Simulations of charge collection of a gallium-nitride-based *pin* thin-film neutron detector

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Introduction

Gallium nitride (GaN) semiconductors have a wide bandgap, high-temperature resistance and high radiation resistance. They have a lower electron-hole pair creation energy (8.9 eV) than diamond and silicon carbide. It is, therefore, a potential material for neutron detection. Charge collection efficiency (CCE) is an essential parameter for semiconductor radiation detectors. However, since the spatial distribution of the electron-ion pairs generated inside the semiconductor depletion layer cannot be directly obtained, it is difficult to obtain the CCE at different positions inside the detector. This research developed a simulation method based on Geant4 and Python to simulate the CCE inside a GaN detector. The algorithm's core is based on the Hecht equation, and on this basis, the drift and diffusion of carriers under different voltages and different depletion layer thicknesses are considered.

Method

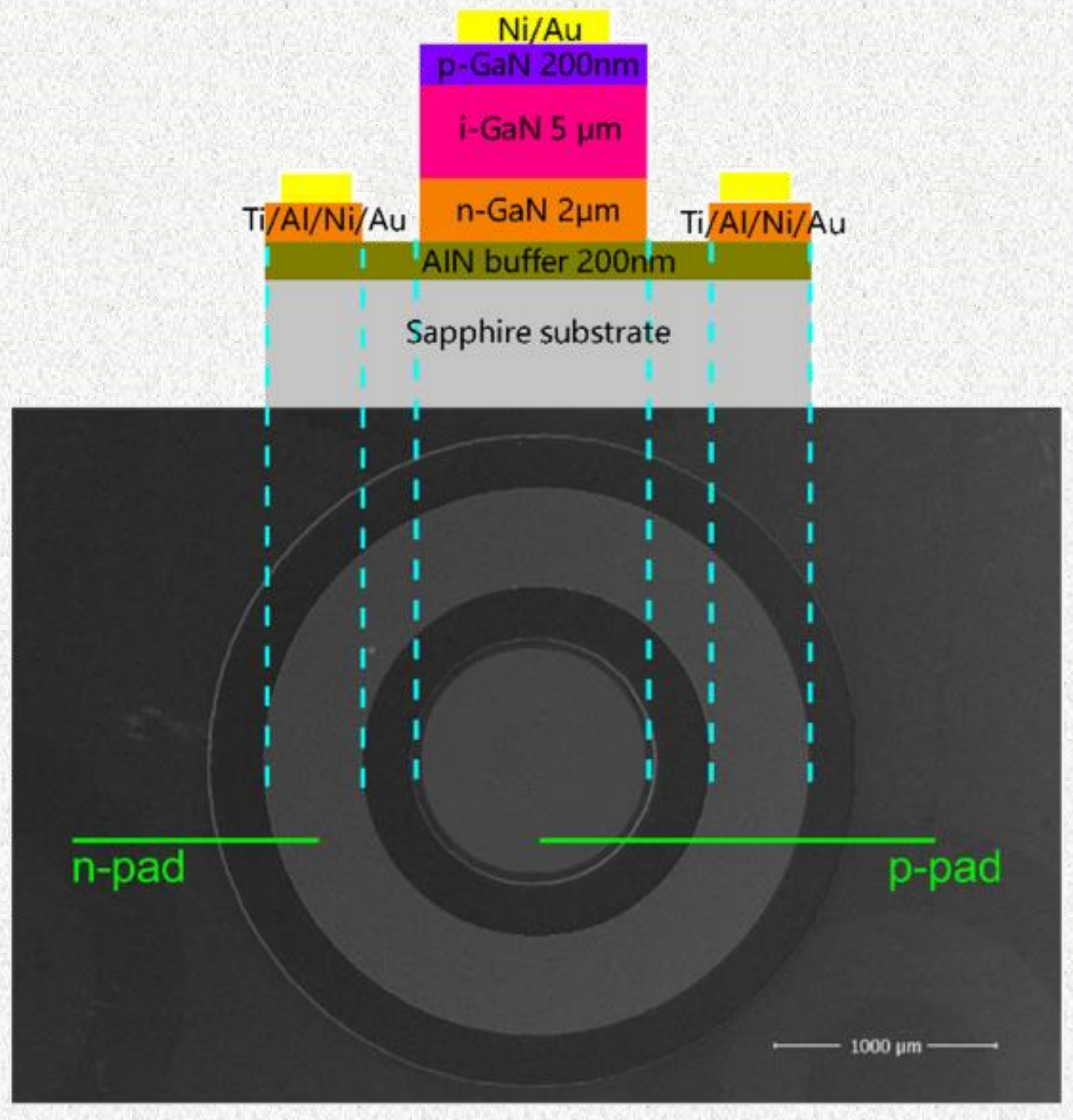

Fig 1. Schematic diagram and scanning electron microscopy image of a GaN based *pin* detector.

