A method to realize hole-initiated multiplication in front-illuminated GaN avalanche photodiodes

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Abstract

A front-illuminated GaN n-i-p avalanche photodiode (APD) with a 25 μm diameter mesa is proposed. The gain is demonstrated to be higher in n-i-p devices compared with conventional p-i-n ones by simulation based on Spinelli analytical model.

1. Introduction

Ultraviolet (UV) sensors with ultrahigh sensitivity are strongly needed in defense and commercial applications such as military warning and guidance, biological and chemical monitoring. In order to detect weak signal, sensors with high gain and low noise are needed to be developed. GaN based avalanche photodiodes (APDs) have been intensively researched as a candidate for semiconductor UV sensor. The avalanche mechanism makes it able to magnify the signal in device [1]. It has been proved that holes in GaN ultraviolet APDs have a higher ionization coefficient compared with electrons by using ensemble Monte Carlo simulation [2]. This result predicted that hole-initiated multiplication APDs would have a better performance than electron-initiated multiplication APDs [3]. The conventional trial to realize hole-initiated multiplication is based on back-illuminated GaN p-i-n structure and has successfully verified that the hole-initiated multiplication mechanism contributes to performance improvement [4,5]. However, limitation still exists that the functional layers should not be epitaxially grown on native substrate whose absorption of signal light is significant [1]. The limitation of substrate would bring down the crystal quality and impact the device performance. To solve this problem, front-illuminated mechanism should be introduced into hole-initiated multiplication APDs.

2. Device design

The device structure of conventional front-illuminated GaN p-i-n and our n-i-p APDs are compared in Figs. 1(a) and 1(b). The most significant difference is that the epitaxial order of p and n layer is inverse. The band diagrams illustrated in Figs. 2(a) and 2(b) exhibit absorption and multiplication mechanism of the two kinds of APDs. For conventional p-i-n APD, incident light is mainly absorbed by the p-i interface, photo-generated electrons drift through i region and cause the multiplication process. As with n-i-p APDs, Incident light is mainly absorbed by the n-i interface, photo-generated holes drift through i region and cause the multiplication process. Therefore, multiplication in p-i-n APDs and n-i-p APDs are initiated by electrons and holes, respectively.

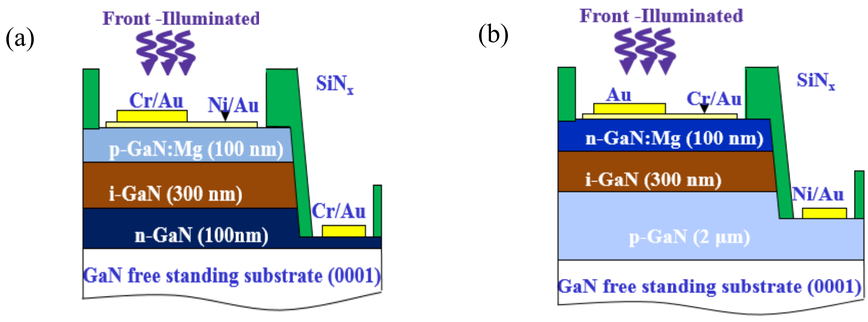

Fig.1. Device structures of (a) conventional GaN p-i-n APD and (b) GaN n-i-p APD.

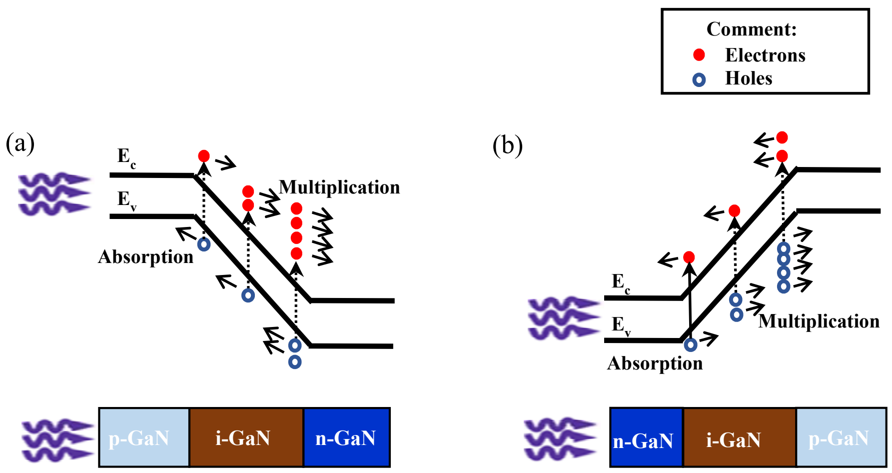

Fig.2. Band diagrams showing absorption and multiplication mechanism of (a) conventional GaN p-i-n APD and (b) GaN n-i-p APD structure.

