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Letter

High-power and broadband microwave detection with a quasi-vertical GaN Schottky barrier diode by novel post-mesa nitridation

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Abstract
We report a high-performance GaN Schottky barrier diode (SBD) on a sapphire substrate with a novel post-mesa nitridation technique and its application in a high-power microwave detection circuit. The fabricated SBD achieved a very high forward current density of 9.19 kA cm^{-2} at 3 V, a low specific on-resistance ($R_{ON,sp}$) of 0.22 mΩ cm^2 and breakdown voltage of 106 V. An extremely high output current of 400 mA was obtained when the detected power reached 38.4 dBm@3 GHz in pulsed-wave mode with a small anode diameter of 70 μm. Meanwhile, broadband detection at frequencies ranging from 1 to 6 GHz was achieved at 33 dBm in continuous-wave mode.

Keywords: GaN, vertical, quasi, Schottky barrier diode (SBD), microwave power detector

(Some figures may appear in colour only in the online journal)

1. Introduction

As a wide bandgap semiconductor material, GaN has superior properties of a higher critical electric field and a higher electron saturation velocity than silicon [1–3]. GaN-based devices can operate in high-power, high-frequency and high-temperature conditions, showing tremendous potential in RF (radio frequency) and microwave power applications [4]. In a PIN diode based quasi-active microwave limiter, a Schottky barrier diode (SBD) based power detector is often utilized to generate bias current for the PIN diode to lower the limiting threshold level [5–8]. Therefore, a high-power and high-output-current microwave SBD is required. Highly sensitive silicon- or GaAs-based SBD detectors have been demonstrated for microwave power detection at high frequency; however, they are limited at a microwave detectable

[6] Contributed equally to this work.

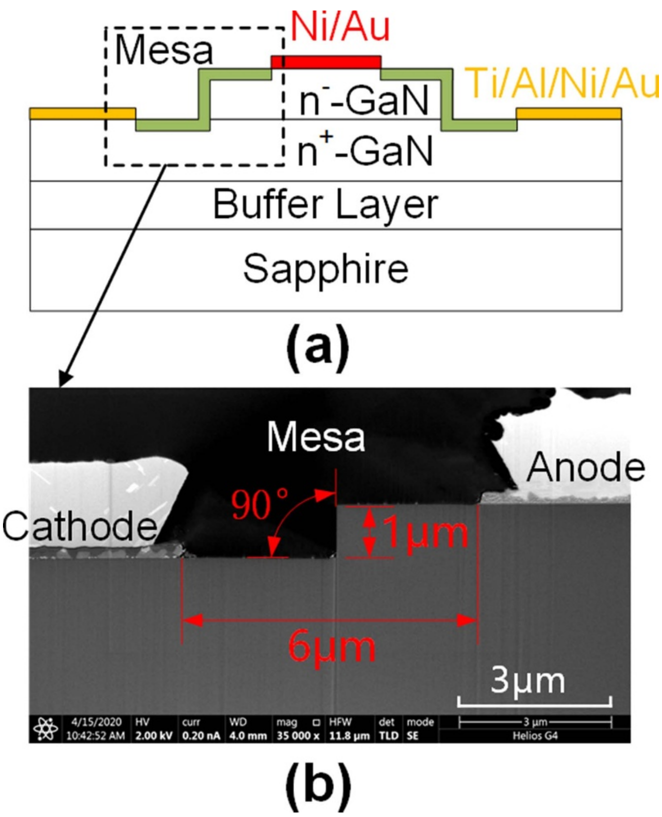

Figure 1. (a) Schematic diagram of quasi-vertical GaN SBD, and (b) FIB photograph which zooms in on the device mesa structure.

