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

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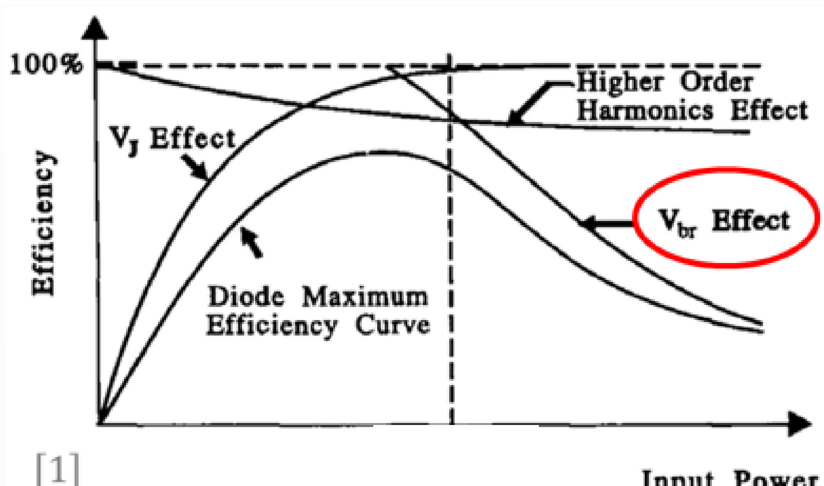
Background & Purpose

- Space Solar Power Systems (SSPS) has a plan to use wireless power transfer (WPT) system.
- The WPT system transmits Giga-W-class energy signals generated on SSPS from space to earth.
- The high power reception capability and high efficiency performance on a rectenna are required.



General relationship between microwave to dc power conversion efficiency and input power

When high input operation of rectenna

Significant efficiency loss

Increasing breakdown voltage of rectifying device

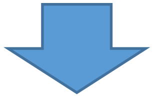
In this research

Proposes an optimum diode device that enables high input and high efficiency operation

Previous research

Freq.(GHz)	Input power (W)	Efficiency(%)	Circuit type	Ref.
5.9	10	32.6	Single shunt series	C band GaN diode rectifier with 3W DC output for high power microwave power transmission applications. 2016IMS DOI: 10.1109/MWSYM.2016.7540129
5.78	26.3	44.8	Single shunt series	10 W Class High Power C-Band Rectifier Using GaN HEMT . 2019WPTC, WPP90
2.14	10	85	Diode and Transistor Rectifiers	High-Efficiency Harmonically Terminated Diode and Transistor Rectifiers . IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, VOL. 60, NO. 12, pp. 4043-4052, DECEMBER 2012
0.985	10.7	81.3	class F synchronous rectifier	High efficiency GaN HEMT class-F synchronous rectifier for wireless applications. 2015WPTC DOI: 10.1109/WPT.2015.7140165

Input power is limited by the breakdown voltage of the diode.
There is a proportional relationship between breakdown voltage and series resistance.
It is known that increasing series resistance degrades diode performance.



In this research, proposes an optimal diode structure that increases the breakdown voltage without degrading the diode performance.

Advantages of wide band gap semiconductors

Figure of merit for diodes

$$\tau = R_{ON}C = \frac{4}{\mu {E_C}^2} V_B$$

V_B : Breakdown Voltage
μ : Electron mobility
E_C : Breakdown electric field

Breakdown voltage is determined by breakdown electric field and semiconductor impurity concentration distribution (mobility)

⇒GaN has a high level breakdown electric field; more than 8 time values compared with those of GaAs and Si

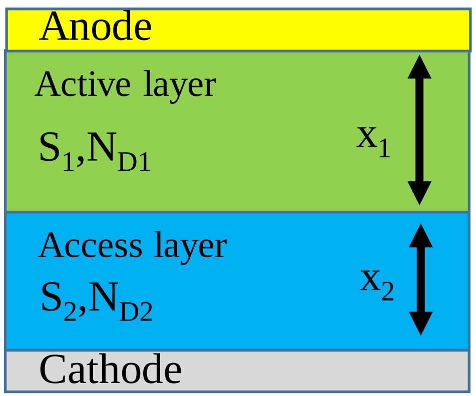
- Physical property value of semiconductor -

