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Communication

First Demonstration of L-Band High-Power Limiter with GaN Schottky Barrier Diodes (SBDs) Based on Steep-Mesa Technology

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Abstract: Gallium nitride (GaN) has attracted increased attention because of superior material properties, such as high electron saturation velocity and high electrical field strength, which are promising for high-power microwave applications. We report on a high-performance vertical GaN-based Schottky barrier diode (SBD) and its demonstration in a microwave power limiter for the first time. The fabricated SBD achieved a very low differential specific on-resistance ($R_{ON,sp}$) of 0.21 m$\Omega\cdot$cm^2, attributed to the steep-mesa technology, which assists in reducing the spacing between the edge of the anode and cathode to 2 µm. Meanwhile, a low leakage current of ~10^{-9} A/cm^2@−10 V, a high forward current density of 9.4 kA/cm^2 at 3 V in DC, and an ideality factor of 1.04 were achieved. Scattering parameter measurements showed that the insertion loss (S_{21}) was lower than −3 dB until 3 GHz. In addition, a microwave power limiter circuit with two anti-parallel diodes was built and measured on an alumina substrate. The input power level reached 40 dBm (10 watts) in continuous-wave mode at 2 GHz, with a corresponding leakage power of 27.2 dBm (0.5 watts) at the output port of the limiter, exhibiting the great potential of GaN SBD in microwave power limiters.

Keywords: vertical; GaN SBD; L band; Schottky diode limiter; high power

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1. Introduction

Microwave power diode limiters have been widely used in the RF (Radio Frequency) front-end in a variety of wireless communication systems [1], such as cellular infrastructure (including 5G) and microwave radio communications [2]. A diode limiter prevents the damage of sensitive receiver components by allowing RF signals below a certain threshold to pass through, but larger signals exceeding the threshold are attenuated [3]. The development of modern RF receivers requires a high-performance diode limiter [4] that can operate in a wide bandwidth and at a high-input power level with compactness, easy integration and low cost. Many studies have been carried out on Si-based diode limiters in recent years [5–7]; however, they showed scant room for further improvement as the silicon reached its theoretical limitations. Gallium nitride (GaN) has the superior material properties of high electron saturation velocity, high electrical field strength, and high operating temperature [8,9], which makes it well suited for high-power microwave limiter applications.

High performance vertical GaN p-n diodes [10–12] and SBDs [13,14] have been demonstrated for high breakdown and good thermal properties. Most of the GaN diodes have been reported in high-voltage applications [15,16], microwave rectifiers [17,18] and frequency doublers [19]. A GaN microwave power SBD limiter has rarely been reported to date.

In this work, we have experimentally demonstrated a vertical GaN SBD for L-band microwave power limiters for the first time. By using steep-mesa technology, the spacing between the anode and cathode can be reduced to 2 μm, leading to a further reduction of differential on-resistance (R_{on}) of the SBD. The fabricated SBD has a low differential $R_{ON,sp}$ of 0.21 mΩ·cm^2 and a very high forward current density of 9.4 kA/cm^2 at 3 V. The insertion loss of the SBD was increased from −20 dB to −3 dB over a frequency range of 0.1–3 GHz. The GaN SBD power limiter has shown a peak input power of 40 dBm with a leakage power of 27.2 dBm at 2 GHz.

2. Materials and Methods

Figure 1a–c shows the cross-section schematic, a cross-section SEM image, and a top-view SEM image of the fabricated vertical GaN SBD. The epitaxial structure was grown on c-plane sapphire substrates by metalorganic chemical vapor deposition (MOCVD), and consisted of a buffer layer, a 2 μm n^+-GaN conducting layer (N_D: 6 × 10^{18} cm^{-3}), and a 0.9 μm n^--GaN drift layer (N_D: 9 × 10^{15} cm^{-3}). The spacing between the anode and cathode (L_{AC}) was varied from 2 μm to 10 μm.

