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Fully Depleted SiPMs Optimized for Automotive NIR ToF in 180nm Technology

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I. Introduction

In recent years, Single Photon Avalanche photo Diodes (SPADs) are getting a lot of attention in the fast growing applications and markets of Time of Flight (ToF) and 3D imaging. In particular, in the automotive market, where many *Light Imaging, Detection, and Ranging* (LiDAR) systems use SPAD as their sensor. A special device, based on SPAD technology, is specifically attractive for LiDAR systems, namely the Silicon Photo Multiplier (SiPM). This is a parallel connected array of SPADs which gives the combination of sensitivity, down to a very few photons, and excellent time resolution, providing information about the number of simultaneously impinging photons. This is in contrast to the classical SPAD, which has only a digital "zero/one" behavior. Automotive LiDARs and other ToF applications uses near Infra-Red (NIR) illumination and thus a good Photon Detection Efficiency (PDE) is required for these wavelengths, usually 905nm or even 940nm. In order to have good PDE in the NIR regime, one needs a thick absorbing region in the SPAD device. This is very challenging for CMOS based SPAD devices, where the multiplication depth is dictated by ion implants. Furthermore, the deep absorption usually generates electrons that reach the multiplication region by slow diffusion mechanism and creates a lag that deteriorates the ToF performance. We present in this paper the optimization of such an SiPM by means of layout and process.

II. "Single Ended" vs. "Two Ended" SPAD

Many SPAD designs are using the "Two Ended" SPAD approach where the PN junction of the SPAD is isolated from the bulk by a deep N-well. The photons absorbed in the bulk under this deep N-well cannot create an avalanche and thus, are not usable for light detection. The depth of the N-well, dictated by the implant energy, becomes the limiter for NIR sensitivity. The advantage of this scheme is the ease of designing of active quenching circuits.

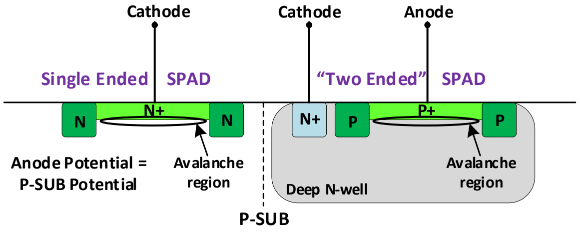

Fig. 1 *The illustration of the single ended and "two ended" SPAD types*

In contrast, the single ended SPAD uses the Si epi layer as its anode, thus allows absorbing much deeper photons that enhance the NIR response. The classical passive quenching is usually good enough for LiDAR applications as discussed below, though active quenching schemes are also available for this single ended configuration [1]. In order to have high performance for ToF, the collection of electrons for a breakdown event should be dominated by electrical field induced drift rather than by slow diffusion mechanism. In the evolution of these kind of SPADs in TowerJazz, two approaches were used:

1. Using the built-in field caused by up-diffusion of Boron coming from the highly doped bulk into the lightly doped active epi layer. This is an efficient solution for rather thin epi layer of 5.5um 30 ohm*cm, as shown in figure 2

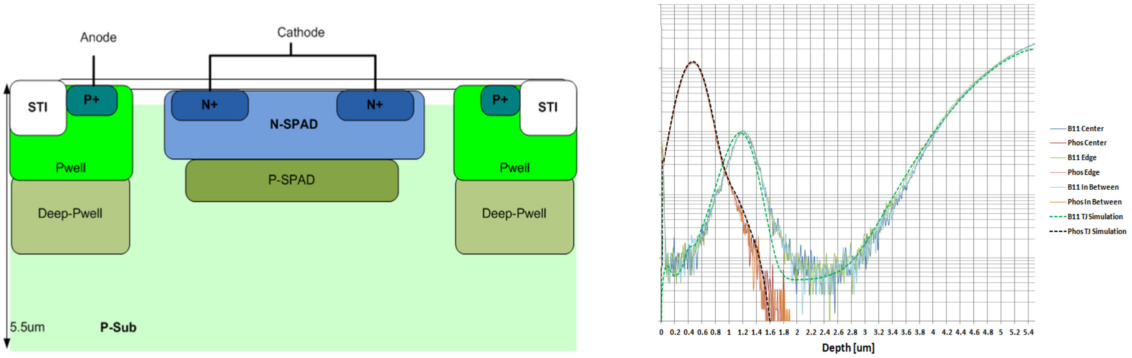

Fig. 2 *Single Ended SPAD with vertical field caused by Boron up-diffusion*

2. A "Fully depleted" SPAD, where the depletion region penetrates through the epi layer [2]. This can be achieved by the usage of a high resistive epi material and a careful design of the implant scheme of the multiplication region of the SPAD's junction. The simulated potential and electrical field for such a scheme is shown in figure 3.
   This approach enables the use of a thicker epi layer and allows for a higher NIR response. 9um epi results, as compared to the 5.5um epi, are presented in Fig. 3.