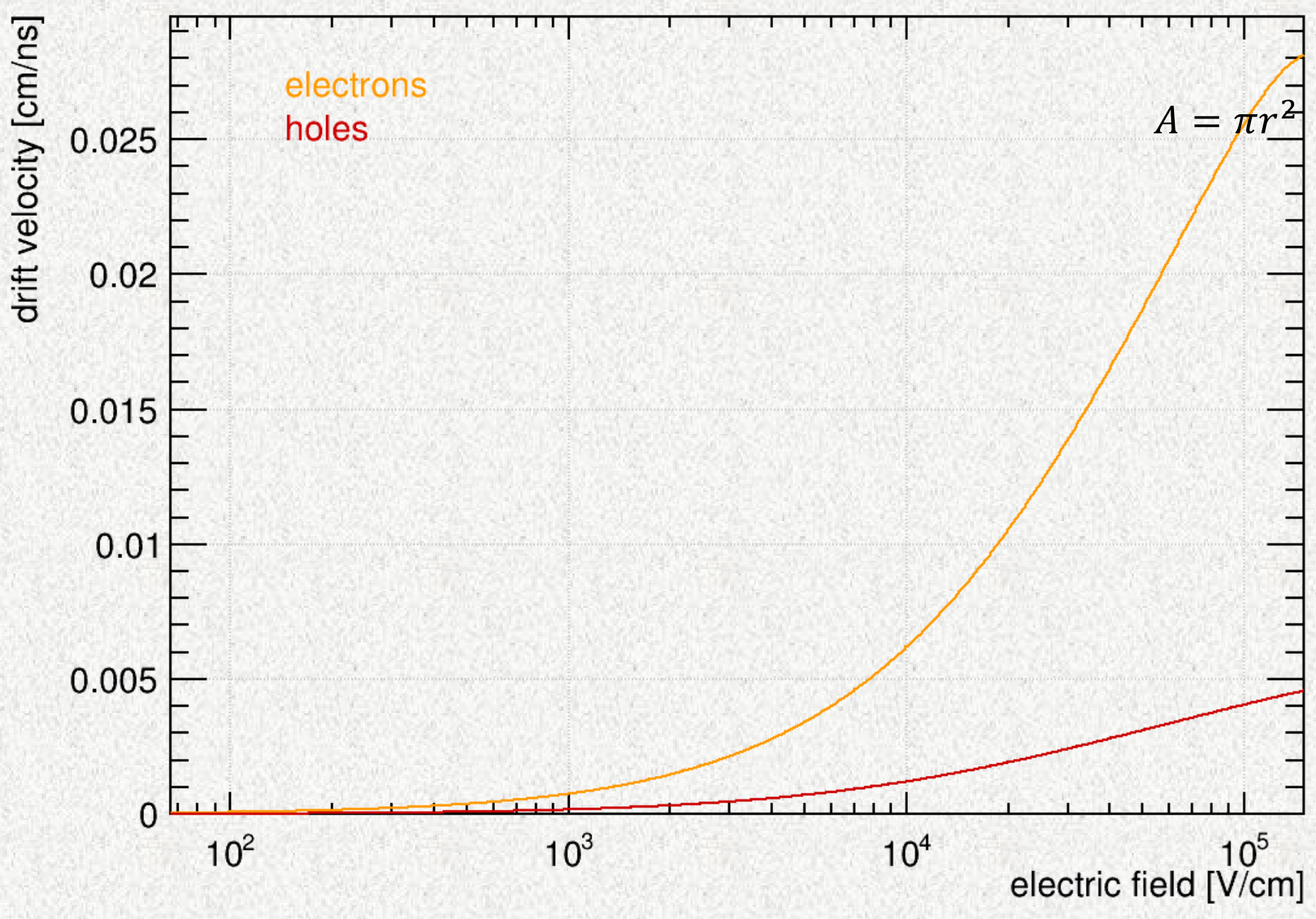

Fig 2. Carrier drift velocity as a function of electric field intensity for GaN.

The whole structure of the detector is shown in Fig 1. To simplify the simulation model, only the p-type, i-type, and n-type layers are simulated. Different from the structure showed in Fig 1, for neutron detection, a lithium fluoride (LiF) converter layer is added at the top of the p-type layer. The version of Geant4 is 10.7, and the physics list used is FTFP_BERT_HP. Fig 2 shows the carrier drift velocity as a function of electric field intensity for GaN. The electron mobility model is from F. Schwierz (2005), and the low-field hole mobility is from T. T. Mnatsakanov et al. (2003). First, the 2-carrier Hecht equation is used to simulate the CCE of the detector and the result is compared by. By changing the carrier lifetime, the CCE of the detector under different bias voltages is obtained.

Geant4 is then used to obtain the spatial distribution of carriers. The Hecht equation is used to calculate CCE at different depletion layer depths.

$$\eta = \frac{\lambda_e}{L}\left[1 - exp\left(\frac{L\text{-}x_0}{\text{-}\lambda_e}\right)\right] + \frac{\lambda_h}{L}\left[1 - exp\left(\frac{x_0}{\text{-}\lambda_h}\right)\right] \qquad (1\text{-}1)$$

Equation 1. Hecht equation. L is the distance between cathode and anode. λ_e and λ_h are drift length of electrons and holes in the applied electric field. x_0 is the position where the e-h pairs are generated.

