Numerical Analysis of Different Impact Ionization Models in Single-Photon Avalanche Diodes

Li-An, Huang
Graduate Institute of Photonics and Optoelectronics
National Taiwan University
Taipei, Taiwan

Jau Yang Wu
College of Industry-Academia Innovation
National Taiwan University of Science and Technology
Taipei, Taiwan

Yuh-Renn Wu*
Graduate Insitute of Photonics and Optoelectronics
National Taiwan University
Taipei, Taiwan
yrwu@ntu.edu.tw

***Abstract*—Two impact ionization models are examined within our custom TCAD framework to analyze the intensity and spatial distribution of impact ionization in the SPAD under different bias voltages and compare the breakdown voltage to the experimental results. The goal is to reduce the noise levels and improve the efficiency for quantum key distribution applications.**

***Keywords*—TCAD, Impact Ionization, SPAD**

I. INTRODUCTION

The Single-Photon Avalanche Diode (SPAD) is widely used in Quantum Key Distribution (QKD) and various other low-light applications such as Light Detection and Ranging (LIDAR). SPADs are capable of detecting single photons with extremely high sensitivity and precise timing resolution, making them essential in applications that require high-speed and low-noise photon detection. Its operation relies on the creation of a strong electric field to accelerate a photo-generated electron–hole pair. One of the most common methods is creating a pn junction, then applying high reverse bias to create a depletion region. As this carrier pair gains energy, it undergoes collisions with the crystal lattice, generating additional pairs through a process known as impact ionization multiplication, leading to an avalanche effect.

In this research, we first used our own TCAD software, 2D-DDCC, to replicate the results of the device in [1] (Schematic structure 2, S2) as shown in Fig.1 (a) and the doping concentration shown in Fig. 1(b). The 2D FEM based Poisson and drift-diffusion equation solver with cylindrical coordinates are used in the simulation. The generation term in the equation of continuity is used to treat the impact ionization. Two models, the Chynoweth model [2] and the Okuto-Crowell model [3], were applied to simulate the electric characteristics of SPAD to determine the avalanche breakdown voltage. By tuning the doping profile, we were able to modify the impact ionization distribution and even restrict the impact ionization process in the specific region to avoid the current flow through defect-prone areas such as the Si/SiO_2 interface.

A higher excess bias results in a stronger electric field, thereby increasing the trigger probability of the SPAD. Also, the shorter buildup time for avalanche reduces the time jitter [4]. Therefore, the applied voltage is usually set as high as the dark count rate allows. However, numerical simulation beyond the breakdown voltage fails due to unstable positive loop gain, which makes it hard to get convergence.

TABLE I DOPING CONCENTRATION OF EACH REGION

P ++	N++	HVPW	HVNW	NBL	P-sub
1×10^{20}	1×10^{20}	2.8×10^{16}	1×10^{16}	9×10^{16}	5.8×10^{15}

Unit: 1/cm³

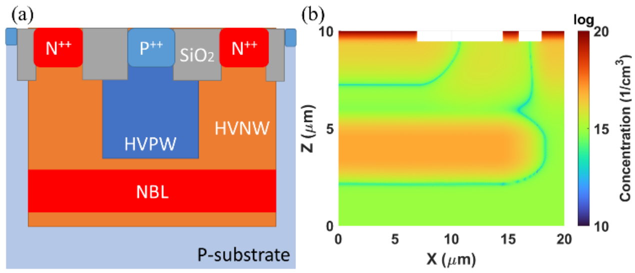

Fig 1 (a) Cross-sectional structure of the simulated device. (b) Doping concentration profile used in the simulation. Owing to structural symmetry, only one half of the device is considered in the simulation domain.

