Investigation of Un-doped GaN Cap Layer on RF and Trap Related Characteristics in AlGaN/GaN HEMTs

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Abstract

In this work, the influence of un-doped GaN cap layer on AlGaN/GaN high electron mobility transistors (HEMTs) has been studied by using DC, pulsed I-V, capacitance-voltage (C-V), and load-pull characterizations. The device without cap layer is found to exhibit smaller dynamic range (V_{on}-V_{th}) compared to that of the device with cap layer. However, the lower interface trap density in the device without cap layer can lead to higher drain current with different quiescent points, resulting in better RF power and gain at 2.7 GHz.

INTRODUCTION

GaN-based high electron mobility transistor (HEMT) is promising for high power and high frequency device applications, owing to its wide bandgap, high saturation electron velocity and low on-resistance. However, GaN-based devices suffer from the existence of traps at passivation/III-V interface, leading to threshold voltage instability [1] and current collapse [2]. Recently, many methods have been reported to improve the interface property, by using different passivation materials and deposition techniques, such as Al_2O_3 grown by atomic layer deposition (ALD) [3], SiN deposited by plasma enhanced chemical vapor deposition (PECVD) [4], SiN deposited by low pressure chemical vapor deposition (LPCVD) [5], and nitridation interlayer prior to gate dielectric [6].

In the early stage of GaN HEMT development history, it is believed that GaN cap is helpful to protect the surface and suppress the surface traps [7-9], which could also be caused by immature pre-treatment and improper passivation process. In order to suppress the high electrical field induced defect and inverse piezoelectric effect, GaN cap layer has been widely used in GaN HEMTs [10-11]. However, because of the high voltage operation, the electrically degraded devices always contain the pit-like defects at the gate edge side, which degrade the I_{dmax} [12-13]. The negative polarization charges at the interface of the GaN cap layer and the AlGaN layer cause the increase of the barrier height [14], reducing the gate leakage current and increasing the Schottky turn on voltage. However, the negative polarization charges also suppress the carrier density of the 2-dimensional electron gas (2DEG) and result in an increase of the sheet resistance [15]. The insertion of the GaN cap layer also increase the distance between the gate electrode and the 2DEG channel, hence inevitably compromising the gate controllability.

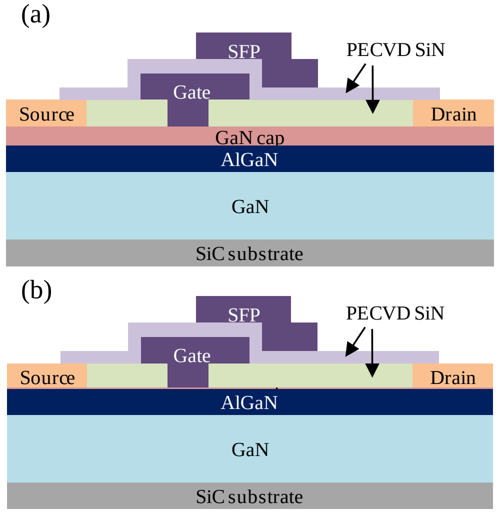

Fig. 1. Schematic of the 0.4-um AlGaN/GaN HEMTs with (a) and without (b) GaN cap layer.

In this paper, we apply C-V measurement, DC, pulsed IV, and RF techniques to investigate the trapping behaviors and the influence of un-doped GaN cap on AlGaN/GaN HEMTs.

EXPERIMENTAL

The structure of the AlGaN/GaN HEMT in this work is shown in Fig. 1. AlGaN/GaN heterostructure with and without 3-nm GaN cap layer are grown on 4-inch SiC substrate by metal organic chemical vapor deposition (MOCVD). Ohmic metal were formed by electron beam evaporation of Ti/Al/Ti/Au metal stacks, followed by rapid thermal annealing at 855℃ for 30 s in N2 ambience. A SiN layer of 80 nm thickness was deposited by PECVD as a first passivation layer. ICP etch was applied for gate opening. Schottky contact was formed by evaporated Ni/Pd/Au . A second SiN layer of 200 nm thickness was deposited by PECVD as interlayer of gate metal and source field plate (SFP).

