Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 9-10, 2024

Design of the Low Voltage Single Photon Avalanche Diode for Enabling Radiation Sensor Network System

Jinseok OH[a, b], Chanho Kim[a], Min Sun Lee[a], Inyong Kwon[c,*]
[a]*Korea Atomic Energy Research Institute (KAERI), Daejeon 34057, South Korea*
[b]*Korea University of Science and Technology (UST), Daejeon 34113, South Korea*
[c]*Yonsei University, Wonju 26493, Korea*
[*]*Corresponding author: ikwon@yonsei.ac.kr*

***Keywords :** single photon avalanche diodes (SPADs), premature edge breakdown (PEB), depletion region, breakdown voltage, guard ring, dark count rate (DCR), photon detection probability (PDP), standard CMOS

1. Introduction

Single photon avalanche diode (SPAD) is used to detect the photon with precision in various applications. In the past, the avalanche photon diode (APD) operated at the linear mode enabled to get the output signal that is proportional to the intensity of light, but it has a low output gain and sensitivity because many photo-electrons are required to induce the avalanche effect under around the breakdown voltage. On the other hand, the SPAD can trigger the signal at the single photon level with high gain due to the high electric field generated by the bias over the breakdown voltage. Hence, the SPAD is adopted in application that require precision photon counting such as fluorescence lifetime imaging (FLIM), light detection and ranging (LiDAR), time-of-flight (ToF), Raman spectroscopy and radiation detector.

The SPAD has been actively studied along with the development of applications. Some studies have shown the performance improvement in SPAD or APD by implementing junction engineering [1], particular CMOS fabrication processes [2], and additional gate control [3]. As the scale of the system including a photon detector has been decreasing, the small-size photon diode that composes the photon sensor as a form in an array of pixels is required with low operating voltage. At the same time, the devices must be operated at the low noise levels.

In this work, the SPAD was designed to be utilized for sensor networks in nuclear power plants (NPP) in Fig 1 [4]-[5]. The many sensor devices will be scattered to detect movement of radiation as a type of the mesh in event of severe accidents in the NPP and must be operated to detect released radiation in a harsh environment. So, the photon sensor to be used in radiation detector has small size and low operating voltage for saving power consumption. Therefore, the proposed SPAD provides a compact size by fabricating in a common process and is able to develop a smaller system through integration with a readout circuit. Additionally, the low operating voltage can be materialized by decreasing the breakdown voltage into the junction engineering with design elements.

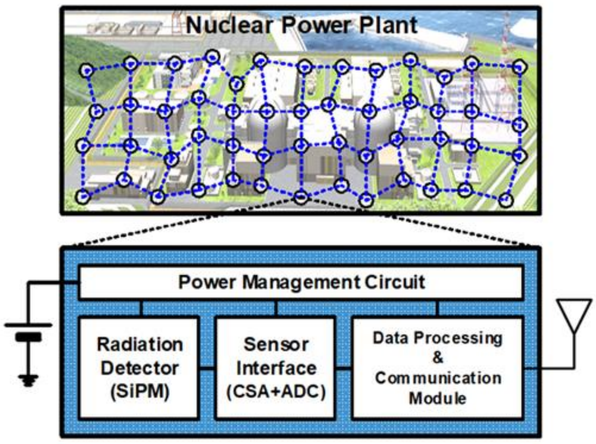

Fig. 1. The diagram of sensor network system. Upper is entire sensor network diagram in the nuclear power plant. Bottom is schematic of a wireless radiation detector.

In the case of small-size SPAD, the dark count rate (DCR) can be decreased due to the lower density of mobility carriers for the unit area in the junction. However, the premature edge breakdown (PEB) contributing to the dark count is increased since portions of the edge side are more occupied. To prevent the PEB, the shallow trench isolation (STI) guard-ring (GR) is typically adopted to reduce the electric field at the edge of the junction. Moreover, different types of GR have been used to reduce the surface defect that is occurred around the STI surface. Consequently, the proposed SPAD was optimized to expand the Silicon photomultiplier (SiPM) at each parameter like breakdown voltage, DCR and photon detection probability (PDP).

