

Effects of SiN Passivation and High-Electric Field on AlGaIn–GaIn HFET Degradation

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Abstract—The authors report on the effects of silicon nitride (SiN) surface passivation and high-electric field stress (hot electron stress) on the degradation of undoped AlGaIn–GaIn power HFETs. Stressed devices demonstrated a decrease in the drain current and maximum transconductance and an increase in the parasitic drain series resistance, gate leakage, and subthreshold current. The unpassivated devices showed more significant degradation than SiN passivated devices. Gate lag phenomenon was observed from unpassivated devices and removed by SiN passivation. However, SiN passivated devices also showed gate lag phenomena after high-electric field stress, which suggests possible changes in surface trap profiles occurred during high-electric field stress test.

Index Terms—GaIn, HFET, hot carriers, microwave transistor, passivation, reliability, trapping.

I. INTRODUCTION

AlGaIn–GaIn heterostructure material system has been a strong candidate for high-power, high-frequency, and high-temperature applications due to its superior material properties such as high-breakdown electric field (≤ 3 MV/cm), high-sheet charge density ($\geq 1 \times 10^{13}$ cm $^{-2}$), high-electron velocity (2.8×10^7 cm/s), and thermal stability.

AlGaIn–GaIn HFETs had a problem of a drain current slump during microwave operation at high-drain voltage [1]. It was suggested that the surface states in the gate–drain access region play an important role in this dispersion [2]. Surface passivation has been reported to be one solution to remove the net surface charges and reduce current slump [3]. An optimized device with SiN passivation has demonstrated a continuous wave (CW) of 11.2 W/mm of saturated output power density at 10 GHz [4].

As the power performance of AlGaIn–GaIn HFETs is getting mature reliability becomes a major concern to realize the potential of these devices. Several studies on the device reliability have reported the degradation of these devices under dc and RF stress [5], [6]. Typical degradation characteristics of these devices consist of a reduction in drain current, maximum transconductance, and microwave output power. Hot electron-induced degradation similar to AlGaAs–GaAs HEMTs has been observed, possibly from an induced depletion of the 2DEG from the electron trapping between the gate and drain, resulting in a degradation in performance [7]. However, no clear evidence of electron trapping has been reported as a cause of observed degradation in AlGaIn–GaIn HFETs.

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In this work, we present the effects of SiN passivation and hot electron stress on reliability and gate lag phenomena of undoped AlGaIn–GaIn HFETs. While SiN passivation improved the device reliability and power performance, hot electron stress has exacerbated the current slump which had been alleviated by SiN passivation. Gate lag measurements on the stressed devices with SiN passivation revealed pronounced effects of charge trappings induced by high-electric field stress.