Results & Discussion

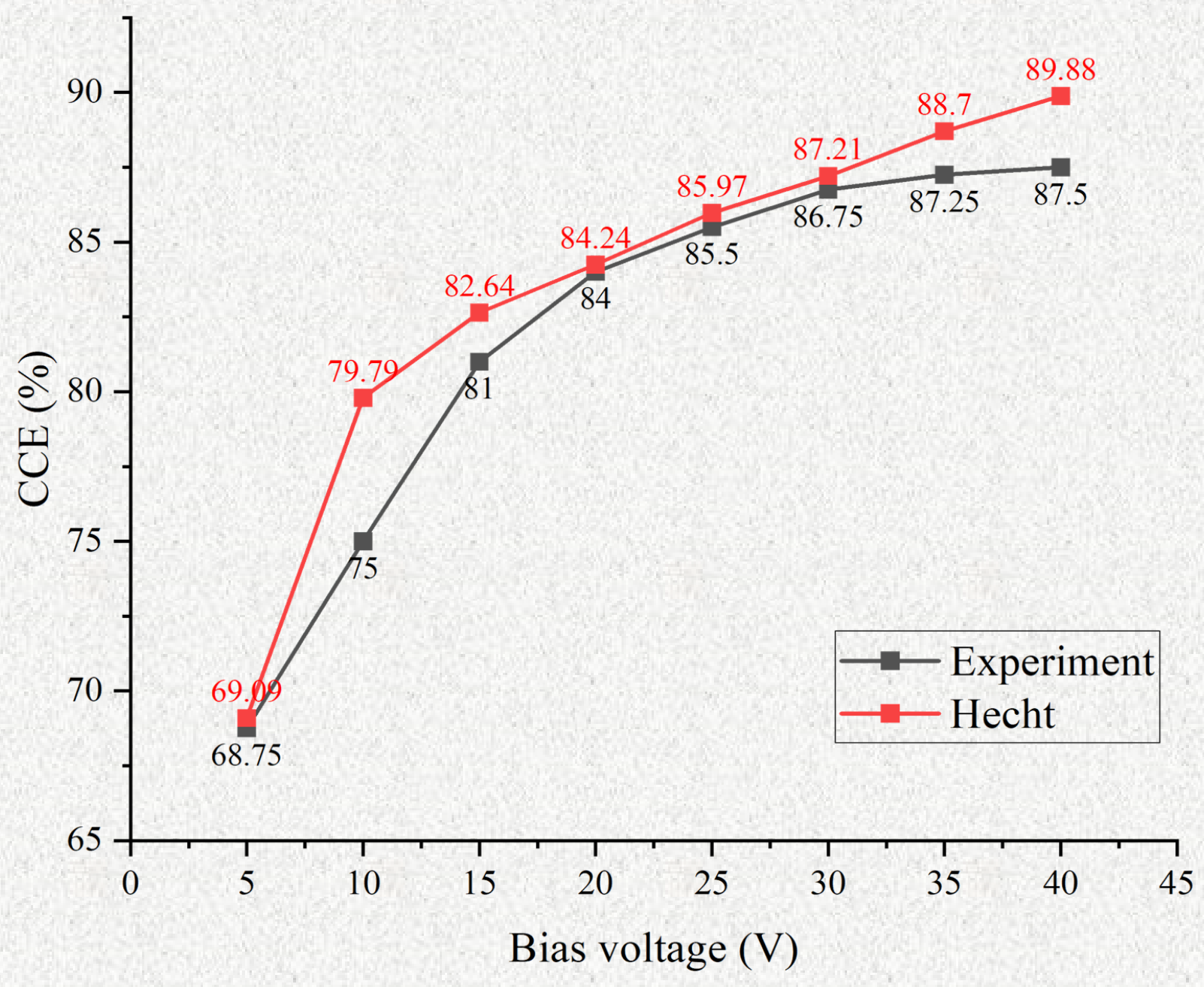

Fig 3. Comparison of CCE verse voltage relationships obtained from simulation and experiment.

