Charge Trapping at Surface in GaN HEMTs

Hsiang Chen, Phillip Preecha, John Lai, Guann-Pyng Li

Dept. of Electrical Engineering, Univ. of California, Irvine, Irvine, CA 92697,
Phone: 1-949-824-2047 Fax:1-949-8242047 E-mail: hchen5@uci.edu

Keywords: GaN HEMT, electroluminescence, off-state breakdown, hole trapping, threshold voltage

Abstract

Electron trapping after on-state stress and hole trapping after off-state breakdown stress has been observed by comparing the EL images and electrical characteristics in GaN HEMTs. Temperature measurement and 2D device simulation has been done to confirm the hole trapping phenomenon. With off-state breakdown stress, three devices all showed the same trend of electrical characteristics changes – a decrease of the threshold voltage and an increase of the gate leakage current. The changes of electrical characteristics were similar in different devices, but the changes in EL images varied. The technique promises a potential characterization tool for device and material screening.

INTRODUCTION

Recent advancement in AlGaN/GaN HEMTs has promised its potential in high power and high frequency applications. However, the surface charge trapping and material defects could degrade its device long term reliability. Electro-luminescence (EL) from HEMTs operating at normal saturation mode has been used to study surface traps of GaN HEMTs, showing hot carrier effects on surface passivation [1]. In this paper, we will investigate the effects of hot electrons (device biased at on-state saturation mode) and of hot holes (biased at off-state near breakdown condition) on device stability. By comparing changes in electro-luminescence (EL) images and electrical characteristics of device before and after being stressed at on-state or off-state conditions, trapping of electrons [2] and holes [3] was observed to occur at random locations along gate width.

DEVICE FABRICATION

The AlGaN/GaN heterostructure was grown by metal organic chemical vapor deposition (MOCVD) on a SiC substrate. The device structure consists of a 0.1µm AlN nucleation layer, a 1µm thick GaN buffer layer, and an undoped 250Å $Al_{0.28}Ga_{0.72}N$ barrier layer. Two gate fingers with Pt/Au metal stack with a gate length of 0.2µm were patterned by the electron beam lithography and followed by the PECVD nitride passivation. The gate-source

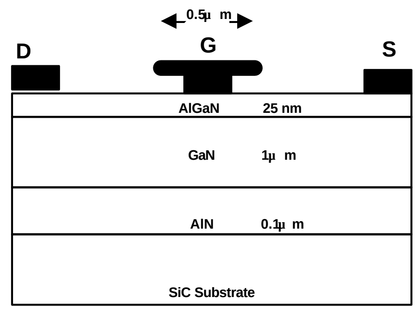


Figure 1 Schematic cross section of the GaN HEMT. Figure not to scale.

and gate-drain spacing were 1µm for each gate. The gate width of Device 1, 2, and 3 is 100µm. Schematic cross section of the GaN HEMT is shown in Fig 1. The threshold voltage was about -5V. The maximum transconductance were 250 ms/mm and the maximum drain current was greater than 1 mA/mm. The gate width of the device is 100µm. The width of T-gate wing is 0.5µm. The EL emission region is very close to the gate and between the gate and the drain so part of emission light may be covered by the gate wing.

MEASRUING SYSTEM SETUP

To investigate EL emission from HEMTs, we used a hyperspectrum imaging system [4], consisting of a microscope probe station with a high resolution liquid N2 cooled CCD camera , and an Acousto-optic Tunable Filter (AOTF) as a band pass filter with FWHM from 6nm to 10nm (varied with wavelength) can be incorporated into this

