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

Z. Zhang* and M. Aspinall

Lancaster University, Bailrigg, Lancaster, LA1 4YW, U.K.

E-mail: z.zhang56@lancaster.ac.uk

ABSTRACT: The development of new fast neutron reactors and nuclear fusion reactors requires new neutron detectors in extreme environments. Due to its wide bandgap (3.4 eV) and radiation resistance capability, gallium nitride (GaN) is a candidate for neutron detection in extreme environments. This study introduces a novel simulation method of charge collection efficiency (CCE) for GaN pin thin-film neutron detector based on the Hecht equation and Monte Carlo simulation. A modified 2-carrier Hecht equation is used to simulate the CCE of the detector with a different depth depletion region. After obtaining the neutron energy deposition distribution in the sensitive volume of the detector, the Hecht equation is used to calculate the charge collection efficiency at different positions of the detector under a uniform electric field. The maximum relative error between the simulated CCE and the experimental CCE value is about 6.3%.

KEYWORDS: Charge transport and multiplication in solid media; Detector modelling and simulations II (electric fields, charge transport, multiplication and induction, pulse formation, electron emission, etc.); Radiation-hard detectors

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*Corresponding author.

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Contents

1 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, the carrier lifetime in gallium nitride is very short, about μs for electrons and ns for holes [1, 2]. It is hard to measure the carrier lifetime and drift length directly.

On the other hand, 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 novel method based on the Hecht equation and Monte Carlo toolkit Geant4 [3] to simulate the CCE of a GaN detector. On this basis, the drift and diffusion of carriers under different voltages and different depletion region width are considered.

2 Method

The whole structure of the detector is shown in figure 1 (left). A 16.9 μm lithium fluoride (LiF) converter layer is added at the top of the p-type layer to convert neutrons into charge particles [4]. The version of Geant4 is 10.7, and the physics list used is FTFP_BERT_HP. The electron mobility velocity [5] and low-field hole [6] velocity used in simulations is shown as a function of electric field intensity for GaN in figure 1 (right). First, a 2-carrier Hecht equation is used to simulate the CCE of the detector. The result is compared with the experimental result [7], as shown in figure 2. When the applied bias voltage is below 30 V, the detector is not fully depleted. In the field-free region, the main contribution to CCE is the diffusion of holes. This is due to the direction of the electric field which will repel electrons from diffusing into the depletion region. However, compared with the CCE in the depletion layer, the CCE contributed by hole diffusion is very small and it can be omitted. The derivation of the 2-carrier Hecht equation is shown in (2.1). Neutron radiation mainly affects the lifetime of carriers. By changing the carrier lifetime, the CCEs of the detector under different bias voltages and neutron fluxes are obtained, as shown in figure 3.

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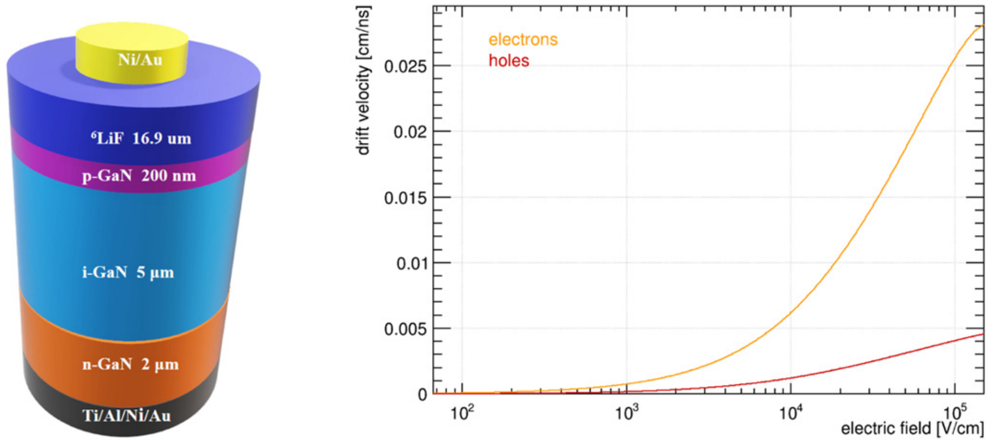

Figure 1. Left: the structure of a GaN based pin detector. Right: carrier drift velocity as a function of electric field intensity for GaN.

