AlGaN/GaN Dual-Channel Lateral Field-Effect Rectifier with Punchthrough Breakdown Immunity and Low On-Resistance

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Abstract

An AlGaN/GaN dual-channel lateral field-effect rectifier (DCL-FER) with improved balance between the reverse breakdown voltage and on-resistance is proposed. Instead of utilizing a long single enhancement - mode (E-mode) schottky-controlled channel to enhance the punchthrough breakdown voltage but inevitably sacrifice the on-resistance, the DCL-FER features a dual-channel consisting of one E-mode section and one depletion-mode (D-mode) section in series. The D-mode channel provides higher carrier density that facilitates high on-current or low on-resistance, while still preventing the E-mode channel from being punched through under high reverse voltage. For rectifiers with the same physical dimensions (a drift region length of 5 µm and a total Schottky-controlled channel length of 2 µm), the DCL-FER delivers comparable breakdown voltage while featuring 53 % lower on-resistance.

INTRODUCTION

Wide bandgap GaN-based semiconductor materials are attracting considerable attention as the preferred material for power electronics applications [1], owing to the high breakdown electric-field, high carrier density, and high saturation velocity. Two types of power devices, namely, transistor power switches and power rectifiers, form the basis of active devices for most of the power electronic systems including switching-mode power supplies (SMPS) and power factor correction (PFC) circuits. Regarding the rectifiers, desirable device characteristics include low forward turn-on voltage ($V_{F, ON}$), low specific on-resistance ($R_{ON, SP}$), and high reverse breakdown voltage (BV). In developing power rectifiers, extensive works have been carried out on fabricating high-breakdown and low on-resistance Schottky barrier diodes (SBDs) and p-i-n diodes on both bulk and epitaxial GaN [2], [3]. To achieve monolithic integration of power transistors and rectifiers, a lateral field-effect rectifier (L-FER) compatible with the normally-off HEMT device was reported recently, with record-low turn-on voltage and low on-resistance [4], [5].

As the L-FER's cathode and anode are both in Ohmic contacts to the 2DEG (two-dimensional electron gas) channel and the on-off states are controlled by a Schottky contact, the punchthrough or drain-induced barrier lowering (DIBL) effects that have been shown to degrade the breakdown behavior of AlGaN/GaN HEMT [6] could also degrade the breakdown performance of the L-FER. To provide complete punchthrough immunity, longer channel length (> 1 µm) is usually required, depending on the background doping and buffer layer design [4], [5]. However, devices with longer channel inevitably exhibit larger $R_{ON, SP}$ and are undesirable for power devices. Therefore, the conventional L-FER confronts impassable obstacles in achieving high BV (or channel punchthrough breakdown immunity) and low on-resistance simultaneously.

In this paper, an AlGaN/GaN dual-channel L-FER (DCL-FER) is proposed to obtain low on-resistance while maintaining the same punchthrough immunity. A single channel is replaced by two sections: an enhancement-mode (E-mode) section and a depletion-mode (D-mode) section. The D-mode section is able to provide not only the punch-through immunity, but also enhanced conductivity to achieve low on-resistance. The device concept is demonstrated with experimental results and also supported by 2D device simulation.

PUNCHTHROUGH IN CONVENTIOANL L-FER

The schematic cross-section of the conventional L-FER [4] is shown in Fig. 1 (a). The anode electrode (A) is made of electrically shorted ohmic contact to the 2DEG and Schottky contact on top of an adjacent E-mode channel, while the cathode electrode (C) is formed by an ohmic contact to 2DEG. The key fabrication process of the L-FER is the CF_4 plasma ion implantation prior to the Schottky metal deposition. This implantation effectively incorporates negatively charged fluorine ions to the AlGaN/GaN heterostructures and shifts the channel threshold voltage to a positive value, providing reverse blocking capability. When forward biased ($V_A > V_C$), 2DEG will be induced in the channel and the rectifier is at the "on-state". When reverse