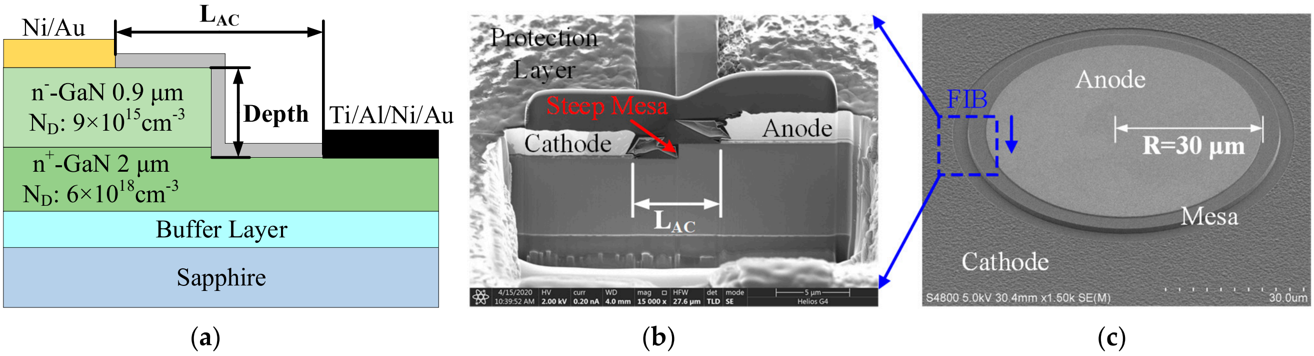


Figure 1. (**a**) Cross-section schematic; (**b**) cross-section of the SEM image; and (**c**) top view of the SEM image of the vertical GaN-on-sapphire SBD.

Figure 2a–e describes the fabrication steps for the vertical GaN SBD. First, the 1 μm mesa was formed by a combination of inductively coupled plasma (ICP) dry etching with Cl_2/BCl_3 gas mixture and tetramethylammonium hydroxide (TMAH) wet etching. Both a photoresist (PR) and a silicon oxide (SiO_2) hard-mask were employed for the mesa etch. The ICP etching conditions were optimized to form a steep-mesa structure with the following parameters [20]: 360 W ICP power, 42 W RF (radio frequency) power, and 100 sccm/10 sccm Cl_2/BCl_3 flow rates. Second, the ohmic metal (Ti/Al/Ni/Au) was deposited on the n^+-GaN layer and annealed at 650 °C for 1.5 min. A specific contact resistivity as low as 1.08 × 10^{-6} Ω·cm^2 was obtained for ohmic contact, extracted from the circular transmission line method (CTLM) measurements. Then, the Schottky metal (Ni/Au) was formed on n^--GaN layer with a radius of 30 μm. Finally, the SiO_2 passivation layer was deposited by plasma-enhanced chemical vapor deposition (PECVD).

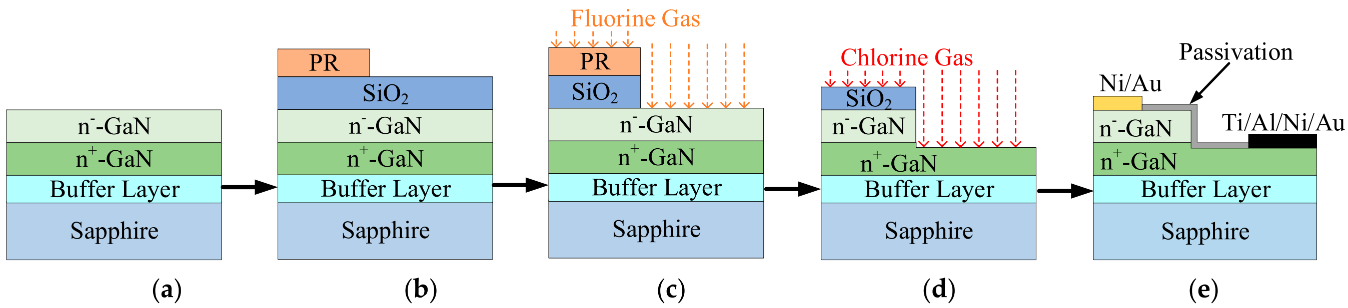


Figure 2. Simplified fabrication steps of the vertical GaN SBD. (**a**) Epitaxy structure of vertical GaN SBD on sapphire substrate; (**b**) photoresist (PR) and SiO_2 mask on GaN; (**c**) fluorine-based hard mask etching; (**d**) chlorine-based mesa etching; (**e**) electrode deposition and SiO_2 passivation.

