Mapping of Local Threshold Voltage in AlGaN/GaN HEMTs

Anjali Anjali[1], James Pomeroy[1], Jr-Tai Chen[2], and Martin Kuball[1]

[1]Center for Device Thermography and Reliability, H.H. Wills Physics Laboratory, University of Bristol, Tyndall Avenue, Bristol BS8 1TL, UK.
[2]SweGaN AB, Pursergatan 1, 582 78 Linköping, Sweden.

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Abstract

An innovative Electroluminescence (EL) method is introduced for precisely probing and mapping local threshold voltage variations within devices. Consistency of the optical to electrical determination of threshold voltage is demonstrated. We can probe variations in threshold voltage along the gate finger with 1 µm spatial resolution, and less than 10 mV voltage resolution. Threshold voltage spatial variation characterization can be a useful tool for device screening and reliability analysis as well.

INTRODUCTION

Gallium Nitride (GaN) has emerged as a highly promising material for High Electron Mobility Transistors (HEMTs) to meet the stringent requirements of applications demanding elevated power levels, high operating frequencies, and tolerance to high temperature[1]. It offers superior characteristics such as increased electron mobility, higher current density, enhanced breakdown capabilities, and high output power for both RF and power devices. Despite these advantages, the reliability of GaN HEMTs remains a subject to intense studies due to issues as leakage current, trapping effects, dispersion, and their impact on drain current, and breakdown voltage.[2] The threshold voltage is a critical operational parameter for power and RF transistors; device degradation often results in an increase in gate leakage current as well as a threshold voltage (V_{th}) shift. Leakage pathways, defects, or trap generation during device stress are often localized. However, until now, V_{th} could only be measured electrically, which is an average over the whole transistor periphery. In this study, we present a methodology that employs Electroluminescence (EL) as a tool to measure the local threshold voltage along the gate width, providing a high-spatial resolution V_{th} map. Possible applications are fast quality control or reliability testing.

DEVICE AND STRUCTURE

Fig 1 illustrates the structural design of the AlGaN/GaN HEMT device under test (DUT). The DUT is fabricated using QuanFINE technology, which is also known as a buffer-free design. The epitaxy is on a 480 µm thick semi-insulating 4H SiC substrate, consisting of a 60 nm AlN nucleation layer, followed by a 250 nm thick UID GaN channel, a 14 nm AlGaN barrier layer containing 29% aluminum, and a 2 nm GaN cap layer. Measurements were carried out on a 2-finger transistor with a T-gate, with a foot of lengths of 250 nm, a gate width of 50 µm, and a channel length of 4 µm. Note that while this specific device was used for demonstration, this technique is generic and can equally be applied to other epitaxies and transistor designs. EL images were captured through a 0.5 numerical aperture 50x objective lens coupled with a cooled, back-illuminated CMOS camera. DC bias was used for the transistors.

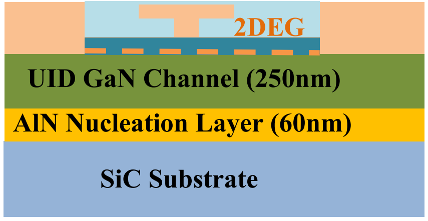

Fig 1. Schematic structure of buffer-free AlGaN/GaN HEMT.

RESULTS AND DISCUSSION

In Fig 2(a), bidirectional Id-V_{GS} transfer characteristics are depicted at V_{DS} = 10V. V_{th} is around -3V at V_{DS} = 0.5V. In Fig 2(b), typical EL images of the device are shown, with the device operated at 10V source drain (V_{DS}) bias, sweeping gate voltage, V_{GS}, from -3V to -1V. EL is emitted due to the acceleration of charge carriers on passage of a high electric field, which is also knows as Bremsstrahlung effect[4]. EL emission occurs at the drain side of the gate. The EL-V_{GS} curve (shown in Fig 2.(c)) exhibits a distinctive bell-shaped pattern, typically attributed to the interplay of current density and applied electric field. Naturally, the EL intensity is zero when the channel is pinched- off and starts to rise when V_{GS} rises above V_{th}; at this point (V_{GS} = -3 V). Fig. 2(b) reveals non-uniform EL emission, in contrast to the uniform emission observed in the on-state measurement image. This indicates that there are small spatial variations V_{th} for the DUT. The method for determining the precise local V_{th} value from the measured photo-emission intensity images is outlined in the following.