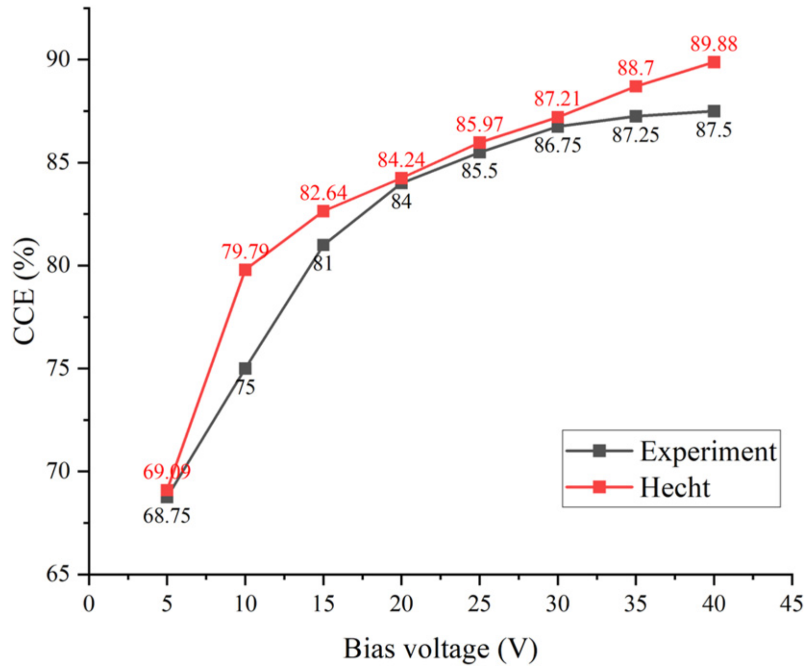

Figure 2. Comparison of CCE versus voltage relationships obtained from simulation and experiment.

The Monte Carlo toolkit Geant4 is used to obtain the spatial distribution of carriers to get the spatial distribution of CCE. The 2-carrier Hecht equation is used to calculate CCE at different depletion layer depths. The derivation of the 2-carrier Hecht equation in terms of positions and CCE are shown in (2.2).

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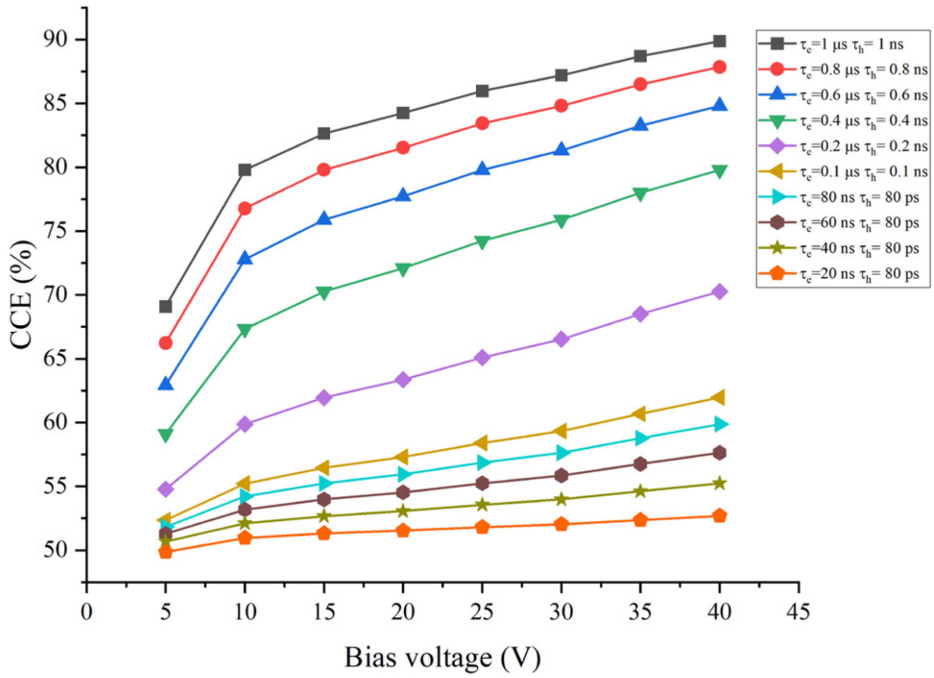

Figure 3. Comparison of CCE versus voltage relationships obtained from simulations with different carrier lifetime.

