Trap Analysis of GaN-Insulated-gate-HEMT for High Reliability

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Abstract

In this paper, we describe the analysis of trap issues of the GaN insulated-gate HEMTs (MIS-HEMTs) to obtain high reliability. SiN was used for the insulated layer in this study. Trap effect was investigated using the pulsed I-V measurement, focusing on the effect of the initial gate and drain voltage. Current collapse could be suppressed by optimizing the heterointerface between SiN and GaN-HEMT layer. However, we found that the increase of maximum current (Imax) was observed when the initial state was a forward gate bias condition with a high electric field, such as an initial gate voltage of 2 V and a drain voltage of 50 V. This Imax shift phenomena never occurred at the Schottky-gate HEMT structure. We confirmed that Imax shift could be suppressed by optimizing SiN layer quality. This measurement method is essential for developing and optimizing the reliability of GaN-MIS-HEMTs for mass-production.

INTRODUCTION

Wireless mobile networks are expected to move up to 4G technologies by 2010 (Fig. 1). As transmission speeds will be over 100 Mbps, power consumption of transmission amplifiers (PAs) will be increased drastically. This results in significantly higher power and more physical space in the bas station system. Thus, next generation networks including WiMAX will necessitate much higher power efficiency to dramatically reduce the increased power consumption. Switching-mode or envelop tracking PAs are candidates for high-efficiency PAs. In these architectures, transistors will be used at saturation region with high-efficiency (Fig. 2).

GaN-HEMTs have attracted much attention to realize high efficiency with switching-mode and envelop tracking Pas, compared with conventional LDMOS and GaAs [1]. This is because GaN-HEMTs have superior advantages, such as, high breakdown voltage (BVgd), low source-drain capacitance (Cds), and high saturation efficiency.

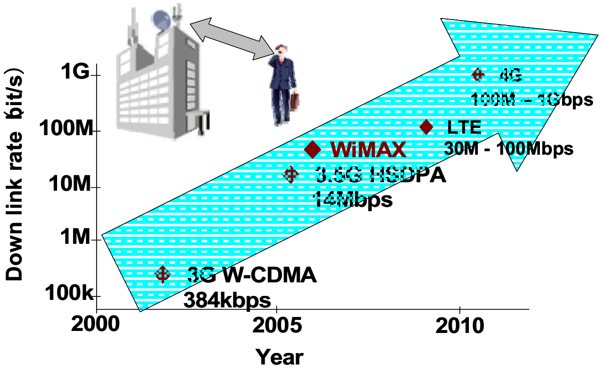


Fig.1 Trend of down link rate for future mobile communication system.

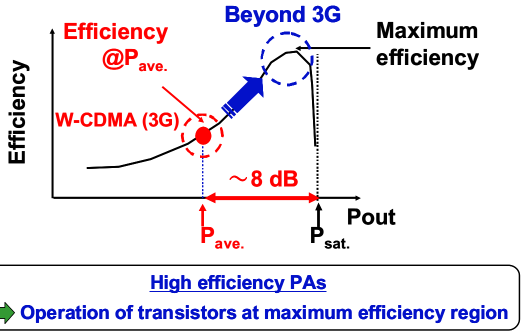


Fig. 2 Trend of the PA development for future mobile communication system.

However, at saturation region, forward gate leakage current increases as input power increases. This is the nature of the Schottky-gate device, creating problems in terms of reliability and amplification characteristics. To suppress the forward gate leakage current, there is a method which employs the insertion of an insulation layer, such as silicon nitride (SiN) or silicon dioxide (SiO_2), directly below the gate.

We have previously developed GaN-insulated-gate (MIS) HEMT which can be operated at 60 V with 110 W [2]. However, trap issues are most important when discussed for verifying high reliability. In this paper, we analyzed trap phenomena of MIS-HEMT, focusing on the effect of both pinched-off state and on-state. We will discuss the effect of maximum current (Imax) shift at the pulsed I-V method when the initial state was on-state with high electric field.

EXPERIMENTAL

Our developed GaN-MIS-HEMT transistor consisted of SiN/n-GaN/n-AlGaN/GaN structure. (Fig. 3) [2]. Using the SiN/n-GaN interface, instead of the SiN/n-AlGaN interface, oxidation of the surface could be prevented. Recessed ohmic technology was used to reduce ohmic contact resistance. Gate length was 0.5 µm. Gate width was 100 µm. As a result, maximum output of 110 W with no forward gate leakage was achieved.

