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Evidence for impact ionization in AlGaN/GaN HEMTs with InGaN back-barrier

N. Killat, M. Ťapajna, M. Faqir, T. Palacios and M. Kuball

Electroluminescence (EL) spectroscopy in combination with drift-diffusion simulations was used to prove the presence of impact ionization in AlGaN/GaN HEMTs illustrated on InGaN back-barrier devices. Regardless of the level of gate leakage current, which is dominated by contributions such as surface leakage current and others, EL enabled to reveal hole generation due to impact ionization. Hole currents as low as 10pA were detectable by the optical technique used.

Introduction: AlGaN/GaN HEMTs represent a promising technology for high power RF applications. Besides charge carrier trapping, impact ionization due to high electric fields in the device channel [1-3] can limit device reliability and consequently the use of GaN-based HEMTs. The presence of impact ionization has been debated for GaN HEMTs with controversial evidence due to high leakage in many devices [3], illustrating the limitations of the commonly applied method of gate current analysis for GaN HEMTs. Therefore, a new methodology is needed to probe impact ionization in AlGaN/GaN HEMTs independently of the gate leakage current level. A bell-shaped dependence of the gate current versus gate-source voltage has been used in AlGaAs/GaAs HEMTs [4] to prove impact ionization, supported by studies of interband electroluminescence (EL). So far neither has been unambiguously observed in GaN-based HEMTs. This letter presents the direct evidence for impact ionization in GaN HEMTs by EL spectroscopy in combination with drift-diffusion simulations illustrated on AlGaN/GaN HEMTs with InGaN back-barrier.

Experimental details: AlGaN/GaN/SiC HEMTs with a 1 nm thin InGaN layer (10% In content) 11 nm beneath the AlGaN/GaN interface were studied, with the InGaN layer introduced as optical hole probing device layer benefiting from its high optical quantum efficiency [5]. The devices had a source-drain gap of 2.3 μm and a gate length of 0.2 μm with a gate width of 2×75 μm. Further information on the device structure can be found in Ref. [6]. Initially, the commonly used method of gate current analysis for detecting impact ionization [2] was applied to attempt to probe hole currents. The hole current generated by, e.g., impact ionization is expected to be in the range of nA [1], which requires a very low gate leakage current level in order to distinguish between hole current by impact ionization and other gate leakage current contributions. The inset of Fig. 1 shows, however, that the leakage current level of the devices used is too high in order to draw conclusions on the presence of a hole current. EL spectroscopy was used to probe the hole current independently from the level of gate leakage current. EL spectra emitted from the source-drain gap were recorded using a Renishaw RM system, while the device was operated at a drain-source and gate-source bias of 20 V and 0 V, respectively.

Results: The EL spectrum shown in Fig. 1 reveals a tail in the red-infrared spectral range typically observed in GaN-based HEMTs, which is related to hot carrier relaxation in the active device region [7]. Furthermore, a peak of the EL signal is apparent at the band-gap energy of InGaN, evidencing the recombination of electrons and holes in the InGaN layer. This clearly proves the presence of holes in the InGaN layer of the device under operation, in addition to electrons from normal device operation. The InGaN device layer acts as charge carrier collecting layer in the device (inset of Fig. 2), and as optical hole probe due to its high optical quantum efficiency. We note that EL around the GaN band-gap energy tends to be optically less efficient, possibly explaining why this has not been observed to date in GaN HEMTs.

Impact ionization [2] as well as charge trapping [8] has been discussed in literature as possible origin for hole currents in GaN-based devices. Therefore, the possibility of hole emission from traps needs to be excluded as mechanism for the here observed interband EL to prove the presence of impact ionization. EL spectroscopy was performed at room temperature and at a back-plate temperature of -140°C with the devices operated at the same bias conditions. The results presented in Fig. 2 show a significant increase of the peak intensity at -140°C compared to room temperature measurements. This strongly suggests thermal hole emission from traps to be very unlikely for the investigated devices, as those are expected to freeze out at low temperatures. On the other hand, the increase of the InGaN band-gap related emission intensity at low temperatures is consistent with impact ionization as the dominant hole generation mechanism due to an increased electron mean-free-path followed by a higher impact ionization rate [1]. The results presented here therefore confirm the occurrence of impact ionization in the investigated devices under the bias conditions used.

To identify in which device layer impact ionization occurs, drift-diffusion simulations were performed using Sentaurus [9] and compared to the experimental data. The device exhibits two channels, at the AlGaN/GaN interface and in the InGaN layer. Fig. 3 shows the dependence of the sheet electron density in the GaN channel and InGaN layer on V_{GS} together with the integrated InGaN peak intensity. The InGaN related EL intensity clearly correlates with the sheet electron density in the InGaN layer, where a second channel is formed, however, not with the sheet carrier concentration in the GaN channel. Since the impact ionization process employs hot electrons to generate holes observed in the EL spectrum, this strongly suggests impact ionization to take place in the InGaN layer. Nevertheless, the small difference in band-gap energy between InGaN (~3.1 eV) and GaN (~3.4 eV) raises the question whether impact ionization may need to be considered even in the GaN channel. Considering the spectrometer system throughput, the estimated hole current from the integrated EL intensity is in the order of 10 pA, illustrating the very high sensitivity of EL spectroscopy for device characterisation.

Conclusion: EL spectroscopy gave direct evidence for impact ionization in the GaN-based HEMTs studied. Even in devices where a high gate leakage current level makes the application of the commonly used gate current analysis for detecting impact ionization impossible, the method can be used to reveal the presence of hole currents with high sensitivity.

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Figure captions:

Fig. 1 EL spectrum of an AlGaN/GaN HEMT with 1 nm thick InGaN back-barrier 11 nm beneath the AlGaN/GaN interface, measured at V_{DS}= 20 V and V_{GS}= 0 V (current density of 0.9 mA/mm). The inset shows the gate current I_G vs. V_{GS} for a drain-source voltage of 1 and 10 V.

