Dark Current Simulation of GaN/AlGaN p-i-n Avalanche Photodiode

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Abstract

We report on 2D simulations of dark current for GaN/GaN/$Al_{0.33}Ga_{0.67}N$ p-i-n photodiode. The simulated result is in good agreement with experiment data indicating that avalanche multiplication is the cause of breakdown and band-to-band tunneling is the main source of dark current before breakdown. Effects of interface charge on avalanche current are investigated in detail.

I. INTRODUCTION

GaN avalanche photodiode (APD) can exhibit visible-blind operation and offer a high gain by avalanche multiplication, thus improving detection sensitivity, and short cut-off wavelength can be obtained by $Al_xGa_{1-x}N$ with x values ranging from 0 to 1. However, the development of GaN APD has been hampered by the high defect densities in the epitaxial layer grown on lattice-mismatched substrates. These defects lead to a premature microplasma breakdown before the electric field reaches the bulk avalanche breakdown level [1]. Recently, there are many reports of avalanche gain of GaN p-i-n APDs on sapphire substrates [2, 3]. However, to our knowledge, there have been few reports of simulation results on confirming and investigating the inner mechanism of avalanche multiplication. It is generally known that the impact ionization coefficient has the following electric field dependence,

$$\alpha(E) = a\exp(-\frac{b}{E}) \qquad (1)$$

where a and b are constants. There are many reports giving the result of a and b for GaN [4,5]. However, they are very different from each other. Since those parameters are still largely unknown, we fit the values from the experimental data. Furthermore, we analyze the dark current mechanism and demonstrate the avalanche gain in GaN/AlGaN APD.

II. DEVICE DESCRIPTION AND THEORETICAL MODELS

Figure 1 shows the 2D structure of our device. The active region consists of p-type GaN:Mg, unintentionally doped GaN, and n-type $Al_{0.33}Ga_{0.67}N$:Si layers with thicknesses of 150, 180, and 700 nm, respectively. The doping concentrations of p, i and n layers are 3×10^{18} cm^{-3}, 1×10^{16} cm^{-3} and 3×10^{17} cm^{-3}.

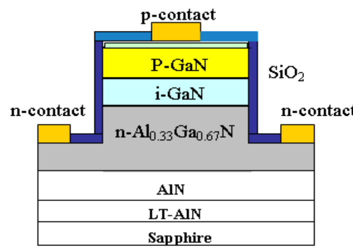

Fig.1. Schematic 2D structure of GaN/GaN/AlGaN p-i-n photodiode.

Steady-state numerical simulations are performed using Sentaurus Device [6], a commercial package by Synopsys. The calculations take into account SRH recombination, Auger recombination, van-Overstraeten/de Man avalanche model, Boltzman statistics, high-field saturation model [7], and band-to-band tunneling model. We fit the values of impact ionization coefficient, band-to-band tunneling coefficient from the experimental data.

III. RESULTS AND DISCUSSION

There are nearly no current if not consider Band-to-Band tunneling effect in the simulation. Due to GaN's large band-gap, the diffusion and generation-recombination current is immeasurably small. By taking Band-to-Band tunneling effect into account, the simulated result fits very well with experimental data at the high voltage as shown in Fig. 2. The tunneling effect in the reverse-biased p/n junctions becomes very important at the high voltage. By taking avalanche multiplication into account, an obviously breakdown appears at a certain high voltage. Above all, we can know that Band-to-Band tunneling effect is the main source of dark current before breakdown and avalanche multiplication may be the cause of breakdown.

The piezoelectric and spontaneous polarization can induce interface charges at nitride heterojunctions. These charges have been included in our simulations by specifying the interface charges between GaN/AlGaN. Due to the lack of the experimental data of interface charge, we fit the value from the experimental data. When the density of the interface charges between GaN/AlGaN is -4×10^{12} cm^{-2} as shown in Fig. 3, the simulation results are in good agreement with the experiment data, verifying the validity of the simulations.

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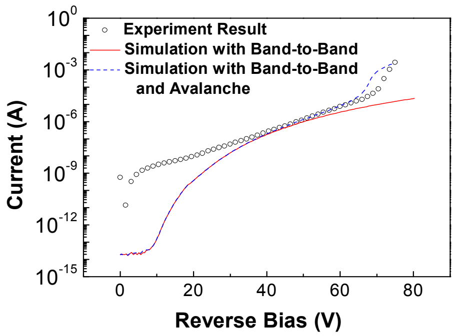

Fig. 2 The Simulated *I-V* characteristics with different models.

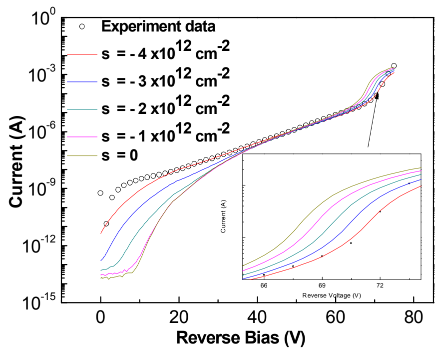

Fig. 3 The Simulated *I-V* characteristics with different interface charges at GaN/AlGaN.

The breakdown voltage increases with the increasing of interface charge density. It is well known that avalanche multiplication effect need certain electric field strength to be happened. It means that under the same bias the strength of electric field in the multiplication area decreases with the increase of the interface charge density. Simulation results confirm our conclusion, as shown in Fig. 4. The electric field strength in the i layer decrease with the increase of the interface charge density.

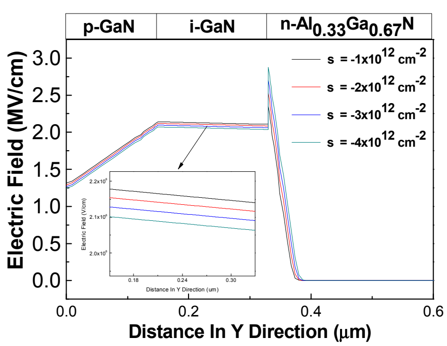

Fig. 4 Electric field strength of the device for different interface charge at GaN/AlGaN under the same bias.

To analyze dark current mechanism, dc output characteristics are calculated as a function of temperature, as shown in Fig. 5. Before breakdown, the dark current is strongly field dependent but weakly temperature dependent, indicating that tunneling is likely the dominant transport mechanism. The magnitude of the reverse-bias breakdown voltage shows a clear positive increase with an increase in temperature. The positive temperature dependence of the breakdown voltage confirms that the abrupt increase is predominantly due to the avalanche effects and not by premature junction breakdown due to microplasmas or mesa-sidewall leakage paths [8].

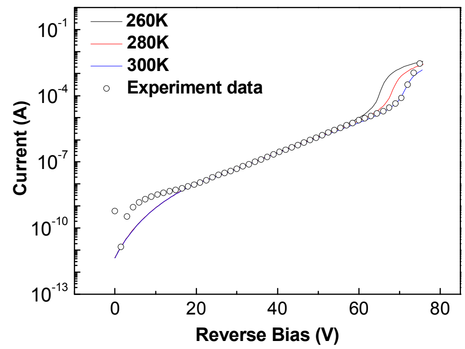

Fig. 5 The Simulated *I-V* characteristics at different temperatures.

IV. Conclusion

We have investigated the dark current mechanism of GaN APDs at the reverse bias. The dark current is strongly field dependent but weakly temperature dependent before breakdown, indicating that tunneling is likely the dominant transport mechanism. The positive temperature dependence of breakdown voltage confirms that the abrupt increase is predominantly due to the avalanche effects. Simulations results show that the polarization-induced interface charges play an important role in the device performance.

Acknowledgements

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