	GaN	GaAs	Si
Band gap(eV)	3.39	1.42	1.12
Breakdown electric field(V/cm)	3.3×10^6	4×10^5	3×10^5
Electron saturation(cm/s)	2.5×10^7	2×10^7	1×10^7
Thermal conductivity(W/cm・deg)	1.3	0.5	1.5
Intrinsic carrier density(cm^{-3})	1.7×10^{-10}	1.8×10^6	1.5×10^{10}
Electric mobility(cm^2/Vs)	2000	8500	1500
Hall mobility(cm^2/Vs)	30	400	470

Diode design

-Active layer design -

①Set the Breakdown voltage V_{BR}→Determines impurity concentration and thickness of active layer



$$N_{D1} = \left[\frac{\varepsilon}{2q} E_C{}^2\right] \frac{1}{V_{BR}}$$

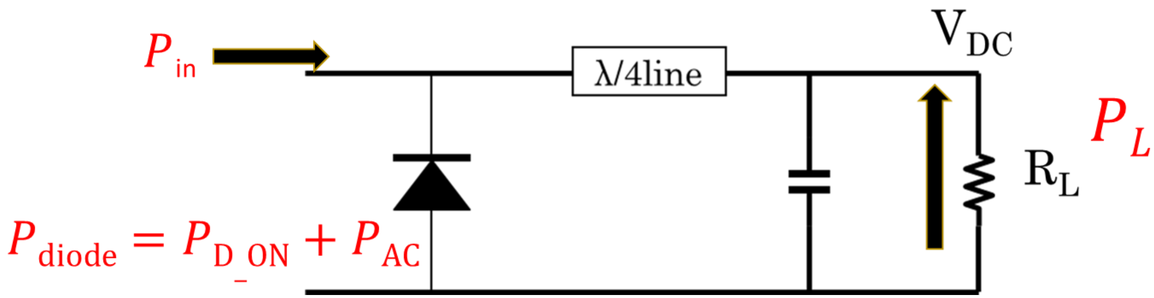
$$x_1 = \frac{\varepsilon}{q N_{D1}} E_C = \left[\frac{2}{E_C}\right] V_{BR}$$

N_D:Impuurity concentration
x:thickness
S:Junction area
Ec: Breakdown electric field
μ : Electron mobility
q:Unit charge
ε : permittivity

②Determines the resistance and capacitance of the active layer

$$R = \frac{4V_{BR}^2}{S\varepsilon\mu E_C^3} \qquad C_{j0} = S\frac{xqN_D}{V_{BR}}$$

Power loss in the rectifier circuit



DC output power

$$P_L = \frac{{V_{DC}}^2}{R_L}$$

Diode Loss

$$P_{diode} \begin{cases} P_{AC} = 4\pi^2 f^2 C^2 (V_F + V_{DC})^2 R_D & (diode - off) \\ P_{D\_ON} = \frac{V_{DC}}{R_L}\left(V_F + \frac{R_D}{R_L}\frac{V_{DC}}{\alpha}\right) & (diode - on) \end{cases}$$

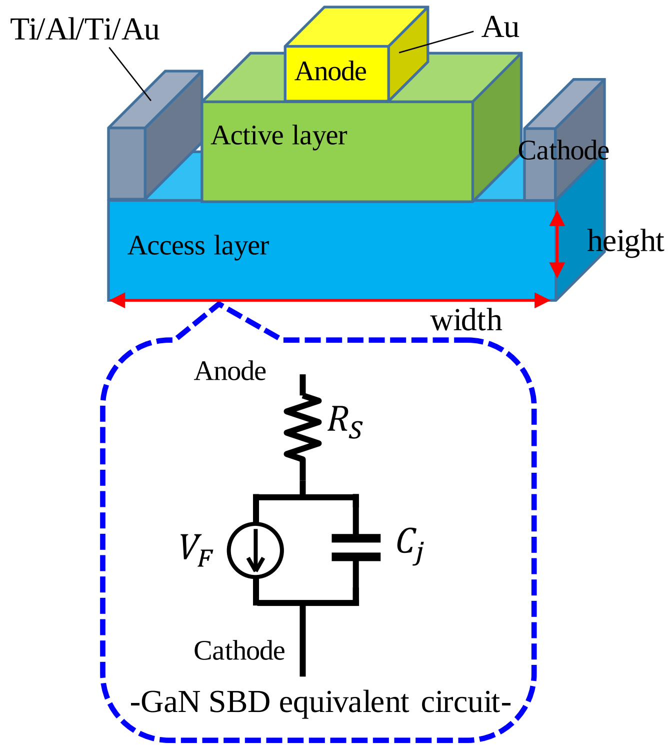
α : Percentage of diode on time in one cycle

