Polarization Effect of a PMT-like Avalanche Photodiode Based on GaN/AlN Periodic Stack Structure

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***Abstract*—APD based on AlN/GaN periodically stacked structure (PSS) has been proposed to obtain a high ionization coefficient ratio of more than 100 and a record high linear-mode gain of 10^4. Here the full p-i-p-i-n SAM structure of the PSS APD is simulated to discuss the influence of the polarization effect which cannot be ignored. The dependence of the device performances on polarization effect and structure parameters in the PSS APD is studied in detail, which will be helpful for the design and optimization of PSS APD.**

Keywords—Avalanche photodiodes, Polarization, linear mode, GaN/AlN，SAM

I. INTRODUCTION

Photomultiplier (PMT) can work at a constant bias (linear work mode) with low noise benefit by only one carrier ionization. But the application of PMT is limited by its disadvantage of bulky and fragile in many frontier domains [1]. Avalanche photodiode (APD) is a better choice for the detection of weak optical signal and single photon with integratable solid-state device. However, both electrons and holes participate in the avalanche multiplication process in APD, so it usually needs to operate in Geiger mode to obtain high gain which will result in large dark currents at the same time. If an APD can work in linear mode with only one carrier ionization, it will be a PMT-like detector and possess the advantages of PMT and APD at same time. As for the linear-mode APD, the high ionization coefficient ratio between electrons and holes is essential for a low noise and high gain [2]. In addition, separate absorption and multiplication (SAM) structure can effectively suppress one of the two carriers injected into multiplication layer [3]. Recently, APD based on AlN/GaN periodically stacked structure (PSS) has been proposed to obtain a high ionization coefficient ratio of more than 100, which was calculated by the Monte Carlo simulations based on the first principle theory [4-6]. With the help of AlN/GaN PSS multiplication region, the ionization coefficient of electron can be enhanced dramatically while the hole only shows a minor variation. Based on the simulation results, a record high linear-mode gain (10^4) has been demonstrated by the PSS APD under a constant bias in experiment [7]. However, the previous simulation by Monte Carlo studied the carrier transport processes inside AlN/GaN PSS separately. The full p-i-p-i-n SAM structure of the PSS APD was not simulated. The significant spontaneous and piezoelectric polarization effects in III-V nitride heterostructures were not taken into account.

Here, the dependence of the device performances on polarization effect and structure parameters in the PSS APD is studied in detail, which will be helpful for the design and optimization of PSS APD.

II. SIMULATION MODELS AND DEVICE STRUCTURE

The front-illuminated PSS APD consists of p-i-p-i(PSS)-n SAM structure, as shown in Fig. 1. From the top to the bottom, these five layers are sequentially named as p-type layer, absorption layer, charge layer, multiplication layer and n-type layer according to their function. 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 AlN/GaN PSS is employed as multiplication region. The general impact ionization process is described as following equation, with the ionization coefficients of electrons and holes extracting from the full-band-ensemble-Monte-Carlo simulations of the AlN/GaN PSS structure corrected with the effect of the polarization. E_{tri}, J_{ntri} and J_{ptri} are the vector field, electron current vector and hole current vector on the triangle.

$$G = \alpha_n(|E_{tri}|)J_{ntri} + \alpha_p(|E_{tri}|)J_{ptri} \quad (1)$$

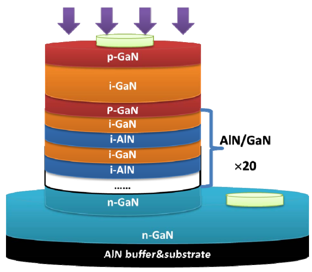

Fig. 1 Schematic structure of PSS-APD.

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. Polarization charge densities are changed from -1 to 1 of the calculated values, considering the screening effect caused by different defects density. The polarization direction in the epitaxial layer with MBE and MOCVD is usually opposite, as shown in Fig. 2. This positive sign indicates that the polarization direction is coincides with the growth direction.

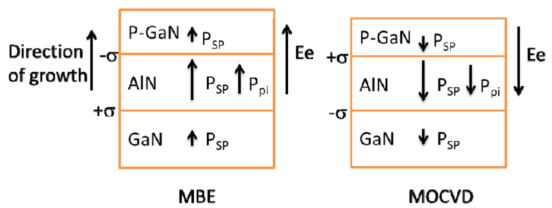

Fig. 2 The polarization direction in the epitaxial layer with MBE and MOCVD.

