]. Here, the guard ring is implemented by a shallow trench isolation (STI). The problem when using STI is that it may dramatically increase the density of deep-level carrier generation centers at its interface, which strongly increases the dark current. In all the cases, the major objective is to work at high frequencies but not to optimize the sensitivity. That is the reason why the surfaces are small (< 900 μm2), the working wavelengths are high (between 600 and 800 nm), and the APDs operate very near the breakdown in order to minimize the junction capacity.

The rest of the paper is organized as follows: Section II presents Laser range Finder. Section III, presents the design of CMOS APD in 0.35μm tech. Section IV presents the results and discussion. Section V presents the electrical and optical simulations performed. Finally, section VI draws some conclusion.
II. LASER RANGE FINDER

Time-of-flight laser range-finding methods are commonly used for Range-Finding applications and can be divided into three categories: pulsed technique, phase-shifting measurement, and frequency modulation continuous wave method [6, 7, 8]. These techniques are based on the time-of-flight measurement of a laser beam and consist in measuring the transit time of the light to reach any diffusing target and return. In the case of using a phase-shifting method, the dc current of an emitting laser diode (LD) is modulated by a sine wave generated by a reference oscillator at the frequency f_{oc}. After reflection from the diffusing surface of the target, a part of the laser beam is collected by a photodiode through a focusing lens. Distance measurement D is deduced from the phase shift Δφ existing between the photoelectric current and the modulated laser signal, as follows (Eqn. 1), where c is the speed of light and τ_d is the time of flight:

\[ \Delta \phi = \frac{2 \pi f_{oc} \tau_d}{c} = 2 \cdot \pi \cdot f_{rf} \cdot \tau_d \] (1)

The distance resolution δD is determined by the Equation 2 using phase-shift resolution δφ.

\[ \delta D = \frac{1}{2\pi f_{rf} \cdot c/2 \cdot \delta \phi} \] (2)

Then, the sensitivity SD is deduced from Equation 3 given below:

\[ S_D = \frac{\delta D}{\delta \phi} = \frac{1}{2\pi f_{rf} \cdot c/2} \] (3)

The maximum measurement range Λ is then

\[ \Lambda = \frac{c}{2 f_{rf}} \] (4)

Hence, this method allows one to obtain a high distance resolution if the modulation frequency f_{rf} is high. To facilitate phase measurement, the photoelectric signal and the oscillator signal frequencies are both reduced by using an electronic heterodyne technique. (Fig. 1)

The photoelectric signal is mixed with a signal given by a balanced modulator whose frequency f_{lo} is close to f_{rf}. This heterodyne detection gives a better phase measurement resolution without changing the phase shift [9].

The major drawbacks of the electronic heterodyne technique are crosstalk effects between emitting and receiving circuits and a low signal-to-noise ratio (SNR). This is due to the low open loop gain Ad(f) of the transimpedance amplifier which works at high frequencies (f_{rf}). To improve the SNR and to minimize the crosstalk effects, one could perform optoelectronic mixing through an APD. With this technique, shown in Fig. 2, the frequency of the useful signal received by the transimpedance amplifier is f_{rf}, which strongly reduces the noise equivalent bandwidth. A supply voltage, in general, on the order of some hundreds of volts, in the case of commercial APD, is needed to apply an electric field important enough to release an avalanche in the multiplication region. Such a value of supply voltage is incompatible with embedded systems. Hence, it would be interesting to integrate an APD in a conventional CMOS technology to realize optoelectronic mixing in the case of a low-noise, low-consumption, compact, and accurate embedded rangefinder. Aside from this, the possibility of implementing the APD, together with the preamplifier circuit, could minimize the parasitic capacitors so as to still improve the bandwidth and the SNR.

III. DESIGN OF CMOS AVALANCHE PHOTODIODE

An APD is designed in AMS 0.35-μm CMOS technology after the optimization of its performances with SILVACO. The highest possible conversion gain is expected, as well as an avalanche voltage as low as possible. 0.35μm technology specs.