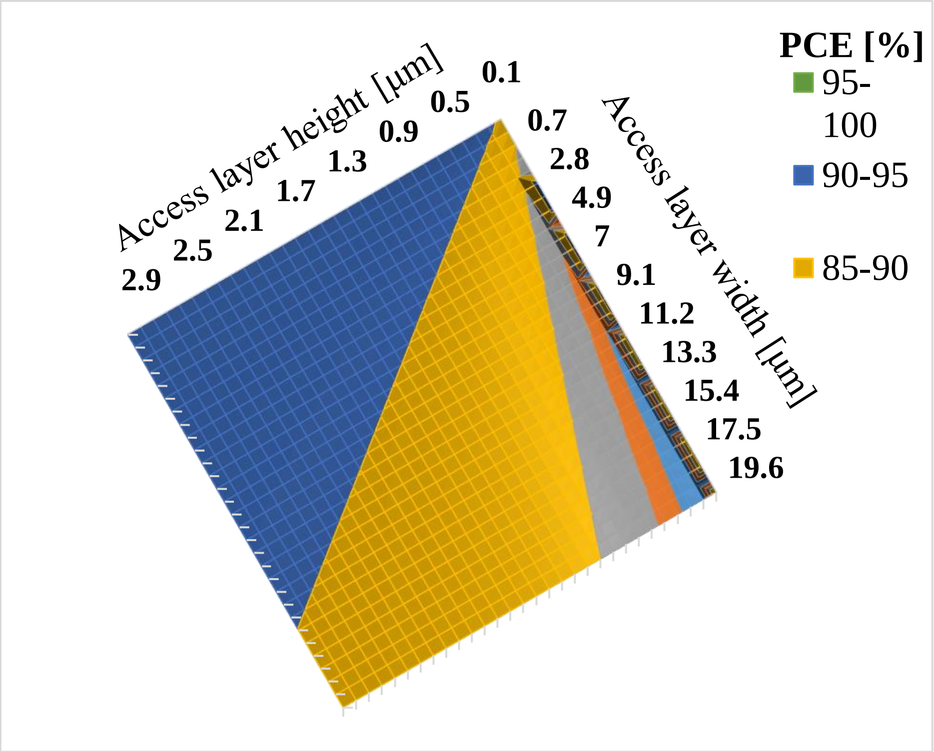
RF/DC Efficiency

$$\eta = \frac{P_L}{P_L + Pdiode} [\%]$$

Simulation results of Rectifier performance; PCE

- Access layer design -





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.

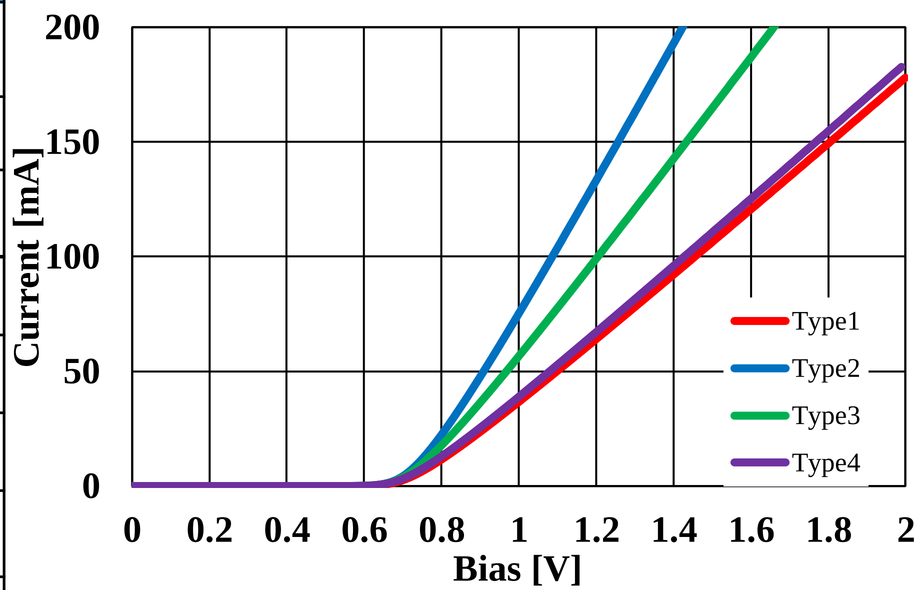
The simulation results shown in the upper right figure show that the efficiency increases as the width and thickness of the access layer decrease.
Access layer height and Access layer width parameters affect the resistance component of the diode and that the efficiency improves as the resistance value decreases.
Regarding the impurity concentration of the access layer, it is necessary to consider the increase of the electric field in the case of reverse bias, but basically, the higher the concentration, the higher the efficiency