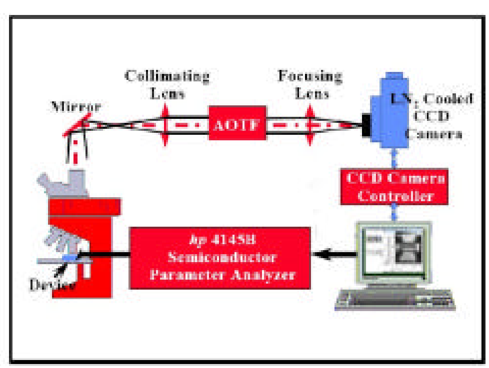
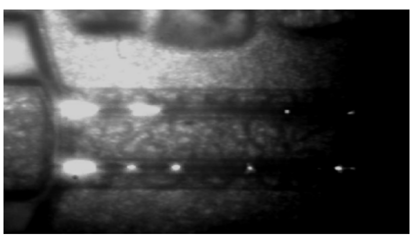


Figure 2 Electroluminescence imaging system.

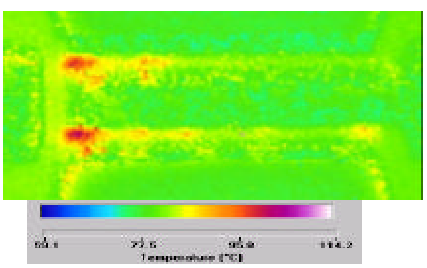
system to measure the EL image at specific wavelength ranging from 500 nm to 1000 nm. The spectral profile of the EL emission measured by the system is one peak profile with the peak wavelength around 800 nm as a signature of hot carrier induced intravalley transition [5]. We also measured the temperature distribution on the surface of the device with an IR imager. The IR imager is similar to EL measuring system except the range of the CCD camera is 3 μm to 4μm in the IR range. By comparing the integrated IR radiation intensity, we can get 2D temperature distribution on the surface of the device under different biased conditions.

EXPERIMENT AND DISCUSSION

Electroluminescence in GaN HEMTs as a signature of hot electron induced emission has been intensively investigated for device biased at on-state. Shown in Fig 1(a) is a typical EL image for device biased at on-state, indicating light emission originating from the region between gate and drain. Fig 1 (b) depicts the IR light intensity as well as temperature distributions (temperature measurement done by



(a)



(b)

Figure 3 (a)A typical electroluminescence image of GaN HEMT overlapped with the device image (D:drain, G:gate,and S:source). (b)2D temperature distribution of the device under the same bias condition.

IR imager) along the gate width for the same device shown in Fig 1 (a) These on-state EL bright spots and high temperature locations were strongly correlated, suggesting that localized current is flowing in the bright spots.

The electrical characteristics and EL images of Device A were compared before and after on-state stress for 2.2 hours. While threshold voltage of this device shifted to more positive shown in Fig 2 after stress, the light intensity at the lower gate became much dimmer shown in Fig 3. These

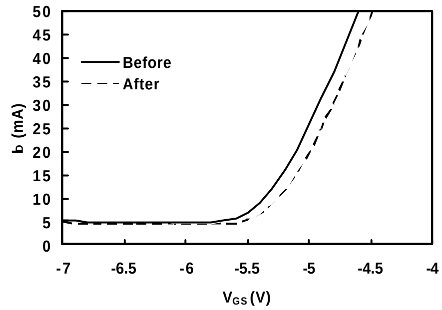
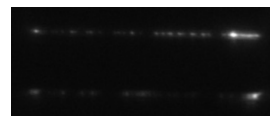
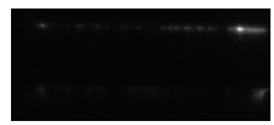


Figure 4 Characteristics of ID versus VGS before and after on-state stress.



