Analysis and Optimization of GaN Diode Structure for High Power and High Efficiency Rectifier

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Abstract

This paper analyzes and optimizes the structure of gallium nitride (GaN) planar Schottky barrier diode (SBD) to maximize the rectifier RF-DC conversion efficiency (PCE) and the operating dynamic range. The analysis indicates a small series resistance and a small zero-bias junction capacitance were needed to improve the wide dynamic range performance of the rectifier circuit. The prototype single-shunt rectifiers using the proposed GaN SBDs for evaluation achieves a conversion efficiency of more than 80% at an input power of 40dBm at 5.8GHz. The high efficiency design rectifier achieves 87% peak PCE with 23dB dynamic range. The wide dynamic range design rectifier achieves 78% peak PCE with 32dB dynamic range.

1 Introduction

Space Solar Power Systems (SSPS) is a future power plant and the system wirelessly transmits Giga-W-class energy from the space to the earth. In the receiving station on the earth, a rectifier is one of the key components[1],[2]. The earth station employs array configuration, which needs a lot of high power and high efficiency rectifiers, resulting in growing demand for a 10-W class rectifier with high efficiency. There are various reports of the 10-W class rectifier, which employs synchronous/self-synchronous class-E, class-F, or inverse class-F configurations /operations [3]-[8]. The inverse class-F rectifiers on ref. [4] and [5] realize an efficiency of 85% at 0.91GHz and 2.14 GHz, respectively. In addition, the C-band single-shunt rectifier[9] and the X-band class-F rectifier[10] achieve the efficiency of 45% and 52%, respectively. All of the above reports use 10-W class GaN HEMT devices. However, the efficiency is not enough for SSPS system, the maximum efficiency of 85% at below S-band, even though the most effective circuit configurations were selected. This paper investigates and proposes an optimal GaN Schottky barrier diode (SBD) with a breakdown voltage of 150 V or more to realize the high efficiency 10-W class rectifier at 5.8 GHz. The analysis is carried out by using a co-simulation technique that simultaneously changes the device structure and the rectifier circuit using the proposed GaN SBD.

2 GaN Schottky Diode Model

In this paper, the Schottky diode and the energy-conversion efficiency based on the diode equivalent circuit model [12] are optimized in terms of semiconductor device parameters. In this model [12], losses are caused by the junction capacitance, series resistance, threshold voltage, and reverse breakdown voltage. To simplify the analysis, only the fundamental frequency and DC term are included in the calculation. The model does not consider higher order harmonics and impedance matching due to simplification.
The diode equivalent circuit model used here employs the following parameters;

- Reverse Breakdown Voltage, V_{BR}
- Voltage threshold, V_F
- Series Resistance, R_S
- Junction Capacitance, C_j

In addition, this model also uses the following parameters;

- Load Resistance, R_L
- Fundamental Frequency, f
- Diode rectification ratio when one cycle is 1, α

Listed below are the diode device parameters which express the diode behavior.

A. Reverse Breakdown Voltage

The reverse breakdown voltage is typically represented by the semiconductor permittivity, doping density, and critical electric field for according to (1).

$$V_{BR}=\frac{\varepsilon}{2qN_D}E_{BR}^2 \quad (1)$$

where q is the electron charge (1.60×10^{19}C), N_D is the donor density of the n-type semiconductor (cm^{-3}), and E_{BR} is the breakdown electrolysis and, ε is the electric permittivity of the semiconductor.

B. Threshold Voltage

The threshold voltage for an n-type Schottky diode is equal to the built in potential V_{bi}. While there are multiple definitions for the threshold or turn-on voltage for a diode, the built-in potential will be used here. The barrier potential Φ_{Bn} is barrier against electron flow between the metal and the n-type semiconductor and is dependent on the metal work function Φ_m and the semiconductor electron affinity χ as shown in (2).

$$\Phi_{Bn}=\Phi_m-\chi \quad (2)$$

The built-in potential V_{bi} takes into account the barrier potential and a doping-depending barrier lowering term shown in (3).

$$V_{bi}=\Phi_{Bn}-(E_C-E_f)=\Phi_{Bn}-\frac{kT}{q}\ln\left(\frac{N_C}{N_D}\right) \quad (3)$$

where E_C is the conduction level in electron volts, k is Boltzmann`s constant (1.38×10^{-23} J/K), T is the temperature in Kelvin, and N_C is the density of states in the conduction band in cm^{-3}[12].