(a)

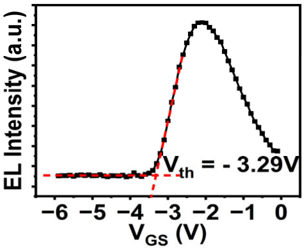

Fig 2.(a) Transfer characteristics of AlGaN/GaN HEMT at V_{DS} = 10V

(b)

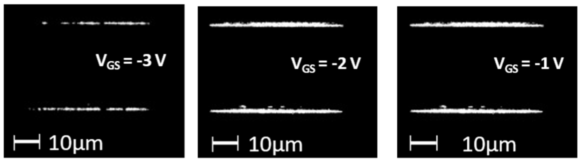

Fig 2 (b) EL image of two-finger gate device in semi-on state at V_{DS} = 10V

(c)

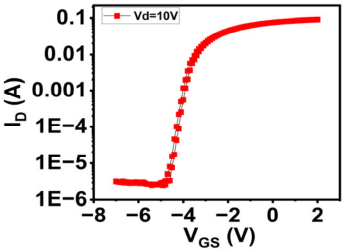

Fig 2 (c) Extraction of V_{th} from EL-V_{GS} curve.

Analogous to the electrical methodology for determining V_{th}, we record changes in EL intensity at each pixel, and extrapolated to zero EL emission as illustrated in Fig 2(c). This method allows us to map the local threshold voltage along the gate finger. To do this, we assume that the EL emission intensity is proportional to the local drain current density at each pixel for a relatively small range of V_{gd}, i.e., the applied electric field, it doesn't change significantly. Following this procedure, Fig 3 presents a spatial map of V_{th} along the gate finger. It is evident that different regions along the gate exhibit distinctly different threshold voltage values, potentially due to local defects, traps, and potentially inhomogeneities in the gate contact. We note that small local variations (~50 mV across 10 μm) detected are demonstrating that Vth can be determined from the emission images with high accuracy. Rotating the device by 180 degrees gave the same result illustrating that these changes in threshold voltage are not measurement artefact from the imaging system, but are device property. This approach provides precise information about the local threshold voltage with an accuracy of about 10 mV, as performed here.

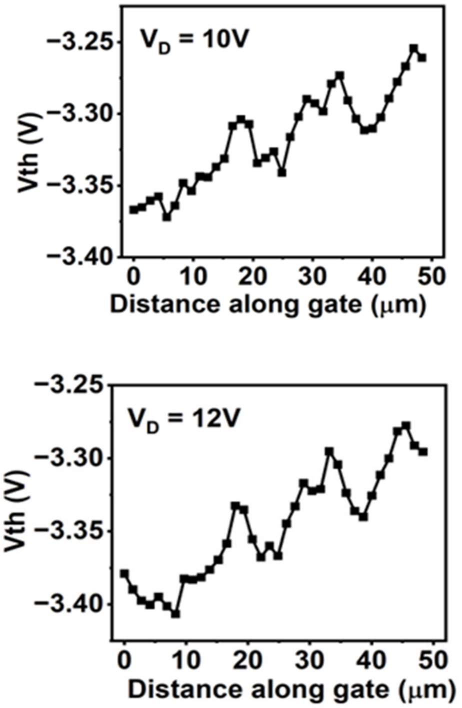

Fig 3. Map of threshold voltage along the gate width at different drain-bias, at (a) V_{DS} = 10 V, and (b) V_{DS} = 12 V.

To assess consistency of the developed approach, we compare EL-determined threshold voltage to the standard electrical determination of threshold voltage. The electrical threshold voltage for V_{DS} values of 10V and 12V is measured at -3.29V and -3.33V, respectively while the EL method provided -3.33V and -3.36V, respectively, when averaged along the gate finger, showing good agreement.

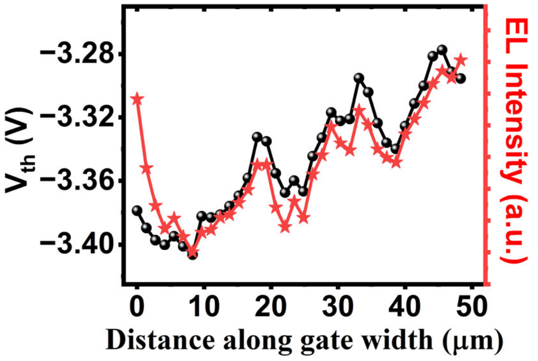

Fig 4. Correlation of EL intensity near pinch off (V_{GS} = -3.3V, V_{DS} = 12V) and local threshold voltage along the gate (V_{DS} = 12V).

Fig 4 displays the EL determined threshold voltage (circled) along the gate finger as well as EL intensity (starred) along the gate finger, measured near pinch-off, the later a faster measurement. While EL intensity at a single bias point cannot be used to quantify the threshold voltage, its spatial pattern has an approximate relationship to the local threshold voltage (other factors such as light absorption affect intensity in some areas). By itself it can be used to provide feedback for device properties in quality assessment in a manufacturing environment.

CONCLUSIONS

An electro-optical methodology was developed as a probing technique for mapping the local threshold voltage in AlGaN/GaN HEMTs, shedding light on non-uniformity within devices. This can pinpoint and identify potential "weak points" in a device at an early stage, effectively serving as a screening tool and to monitor degradation.

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