Correlation between Electroluminescence and Current Collapse in AlGaN/GaN HEMTs

S. Ohi, Y. Sakaida, J. T. Asubar, H. Tokuda, and M. Kuzuhara

Graduate School of Engineering, University of Fukui, 3-9-1 Bunkyo, Fukui 910-8507, Japan
Phone: +81-776-9714 E-mail: ooishinntarou@gmail.com, kuzuhara@fuee.u-fukui.ac.jp

Keywords: AlGaN/GaN, HEMT, Current Collapse, Electroluminescence, O_2 plasma

Abstract

This paper describes experimental results on the correlation between current collapse and electroluminescence observed under high drain bias conditions in AlGaN/GaN HEMTs with high breakdown voltages over 1000 V. The electroluminescence characteristics were categorized into 2 groups: one from the drain edge with a strong white-appearance emission and the other from the whole gate-to-drain area with a weak red-appearance emission. When the luminescence results were compared with the measured current collapse, it was found that the weak red-appearance emission was only observed from the device with reduced current collapse, while the strong white-appearance emission appeared for the device showing strong current collapse. Since clear band edge emission was not detected in the emission spectra, luminescence was likely due to intraband electron transition in the conduction band. A series of analyses of luminescence characteristics from different AlGaN/GaN HEMTs strongly suggest that the current collapse is indeed dominated by the surface trapping effects that arise in relation to the potential profile between gate and drain.

INTRODUCTION

AlGaN/GaN HEMTs are one of the most promising candidates for realizing ultra low-loss power switching devices [1, 2]. However, the performance of these devices is still limited by current collapse. In our previous study [3], we have found that O_2 plasma treatment for the surface of AlGaN prior to SiN passivation resulted in reduced current collapse. Meanwhile, there have been reports that AlGaN/GaN HEMTs emit luminescence signal when operated at high drain bias voltages [4-6]. Meneghini et al. observed luminescence at the drain edge from unpassivated GaN-based Gate Injection Transistors [4], whereas Tang et al. reported luminescence at the gate edge of the drain side in AlN-passivated AlGaN/GaN HEMTs [5]. Wakejima et al. observed a shift of luminescence location during continuous drain biasing [6].

In this paper, we present a clear correlation between electroluminescence and current collapse in AlGaN/GaN HEMTs subjected to O_2 plasma treatment prior to SiN passivation. The mechanism of the luminescence will be discussed in relation to the potential distribution between gate and drain under high drain biasing conditions.

EXPERIMENTS

Figure 1 shows the cross-sectional schematic illustration of AlGaN/GaN HEMTs fabricated on a 4H-SiC substrate used in this study. The epitaxial structure consists of a 500 nm GaN channel layer and a 25 nm $Al_{0.2}Ga_{0.8}N$ barrier layer. For ohmic and gate electrodes, we used Ti/Al/Mo/Au (15/60/35/50nm) and Ni/Au (50/150 nm) stacks, respectively. Prior to surface passivation by SiN or SiO_2, the AlGaN surface was subjected to O_2 plasma treatment (100 W, 1 min). As references, we also fabricated devices without O_2 plasma treatment, i.e., reference A with SiN passivation and reference B with SiO_2 passivation. To investigate the effect of GaN cap layer, we have also prepared a reference device with an undoped 2 nm-thick GaN cap layer (reference C). All devices were with a gate length of 3 μm and the gate-to-drain spacing (L_{gd}) was chosen to be 25 μm.

For evaluation of current collapse, we have measured the dynamic on-resistance (R_{on}) by applying a gate pulse with a load resistance connected in series with the device. Detailed description on the evaluation scheme of current collapse is found in [7].

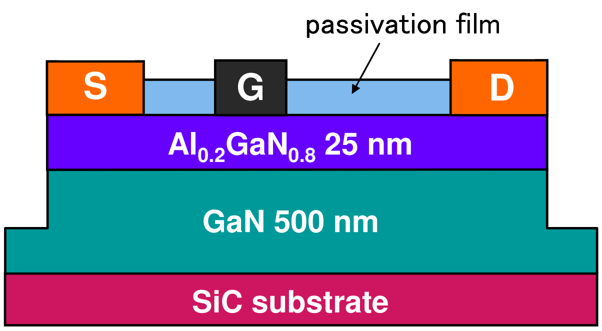

Fig.1 Cross-section of fabricated AlGaN/GaN HEMT.

