Single-Chip Boost Converter Using Monolithically Integrated AlGaN/GaN Lateral Field-Effect Rectifier and Normally Off HEMT

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***Abstract*—We demonstrate a single-chip switch-mode boost converter that features a monolithically integrated lateral field-effect rectifier (L-FER) and a normally off transistor switch. The circuit was fabricated on a standard AlGaN/GaN HEMT epitaxial wafer grown with GaN-on-Si technology. The fabricated rectifier with a drift length of 15 μm exhibits a breakdown voltage of 470 V, a turn-on voltage of 0.58 V, and a specific on-resistance of 2.04 m$\Omega \cdot$ cm^2. The L-FER exhibits no reverse recovery current associated with the turn-off transient because of its unipolar nature. A prototype of GaN-based boost converter that includes monolithically integrated rectifiers and transistors is demonstrated using conventional GaN-on-Si wafers for the first time to prove the feasibility of the GaN-based power IC technology.**

***Index Terms*—AlGaN/GaN, boost converter, field-effect rectifier (FER), fluorine plasma ion implantation, normally-off HEMT, switch-mode power supply.**

I. Introduction

WIDE-BANDGAP GaN-based semiconductor materials are attracting a great deal of interest as the preferred materials for devices aimed at high-power, high-frequency, and high-temperature operations [1], [2]. Recently, intensive investigations have been conducted to apply GaN-based devices for power electronic applications to realize the theoretical superiority of AlGaN/GaN HEMT as a power switch element in switch-mode power converters [3], [4]. It is noted, however, that the demonstration of dc–dc boost converter, which requires both a transistor switch and a rectifier, has been carried out using separate AlGaN/GaN HEMT chip and SiC rectifier chip [4]. For the development of low-cost GaN-based integrated power converters that require both HEMT switches and rectifiers, it is desirable to integrate high-performance power transistors and rectifiers on the same epitaxial wafer with the same fabrication process. Up to now, the development of GaN-based discrete high-voltage power transistors and rectifiers [5]–[11] has been mainly carried out on different epitaxial structures, hindering the monolithic integration of power transistors and rectifiers for power integrated circuits. This is mainly due to the incompatibility between the epitaxial structures of HEMT and rectifiers in the form of Schottky barrier diode (SBD) or p-i-n diode. In our earlier work, a lateral field-effect rectifier (L-FER) that is compatible with the normally off HEMT structure has been reported [12], [13].

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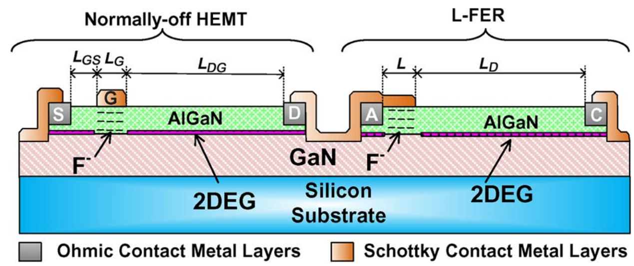

Fig. 1. Schematic cross section of the monolithic integration of L-FER with a normally off HEMT for single-chip boost converter application. L and L_D are the length of the Schottky contact region (CF_4 plasma treatment region) and the drift length of the L-FER, respectively. $L_{\rm GS}$, L_G, and $L_{\rm GD}$ are the gate–source distance, gate length, and gate–drain distance of HEMT, respectively.

In this letter, an L-FER and a normally off HEMT are monolithically integrated to demonstrate a single-chip switch-mode boost converter. Compared to the results already shown in [13], detailed benchmarking of the L-FER's dc performance is presented, together with the rectifier's transient switching behavior. A prototype of the boost converter is demonstrated using the GaN-on-Si platform, and the loss analysis is then obtained.

