# A Custom C Band High-Power GaN-Based Rectifier for WPT Systems

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***Abstract* — This study presents the development of a 5.8 GHz high-power voltage doubling rectifier for wireless power transfer (WPT) applications, leveraging advanced gallium nitride (GaN) Schottky barrier diode (SBD). The GaN SBD, designed for high-frequency and high-power operation, features a wide bandgap, high electron mobility, and high saturation velocity, ensuring superior performance in microwave power rectification. Key characteristics include a high breakdown voltage larger than 200 V, a low zero-bias junction capacitance of 0.34 pF, a turn-on voltage of 1.25 V, and an on-resistance of 10.5 Ω. These properties enable efficient rectification at the C band. The GaN SBD is integrated into an optimized rectifier circuit featuring a harmonic compression structure to enhance performance, a peak RF-to-DC conversion efficiency of 77.4% is achieved at an input power of 39 dBm. These results highlight the potential of high-power GaN SBDs in advancing high-frequency, high-power WPT systems.**

***Keywords* — *rectifier, WPT, GaN, Schottky barrier diode.***

## I. Introduction

Compared to conventional wired charging methods, wireless charging systems have been widely adopted in electric vehicles, biomedical implants, uncrewed aerial vehicles, consumer electronics, underwater power supplies and other high-frequency device applications. The advantages, such as convenience, safety and reliability, make them a more appealing and efficient alternative. Recently, there has been significant interest in high-power transfer at microwave frequencies, particularly in applications like space-based solar power systems, due to their environmentally friendly and cost-effective approach to energy acquisition. As a result, developing devices with high power-handling capacity and efficiency for WPT has gained significant attention.

Schottky barrier diodes (SBDs) are widely used as rectifying components for their essential low junction capacitance, parasitic resistance, threshold voltage, and high breakdown voltage for RF-DC conversion [1]-[3]. Higher input power increases the risk of diode damage due to the heat generated by the diode current, and the diode's breakdown voltage imposes an inherent limit on the maximum input power it can handle. In microwave WPT systems, diodes must operate at high speeds, making it particularly challenging to design components and simultaneously achieve high power-handling capacity and efficiency. While increasing the number of diodes or utilizing HEMT can theoretically enhance power handling for RF rectification, these approaches often lead to lengthy design processes with reduced efficiency [4], [5]. Additionally, their power conversion efficiency remains lower compared to single-diode-based rectifiers. GaN-based diodes have gained significant attention in contemporary research as an efficient, cost-effective solution for high-power microwave rectification. With their ability to balance performance and simplicity, GaN diodes outperform traditional semiconductors like silicon (Si) and gallium arsenide (GaAs), which face challenges in handling high power densities at microwave frequencies [6]. Thanks to the wide bandgap of 3.4 eV, superior electron mobility, and excellent thermal conductivity, GaN diodes have become a preferred choice for high-power and high-frequency applications, leveraging their outstanding material properties to meet the demands of modern technologies.

Considering these aspects, we propose a 5.8 GHz GaN-based high-power voltage-doubling rectifier with a harmonic compression structure. The GaN SBD is newly developed with a high $V_{BK}$ and a low $C_j$ to enhance power handling capacity at the C band. The fingerprint SBD is fabricated on a GaN on SiC substrate. The average turn-on voltage ($V_{on}$) and on-resistance values are measured to be 1.25 V (at 1 mA/mm) and 2.85 Ω·mm, respectively, with a diode series resistance of 10.5 Ω and an ideality factor ($n$) of 1.27. The Y-shaped anode and anode-cathode distance $L_{AC}$ = 1.875 μm with acceptable passivation results in a breakdown voltage $V_{BK}$ > 200 V. Based on this newly developed diode, a complete rectifying circuit is designed. In the design, two microstrip lines, each with a length equivalent to one-eighth of the wavelength, are utilized to neutralize the reactive component of a diode's impedance and suppress second harmonic signals in the rectification process, thereby enhancing the RF-to-DC power conversion efficiency. Experimental verification demonstrates that the implemented voltage doubler rectifier attains a peak efficiency of 77.4% with an input power of 39 dBm and a DC load of 400 Ω.

