Microelectronics Reliability 55 (2015) 2493–2498

Contents lists available at ScienceDirect

Microelectronics Reliability

journal homepage: www.elsevier.com/locate/mr

Study of hot electrons in AlGaN/GaN HEMTs under RF Class B and Class J operation using electroluminescence

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ARTICLE INFO

Article history:
Received 22 July 2015
Received in revised form 13 September 2015
Accepted 23 September 2015
Available online 28 September 2015

Keywords:
Microwave field-effect transistor (FETs)
AlGaN/GaN
Electroluminescence
Class B
Class J
RF degradation
Hot-electrons
Electron temperature

ABSTRACT

Electroluminescence microscopy and spectroscopy have been used to investigate hot electron concentration and electron temperature during RF operation. Two modes of operation were chosen, Class B and Class J, and compared with DC conditions. Hot electron concentration and temperature were on average lower for both RF modes than under comparative DC conditions. While these average values suggest that degradation due exclusively to hot electrons may be lower for RF than for DC conditions, the peak values in EL intensity and electric field along dynamic load lines have also to be taken into account and these are higher under Class J than Class B.

1. Introduction

AlGaN/GaN high-electron-mobility transistors (HEMTs) offer a very promising solution to the increasing demand for high power switches and radio frequency (RF) power amplifiers. The GaN large band gap, high breakdown field and saturation velocity make this material well suited for high power operation from microwave to millimeter wave frequencies. However, GaN based devices still face some reliability issues when operating conditions are pushed to the extremes. For example, reliability under RF operation is still not fully resolved, and works among groups are still in progress for the complete understanding of this issue [1–6].

Gate metal instabilities [4] and inverse piezoelectric effects [5] have been identified as sources of early device failure after accelerated RF life tests for different applied frequencies (X-band or L-band). Some correlation has been observed between the increase in drain-to-source on-state resistance and output power degradation, most likely due to an increased surface charge between the gate and drain [2]. RF degradation tests are expensive to perform and not always trivial to interpret [1], hence pulsed I-V signal configuration and DC lifetime testing are often used as alternatives [4]. However it is not fully clear how reliable DC testing is in assessing RF degradation, as failure mechanisms can be different in the two cases. Some groups have reported increased RF degradation compared to DC lifetime testing [3] while according to other studies, RF and DC excitations show the same degree of degradation [7,8]. Hot carriers have been suggested to be responsible for generating traps in the gate-drain access region and, due to negative charge injection, for the increase in access resistance values observed [3,9].

Electroluminescence (EL) imaging and spectroscopy have been shown in the past to be efficient tools for monitoring hot electron concentrations and energy during operation [6,10,11,12] as well as for assessment of device degradation after test. EL intensity has been reported to be correlated with degradation under DC conditions [13,14], which has been suggested to be due to high energy carriers modifying defect states or creating new defects inside the device epilayers [15]. The direct observation of hot electrons during RF has been recently reported during Class B operation [6]. It was shown that hot electron density under Class B operation is lower, on average, than under comparable DC operation. Also, hot electrons under RF device operation exhibited a lower average electron temperature compared to DC, by up to 500 K. The results suggested that potential hot electron degradation mechanisms under Class B mode could be lower than under DC if no other degradation mechanisms were present (e.g. field-driven degradation).

In the present work, this earlier method is extended to the understanding and comparison of hot electrons under Class B and Class J

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http://dx.doi.org/10.1016/j.microrel.2015.09.023

