Study of passivation defects by electroluminescence in AlGaN/GaN HEMTS on SiC

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Received 17 July 2007
Available online 4 September 2007

Abstract

This paper presents a new method of passivation control by electroluminescence (EL) in 0.15 μm AlGaN/GaN HEMT. The electroluminescence signature in one finger HEMTs (W = 1 × 100 μm), and eight fingers ones (W = 8 × 125 μm), is modified by defects located at the passivation/semiconductor interface and is characterized by a light emission along the drain contact. This abnormal emission reveals some modification of the electric field distribution in the gate-drain space probably induced by traps located at the passivation/semiconductor interface. These traps contribute to the creation of a virtual gate in the gate-drain space.

1. Introduction

AlGaN/GaN high-electron-mobility transistors (HEMTs) have received much attention for their ability to operate at high-power levels. They are very useful components for the development of base stations in the telecommunications networks and for civil, military and space radar applications. There are several economic and technological stakes, which require the development of suitable techniques for failure analysis on GaN based HEMTs. The failure analysis techniques implemented for GaAs components are not directly transposable to the GaN components because of the different bandgaps of the two semiconductor materials.

These materials require the development of new methodology for physical analysis, such as specific polishing techniques and FIB cross-section preparation, new chemical decoration and delayering techniques.

When the component presents a passivation-related problem, traps located at the semiconductor surface contribute to the creation of a virtual gate, which modifies the distribution of the electric field in the structure. This causes a reduction in the off-state breakdown voltage BV off [1], and maximum output power, Pmax.

This study has assessed the capability of the electroluminescence (EL) detection to identify the devices presenting passivation defects located by observation of transverse cross-sections in the drain-source space.

2. Technology description and electro-optical signatures

The study was carried out by performing emission microscopy measurements on PHEMOS equipment with a CCD camera cooled to −40 °C, on two types of 0.15 μm AlGaN/GaN enhanced barrier-HEMT on SiC substrate of the same technology, with respectively one finger (W = 1 × 100 μm) and eight fingers (W = 8 × 125 μm).
The Ni/Au gate is passivated by SiON/SiN and located closer to the source than to the drain. The ohmic contacts are composed of a Ti/Al/Au/Ni stack with a Ti/Pt/Au thickening.

The emission microscopy analysis is not destructive and allows to locate defects in active components (integrated circuits, MMIC, transistors and diodes). This technique is applicable to Si, compound semiconductors and high bandgap devices [2,4]. It uses photon emission due to recombination of electron-hole pairs induced by current flows, leakage current or tunnel effect in the components.

For GaN HEMTs without surface passivation, Ohno et al. [3] has observed that the EL signature is located at the drain edge, suggesting that the high-field region was formed at the drain edge in the gate-drain space. This is in contrast to standard passivated III–V HEMTs where a high-field region is formed at the gate edge in the gate-drain space and then, the EL signature localised at the gate edge [3,4].

As stated by Ohno, this difference can be explained by a virtual gate, formed between the gate and drain electrodes by electrons injected from the gate to surface states. As the high electric field was formed at the drain edge for GaN HEMTs without surface passivation, a large potential drop occurs at the drain edge [3]. On the contrary, for devices with SiN passivation, electron trapping by surface states is reduced, and the high electric field at the drain edge is relaxed. So, the potential drop occurs at the gate edge in the gate-drain space.

For GaN HEMTs which may suffer from hot electron induced defects, gate leakage current cannot be used as an indicator of hot electron generation as for GaAs HEMTs. Indeed, many parasitic effects contribute to the gate leakage current, such as thermo-ionic trap-assisted tunnelling effect and leakage through surface conductive paths between gate and drain at the surface. To overcome this problem, we use electroluminescence measurements as an alternative method to evaluate hot-carrier effects and their dependence on bias conditions [5].

3. Experiments

3.1. One-finger components

The mono-finger transistor presents a strong EL intensity along the drain contact (Fig. 1a and b), for open channel bias conditions: $V_{GS} = 0$ V and $-1$ V with $V_{DS} = 10$ V. It is similar to the EL signature observed by Ohno et al. [3] in unpassivated GaN HEMTs. For bias conditions close to the pinch-off, at $V_{GS} = -5$ V and $V_{DS} = 10$ V, the EL is localised along the gate in the drain-gate space (Fig. 1c) with a lower intensity than the one observed along the drain contact in open channel bias conditions.

As under pinch-off bias conditions, the EL signature is located along the gate as expected, the location of the emission area along the drain contact in open channel bias conditions reveals surface related defects in the gate-drain space.