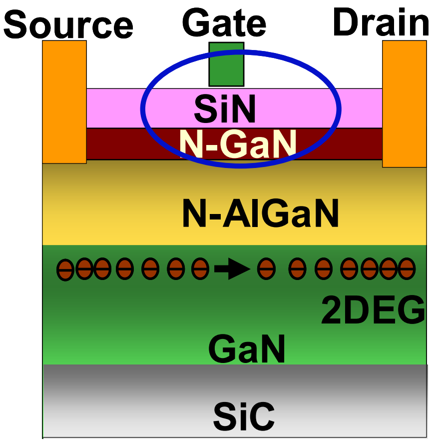


Fig. 3 Investigated GaN-MIS-HEMT structure

Pulsed I-V method was used to measure trap phenomena. Pulse period was 1 ms and pulse duration was 1 µs. The effect of initial state was investigated as shown in Fig. 4. Four different initial bias points, such as (Vg, Vd) of (A) (-10 V, 50 V), (B) (+2V, 50V), (C) (+2 V, 10 V), and (D) (Vg, Vd) of (0 V, 0 V) were compared.

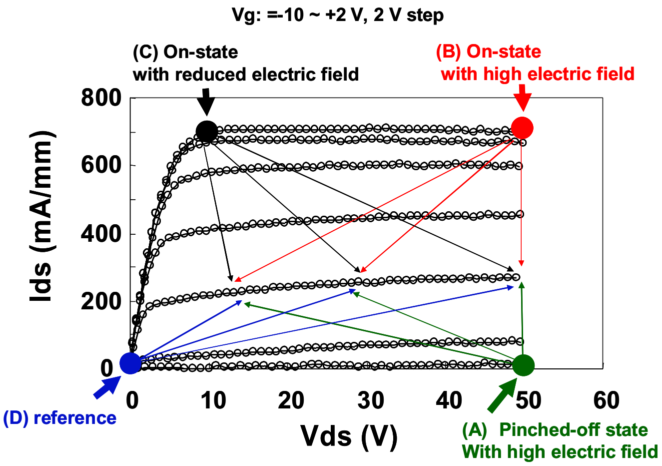


Fig. 4 Summary of the initial bias conditions of pulsed I-V.

RESULTS

In table I, the purpose of this initial state and the results were summarized.

1) Effect of reversed gate bias

Current collapse or increase of Ron is most important phenomena to be studied in the pulsed I-V. To investigate current collapse, most commonly used initial state is the pinched-off state and high electric field, such as initial bias of case (A), (Vg, Vd) of (-10 V, 50 V), in Fig.4. Referenced pulsed I-V was measured from the initial bias of (Vg, Vd) of (0 V, 0 V). We observed no current collapse, i.e., increase of Ron as shown in Fig. 5. Imax was never changed. Important parameters for suppressing current collapse in MIS-HEMT were C-V characteristics of SiN/n-GaN interface.

However, a threshold voltage (Vth) shift toward negative direction was observed (Fig 5). This might be attributed to trapped electron inside of SiN just under the gate electrode (Fig. 6). These electrons might come from the gate electrode. Current collapse such as increasing Ron is generally attributed to the captured electrons at the SiN/AlGaN interface near the gate edge. Thus, no electron might be captured at the interface in this MIS-HEMT (Fig .6).

TABLE I
SUMMARY OF PULSED I-V MEASUREMENTS

	2DEG	Electric field	Initial bias		Current collapse	Imax shift (mA/mm)	Vth shift (V)
			Vg (V)	Vd (V)			
(A)	off	high	-10	50	no	-30	-1
(B)	on	high	+2	50	no	+150 (poor) -50 (good)	+2(poor) 0 (good)
(C)	on	low	+2	10	no	no	no
(D)	Reference		0	0	no	no	no

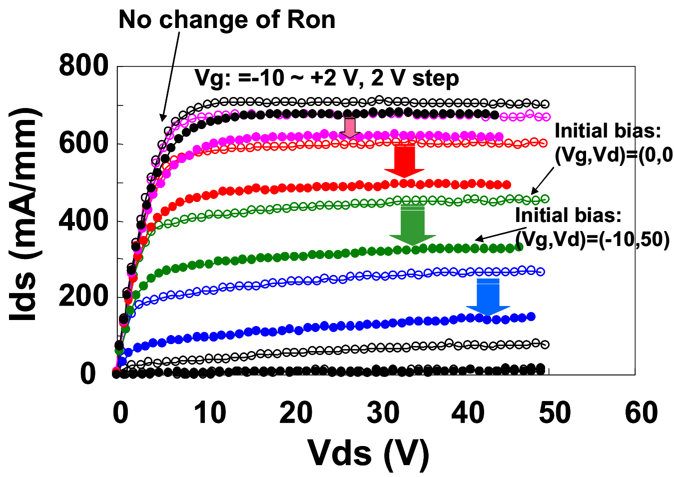


Fig. 5 Pulsed I-V results of GaN-MIS-HEMT for measuring current collapse. Closed-points correspond to the I-V at the conventional initial bias condition, such as (Vg, Vd) of (-10 V, 50 V), case (A) in Fig. 4. Open-points correspond to the I-V at the referenced initial bias condition, such as (Vg, Vd) of (0 V, 0 V), case (D) in Fig. 4.