(a)



(b)

Figure 5 The EL image of the same device (a)before and (b) after on-state stress under the same bias condition

correlations suggest that electrons are trapped the device surface, which causes a depletion of channel electrons, which is consistent with a previous report [6]. In contrast to the on-state stress, another 3 devices were stressed at off-state near breakdown conditions, in which both hot electrons and holes were produced. When impact ionization occurred during the breakdown, plenty of electron-hole pairs were generated and these holes flowed to the gate, since the gate was negatively biased. Some of these holes could be trapped in the silicon nitride passivation layer. This is because the valence band discontinuity of SiN/AlGaN/GaN would favor the transfer of generated hot holes toward silicon nitride. In contrast to transient hole trapping as previous reports [3],[7], these holes stay in the nitride layer and have a long term effect on electrical characteristics. Hole trapping leading to an increase in the drain to source current, and a decrease in the threshold voltage has also been shown in AlGaAs/InGaAs PHEMTs because some hot holes generated by impact ionization overcoming the AlGaAs/InGaAs barrier are captured in the AlGaAs layer [8] When the HEMT is biased at off-state breakdown condition (V_{GS}=-7 V, V_{DS}= 23V), high electric field can occur near the gate area. The 2D simulation has confirmed the phenomenon as shown in Fig 6 [9]. Holes can be accelerated by the vertical electric field to overcome the potential barrier and get injected into Si3N4. These holes can attract channel

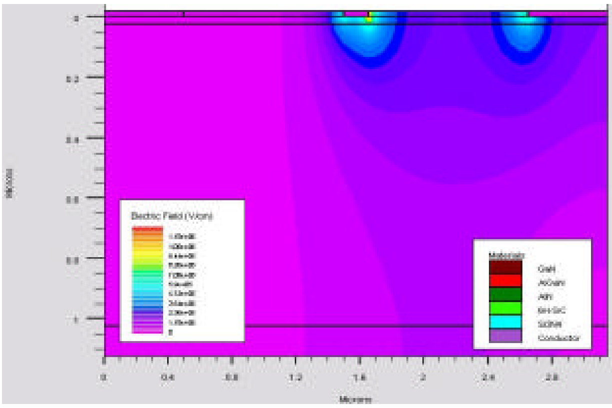


Figure 6 Electric field distribution of the GaN HEMT at V_{GS}=-7V, V_{DS}=23V.

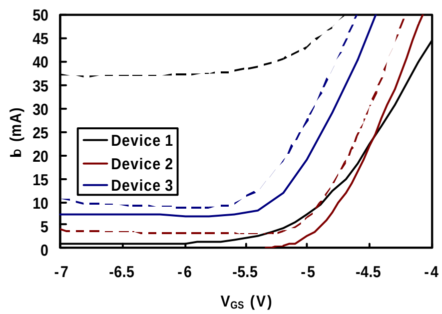
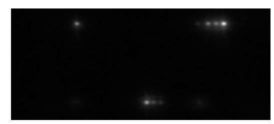


Figure 7 ID versus VGS of three different devices before(solid line) and after (dotted line) after off-state breakdown stress.

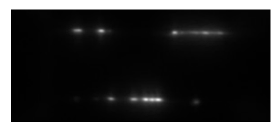
electrons to induce current in off-state conditions leading to light emission in those current flowing spots.

The electrical measurement (Fig 7) showed that the threshold voltage was shifted to more negative and the drain current was increased after the off state stress. This could be explained by having more induced channel electrons due to hole trapping in the passivation layer. In addition, another evidence indicating hole trapping is an increase in the gate leakage current with the positive surface charge to increase surface generation/recombination current in the Schottky barrier diode in AlGaN/GaN HEMTs.

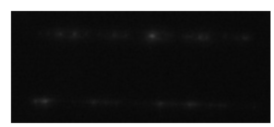
Although the changes of electrical characteristics were similar in different devices, the EL images changes varied. Fig 8 (a) and (b) depict the off-state EL image of Device 1 showing an enlargement of emitting areas after the off-state breakdown stress. This phenomenon may be due to extremely strong electric field in some specific regions. When impact ionization happens in relatively high electric field regions, more holes are injected and accumulated in the regions. These holes can diffuse along the gate width direction to nearby regions and hence the light emission and the current flowing spots are expanded. The EL images of Device 2 is shown before and after stress in Fig 8 (c) and (d), respectively. There were some very bright spots appearing randomly after stress. This may be because there was a high electric field in these same locations (shown by the arrows). Variations in the material properties or device structure along the gate width are likely causes for these local enhancement of the electric field intensity. The EL after stress in Device 3 was more uniform after stress than in the other devices, which suggests a more uniform generation of holes in the passivation layer along the gate, as shown in Fig 8 (e) and (f). This data suggests Device 3 may have had better uniformity in materials growth than Devices 1 and 2.