3. Results and Discussion

Figure 3a shows the forward I-V characteristics in the semi-log scale for the vertical GaN-on-sapphire SBDs with various L_{AC}. A high on/off current ratio (I_{on}/I_{off}) of 10^{13}, ideality factor (η) of 1.04, and low turn-on voltage (Von) of 0.7 V (extracted at 1 A/cm^2) were extracted from the forward I-V curves of the GaN SBDs with various L_{AC}. Figure 3b shows the forward I-V characteristics in linear scale and differential $R_{ON,sp}$ for the GaN SBD. The GaN SBD with a small L_{AC} of 2 μm had a high forward current density (defined as the total current divided by the anode area) of 9.4 kA/cm^2 at 3 V, and a low differential $R_{on,sp}$ of 0.21 mΩ·cm^2. The differential $R_{on,sp}$ of the SBD with a large L_{AC} of 10 μm was 1.16 times higher than that with a small L_{AC} of 2 μm, which was attributed to the additional resistance introduced by increasing L_{AC}. A steep-mesa etching technology was expected to form a near-90° mesa structure and add sufficient freedom to reduce the spacing between the anode and cathode, enabling a low differential R_{on} in the vertical GaN SBD.

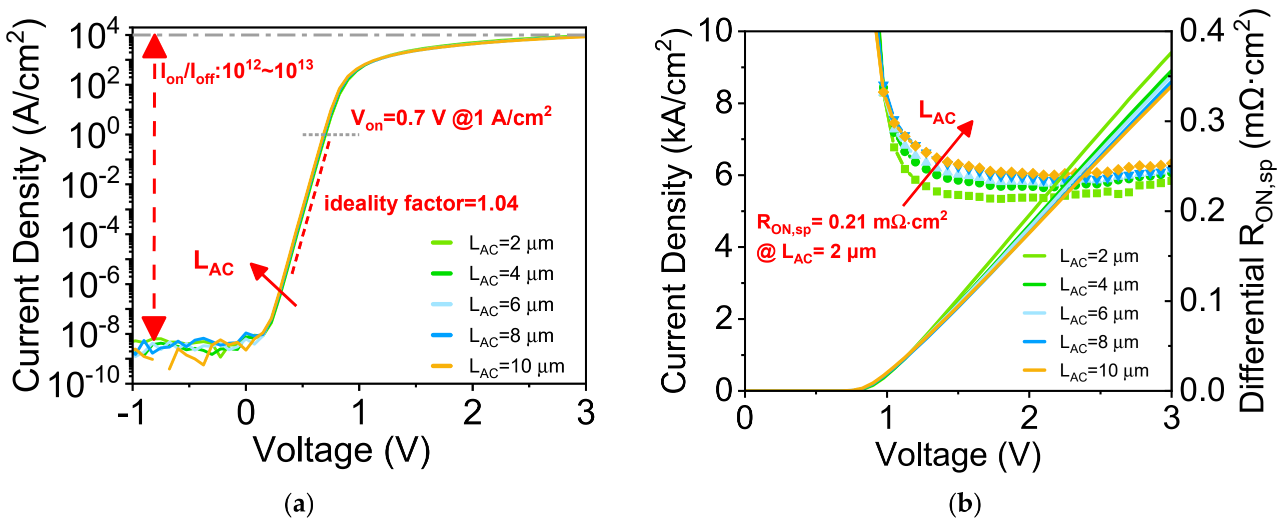


Figure 3. (**a**) Forward I-V characteristics in semi-log scale, and (**b**) in linear scale (left) and differential $R_{ON,sp}$ vs. voltage (right) for vertical GaN SBDs with different spacing between the anode and cathode (L_{AC} = 2, 4, 6, 8, 10 μm).