Diode Parameters and I-V characteristics

- The expected diode parameters for high efficiency are exhibited.
- Regarding diodes that are expected to have the same maximum efficiency, the following four diodes will be referred to in order to confirm differences other than maximum efficiency due to differences in resistance and capacitance values.

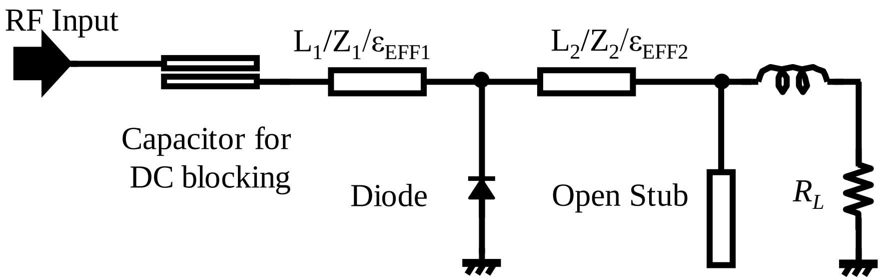
	Type1	Type2	Type3	Type4
Anode Area[μm]	150×3	150×3	150×3	100×2
Rs[ohm]	6.8	3.2	3.1	7.1
Cj0[pF]	0.33	0.33	0.33	0.15

Frequency f [GHz]	5.8
Output voltage V_{out} [V]	40
Breakdown voltage V_{BR} [V]	150
Impurity concentration of active layer N_{D1} [/cm^3]	7.38×10^{16}
Active layer thickness X_1 [μm]	1.5



The four diodes shown in the table, Type1 to Type4, are evaluated as high efficiency rectifiers and wide dynamic range rectifiers.

