Numerical simulation on the dependence of photoresponse on the thickness of the charge layer for GaN SAM avalanche photodiodes

Xiaodong Wang
The 50th Research Institute of
China Electronics Technology
Group Corporation
Shanghai, China
wxd06296@163.com

Muran Wang
The 50th Research Institute of
China Electronics Technology
Group Corporation
Shanghai, China
8129918@qq.com

Huiyuan Cui
The 50th Research Institute of
China Electronics Technology
Group Corporation
Shanghai, China
1290358865@qq.com

Zewen Wang*
The 50th Research Institute of
China Electronics Technology
Group Corporation
Shanghai, China
hit_wzw@163.com

Yulu Chen
The 50th Research Institute of
China Electronics Technology
Group Corporation
Shanghai, China
yukiylc@163.com

Weiyi Ma
The 50th Research Institute of
China Electronics Technology
Group Corporation
Shanghai, China
maweiyi126@126.com

***Abstract*—GaN avalanche photodiode (APD) has important application prospects in the field of solar-blind ultraviolet (UV) detections. The back-illuminated GaN-based detector has been widely studied due to the advantages such as easy integration with readout circuit. Numerical model of GaN APD is established. The influence of the key function layer (charge layer) thickness on the device response and response current is also studied. Besides, the ideal charge layer thickness with the highest response is calculated.**

I. INTRODUCTION

GaN-based photodetector can easily achieve high-sensitivity visible- or solar-blind detections [1,2], both of which take advantage of faint background radiation in the UV regime to reduce the requirement of costly and efficiency-limiting filter. As a result, GaN-based UV detectors find their uses in many national defense, commerce, and scientific applications, including missile detection and interception, biological and chemical agent detection, flame and environment monitoring, and UV astronomy [3,4]. Photomultiplier tube (PMT) is the earliest high-sensitivity UV detector with an internal gain larger than 10^6. However, this kind of detector is bulky and fragile. In order to overcome above drawbacks, GaN-based APD emerges as a promising candidate, possessing not only small volume but also faster response by exploiting the impact ionization under high electric field.

Most of early GaN APDs were designed as front-illuminated structure, because it can grow thick GaN n-type layers on sapphire and even silicon substrates, so as to reduce the difficulty of material growth and the dislocation density. However, the popularity of back-illuminated GaN APDs becomes far beyond that of front-illuminated structures due to their advantages in three aspects. First of all, the collision ionization coefficient of holes in GaN material system is much higher than that of electrons. The back-illuminated structures can effectively improve the hole-injection efficiency in the multiplication region to realize hole multiplication, and then improve the gain and reduce the noise. Secondly, higher gain uniformity and breakdown voltage reproducibility can be achieved in back-illuminated designs. Thirdly, it is much easier to integrate back-illuminated structures with readout circuits.

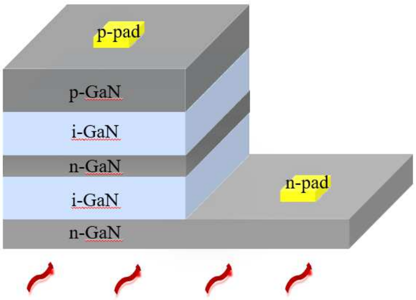

Fig. 1. Schematic cross-section view of the back-illuminated GaN APD.

II. STRUCTRAL AND PHYSICAL MODELS

The schematic cross-section view of the back-illuminated GaN APD is shown in Fig. 1. The structure is composed of p-i-n-i-n five epitaxial layers grown on the substrate. The hole and electron concentrations are 3×10^{18} and 2×10^{18} cm^{-3} for p-type GaN:Mg and n-type GaN:Si regions, respectively. The i-type regions are undoped GaN with a residual electron concentration of 1×10^{16}cm^{-3}. For convenience, the five layers from the top to the bottom are sequentially named as p-type layer, multiplication layer, charge layer, absorption layer, and n-type layer.

III. RESULTS AND DISCUSSIONS

Thickness of charge layer is critical parameters characterizing the material property of GaN avalanche photodiodes, and also can be conveniently controlled during the crystal film growth. Thickness of charge layer affects the internal electric field distribution of the device, and then affects the response current and response under different bias voltages.