Figure 4a shows the reverse I-V characteristics of the GaN SBDs with various L_{AC} at room temperature. The GaN SBDs with various L_{AC} showed a similar breakdown voltage (BV) of 106 V at 1 A/cm^2 and a similar leakage density of 10^{-8} A/cm^2 until –30 V. L_{AC} had minor impact on reverse BV, which can be explained by the electric field distributed mostly in the drift layer. When the reverse bias exceeded 30 V, the leakage behavior showed a variable range-hopping (VRH) process, which could be attributed to the threading dislocation in the bulk [21]. Figure 4b shows the temperature-dependent

I-V characteristics of the SBDs, which ranged between 300 and 425 K. With increasing temperature, the current density increased from 300 K (room temperature) to 425 K when the forward voltage was below 1 V, which was attributed to the thermionic emission (TE) behavior. However, the current density decreased with temperature at high forward bias (>1 V), mainly attributed to a decrease of electron mobility in the drift region. Thermionic emission behavior can usually be proved by a Richardson plot as follows [22,23]:

$$\ln J_s/T^2 = \ln A^* - \frac{q\varphi_{B0}}{kT} \quad (1)$$

where J_s, k, and A^* are the saturation current density, Boltzmann's constant, and Richardson's constant, respectively. In the inset of Figure 4b, the Richardson plot of $\ln(J_s/T^2)$ versus 1000/T is linear, and the calculated A^* is about 26.25 A·(cm·k)$^{-2}$, which are very close to the theoretical value of 26.64 A·(cm·k)$^{-2}$ [22]. As a result, the temperature-dependent I-V characteristic of our GaN SBD can be well explained by the TE model.

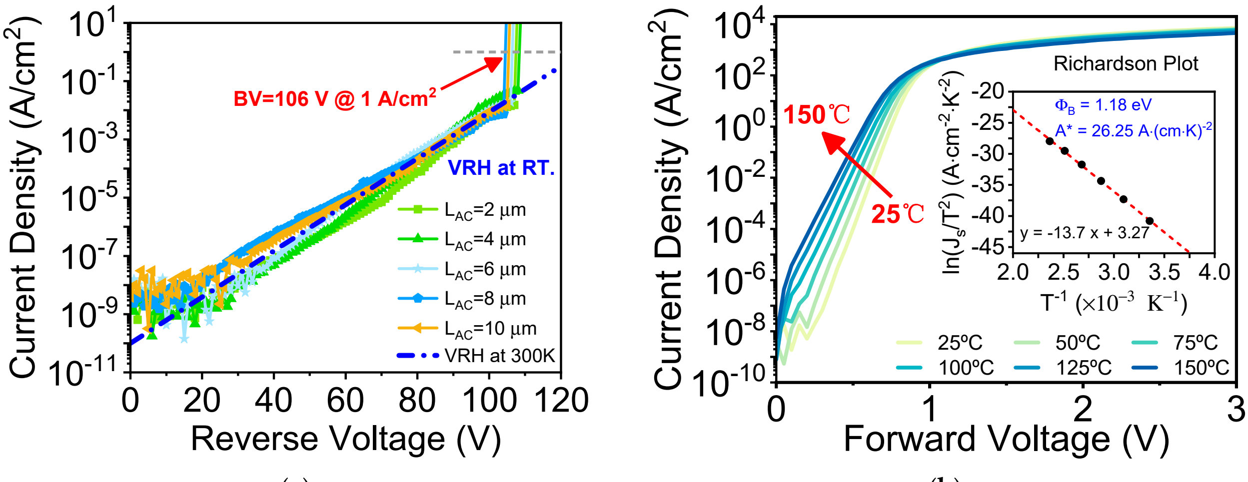


Figure 4. (**a**) Reverse I-V characteristics of the vertical GaN SBDs with various L_{AC}. (**b**) Temperature-dependent I-V characteristics of the GaN SBD with L_{AC} of 2 µm in semi-log scale at temperatures ranging from 25 °C to 150 °C and corresponding Richardson plot (inset).