RESULTS AND DISCUSSION

Table I summarizes measured DC characteristics of the fabricated HEMT devices. The static on-resistance was estimated at a gate voltage (V_{gs}) of +1 V. The maximum drain current (I_{d_max}) was measured at V_{gs}= +1 V. The

13

breakdown voltage (V_{br}) was defined by the drain-to-source voltage (V_{ds}) when the drain current increased to 1 mA/mm while keeping V_{gs} under pinched-off conditions. Except the device with a GaN cap (reference C), which has a little higher R_{on} and smaller I_{d_max}, essentially the same DC characteristics were obtained, including a very high V_{br} of over 1700 V.

Table I Summary of DC characteristics.

Device	Passivation	GaN cap	R_{on} (Ω mm)	I_{dmax} (A/mm)	V_{br} (V)
Reference A	SiN	no	15	0.49	1700
Reference B	SiO_2	no	15	0.49	1800
Reference C	SiN	yes	14	0.43	1700
O_2 plasma treated	SiN	no	16	0.50	1800

Electroluminescence (EL) from the device surface was measured by increasing the drain bias while keeping the gate voltage so that the device was under pinched-off conditions. Spatial luminescence profiles were measured by taking pictures using an optical microscope combined with a full-frame 35 mm CMOS sensor camera. Emission spectra were monitored by photonic multichannel analyzer (PMA-12, Hamamatsu Photonics K.K.). The measured EL intensity was corrected by the spectral response calibration function.

Figure 2 shows typical emission profiles of the pinched-off HEMT without O_2 plasma treatment (reference A). When the applied V_{ds} exceeds 1000 V, the device started to show white-appearance emission at the drain contact edge and its intensity grows rapidly by further increasing V_{ds}, and finally the device was burned out at around V_{ds} = 1700 V. Almost the same emission trend was observed for the reference device with SiO_2 passivation (reference B). Meanwhile, more uniform red-appearance emission was

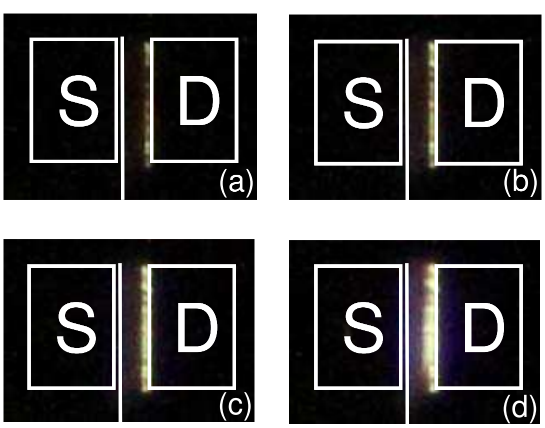

Fig. 2 Electroluminescence profile of the device without O_2 plasma treatment (reference A). (a) V_{ds} = 1000 V, (b) V_{ds} = 1100 V, (c) V_{ds} = 1200 V, and (d) V_{ds} = 1400 V.

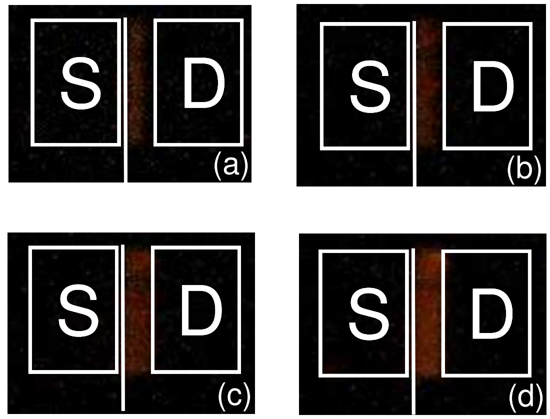

Fig. 3 Electroluminescence profile of the device with O_2 plasma treatment. (a) V_{ds} =800 V, (b) V_{ds} = 1200 V, (c) V_{ds} = 1400 V, and V_{ds} = 1600 V.

observed for the device with O_2 plasma treatment, as shown in Fig. 3. Even under a very high drain bias of 1600 V (near catastrophic breakdown at 1800 V), the device appeared to show only red-appearance emission in the whole area between gate and drain. Similar red-appearance emission was also observed for the device with a GaN cap layer (reference C).