## II. Microwave Rectifier Circuit Design


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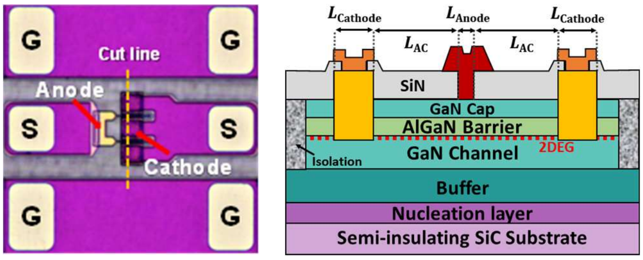
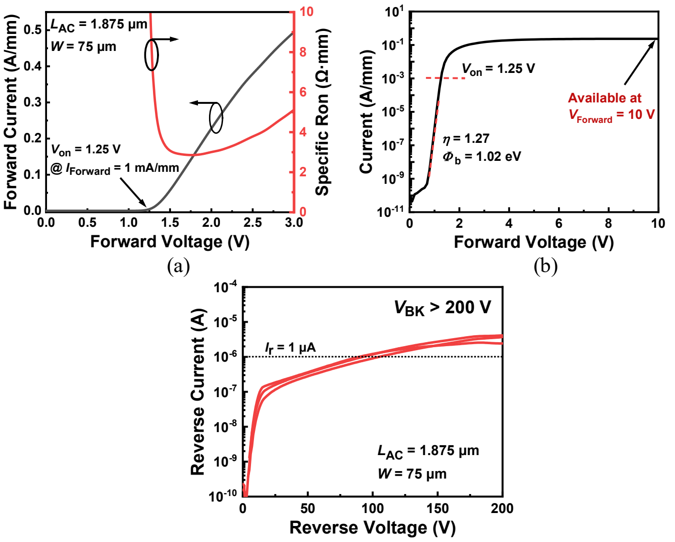



(a) (b)

Fig. 1. (a) Two-finger diode top view of GaN-on-SiC fingerprint SBD with GSG RF pads. (b) Cross-sectional schematic view of the fingerprint GaN SBD with Y-shape anode.




(a) (b)

(c)

Fig. 2. *I-V* characteristics of fingerprint GaN SBD. (a) Forward current and specific turn-on resistance. (b) Logarithmic plot. (c) Reverse condition with $V_{BK} > 200$ V.

## A. GaN SBD Development

The GaN heterojunction epitaxial wafer was grown on a 100 mm semi-insulating SiC substrate by metal-organic vapour deposition (MOCVD), consisting of an AlN nucleation layer, a Fe-doped buffer, a 300 nm GaN channel layer, a 16 nm AlGaN barrier layer, and a 2 nm in-situ GaN cap layer. The fingerprint GaN SBD top view with RF pads and the cross-sectional schematic are shown in Fig. 1 (a) and (b). Fabrication of the device started with the Ohmic region recess, which was defined by a lithography and chlorine-based inductively coupled plasma (ICP) etching. Then, an E-gun evaporation system deposited a Ti/Al-based optimized metal stack followed by rapid thermal annealing at 825 °C for 30 seconds in the $N_2$ ambient, resulting in a 25 μm cathode length ($L_{Cathode}$). Then, the device isolation is realized using multiple energy boron ion implantation, which defines the device's active region. The Ohmic contacts are formed on top of the semiconductor surface followed by a plasma-enhanced chemical vapour deposition (PECVD) Silicon Nitride (SiNx) passivation layer under 300 °C to passive the surface states. The Y-shape anode feet were defined by an ICP etching, with $L_{Anode}$ = 0.25 μm and the head width 0.35 μm. Finally, the RF pads were fabricated to allow on-wafer RF measurements suitable for 100 μm pitch ground-signal-ground (GSG) probes.