II. METHODOLOGY

Accurately modeling impact ionization is crucial for simulating the avalanche process, as even small variations in Nthe generation rate can substantially influence the simulation outcomes. We choose parameters of the Chynoweth model in [5] and the Okuto-Crowell model in [6]. The generation rate of impact ionization is calculated by the equations (1) and (2):

$$G_n = \alpha_n \times \frac{|J_n|}{e} \tag{1}$$

$$G_p = \alpha_p \times \frac{|J_p|}{e} \tag{2}$$

G_n and G_p represent the impact ionization generation rate for electron and hole, respectively, with unit cm^{-3}. α_n, α_p are the impact coefficients for electrons and holes. J_n and J_p are the current densities for carriers, and e is the elementary charge. The Chynoweth model is shown in the equation below:

$$\alpha_n(E) = A_n \exp\left(\left|\frac{B_n}{E}\right|^{C_n}\right) \tag{3}$$

$$\alpha_p(E) = A_p \exp\left(\left|\frac{B_p}{E}\right|^{C_p}\right) \tag{4}$$

A_n and A_p are prefactors with the unit of cm^{-1}. B_n and B_p are the critical fields with unit V/cm. C_n and C_p are the tuning factors with no unit. E is the local field. The parameters for the Chynoweth model are shown in Table II

TABLE II CHYNOWETH MODEL PARAMETERS FOR SILICON

	A (1/cm)	*B(V/cm)*	*C*
Electron	7.03×10^{5}	1.231×10^{6}	1.0
Hole	1.582×10^{6}	2.036×10^{6}	1.0

Unlike the Chynoweth formulation, this extended model introduces a field-dependent polynomial prefactor and a tunable exponential field sensitivity, allowing better agreement with experimental results over a wide range of electric fields. The impact ionization coefficient can be described in equations (5) and (6), and the magnitudes are shown in the Table. III.

$$\alpha_n(E) = A_n \left(\frac{E}{E_0}\right)^{\gamma_n} \exp\left(\left|\frac{B_n}{E}\right|^{\Delta_n}\right) \quad (5)$$

$$\alpha_p(E) = A_p \left(\frac{E}{E_0}\right)^{\gamma_p} \exp\left(\left|\frac{B_p}{E}\right|^{\Delta_p}\right) \quad (6)$$

TABLE III OKUTO-CROWELL MODEL PARAMETERS FOR SILICON

	A (1/cm)	B (V/cm)	γ	Δ
Electron	0.426	4.81×10^5	1.0	2.0
Hole	0.243	6.53×10^5	1.0	2.0

By comparing the two models in Fig 2, it is observed that significant differences arise under low electric field conditions; the Okuto-Crowell model was not activated until the electric field reached 4.2×10^4 V/cm. Even though the magnitude of the coefficients is quite small in the low electric field region, they cause remarkable influences in the calculation.

Considering the alignment between the current and the electric field, E in Eq (3) and (5) is substituted by $\frac{\vec{J_n}\cdot\vec{E}}{|Jn|}$ and E in Eq. (4) and (6) is substituted by $E_{eff} = \frac{\vec{J_p}\cdot\vec{E}}{|Jp|}$.

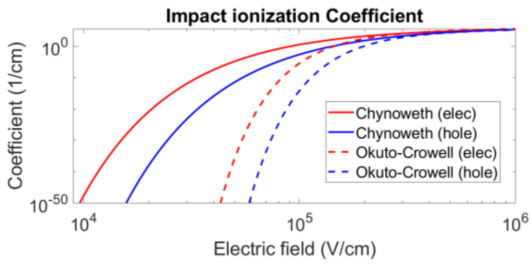

Fig 2 Impact Ionization Coefficient of the Chynoweth model (solid line) and the Okuto-Crowell model (dash line).

III. RESULT AND DISCUSSION

Fig. 8 in Ref. [1] shows that both simulation drain current and measured drain current were breakdown at about the V_D = -77 V, which is quite close to our results using the Okuto-Crowell model, and the magnitude of current is better agreement with the measured one than simulation results, so we'll focus on results of Okuto-Crowell model in following discussion. The Chynoweth model has a smaller breakdown voltage around -74V but exhibits a smoother transition in the region before avalanche breakdown.

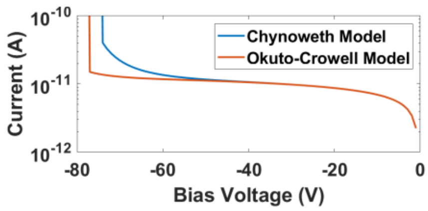

Fig 3 I–V characteristics of the device using two different models.