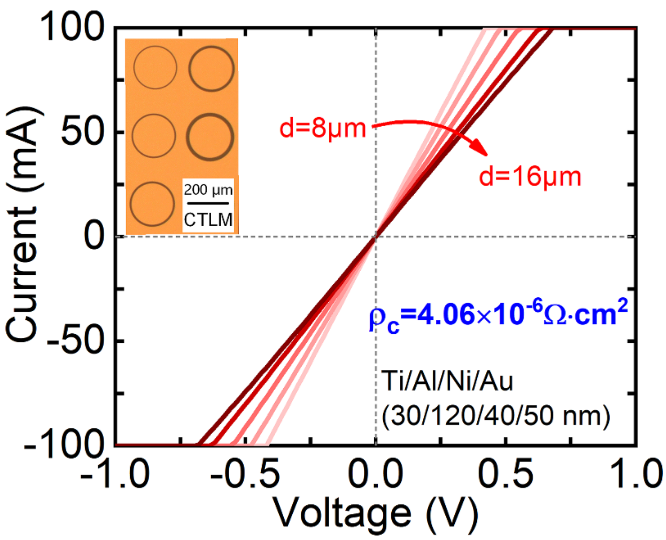

Figure 2. The I–V curves of Ti/Al/Ni/Au contact on n^+-GaN as a function of contact spacing, measured from CTLM patterns. The inset is an optical microscopy image of CTLM patterns. The inner radius of the measured pattern was 100 μm with a different spacing of d (d = 8, 10, 12, 14, 16 μm) to the outer ring.

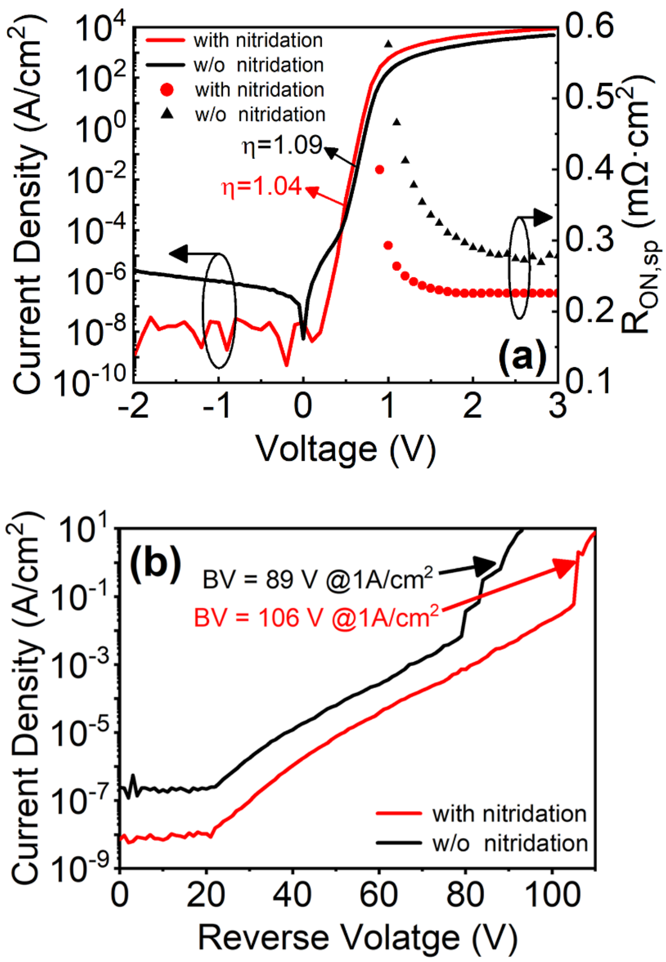

Figure 3. (a) Measured forward J–V (left) and $R_{ON,sp}$ (right), and (b) reverse J–V characteristics of the quasi-vertical GaN SBD with post-mesa nitridation and the reference with an anode diameter of 70 μm.

power level, due to the low breakdown field strength of Si and GaAs [9–12]. On the other hand, GaN SBDs are promising candidates for improving microwave detection power. Lateral GaN SBDs have been reported for rectifying circuits, but they are limited by cost and mass production difficulties [13–15]. High-performance vertical GaN SBDs have emerged in recent years [16–18].