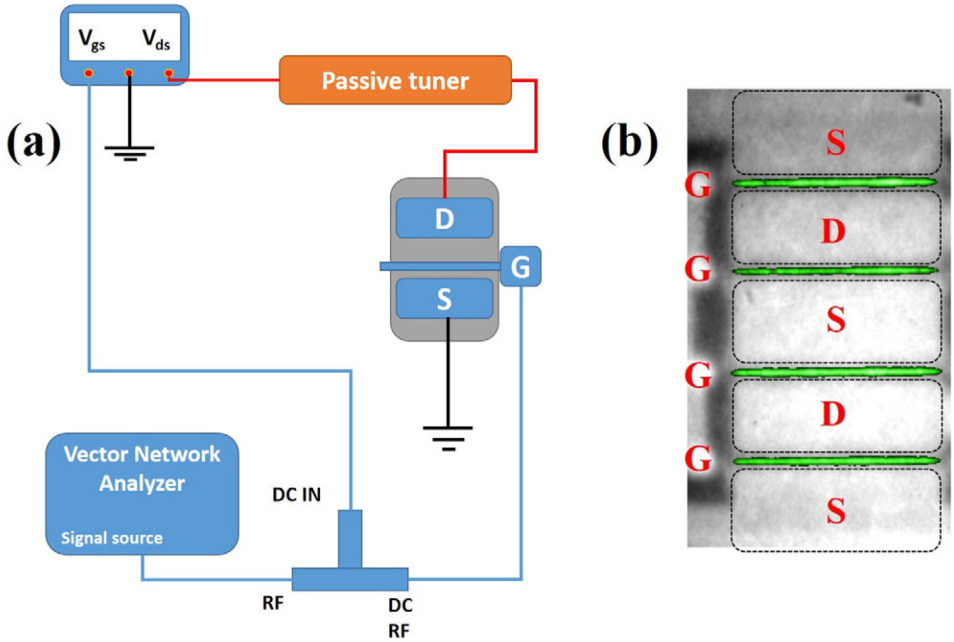

Fig. 1. (a) Schematic of the circuit used for the measurements. (b) False-color EL image of AlGaN/GaN HEMT, overlaid on a white-light image for a 4×100 μm-wide device. The device was operated under DC V_{DS} = 20 V and V_{GS} = −3 V.

modes of operation of AlGaN/GaN HEMTs using EL microscopy and spectroscopy. Class B is a standard mode used in RF power amplifier design offering high efficiency while amplifying only half of the input wave cycle. The Class J mode has shown the potential of obtaining the same efficiency and output power, but without requiring a band-limiting second harmonic short circuit termination [16]. The comparative analysis in terms of hot electrons of these two modes, which represent two extremes on a continuum of modes having different maximum drain voltage swings, but which cannot easily be distinguished by simple RF performance measurements, is important in assessing the vulnerability of power amplifiers to degradation.

2. Experimental details

The 4 × 100 μm HEMTs studied here were AlGaN/GaN heterostructures with a Fe-doped GaN buffer layer on a semi-insulating SiC substrate, with a 0.25 μm gate length. During testing, the devices were operated in specific RF operating modes, Class B and Class J, using a matching section circuit (passive tuner), built following active load-pull characterization of the devices. A 1 GHz signal was applied to the gate of the device using a vector network analyzer (VNA) (see Fig. 1(a) for the schematic of the setup). An average DC drain current was measured for each fixed input RF power. Class B operation involves applying a resistive load at the fundamental frequency and a short circuit to higher harmonics, and was selected since it is commonly used for delivering high power added efficiency (PAE). The result is a nominally sinusoidal voltage and a half wave rectified current waveform, which only flows while the voltage is at a minimum, therefore minimizing dissipation and maximizing PAE. The Class J mode is a variant of Class B which can also deliver efficient wideband amplifier operation [16,17]. In Class J, the current waveform and hence the quiescent DC bias state are unchanged. The voltage waveform is however modified, becoming half wave rectified, by the introduction of reactive terminations at both the fundamental and second harmonic, such that the RF output power and PAE is also unchanged. The really significant difference between these modes is that the output voltage waveform has much higher peak for Class J than Class B. For each operating mode the dynamic current–voltage locus was varied by changing input RF power. The same bias point was used for both operating modes. An optical microscope, with a 50× objective, was used for EL light detection, from the backside of the device allowing collection of the emission from the whole operating region under metal contacts. A Hamamatsu CCD camera was used for EL microscopy, while a Renishaw InVia spectrometer was used for spectral acquisition. During operation, the device temperature was monitored with micro-Raman thermography. Further details on this technique can be found in Ref [18].

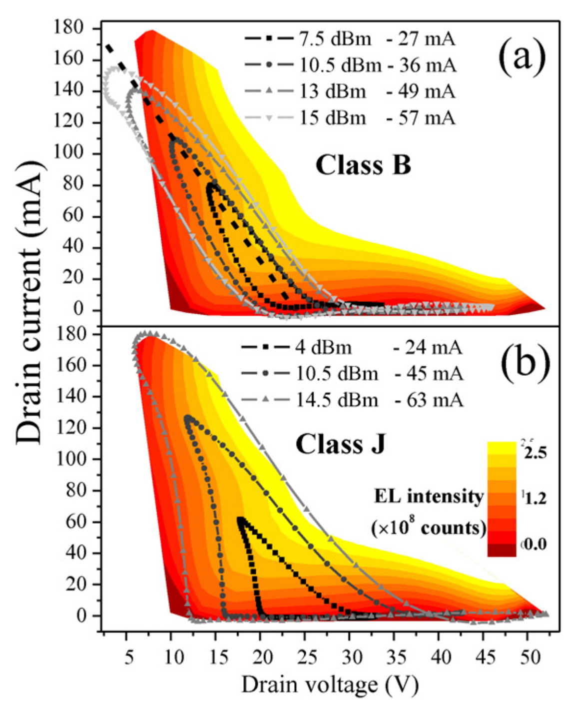

Fig. 2. Contour maps of the EL intensity in I_{DS}-V_{DS} plane, obtained under DC conditions. Superimposed are the load lines for Class B (a) and Class J (b) used for EL experiments at the indicated input RF power levels and drain currents. In the top part the 125 Ω DC load line used for comparisons is also shown (short dash).