II. Device Structures and Characteristics

The schematic cross section of the monolithically integrated L-FER and normally off HEMT is shown in Fig. 1. The cathode electrode (C) of the L-FER is made of an electrode in ohmic contact with the 2DEG, while the anode electrode (A) is made of an electrically shorted Schottky contact and an ohmic contact. By tying up the Schottky contact and ohmic contact together, the forward turn-on voltage of the rectifier is determined by the threshold voltage of the channel instead of the on-voltage of Schottky or p-n junctions. The key fabrication process of the L-FER is the incorporation of fluorine ions under the Schottky contact by CF_4 plasma treatment that effectively depletes the 2DEG under the Schottky contact region and then pinches off the conduction path [14]. The sample used in this letter and the fabrication process are similar to those reported in [12], with the exception of no passivation layer for this work.

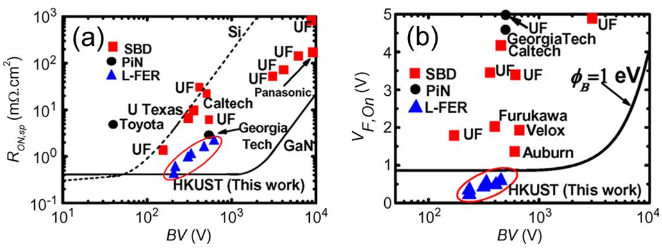

Fig. 2. (a) Specific on-resistance ($R_{\mathrm{ON,sp}}$) versus BV for GaN-based rectifiers reported in the literature. The dot and solid lines show the theoretical results for Si and GaN, respectively. (b) Forward turn-on voltage ($V_{F,\mathrm{ON}}$) versus BV for GaN-based rectifiers. The curves show the theoretical values expected for a barrier height of 1 eV [11].

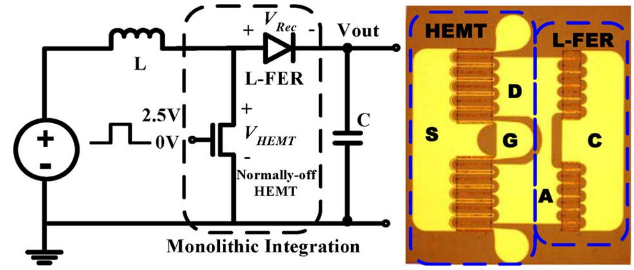

Fig. 4. (Left) Demonstrated monolithic GaN-based boost converter and (right) chip micrograph of the integrated device with interdigital layout, where the drain (D) of the normally off HEMT and the anode (A) of the L-FER share the same electrode.

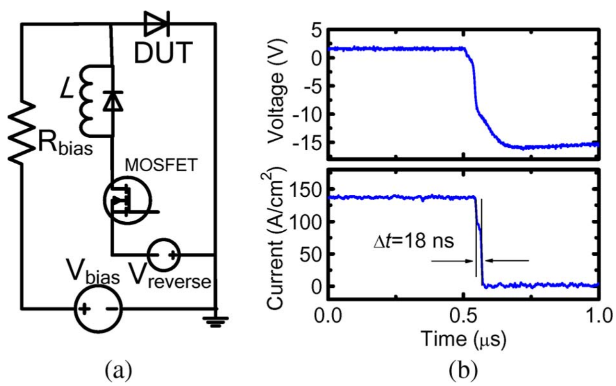

Fig. 3. (a) Schematic diagram of the test circuit. (b) Dynamic switching waveform, including (top) voltage and (bottom) current density across the L-FER. Δt is the turn-off time. The active device area is 0.0195 mm^2.

The specific ohmic-contact resistance is $\sim 0.7\ \Omega \cdot$ mm. The CF_4 plasma at 135 W for 170 s is implemented, which shifts the channel threshold voltage from -2.1 to $+\,0.9$ V.