The 1-carrier Hecht equation is given below [8]:

$$\frac{Q}{Q_0} = \int_0^{x_\mathrm{d}} \frac{Q_0\,\mathrm{e}^{\frac{-x}{\lambda}}}{x_\mathrm{d}}\,\mathrm{d}x = \frac{\lambda}{x_\mathrm{d}}\left(1-\mathrm{e}^{\frac{-x_\mathrm{d}}{\lambda}}\right). \tag{2.1a}$$

The 2-carrier Hecht equation can be defined from (2.1a)

$$\frac{Q}{Q_0} = \frac{\lambda_\mathrm{h}}{x_\mathrm{d}}\left[1-\frac{\lambda_\mathrm{h}}{x_\mathrm{d}}\left(1-\mathrm{e}^{\frac{-x_\mathrm{d}}{\lambda_\mathrm{h}}}\right)\right] + \frac{\lambda_\mathrm{e}}{x_\mathrm{d}}\left[1-\frac{\lambda_\mathrm{e}}{x_\mathrm{d}}\left(1-\mathrm{e}^{\frac{-x_\mathrm{d}}{\lambda_\mathrm{e}}}\right)\right]. \tag{2.1b}$$

In (2.1a) and (2.1b), x_d is the depletion region width and λ_e and λ_h are drift length of electrons and holes for GaN in the applied electric field. Q_0 is the total charges created by charged particles in GaN.

To obtain the CCE at different positions inside the detector, the Shockley-Ramo theory is used to derive the other form of the Hecht equation.

Due to the defects created by radiation damage, the charge will be captured by these defects during the movement

$$i = \frac{\mu\nu}{d^2} q_0\,\mathrm{e}^{\frac{-t}{\tau}}. \tag{2.2a}$$

In (2.2a), the carrier mobility is μ, the carrier velocity is ν, the carrier lifetime is τ, and d is the drift distance. The corresponding induced charge is:

$$Q(t) = \int_0^t \mathrm{i}dt = \frac{q_0\mu\nu\tau}{d^2}\left[1-\mathrm{e}^{\frac{-t}{\tau}}\right]. \tag{2.2b}$$

The drift time for electron is $t_0 = \frac{x}{\mu E}$ and for hole is $t_0 = \frac{x_d - x}{\mu E}$. L is the layer thickness between the two electrodes. Then we can obtain a Hecht equation in terms of positions and CCE

$$\frac{Q}{Q_0} = \frac{\lambda_e}{L}\left[1 - e^{\frac{L-x_0}{-\lambda_e}}\right] + \frac{\lambda_h}{L}\left[1 - e^{\frac{x_0}{-\lambda_h}}\right]. \tag{2.2c}$$

3 Result and discussion

As shown in figure 2, the maximum difference between experiment and simulation is about 6.39% with 10 V bias voltage. The difference between experimental data and simulation data is greatest below 20 V because the detector is not fully depleted under low bias voltages. Discrepancies between experimental and simulation data could be reduced with more accurate data on depletion region widths under low bias voltages. When displacement damage accumulates, the carrier lifetime will be degraded mainly due to Shockley-Read-Hall (SRH) recombination. As shown in figure 3, the CCE degrades significantly under high bias voltages and that CCE is more sensitive to neutron radiation under high, instead of, low bias voltages. Figure 4 shows a comparison of CCE versus depletion region depth for different bias voltage. As the external voltage increases, the width of the depletion region will continue to increase. In the depletion region, the attenuation of CCE is not apparent. However, if the e-h pairs are generated in the field-free region, only the diffusion of holes will contribute to the CCE. Figure 5 shows that as a higher voltage is applied, the more uniform the distribution of e-h pairs will be, and most e-h pairs are generated at the top of i-type GaN near the converter layer.