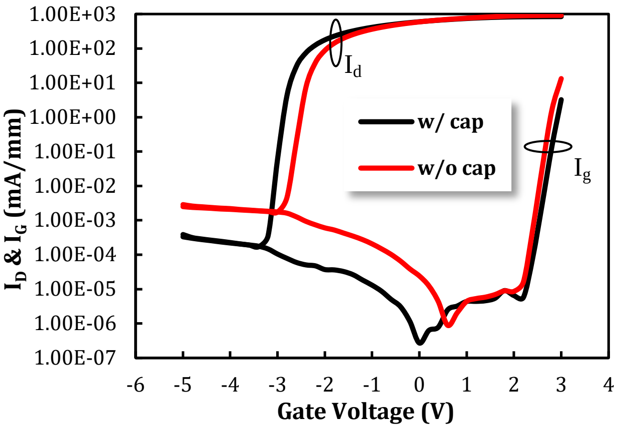

Fig. 2. Transfer characteristics of the AlGaN/GaN HEMTs with and without GaN cap.

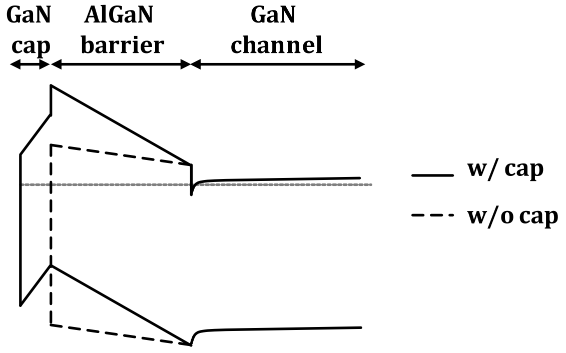

Fig. 3. Schematic illustration of energy-band diagram for AlGaN/GaN HEMTs with GaN cap layer and without GaN cap layer.

DEVICE CHARACTERISTICS AND PERFORMANCE

Fig. 2 shows the CW I_d-V_g transfer characteristics of the devices with and without GaN cap layer. The device with cap layer shows a level of leakage nearly one order of magnitude lower than that of the device without cap layer. This can be attributed to the barrier height increase caused by the insertion of the GaN cap layer, as illustrated in Fig. 3. The increase of the barrier height also leads to an increase (≈ 0.2 V) of the gate turn-on voltage (V_{on}). Because of the existence of the GaN cap layer, the distance between the gate metal and the 2DEG channel increases, also causing a positive shift (≈ 0.38 V) of the threshold voltage (V_{th}). That is, the capped device has a more negative V_{th} and a higher V_{on} as compared to those of the un-capped one. Since it is generally believed that larger $|V_{on}$-$V_{th}|$ (dynamic range) features better RF performance and ruggedness up to much higher compression regions, the capped device is thus expected to exhibit better RF performance.

To confirm that, the devices (operated in class AB at I_{ds} = 12.5 mA/mm, V_{ds} = 50 V) were characterized at 2.7 GHz using a load-pull system, matched for having maximum output power (P_{out}). Fig. 4 shows the large-signal measurement results for the capped and un-capped devices. The peak output power density and the gain of the devices with and without cap layer are 11.6, 11.1 W/mm, and 20.0, 20.7 dB, respectively. Apparently, the un-capped device features a significant higher gain and a better compression behavior than those of the capped one. This is not in line with what we expected.

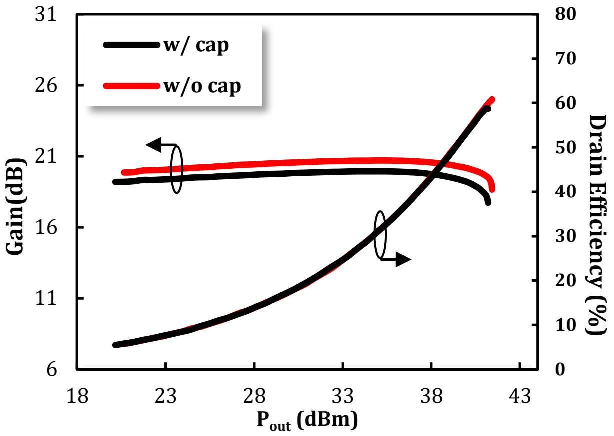

Fig. 4. Gain and Drain Efficiency vs. P_{out} for AlGaN/GaN HEMTs with and without GaN cap.