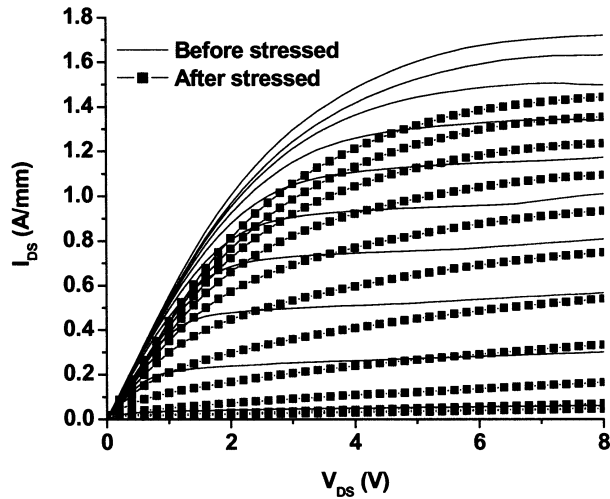
II. DEVICE FABRICATION

Undoped AlGaIn–GaIn heterostructures were grown by OMVPE on 2" undoped SiC substrates. They have an AlGaIn nucleation layer (~ 200 Å), followed by AlN subbuffer, an unintentionally doped GaIn buffer (~ 1 μm), and finally an unintentionally doped AlGaIn top barrier layer (~ 250 Å). The Al mole fraction determined by X-ray diffraction was nominally 35%. Device isolation was done by a mesa etch with a Cl $_2$ -based ECR plasma. Source and drain ohmic contacts were obtained by evaporating Ti–Al–Ti–Au (20 nm/100 nm/45 nm/55 nm) and with annealing at 800 °C in N $_2$ for 30–60 s. The ohmic contact resistance and sheet resistance measured from TLM patterns ranged from 0.3–0.5 Ωmm and 400–450 Ω/□, respectively. The mushroom gates were defined by e-beam lithography with a three-layer resist process. Ni–Au (25 nm/375 nm) metals were used to form Schottky contacts. After the contact pads were made by evaporation of Ti–Au (20 nm/360 nm), SiN film (~ 18 nm) was deposited as a passivation layer using PECVD at 300 °C. In this work, we tested 1×0.3 μm $\times$ 100 μm and 1×0.3 μm $\times$ 200 μm devices.

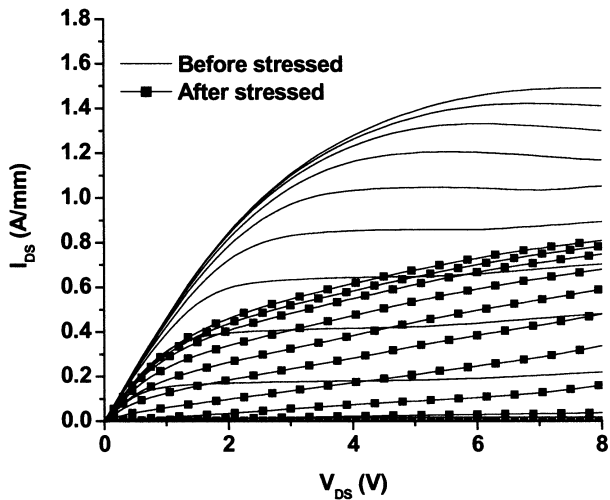
III. RESULTS

A. SiN Passivation

Both SiN passivated and unpassivated devices were subjected to high-electric field stress testing for 12 h. The stress bias condition was $V_{DS} = 20$ V and $V_{GS} = -8$ V. This condition pinches off the device channel, assigning a high-electric field between gate and drain, and a self-heating effect on the degradation can be neglected. Output characteristics of stressed devices are shown in Fig. 1, clearly showing that unpassivated device was severely degraded (-37% in I_{MAX}) compared with passivated one (-16% in I_{MAX}), indicating an improved hot electron reliability after SiN passivation. It suggests SiN passivation layer can alleviate hot electron-induced degradation by reducing the density of surface states available for electron trapping. It agrees with the fact that the density of the trap was decreased after the passivation [8]. An increase in the



(a)

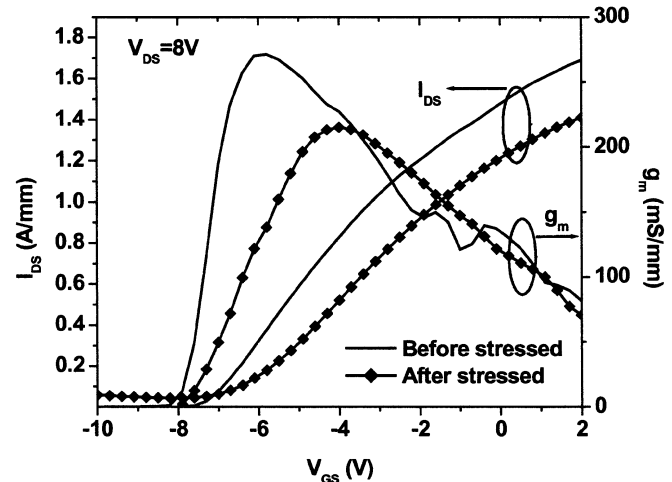


(b)