Figure 5a shows the junction capacitance of the GaN SBD varied with the applied reverse voltage from 0 V to 5 V at a measurement frequency of 1 MHz. The junction capacitance ($C_{j,0}$) at zero bias was between 0.59 and 0.62 pF with various L_{AC}. The extracted C^{-2}-V plot shows a normal linearity, which indicates the relatively uniform net donor concentration along the depth direction. Figure 5b shows the transmission characteristics of the GaN SBD with a L_{AC} of 2 µm over a frequency range of 0.1–5 GHz. The anode and cathode were wire-bonded to co-planar waveguide transmission line test fixture modules, as shown in the inset of Figure 5b. The measured results showed that the insertion loss (S_{21}) was lower than –3 dB from 0.1 GHz to 3 GHz when the diode was in an off-state. The insertion loss increased with increasing input frequency, which was attributed to the off-state junction capacitance of the GaN SBD [24]. For an ideal limiter, the output power should have no attenuation when a low power signal is incidentally added to the input port. Therefore, a low junction capacitance is required to realize a low insertion loss for the GaN SBD, which is critical to the limiter performance below the threshold level.

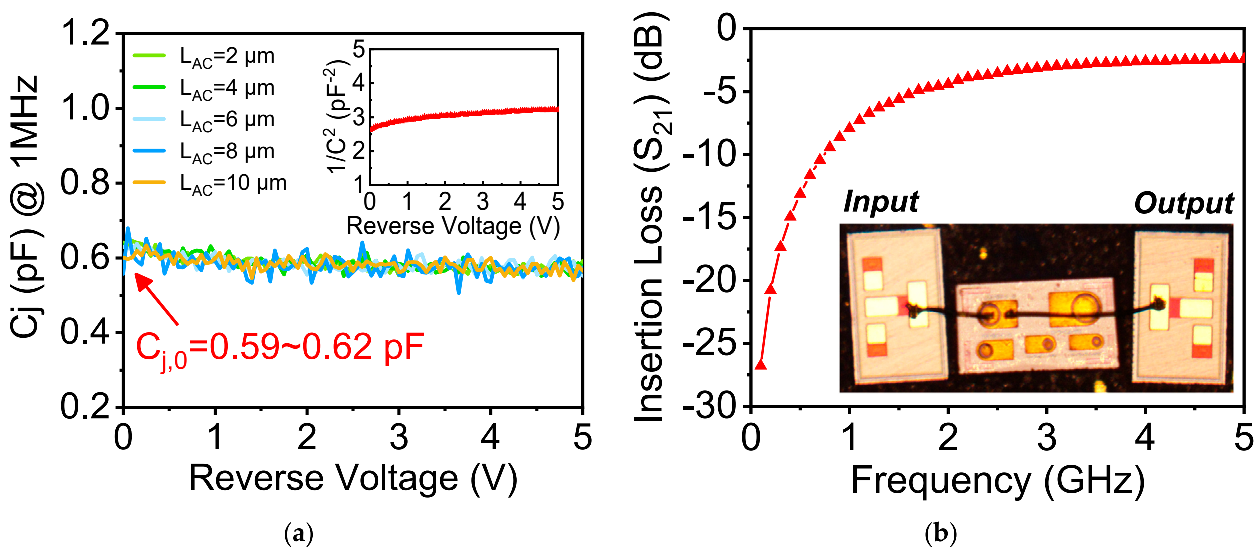


Figure 5. (**a**) C-V characteristics of the GaN SBD at a measurement frequency of 1 MHz with an anode radius of 30 μm and different L_{AC} of 2, 4, 6, 8, and 10 μm. Inset is the corresponding C^{-2}-V plot. (**b**) Insertion loss (S_{21}) of the GaN SBD over a frequency range of 0.1 GHz to 5 GHz in the small-signal S-parameter measurements. Inset is the wire-bonded GaN SBD with two GSG test fixture modules.

Figure 6a shows a typical radio transceiver block diagram. The limiter is located at the receiver stage to protect the low-noise amplifier (LNA) and transceiver from the high-power microwave signal transduced by the antenna. Figure 6b shows the circuit schematic and a photograph of the one-stage anti-parallel diode limiter using the wire-bonded vertical GaN SBD ($R_{on,diff}$ = 8 Ω, $C_{j,0}$ = 0.6 pF). The two capacitors were used as a DC block (not shown in the photograph). The anti-parallel GaN SBDs were used to clip the input's large signal symmetrically. For a low input power level, the diodes were both in an off-state. When the input power exceeded the threshold level, the diodes were both in an "on-state" and become low impedance, forming a conducting path to ground. Therefore, the peak amplitude of the input power was limited at the threshold level to prevent damage of the LNA stage.

