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A comparative study of surface passivation on AlGaN/GaN HEMTs

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Abstract

Using a Si_3N_4 layer as passivation layer, effects of surface passivation on device performances have been investigated. After passivation, devices exhibited better pinch-off characteristics and lower gate leakage current. For a device with a gate-length of 0.25 μm, the I_{dss} increased from 791 to 812.2 mA/mm and the peak extrinsic transconductance increased from 207.2 to 220.9 mS/mm. The f_T and f_{MAX} values decreased from 53 and 102.5 to 45.9 and 90.5 GHz, respectively, due to the increase of parasitic capacitances. Microwave noise measurements showed that devices exhibited 0.2–0.25 dB increase in minimum noise figure (NF_{min}) after passivation.

Keywords: Passivation; GaN; AlGaN; HEMT; Minimum noise figure

1. Introduction

AlGaN/GaN high electron mobility transistors (HEMTs) have demonstrated excellent device characteristics [1–9], which make them excellent candidates for high temperature, high power, high frequency, and low noise applications. However, these devices suffer from current degradation and transconductance dispersion. It is believed that this current degradation is a result of trapping of electrons in the active surface area. These trappings are caused by surface states created by defects and dislocations accessible to the surface, and ions absorbed on the surface. Efforts have been conducted to investigate the effect of frequency-dependent slump and even collapse in drain current which degrades the device performance. Researchers from a couple of laboratories have studied the effect of passivation on breakdown voltages, RF output power and power-added efficiency [10–12]. Using SiN layer as a passivation layer on AlGaN/GaN HEMTs, an increase in output power and breakdown voltages were demonstrated [11]. In this paper, we will present results of the comparative study of passivated and unpassivated AlGaN/GaN HEMTs with a gate-length of 0.25 μm. The effects of passivation on DC, RF, and microwave noise performances of AlGaN/GaN HEMTs will be discussed.

2. Device layer structure and device processing

The layer used in this study was grown by metal-organic chemical vapor deposition on sapphire substrates. The epilayer consists of undoped 2 μm GaN and 25 nm $Al_{0.35}Ga_{0.65}N$. Hall measurements showed a sheet carrier concentration of 1.3×10^{13} cm^{-2} and an electron mobility of 1330 cm^2/Vs at room temperature. The mesa etching was achieved in a Cl_2 plasma by an inductively

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coupled-plasma reactive ion etcher. Ohmic contacts were obtained by Ti/Al/Ti/Au evaporation and rapid thermal annealing at 800 °C for 30 s. The ohmic contact resistance is about 0.2 Ω mm. Ni/Au mushroom-shaped gates with a gate-length of 0.25 μm but with a wide (1 μm) T-gate head were fabricated by electron beam lithography. The devices had a gate width of 100 μm and a source-drain spacing of 3 μm. Prior to device passivation, DC, RF, and noise performances of devices were measured. Then, Si_3N_4 with a thickness of 250 nm was deposited on the sample using plasma-enhanced chemical vapor deposition at 300 °C after a regular cleaning procedure in warm acetone and isopropyl alcohol and dipping in diluted HF. At last, probing windows were opened and Si_3N_4 were etched away for on-wafer measurements. After passivation, DC, RF, and noise performances of the same devices were measured again for comparison.

3. Passivation effects on device characteristics

3.1. Passivation effect on DC characteristics

Fig. 1(a) shows *I–V* characteristics of a typical device before and after passivation. The gate was biased from 1 to −5 V in a step of −1 V. The values of I_{dss} (I_{max}) increased from 791 (912.1) to 812.2 (977.8) mA/mm at $V_{ds} = 6.7$ V, indicating a higher sheet carrier concentration in the channel. This is probably due to an increase in positive charge at Si_3N_4/AlGaN interface which is great enough to neutralize the AlGaN polarization charge, thereby eliminating or decreasing the surface related depletion from two dimensional electron gas [11]. At the same time, the device had better pinch-off characteristics, which will be clearly demonstrated later. The DC transfer characteristics of the device is shown in Fig. 1(b). The drain bias was 6 V. The peak value of g_m increased from 207.2 to 220.9 mS/mm. It should be mentioned that the threshold voltage of the device shifted toward the reverse direction, from −4.2 to −4.58 V.