C. Series resistance

The series resistance R_S is geometrically dependent in addition to its material dependencies as shown in (4).

$$R_S=(\frac{1}{qN_D\mu_n})(\frac{d}{S}) \quad (4)$$

where μ_n is the semiconductor electron mobility, d is the epitaxial layer thickness, and S is the junction areas.

D. Junction Capacitance

The Schottky diode junction capacitance Cj is also geometry dependent, although compared to the series resistance, proportional to the junction areas as shown by (5).

$$C_j=C_{j0}\left(1-\frac{V_o}{V_{bi}}\right)^{-0.5} \quad (5)$$

where Cj_0 is the diode`s zero bias junction capacitance, V_o is the output self-bias dc voltage across the resistive load [2]. The operating frequency is 5.8GHz and the target breakdown voltage is 150V or more in this analysis. When the breakdown voltage is determined, the impurity concentration of the active layer is derived from (3). In addition, the depletion layer width at the time of reaching breakdown electrolysis is shown by (6)

$$t=\frac{\varepsilon}{qN_D}E_{BR}=\frac{2V_{BR}}{E_{BR}} \quad (6).$$

From the above equations, the donor density of the n-type semiconductor N_D=7.38×10^{16}cm^{-3}, and the depletion layer width t =1.5µm are calculated.

3 Simulation

The structure of the GaN Schottky diode and its equivalent circuit used for simulation in the single shunt rectifier circuit are shown in Fig. 1. [14]. The fixed diode parameters are exhibited on Table 1.

The impact of the impurity concentration on the energy harvesting efficiency was analyzed. The impurity concentration in the access layer was varied between 1.0×10^{18}cm^{-3} and 5.0×10^{19}cm^{-3}, and the anode area was varied between 200µm^2 and 2000µm^2. These results provide the access layer concentration of 5.0×10^{18}cm^{-3} and the anode area of 450µm^2 (150µm×3µm) to maximize the efficiency. The load resistance of the evaluation model is 100 Ω. The diode efficiency η is given as,

$$\eta=\frac{\frac{V_{DC}^2}{R_L}}{P_{in}}\times100 \quad (7).$$

The simulation results shown in Fig.2 indicate that the efficiency increases as the width of the access layer decreases and the thickness of the access layer increases. These two parameters impact on the resistance component of the diode, and it has been shown that the efficiency increases when the resistance value becomes small. In addition, the simulation results exhibit that the efficiency

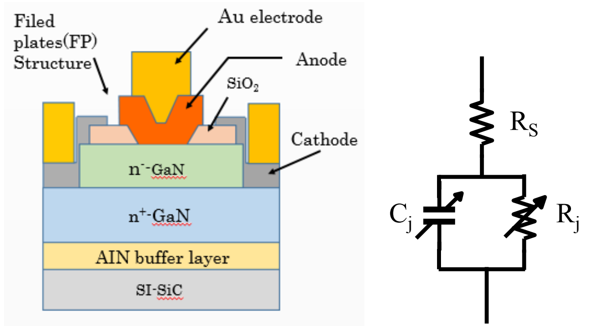

Fig. 1. Structure of GaN Schottky diode and equivalent circuit

Table 1 GaN Schottky diode parameters

Frequency f [GHz]	5.8
Output voltage V_{out} [V]	40
Breakdown voltage V_{BR} [V]	150
Impurity concentration of active layer N_{DI} [/cm^3]	7.38×10^{16}
Active layer thickness X_I [µm]	1.5

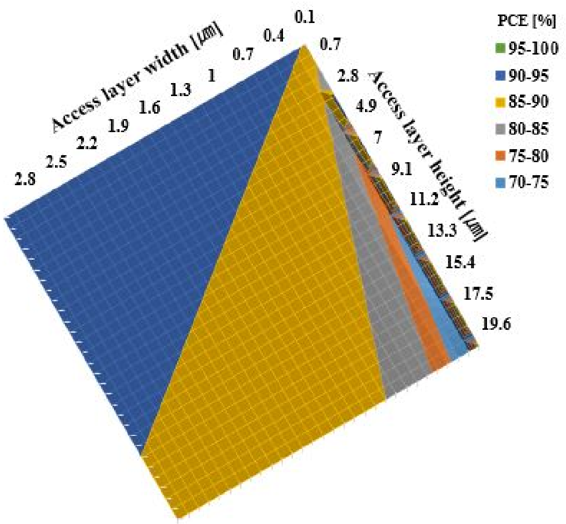

Fig. 2. GaN Schottky diode structure and energy-conversion efficiency when Access layer width and height varied with V_{out}=40V, C_{j0}=0.325pF, V_{bi}=0.912V, R_L=150Ω, r=50Ω and α=0.3.

increases as the anode area increases, however, in this case the entire device increases with the anode area. At this time, the value is finally 450 µm^2 described above. Furthermore, with regard to the impurity concentration of the access layer, we have to consider an electric field increase at the case of reverse bias, although the higher concentration provides higher efficiency.