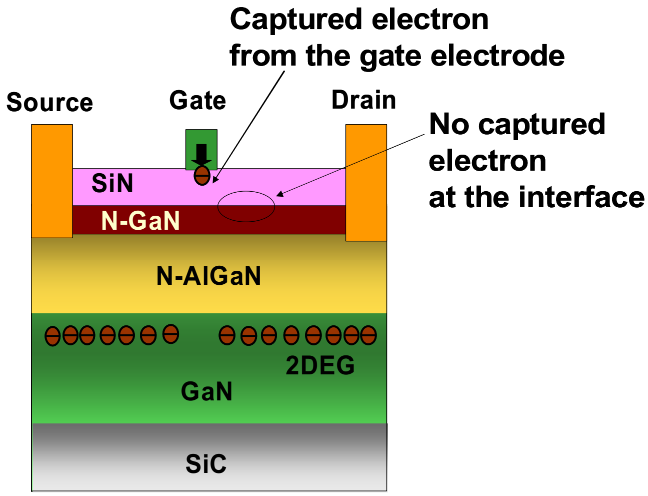


Fig. 6 Schematic cross section of proposed mechanism in Vth shift in Fig 5.

2) Effect of forward gate bias

The purpose of developing MIS-HEMT is to be operated at the forward gate bias region. Thus, we investigated the effect of the on-state in addition to the pinched-off state. First, a high drain voltage of 50 V was applied when a forward gate bias was applied, such as initial bias of case (B), (Vg, Vd) of (+2 V, 50 V), in Fig. 4. This bias region is most important operation area in MIS-HEMT.

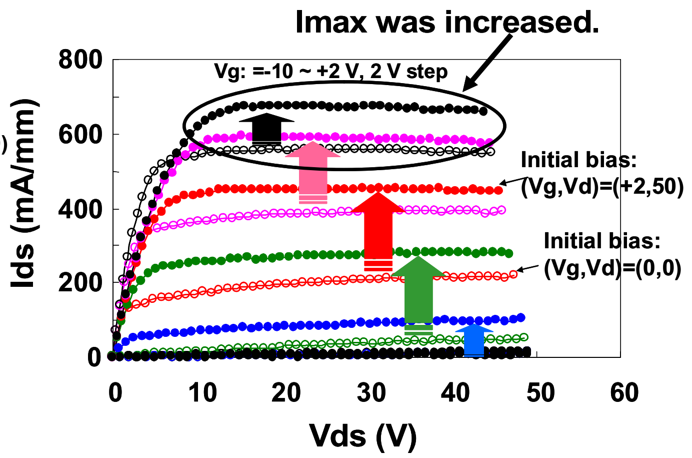


Fig. 7 Pulsed I-V results for GaN-MIS-HEMT. Closed-points corresponds to the I-V at the initial bias condition, such as (Vg, Vd) of (+2 V, 50 V), case (B) in Fig. 4. Open-points correspond to the I-V at the referenced initial bias condition, such as (Vg, Vd) of (0 V, 0 V), case (D) in Fig. 4.Two cases were compared. Significant increase of Imax was observed.

A Vth shift of over 2 V toward positive direction was observed compared with the referenced I-V (Fig. 7). Moreover, significant increase of Imax was also observed. These phenomena were never observed when the Schottky-gate HEMT device was investigated.

Transient characteristics were also investigated. Slow current transient around 1-100 µs was observed when a gate bias was changed from +2 V to -10 V at Vds of 50 V. These shifts lead to low reliability.

3) Effect of electric field in the on-state

To investigate the effect of electric field near the gate electrode when a forward gate bias was applied, we varied the initial drain voltage from 50 V to 10 V. Pulsed I-V of the initial bias of case C, (Vg, Vd) of (+2 V, 10 V), were investigated. No Vth shift was observed in this case. Transient characteristics were also studied when a gate bias was changed from +2 V to -10 V at Vds of 10 V. This transient exhibited also stable. This suggests that low electric field did not cause the increase of Imax, although a forward gate bias was applied. Thus, the combination of the high electric field around insulated layer and the forward gate bias resulted in increasing Imax.