Fig. 2 EL emission from InGaN layer in the device at different temperatures, measured during device operation at V_{DS}= 20 V and V_{GS}= 0 V. The EL intensity is normalised with respect to the drain current. The InGaN EL peak shift is related to the temperature difference. The inset shows a conduction band diagram of the device extracted from drift-diffusion simulations, neglecting polarisation effects at the InGaN back-barrier.

Fig. 3 Comparison between integrated InGaN band-gap related EL peak intensity and simulated sheet electron density in the GaN channel and InGaN layer for V_{DS}= 20 V.

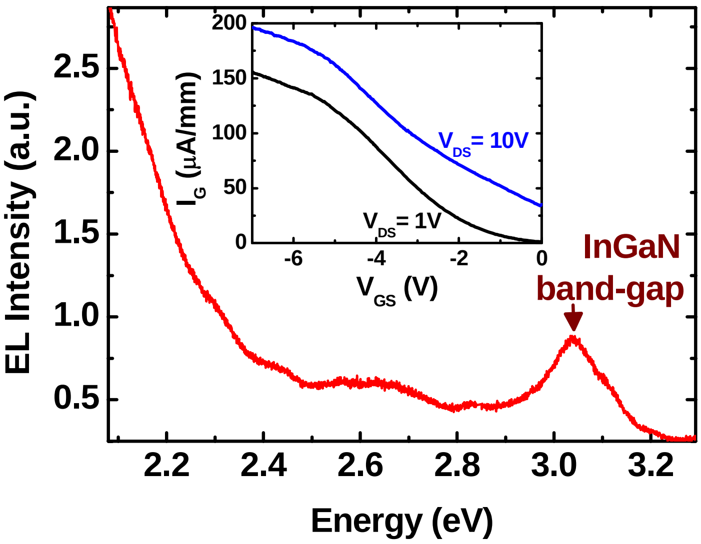
EL Intensity (a.u.)
2.5
2.0
1.5
1.0
0.5
2.2
2.4
2.6
2.8
3.0
3.2
Energy (eV)
InGaN band-gap
I_G (μA/mm)
200
150
100
50
0
-6
-4
-2
0
V_{GS} (V)
V_{DS}= 10V
V_{DS}= 1V

Fig. 1

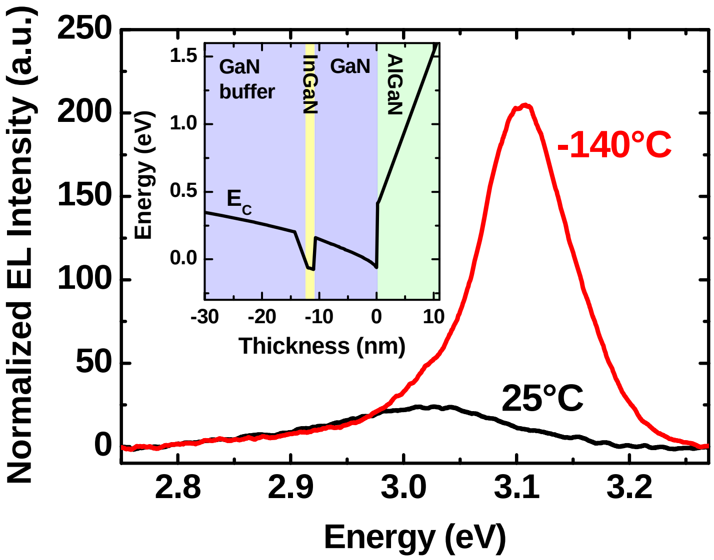
Normalized EL Intensity (a.u.)
250
200
150
100
50
0
2.8
2.9
3.0
3.1
3.2
Energy (eV)
-140°C
25°C
GaN buffer
InGaN
GaN
AlGaN
E_C
Energy (eV)
1.5
1.0
0.5
0.0
-30
-20
-10
0
10
Thickness (nm)

Fig. 2

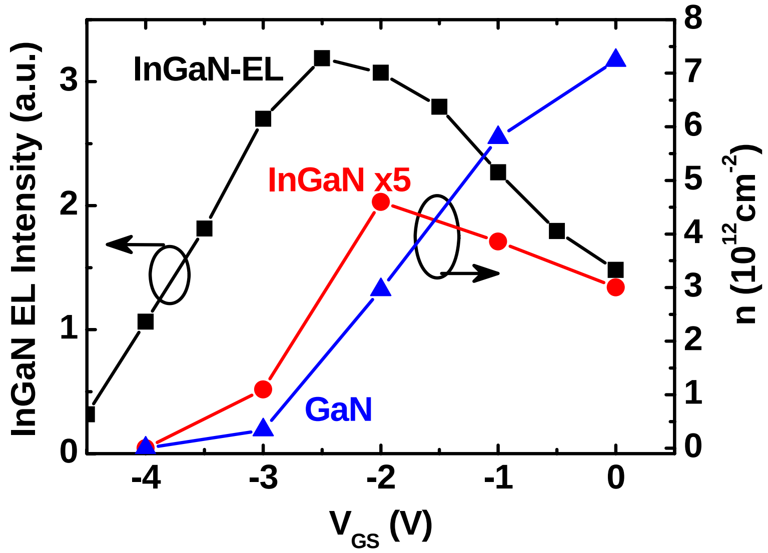
InGaN-EL
InGaN x5
GaN
InGaN EL Intensity (a.u.)
0
1
2
3
n (10^{12}cm^{-2})
0
1
2
3
4
5
6
7
8
-4
-3
-2
-1
0
V_{GS} (V)

Fig. 3