Fig. 2(a) shows gate-diode characteristics before and after passivation. In the measurements, the drain was shorted to the source. Clearly, the gate leakage current after passivation is lower. At $V_{gs} = -10$ V, the gate current decreased from 0.61 to 0.36 nA, which indicates a higher gate-to-drain breakdown voltage after passivation. To investigate the pinch-off characteristics and drain-to-source breakdown voltage, the drain current at off-state, shown in Fig. 2(b), was measured before and after passivation. In the measurements, the gate was biased at −8 V to completely pinch the channel off. The data shown in Fig. 2(b) demonstrate a clear decrease in drain current at drain bias up to 10 V. At

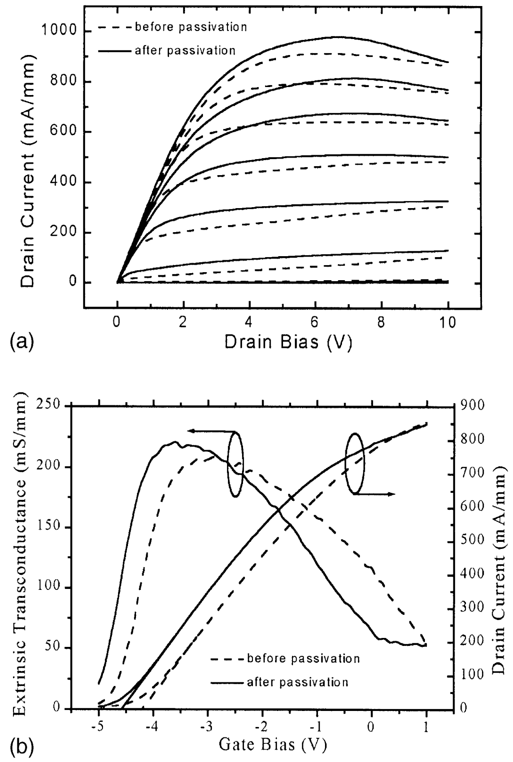

Fig. 1. (a) DC *I–V* characteristics of a typical 0.25 μm AlGaN/GaN device before and after passivation. The gate was biased from 1 to −5 V, (b) DC transfer characteristics of the device before and after passivation. The drain bias was 6 V. The threshold voltage of the device changed from −4.2 to −4.58 V after passivation. The peak value of extrinsic transconductance increased from 207.2 to 220.9 mS/mm.

$V_{ds} = 10$ V, the drain current decreased from 1.1 to 0.25 mA/mm, indicating a higher drain-to-source breakdown voltage. To avoid stress-induced device degradation, complete breakdown measurements were not performed in above gate leakage and off-state drain current measurements. Nevertheless, we still can conclude that higher breakdown voltages in both drain-to-source and drain-to-gate are achieved by Si_3N_4 passivation.

3.2. Passivation effect on f_T and f_{MAX}

Small signal measurements were performed before and after passivation. Fig. 3(a) shows values of f_T and f_{MAX} as a function of gate bias at room temperature. In the measurements, the drain was biased at 7 V. Though the peak g_m increased after passivation, the peak f_T value decreased from 53 to 45.9 GHz. The peak f_{MAX} value decreased from 102.5 to 90.5 GHz also. This is due

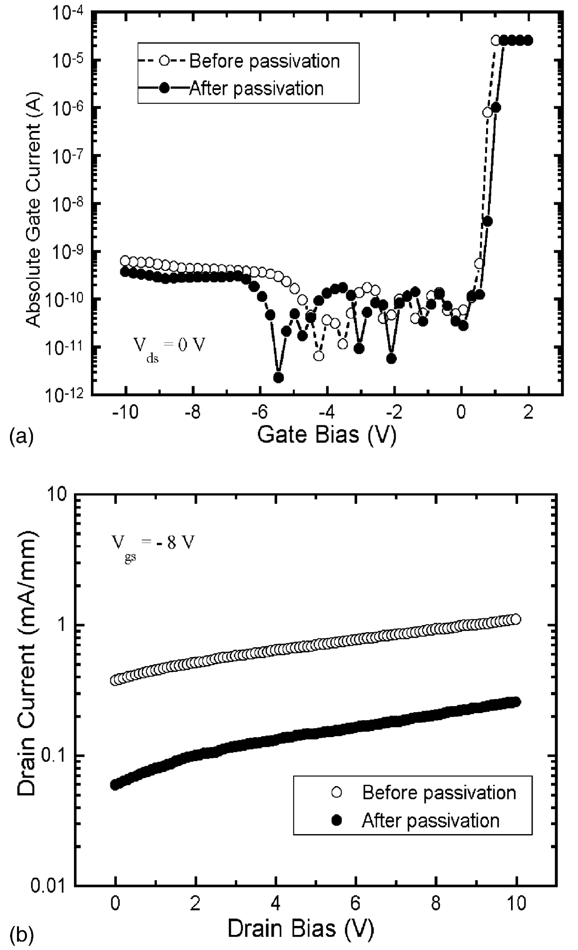

Fig. 2. (a) Gate-diode characteristics of the typical 0.25 μm AlGaN/GaN device before and after passivation. In the measurement, the drain was shorted to the source, (b) Off-state drain current of the typical 0.25 μm AlGaN/GaN device before and after passivation. In the measurement, the gate was biased at −8 V to pinch the channel off completely.