To understand the cause behind this contradiction, trapping analysis utilizing C-V measurements on MIS diodes

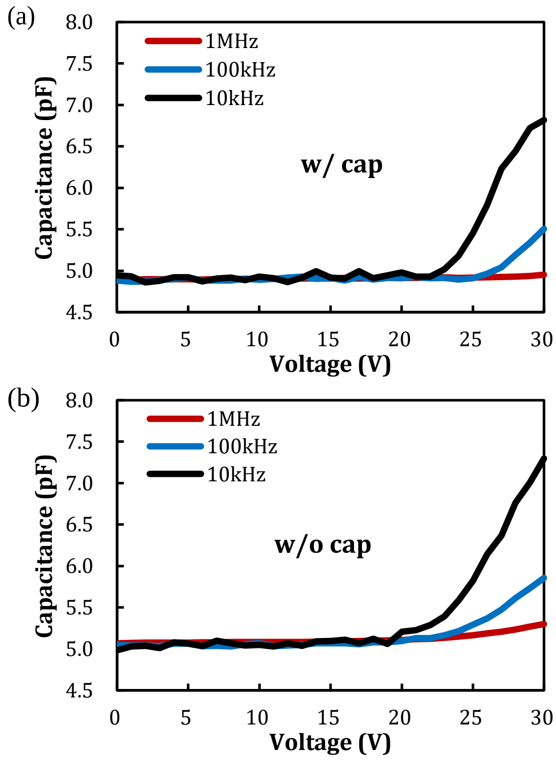

Fig. 5. Frequency dispersion of the C-V characteristics of the MIS diodes with and without GaN cap.

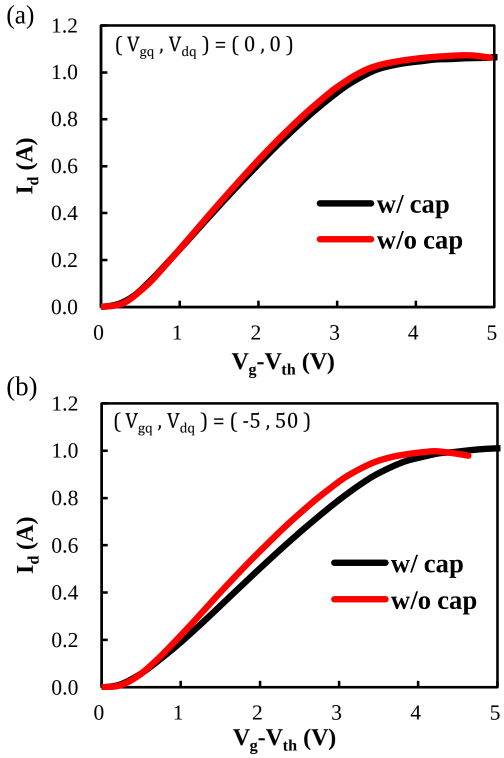

Fig. 6. Id vs. (V_{gs}-V_{th}) characteristics by the double pulse measurement for AlGaN/GaN HEMTs with and without GaN cap.