2. Design Configuration

The proposed SPADs fabricated in common 180 nm CMOS process are designed as each layer in Table Ⅰ. The PSD/ n-well thin junction devices (model 1 and 2) are designed as conventional models to compare the other devices. The PSD/DNW thick junction models (model 3 and 4), which are the mainly proposed models.

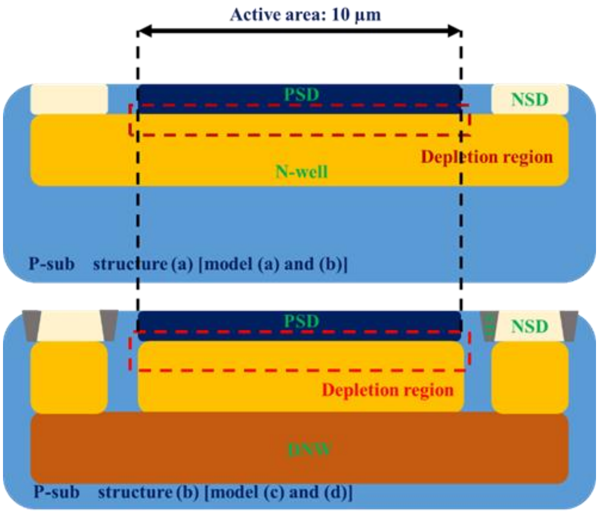

Fig. 2. Cross-sections of four models. The designed models were generally divided into two architectures: (a) a PSD/ N-well depletion structure and (b) PSD/ N-well/ DNW depletion structure. In both architectures, the active diameter was 10 μm.

The thick junction models have a wide absorption region contributing to photon sensitivity.

3. Measurement and characterization

2.1 I-V Curve Measurements

The current according to the voltage was measured in I-V probe station. The measure breakdown voltage was 10.75 V and it was used with excess voltage to operate the SPAD for other parameter experiments. All designed devices achieved a low operating voltage due to the shallow junction.

2.2 Dark Count Characterization

To measure pure dark current noise factor, the SPAD was tested in "dark" state where photons couldn't come in the devices. Moreover, to characterize dark count depending on the bias, the excess voltage of each device was supplied from 0.01 V to 0.1 V. After that, the measured data was converted dark count depending on the shape of pulses. The DCR of model 3, which is the proposed model, is plotted as shown in Fig. 2 and achieved DCR of minimum 11.5 Hz to maximum 113.1 kHz at the room temperature.

2.3 Photon Detection Probability

The photon detection experiment composed pulsed laser of 405 nm, attenuator, neutral filet (ND) and light flux controller was implemented to explore the optical sensitivity of the SPADs at excess voltage of 0.04 V. The photon detection probability (PDP) was calculated as following equation:

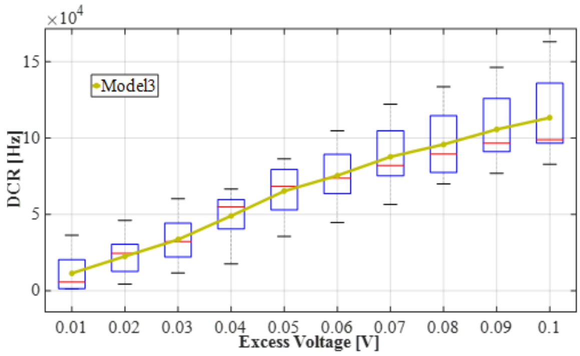

Fig. 3. Measured DCR of model 3 for characterization at the room temperature.