The detailed output characteristics of an L-FER are reported in [13]. The $R_{\mathrm{ON,sp}}$ versus BV of the L-FERs are summarized, together with GaN-based rectifiers reported in the literature, in Fig. 2(a). The $R_{\mathrm{ON,sp}}$'s of our proposed rectifiers are the lowest compared to others with the same voltage rating and follow the same trend line as SBDs and p-i-n diodes with higher voltage ratings. It is also noted that the L-FER can be directly fabricated on the standard HEMT structure and integrated with HEMTs, while the SBDs and p-i-n diodes cannot. Fig. 2(b) compares the forward turn-on voltages ($V_{F,\mathrm{ON}}$'s) of the L-FERs with that of other GaN-based rectifiers. The L-FERs exhibit significantly lower $V_{F,\mathrm{ON}}$'s than the vertical SBDs and p-i-n rectifiers [5]–[11], [15], [16]. This is attributed to the L-FERs' turn-on control mechanism that is based on the threshold voltage of the 2DEG channel, instead of the built-in potential in Schottky junction or p-n junction.

The dynamic switching characteristics of an L-FER with $L = 2\ \mu$m, $L_D = 15\ \mu$m, and anode width $W = 1$ mm are studied using a method proposed by Winterhalter *et al.* [17]. In this test circuit, as shown in Fig. 3(a), the voltage source V_{bias} sets up the forward current to the device under test (DUT), when the power MOSFET is "off." When the power MOSFET is "on," the reverse voltage is applied to the DUT with the voltage source V_{reverse}. The rate at which this reverse voltage is applied to the DUT is determined by the value of the inductance L. The measured results of the voltage and current density across the DUT are shown in Fig. 3(b). The turn-off time is 18 ns. The L-FER based on the AlGaN/GaN heterostructure is a majority carrier unipolar device and does not have any stored minority carriers. Therefore, there is no reverse recovery current associated with the turnoff of the L-FER. The output capacitance is measured to be 1 pF/mm at a forward bias of 2 V and 0.16 pF/mm at a reverse bias of -10 V.

A normally off AlGaN/GaN HEMT with a 1.5-μm gate length and a 12-μm gate–drain distance has been fabricated in the same process run. The device exhibits a threshold voltage (V_{th}) of 0.9 V, a maximum drain current ($I_{\max}$) of 350 mA/mm at $V_{\mathrm{GS}} = 3$ V and $V_{\mathrm{DS}} = 10$ V, and a peak transconductance (G_m) of 175 mS/mm. The OFF-state breakdown voltage (BV) is 370 V at a drain-current leakage of 1 mA/mm, and the specific on-resistance ($R_{\mathrm{ON,sp}}$) is about 1.34 m$\Omega \cdot$ cm^2 at $V_{\mathrm{GS}} = 3$ V. At a drain bias V_{DS} of 20 V and a gate bias V_{GS} of 2 V, the input capacitance is 3.1 pF/mm, the output capacitance is 0.7 pF/mm, and the reverse transfer capacitance is 0.12 pF/mm.

III. SINGLE-CHIP BOOST CONVERTER

A boost converter, a major component for switch-mode power supply, was demonstrated using the integrated L-FER/HEMT pair, as shown in Fig. 4. In this demonstration, an L-FER ($L = 1\ \mu$m, $L_D = 15\ \mu$m, and anode width $W = 1$ mm) and a normally off HEMT ($L_{\mathrm{GS}} = 1.5\ \mu$m, $L_G = 1.5\ \mu$m, $L_{\mathrm{GD}} = 12\ \mu$m, and gate length $W = 2$ mm) are integrated. The chip size is 0.36 mm^2, including an active device area of 0.0625 mm^2. In addition, off-chip components, including a capacitor of 47 nF (RS 640-5877), an inductor of 330 μH (RS 134-942), and a load resistor of 5 kΩ, are used in this demonstration. A large inductance value was used so that the boost converter was operating only in continuous conduction mode (CCM) for the results reported here. Characterizations of the boost converter under both CCM and discontinuous conduction mode are ongoing and will be reported elsewhere.