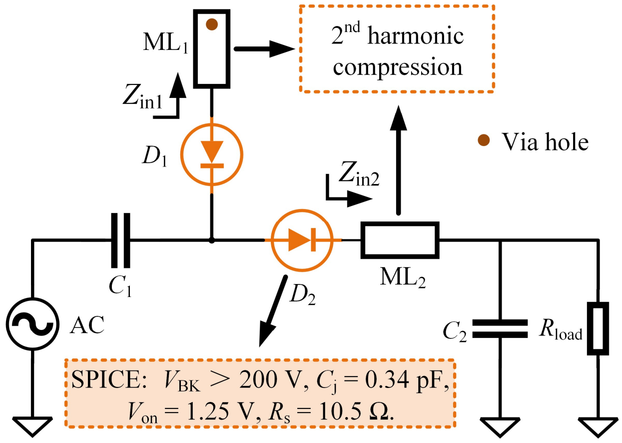



Fig. 3. Diagram of the voltage-doubling rectifier with GaN SBD SPICE.

Fig. 2 (a) shows the DC measured results of a two-finger SBD with width W = 75 μm and anode-cathode distance $L_{AC}$ = 1.875 μm. A forward current density of 500 mA/mm can be achieved at forward voltage $V_{Forward}$ = 3 V, and the inserting figure shows the specific $R_{on}$, sp of 2.85 Ω·mm. Also, the turn-on voltage ($V_{on}$) is extracted to be 1.25 V, which is defined by the forward current $I_{Forward}$ of 1 mA/mm. The device can handle $V_{Forward}$ of 10 V, and an ideality factor ($n$) of 1.27 and Schottky barrier height ($\varphi_b$) of 1.02 eV is extracted, as depicted in Fig. 2 (b). The reverse *I-V* performances of the GaN diode are displayed in Fig. 2 (c). High breakdown voltage ($V_{BK}$) of over 200 V and BFOM of is acquired, noted that the reverse leakage current ($I_{reverse}$) is 10 μA over the entire voltage range. Furthermore, the diode reverse voltage can still reach 90-102 V even with an $I_{reverse}$ of 1 μA and shows good consistency (Fig. 2 (c)). A junction capacitance of 0.34 pF is achieved at zero bias.

## B. Harmonic Compression Structure Rectifier Design

We proposed a 2nd harmonic compression topology to improve rectifier performance, removing the conventional cascading LC combination filters. The configuration shows inductive impedance at the operating frequency and effectively behaves as an open circuit at the second-harmonic frequency.

Fig. 3 depicts the schematic of the designed voltage-doubling rectifier incorporating a harmonic compression mechanism. The rectifier system consists of a shorted microstrip transmission line ($ML_1$), an output transmission line ($ML_2$), a DC blocking capacitor ($C_1$), and two identical GaN diodes ($D_1$ and $D_2$). The circuit is completed with a parallel capacitance ($C_2$) and a DC load ($R_{load}$). In the rectifier diagram, $ML_1$ is an eighth-wavelength short-ended microstrip line with a characteristic impedance of $Z_{ML1}$. According to transmission line theory, the input impedance of $ML_1$ at DC, the fundamental frequency ($\omega_f$), and the 2nd harmonic can be expressed as follows [7]:

$$Z_{in1} = jZ_{ML1}\tan\left(\frac{\pi}{4}\frac{\omega}{\omega_f}\right) = \begin{cases} 0, & \omega = 0 \\ jZ_{ML}, & \omega = \omega_f \\ \infty, & \omega = 2\omega_f \end{cases} \quad (1)$$

At DC ($\omega = 0$), $ML_1$ acts as a short circuit, ensuring a DC path during rectification. The shorted microstrip transmission

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line exhibits an inductive impedance at the fundamental frequency ($\omega = \omega_f$), designed to compensate for the capacitive reactance of the SBD. $ML_1$ functions as quarter-wavelength transmission lines at the second-harmonic frequency ($\omega = 2\omega_f$) and changes to an open circuit, effectively transforming the voltage and current across the SBD to achieve harmonic compression behaviour. This transformation optimizes and reshapes the voltage and current distribution waveform across the SBD, enabling effective harmonic compression. Similarly, an additional transmission line (ML2) with a length of one-eighth wavelength and a characteristic impedance of $Z_{ML2}$ also demonstrates harmonic suppression characteristics at the 2nd harmonic. The input impedance of ML2 can be expressed as:

