6A-Operating Current GaN-Based Enhancement-Mode High Electron Mobility Transistors

Chih-Hao Wang[1], Liang-Yu Su[1], Finella Lee[1], and JianJang Huang[1,*]
[1]Graduate Institute of Photonics and Optoelectronics, National Taiwan University, No. 1, Sec. 4, Roosevelt Road, Sec. 4,
Taipei 10617, Taiwan
Phone: (886) 2-3366-3665 EMAIL: r02941015@ntu.edu.tw, jjhuang@ntu.edu.tw

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Abstract

This paper demonstrates an enhancement-mode (E-mode) GaN based high electron mobility transistors (HEMT) with a p-type cap layer on the Si substrate. The E-mode device is realized by growing a p-type cap layer on the top of the AlGaN/GaN epi-structure. We first characterized device performance based on a small gate-width device and then the high current multi-finger gate power devices were demonstrated. The threshold voltage (V_{th}) of the device is 1.5 V. And the saturation drain of power devices can be operated up to 6.42 A.

INTRODUCTION

Gallium Nitride (GaN) based high electron mobility transistor (HEMT) is a promising device in the category of power electrical devices. The two-dimensional electron gas (2-DEG) exists in the interface of GaN because of the built-in polarization electric field caused by the contact between AlGaN and GaN [1]. Therefore, the 2-DEG layer produces high electron mobility in AlGaN/GaN HEMTs [2]. In addition, GaN is a kind of wide-band-gap material [3]. Thus, it can sustain high voltage efficiently. AlGaN/GaN HEMTs with high breakdown voltage and large current become a novel candidate for power electrical devices.

However, a GaN based HEMT is a depletion mode or normally-on device. A negative threshold voltage is not an appropriate design for applications of high power electrics. There are some ways to achieve enhancement-mode or normally-off HEMT. One of them is using p-type GaN cap layer to realize E-mode devices [4]. The amount of p-type dopant can deplete the electron in 2-DEG layer when it is not added any bias voltage. Thus, the characteristics with stable and positive V_{th} can be attained.

In this work, E-mode HEMTs are fabricated as small devices and power devices [5]. The small device is a single field-effect transistor (FET) structure; then, we develop large-area HEMTs to achieve the characteristics with high output current and large operating voltage according to the experience of the small device. The process of power devices is shown in Fig. 1. The p-GaN etching control of E-mode HEMT has been discussed in our previous research [6]. Figure 2 is the actual picture of the power device. A power device is parallel forty-five-finger FET structure and total width is 45 mm. Threshold voltage of them is 1.5 V. We conclude with an E-mode GaN based HEMT power device with a large output drain current of 6.42 A and a large operating gate voltage of 8 V.

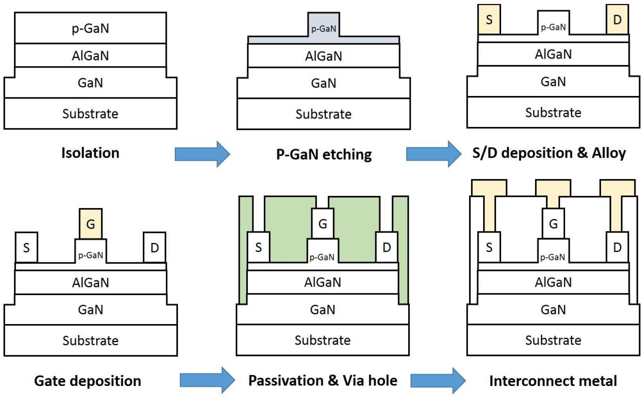

Figure 1: Fabrication procedures of the power device.

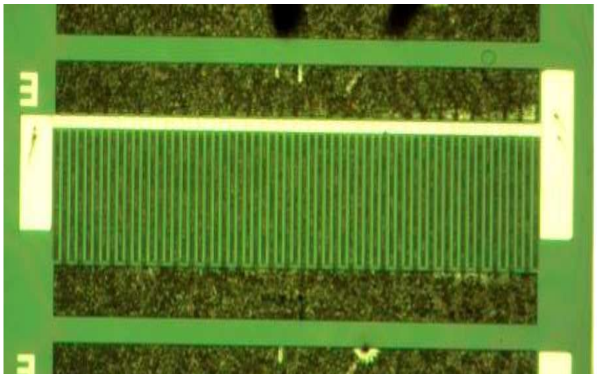

Figure 2: Picture of the power device.