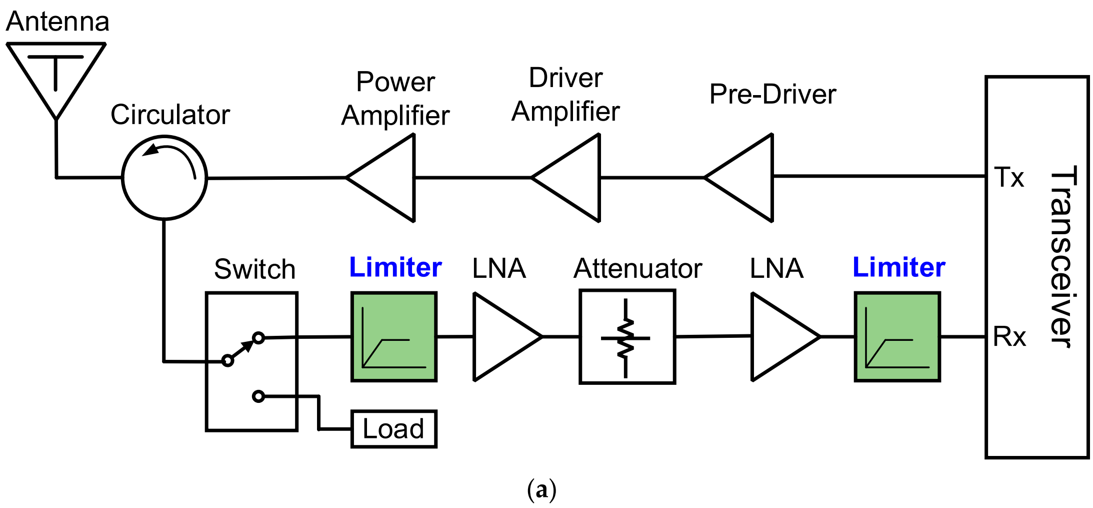
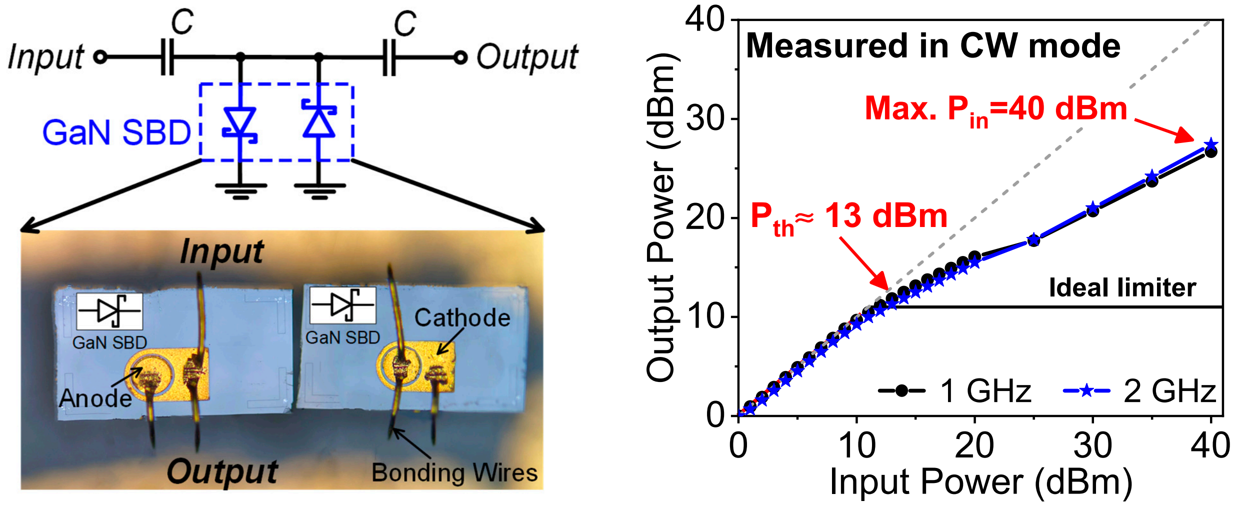


Figure 6. *Cont.*



(**b**) (**c**)

Figure 6. (**a**) Radio transceiver block diagram. (**b**) Circuit schematic and microscope image of the one-stage anti-parallel diode limiter using the wire-bonded GaN SBD. (**c**) Output power versus input power for the GaN SBD limiter at 1 GHz and 2 GHz.