$$Z_{in2} = Z_{ML2}\frac{Z_{load} + jZ_{ML2}\tan\left(\frac{\pi}{4}\frac{\omega}{\omega_f}\right)}{Z_{ML2} + jZ_{load}\tan\left(\frac{\pi}{4}\frac{\omega}{\omega_f}\right)}$$

$$= \begin{cases} R_{load}, & \omega = 0 \\ Z_{ML2}\frac{Z_{load}+jZ_{ML2}}{Z_{ML2}+jZ_{load}}, & \omega = \omega_f \\ \frac{Z_{ML2}^2}{Z_{load}}, & \omega = 2\omega_f \end{cases} \quad (2)$$

$$= \begin{cases} R_{load}, & \omega = 0 \\ jZ_{ML2}\frac{Z_{ML2}-1/\omega C_2}{Z_{ML2}+1/\omega C_2}, & \omega = \omega_f \\ j\omega Z_{ML2}^2 C_2, & \omega = 2\omega_f \end{cases} \quad (3)$$

$$= \begin{cases} R_{load}, & \omega = 0 \\ jZ_{ML2}, & \omega = \omega_0 \\ \infty, & \omega = 2\omega_f \end{cases} \quad (4)$$

In (2), $Z_{load} = 1/(1/R_{load} + j\omega C_2)$, where $1/R_{load}$ can be approximated as zero, given that the DC load of the rectifier typically exceeds several hundred ohms. In (3), by selecting $C_2$ and $Z_{ML2}$ appropriately, $Z_{ML2}$ can be made much larger than $1/\omega C_2$, and $\omega C_2 Z_{ML2}^2$ can effectively be treated as infinite at the operating frequency. In (4), at DC, the input impedance of $ML_2$ ($Z_{in2}$) equals $R_{load}$, with $ML_2$ providing a DC path for output DC power while leaving the value of $R_{load}$ unaffected. At $\omega_f$, the harmonic compression network exhibits an inductive impedance that counteracts the capacitive reactance of diode $D_2$. Meanwhile, at $2\omega_f$, $Z_{in2}$ becomes infinite, effectively attenuating the harmonic power.

## III. Implementation and Validation

The design process utilizes the ADS EM simulation, incorporating the non-linear model of the GaN diode with SPICE for harmonic balance analysis. Key evaluation metrics include RF-to-DC power conversion efficiency ($\eta$) and output DC voltage ($V_{out}$) at different input RF power ($P_{in}$). The DC load resistance is systematically adjusted to determine the optimal operating conditions. Accurate electromagnetic tuning is also applied to optimize the dimensions of the diagram network.

A 5.8 GHz voltage-doubling rectifier was designed, manufactured, and evaluated following simulation analysis. The circuit was constructed using a Rogers 3003 substrate, which has a thickness of 0.51 mm, a loss tangent of 0.001, and a relative permittivity of 3. The physical configuration of the fabricated rectifier is depicted in Fig. 4, with the dimensions of the microstrip transmissions. A 2-pF capacitor ($C_1$) is incorporated as a DC block. In contrast, a 100-pF capacitor ($C_2$) serves as a filter to smooth the rectified DC output. The design includes a DC load resistance of 400 Ω ($R_{load}$). The RF-to-DC conversion efficiency is determined using the following expression:

$$\eta = \frac{V_{out}^2/R_{load}}{P_{in}} \quad (5)$$

The rectifier performance is validated across an input power range of 10 to 50 dBm, achieving a peak conversion efficiency of 77.4% at an input power level of 39 dBm, which shows high-quality operation in high-power regions. The RF-to-DC power conversion efficiency exceeds 70% from 31 to 40 dBm of the input power range (Fig. 6). Within this input power range, the S11 parameter remains below -10 dB. In comparison to other advanced C-band rectifiers reported in [8]-[10], the proposed design achieves significantly enhanced performance, particularly in terms of efficiency relative to input power, as summarized in Table I. This notable improvement is primarily attributed to the innovative harmonic compression structure and the distinct characteristics of the GaN diode. These advancements contribute to the power rectifier achieving exceptional efficiency and remarkable power-handling capability.