DEVICE FABRICATION

E-mode HEMTs were grown on a Si substrate by metal organic chemical vapor deposition (MOCVD) and were composed of a 2.4 µm buffer, a 1.2 µm GaN, a 10 nm $In_{0.25}Ga_{0.75}N$ barrier, and a 60 nm p-type GaN layer with Mg^+ doping concentration of 5×10^{19} cm^{-3}. First, we defined mesa as isolation by inductively coupled plasma reactive-ion etching (ICP-RIE), and etched the p-GaN layer to define the

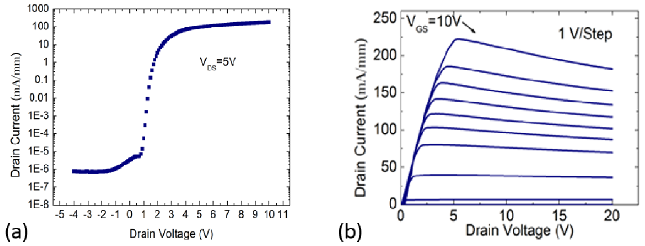

Figure 3: (a) Transfer characteristics of small devices (b) Output characteristics of small devices.

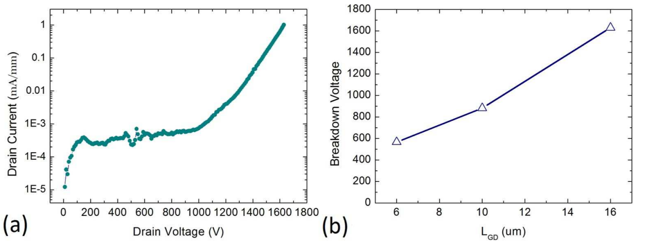

Figure 4: (a) Breakdown characteristic of small devices with L_{GD} = 16 µm at V_{GS} = 0 V. (b) Breakdown voltages of small devices with various L_{GD}.

position of the electrodes. P-GaN layer etching was a quite tough step and it had been discussed in our previous research [6]. Second, the Ti/Al/Ni/Au, which was 25 nm, 150 nm, 50 nm and 125 nm, respectively, was deposited as source/drain metal by E-gun and it was annealing at 900 °C with N_2 so that the source/drain metal could reach ohmic contact with AlGaN. Then, Ni/Au, which was 25 nm and 1000 nm, was deposited as gate metal. Using different metal as gate electrode might have an impact on the performance of HEMT and it had been also discussed in our previous research [7]. The polymer benzocyclobutene (BCB) was used as the passivation layer, then following by via etching by RIE. After via etching, the interconnecting metal Ni/Au, which was 25 nm and 1200 nm, was deposited to make the metal layer thicker. The purpose of the interconnecting metal was linking each gate finger and it became a gate bridge cross the source. In Fig. 2, the top pad and the down pad were source and drain, respectively. Left and right pad were both connected to gate because it reduced the resistance of interconnecting metal to one half.

RESULTS AND DISCUSSION

At first, small devices are fabricated. Its gate-source length (L_{GS}), gate length (L_G), gate-drain length (L_{GD}), and gate width is 2, 4, 6, and 50 µm, respectively. The transfer curve of small devices is shown in Fig. 3 (a) and the threshold voltage (V_{th}) of it is a value of 1.5 V. For analysis easily, the threshold voltage, V_{th}, is defined that the bias of gate is at a drain current of 1 mA/mm when V_{DS} is 5 V. Besides, it can work in a large gate voltage of 10 V, shown in Fig. 3 (b).