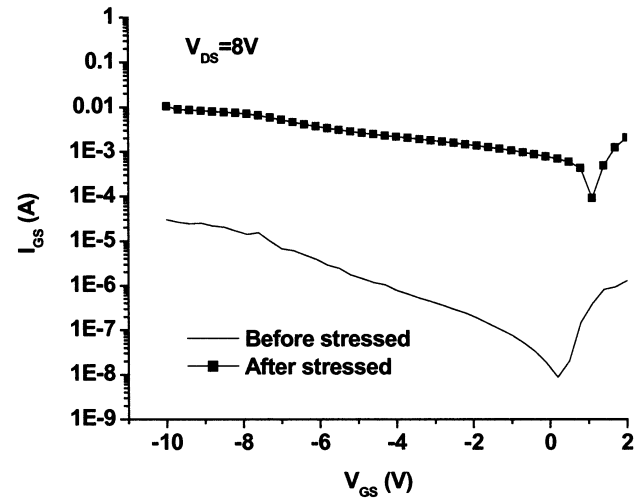
Fig. 1. Output characteristics of AlGaIn-GaN HFETs before (solid line) and after (marked line) hot electron stress. $V_{GS} = +2$ V from the top, -1 V/step. Device was stressed at $V_{DS} = 20$ V and $V_{GS} = -8$ V for 12 h.

maximum current is always observed after SiN passivation due to reduction in the net surface charge. Drain and source series resistance were extracted from S-parameter measurement before and after the stress test. After the stress, the drain series resistance of the passivated device increased from 1.05 to 1.3 Ω mm, while the source series resistance changed negligibly. It indicates that electron trapping induced by high-electric field between gate and drain extended surface depletion and increased resistance. Fig. 2 shows a decrease of maximum transconductance, an increase of gate leakage currents, and the pinchoff degradation, i.e., an increase of subthreshold current of the passivated device after stress. It is likely that these changes are caused by the modification of charge profiles underneath the gate contact and the degradation of Schottky contact on AlGaIn barrier layer. These changes have been also observed from unpassivated devices.

SiN passivation and UV laser illumination have been performed on unpassivated devices after high-electric field stress test and the degradation was not recovered. SiN-passivated de-



(a)



(b)

Fig. 2. (a) Transfer characteristics and (b) gate leakage current of SiN passivated device at $V_{DS} = 8$ V before (solid line) and after (marked line) hot electron stress at $V_{DS} = 20$ V and $V_{GS} = -8$ V for 12 h.

vices also did not show any recovery from the degradation after UV laser illumination.

B. Gate Lag Measurements

Gate lag (or gate transients) occurs when the gate is pulsed with a large voltage step. It is generally known that gate lag measurements are more sensitive to surface effects [9], [10].

Gate lag measurements were performed on our AlGaIn-GaN HFETs with SiN passivation before and after the high-electric field stress testing in order to investigate the effects of surface states on the device degradation. For gate lag measurements, a 100 ns pulse was applied to the gate with low duty cycle ($10^{-4}\%$) to eliminate self-heating effects. During the measurement, the drain bias was swept from 0 to 20 V in 30 steps and the gate electrode was pulsed for each measurement from its quiescent value at pinchoff condition, typically -7 V, toward $+1$ V in 1-V steps to obtain pulsed IV curves. Unpassivated AlGaIn-GaN HFETs showed strong dispersion between pulsed and static IV characteristics which is usually dominated by sur-