Figure 4 shows the measured EL intensity as a function of photon wavelength. A broad emission spectrum, that covers all visible wavelength range of 380 to 750 nm, was obtained for the device without O_2 plasma treatment (reference A), while only a long-wavelength emission over 600 nm was observed for the device with O_2 plasma treatment. Note that no luminescence peak at 3.4 eV was detected for both devices with and without O_2 plasma treatment, indicating that EL is not dominated by band-to-band emission and is more likely to be due to the intraband transition of accelerated electrons in the conduction band [8-10].

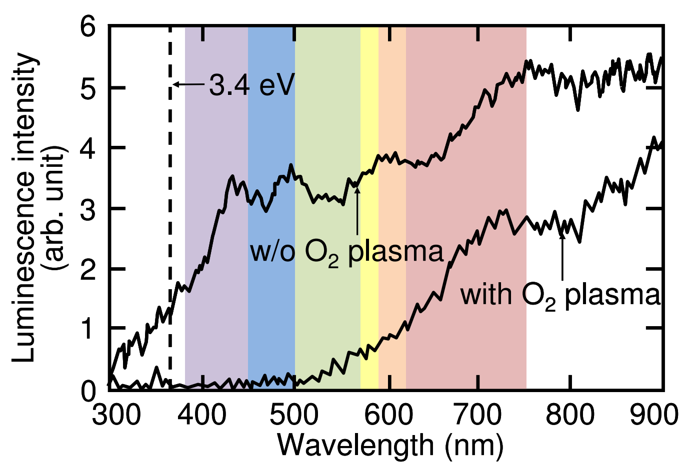

Fig. 4 Measured EL intensity as a function of photon wavelength. Visible spectrum range from 380 to 750 nm is covered for device without O_2 plasma treatment.

Table II summarizes the measurement results of EL and dynamic R_{on}. The dynamic R_{on} was estimated with a pulse on-time of 1 μs, a pulse duty cycle of 10^{-4}, an off-state V_{gs} of -5 V, an on-state V_{gs} of +1 V, and an off-state V_{ds} of 100 V. From Table II, a clear correspondence is observed between EL and dynamic R_{on}, where the device with white-appearance emission at the drain contact edge exhibited a large dynamic R_{on} (i.e., significant collapse) while that with red-appearance emission between gate and drain showed reduced current collapse with a smaller dynamic R_{on} by a factor of more than 5.

Table II Summary of EL measurements results under high drain bias voltages and results of dynamic on-resistance for 4-types of AlGaN/GaN HEMTs.

Device	Passivation	GaN cap	Emission	Location	Dynamic R_{on} (Ωmm)
Reference A	SiN	no	white	drain edge	$1x10^4$
Reference B	SiO_2	no	white	drain edge	$1x10^4$
Reference C	SiN	yes	red	gate-to-drain	$2x10^3$
O_2 plasma treated	SiN	no	red	gate-to-drain	$5x10^2$

