Effect of different guard ring structures on electrical and thermal characteristics of single photon avalanche diodes

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Abstract — Single photon avalanche diodes (SPADs) applied for the automotive application, which requires the temperature stability for the severe ambient environment. Therefore, it is necessary to analyze the device electrical and thermal characteristics for temperature variations. In this paper, through the electrical and thermal experiments, SPAD with three different guard ring structures effects are studied and the trends is also verified using ATLAS technology computer-aided design (TCAD) simulation.

Keywords — Single photon avalanche diode, device reliability, temperature dependence, guard ring.

I. INTRODUCTION

Single photon avalanche diode (SPAD) can detect the photon sensitivity at high speed. Si-based (complementary metal-oxide-semiconductor) CMOS SPAD process due to the low-cost in manufacturing and the capability of scaling. However, CMOS SPAD also need the guard ring to prevent the edge breakdown [1]. In this paper, the effects of different guard ring structures on the SPAD electrical and thermal characteristic variations are investigated. ATLAS technology computer-aided design (TCAD) simulation is also performed to analyze the trends for SPADs [2].

II. SPAD TEST STRUCTURE FABRICATION

All the devices in this experiment have been fabricated with Dongbu 0.11-μm CMOS technology process. As shown in Fig 1, the device under test (DUT) 1 is the p′n-well structure with the p-well guard ring. DUT 2 has a shallow trench isolate (STI) guard ring structure. DUT 3 has the hybrid of the isolated p-well and STI guard ring structure. Three tested structures for each guard ring structure are measured for the reproducibility. Here, the current-voltage (I-V) characteristics are measured to extract the breakdown voltage ($V_{BR}$), the on current ($I_{ON}$), and the off current ($I_{OFF}$) at 300k, 360 K and 400 K. The normalized $V_{BR}$, $I_{ON}$ and $I_{OFF}$ were defined as in Eq. 1, respectively.

$$\text{Normalized } X \left( V_{BR} \right) = \frac{X \left( \text{at } T_\text{measured} \right)}{X \left( \text{at } 300 \text{ K} \right)} \quad (1)$$

III. RESULT AND DISCUSSION

The characteristics of the SPADs are varied according to the temperature. As shown in Fig 2, $V_{BR}$ increases as the temperature increases. When the temperature increases, increasing $V_{BR}$ is due to the decrease in electric field (E-field) and mobility, and the increase of the intrinsic carrier concentration and the phonon population [3].

$I_{ON}$ tends to decrease when the temperature increases since the number of carriers is increased due to the mobility reduction. While the temperature increases, the carriers trapped in the defects are released, and the mobility further decreases. In addition, as the temperature increases, the leakage current is also increased. DUTs 2 and 3 starts the tunneling process earlier than DUT 1. It is because the trap assisted tunneling (TAT) caused by the defects impact on the tunneling which can decrease the increment of the reverse current after avalanche process [4]. Therefore, the temperature dependency of DUT 1 is smaller than DUT 2 and DUT 3.

The modeling and simulations of three different types of the guard ring structures have been conducted. It is observed that the simulated data show the same tendency with the measured data. In case of $V_{BR}$, DUT 2 and DUT 3 show the higher increasing rate than that of DUT 1 as observed in the measured result. Fig. 5 shows the E-field of DUT 1, DUT 2 and DUT 3 and the cutline of the electric field for the 2-D profiles. The E-field at the interface in DUT 2 and DUT 3 is higher than that of DUT 1 as shown in Fig. 6. It is indicating that DUT 2 and DUT 3 require more bias voltage to reach $V_{BR}$ than DUT 1.

IV. CONCLUSIONS

The effects of the three different guard ring structures on electrical and thermal characteristics on SPADs have been investigated. Based on the results, it can be concluded that the SPAD with p-well guard ring showed better in electrical and thermal stability than the STI-based guard rings.

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REFERENCES