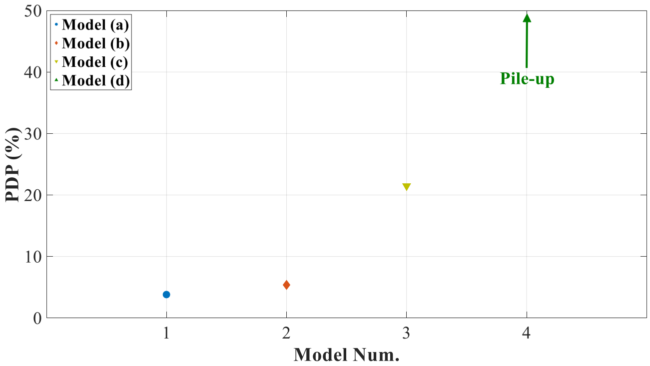

Fig. 3. PDP comparison of models. For model (d), the output signal was saturated.

TABLE 1. PARAMETERS OF EACH SPAD

Model Num.	Total* / Active radius	Use to Guard-ring type in the n+	Active area Layer	P - N Junction layer
Model (a)	15/10 μm	P-sub	P-imp*	PSD/ N-well
Model (b)	15/10 μm	P-sub	PD-imp*	PSD / N-well
Model (c)	16/10 μm	P-well +STI	P-imp	PSD/ N-well/ DNW
Model (d)	16/10 μm	P-well +STI	PD-imp	PSD/ N-well/ DNW

* P-imp is typically used as the implanted layer.
* PD-imp (P-imp diffusion) is more diffused than the general implant layer.

$$\mathrm{PDP}\ (\%) = \frac{CPS - DCR}{n_{incident} * \delta_{active\ area}} * 100.$$

, where CPS is the count rate of SPADs, DCR is the measured dark count, n is number of incident photon generated by light source, and δ is a rate of the active area, which incident photon can be triggered in the SPAD. Calculated PDP of each SPAD is indicated in Fig. 3.

In this work, the model 3 and 4, which share the same junction design, showed a high-count pulse with PDP of 24.48 % for model 3 at 405 nm, but model 4 was saturated by pulses above the CPS. In contrast, model 1 and 2 achieved PDP of < 10 % and recorded a low sensitivity.

3. Conclusions

The proposed SPAD was designed in consideration of small size and low operating bias, to be used as the radiation detectors for sensor networks monitoring severe accidents in nuclear power plants (NPP). The characterized parameters of the proposed device can be utilized when the SPAD is extended to an array for SiPM. Furthermore, the performance can be improved by integrating it with the readout circuit. The experimental and measurement results will be presented at the conference.

Acknowledgements

This work was supported in part by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science and ICT (RS-2022-00144324, RS-2022-00144419 and 2022M3F3A2A01072855)

REFERENCES

[1] LEE, Haewon; CHOI, Hyejeong; YUN, Ilgu. Junction Engineering-Based Modeling and Optimization of Deep Junction Silicon Single-Photon Avalanche Diodes for Device Scaling. IEEE Transactions on Electron Devices, 2022.

[2] VORNICU, Ion, et al. Design of High-Efficiency SPADs for LiDAR Applications in 110nm CIS Technology. IEEE Sensors Journal, 2020, 21.4: 4776-4785.

[3] W. Jiang, Y. Chalich, R. Scott and M. J. Deen, "Time-Gated and Multi-Junction SPADs in Standard 65 nm CMOS Technology," in IEEE Sensors Journal, vol. 21, no. 10, pp. 12092-12103, 15 May15, 2021, doi: 10.1109/JSEN.2021.3063319.K. Elissa, "Title of paper," unpublished.

[4] H. Jeon, I. Kwon and M. Je, "Radiation-Hardened Sensor Interface Circuit for Monitoring Severe Accidents in Nuclear Power Plants," in IEEE Transactions on Nuclear Science, vol. 67, no. 7, pp. 1738-1745, July 2020, doi: 10.1109/TNS.2020.3002421.