Rectifier Circuits for Evaluation

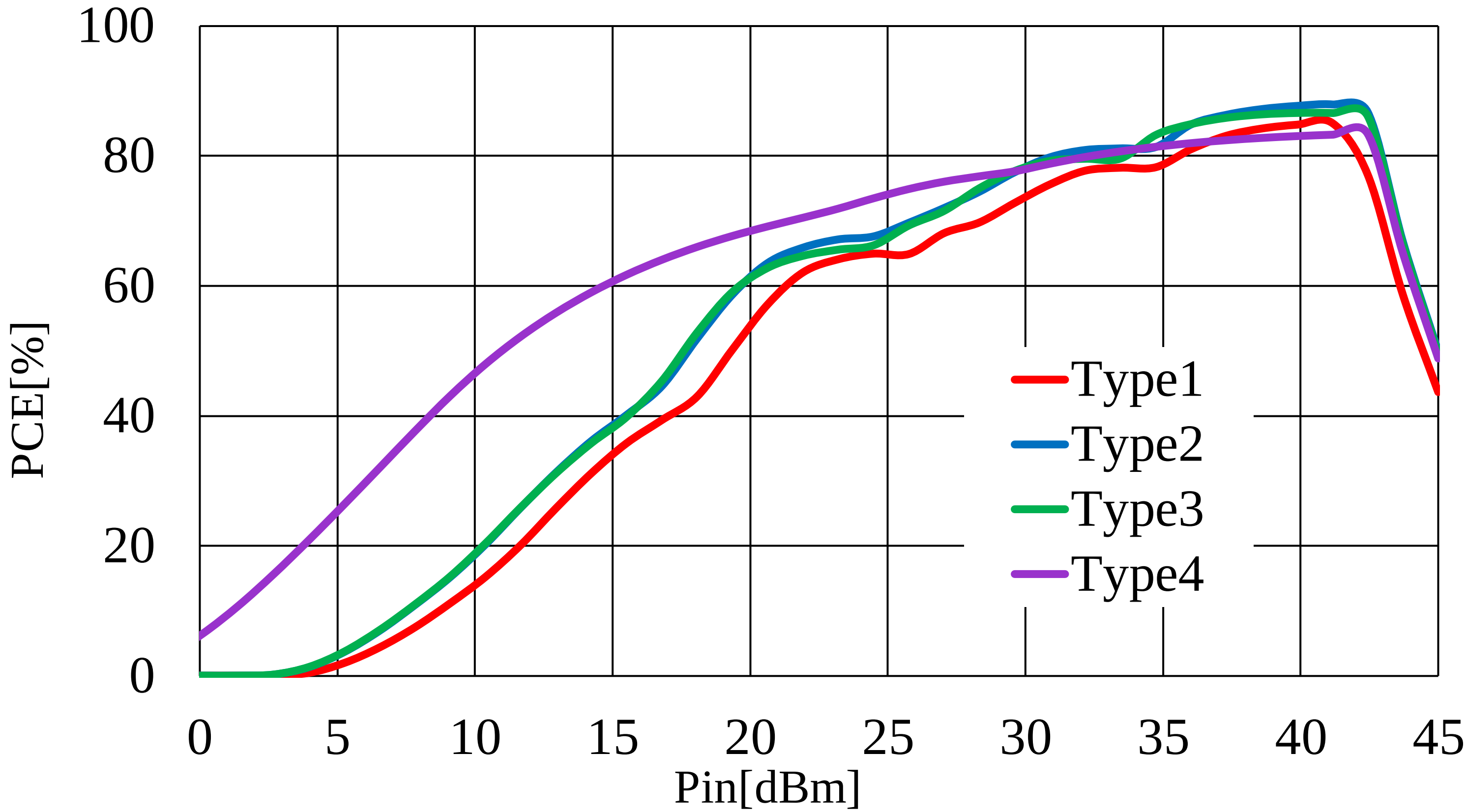


High efficiency type and wide dynamic range type rectifiers were designed on a 0.76 mm thick Rogers 3035 board.

- Evaluation model -

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

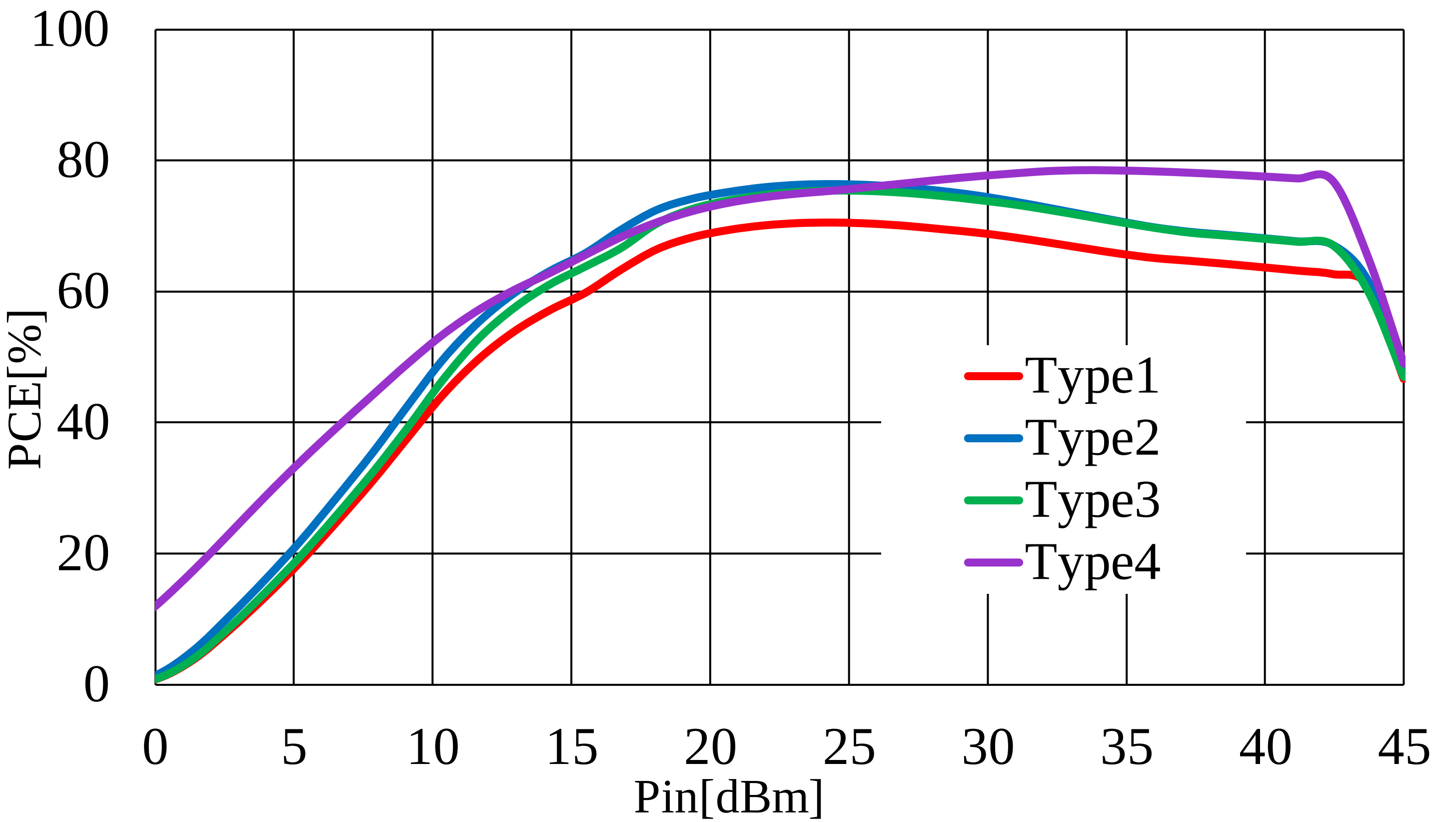
Simulation Results for High Efficiency design



