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Current collapse suppressed GaN diodes with 38 Watts high RF power rectifier capability

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Microwave power transmission (MPT) could realize the point-to-point long-distance transfer of energy without any wires, which makes it attractive for solar-powered satellites, drones, and implantable medical devices, and has aroused enormous attention [1]. Microwave rectifiers could convert RF (radio frequency) energy into DC (direct current) power, which is the essential element of the receiving end of the MPT system [2, 3].

Si and GaAs Schottky barrier diodes (SBDs) are commonly used in microwave rectifiers, but their power capacity is mostly within 100 mW limited by the narrow bandgap properties. Microwave rectifiers with GaN SBDs are developed for high power applications, while the current collapse inherently limits the maximum power and reduces overall efficiency.

In this study, composite passivation with a SiN/SiO_2 multilayer stack was developed to suppress the current collapse of GaN SBDs. Utilizing this technique, a state-of-the-art RF rectifier with a power capability of 38.5 Watts was realized.

Advanced passivation study of the GaN SBDs. The cross-sectional schematic of the GaN SBD is shown in Figure 1(a), and fabrication details are similar to our previous work [4]. In particular, this paper develops a composite passivation technique, first depositing 20 nm SiN by low-pressure CVD (LPCVD) to reduce surface states and lateral leakage, and then growing 120 nm low-k SiO_2 by plasma-enhanced CVD (PECVD) to reduce parasitic capacitance, and finally a further 320 nm SiN/SiO_2 multi-layer stack ((40 nm SiN + 40 nm SiO_2) × 4) was grown to release stress [5–7]. For comparison, diodes with SiN/SiO_2 (20/120 nm) and SiN/SiO_2/SiN (20/120/300 nm) passivation are also manufactured.

I_F-$R_{\rm on}$-V_F characteristics are shown in Figure 1(b). Low on-resistance (defined as the minimum differential on-resistance) of 1.2 Ω·mm and turn-on voltage of 0.44 V are achieved simultaneously. Moreover, a relatively high I_F of 1.2 A/mm is realized at a voltage bias of only 4 V. C_j-f_T-V is plotted in Figure 1(c), where low zero-bias junction capacitance of 0.56 pF/mm and high cut-off frequency (defined as $f_T = 1/(2\pi \times R_{\rm on} \times C_{j0})$) of 235 GHz could be extracted. I_R-V_R characteristic is shown in Figure 1(d). A high BV of 115 V is achieved, yielding an extraordinary Johnson figure-of-merit (J-FOM $= f_T \times BV$) of 27.0 THz·V.

The dynamic characteristics of different passivated GaN diodes are comprehensively investigated in Figures 1(e)–(g). Diodes are reversely biased at a fixed high stress voltage of −100 V and forward I-Vs are monitored after stress time from 1 ms to 3600 s. The multi-layer composite passivated diode has minimal current decay. The dynamic $R_{\rm on}$ degradation versus stress time is summarized in Figure 1(h). After −100 V reverse voltage stress for 3600 s, $R_{\rm on}$ degeneration of 37% and 14% are observed at devices with passivation of SiN/SiO_2 (20/120 nm) and SiN/SiO_2/SiN (20/120/300 nm). While devices with multilayer SiN/SiO_2 stack passivation provided negligible Ron collapse of only 4%, thereby improving long-term stability and reliability.

Rectifier with GaN SBDs. Based on advanced device technology, this paper realizes a record-breaking high-power microwave rectifier. The photograph and schematic of the microwave rectifier are shown in Figures 1(i) and (j). The anode width of the GaN diode used in the rectifier is 0.5 mm. In order to further improve the power handling capability, six diodes are arranged into an array with every two diodes connected in series and then in parallel.

The matching network, low-pass filter, and DC filter are carefully designed by ADS from Keysight, and manufactured on RF substrate F4BM-2 with a thickness of 0.7 mm, a relative dielectric constant of 2.65, and a loss tangent of 0.001. Diodes were mounted on the Cu heat sink with conductive silver paste and bonded to the circuit with Au wires. The SMA (subminiature version A) connector is welded to the RF input port, and the two cables are welded to the DC output port. The size of the rectifier circuit is only 22 mm × 22 mm, which is quite compact and is comparable with the size of a 1 Yuan coin.