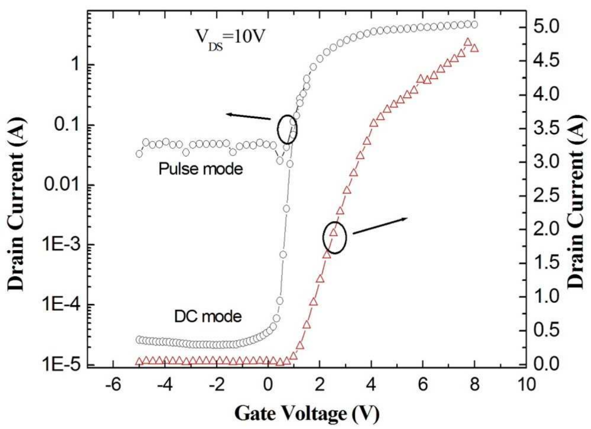

Figure 5: Transfer characteristics of the power device. The drain current is expressed in logarithmic (left) and linear (right) scale.

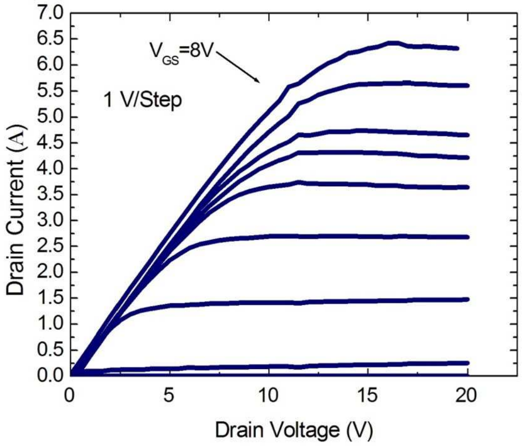

Figure 6: Output characteristics of the power device.

Analysis of breakdown voltage has been test. The breakdown voltage, V_{BD}, is defined that the V_{DS} is at a drain current of 1 mA/mm when the HEMT is at off-state. The small device has a high breakdown voltage of 1630 V with L_{GD} = 16 µm, shown in fig. 4 (a). In Fig. 4 (b), breakdown voltage was measured in various length of gate to drain. It is observed that the breakdown voltage is higher with longer L_{GD}. It can be explained that the breakdown voltage is dominated by lateral breakdown when the L_{GD} is short. In the fabrication of power device, L_{GD} = 10 µm was used to realize the power device.

In order to achieve the purpose of large current, large-area HEMTs with p-GaN cap layer are adopted. A large-area HEMT is a parallel connection structure with forty-five fingers. There is a trade-off in the size of each finger. To attain the high output current characteristic the total length is as short as better; however, as the size of the gate length shorter the fabrication of the transistor becomes more and more difficult. Finally, each finger's gate-source length, gate length, and gate-drain length is 3, 4, and 10 µm, respectively. The width of each finger is 500 µm. Since every finger can be equivalent to two small single HEMTs, the total width is 45x2x500 µm = 45 mm.

The transfer characteristic is shown in Fig. 5. The on/off ratio of the large-area HEMT is about five orders and threshold voltage of it is 1.5 V. Pulse mode can reduce the heat problem in high current measurement. However, in Fig. 5, it can be found that the off-state leakage current in pulse mode is higher than in DC mode. There are two reasons to explain this result. First, the shorter pulse width with shorter integration time may reduce the accuracy in low current measurement. The other factor is that the current sensing range cannot change in pulse mode. As the result, the accuracy of low current measurement in DC mode is better than in pulse mode. The output characteristics of large-area HEMT is shown in Fig. 6. It can be observed that the power device has a higher saturation current of 6.42 A when V_{GS} is 8 V.

CONCLUSIONS

In this research, we present an E-mode AlGaN/GaN HEMT with a heavily-doped p-GaN cap layer as power devices which can provide nice characteristics. The power device can still work even when V_{GS} is over 8 V. The E-mode HEMT with a saturation current of 6.42 A is achieved. According to above advantages, the application of power devices with E-mode HEMTs can be expected.

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ACRONYMS

2-DEG: Two-Dimensional Electron Gas
BCB: Benzocyclobutene
DC: Direct Current
D-mode: Depletion-mode
E-mode: Enhancement-mode
HEMT: High Electron Mobility Transistor
ICP-RIE: Inductively Coupled Plasma Reactive-Ion Etching
MOCVD: Metal Organic Chemical Vapor Deposition