4 Rectifier Circuit

A single shunt rectifier(shown in Fig. 4) is employed for evaluating the proposed diodes described in section 3. Four diodes, Type1, Type2, Type3, and Type4, shown in Table

Table 3 Physical dimensions of microstrip line on prototype rectifiers

Rectifier design	High efficiency rectifier				Wide dynamic range rectifier			
Diode type	Type1	Type2	Type3	Type4	Type1	Type2	Type3	Type4
Line length, L_1[mm]	8.4	8.4	8.3	9.2	5	5	5	8.1
Characteristic impedance, Z_1[ohm]	116.5	108.7	108.7	108.5	132.5	132.5	132.5	116.5
Effective dielectric constant, ε_{Eff1}	2.50	2.53	2.53	2.53	2.45	2.45	2.45	2.50
Line length, L_2[mm]	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7
Characteristic impedance, Z_2[ohm]	80.5	76.1	76.1	66.9	76.1	79.0	83.1	70
Effective dielectric constant, ε_{Eff2}	2.65	2.67	2.67	2.73	2.67	2.66	2.66	2.63

2 are considered for high efficiency and wide dynamic range rectifiers. The anode areas of Type1, Type2, and Type3 are the same value, 450μm^2 (150μm x 3μm). While the anode area of Type4 is 200μm^2 (100μm x 2μm) to change the zero-bias capacitance. The corresponding series resistances, Rs, of Type1, Type2, Type3, and Type4 are 6.79Ω, 3.19Ω, 3.09Ω, and 7.1Ω, respectively. Other parameter values are the same as those of Type2. Fig. 3 shows the I-V characteristics of each diode exhibited in Table2.

Two types of the rectifier, the high efficiency type and the wide dynamic range type were designed on 0.76mm-thick Rogers 3035 substrate. Fig.4 shows the equivalent circuit of the single-shunt rectifier for evaluation. The 10-W class high efficiency design rectifier and the wide dynamic range design rectifier are designed at 5.8GHz for evaluation. Physical parameters of each transmission line are exhibited in Table3. Fig.5 and Fig.6 shows the simulation results of the PCEs of each rectifier. From Fig. 5 and Fig. 6, it can be seen that the maximum efficiency depends on the series resistance of the diode. Type2 or Type3 diodes provide high efficiency performance. Fig. 6 indicates that the maximum efficiency widely varies, while the dynamic range of more than 50% PCE slightly varies. This is because the Type1, Type2, and Type3 diodes have the same zero bias junction capacitance. These results indicate that the wide dynamic range design rectifier employing the Type4 diode provides wider dynamic range of 50% or more PCE.

To compare the overall performance of rectifiers, two Figure-Of-Merits (FOMs) are proposed. The proposed FOMs are defined as the following equations;

$$FOM1 = \eta_{MAX} \times P_{in(Peak)} \times \frac{dynamic\ range}{P_{in(Center)}} \times dyn_{\eta} \quad (8)$$

$$FOM2 = \frac{\eta_{MAX}}{dyn_{\eta}} \times dynamic\ range \quad (9)$$

where, η_{MAX} is the maximum efficiency, $P_{in(peak)}$ (mW) is the input power at the maximum efficiency, dynamic range is the dynamic range (dB) defined by dyn_{η}, $P_{in(Center)}$ is the input power (mW) at the middle point of the dynamic range, and dyn_{η} is the minimum efficiency that defines the dynamic range. Table 4 shows the comparison with reported rectifiers. Both FOMs of the rectifiers employing the proposed diodes are higher values than those of the reported rectifiers. These results indicate that not only the value of the series resistance R_S is small but also the value of the zero bias junction capacitance C_{j0} is important to realize the wide dynamic range rectifier, resulting in Type4 diode.