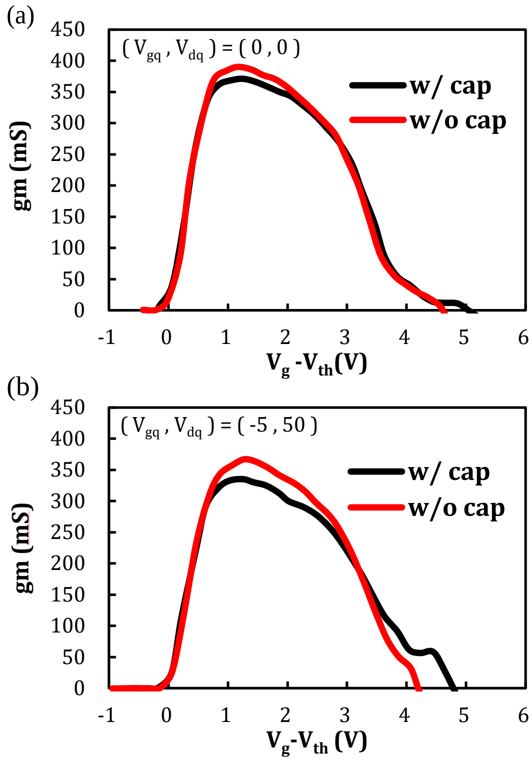

Fig. 7. Gm vs. (V_{gs}-V_{th}) characteristics by the double pulse measurement for AlGaN/GaN HEMTs with and without GaN cap.

are performed. The density of fixed charges occurred at the passivation/III-N interface can therefore be derived from the frequency dispersion of the measured C-V characteristics [16-18]. Usually, there are two different regions in the measured C-V curves. The first one for negative applied voltage corresponds to the carrier accumulation at the 2DEG channel, and the second one for positive applied voltage accounts for the effects due to the dielectric/III-N interface. Fig. 5 shows the second region of the measured frequency dispersion of the C-V characteristics of the MIS diode structures with and without GaN cap layer. The measured frequencies are 10 kHz, 100 kHz, and 1 MHz, as respectively indicated. The density of interface traps (D_{it}) is then calculated by the following equation [19]:

$$D_{it}=\frac{C_{SiN}}{q}\frac{V_2\text{-}V_1}{E_2\text{-}E_1}=\frac{C_{SiN}}{q}\frac{\Delta V}{\Delta E}$$

where ΔV is the on-set voltage shift for f_1 and f_2, C_{SiN} is the capacitance of PECVD-SiN dielectric, q is the magnitude of electronic charge, ΔE is the difference of the energy levels between which the interface states distributed and given by

$$\Delta E=E_1\text{-}E_2=kT\ln(\frac{f_2}{f_1})$$

where k and T (= 300 K) are Boltzmann constant and temperature, respectively. From E_C – 0.35 eV to E_C – 0.30 eV, D_{it} for the MIS diodes with and without GaN cap are estimated to be 3.7×10^{13} and 2.8×10^{13} $cm^{-2}eV^{-1}$, respectively. Clearly, the D_{it} value of the un-capped diode is 30% lower as compared with that of the capped one.

The C-V analysis shows that the capped device has a serious frequency dispersion, which might potentially degrade the RF performance. The transfer curves obtained by the double pulse measurement technique as a function of gate overdrive voltage (V_g-V_{th}) for different quiescent points are shown in Fig. 6. Two quiescent points are used, i.e., (V_{gq}, V_{dq}) = (0 V, 0 V) and (-5 V, 50 V) respectively corresponding to the cases in which negligible and significant charge trapping are activated in the device. Pulse width and duty cycle are 1 μs and 1%, respectively. It is found that both types of devices behave similarly for (V_{gq}, V_{dq}) = (0 V, 0 V), while different I_d degradation behaviors are observed when (V_{gq}, V_{dq}) = (-5 V, 50 V) is used. The I_d drop for the device without GaN cap layer is significant lower. Fig. 7 shows gm versus overdrive voltage (V_g-V_{th}) curves measured by the double pulse method. As a result of the slightly loss of the gate controllability due to an increase of the distance between the gate metal and the 2DEG channel, the gm peak of the device without cap layer for (V_{gq}, V_{dq}) = (0 V, 0 V) is 4.9% higher than that of the one with cap layer. For the same device, the difference of the gm peak between different quiescent points is found to be 9.7% and 5.9% for the devices with and without cap, respectively. This result indicates that a lower level of trapping centers exists in the

SiN/AlGaN interface than that exists in the SiN/GaN interface. Our analysis shows that the observed RF performance for the two types of devices is dominated by the amount of the resulting interface trap density and the corresponding frequency dispersion.

CONCLUSIONS

We have studied the influence of un-doped GaN cap layer on AlGaN/GaN HEMTs by using various characterization methods. We conclude that the cap layer can significantly degrade the RF performance if the interface properties are not properly tailored.

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