In this work, we demonstrate a quasi-vertical GaN SBD with a very high forward current. The improved forward characteristics of the diode with post-mesa nitridation assist to increase the detectable microwave power.

2. Device structure

The GaN epi structure was grown on a c-plane sapphire substrate and consisted of a 3 μm buffer layer, a 2.5 μm n^+-GaN conducting layer (N_D: 1 × 10^{18} cm^{-3}) and a 0.7 μm n-GaN drift layer (N_D: 1 × 10^{16} cm^{-3}). Figures 1(a) and (b) show the schematic diagram of quasi-vertical GaN SBD and a focused ion beam (FIB) photograph which zooms in on the device mesa structure, respectively.

First, the mesa was fabricated by inductively coupled plasma (ICP) etching with a Cl_2/BCl_3 gas mixture. The detailed ICP etching process used to form the mesa structure was reported in the previous work [19]. Next, N_2 plasma treatment was carried out for 4 min at an RF power of 55 W in a plasma-enhanced chemical vapor deposition system. Then, the cathode metal (Ti/Al/Ni/Au, 30/120/40/50 nm) was deposited

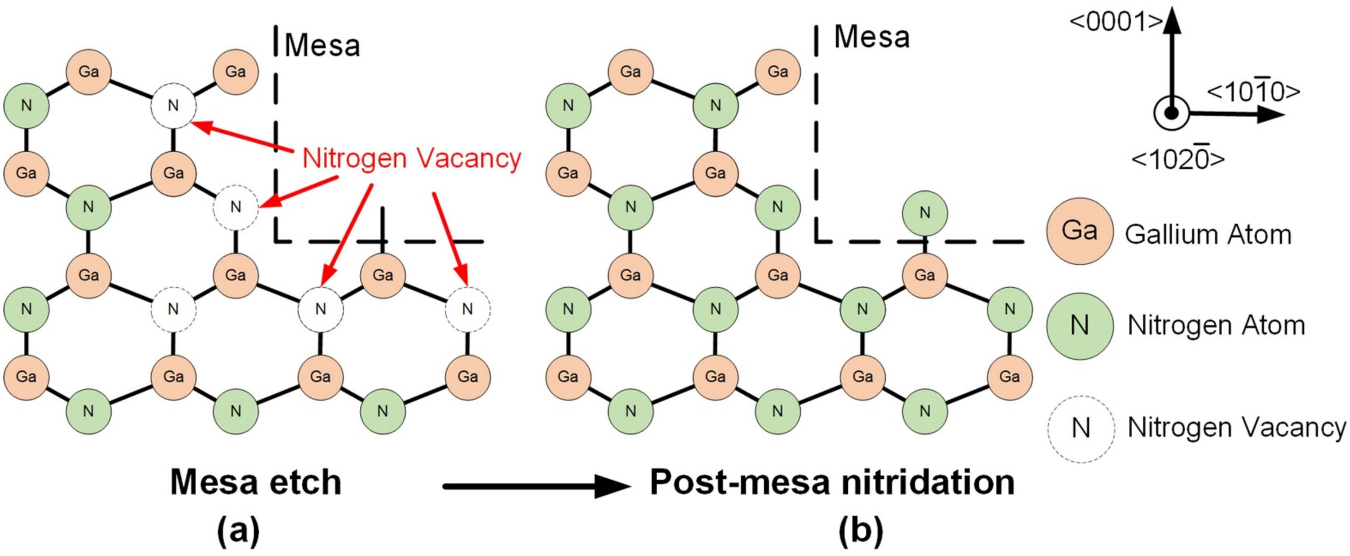

Figure 4. Schematic of the atomic arrangement of the GaN surface (a) after mesa etching and (b) N_2 plasma treatment.

on the bottom of the mesa and annealed in N_2 at 600 °C for 1 min to form an ohmic contact. As shown in figure 2, a specific contact resistivity as low as 4.06 × 10^{-6} Ω cm^2 was obtained for cathode metal contacts on *n*-GaN, extracted from the circular transmission line method (CTLM) measurements. After that, the circular anode metal (Ni/Au) with a diameter of 70 µm was deposited on top of the mesa to form a Schottky contact. Finally, a 2.6 µm power metal (Au) was plated on the anode and the cathode to aid wire-bonding on the test board.