To investigate the avalanche mechanism in the device, the spatial distribution profiles of impact ionization were analyzed at the breakdown voltage and shown in Fig 4 (a) and 3(b). It's obviously the impact ionization was crowded in lateral and vertical junction between the HVPV and the HVNV. The separation of the distribution into two distinct regions is presumed to result from the poor alignment of the current and the electric field.

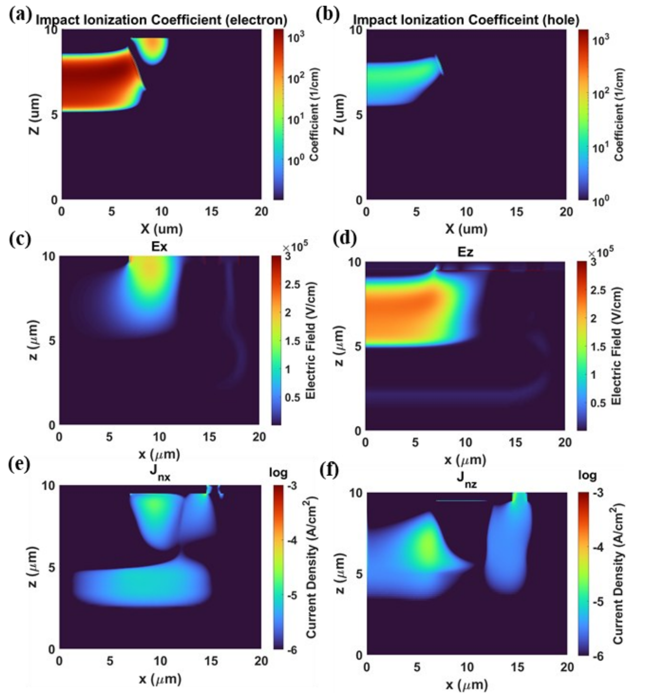

Fig 4 (a) and (b) show the impact ionization coefficient distribution of the Okuto-Crowell model at breakdown voltage (V = -77V) generated by electron and by hole, respectively. (c) and (d) show the electric field in the x direction and the z direction in a linear scale. (e) and (f) show the J_{nx} and J_{nz} in log scale, respectively.

IV. CONCLUSION

We successfully reproduced the experimental results by applying the Okuto–Crowell model. The simulated I–V characteristic exhibits a sharp transition at the breakdown voltage, indicating the occurrence of the avalanche effect. To prevent current from flowing into the region near the oxide, the lateral electric field must be suppressed, while a stronger vertical electric field is preferred. Additionally, the location of the impact ionization "hot spot" plays a critical role. Due to the non-uniform current distribution, the generation rate can vary significantly across the junction, even if the impact ionization coefficient remains nearly constant.

REFERENCES

[1] J.-Y. Wu, P.-K. Lu, and S.-D. Lin, "Two-dimensional photo-mapping on CMOS single-photon avalanche diodes," Optics Express, vol. 22, no. 13, 2014, doi: 10.1364/oe.22.016462.

[2] A. G. Chynoweth, "Ionization Rates for Electrons and Holes in Silicon," Physical Review, vol. 109, no. 5, pp. 1537–1540, 1958, doi: 10.1103/PhysRev.109.1537.

[3] Y. Okuto and C. R. Crowell, "Ionization coefficients in semiconductors: A nonlocalized property," Physical Review B, vol. 10, no. 10, pp. 4284–4296, 1974, doi: 10.1103/PhysRevB.10.4284.

[4] M. A. Itzler et al., "Avalanche buildup and propagation effects on photon-timing jitter in Si-SPAD with non-uniform electric field," presented at the Advanced Photon Counting Techniques III, 2009.

[5] R. Van Overstraeten and H. De Man, "Measurement of the ionization rates in diffused silicon p-n junctions," Solid-State Electronics, vol. 13, no. 5, pp. 583–608, 1970, doi: 10.1016/0038-1101(70)90139-5.

[6] Y. Okuto and C. R. Crowell, "Threshold energy effect on avalanche breakdown voltage in semiconductor junctions," Solid-State Electronics, vol. 18, no. 2, pp. 161–168, 1975, doi: 10.1016/0038-1101(75)90099-4.