Power-conversion efficiency of high efficiency rectifier with 330 ohm load resistance

- Type4 realizes more the widest dynamic range performance in the models.
- Different characteristics are caused by zero bias junction capacitance.

Simulation Results for wide dynamic range design



Power-conversion efficiency of wide dynamic range rectifier with 330 ohm load resistance

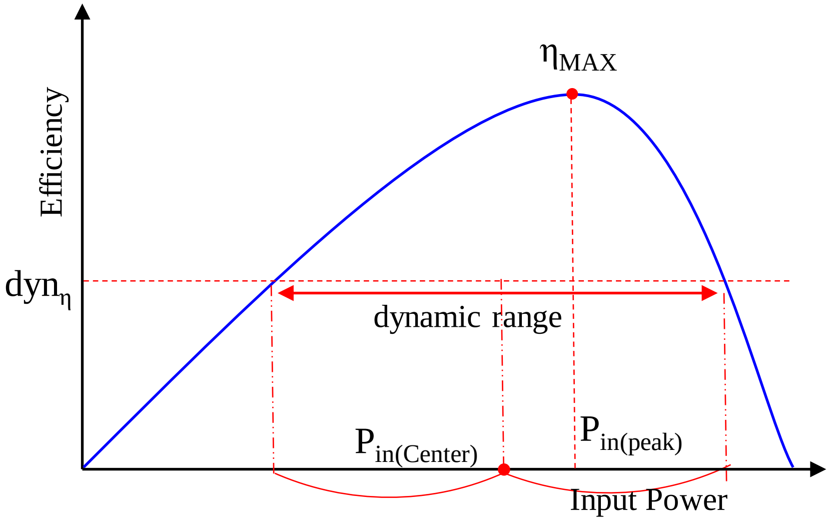
- The maximum efficiency widely varies, while the dynamic range of more than 50% PCE slightly varies.
- The maximum efficiency depends on the diode series resistance.

Figure Of Merits

The following two figures of merit (FOM) are proposed to compare the performance of rectifiers.