3. Results and discussion

Figure 3(a) shows the forward *J*–*V* in semi-log scale (left) and specific differential on-resistance ($R_{ON,sp}$) in linear scale (right) of the quasi-vertical GaN SBD with post-mesa nitridation and the reference, both with an anode diameter of 70 µm. The nitridation diode reached a forward current density of 9.19 kA cm^{-2} at 3 V, which is 1.37 times higher than the reference diode. Meanwhile, a low $R_{ON,sp}$ of 0.22 mΩ cm^2, forward voltage (V_F) of 0.76 V at 1 A cm^{-2} and nearly unity ideality factor (η) of 1.04 was obtained, showing a better forward performance than the reference. Figure 3(b) shows the reverse characteristics at room temperature. The diode with post-mesa nitridation demonstrates a higher breakdown voltage (BV) of 106 V than the reference of 89 V (defined at 1 A cm^{-2}). The improved forward characteristics might be attributed to the post-mesa nitridation technique, leading to the reduction of sidewall traps or defects or additional current choke in the access region outside the mesa. For the reverse characteristic, leakage current along the sidewall is one of the main leakage paths for diodes, as ICP dry etching might create surface damage (e.g. N vacancies) [20]. Therefore, a post-mesa nitridation technique was developed to remove the sidewall damage and reduce leakage.

Figure 4 shows the schematic of the atomic arrangement of the GaN surface after mesa etching and with post-mesa N_2 plasma treatment. In figure 4(a), the nitrogen vacancy (V_N) was formed near the etched surface of the mesa. A large amount of V_N was introduced as donor-like traps, resulting in band bending and increase of the surface state density of the etched GaN [21]. The traps create a primary path for leakage current along the etched mesa sidewall. In addition, the etching damage caused high-density defects on the sidewall and the bottom of the mesa, so the scattering effect of the defects significantly reduces conductivity in these regions. As shown in figure 4(b), during the N_2 plasma treatment on the GaN surface, nitrogen radicals reacted with Ga atoms and then formed a new Ga–N bond, leading to a reduction of surface defect density and a significant reduction of leakage current. Meanwhile, the defects in the etched area are reduced, thus improving the forward characteristics.

A temperature-dependent *I*–*V* characteristic measurement was carried out by using Keysight B1500 apparatus in the measurement temperature range of 298–423 K, as shown in figure 5(a). The forward current density decreases with the increased chuck temperature when the forward voltage is beyond 1 V, mainly attributed to a decrease of electron mobility in the drift region. The decrease of the turn-on voltage with the increase of temperature is due to the increase of thermionic emission (TE) current at low bias (<1 V), where the effect of series resistance is small and can be neglected. TE behavior can usually be proved by a Richardson plot as follows [22]:

$$\ln\left(J_s/T^2\right) = \ln A^* - \frac{q\varphi_{B_0}}{kT} \quad (1)$$

where J_s, k and A^* are the saturation current density, Boltzmann's constant and Richardson's constant, respectively. In figure 5(b), the Richardson plot of ln(J_s/T^2) versus 1000/*T* is linear, and the calculated A^* is about 26.04 A (cm k)$^{-2}$, which is very close to the theoretical value of 26.6 A (cm k)$^{-2}$ [22]. Therefore, the forward current flows of post-mesa nitridation quasi-vertical GaN