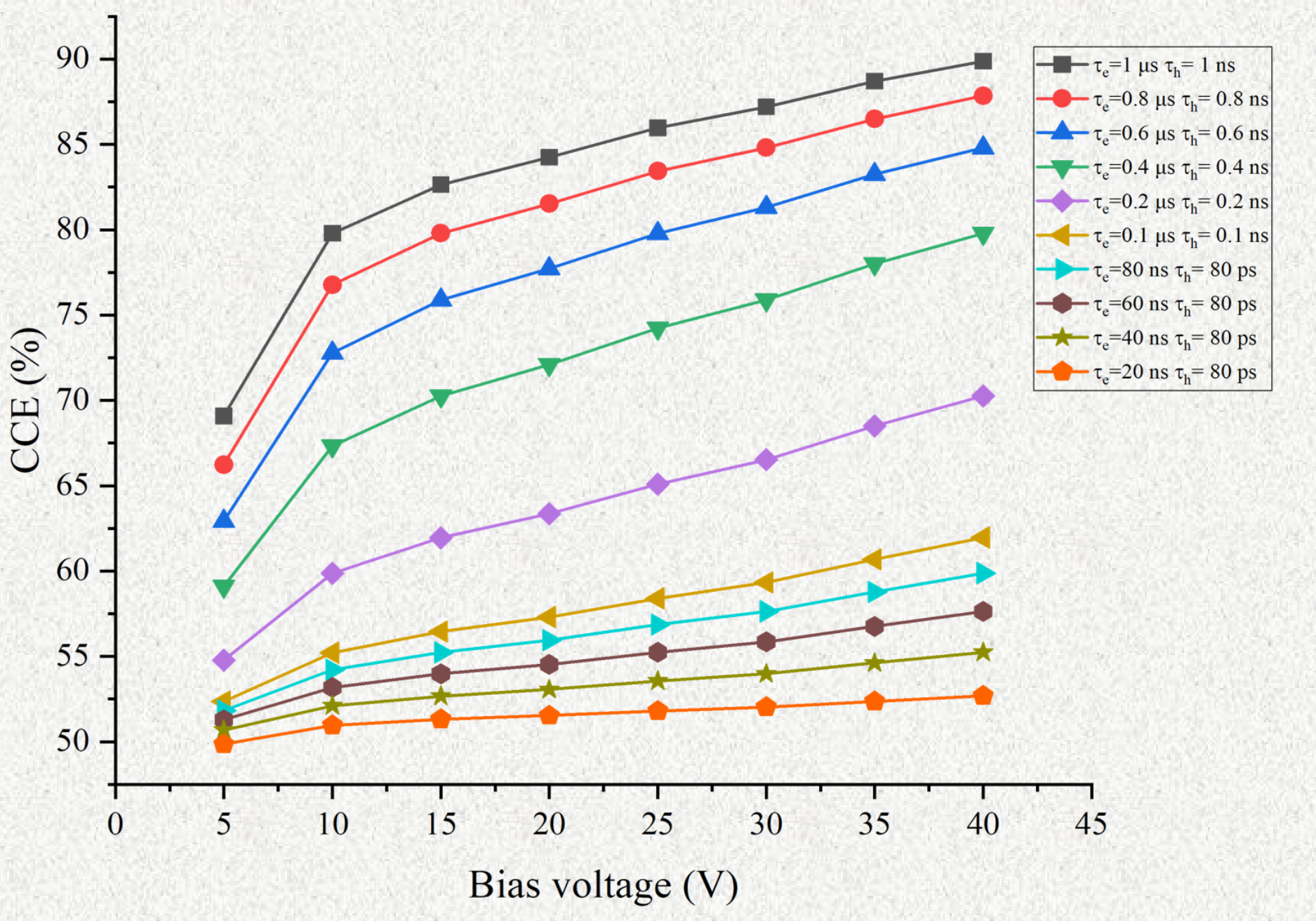

Fig 4. Comparison of CCE verse voltage relationships obtained from simulations with different carrier lifetime.

