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# The Influence of Periodic Ultra-thin AlN Interlayers in Multiplication Region on the GaN Avalanche Photodiode

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Abstract—GaN APD with periodic ultra-thin AlN interlayers in multiplication region has been proposed to obtain a high gain at constant voltage mode. The influence of the AlN interlayers on the multiplication process was numerically simulated and analyzed. The results predict that the multiplication process contains three different stages with the increase of the reverse voltage. The experimental results agree with the numerically simulation very well and a high gain of  $6\times10^4$  at constant voltage mode was obtained.

Keywords—Avalanche photodiodes, constant voltage mode, AlN interlayers, high gain

## I. INTRODUCTION

GaN p-i-p-i-n separate absorption and multiplication (SAM) structure APD with AlN(10 nm)/GaN(10 nm) periodically stacked structure (PSS) in multiplication region has been proposed to obtain a high ionization coefficient ratio of more than 100 [1]. A record high gain (10<sup>4</sup>) has been demonstrated by the PSS APD under a constant bias voltage (CV) in experiment [2], which is promising for ultraviolet single photon detection operating in photon counting mode.

The carrier transport processes inside AlN/GaN PSS have been calculated by Monte Carlo method and the influence of the polarization effect caused by the PSS have also been studied in our previous work [3]. The fundamental difference between the p-i-p-i-n SAM structure APD and PSS APD is the periodic AIN interlayers. However, it is still unclear what is the influence of the AlN interlayers when the multiplication region of SAM structure is gradually changed from uniform GaN to AlN/GaN PSS and where is the upper limit of the gain under CV mode. Here, periodic ultra-thin AlN interlayers with thickness of 2 nm, 5 nm and 10 nm are introduced into the multiplication region of GaN SAM APD, the corresponding energy band structures and electric field distributions under bias voltage are calculated and analyzed. We find that the electric field distributions in absorption and multiplication region are affected significantly by the thickness of AlN interlayers, leading to three different multiplication stages with the increase of the reverse voltage. The theory prediction was proved by experimental results and the gain of the prepared PSS APD shows three different curve shape from exponential to parabola and then to exponential. As a results, a high gain of  $6 \times 10^4$  at CV mode (36V) was obtained.

## II. SIMULATION MODELS AND DEVICE STRUCTURE

The front-illuminated GaN APD consists of periodic ultrathin AlN interlayers in p-i-p-i-n multiplication region structure, as shown in Fig. 1. From the bottom to the top, there are five functional regions on the substrate, sequentially named as n-type contact layer, multiplication layer with periodic AlN interlayers, charge layer, absorption layer, and p-type contact layer. The incident light is absorbed mainly in the topmost i-type GaN to generate electron-hole pairs. The second p-type GaN insert layer is charge layer which can suppress holes injected into multiplication region. The i-type GaN/AlN periodic layers are employed as multiplication region.



Fig. 1 Schematic structure of GaN APD with periodic AlN interlayers in p-i-p-i-n multiplication region.

Same as the simulations method in our previous paper[8], both spontaneous polarization and piezoelectric polarization are taken into account in the simulations at the heterostucture interface between the p-interlayer and the AlN multiplication layer, and the AlN/GaN interface in the multiplication layer introduced by the band offset. epitaxy wafer growth by MOCVD is a Ga face structure, so the polarization direction is coincides with the growth direction.

### III. RESULT AND DISCUSSION

For the p-i-p-i-n SAM structure APD with uniform GaN multiplication layer, the corresponding electric field distribution is shown in Fig. 2 (a). Due to the limited electric field adjustment ability of the p-type charge layer, there is a little difference in the slope of the conduction band between the absorption and multiplication regions. At the same time, with the increase of bias voltage, the electric fields in the absorption region and the multiplication region increase simultaneously and there is no obvious difference.

When periodic 2 nm AlN interlayers was inserted into the multiplication layer, the conduction band becomes completely different, as shown in Fig.2 (b). In our previous articles [3], it has been proved that the great separation of absorption and multiplication regions comes from the effect of polarization effect.



Fig. 2 The band energy versus reverse bias for p-i-p-i-n SAM structure GaN APD with (a) uniform GaN multiplication layer and (b) multiplication layer with periodic 2 nm AlN interlayers.

The transport process of photo-generated electronics can be divided into 3 different kinds with the increase of the reverse voltage. When the bias voltage changes from 0 to about 10 V, the conduction band in absorption region maintain unchanged and there are several triangle barriers in the multiplication region higher than that in absorption region. The electron energy reaching the first AlN interlayer should be the same below 10 V and the small electric field in absorption region is not enough for electronics to pass over the first barrier, but they have a certain probability to pass through the barriers by tunneling. Then the electronics will continue to pass through the second and residual barriers by tunneling, the probability increases exponentially with the increase of electron energy. Therefore, the photocurrent will increase in exponent with the bias voltage. When the bias voltage changes from 10 to 30 V, the conduction band in absorption region still maintains unchanged and only the first barrier need to pass through by tunneling in the multiplication region, which shows a constant probability since the electron energy is the same before the first barrier. In the multiplication region, electrons will accelerate in the AlN interlayers but decelerate in the GaN layers, leading to a spatial discretization acceleration process. The photocurrent will increases in parabola with the bias voltage, which is consistent with the reported measured gain behavior of AlN(10 nm)/GaN(10 nm) PSS APD [1,2]. When bias is larger than 30 V, the slope of conduction band in absorption region increases with the bias voltage and the electronics can pass over the first barrier with a large energy and continue to accelerate in the whole multiplication region.

The electric field distributions at different bias were also calculated and deliberately offset 20 nm with respect to each other, as shown in Fig. 3. It is obvious that the electric field distributions can be divided into three stages with the increase of bias voltage. When the voltage belows 30 V, the electric field in absorption region maintains a small negative value (the electric field is defined as positive in the downward direction), while it is positive value in the GaN multiplication layer and negative value in AlN interlayers.



Fig. 3 The electrical field versus reverse bias below 30 V (top) and above 30 V (bottom) with the 2nm thick AlN insert layer.

In order to further analyze the influence of AlN interlayers, we calculated the energy band of AlN interlayers with thickness of 5 nm and 10 nm, as shown in Fig. 4. It shows that the transition voltage from the second stage to the third one will increase with the thickness of AlN interlayers. The transition voltage is 90 V for 2 nm AlN interlayer and 190 V for 10 nm AlN interlayer.



Fig. 4 the band energy versus reverse bias with the 2 nm (a) and 10 nm (b) thick AIN insert layer.

To verify this theory prediction, PSS APD with periodic ultra-thin AlN interlayer of 2 nm were prepared. The gain was obtained from the measured IV curves of photocurrent and dark current, as shown in Fig. 5. It shows an obvious three different multiplication stages with the increase of the reverse voltage, corresponding to three transport processes of photo-generated electronics and agreeing with previous qualitative analysis very well. A high gain of  $6 \times 10^4$  at CV mode (36V) was obtained.



Fig. 5 the measured optical gain of the APD with 2 nm thick AlN insert layer.

#### IV. CONCLUSION

The periodic ultra-thin AlN interlayers in the multiplication of GaN APD give a significant influence to the transport process of photo-generated electronics. The numerically simulated results predict that the multiplication process contains three different stages with the increase of the reverse voltage, which is proved by the experimental results.

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