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

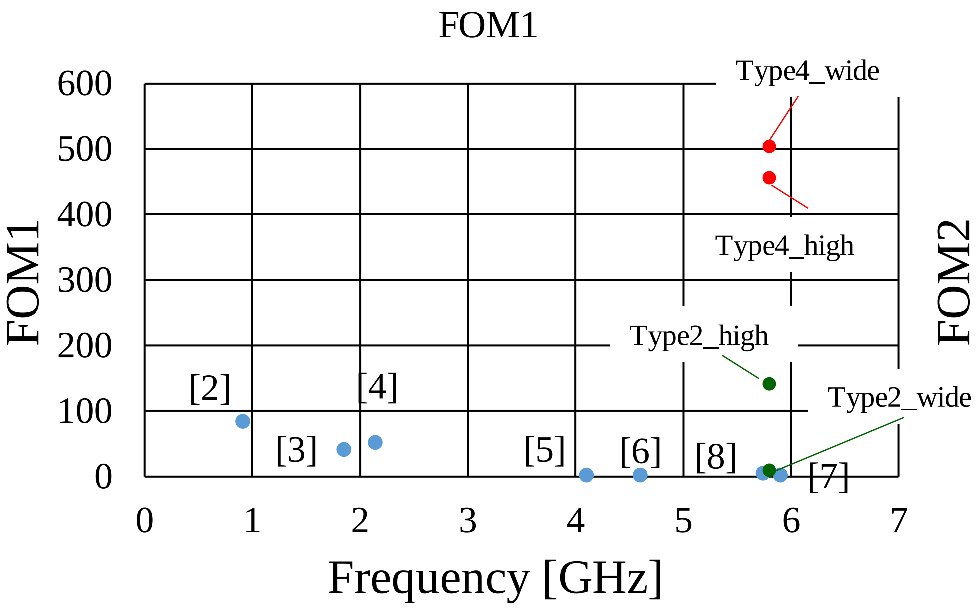
$$FOM2 = \frac{\eta_{MAX}}{dyn_{\eta}} \times dynamic\ range$$

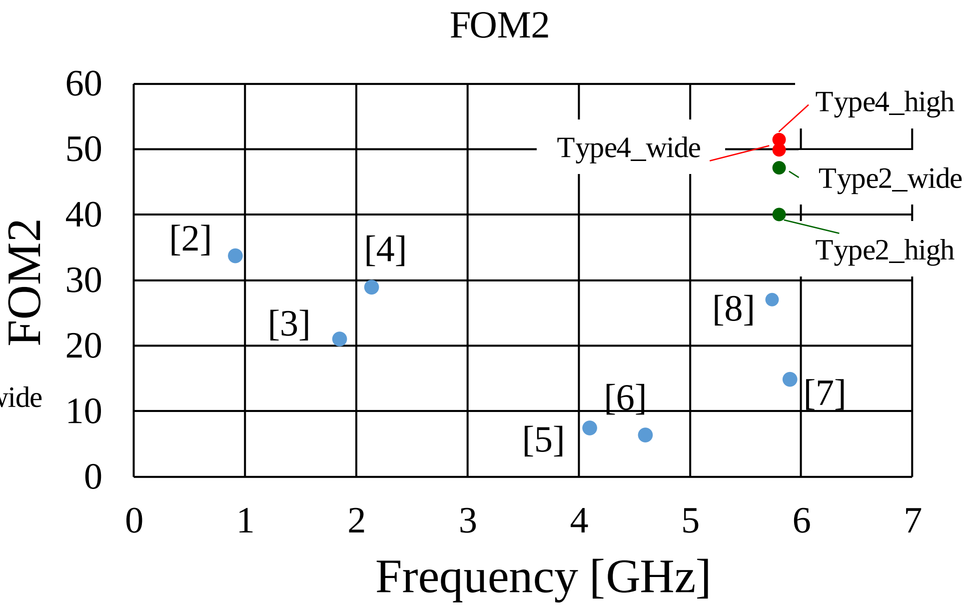


- η_{MAX} ; maximum efficiency
- $P_{in(peak)}$; input power at the maximum efficiency
- dynamic range ; dydnamic range (dB) defined by dyn_{η}
- $P_{in(Center)}$; input power (mW) at the middle point of the dynamic range
- dyn_{η} ; minimum efficiency that defines the dynamic range

- FOM1 is highly regarded for high input operation and high dynamic range rectifier circuit.
- FOM2 is highly regarded for high dynamic range rectifier circuit.

Comparison with conventional rectifiers





▪FOMs of Type2 and Type4, which have particularly good performance among the proposed diodes.

▪The rectifier circuit with the proposed diodes shows the highest values for both FOM1 and FOM2 ratings.

Summary

・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%.

・A small series resistance and a small zero-bias junction capacitance improve the performances of the rectifier circuit.

Refernces

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