The main characteristics of the AMS CMOS 0.35-μm technology are reported in Table 1.
weak depths and the high doping values can be pointed out.

Table 1 Main characteristics of the AMS CMOS 0.35-µm technology

<table>
<thead>
<tr>
<th>Layer</th>
<th>Doping (cm⁻³)</th>
<th>Depth (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate P</td>
<td>$1.25 \times 10^{19}$</td>
<td>-</td>
</tr>
<tr>
<td>N Well</td>
<td>$1.28 \times 10^{19}$</td>
<td>1.2</td>
</tr>
<tr>
<td>P Well</td>
<td>$2.00 \times 10^{19}$</td>
<td>1.2</td>
</tr>
<tr>
<td>Contact N+</td>
<td>$5.00 \times 10^{18}$</td>
<td>0.2</td>
</tr>
<tr>
<td>Contact P+</td>
<td>$5.00 \times 10^{18}$</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Note that the small interval d separating both n-wells is smaller than the minimum value allowed by the AMS design rules. Finally, the guard ring is constituted by a weakly doped N-ring due to the n-wells lateral diffusion, whose geometry is not optimum but sufficiently decreases the breakdown voltage of the peripheral junction.

A cross-sectional view is shown in Fig 3. In CMOS technology, the multiplication of the photo generated carriers is realized in the absorption area, a very thin region where the electrical field is maximal. It is therefore impossible to separate the absorption area of the photons and the multiplication region of the carriers. The conception of this structure consists principally in taking into account two main difficulties. The first one concerns the technological constraints imposed by AMS. The main characteristics of the AMS CMOS 0.35-µm technology are reported in Table 1. The weak depths and the high doping values can be pointed out.

![Cross-sectional view of the CMOS APD developed with a guard ring.](image)

**Fig. 3 Cross-section view of the CMOS APD developed with a guard ring.**

The second difficulty is avoiding the early breakdown of the P’N peripheral junction due to the higher electrical field at the peripheral junction than at the planar junction.

IV. RESULTS AND DISCUSSION

The spectral responsivity $S_{\lambda APD}$ (in amperes per watt) of the APD has been measured by comparing the photoelectric current of the APD with the one obtained by a commercial photodiode PIN (BPW34) whose $S_{\lambda PIN}$ values are well known (4). The results obtained are reported in Fig. 4

$$S_{\lambda APD} = \frac{I_{\phi APD}}{P_{opt}} = \frac{I_{\phi APD}}{I_{\phi PIN}} \cdot \frac{A_{PIN}}{A_{APD}} \cdot S_{\lambda PIN}$$

(5)

With $A_{APD}$ and $A_{PIN}$, respectively, as the active areas of the studied APD and the reference PIN and with $I_{\phi PIN}$ and $I_{\phi APD}$, respectively, as the photocurrents of the reference photodetector and the APD. $P_{opt}$ is the optical power received by both photodiodes.

A better responsivity is obtained for short wavelengths. This is due to the penetration depth of photons in the device. In fact, the ideal photon penetration depth is equal to the P’ layer depth (0.1 µm) plus the depletion region depth (0.13 µm at −1V).

Table 2 Absorption Rate for Several Wavelengths.

<table>
<thead>
<tr>
<th>λ (nm)</th>
<th>σ (cm⁻³)</th>
<th>Absorption rate (e⁻)</th>
</tr>
</thead>
<tbody>
<tr>
<td>650</td>
<td>4.625</td>
<td>19</td>
</tr>
<tr>
<td>550</td>
<td>1.5688</td>
<td>0.918</td>
</tr>
<tr>
<td>450</td>
<td>3.2581</td>
<td>0.44</td>
</tr>
</tbody>
</table>
Based on Table 2, the absorption rate of photons in an absorption depth of 0.28 µm with \( \lambda = 450 \) nm is around 74%, whereas with \( \lambda = 650 \) nm, the photons absorption rate is around 22%. The junction depth is the limiting factor of the integrated APD for working with high wavelengths.