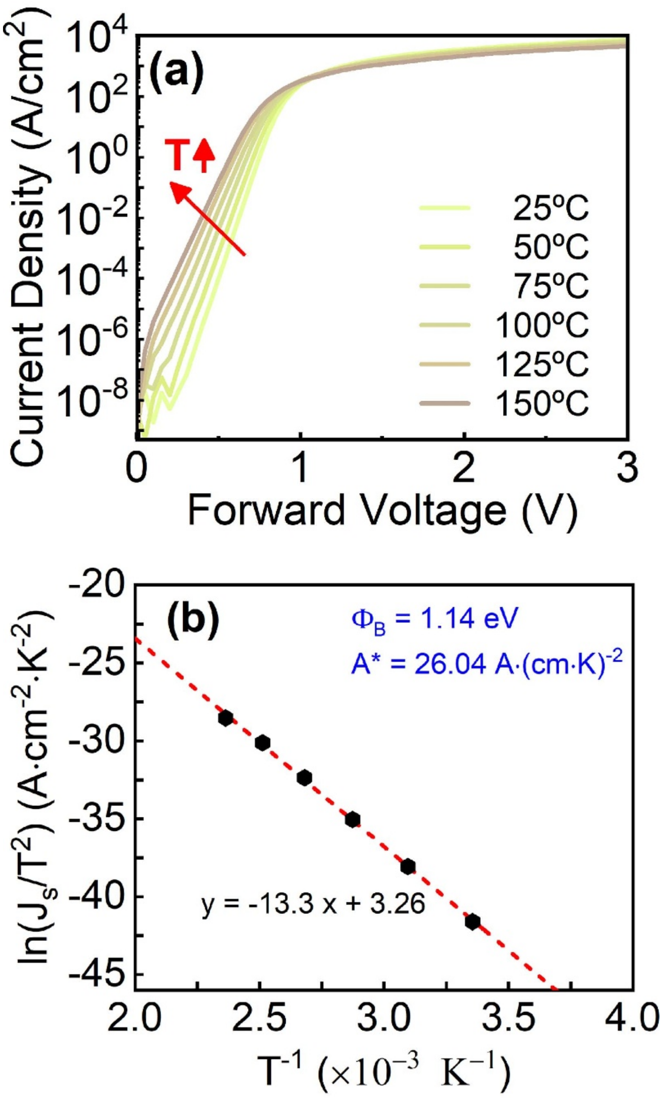

Figure 5. (a) Forward *J–V* characteristics of quasi-vertical GaN SBD with post-mesa nitridation in semi-log scale at temperatures ranging from 25 °C to 150 °C and (b) corresponding Richardson plot.