Table 2 Diode parameters used for evaluation

	Type1	Type2	Type3	Type4
Anode Area[μm^2]	150×3	150×3	150×3	100×2
Rs[ohm]	6.8	3.2	3.1	7.1
Cj0[pF]	0.33	0.33	0.33	0.15

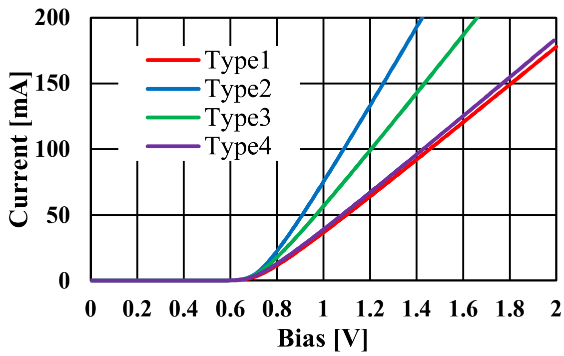

Fig. 3. I-V characteristics of diodes.

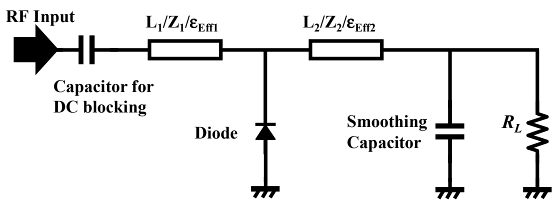

Fig. 4. Rectifier circuit for evaluation

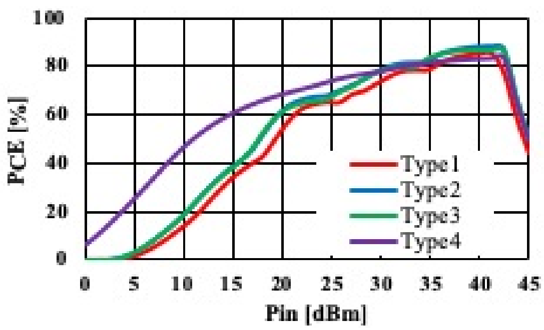

Fig. 5. Power-conversion efficiency of high efficiency rectifier with 330 Ω load resistance.

5 Conclusion

This paper investigated and proposed a GaN schottky diode structure that can provide high level efficiency with more than 10W input power capability. The relationship between the GaN Schottky diode device parameters and the efficiency of the rectifier was investigated by using theoretical analysis and simulation. The single-shunt rectifiers employing the optimized diode realized a PCE of over 80% at 40dBm input power and over 30 dB dynamic input power range with over 50%. In addition, the results indicate that a small series resistance and a small zero-bias junction capacitance were needed to improve the performances of the rectifier circuit. To achieve this performance, high-concentration GaN device processing technology on the order of micrometers is essential. We will indicate the detailed comparison of diode structures in further detailed performance analysis and will present the fabrication results at the conference.

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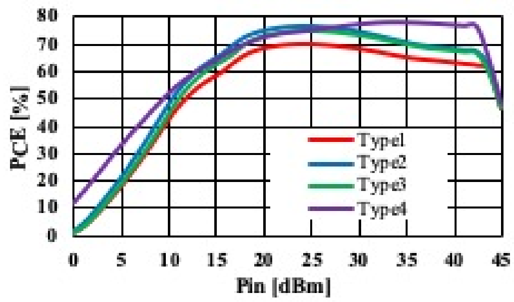

Fig. 6. Power-conversion efficiency of wide dynamic range rectifier with 330 Ω load resistance.

Table 4 Comparison of RF rectifier performances

Ref.	Device	Freq. (GHz)	η_{max}	$P_{in(Peak)}$ (mW)	*dynamic range* (dB)	$P_{in(Center)}$ (mW)	*dyn_η*	FOM1	FOM2
[4]	Cree CGH40010F	0.91	0.85	11912	19.8	1191	0.5	84.16	33.66
[15]	Cree CGH40010F	1.85	0.84	8511	15	1585	0.6	40.60	21.0
[5]	Qorvo TGF2023-02	2.14	0.85	10000	17	1413	0.5	51.13	28.9
[16]	HSMS-282F	4.1	0.60	1100	6.43	1350	0.52	1.630	7.42
[17]	HSMS-282F	4.6	0.55	1500	6.02	1500	0.52	1.720	6.37
[18]	SEI GaN Diode	5.9	0.33	10000	9	3548	0.2	1.674	14.85
[9]	Qorvo TGF2023-02	5.74	0.45	26300	12	6607	0.2	4.299	27.0
This work Type2_high	GaN Diode	5.8	0.87	7713	23	546	0.5	141.3	40.02
This work Type2_wide	GaN Diode	5.8	0.76	281	31	368	0.5	9.000	47.12
This work Type4_high	GaN Diode	5.8	0.83	13044	31	368	0.5	456.0	51.46
This work Type4_wide	GaN Diode	5.8	0.78	2219	32	55	0.5	503.5	49.92

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