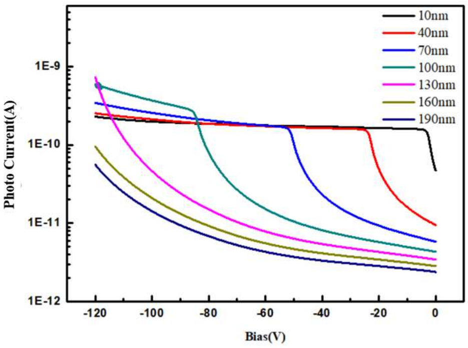

Fig. 2. Photo current at varing bias with different charge layer thickness. The wavelength of the incident light is 360 nm.

The photocurrent level of the device directly measures the response of the device to the incident light energy. Therefore, in this paper, photo current with varying bias at different charge layer was systemically studied. The wavelength of the incident light is 360 nm. As can be seen from Fig. 2, the response current level of the device is between 10^{-12} A and 10^{-9} A, showing a monotonic upward trend with the increase of the bias. the upward trend is fast in the case of low bias. There is a transition point between variable speed rise and slow rise, which moves to higher bias with the increase of n-type layer thickness.

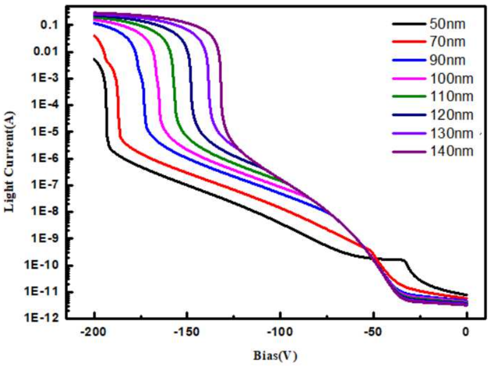

Fig. 3. Light current at varing bias with different charge layer thickness. The wavelength of incident light is 360 nm and the device bias is fixed as 120 V.

The electrical output characteristics of the device under illumination are related not only to the photocurrent, but also to the IV characteristics of the device itself. Therefore, the light current including both photoelectric current information and dark current information is studied. From Fig. 3 we can see that when the bias is lower than 30 V, the device current level is maintained at about 10^{-10}~10^{-11} A, which increases significantly with the increase of bias. The avalanche breakdown voltage of the device shows a monotonic downward trend with the increase of charge layer thickness. When the thickness of the charge layer is 50 nm, the avalanche breakdown voltage is about 180 V.

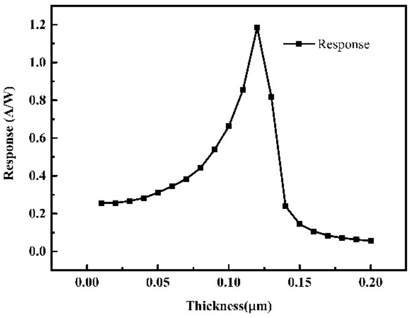

Fig. 4. Response of GaN APD with charge layer thickness from 20 to 200 nm.

It can be seen from the photo current that the device response under different bias is not linearly dependent on the n-type layer thickness, which is the result of the combined action of many factors such as built-in electric field, applied electric field and recombination of electrons and holes. Therefore, there is an ideal charge layer thickness to optimize the response of the device. The relationship between the device responses to the incident light with the wavelength of 360 nm is studied when the device bias is fixed as 120 V. Fig. 4 shows that with the increase of thickness, the device response increases first and then decreases. When the thickness is about 110 nm, the response reaches the optimal value of 1.2 A/W.

IV. CONCLUSION

In this work, GaN APD detector numerical model is accurately established. The results show that when the device bias is large than 50 V,the circuit level increases rapidly. At the same time, the avalanche breakdown voltage has a linear relationship with the charge layer thickness, and the maximum value is 180 V at 50 nm. In conclusion, the thickness of the device charge layer has a significant impact on the performance of the device, and its thickness should be strictly controlled to ensure the reliable performance of the device.

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