Simulation of Geiger Mode Silicon Carbide Avalanche Photodiode

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***Abstract*—The breakdown probability and timing jitter of silicon carbide single-photon avalanche diodes were simulated with a random path length Monte-Carlo model. The results are in good agreement with the measured device characteristics.**

***Index Terms*—Avalanche photodiode, photodetector, timing jitter**

I. INTRODUCTION

Silicon carbide (SiC) single photon avalanche diodes (SPADs), have recently been studied for extremely low-level ultra-violet (UV) detection [1,2]. High single-photon detection efficiency (SPDE) of up to ~ 38% with low dark count rate was reported on 4H-SiC SPADs at room temperature [2]. Despite the fact that some of the fundamental material parameters of SiC are not well known, reports on modeling linear mode SiC APD have achieved results consistence with experiment data.[3,4] In this work, we report simulation of the Geiger-mode performance of SiC APDs with a random path length (RPL) Monte Carlo model.

II. METHOD

The RPL model was first investigated by Ong, *et al.* [5] for simulations of the characteristics of linear-mode APDs. It was extended by Tan, *et al.* to studies of the breakdown probability and timing jitter of SPADs [6]. Ng, *et al.* investigated the impact of the non-local effect on the excess noise of SiC APDs with this model. [3]

In the non-local impact ionization model with hard dead space, the chance that a carrier generated at location x_0 travels to a new location x in the depletion region without experiencing impact ionization can be described as the survival probability $P_{se}(x|x_0)$. For electrons, this is related to the electron ionization coefficient by

$$P_{se}(x \mid x_0) = \exp(-\int_{d_e(x0)}^{x} \alpha^*(x_0+z)dz),$$

where $\alpha^*(x)$ is the enabled impact ionization coefficient of electrons and d_e is the dead space for electrons generated at x_0. Here we assume that the residue kinetic energy of carriers after triggering impact ionization and the kinetic energy of the carriers immediately after impact ionization are both negligible. The expression for the survival probability for holes is similar. In the random path length model, the distance that a carrier generated at x_0 travels before experiencing impact ionization is $|x_0-x_1|$ in which the x_1 is the solution of the equation

$$P_{se}(x \mid x_0) = R,$$

where R is a random number between 0 and 1. If x_1 is within the depletion region, an impact ionization will be triggered at x_1 and a new electron-hole pair will be generated. Otherwise if x_1 is outside the depletion region, the carrier is considered to have transited to the contact layer.

In order to investigate the breakdown probability and jitter of SPADs, we assume that all carriers move in the depletion region with a constant velocity (average drift velocity). The time and position in the depletion region of all carriers were tracked for each injected carrier. Therefore, the current flowing in the device can be calculated by:

$$I(t) = q\frac{N(t,\Delta t)}{\Delta t},$$

where N(t, Δt) is the number of carriers that arrived at the edge of the depletion region in a time interval Δt at time t. The tracking process for each injected carrier is terminated when one of the following criteria has been satisfied: 1) the current initiated by the injected carrier reaches a certain threshold value; 2) all the carriers are collected before the threshold current was achieved, or 3) a certain amount of time (maximum tracking time) has transpired. Criterion 1) corresponds to the situation that the injected carrier has initiated a detectable current pulse, which will be registered in a counter at the device output. In this case, the avalanche build-up time is the time from the injection of the carrier to the point when the current reaches the threshold. Criteria 2) and 3) correspond to the situations that the current failed to reach the threshold within the maximum tracking time representing the gate width in gated-mode operation. Multiple runs need to be performed in order to achieve reliable statistical averages. The breakdown probability is the percentage of injected carriers that result in a count. Timing jitter is related to the variance of the avalanche build-up time, the diffusion time for carriers generated outside of the depletion region and the pulse width of the incident light pulse.