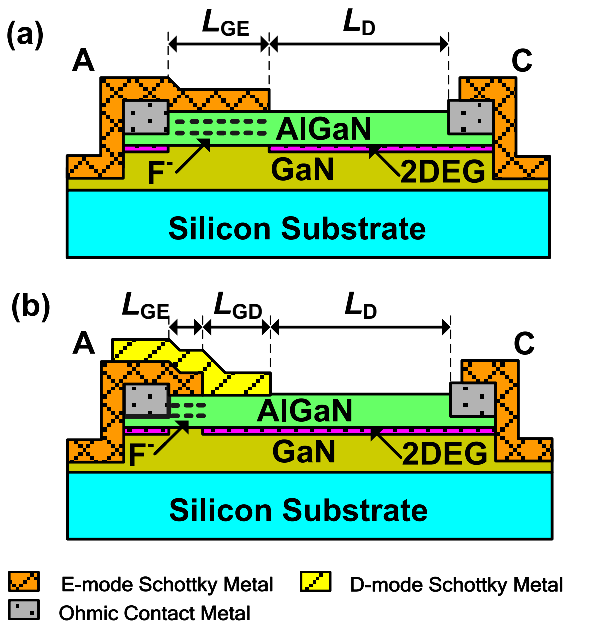

Fig. 1. (a) The schematic cross-section of the conventional L-FER and (b) DCL-FER. Where, L_{GE} , L_{GD}, and L_D are length of the E-mode channel section (CF_4 plasma treatment region), D-mode channel section, and drift region, respectively.

biased ($V_A < V_C$), the rectifier stays in the "off-state".

The sample used in this work was an $Al_{0.26}Ga_{0.74}N/GaN$ epitaxial wafer grown by MOCVD on 4-inch high resistivity silicon substrate. The epitaxial structure includes a GaN buffer, a 17.5 nm undoped AlGaN barrier and a 2 nm GaN cap layer. The starting wafer features a sheet resistance of 480 ohm/square and a pinch off voltage of -1.8 V. The fabrication process started with the formation of device mesa using Cl_2/He plasma dry etching in a STS inductively coupled plasma reactive ion etching (ICP-RIE) system. Then, ohmic contacts were formed using e-beam deposition of Ti/Al/Ni/Au (20 nm/150 nm/50 nm/80 nm) and subsequent rapid thermal annealing (RTA) at 830 °C for 38 s. The ohmic contact resistance was typically measured to be ~0.7 Ω.mm using a standard transfer length method (TLM). Two separate processes of making Schottky contacts were then conducted in sequence. One of them features the CF_4 plasma ion implantation before the metal deposition that shifted the channel's threshold voltage to a positive value, for the realization of E-mode Schottky contact section. The other one features a normally-on channel underneath, for the realization of D-mode Schottky contact section. The Schottky contacts were formed by e-beam evaporation of Ni/Au and lift-off.

The current-voltage (*I-V*) characteristics of L-FERs with an identical drift length of L_D = 5 μm and different E-mode Schottky-controlled channel length L_{GE} (0.5-, 1.0-, 2- and 3-μm) are plotted in Fig. 2. *BV* (measured at a leakage current of 1mA/mm) of 135 V, 196 V, 256 V and 249 V are obtained in these L-FERs respectively. *BV* initially increases with L_{GE}, but saturates when L_{GE} exceeds 2 μm. The *BV*'s dependency on L_{GE} indicates that the punch through effect leads to premature breakdown in L-FERs with the channel shorter than 2-μm, unlike the avalanche breakdown that dominates in long-channel L-FERs. ISE 2D device simulation was carried out to obtain an insight of the *BV*'s dependence on L_{GE} [7]. In the simulation, a shallow donor concentration of 1×10^{15} cm^{-3} with an energy level of 250 meV below the conduction band, and a compensating acceptor-type deep level impurity of 5.7×10^{16} cm^{-3} with an

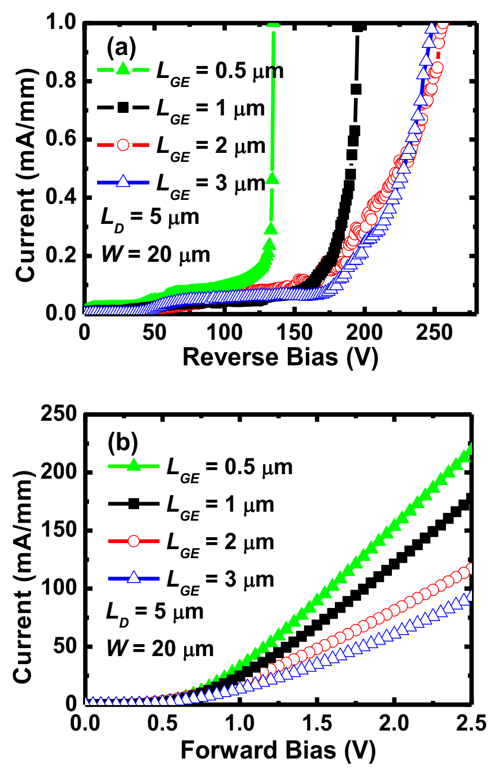

Fig. 2. I-V characteristics of the fabricated conventional L-FERs. (a) off-state, (b) on-state.