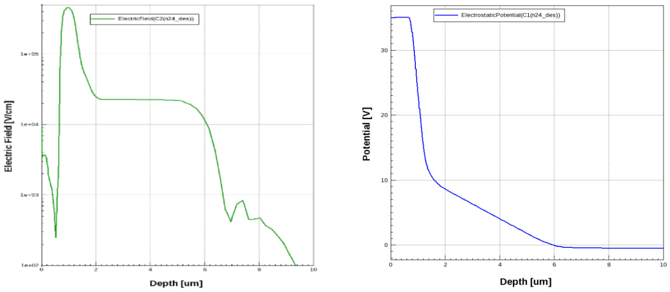

Fig. 3 *Simulated Electric filed and potential for a fully depleted SPAD. The field in the high resistivity depleted epi is almost constant.*

III. Passive Quenching SPADs and SiPM Optimization

The basic SPAD cell is composed of a SPAD diode, a quenching resistor and a coupling capacitor. A high resistance poly resistor ($10k\Omega/\square$) and metal fringe capacitor are used, enabling efficient and dense layout for SPAD array as shown in figure 4. SPAD cells ranging from 20um to 50um where designed. TCAD simulations were used for designing the diode edge, avoiding early breakdown as shown in figure 5. The PDE/PDP curve, the DCR and the jitter for the 5.5um are shown in figure 6 [3].

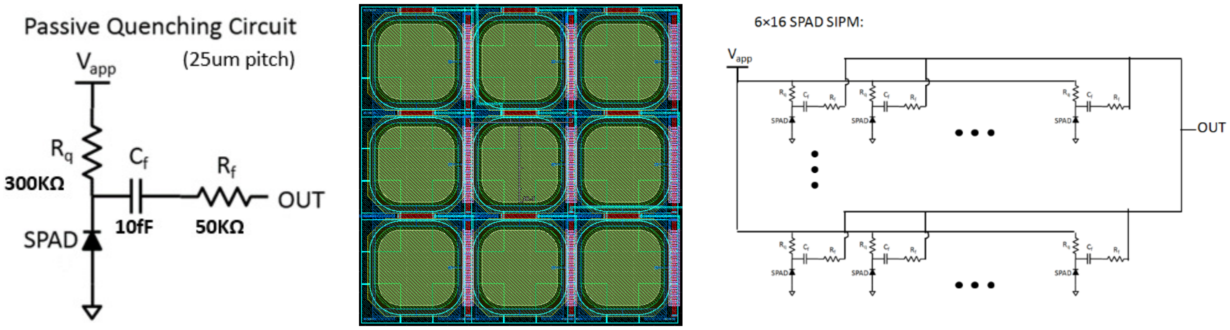

Fig. 4 *basic SPAD cell with passive quenching scheme, typical layout, and SiPM organization*

In figure 7, PDE, DCR and Crosstalk vs. excess bias are shown for the 5.5um up-diffusion based SPAD as well as for the 9.0um fully depleted one. In order to enable the design of a system based on this SPAD device, a SPICE model was created, enabling engineering of the pulse shape of the SiPM [6].

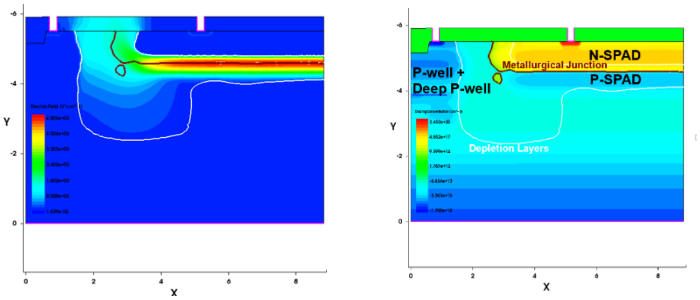

Fig. 5 *Doping profile and electrical field profile for SPAD edge*

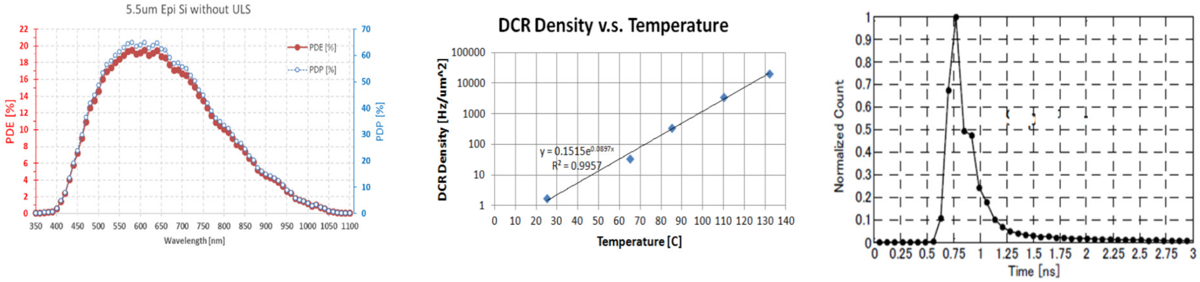

Fig. 6 *PDE/PDP curve, DCR vs. temperature and jitter for the 5.5um epi SPAD*

According to the required operation one may want to mix adjacent events to make an analog signal proportional to the number of events related to the same reflected image, or keep a SPAD-like behavior of single events. Figure 8 shows a usage of this model to tune pull up resistor of an SiPM to meet one of the above approaches.

