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Diode Embedded AlGaN/GaN Heterojuction Field-Effect Transistor

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Abstract—**Monolithically integrated devices are strongly desired in next generation power ICs to reduce the chip size and improve the efficiency and frequency response. Three examples of the embedment of different functional diode(s) into AlGaN/GaN heterojunction field-effect transistors are presented, which can minimize the parasitic effects caused by interconnection between devices.**

Index Terms—**AlGaN/GaN, embedment, heterojunction field-effect transistor, monolithic integration, Schottky barrier diode**

I. INTRODUCTION

AlGaN/GaN heterojunction field-effect transistors (HFETs) are great candidates for next generation power switching applications in various power electronics due to superior physical properties such as high mobility, high breakdown field, and high carrier concentration [1-5]. In order to fulfill the maximum power conversion efficiency of AlGaN/GaN based power devices, the parasitic effects such as parasitic inductance caused by interconnection between devices must be minimized [6]. That is, monolithic integration of different functional devices is highly demanded in future power ICs. In this report, we review three different functional devices developed in our group, which were implemented by embedding AlGaN/GaN Schottky barrier diodes (SBDs) into HFETs; (i) HFET with an embedded freewheeling diode, (ii) reverse blocking HFET, and (iii) bi-directional switch with a monolithically integrated diode bridge circuit.

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II. DIODE EMBEDMENT

1. Embedment of Freewheeling SBD

When AlGaN/GaN HFETs are used as switching devices in converters or inverters, they have freewheeling capability by themselves but the power loss during the reverse conduction mode is large due to the large reverse turn-on voltage characteristics. Therefore, it is common to add a freewheeling diode in parallel with a switching transistor to reduce the loss during the dead time as illustrated in Fig. 1 [7]. However, when a separate diode is added for the freewheeling function, not only does the chip size increase but also the parasitic inductance caused by interconnection limits the efficiency at high frequencies. These issues can be diminished by embedding a freewheeling diode into an AlGaN/GaN HFET.

As shown in Fig. 2, a Schottky contact electrode is inserted between the source and drain electrodes, being connected electrically to the source electrode. When a positive drain voltage is applied, the Schottky anode is reverse-biased and thus no current flows through the anode whereas the FET mode is in normal operation [8].

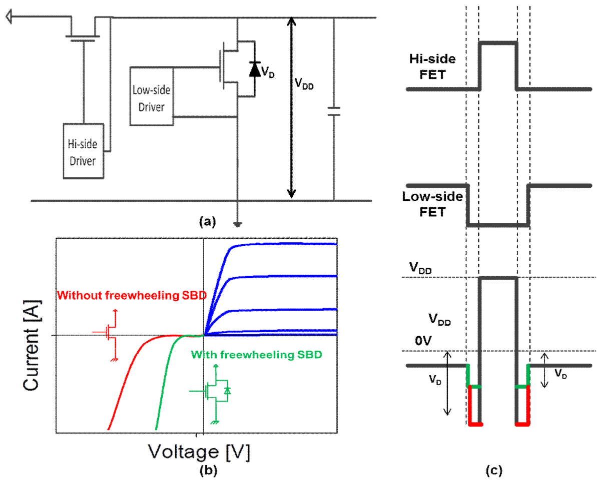

Fig. 1. (a) Typical DC-DC buck converter, (b) current-voltage characteristics of AlGaN/GaN HFET with and without a freewheeling SBD, (c) effects of the reverse turn-on voltage with and without a freewheeling SBD on dead time loss.

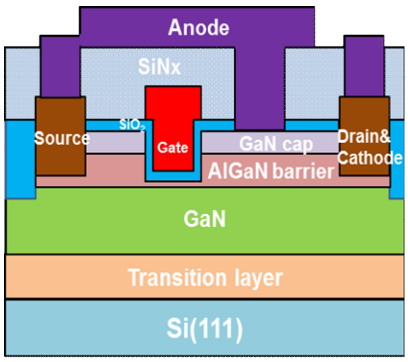

Fig. 2. Cross-sectional schematic of AlGaN/GaN-on-Si MOS-HFET with an embedded freewheeling SBD.

On the other hand, when a negative drain voltage is applied, the Schottky anode is forward-biased allowing the current flow from the source to the drain. Therefore, the reverse conduction mode can be achieved via the Schottky anode even when the FET is under the off-state condition.