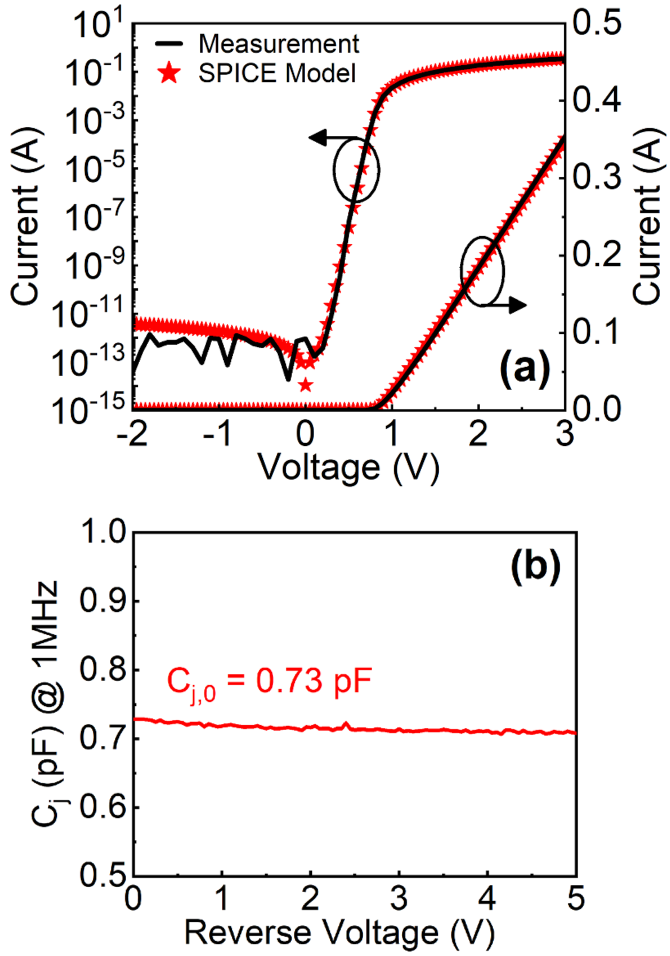

Figure 6. (a) Measured and simulated forward *I–V* in semi-log scale and in linear scale (right). (b) *C–V* characteristics of quasi-vertical GaN SBD with post-mesa nitridation with an anode diameter of 70 μm.

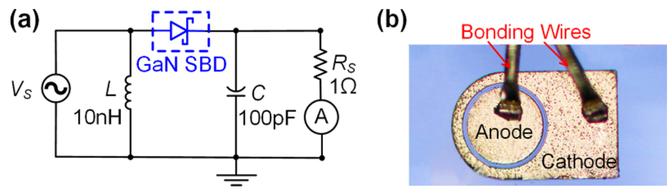

Figure 7. (a) Schematic of the microwave power detector with the GaN SBD. (b) Photograph of the GaN SBD with bonding wires.

SBD can be explained by the TE model with an ideal Schottky contact.

A simple diode SPICE model with key parameters was extracted from *I–V* curves for simulation. Figure 6(a) shows that the simulated result is consistent with the experiment. Figure 6(b) shows the junction capacitance varies 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 is 0.73 pF. Therefore, the cut-off frequency (f_T) of the GaN SBD is 36.9 GHz, calculated with the formula $f \approx (2\pi R_s C_{j,0})^{-1}$.

Figure 7(a) shows a typical circuit schematic of a microwave power detector used to generate a high bias current to load. It consists of a microwave source, an inductor, a GaN SBD, a capacitor and a load resistor. The inductor L is shunted with a microwave source, providing the DC return path to ensure all the AC components appear across the SBD terminal. The GaN SBD is wire-bonded in the circuit, as shown in figure 7(b). The capacitor C is shunted with a load resistor, yielding a DC output and keeping the DC components from high-frequency harmonics. The output current was measured using an amperemeter with an internal impedance of 1 Ω.

Figure 8(a) shows the output current versus P_{in} of the GaN SBD detector at a frequency of 3 GHz in continuous-wave (CW) mode and pulsed-wave mode (PW) mode. In PW mode, the pulsed sinusoidal signal has a duty cycle of 1% and a pulse width of 10 μs. The maximum output current is 210 mA and 400 mA at an input power of 34.7 dBm (CW) and 38.4 dBm