IV. Discussion

There are several approaches for using SPAD and SiPMs in LiDAR systems. The total area of a pixel is mainly dictated by the expected signal strength and the PDE. The number of SPADs within an SiPM is usually related to dynamic range requirements. Thus, the trade-off between SPAD size, PDE, crosstalk, jitter and all other SPAD performance parameters is heavily dependent on the system architecture. Furthermore, the specific architecture has a vast impact on the other device we may want to have on the same die of the SPADs. This can range from active quenching circuits, amplifiers to carry the signal, off-chip ADCs and TDCs.

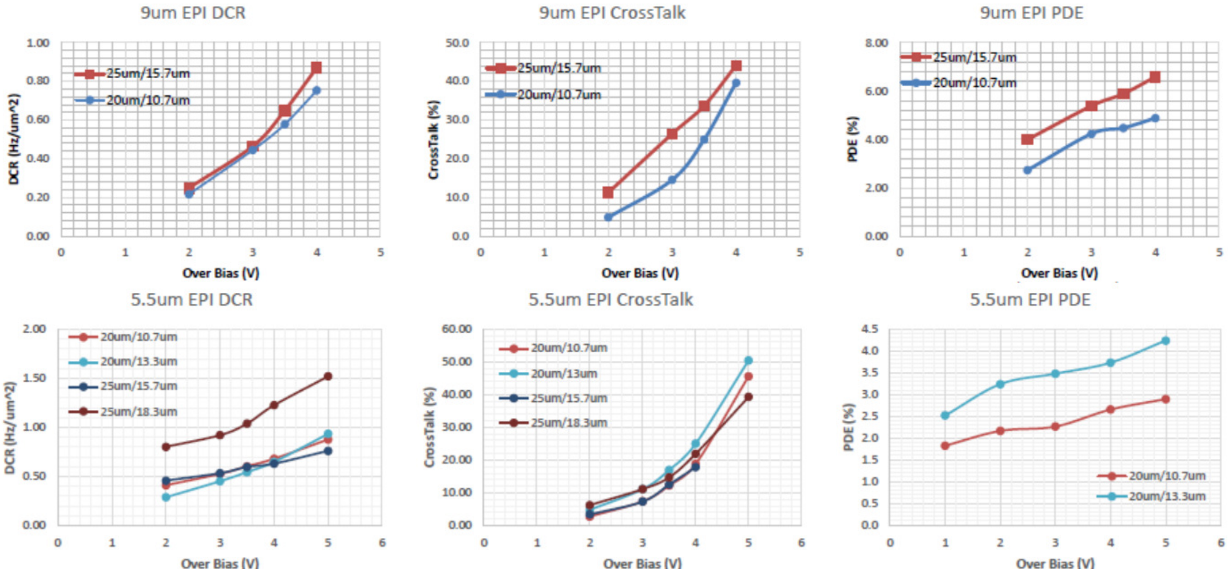

Fig. 7 *DCR, Crosstalk and PDE for 5.5um and 9.0 High Resistivity optimized SiPMs, for different layout designs*

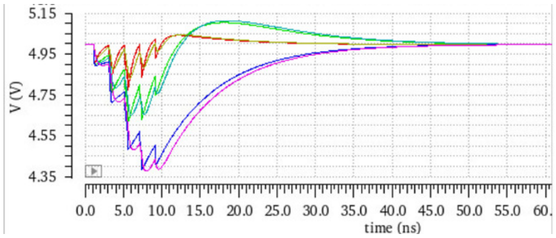

Fig. 8 *SiPM Response for a series of photons for different pull-up resistor and different in-cell resistor*

An even more innovative combination is the addition of CMOS image sensor pixels, used, either as complementary imaging, or as part of the data processing [5]. As a foundry, we need to be open for this diversity. Thus, we characterize different pixel sizes and pixel schemes to be ready for the different trade-offs. We also built the SPAD platform in a way that it is fully embedded into the 0.18um full CMOS technology platform, and even further – can support CMOS image sensors or high voltage transistors (up to 100V) on the same die.

1. Active Reset for the N+P Single Ended SPAD, US 62804839, 2018
2. WEGRZECKA, IWONA, and MACIEJ WEGRZECKI. "Silicon photodetectors-the state of the art." Warsaw (1997): 137-145.
3. Niclass, Cristiano, et al. "NIR-sensitivity-enhanced single-photon avalanche diode in 0.18 µm CMOS." Proceedings of the International Image Sensor Workshop, Vaals, The Netherlands. 2015
4. Zou, Yu, et al. "Fully CMOS analog and digital SiPMs." Optical Components and Materials XII. Vol. 9359. International Society for Optics and Photonics, 2015.
5. Wang, Y. M., Lilong, S. H. I., & Ovsiannikov, I. (2018). U.S. Patent Application No. 15/657,101.