3. Simulation and discussion

To certify that hole initiated multiplication APD has a more perfect device performance than electron-initiated multiplication APD. Simulation based on Spinelli analytical model is applied on the n-i-p structure [6]. For simplification, the electric field is regarded as uniform and i-region bear the whole bias voltage. The gain formulas for hole and electron initiated multiplication APDs are given by (1) and (2), respectively, where M(x) is given by (3).

$$M_p = M(d_e) \cdot \exp(\beta \cdot d_e) \tag{1}$$

$$M_n = M(W - d_h) \cdot \exp(\alpha \cdot d_h) \tag{2}$$

$$M(x) = \frac{exp(-(\alpha - \beta)(W - d_h - x))}{1 - \frac{\alpha}{\alpha - \beta}\left[1 - exp\left(-(\alpha - \beta)(W - d_h - d_e)\right)\right]} \tag{3}$$

where α, β, d_e, d_h reprensent electron ionization coeffecient, hole ionization coeffecient, electron dead space and hole dead space, respectively. W is the width of i-region. α, β, d_e, d_h are related to electric field, of which the formula can be found in literature [2]. Gain-bias relations are compared between electron and hole initiated multiplication APDs as given in fig.3. It can be seen that the gain of hole-initiated multiplication APDs is significantly higher than that of electron initiated multiplication APDs.

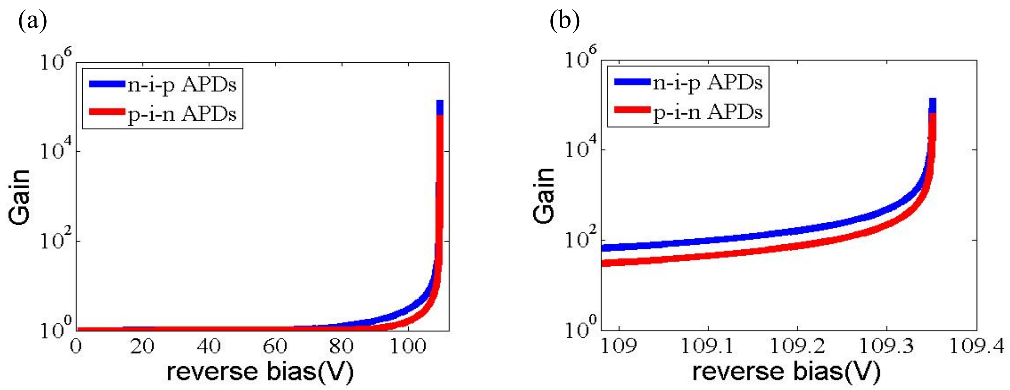

Fig.3. (a) Gain-bias curve compared between n-i-p and p-i-n APDs. (b) Magnified portion of the Gain-bias curve under bias between 109V and 109.4V

Considering the high cost of GaN native substrate, our first trial to realize the n-i-p structure shown in fig. 1(b) is based on sapphire substrate epitaxy. Material epitaxial work and device fabrication process is undergoing. The work to realize n-i-p APDs seems to be challenging for the following three reasons. First of all, regrowth of i- and n-layers on p-GaN/GaN/sapphire template is required to avoid memory effect of magnesium. Second, inductively coupled plasma (ICP) etching may bring damage to the p-type GaN. Renovation by acid etching technique should be used after ICP etching. Third, as signal light is illuminated from the top of n-GaN layer. Transparent n-type electrode should be developed.

4. Conclusion

A front-illuminated GaN n-i-p avalanche photodiode is proposed and demonstrated theoretically. The gain is demonstrated to be higher in n-i-p devices compared with conventional p-i-n ones by simulation based on Spinelli analytical model.

5. Acknowledgments

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6. References

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