The device fabrication steps are summarized briefly in Table 1. The gate dielectric film was SiO_2 and both gate metal and Schottky anode contact were formed by Ni/Au. The forward and reverse current-voltage characteristics are shown in Fig. 3 along with the forward breakdown characteristics. The measured gate threshold voltage for the forward FET mode was 2.8 V and the reverse turn-on voltage in the freewheeling mode was 1.2 V. The gate threshold voltage depends on the MOS gate whereas the reverse turn-on voltage depends on the Schottky barrier height of the anode contact [8]. The breakdown voltage

Table 1. Process flow for AlGaN/GaN-on-Si MOS-HFET with an embedded freewheeling SBD

Seq.	Step	Process
1	Mesa isolation	BCl_3/Cl_2 ICP-RIE
2	Gate recess	BCl_3/Cl_2 ICP-RIE
3	Gate oxide deposition	SiO_2 deposition
4	Ohmic formation	Si/Ti/Al/Mo/Au
5	Gate formation	Ni/Au
6	Passivation	SiN_x deposition
7	Source connected anode formation	Ni/Au

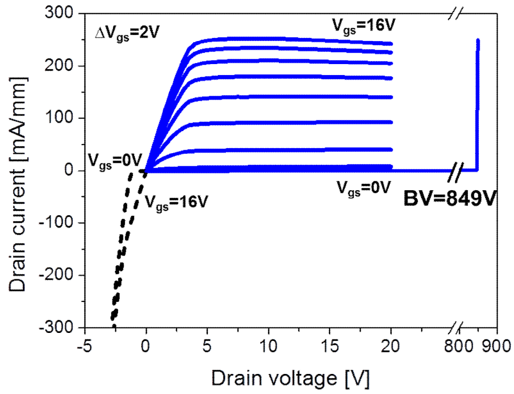

Fig. 3. Current-voltage and breakdown characteristics for the fabricated AlGaN/GaN-on-Si MOS-HFET with an embedded freewheeling SBD.

is governed by the distance between anode and drain.

2. Embedment of Reverse Blocking SBD

Despite the need for the freewheeling capability of the power switching device discussed above, the reverse conduction is not desired for many other applications. Circuits may be destroyed under abnormal situation when the reverse current flows back to the system [9]. In such cases, an extra protection circuit or diode needs to be connected to the FET. A simple approach would be the addition of a reverse blocking diode to the output drain node. Lu *et al.* reported a Schottky drain electrode to block the reverse current in AlGaN/GaN HFET [10]. However, the drawback in this approach is the forward on-set characteristics caused by the turn-on voltage of the Schottky drain, which increases the on-state loss as illustrated in Fig. 4. In order to reduce the on-set voltage, a gated-ohmic configuration [11] was employed for the drain of AlGaN/GaN HFET as illustrated in Fig. 5.

The device fabrication steps are summarized briefly in Table 2. The precise control of the recess depth is the key

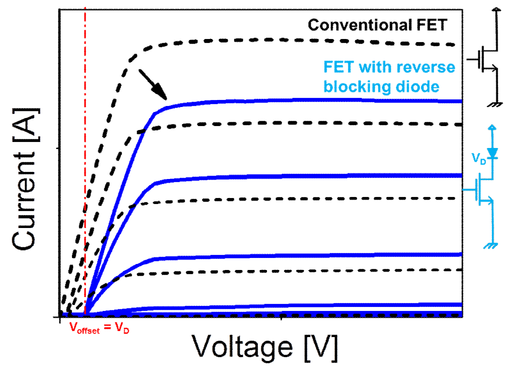

Fig. 4. Forward on-set characteristics caused by adding a Schottky drain, which increases the on-state loss.

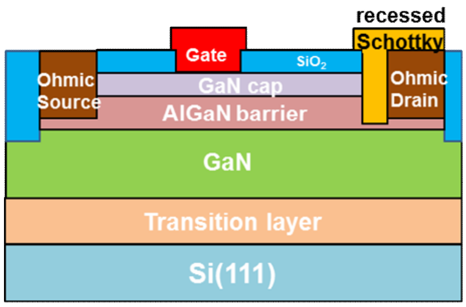

Fig. 5. Cross-sectional schematics of a reverse blocking AlGaN/GaN-on-Si HFET with a gated-ohmic drain electrode.

Table 2. Process flow of AlGaN/GaN HFET with a reverse blocking SBD

Seq.	Step	Process
1	Mesa isolation	BCl_3/Cl_2 ICP-RIE
2	Ohmic formation	Si/Ti/Al/Mo/Au
3	Gate oxide deposition	SiO_2 deposition
4	Gate opening	BOE (7:1)
5	Gate metal deposition	Ni/Au
6	Recessed drain region	BCl_3/ Cl_2 ICP-RIE
7	Drain overlay metal deposition	Ni/Au

process. The thickness of the remaining AlGaN barrier layer underneath the recessed Schottky region was only 3 nm that was thin enough to deplete the 2DEG channel at zero bias. The channel under the recessed region can be opened with a small positive drain voltage, allowing the current path from the ohmic contact region, so-called the 'gated-ohmic' characteristics [12]. When the drain voltage is higher than the turn-on voltage of the recessed SBD, the current can flow from both ohmic drain and recessed Schottky regions.