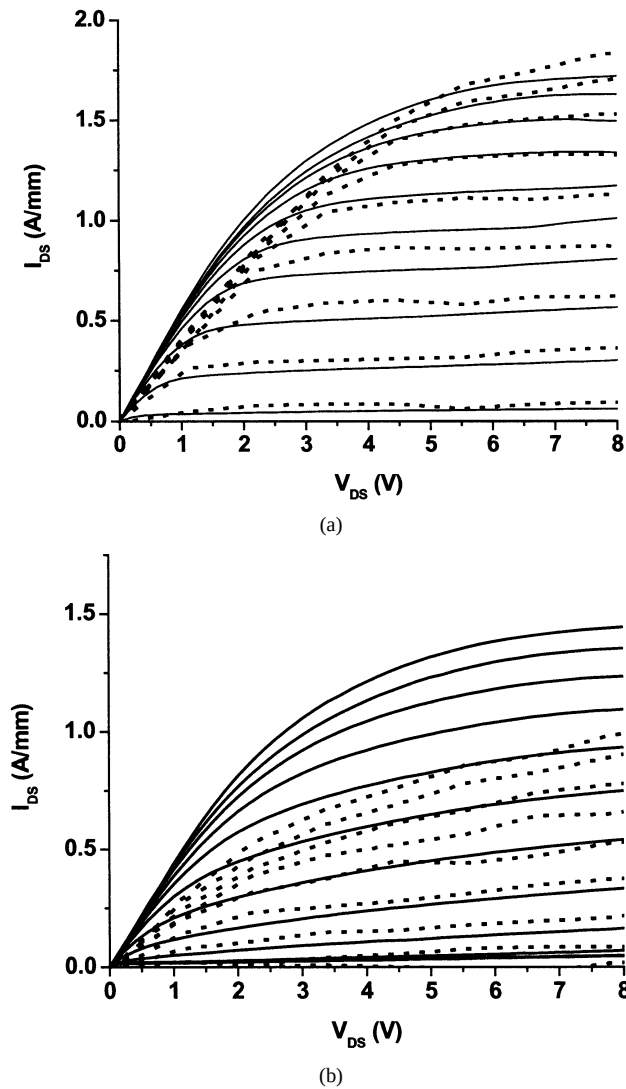


Fig. 3. Static (solid line, $V_{GS} = +2$ V from the top, -1 V/step) and pulsed (dotted line, $V_{GS} = +1$ V from the top, -1 V/step) IV characteristics (a) before and (b) after hot electron stress. Note that the output current is reduced and the dispersion is aggravated after hot electron stress.

face states that act as electron traps located in the gate–drain access region [11].

Fig. 3(a) shows that this dispersion was eliminated after depositing SiN passivation layer, which is believed to reduce the surface charges. Larger output current was observed from pulsed IV measurements because self-heating was diminished. Accordingly, the saturated output power density measured at $V_{DS} = 15$ V at 10 GHz was increased from 1.7 to 3.7 W/mm. This device was stressed at $V_{DS} = 20$ V and $V_{GS} = -8$ V for 12 h and the degradation of drain current was observed. Pulsed IV was measured on the stressed device and showed aggravated dispersion, as shown in Fig. 3(b). This post-stress gate lag can be attributed to a possible increase in the density of electron traps in the ungated region between gate and drain since surface passivation with SiN removed the dispersion before stress test. It has been suggested that traps can be created by hot electron bombardment at semiconductor interfaces [12].

IV. CONCLUSION

This letter shows SiN passivation can improve the reliability of AlGaIn–GaN HFETs under hot electron stress as well as device output characteristics since electron trapping to surface states can be mitigated by SiN passivation. It agrees with the fact that gate lag response also improved after SiN deposition. However, gate lag response of SiN passivated device was significantly degraded after hot electron stress. During high-electric field stress, hot electrons generated by high-electric field between gate and drain can gain enough energy to escape from 2DEG channel and tunnel into neighboring interface states or even create the traps at AlGaIn–GaN or SiN–AlGaIn interfaces. The trapped charges can deplete the channel and reduce the output current of the devices with or without SiN passivation. The hot electron-induced traps can enhance the trapping effects and cause the dispersion between pulsed and static IV curves of SiN passivated devices. Microwave power performance, which once improved after SiN passivation, will suffer from the dispersion induced by hot electron-induced traps. Further investigation is underway to understand the nature of the traps induced by hot electron stress.

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