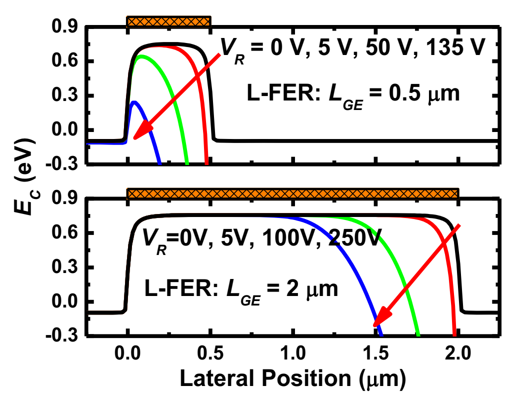

Fig. 3. Simulated E_C (eV) versus lateral channel position of the L-FER. Top, L_{GE} = 0.5 μm; bottom, L_{GE} = 2 μm. The lateral position of the schottky contact is depicted on top of each figure as reference.

energy level of 0.6 eV above the valence band were utilized in the GaN buffer [8]. Figure 3 shows the simulated conduction band minimum (E_C) in the 2DEG channel at the hetero-interface versus lateral position in L-FERs, at various reverse bias. Since the channel features a positive threshold voltage, an energy barrier exists under the Schottky contact and blocks the current flow. However, the barrier width of both devices keeps narrowing with increased reverse bias voltage, and the barrier height will eventually become lower. For the L-FER with L_{GE} = 2 μm, the barrier height remains unchanged even with a reverse bias of 250 V; however, in the L-FER with L_{GE} = 0.5 μm, the barrier height is lowered from ~0.7 eV (zero biased) to ~0.3 eV (biased at 135 V) in addition to the significant reduction in the barrier thickness, leading to punchthrough induced breakdown.

For power electronics applications, punchthrough breakdown should be avoided to fulfill the high breakdown capability of GaN. An easy solution as illustrated above is by utilizing a long schottky controlled channel, e.g. 2 μm. However, as shown in Fig. 2 (b), increasing the E-mode Schottky-controlled channel length inevitably sacrifices the on-current, or on-resistance. At the forward bias of 2.5 V, a forward on-current of 117 mA/mm is obtained in the 2 μm-channel L-FER. This current is 53 % of the on-current 219 mA/mm achieved in the 0.5 μm-channel device, yielding the same degree of degradation in the on-resistance. To minimize the punchthrough breakdown effect, better channel confinement using epitaxial-grown [9] or ion-implanted back-barrier [10] has been proposed. This work proposes a method of achieving the optimized balance of punchthrough immunity and on-resistance by channel engineering.

DUAL-CHANNEL L-FER WITH PUNCHTHROUGH IMMUNITY AND LOW ON-RESISTANCE

In order to achieve punchthrough breakdown immunity and low on-resistance simultaneously, a dual-channel lateral field-effect rectifier (DCL-FER) is proposed. As depicted in Fig. 1 (b), the anode (A) of the new DCL-FER features a dual Schottky contact controlled channel consisting of an E-mode section and a D-mode section in series. The E-mode section blocks the current when the device is reverse biased under low voltage. The extended D-mode section gets pinched off when reverse biased at high voltage, which prevents the E-mode channel section from being punched through. And the D-mode channel poses much higher carrier density at forward bias, leading to higher on-current or lower on-resistance. The fabrication process of the DCL-FER is similar to that of conventional L-FER [4], with only one additional step of forming the D-mode Schottky contact section, and the process is fully compatible with the GaN smart power chip technology [11].

DCL-FERs with L_{GE} = 0.5 μm, L_{GD} = 1.5 μm, and L_D = 5 μm, were fabricated and tested for comparison with conventional L-FERs. Fig. 4 shows the reverse biased I-V characteristics of the DCL-FER and conventional L-FERs. The DCL-FER achieved a *BV* of 245 V, comparable to that of conventional L-FER with L_{GE} = 2 μm (256 V), and 81 % higher than that the 135 V obtained in the L-FER with L_{GE} = 0.5 μm. ISE simulated E_C in the 2DEG channel versus lateral position of the DCL-FER is shown in Fig. 5. When zero biased, the DCL-FER features similar barrier profile to that of L-FER with L_{GE} = 0.5 μm, with a fully turned-on 2DEG

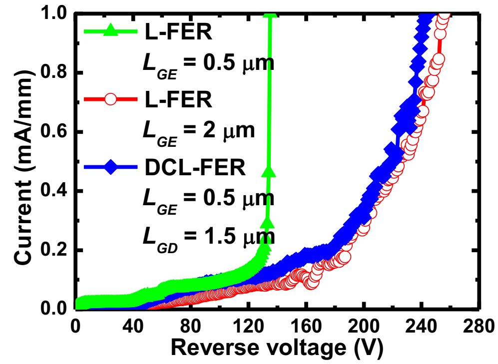

Fig. 4. Off-state I-V characteristics of the fabricated DCL-FER and L-FER.