The current-voltage characteristics of the fabricated device are shown in Fig. 6. For comparison, those for a

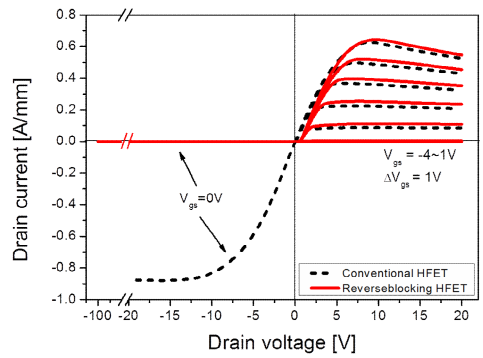

Fig. 6. Comparison of the current-voltage characteristics between AlGaN/GaN-on-Si HFETs with and without a gated ohmic drain electrode.

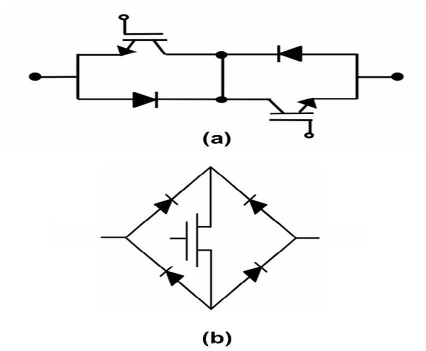

Fig. 7. Typical bi-directional switches (a) two transistors coupled with two diodes, (b) one transistor connected with a diode bridge.

conventional HFET fabricated with an ohmic drain electrode in the same process lot is plotted together. The proposed device exhibited successful reverse blocking characteristics with a forward on-set voltage of only 0.4 V with comparable forward characteristics.

3. Bi-Directional Switch

Matrix converters have received much attention because of their higher efficiency compared to conventional AC-AC converters [13]. A matrix converter is composed of multiple bi-directional switches [14]. As shown in Fig. 7, typical bi-directional switches can be implemented by either two transistors coupled with two diodes or one transistor connected with a diode bridge composed of four diodes. It should be noted that each transistor requires a gate driver whose chip size is added to the overall power IC size.

A bi-directional AlGaN/GaN MOS-HFET with a monolithically integrated diode bridge is illustrated in

Table 3. Process flow of bi-directional AlGaN/GaN HFET

Seq.	Step	Process
1	Mesa isolation	BCl_3/Cl_2 ICP-RIE
2	Ohmic formation	Si/Ti/Al/Mo/Au
3	Gate recess	BCl_3/Cl_2 ICP-RIE
4	Gate oxide deposition	SiO_2 deposition
5	Gate and Schottky formation	Mo/Au

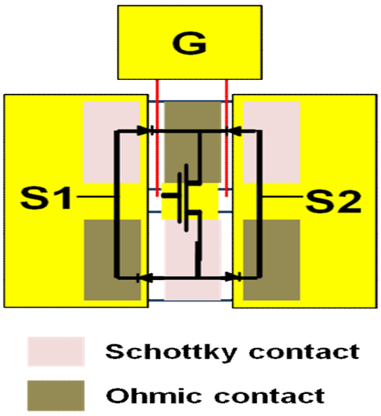

Fig. 8. Bi-directional AlGaN/GaN MOS-HFET with a monolithically integrated diode bridge.

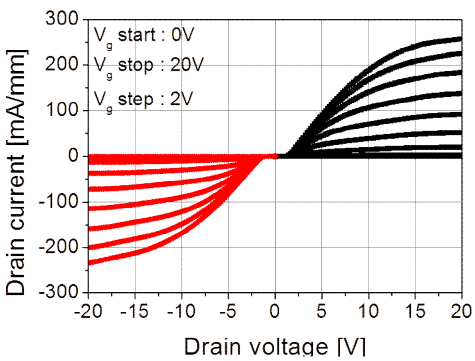

Fig. 9. Current-voltage characteristics of the fabricated bi-directional AlGaN/GaN-on-Si MOS-HFET with a diode bridge.

Fig. 8. Since the drain electrodes of MOS-HFET are replaced by Schottky contacts, no extra space is required for them. The other two SBDs are monolithically integrated with the source electrode [15]. The device fabrication steps are summarized in Table 3. The Mo/Au stack was used for gate and Schottky formation to reduce the Schottky barrier height while improving the adhesion between gate and gate oxide layer.

When the HFET is off, no current flows between S1 and S2. When the MOS-HFET is on, the current flows bi-directionally depending on the polarity of the applied voltage between S1 and S2. This configuration can save the overall chip area significantly due to the monolithic integration technology. In addition, this configuration requires only one gate driver.

The bi-directional switching characteristics are shown in Fig. 9. The gate threshold voltage was 6 V for both forward and reverse modes with symmetric bi-directional characteristics.

III. Conclusion

Diode embedded AlGaN/GaN HFETs presented in this report can be widely applied to small size future power ICs. The embedded diode configurations can significantly reduce the chip size and minimize the parasitic inductance, which will give the significant benefit in conversion efficiency, especially at high switching frequencies.

Acknowledgments

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