The measured waveforms operating at a switching frequency (f_{sw}) of 1 MHz, a duty cycle (D) of 55%, and an input voltage (V_{in}) of 10 V are shown in Fig. 5. An output voltage (V_{out}) of 21 V and a power efficiency of 84% are obtained, with a 0.8% ripple level. The contribution from each loss mechanism has been calculated based on the measurement results and is shown in Fig. 6. About 69% of the total loss comes from the ON-state resistances of HEMT ($R_{\mathrm{DS\_on}}$) and L-FER (R_{on}) devices. Fig. 7 shows the dependence of power efficiency and output voltage on input voltage. The main reason for the large ON-state resistance is the increased dynamic on-resistance caused by current collapse at higher switching amplitude and

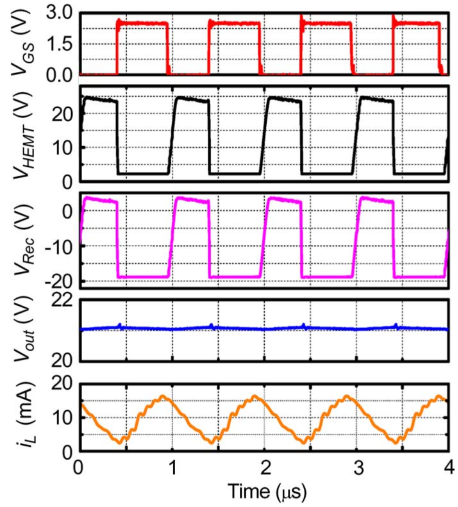

Fig. 5. Measured voltage waveforms of the fabricated monolithic GaN-based boost converter operating at a switching frequency $(f_{\rm sw})$ of 1 MHz, duty cycle (D) of 55%, and input voltage $(V_{\rm in})$ of 10 V, where $V_{\rm GS}$, $V_{\rm HEMT}$, $V_{\rm Rec}$, $V_{\rm out}$, and i_L are the gate–source voltage of the HEMT, drain–source voltage of the HEMT, anode–cathode voltage of the L-FER, output voltage, and inductor current, respectively.

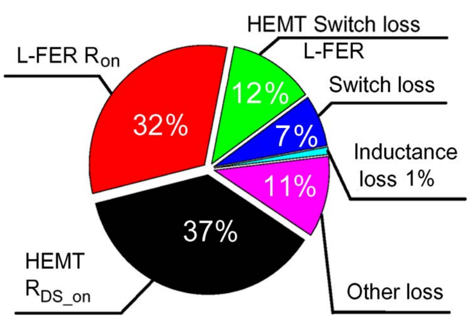

Fig. 6. Power-loss analysis of the demonstration with $f_{\rm sw}$ of 1 MHz, $V_{\rm in}$ of 10 V, and D of 55%. The loss from gating the HEMT on and off is not included in our calculation.

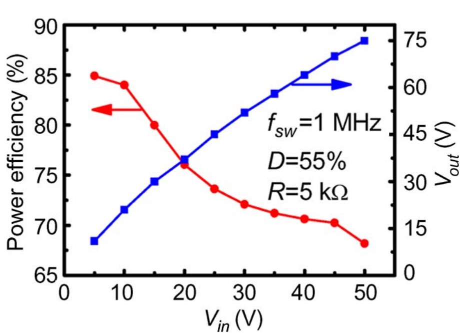

Fig. 7. Dependence of power efficiency and output voltage $(V_{\rm out})$ on input voltage $(V_{\rm in})$.

high switching frequency, which can be reduced by optimized surface passivation and field-plate techniques [3]. Process optimization is expected to improve the efficiency of GaN-based power converters, so that they can eventually surpass the performance of silicon-based converters.

IV. Conclusion

An AlGaN/GaN HEMT-compatible L-FER is demonstrated by utilizing the CF_4 plasma treatment technique. The rectifier features low on-resistance, low turn-on voltage, high reverse BV, and high switching speed. By monolithically integrating the L-FER and normally off HEMT using an industry-standard GaN-on-Si wafer, a prototype of boost converter with 1-MHz switching frequency is demonstrated for the first time to prove the feasibility of GaN-based integrated switch-mode power converters.

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