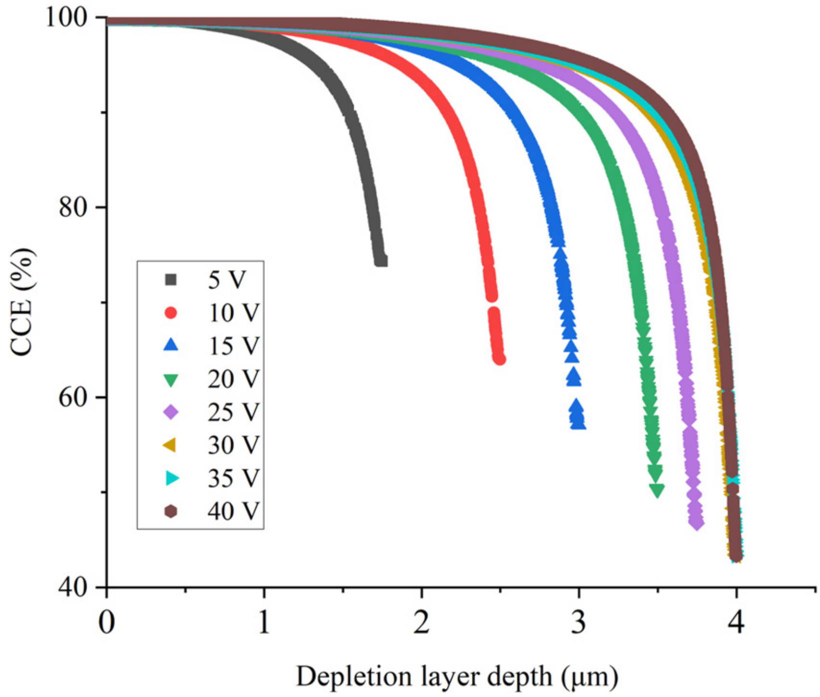

Figure 4. Comparison of CCE versus depletion region depth relationships obtained from simulations with different bias voltage.

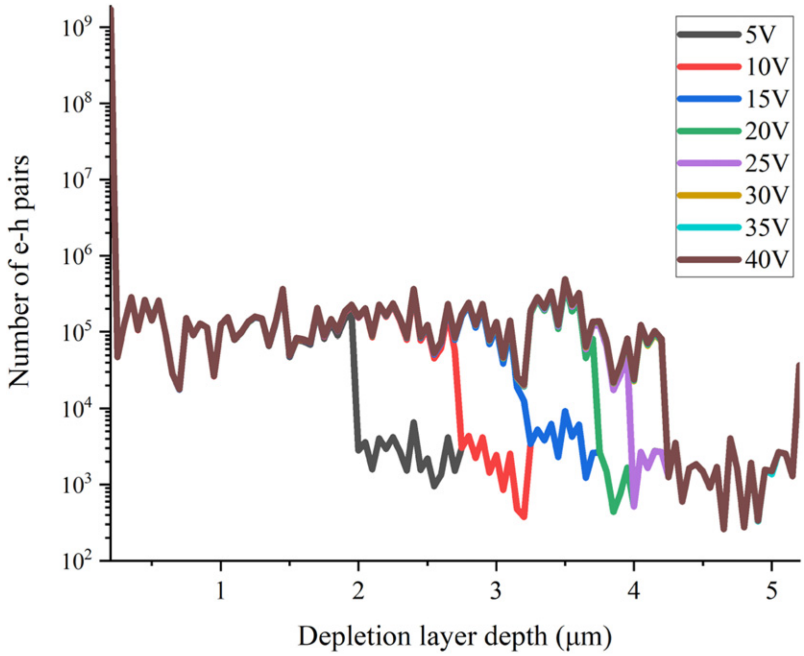

Figure 5. Comparison of the number of e-h pairs created by charged particles from the interaction between neutrons and the converter layer versus voltage relationships obtained from simulations at different depletion region width.

4 Conclusion

In this research, a novel CCE simulation method for GaN-based pin thin-film neutron detector based on the Hecht equation is introduced. The simulation results are in excellent agreement with the experimental results. The CCE of different positions inside the detector is calculated, and the effect of radiation damage on the CCE of the detector has also been studied, which shows that the CCE is more sensitive to neutron irradiation when operated at a high bias voltage.

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