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GaN Schottky Barrier Diodes for Microwave Rectification with Enhanced Cut-off Frequency

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Abstract

This paper presents a method to increase the cut-off frequency of GaN Schottky barrier diodes (SBDs) without reducing too much of the anode area and power capacity. SBD models are proposed first to understand the mechanism of parasitic resistance. Then patterned SBD and multi-feeds techniques are adopted to reduce the parasitic effect. SBDs with U-shaped and ω-shaped anodes were finally designed and fabricated. The parasitic resistances in both the two types are reduced, while the resistance is further reduced along the finger direction for the ω-shaped one. Compared with traditional finger-type GaN SBDs, the series resistance of the ω-shaped one is reduced to 1.96 Ω with reduction rate of 13.3%. The cut-off frequency of 121.57 GHz is achieved which is enhanced by more than 32.1% compared with traditional finger-type without sacrificing the breakdown performance (40 V).

1. Introduction

Microwave wireless power transmission (MWPT) is considered as a technology which improves the quality of human life [1-3]. However, limited by efficiency, system volume, radiation safety and other factors, MWPT is still far away from commercialization [4-5]. As one of the core components of the MWPT system, the performance of the microwave rectifier significantly affects the entire system. In recent years, Si and GaAs Schottky barrier diode (SBD) based microwave rectifiers have been widely reported. However, the conversion efficiency is still not satisfied, especially at high power cases [6-9]. Therefore, microwave rectifiers with high power capacity and efficiency have become an urgent demand for MWPT system.

GaN SBD is regarded as one of the best solutions for high power microwave rectification. The superior electrical properties such as wide bandgap, high breakdown electric field, and fast reverse recovery make the GaN SBDs with extraordinary performance on power and frequency [10-12]. In [13], a quasi-vertical GaN SBD with small anodes was reported to be able to apply in 110 GHz. But the cut-off frequency is apparently achieved at the cost of power capacity and breakdown voltage (V_b =15.6V). In our previous work, the quasi-vertical GaN SBD with finger-type layout was proposed to reduce the series resistance (R_s) without sacrificing the power capacity [14]. However, the cut-off frequency is hard to increase due to the parasitic resistance generated by the potential imbalance between fingers.

In this paper, patterned SBDs and multi-feeds techniques are proposed to further reduce the SBD series resistance and increase the cut-off frequency without sacrificing power capacity. Quasi-vertical GaN SBDs with U-shaped, ω-shaped are designed, fabricated, and measured based on the characteristics of GaN material and the SBD model. Compared with the traditional finger-type SBDs, the average R_s of the ω-shaped one is reduced by more than 13.3 % and the cut-off frequency is increased by 32.1%. Considering the quality of the GaN material is hard to enhance in the short term, the SBD performance can be pushed to its limitation by the two techniques, which finally improve the efficiency and power capacity of microwave rectifiers.

2. Experiments

The R_S of the quasi-vertical GaN SBD can be divided into three parts, i.e., drift layer resistance (R_{N^-}), access layer resistance (R_{N+}), and contact resistance (R_C). For the quasi-vertical SBDs with finger-type/finger-like-shaped layout, the R_{N^-} can be decomposed into X and Z directions (defined as R_X and R_Z), and the R_{N+} is mainly distributed along Y direction (defined as R_Y), as the model shown in Fig. 1 (a) and (b), respectively. Therefore, the resistance of finger-type SBDs with single feed can be calculated by

$$R_{N^-} = R_{of} = \frac{R_Z^3+3R_XR_Z^2+R_X^2R_Z}{R_X^2+3R_XR_Z+3R_Z^2}\ , \quad (1)$$