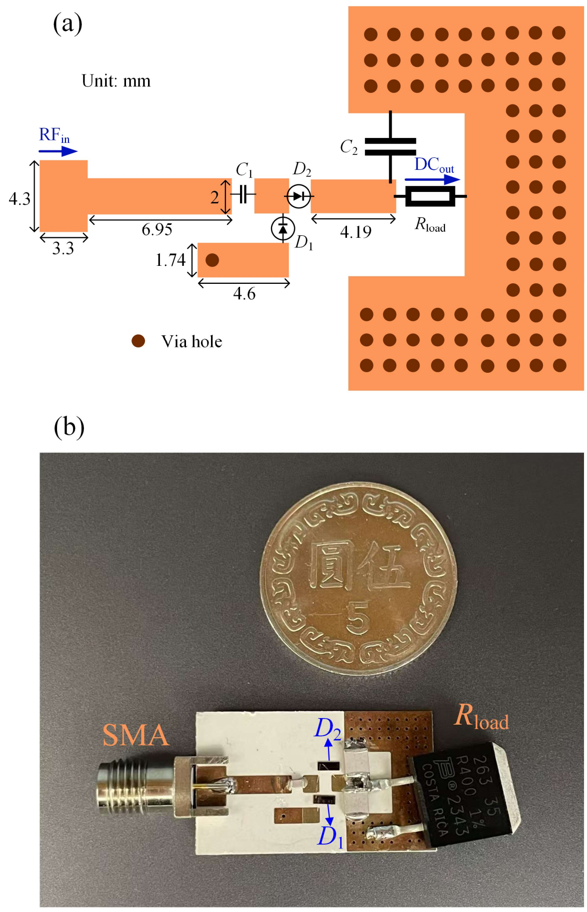


Fig. 4. (a) Schematic layout of proposed 5.8 GHz voltage-doubling rectifier. (b) Physical photograph of the fabricated rectifier circuit.

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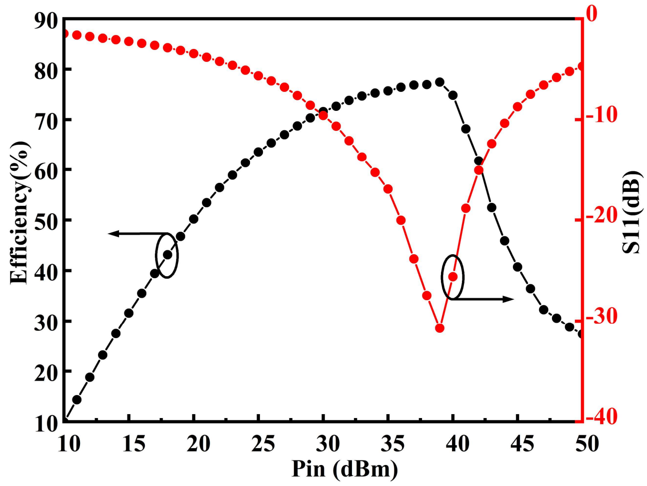


Fig. 5. EM simulation RF-to-DC power conversion efficiency and S11 of the rectifier and the association as a function of the RF input power.

TABLE I. COMPARISONS WITH PREVIOUS WORKS

| Refs. | Freq (GHz) | Diode | Peak efficiency | $P_{in}$ (dBm) |
|---|---|---|---|---|
| [8] | 5.8 | GaN SBD | 72.4% | 33.4 |
| [9] | 5.8 | Si SBD | 77% | 22.3 |
| [10] | 5.8 | GaN SBD | 81.9% | 29 |
| This work | 5.8 | GaN SBD | 77.4% | 39 |

## IV. CONCLUSION

A high-power, high-efficiency 5.8 GHz voltage-doubling rectifier is designed utilizing the newly developed GaN Schottky barrier diode. The diode features a high breakdown voltage exceeding 200 V with a low junction capacitance, enabling enhanced power handling capability at the C band. The rectifier, incorporating harmonic compression microstrip lines, achieves a maximum efficiency of 77.4% at an input power of 39 dBm.

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