The enhancement of the high electric field at the drain edge can be explained by considering the possibility of a virtual gate formation [6,7]. The schematic drawing of the charge distribution and potential profile between the gate and drain electrodes is shown in Fig. 2. The general trend is that the virtual gate becomes reverse biased while the gate is biased toward pinch-off and the drain bias increased.

On the other hand, in the device with correct surface passivation, the EL region is observed along the gate edge in the gate-drain space.
For devices with efficient surface passivation, electron trapping by surface states is reduced, which is expected to relax the electric field in the gate-drain space. Then, a potential drop occurred at the gate edge, and moderate field strength was formed as shown in Fig. 2b.

Therefore, it is assumed that the emission irregularity (Fig. 1a and b) along the gate finger drain side is due to a non uniform distribution of the electric field caused by the surface defects located at the passivation-semiconductor interface. The SEM observation of FIB (Focus ion beam) cross-section, performed on the mono-finger transistor (Fig. 3) shows the delamination of the passivation layer in the gate-drain space. The cross-section was carried out by FIB to avoid the creation of artifacts compared to cross-section polishing, which induces mechanical stress and may increase delamination at the passivation-semiconductor interface.

3.2. Eight finger devices

In eight-finger transistors and for bias conditions close to the pinch-off, at $V_{GS} = -5.6$ V and $V_{DS} = 10$ V, the light emission is localized along the gate in the gate-drain space (Fig. 4), whereas in on state bias conditions ($V_{GS}$ close to 0 V), two types of EL signature are observed. An EL signature is detected along the gate as well as an abnormal emission along the drain ohmic contact (Fig. 5a and b).

The intensity of the two types of emission increases with $V_{DS}$, which confirms that the double electroluminescence signature is not a measurement artifact. Let us note that the colour scale is roughly multiplied by 20 in the case of open channel conditions while $V_{DS}$ increases from 13.6 V to 16 V.

It is noticeable that a double electroluminescence signature has never been observed on AlGaN/GaN HEMT.

Indeed, for open channel bias conditions, the expected EL signature along the gate in the gate-drain space is observed in eight fingers HEMT whereas, it is not detectable in one finger ones. This can be explained by:

- A higher number of carriers in the channel in eight fingers HEMTs. Indeed, the gate development is multiplied by 10 in comparison with one finger devices. This enhances electronhole recombination probably close to the gate and trap filling in the gate-drain space. Thus, the EL intensity is expected to increase.

- The decrease of the bandgap energy while the temperature increases [9,10]. As experimentally observed by Shigekawa et al. [8], the channel temperature increases more steeply with the dissipated power density in wide devices. Consequently, it is obvious that the channel temperature is higher in eight fingers HEMTs than in one finger ones. Therefore, the reduction of the bandgap energy and the resulting shift of the associated wavelength may facilitate the detection of emitted photons with the PHEMOS75 camera which wavelength ranges between 400 nm and 1000 nm.

In addition, the EL intensity along the drain ohmic contact is lower than along the gate. It can be explained by the electron mobility decrease with the temperature increase in
Therefore, due to a lower energy, less electrons will be injected into the traps located at the SC-passivation interface and in the passivation layer.

Let us note that the EL signature of eight fingers HEMT along the drain ohmic contact is only observed for open channel bias conditions and not at pinch-off. Therefore, the abnormal EL signature observed along the drain contact could be explained by a degradation located at the SC-passivation interface. The surface origin of the defect is confirmed as well as for the one finger devices.

The SEM observation of FIB (Focus ion beam) cross-section, performed on one eight fingers transistor (Fig. 6) shows the delamination of the passivation layer in the drain-source space.

4. Conclusion

In this work, the electroluminescence signature has been studied in one finger and eight fingers AlGaN/GaN HEMTs. A correlation between the electroluminescence signatures with passivation defects has been established in these devices.

In one finger HEMTs, the expected electroluminescence signature located along the gate in the gate-drain space has been observed under pinch off bias conditions whereas for open channel bias conditions, the light emission appears along the drain ohmic contact. This latter signature has been correlated to a delamination located at the passivation/semiconductor interface; it also reveals some modification of the electric field distribution in the gate-drain space which is probably induced by traps located at the interface. These traps contribute to the creation of a virtual gate in the gate-drain space.

Let us note that as well in one finger as in eight finger HEMTs, the passivation defects have been correlated with the electroluminescence signature along the drain contact whereas the one along the gate edge in the gate-drain space mainly changes with the bias conditions.

These results will be interesting to identify the devices presenting potential unreliable passivation at the stage of front-end manufacturing.

References