Photoresponse simulation for separate absorption and multiplication GaN/AlGaN avalanche photodiode

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Abstract

We present the detailed procedure for modeling of separate absorption and multiplication (SAM) GaN/AlGaN avalanche photodiode (APD). The bias-dependent spectral responsivity characteristics are obtained by using the constructed two-dimensional numerical model. It is found that the spectral responsivities with wavelength from 240 to 450nm are entirely increased with the increased bias.

I. INTRODUCTION

GaN-based photodetector can conveniently realize high-sensitivity visible-blind [1] and solar-blind [2] detections, both of which take advantage of faint background radiation in the ultraviolet (UV) regime to reduce the requirement of expensive and low-efficiency filter. As a result, GaN-based UV detectors have achieved extensive applications including missile detection and interception, biological and chemical agent detection, flame and environment monitoring, and UV astronomy, involving national defense, commerce, and scientific research [3-5].

GaN avalanche photodiode (APD), as one kind of GaN-based photodetector, possesses not only small volume but also faster response by exploiting the impact ionization under high electric field [6]. Traditional p-i-n GaN APD encounters the problem of low hole-injection efficiency, which has been overcome by the novel separate absorption and multiplication (SAM) GaN APD [7]. Therefore, since the SAM structure of GaN APD was first proposed by Pau *et al.* [8] in 2008, so great attentions have been attracted that many variations in this basic structure (e.g, SAM GaN/SiC APDs, SAM AlGaN solar-blind APDs) followed [9].

In our recent paper [10], we have systematically investigated gain and photoresponse characteristics of back-illuminated SAM GaN APD, and at the end of this paper, a new SAM GaN/AlGaN heterojunction APD with higher gain and larger photoresponse was proposed. It has been demonstrated that this new design can effectively suppressing dark current, enhancing holes injection, and improving absorption efficiency. But, the comprehensive analysis of responsivity for this new design is still missing. In order to fill this gap, in this paper we present the detailed procedure for modeling of SAM GaN/AlGaN APD. By using the constructed two-dimensional numerical model, bias-dependent spectral responsivity characteristics are shown.

II. SIMULATION MODELS AND DISCUSSION

The two-dimensional numerical simulations were performed using Sentaurus Device, a commercial package by Synopsys [11]. The drift-diffusion model [12-16], including the Poisson equation and continuity equations, is adopted for simulating the carrier transport. The carrier generation-recombination process consists of SRH, Radiative, Auger, and optical generation-recombination terms. Additionally, band-to-band tunneling (BBT) model and impact ionization model are incorporated into continuity equations. High-field saturation model and ray-tracing model are selected for calculating carrier mobility and optical generation rate, respectively.

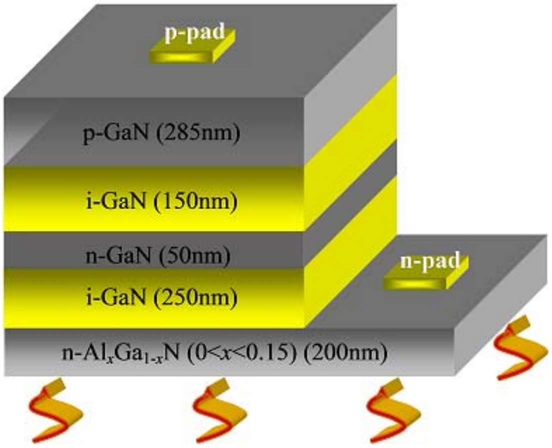
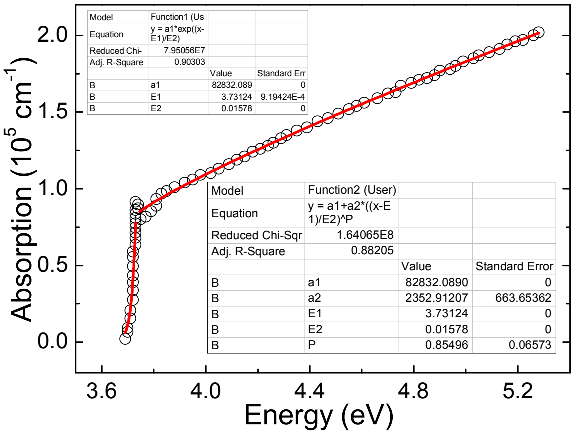


Fig. 1. Schematic cross-section of SAM GaN/AlGaN APD.



