Electro-optical characteristics of separate absorption and multiplication GaN avalanche photodiode

X. D. Wang[a], W. D. Hu[a, *], X. S. Chen[a, *], J. T. Xu[b], X. Y. Li[b], and W. Lu[a, *]

[a] National Lab for Infrared Physics, Shanghai Institute of Technical Physics, Chinese Academy of Sciences, 500 Yu Tian Road, Shanghai, China 200083

[b] State Key Laboratories of Transducer Technology, Shanghai Institute of Technical Physics, Chinese Academy of Sciences, Shanghai, China 200083

Abstract

The fabrication and electro-optical characteristics for separate absorption and multiplication GaN avalanche photodiode have been presented. The multiplication gain as a function of reverse bias at room temperature is also obtained. It is found that multiplication gain monotonically increases with increasing reverse bias, high multiplication gain of 3×10^5 at 110V is achieved

I. INTRODUCTION

Ultraviolet (UV) photodetectors find their use in numerous applications in the defense, commercial, and scientific areas. Many of these applications require high sensitivity, low noise, and visible- or solar-blind detection. Current high-sensitivity UV detectors, such as silicon and silicon carbide based UV detectors, present high detectivity due to their large internal gain. However, these detectors require additional filtering to operate in the UV spectrum making them less favorable [1-2]. Photomultiplier tubes (PMTs) offer high sensitivity UV detection with a photo-current gain as high as 10^6 [3]. The PMTs, however, generally require a high-voltage power supply (>1200W) as well as a cooled photocathode, and hence PMT systems are relatively large, expensive, bulky, and fragile.

Photodetectors based on III-N materials can potentially provide improved receiver sensitivity, low noise, and low dark-current densities for short-wavelength radiation in the UV spectral region. Wide-band-gap semiconductor *p-i-n* photodetectors, such as GaN *p-i-n* diodes, can exhibit intrinsically visible-blind operation and also can offer a high internal gain by avalanche multiplication, thus improving detection sensitivity, especially using Geiger-mode operation. In addition, wide-band-gap APDs are also capable of lower noise and faster response time compared with UV photodetector devices that employ photoconductive gain [4].

Back-illuminated GaN APDs have shown single-photon detection capabilities [5]. However, their performance in linear mode is still limited by the maximum gain achievable and the noise characteristics. The use of separate absorption and multiplication (SAM) regions in APDs is a common approach to reduce multiplication noise and enhance gain through impact-ionization engineering [6-7].

In this paper, we present the fabrication and electro-optical characteristics of SAM GaN APDs, which allow for nearly pure injection of holes into the multiplication region and lower noise performance. The multiplication gain at room temperature is also obtained.

II. SIMULATION MODELS AND DEVICE STRUCTURE

The steady-state two-dimensional numerical calculations were performed using Sentaurus Device, a commercial package by Synopsys [8]. For plain drift-diffusion simulation the well known Poisson equation and continuity equations are used. The carrier generation-recombination process consists of Shockley-Read-Hall, Radiative, Auger, and optical generation-recombination terms. Additionally, the impact ionization model and tunneling effects (band-to-band and trap-assisted tunnelings) are included in the continuity equations. Band-to-band tunneling (BBT) is represented as an additional generation-recombination contribution and trap-assisted tunneling (TAT) is incorporated into SRH recombination rate. Moreover, A significant amount of structural defects, such as threading or misfit dislocations, and processing damage, such as plasma damage or thermal damage, exist in the GaN due to the immaturity of the GaN technology. It has been indicated that these defects and damage can be translated into the bulk traps [9]. Thus, we assume a single acceptor type electron bulk level for simplicity. The values of the levels are fitted from the experimental data for the GaN. The trap density of GaN is $N_{GaN}=2.5\times10^{16}cm^{-3}$ with a capture cross section of $\sigma_{AlGaN}=1.0\times10^{-15}cm^{-2}$, locating approximately 1.8eV below the conduction band.

Samples were grown by metal-organic chemical-vapor deposition (MOCVD) on transparent AlN templates on double side polished *c*-plane sapphire substrates. They consisted of *p-i-n-i-n* GaN structures with hole and electron concentrations of $3\times10^{18}cm^{-3}$ and $2\times10^{18}cm^{-3}$ for the p-type GaN:Mg and n-type GaN:Si layers, respectively. The *i* regions consisted of two unintentionally doped GaN layers with a residual electron concentration of $2\times10^{16}cm^{-3}$. The detailed structural information of SAM GaN APD is shown in Fig. 1. Several arrays of $225\mu m^2$ mesa structures were defined via photolithography, dry etching, metal evaporation, and SiO_2 passivation.