$$R_{N^+} = R_Y = \frac{d}{l}R_{\square}, \quad (2)$$

$$R_Z = \frac{h}{qns\mu_{N^-}}, \quad (3)$$

Where $R_{\square}$ is the sheet resistivity of N^+-layer, l is the length of anode, s is the acreage of N^--mesa, h is the thickness of N^--layer, d is the distance between anode and cathode, μ_{N^-} is the electron mobility of N^--layer, n is the drift layer impurity density and q is the elementary charge. Ideally, R_X can be considered as zero, which means the R_s of the SBD can be significantly reduced by increasing length and number of the finger. In practical, this will lead to serious side effects, i.e., increasing R_X and R_p. Where R_p is a parasitic resistance between fingers, which is mainly caused by the potential imbalance between fingers, as observed in Fig 1 (b). The model indicates that the increasing of finger's area and amount may even degrades the cut-off frequency ($f_C=1/2\pi RC$) of SBD since the effect of R_p and R_X is positively associated with finger number and length.

Patterned SBD technique that connects the separated fingers is adopted to balance the potential between fingers. Meanwhile, multi-feeds technique was used to alleviate the effect of R_X (The feed is defined as the number of points

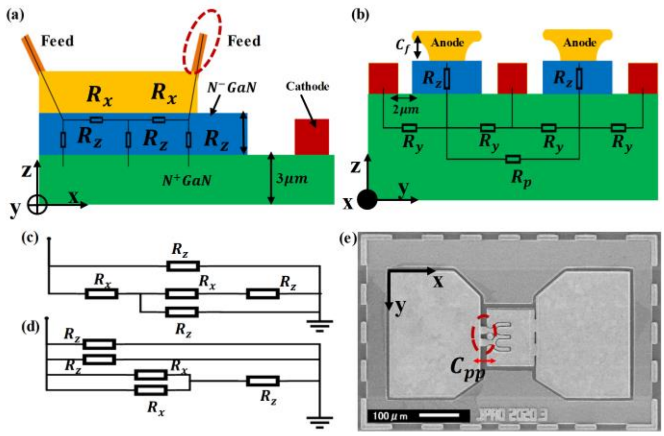

Fig. 1. (a) Normal section of GaN SBD with one/two feeds, (b) Cross section, (c) Equivalent circuit of SBD with one feed, (d) two feeds (e) SEM image of ω-shaped SBD with pads

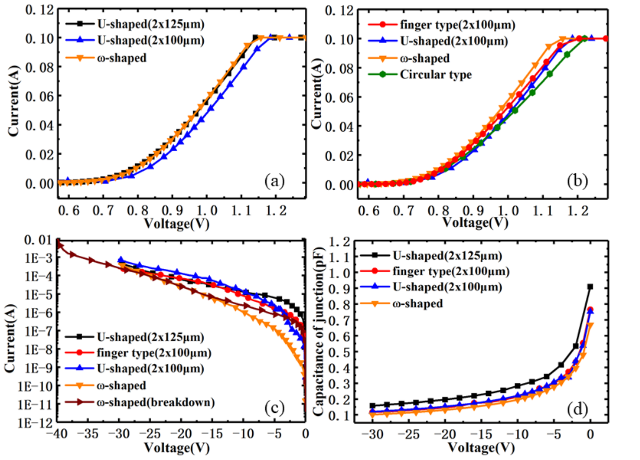

Fig. 2. (a) Representative I-V characteristics of multi-feeds versus single feed, (b) Finger/U/ω-shaped versus circular-type, (c) reverse leakage. (d) Representative characteristics for junction capacitance.

where current flows into the anode, see the dot line in Fig.1 (a) and Fig.1 (e)). Fig 1 (c) and (d) show the equivalent circuit of the finger-type SBD with one and two feeds. The N^--layer resistances of one feed (R_{of}) and two feeds (R_{tf}) SBDs are respectively given by Eq. (1) and Eq. (4),

$$R_{tf} = \frac{2R_Z^2+R_XR_Z}{2R_X+6R_Z} \quad . \tag{4}$$

It can be calculated that R_{tf} is smaller than R_{of}, i.e., the total resistance can be decreased.