The internal gain \( M \) of the APD is shown in Fig. 5. Note that better values of the internal gain are obtained for the largest wavelengths; however, these are not interesting because the absorption coefficient (as well as the responsivity) decreases strongly with the wavelength, reducing the SNR. When biased at \(-6\) V, the APD has an internal gain of about 75 at \( \lambda = 650 \) nm.

Finally, the APD is designed in an optoelectronic mixer in the rangefinder, with \( f_{RF} = 1 \) MHz. This low frequency gives a measurement range \( \Lambda = 150 \) m and a distance resolution \( \delta D = 4.2 \) cm. The rangefinder can thus be easily embedded in a vehicle for an obstacle-detection application, where this low resolution is sufficient.

V. SIMULATION RESULTS

Electrical and optical simulations presented in this section have been performed using ATLAS© Software.

A. P’N Structure

The first simulation concerns the electrical field in the structure to ensure the efficiency of the guard ring. The horizontal distribution is reported in Fig. 6. At a reverse bias voltage of \(-5\) V, the maximum horizontal electrical field at the peripheral junction is about 2.901 V.cm\(^{-1}\). In the same condition, the vertical electrical field is about 7.552 V.cm\(^{-1}\). The electrical field is stronger vertically in the multiplication region than horizontally at the peripheral junction.

Then the spectral responsivity of the device has been studied and presented in Fig. 7. It presents a maximum around 450 nm. The simulation is performed for \( V_{apd} = -1 \) V not to be in avalanche mode. At this reverse bias value, the depletion region depth is equal to 0.355 µm. Table 2 represents the absorption rate according to the wavelength. One can easily notice that \( \alpha \) greatly increases for short wavelengths. That is why a cut-off of the photoresponse can be observed in short wavelengths range. The photons are essentially absorbed very close to the surface, where the recombination time is extremely short.
The study of the electrical field in this structure has brought us to determine the best structure with the suitable gap width d. The best structure is obtained for a gap width of 1 µm. The vertical electrical field distribution is reported in Fig. 8 When reverse biased at −5 volts, the maximum horizontal electrical field at the peripheral junction is about 7.985 V.cm⁻¹. In the same condition, the vertical electrical field is about 0.905 V.cm⁻¹. The chosen guard ring is efficient and decreases efficiently the electrical field at the peripheral junction.

The spectral responsivity of the N⁺P avalanche photodiode is presented in Fig. 9; the maximum is around 350 nm. In this case, a better responsivity is obtained for short wavelengths [6]. This is due to the absorption depth of photons in the device which is thinner than the P⁺N one. At −1 volt, the depletion region depth is equal to 0.082 µm.

VI. CONCLUSION

In this paper, the feasibility of performing optoelectronic mixing with a CMOS APD is presented and discussed. The use of an APD as an optoelectronic mixer leads to an improvement of the SNR in a laser phase-shift rangefinder and to a decrease in crosstalk. The CMOS APD developed operates at −5 V, which is compatible with an embedded system. Its ability to realize optoelectronic mixing has been validated at a low frequency (f_	ext{rf} = 1 MHz) which is suitable for an obstacle-detection application.

This paper presents the conception and simulation of avalanche photodiodes designed in a standard 0.35 µm CMOS technology. Two designs have been presented, a P⁺N device with a P-tub as guard ring and a N⁺P one with a lateral diffusion of two P-tubs as guard ring. The performances of both devices have been compared in terms of responsivity, noise and gain. The optical simulations present a good responsivity in the short wavelengths. Both structures present interesting characteristics. The future of this presented work is to conceive a CMOS array composed of a linear or matrix arrangement of APDs to be designed in a 3-D camera, each APD being individually designed in the CMOS ASIC. This configuration will permit one to work at higher frequencies (f_	ext{rf} = 40 MHz) in order to significantly improve the resolution (δD = 1 mm). A 3-D camera in the range 0.5–5 m, using a PIN photodiode, has already been developed.

For robotic applications, the scanning system must be of small size and as fast as possible. Hence, the laser beam is deflected by two micro-mirrors. Further work includes the design of a scanner-less camera.
REFERENCES