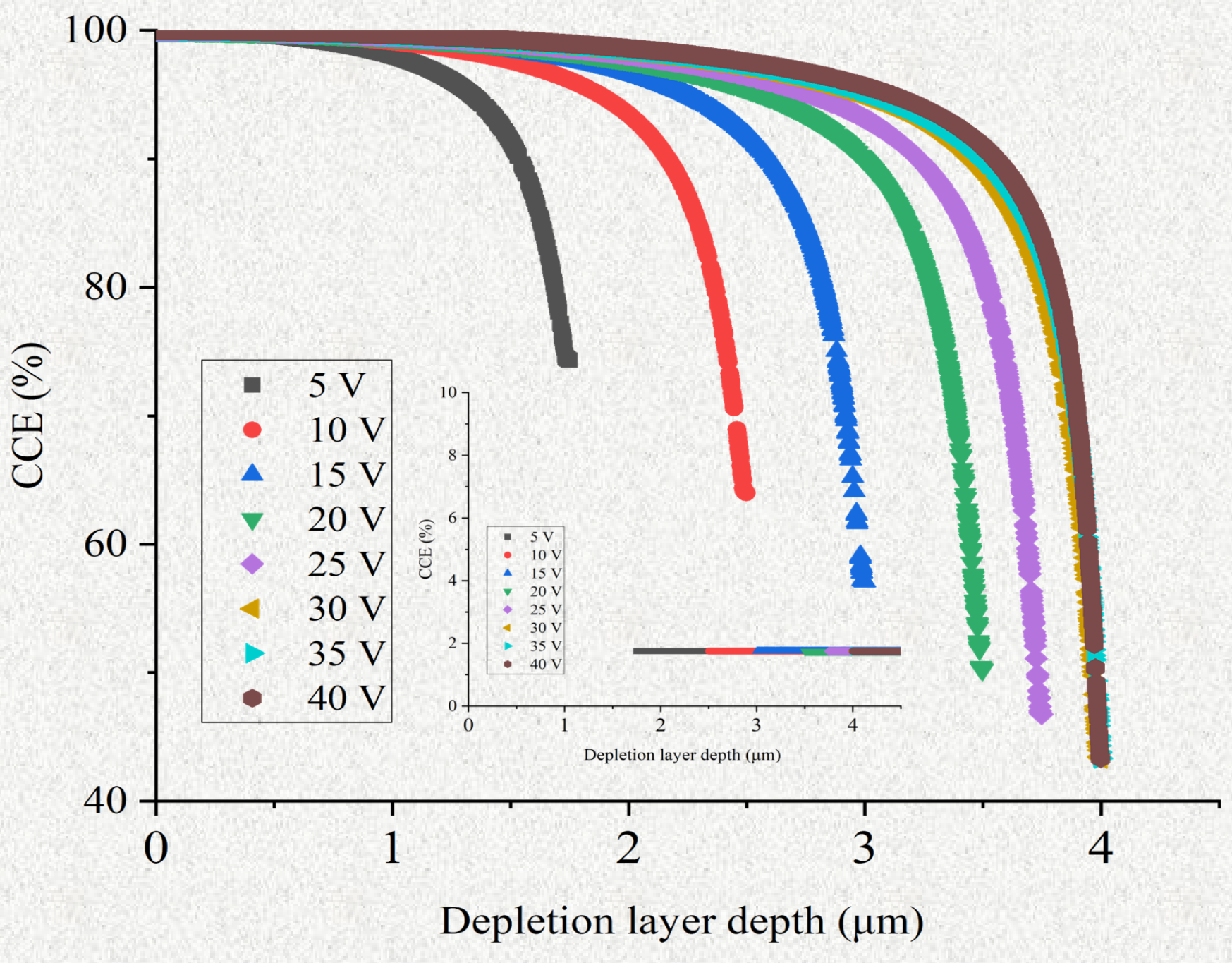

Fig 5. Comparison of CCE verse depletion thickness relationships obtained from simulations with different bias voltage.