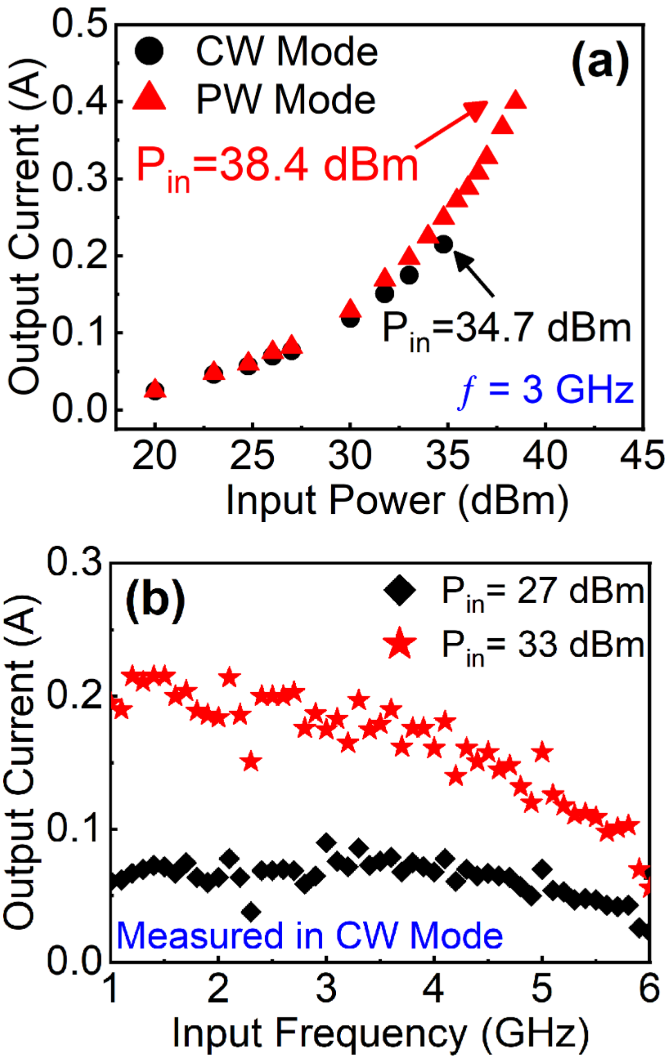

Figure 8. (a) The output current as a function of P_{in} at 3 GHz in CW and PW mode. (b) Output current as a function of input frequency at 27 dBm and 33 dBm in CW mode.

(PW), respectively. When the P_{in} is beyond the maximum power, the SBD suffers from catastrophic failure because of self-heating. Performance might be much improved with GaN-on-SiC SBDs.

Figure 8(b) shows the output current versus frequency at an input power of 27 dBm and 33 dBm in CW mode. The output current gradually decreases with increased frequency from 1 GHz to 5 GHz and significantly declines when reaching 6 GHz.The proposed GaN SBD-based detector can generate high output current at high input power in a broad band, implying that the GaN SBD is a good candidate for PIN-based quasi-active microwave limiters [5].

Table 1 lists the characteristics of commercial silicon detector SBDs and our GaN detector SBD. The GaN SBD shows the best performance with the highest detectable power level among all other listed commercial Schottky diodes for the first time, attributed to the high electron saturation velocity and high electrical field strength of GaN. Meanwhile, the GaN SBD has a higher BV and a lower leakage current than the others.

Table 1. Characteristics of Schottky detector diodes.

Reference	This work	Avago HSMS 2820	Infineon BAT6302
Material	GaN	Si	Si
BV (V)	106	15	40
$C_{j,0}$ (pF)	0.73	0.7	0.35
R_S (Ω)	5.9	6	—
V_F (V)	0.76	0.34	0.44
I_s (A)	2E-13	2.2E-8	—
η	1.04	1.08	—
Max. CW P_{in} (dBm)	33@6 GHz	30@0.9 GHz	15@5.5 GHz
Max. PW P_{in} (dBm)	38.4@3 GHz	—	—

$C_{j,0}$ = junction capacitance at zero bias, R_s = series resistance, V_F = forward voltage at 1 mA, I_s = reverse saturation current, η = ideality factor, Max. CW P_{in} = maximum incident power in continuous-wave mode, Max. PW P_{in} = maximum incident power in pulsed-wave mode.

4. Conclusion

In conclusion, we have experimentally demonstrated a quasi-vertical GaN SBD with post-mesa nitridation for high power and broadband microwave detection. Firstly, the fabricated quasi-vertical GaN diode reached a high forward current density of 9.19 kA cm^{-2} at 3 V, a low $R_{ON,sp}$ of 0.22 mΩ cm^2, a nearly unity ideality factor (η) of 1.04 and a BV of 106 V. The diode can withstand up to a very high input power of 38.4 dBm@3 GHz in PW mode to yield high output current of 400 mA. Finally, under a high input power of 33 dBm in CW mode, the detection frequency band is higher than 5 GHz to achieve broadband detection. Therefore, the results suggest great potential for high-power microwave detection applications using the quasi-vertical GaN SBD by post-mesa nitridation.

Acknowledgments

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