III. RESULT AND DISCUSSION

We investigated the effects of the polarization charge between the interfaces growth by MBE first, as shown in Fig.3. The electric field intensity increases in AlN/GaN PSS multiplication region and decreases simultaneously in absorption region with increasing the polarization in the interference. It shows that the positive polarization field has a similar effect to the p-interlayer. With increase of the polarization charge, the electric field of the AlN/GaN multiplication layer increases (red arrow). When the polarization coefficient is 0.4, the average electric field of the AlN/GaN PSS ((1.5+4.5)/2=3MV/cm) is much larger than that of without polarization (1.6 MV/cm). But the excessively polarization charge concentration will make the electric field in absorption region too low, then the p-i-p-i-n structure will degenerate into a p-i-n APD and he photon-generated carrier don't have enough electric field drift into the multiplication region, then lose the characteristic of electron-initiating multiplication. For the enough thickness of I absorption layer 300 nm, there is little photon reach through the PSS multiplication , so the photocurrent is almost to zero. Therefore, when the polarization effect is strong, the p-type insert layer should be appropriately reduced or even removed when MBE is grown. The polarization effect can realize the electric field redistribution in the absorption and the multiplication region.

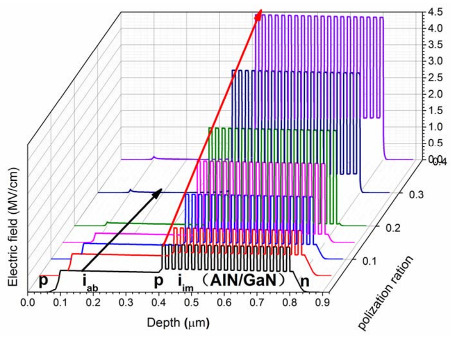

Fig. 3 Electric field intensity versus positive sign polarization charge concentration.

Note that the electric field in AlN/GaN PSS is considered as a constant in the Monte-Carlo simulations, but our simulation results show that electric field in AlN and GaN are different, and the ratio increases with the increase of polarization. Actually, in AlN barrier, the greater electric field accelerates the electrons to obtain kinetic energy due to the electron scattering inside the AlN layer is small, while the scattering of the GaN layer is large and the small electric field intensity avoiding the energy loss by large electron scattering in GaN layer. It is a good explanation that the measured IV has a good behavior that in the Monte Carlo calculations that underestimate the electron impact ionization. The existing montage algorithm can be modified based on the actual polarization.

As for the PSS-APD growth by MOCVD, the electric field intensity decreases in AlN/GaN PSS multiplication region and increases simultaneously in absorption region with increasing the polarization in the interference. Fully consider the polarization effect is necessary, and the p-type doping concentration in separation layer need to be increasing to achieve the effect of separation absorption layer and the multiplication layer. We can expect the electron impact coefficient is smaller in the MBE growth APD than the MOCVD one attribute to the smaller electric field intensity ratio in AlN to GaN.

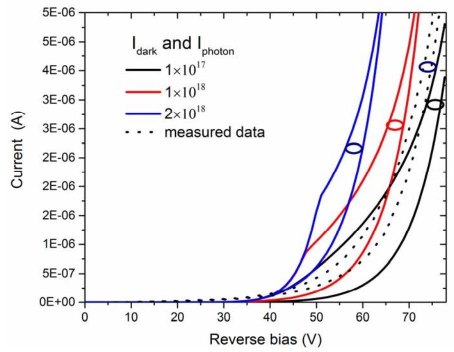

Fig. 4 I-V characteristics and multiplication gain (insert) for PSS-APD with different doping concentration and the measured IV curve.

There is an optimal p-doping concentration and interlayer thickness in a specified device, as shown in Fig.4. And our simulation results are consistent with the measure IV in MBE-APD. The p interlayer designs are different between the devices fabrication using MBE-growth material and the MOCVD-growth material.

IV. CONCLUSION

In summary, a front-illuminated PSS APD consists of p-i-p-i (PSS)-n SAM structure has been simulated. The ionization coefficients extracting from the full-band-ensemble-Monte-Carlo simulations need to be corrected due to the opposite polarization effects in different grown ways. And the p-doping concentration needs to be design carefully to balance the influence of the polarization effect.

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