To verify the proposed model, U-shaped and ω-shaped GaN SBDs based on patterned SBDs and multi-feeds technique are designed and fabricated. As the comparison, traditional finger-type and circular-type SBDs were also fabricated.

More than 200 SBDs with various types were measured. The data were averaged to reduce the influences of process and material errors. Fig.2 (a) shows that the average R_s of the ω-shaped SBDs is decreased to 1.96 Ω, which is an 8.2% reduction compared with that of the U-shaped (2×100 μm, 2.08 Ω). The enhancement is mainly attributed to multi-feeds technique that reduces the effect of R_X, which implies that R_X is not negligible when finger is long. The Comparison between the U-shaped, ω-shaped, and traditional circular-type and finger-type SBDs is given in Fig.2 (b). It can be found that, although the area of the circular-type SBDs (radius=90 μm) is large enough, the value of R_S (2.8 Ω) is still higher than that of the finger-type one. Benefiting from the patterned SBDs, the average R_s of both the U-shaped (2×100 μm) and ω-shaped are lower than that of the finger-type (2.26 Ω), with the reduction rate of 8.3 % and 13.3 %, respectively. The leakage current of the SBDs at reverse 30 V is all less than 1 mA, and a breakdown voltage of 40 V is achieved, as shown in Fig.2 (c). Fig. 2 (d) shows the junction capacitance (C_j) of the SBDs with different voltage. the zero-biased junction capacitance (C_{j0}) of the ω-shaped SBD is 0.668 pF, which is about 87.3 %, 88.8 % and 73.4 % of the finger-type (0.765 pF), U-shaped (2×100 μm, 0.752 pF) and U-shaped (2×125 μm, 0.91 pF). Since the R_s and C_j are reduced at the same time, the average cut-off frequency of ω-shaped increases to 121.57 GHz, which is improved by 32.1% compared with the traditional finger-type SBDs.

3. Conclusions

This paper presents a method to enhance cut-off frequency of the GaN SBDs without reducing too much of the anode acreage. By proposing an ω-shaped GaN SBD, both the series resistance and junction capacitance are reduced. Compared with traditional finger-type GaN SBDs, the cut-off frequency of the proposed structure is enhanced by 32.1 % and the series resistance is reduced by 13.3 %, with the breakdown voltage maintained at 40V.

References

[1] K. M. Z. Shams and M. Ali, IEEE Sensors J. 7 (2007) 1573.
[2] M. Simic, C. Bil and V. Vojisavljevic, Procedia Comput. Sci. 60 (2015) 1846.
[3] J. M. Miller *et al.*, IEEE J. Emerg. Sel. Topics Power Electron. 3(2015) 147.
[4] S. Wan and K. Huang, IEEE Antennas Wirel. Propag. Lett. 17(2018) 538.
[5] B. Strassner and K. Chang, Proc IEEE Inst Electr Electron Eng. 101 (2013) 1379.
[6] C. Liu *et al.*, IEEE Trans. Microw. Theory Techn. 65 (2017) 600.
[7] Q. W. Lin and X. Y. Zhang, IEEE Trans. Microw. Theory Techn. 64 (2016) 2943.
[8] M. Huang *et al.*, IEEE Trans. Microw. Theory Techn. 67 (2019) 1974.
[9] S. Ladan and K. Wu, IEEE Trans. Microw. Theory Techn. 63 (2015) 937.
[10] N. Yıldırım, K. Ejderha and A. Turut, J. Appl. Phys. 108 (2010) 114506.
[11] J. L. Keon et al., J. Appl. Phys. 100 (2006) 124507.
[12] S. Han, S. Yang and K.Sheng, IEEE Electron Device Let. 39 (2018) 572.
[13] Z. Feng *et al.*, *2016 IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes for RF and THz Applications* (2016) 1.
[14] T. Pu *et al.*, *2018 IEEE MTT-S International Wireless Symposium* (2018) 1.