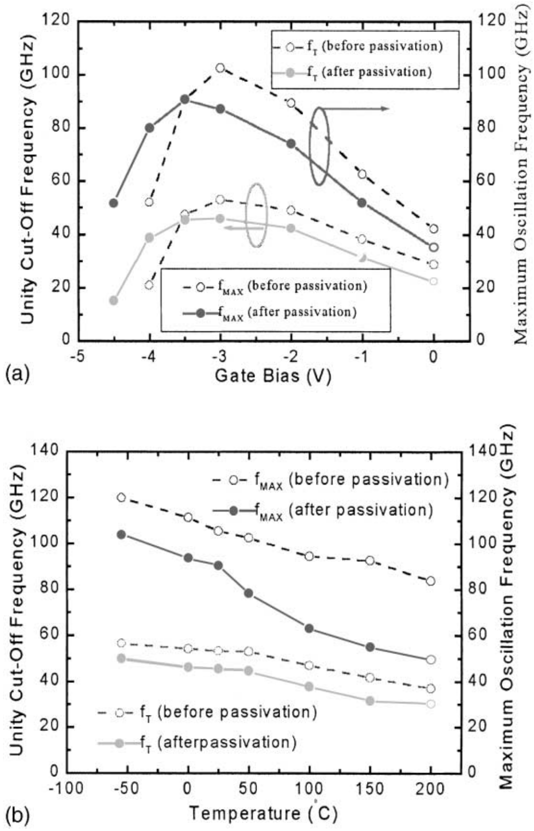

Fig. 3. (a) f_T and f_{MAX} values as a function of gate bias before and after passivation for a typical 0.25 μm device at room temperature. The drain was biased at 7 V in the measurements, (b) f_T and f_{MAX} values before and after passivation for a typical 0.25 μm device dependence of substrate temperature.

to the increase of C_{gs} and C_{gd} caused by the high dielectric constant of Si_3N_4. After passivation, the gate bias of peak f_T and f_{MAX} shifted towards the negative direction, consistent with the shifts of threshold voltages and gate biases of peak g_m. The f_T and f_{MAX} dependences on substrate temperature are shown in Fig. 3(b). After passivation, the f_T values had about 6–10 GHz decrease from −55 to 200 °C while the decrease of f_{MAX} values is much higher especially at high temperatures, for example, from 83.9 to 49.6 GHz at 200 °C. The trend indicates that the decrease of f_T and f_{MAX} values may become even larger at higher temperature. Current efforts are being directed to device modeling to investigate changes in device parameters against temperature.

3.3. Passivation effect on microwave noise performance

Fig. 4 shows NF_{min} and G_a values of a typical device against frequency before and after passivation. In the measurements, the drain was biased at 8 V and the gate was biased at −3.5 V. The broken lines and solid lines are the fits of measured NF_{min} and G_a values before and after passivation, respectively. Since the gate leakage current was smaller after passivation, better noise performance of passivated devices was expected. However, noise measurements after passivation showed that the devices exhibited about 0.2–0.25 dB increase in NF_{min}, demonstrated by the linear fits of measured NF_{min} values. This is mainly due to the 1–1.5 dB decrease of G_a, attributed to the increased C_{gs} and C_{gd}. Therefore, the effect on microwave noise performance is a combination of influences of lower gate leakage current and higher surface dielectric constant.

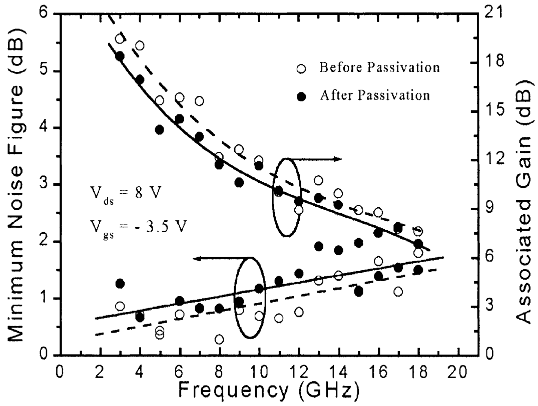

Fig. 4. Minimum noise figure (NF_{min}) and associated power gain (g_a) values against frequency before and after passivation for a typical 0.25 μm device.

4. Conclusions

The effects of surface passivation on device performances of AlGaN/GaN HEMTs were investigated using a SiN layer. After passivation, devices with a gate-length of 0.25 μm exhibited better pinch-off characteristics and lower gate leakage current. The peak value of extrinsic transconductance increased from 207.2 to 220.9 mS/mm. The threshold voltage changed from −4.2 to −4.58 V. Due to the increase of parasitic capacitances caused by the high dielectric constant of SiN, the values of peak f_T and f_{MAX} decreased from 53 and 102.5 GHz to 45.9 and 90.5 GHz, respectively. Though the gate leakage current was smaller, the NF_{min} values had 0.2–0.25 dB decrease after passivation over the measurement frequency range due to the 1–1.5 dB decrease of G_a.

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