III. EXAMPLE AND DISCUSSION

The SiC SAPD reported in reference [1] was investigated as an example here. The 4H-SiC epi- layers from surface to

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substrate are: 200 nm p+ contact layer ($N_A=1\times10^{19}cm^{-3}$), 200 nm p layer ($N_A=2.4\times10^{18}cm^{-3}$), 480 nm p- layer ($N_A=2.8\times10^{15}cm^{-3}$) and 2000 nm n layer ($N_D=4.5\times10^{18}cm^{-3}$). The p+ contact layer was thinned in the detecting area to form a recessed window of depth ~160 nm. A ~230 nm SiO_2 antireflection layer was deposited on top of the SiC.

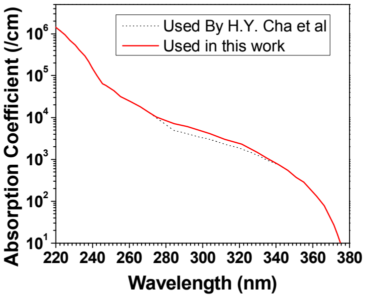

Fig. 1. Absorption spectra of SiC used to fit the quantum efficiency. The dashed line shows the absorption spectra fitted by Ho-Yong Cha[4].

Quantum efficiency vs. the wavelength was calculated with consideration given to photon absorption, minority carrier diffusion and surface recombination [7]. The carrier diffusion coefficients and diffusion lengths for SiC with different doping densities were calculated based on the lifetime and mobility values in [4]. High surface recombination velocity of 10^7 cm/s was used for the recess window surface, which was etched by inductively coupled plasma (ICP). The absorption coefficients for wavelengths below 320 nm used in this work are shown in Fig1, which are similar to those in [4].The photo multiplication gain was calculated with the impact ionization coefficients and dead space threshold energies reported in [3]. Figure 2 shows the simulated gain-voltage relationship, the difference between the measured breakdown voltage and calculated voltage is ~ 3%. The simulated quantum efficiency is compared with the measured result in the inset of figure 2.

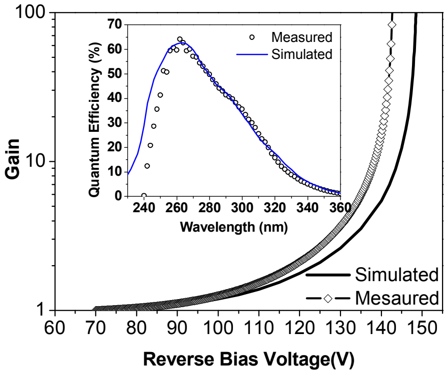

Fig. 2. Simulated and measured photo multiplication gain. Inset shows the quantum efficiencies.

For the Geiger-mode performance simulation, an average drift velocity of 2x105 cm/s for both electrons and holes was assumed and the threshold current of the breakdown was set to 1 □A. A maximum tracking time of 10ns was used to simulate gated quenching. Figure 3 shows the simulated and measured breakdown probabilities for 280 nm illumination. Figure 4. shows the simulated timing jitter for different voltages. The jitter decreases with increasing excess bias, which is consistent with our experimental observations.

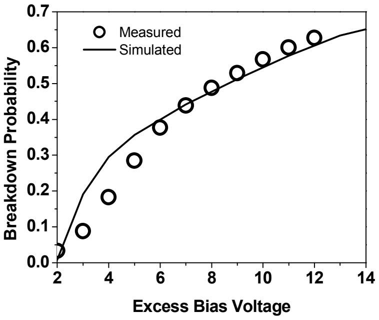

Fig. 3. Simulated and measured breakdown probabilities

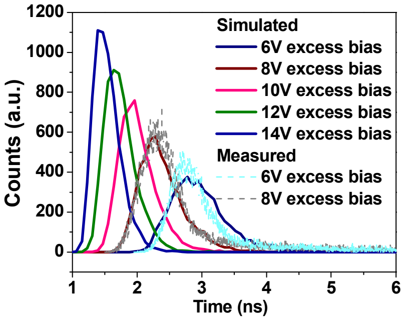

Fig. 4. Simulated and measured jitter

IV. CONCLUSION

Linear-mode and Geiger-mode characteristics of SiC avalanche photodiode were simulated with the random path length model. The results showed good agreement with the measured performance. This model can be used to design and optimize the performance of SiC single photon counting APDs.

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