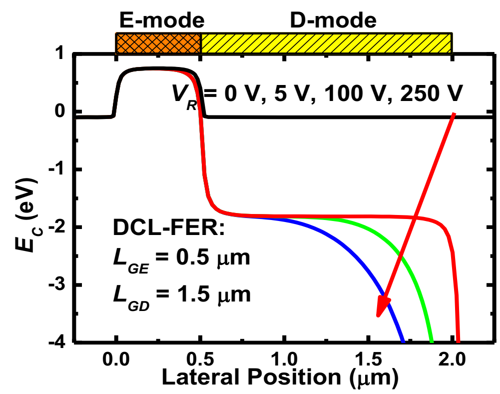

Fig. 5. Simulated E_C (eV) versus lateral channel position of the DCL-FER, with L_{GE} = 0.5 μm and L_{GD} = 1.5 μm. The lateral positions of the E-mode and D-mode schottky contacts are depicted on top of each figure as reference.

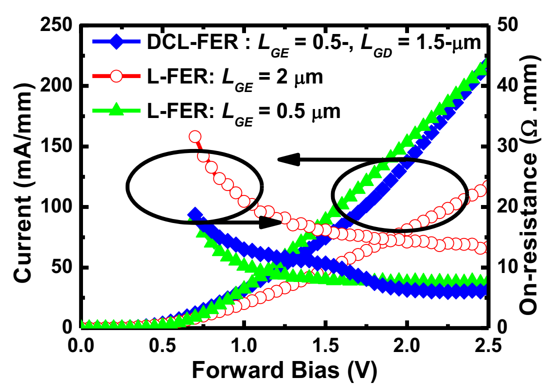

Fig. 6. On-State I-V characteristics and corresponding differential on-resistance of the DCL-FER and conventional L-FERs.

channel under the D-mode Schottky contact. When reverse biased at -5 V, the D-mode section is pinched off and shares a large part of the voltage drop. Any additional reverse bias will be supported by the D-mode channel, preventing the E-mode section from being punched through even at 250 V.

Figure 6 shows the on-state I-V and corresponding on-resistance of the DCL-FER and L-FERs. When forward biased at 2.5 V, the DCL-FER is capable of conducting a current density of 219 mA/mm, delivering a 53 % on-resistance reduction (from 13.3 Ω.mm to 6.3 Ω.mm) compared to the conventional L-FER with L_{GE} = 2 µm, while yielding a figure of merit ($BV^2 / R_{ON,\ SP}$) of 95.3 MW/cm^2 (including an ohmic contact length of 1.5 µm at each electrode). It should be noted that a second turn-on occurs in the DCL-FER at ~1.7 V, which is a result of the Schottky junction being turned-on. This unique feature enables the DCL-FER to deliver an on-resistance that is even lower than the conventional L-FER with L_{GE} = 0.5 µm (7.8 Ω.mm), which suffers from punchthrough induced breakdown. When forward biased between ~0.7 V and ~1.7 V, the DCL-FER poses slightly higher on-resistance than L-FER with L_{GE} = 0.5 µm, as a result of the additional 1.5-µm-long D-mode section.

CONCLUSIONS

An AlGaN/GaN dual-channel lateral field-effect rectifier (DCL-FER) is proposed in this paper. Both experimental results and simulation demonstrated that the new device features punchthrough breakdown immunity and low on-resistance simultaneously. The process of the DCL-FER is fully compatible with the GaN smart power chip technology [11] and makes the DCL-FER the optimum rectifier structure.

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ACRONYMS

L-FER: Lateral Field Effect Rectifier
DCL-FER: Dual-Channel Lateral Field Effect Rectifier
HEMT: High Electron Mobility Transistor
E/D-mode: Enhancement-/ Depletion-mode
2DEG: Two-Dimensional Electron Gas
MOCVD: Metal-Organic Chemical Vapor Deposition
ICP-RIE: Inductively Coupled Plasma Reactive Ion Etching
RTA: Rapid Thermal Annealing
TLM: Transfer Length Method