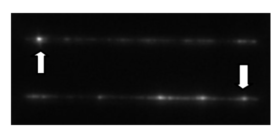
(a) Device1 (Before)



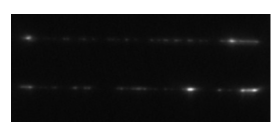
(b) Device1 (After)



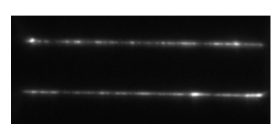
(c) Device 2 (Before)



(d) Device 2 (After)



(e) Device 3 (Before)



(f) Device 3 (After)

Figure 8 The EL images of 3 different devices (a) before and (b) after off-state breakdown stress. The same bias condition for each device before and after stress.

CONCLUSION

By combining the analysis of EL images and electrical characteristics, electron and hole trapping at specific locations in the device have been revealed. This combined analysis technique may assist material growers and process engineers to optimize the design of power GaN PHEMTs.

For a given GaN HEMT in a typical power amplifier (PA) operation, off-state stress on device can happen frequently during the RF cycle. The device characteristic changes during off-state operations will impose additional constraints on circuit performance as well as PA design. This further necessitates the need to fully characterize and understand the off-state breakdown effects on GaN HEMTs. By juxtaposing the electroluminescence images and electrical characteristics of devices before and after stress, the changes of the device in specific locations can be identified. The technique promises a potential characterization tool for device and material and Power amplifiers screening.

ACKNOWLEDGEMENTS

The authors would like to thank the support from UC MICRO and UC Discovery programs.

REFERENCES

[1] Y. Ohno et al, "Effects of Surface Passivation on Breakdown of AlGaN/GaN High-Electron-Mobility Transistors", Appl. Phys. Lett., vol. 84, no.12, pp. 2184, 2004.

[2] R. Vetury et al, "The Impact of Surface States on the DC and RF Characteristics of AlGaN/GaN HFETs", IEEE Trans. Electron Devices, vol. 48, no.3, pp. 560, 2001.

[3] J. M. Tirado et al, "Trapping Effects in the Transient Response of AlGaN/GaN HEMT Devices ", IEEE Trans. Electron Devices, vol. 54, no.3, pp. 410, 2007.

[4] Z. Y. Wang et al, "Deep Submicron PHEMTs Characterization with Spectrally Re- solved Carrier Recombination Imaging", IEDM Technical Digest, pp. 239-242, 1998.

[5] N. Shigekawa et al, "Electroluminescence characterization of AlGaN/GaN high-electron-mobility transistors", Appl. Phys. Lett., vol. 79, no. 8, pp.1196, 2001

[6] G. Verzellesi et al, "Current Collapse and High-Electric-Field Reliability of Unpassivated GaN/AlGaN/GaN HEMTs.", IEEE Trans. Electron Devices, vol. 53, no.12, pp. 2932, 2001.

[7] G. Verzellesi et al, " Experimental/Numerical Investigation on Current Collapse in AlGaN/GaN HEMT's", IEDM Technical Digest, pp. 689, 2002.

[8] G. Meneghesso et al, "Trapped Charge Modulation: A New Cauise of Instability in AlGaAs/InGaAs Pseudomorphic HEMTs", Electron Devices Lett , vol. 17, no.5, pp. 232, 1996.

[9] Device Simulator Altlas Ver.5. 9. 26. C. Atlas User's Manual. Silvaco International March 2005.

ACRONYMS

HEMT: High Electron Mobility Transistor
PECVD: Plasma Enhanced Chemical Vapor Deposition