III. RESULT AND DISCUSSION

* Corresponding author: wdhu@mail.sitp.ac.cn, xschen@mail.sitp.ac.cn, luwei@mail.sitp.ac.cn.

The current-voltage (*I-V*) characteristics under reverse bias were measured in darkness and under illumination using the Xe lamp filtered at 360nm. The optical power on the diode was 4.1nW. The light and dark *I-V* curves were measured alternatively three times in a row to ensure consistent device operation.

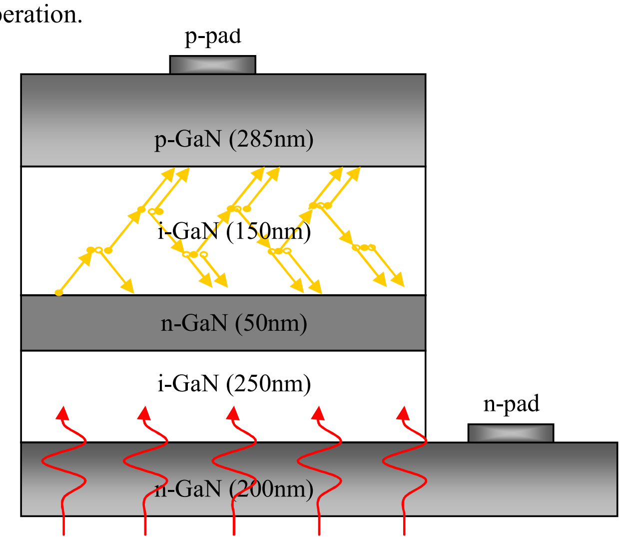

Figure 1. Schematic cross section of SAM GaN APD.

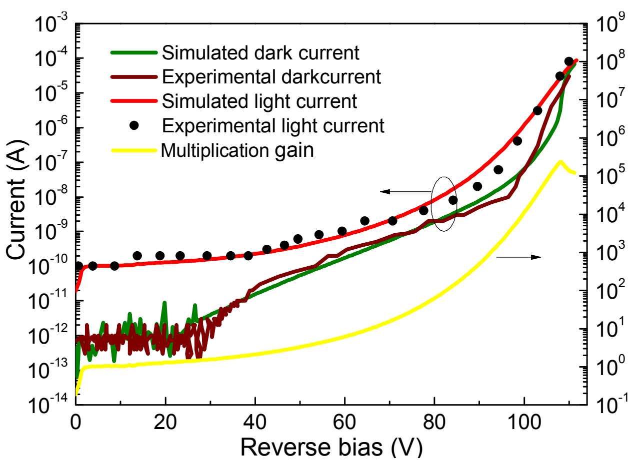

Figure 2 (Color online) Left axis: experimental and simulated dark and light (360nm) currents for SAM GaN APDs. Right axis: calculate multiplication gain.

Figure 2 (left axis) shows the comparison of experimental and simulated dark and light currents. The simulations are in good agreement with the experiments for both dark and light currents, which confirms the proper selection of simulation models. As shown in the Fig. 2, in darkness, the current remains below the measurement limit up to 30V, thus a notable turbulence in dark current characteristics is observed. Beyond that voltage, dark current increases monotonically until reaching the breakdown voltage 96V, at which point the device exhibits a dark current of 10nA. At this voltage, the average electric field intensity in the multiplication layer is about 3MV/cm at 96V, which is in fairly good agreement with the value of the critical electric field in GaN [10], confirming breakdown is attributed to avalanche multiplication. The dark current exponentially rises after avalanche breakdown reaching 81μA at 111V.

Under 360nm illumination, the current remains fairly flat below 40V, and then begins to gradually increase until 80V. To calculate multiplication gain, the difference between light and dark currents is divided by the photocurrent at low bias, a nearly constant value of 0.1nA. Fig. 2 (right axis) shows the calculated gain as a function of reverse bias at room temperature. It is found that the gain monotonically increases with increasing reverse bias. Near the breakdown voltage, avalanche multiplication significantly raises the gain up to 3×10^5 at 110V. Such high value of multiplication gain for our SAM GaN APDs is comparable with that of Photomultiplier tubes

IV. Conclusion

The dark and light currents characteristics for separate absorption and multiplication GaN avalanche photodiode have been obtained experimentally and numerically, respectively. The simulations are in good agreement with experiments. It is demonstrated that avalanche multiplication significantly raises the gain up to 3×10^5 at 110V.

Acknowledgements

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