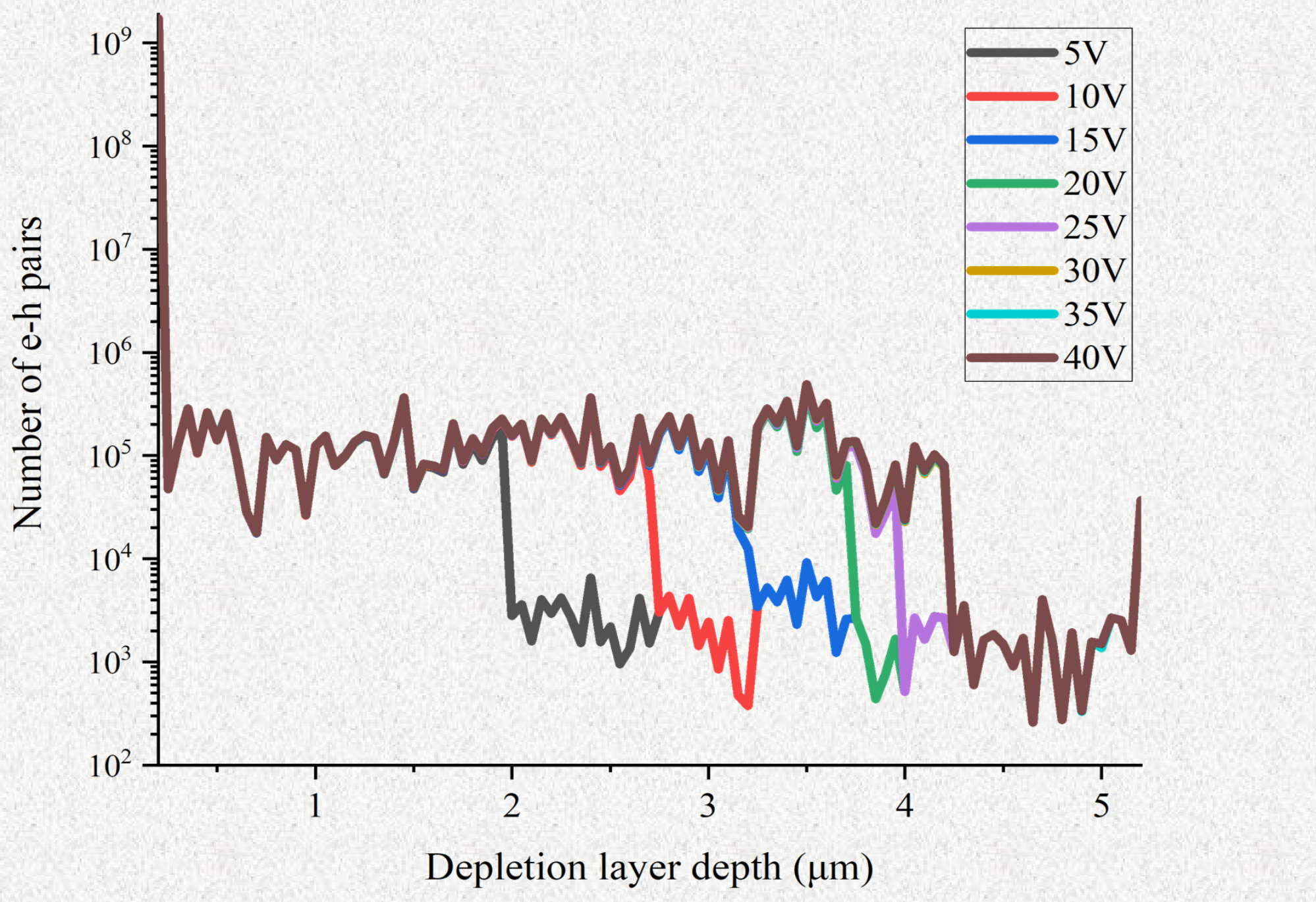

Fig 6. Comparison of the number of e-h pairs verse voltage relationships obtained from simulations at different depletion layer depth.

Fig 3 shows the difference of CCE verses bias voltage for a simulation and an experiment. The maximum error is 6.39% with 10 V bias voltage. When displacement damage accumulates, the carrier lifetime will be degraded mainly due to Shockley-Read-Hall (SRH) recombination. Fig 4 shows a comparison of CCE–voltage relationships obtained from simulations with different carrier lifetimes. The research found that when the external bias voltage is high, the CCE of the detector is sensitive to radiation damage, which means CCE is degraded significantly.

Fig 5 shows a comparison of CCE–depletion thickness relationships obtained from simulations with different bias voltages. As the external voltage increases, the thickness of the depletion layer will continue to increase. In the depletion layer, the attenuation of CCE is not apparent. However, if the e-h pairs are generated outside the depletion layer, only the diffusion of holes will contribute to the final signal, as detailed by the Fig 5 subfigure. Fig 6 shows that as a higher voltage is applied, the more uniform the distribution of e-h pairs will be.

Conclusion

1. A CCE simulation method for GaN neutron detector based on Geant4 and Python has been developed.
2. The CCE of different positions inside the p-i-n GaN detector are calculated.
3. The effect of radiation damage on the CCE of the detector has also been studied.

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