Efficiency and output voltage versus input power with a load resistance of 170 Ω at 1.66 GHz are plotted in Figure 1(k). A peak efficiency of 80.1% is realized at an input power of 38.8 dBm (7.6 W), and a high efficiency of 69% is

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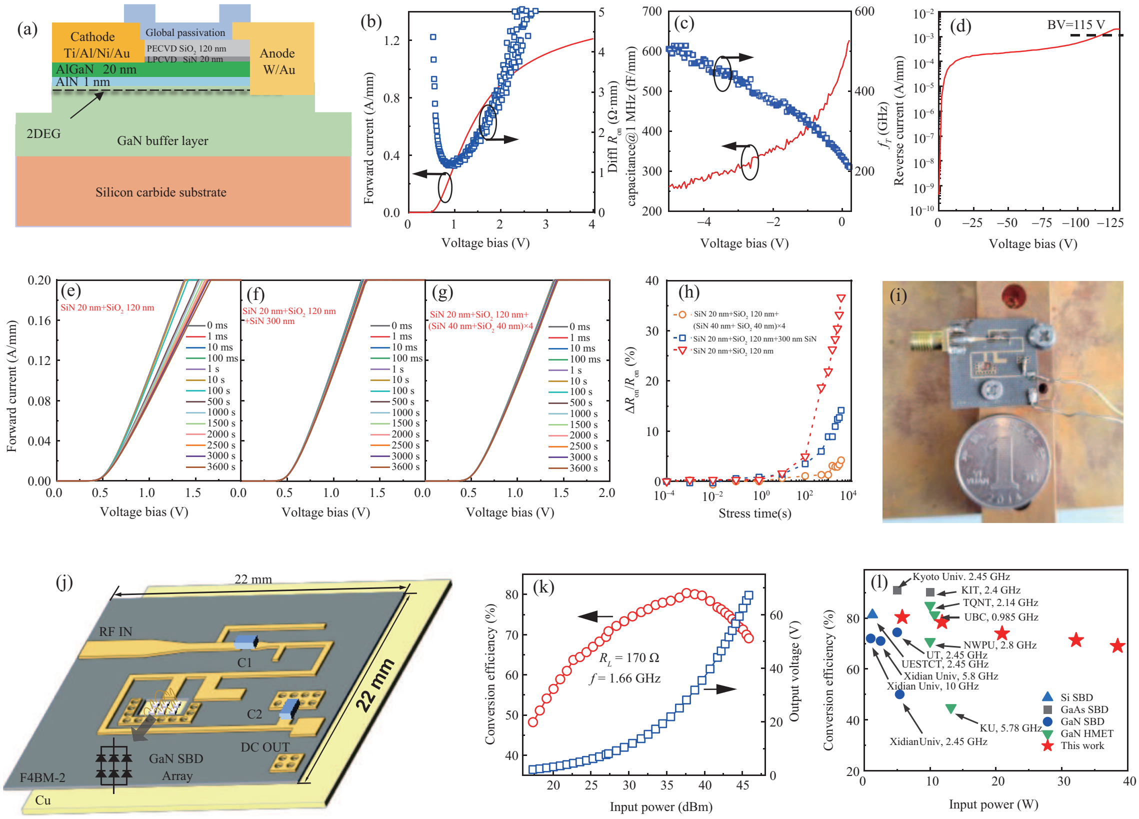

Figure 1 (Color online) (a) Cross-sectional schematic of GaN diodes with advanced passivation. (b) Linear-scale I_F-$R_{\rm on}$-V_F, (c) C_j-f_T-V, and (d) I_R-V_R characteristics of GaN SBD. Dynamic stressing of GaN SBDs with (e) SiN/SiO_2 20/120 nm, (f) SiN/SiO_2/SiN 20/120/300 nm, and (g) SiN/SiO_2/(SiN/SiO_2)×4 (20/120/(40/40)×4) nm at a stress base of −100 V. (h) Extracted $R_{\rm on}$ degradation at various stress times, verifying the effectiveness of the passivation with multi-layer stacks. (i) The photograph of the fabricated rectifier which is comparable with the size of a 1 Yuan coin. (j) Schematic of the high-efficiency and high-power microwave rectifier with bonded GaN SBD array. (k) Conversion efficiency and output voltage versus input power with a load resistance of 170 Ω at 1.66 GHz. (l) Conversion efficiency versus input power of some state-of-the-art watt-level microwave rectifiers.

maintained until the input power is increased to 45.86 dBm (38.5 W). The power density of about 13 W/mm is achieved for the GaN diode.

The performance of our GaN rectifier is benchmarked against some state-of-the-art rectifiers with Si, GaAs, GaN SBDs, and GaN HEMTs in the plot of conversion efficiency versus input power in Figure 1(l). Benefiting from the advantages of high-performance GaN SBDs with suppressed current collapse, the GaN rectifier in this paper possesses dramatically increased power capacity with an extremely compact circuit size.

Conclusion. We have demonstrated current collapse-suppressed GaN diodes with advanced passivation techniques. By implementing the GaN diodes array into a well-designed microwave rectifier, a peak efficiency of 80.1% and state-of-the-art maximum input power of 38.5 W is derived, showing the huge prospect of utilizing GaN diodes in the future MPT application.

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