Model	Function1 (Us		
Equation	y = a1*exp((x-E1)/E2)		
Reduced Chi-	7.95056E7		
Adj. R-Square	0.90303		
		Value	Standard Err
B	a1	82832.089	0
B	E1	3.73124	9.19424E-4
B	E2	0.01578	0

Model	Function2 (User)		
Equation	y = a1+a2*((x-E1)/E2)^P		
Reduced Chi-Sqr	1.64065E8		
Adj. R-Square	0.88205		
		Value	Standard Error
B	a1	82832.0890	0
B	a2	2352.91207	663.65362
B	E1	3.73124	0
B	E2	0.01578	0
B	P	0.85496	0.06573

Fig. 2. Fitting results of absorption spectrum for Al$_{0.11}$Ga$_{0.89}$N at room temperature. Insets list all the fitting parameters.

Figure 1 presents the schematic structure of the simulated device. The p-i-n-i-n five epitaxial layers with 25×25μm^2 mesa

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are contained therein. The concentrations of p-, i-, and n-regions are set to 3×10^{18}cm^{-3}, 2×10^{18}cm^{-3}, and 1×10^{16}cm^{-3}, respectively. From the top to the bottom, these five layers are sequentially named as p-type layer, multiplication layer, charge layer, absorption layer, and n-type layer for convenience. Only n-type layer adopts $Al_xGa_{1-x}N$ as material, the rests of epitaxial layers are uniformly GaN. As an example, Al composition x is chosen as 0.11. In order to simulate the photoresponse characteristics of SAM GaN/$Al_{0.11}Ga_{0.89}N$ APD, the absorption coefficient spectra of GaN and $Al_{0.11}Ga_{0.89}N$ need to be coupled into ray-tracing model. In our recent paper [10], we have fitted the experimental (see [17]) absorption coefficient spectrum of GaN into the following formula:

$$\alpha(E_{ph}) = \begin{cases} \alpha_1 \exp((E_{ph}-E_1)/E_2), E_{ph} < E_1 \\ \alpha_1 + \alpha_2((E_{ph}-E_1)/E_2)^P, E_{ph} \geq E_1 \end{cases} \quad (1)$$

where the fitting parameters are α_1=96135.2943, α_2=524.46621, E_1=3.43639, E_2=0.02135, and P=1.25407, respectively. Due to the lack of experimental reports on absorption spectrum for $Al_{0.11}Ga_{0.89}N$, we simply shifted the absorption coefficient spectrum of GaN toward high photon energies until the absorption edge approaches 3.73eV, which is calculated by linear interpolation between GaN and AlN. As a result, the absorption coefficient spectrum of $Al_{0.11}Ga_{0.89}N$ is shown in Fig. 2. By the same fitting procedure as for GaN, we can get the following fitting parameters: α_1=82832.08907, α_2=2352.91207, E_1=3.73124, E_2=0.01578, and P=0.85496, which are also listed in the insets of Fig. 2.

Using the above described numerical model, we obtained photoresponse spectra at different biases as shown in Fig. 3. It is found that there is a widow region in the photoresponse spectrum of SAM GaN/$Al_{0.11}Ga_{0.89}N$ APD. Despise of the varied bias, the wavelength range of window region is always from 338 to 360nm, which correspond to the absorption edges of $Al_{0.11}Ga_{0.89}N$ and GaN, respectively. According to Fig. 3, the spectral responsivities with wavelength from 240 to 450nm are entirely increased with the increased bias, which does not mean that a higher bias will bring a better performance. It is because the excess noise factor of the device will increase as well as photoresponse with increasing bias, making the device performance deteriorate at a certain bias.

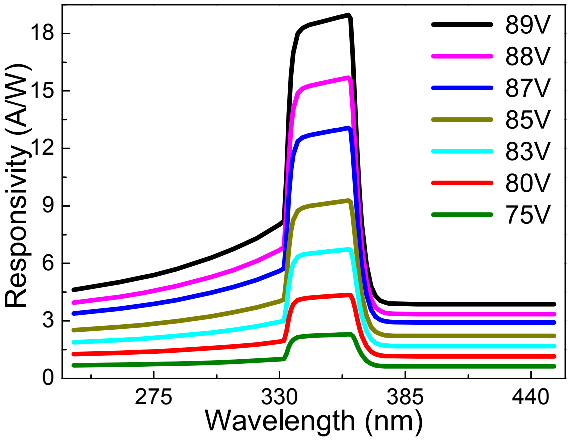

Fig. 3. Bias-dependent spectral responsivity characteristics of SAM GaN/$Al_{0.11}Ga_{0.89}N$ APD.

III. CONCLUSION

The detailed procedure for modeling of SAM GaN/ AlGaN APD is presented in this paper. Since absorption edges of $Al_{0.11}Ga_{0.89}N$ and GaN occur at different energy, a window region with wavelength from 338 to 360nm is observed in the photoresponse spectrum of SAM GaN/$Al_{0.11}Ga_{0.89}N$ APD. Our results show that the spectral responsivities with wavelength from 240 to 450nm are entirely increased with increasing bias.

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