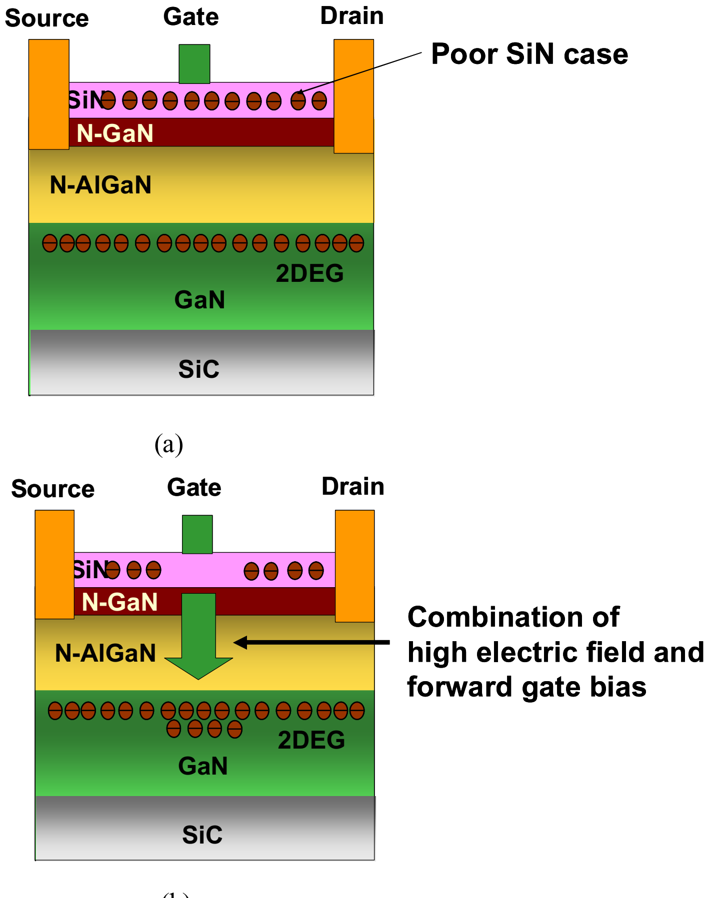
4) Proposed mechanism of the effect of on-state

Compared with Si-LDMOS, high drain voltage is applied to GaN-MIS-HEMT. Thus, novel mechanism to predict the effect of SiN trap is required when positive gate bias is applied.

The proposed mechanism of increasing Imax and positive Vth shift when a forward gate bias was applied with high electric field was illustrated in Fig. 8.

A) When SiN quality is low, electrons might be captured by many trap states in SiN layer even at the zero bias conditions (Fig. 8(a)).

B) When a high drain bias is applied at the forward gate bias conditions, the captured electrons can be emitted by high electric field (Fig. 8(b)). Barrier height of AlGaN layer becomes lower as an increasing forward gate bias. Thus electron emission to two dimensional electron gas occurred easily at the on-state compared with pinch-off state, when high electric field is applied. This results in increasing two dimensional electron gas under the gate electrode. Lower sheet resistance caused increasing Imax and positive Vth shift.



(a)

(b)

Fig. 8 Schematic cross section of proposed mechanism of Imax shift in Fig 7. (a) Initial state when SiN layer quality is poor. (b) High electric field state with a forward gate bias condition.

5) Improvement of MIS-HEMT characteristics

We improved SiN layer quality by optimizing forward C-V performance. When SiN quality was improved, a Vth shift could be suppressed to less than 1 V and Imax was never increased (Fig.9).

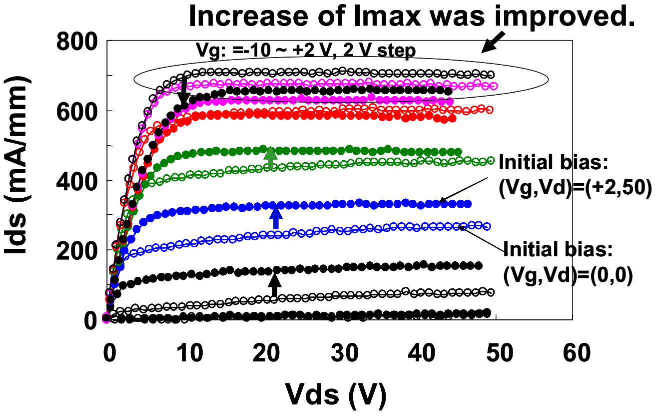


Fig. 9 Improved pulsed I-V results for GaN-MIS-HEMT. SiN quality was improved by optimizing forward C-V characteristics. Closed-points corresponds to the I-V at the initial bias condition, such as (Vg, Vd) of (+2 V, 50 V), case (B) in Fig. 4. Open-points correspond to the I-V at the referenced initial bias condition, such as (Vg, Vd) of (0 V, 0 V), case (D) in Fig. 4.Two cases were compared.

CONCLUSIONS

Trap issues of GaN insulated-gate are investigated using pulsed I-V with varying initial bias points. When a forward gate bias was applied with a high drain voltage, Imax was increased and Vth shift toward positive direction was observed. These phenomena were attributed to SiN layer quality. Thus, we concluded that pulse characteristics from the forward gate bias conditions should be investigated to obtain highly stable operation of GaN-MIS-HEMTs.

ACKNOWLEDGEMENTS

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