According to the model by Vetury et al. [11], current collapse is induced by electron trapping near the gate edge on the AlGaN surface. When electron trapping is enhanced by a high density of trap states, the semiconductor surface would be more negatively charged, leading to the reduced electric field strength near the gate edge. However, this in turn promotes the high field region to move toward the drain direction, and finally resulting in an extremely high field region generated near the drain contact, as shown in Figs. 5 (a), (b), and (c). The very high electric field near the drain contact would generate a higher effective hot electron temperature, widening the spectrum as reported by many authors [9,10,12]. Such hot electron energy distribution is likely to induce white-appearance emission by intraband electron transition only near the drain edge. On the other hand, when the trap density is decreased by some appropriate process treatments, such as O_2 plasma exposure, electron trapping on the semiconductor surface would not be dominant, hence creating rather flat field distribution with much reduced maximum electric field strength between gate and drain, as shown in Figs. 5 (d), (e), and (f). Since the maximum electric field is much smaller in the latter case, electrons would not be accelerated to a higher energy. Hence, with O_2 plasma treatment, rather lower effective hot electron temperature would only induce uniform red-appearance emission in the whole gate-to-drain region.

Similar red-appearance luminescence was observed uniformly between gate and drain for the device with a GaN cap layer, indicating that the surface trap density in GaN was much reduced so that rather flat field distribution was created between gate and drain. However, the value of dynamic R_{on} for the device with a GaN cap is much larger than that for the AlGaN/GaN device with O_2 plasma treatment. This suggests that O_2 plasma treatment is a more favorable method to reduce current collapse than that using a GaN cap layer.

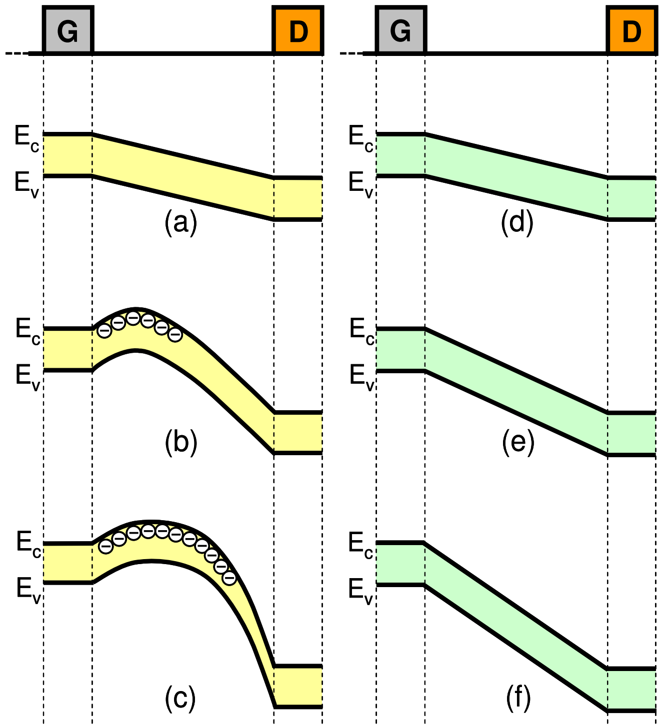

Fig. 5 Schematic drawings of potential distribution between gate and drain for devices under drain bias from low to high values: device with high density of surface trap states (a), (b), and (c), and device with low density of trap states (d), (e), and (f).

CONCLUSIONS

Close correlation was observed between electroluminescence and the degree of current collapse in AlGaN/GaN HEMTs. Excellent current collapse with low dynamic R_{on} was confirmed for a device with O_2 plasma treatment and that with a GaN cap layer. Both devices showed uniform red-appearance emission reflecting the flat field distribution between gate and drain. Meanwhile the device without O_2 plasma treatment or without a GaN cap layer exhibited strong white-appearance luminescence at the drain contact edge, suggesting the formation of high electric field region close to the drain contact. It was found that the electroluminescence analysis is a powerful tool to study current collapse as well as to predict potential and field distribution between gate and drain.

13

ACKNOWLEDGEMENTS

This work was partially supported by a Grant-in-Aid for Scientific Research (C) (No. 25420328) from JSPS and by a Super Cluster Program from JST.

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ACRONYMS

HEMT: High-electron-mobility transistor
R_{on}: On-resistance
L_{gd}: Gate-to-drain spacing
I_{d_max}: Maximum drain current
V_{br}: Breakdown voltage
V_{ds}: Drain-to-source voltage
V_{gs}: Gate-to-source voltage
EL: Electroluminescence