Figure 6c presents the input and output characteristics of the ideal limiter and our GaN SBD limiter. An ideal power limiter has the following characteristics [25]:

$$P_{out} = P_{in} \;\; (when \; P_{in} < P_{th}) \tag{2}$$

$$P_{out} = P_{th} \;\; (when \; P_{in} > P_{th}) \tag{3}$$

where *Pout* is the output power, *Pin* is the input power, and *Pth* is the threshold level. The microwave power limiter circuit with an anti-parallel diode was measured on an alumina substrate. The input power was increased from low power (0 dBm) to high power in CW mode at a frequency of 1 GHz and 2 GHz. The measured results showed a limiting threshold level (or input 1-dB compression point) of 13 dBm. The limiter had a negligible loss when the input power was below 13 dBm at 1 GHz and 2 GHz, which we attributed to the low junction capacitance of our GaN SBD. The leakage power was 16.7 dBm and 27.4 dBm when the input power was 20 dBm and 40 dBm at 2 GHz, respectively. The GaN SBD limiter can handle at least 40 dBm of CW input power at 2 GHz without failure. When the input power was beyond the maximum power, the SBD suffered from a catastrophic failure due to a self-heating problem. In sum, the GaN SBD was successfully demonstrated in a microwave power limiter application, and showed great potential for future work.

4. Outlook

To further improve the performance of the GaN SBD limiter, four aspects should be addressed:

First, the junction capacitance (C_j) of the diode dominates the insertion loss of the limiter at a low input power, especially for a high-frequency signal. Stacking multiple diodes can reduce the total capacitance but increase the threshold level of the diode limiter. The C_j of a GaN SBD can be reduced by decreasing the doping level of the drift layer, increasing the width of the drift layer, or reducing the Schottky contact area; however, this leads to an increase of R_{on}.

Second, a lower R_{on} of the diode can sufficiently attenuate the output power at a high input power that exceeds the threshold level. For the vertical GaN SBD, a high doping level or thin drift layer result in a low R_{on}, but with a low breakdown voltage (BV). Diodes with a low R_{on} and a high BV can be achieved by improving the crystal quality of the GaN, owing to its high electron mobility and low dislocation density in the bulk.

Third, improving the heat dissipation of the GaN diode enhances the power-handling capability of the GaN diode limiter. Advanced thermal management methods are required to cool the GaN SBD, such as using a high thermal conductivity substrate (SiC and diamond) or removing the foreign substrate (sapphire and silicon).

Finally, a multi-stage limiter based on GaN PiN diodes and GaN SBDs can reduce the leakage power and adjust the threshold level [26]. Monolithic and microwave integrated circuits (MMICs) offer the possibility of integrating the multi-stage diode limiter, enabling a better limiting performance with high power handling at a high-frequency band.

5. Conclusions

In conclusion, we have experimentally demonstrated a vertical GaN SBD for L-band microwave power limiters for the first time. Thanks to the steep-mesa technology, the spacing between the anode and cathode (L_{AC}) could be reduced to 2 μm, leading to a further reduction of R_{on}. The fabricated vertical GaN SBD had a high forward current density of 9.4 kA/cm^2 at 3 V, a low differential $R_{on,sp}$ of 0.21 mΩ·cm^2, a near-unity ideality factor (η) of 1.04, and a BV of 106 V. The GaN SBD limiter can withstand up to a very high input power of 40 dBm at 2 GHz in CW mode to yield a low leakage power of 27.4 dBm. Therefore, the results suggest great potential for high-power microwave power limiters using a GaN SBD.

Author Contributions: Y.S. and X.K. contributed equally to this paper. Y.S., writing—original draft; X.K., writing—review and editing; L.X. and H.W., data curation; X.K., S.D., Y.Z., K.W., and X.L., project administration. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

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