InAlN/GaN HEMTs: A First Insight into Technological Optimization

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Introduction

AlGaN/GaN HEMTs have been studied extensively as ideal candidates for high frequency and high power applications. However, according to theoretical predictions [1], [2], $In_xAl_{(1-x)}N$/(In)GaN HEMT performance may be superior in respect to AlGaN/GaN HEMTs, primarily because of expected higher two-dimensional electron gas (2DEG) density n_S. That brings high expectations for HEMT drain current (I_{DS}) capabilities. There are no data published on optimization of ohmic and/or Schottky barrier contacts on InAlN, nor any analyses of the relation of material (like μ) and contact parameters to InAlN/GaN HEMT performance. In this paper the role of HEMT parameters on device performance is analysed using an analytical model [2]. The model considers 2DEG channel parameters like n_S, μ and electron saturation velocity v_S, device geometry-dimensions and contact parameters like R_C and φ_B. It is concluded that the increase of the 2DEG mobility is very critical prerequisite for achieving high performance InAlN/GaN HEMT devices.

Experimental

InAlN/GaN lattice-matched layers were grown by MOCVD on sapphire substrates. Free carrier concentration and mobility values were determined at room temperature by Hall technique to be 2×10^{13} cm^{-2} and 260 cm^{2}V^{-1}s^{-1}, respectively. HEMT gate length was 1 µm, width 200 µm.

Results

In Fig. 1 we show output characteristics of the processed InAlN/GaN HEMT. The maximal I_{DS} was 0.64 A/mm at V_{GS} = 3 V. The output characteristic show signs of self-heating. This trend is initially visible at V_{GS} = 0 V, as the output resistance starts to increase (with increasing gate bias), and is underlined by a negative differential output resistance at V_{GS} = 2 V. At V_{GS} = 3 V the HEMT dissipated power reaches 7 W/mm with possible temperature of ~ 400 °C [3]. Further channel opening may cause thermal runaway and we terminated the measurement at this power level.

The output and transfer characteristics of the InAlN/GaN HEMT were modeled using the material and geometrical parameter values listed in Table 1. The calculations were performed for increasing V_{GS} until the HEMT open channel condition is reached, i.e. $V_{GS} - I_{DS} \times R_S = \varphi_B$. At this gate bias, the HEMT open channel drain current I_{DSO} can be considered as the maximal reachable current. As seen on Figs. 2 and 3, good agreement between the experiment and the model is obtained until V_{GS} ~ 0 V. The discrepancy for higher V_{GS} can be explained by self-heating effects, as the model neglects these phenomena. We measured the maximal g_m = 122 mS/mm. The model indicates that if the self-heating was reduced (such as for SiC substrates), then we may anticipate g_m ~ 165 mS/mm and I_{DSO} ~ 1.35 A/mm.

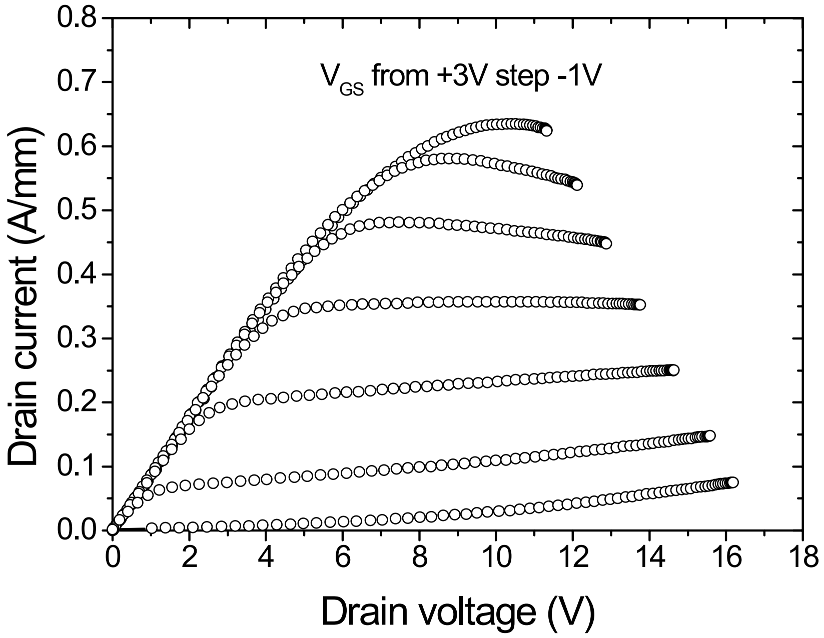

Fig. 1: Output characteristics of 1 µm gate-length InAlN/GaN HEMT. After ref. [5].

Next, using an analytical model, we analyzed three alternative ways of enhancing the InAlN/GaN HEMT capabilities: (i) The source contact resistances is improved by decreasing the source-gate distance to 0.5 µm and by decreasing R_C to 1 Ωmm, (ii) the gate length is shortened to 200 nm, or (iii) the electron mobility is increased to 1000 $cm^2V^{-1}s^{-1}$. Our analytical model does not cover all aspects of complex HEMT performance, nevertheless it can be used as an illustrative tool to describe problems of the state-of-the-art InAlN/GaN HEMTs and suggest future technological improvements. We take I_{DSO} ~ 1.35 A/mm and g_m = 165 mS/mm as reference values for comparisons. Calculated and experimental characteristics are shown in Figs. 2 and 3.

The option (i) brings the enhancement in g_m = 315 mS/mm (up from 165 mS/mm), but no improvement in I_{DSO}. The gate length shortening, option (ii), brings only small improvement in the g_m, but clear improvement in I_{DSO} (2.9 A/mm, up from 1.35 A/mm). The characteristics of 200 nm gate length HEMT (option (ii)) indicate high V_{GS} (in excess of 13 V) needed for the channel to be opened. This was because of the high R_S (caused by the low electron mobility in the source-gate region) coupled with the high I_{DS}. As shown further, the simultaneous and clear improvements of both of investigated DC parameters can be expected only if the electron mobility is increased, option (iii). In this way we may expect g_m = 275 mS/mm and I_{DSO} = 2.8 A/mm. These dramatic improvements can be understood by realizing changes in the character of the electron transport in the HEMT channel if µ is improved. The best HEMT results can be expected if µ fulfils the condition $V_{PO} >> 3\ L_g \times v_{sat}/\mu$ [4], where V_{PO} is the HEMT pinch-off voltage. Only then electrons easily reach the velocity saturation in the channel. Electron mobility values of the state-of-the-art InAlN/GaN 2DEG do not fulfill this condition and thus the InAlN/GaN HEMTs' potential capabilities are not fully exploited. We also calculated estimation for the best device with all improvements (i), (ii) and (iii) simultaneously realized (not shown). For that case we get g_m = 470 mS/mm and I_{DSO} = 3.6 A/mm at V_{GS} = 4.4 V.

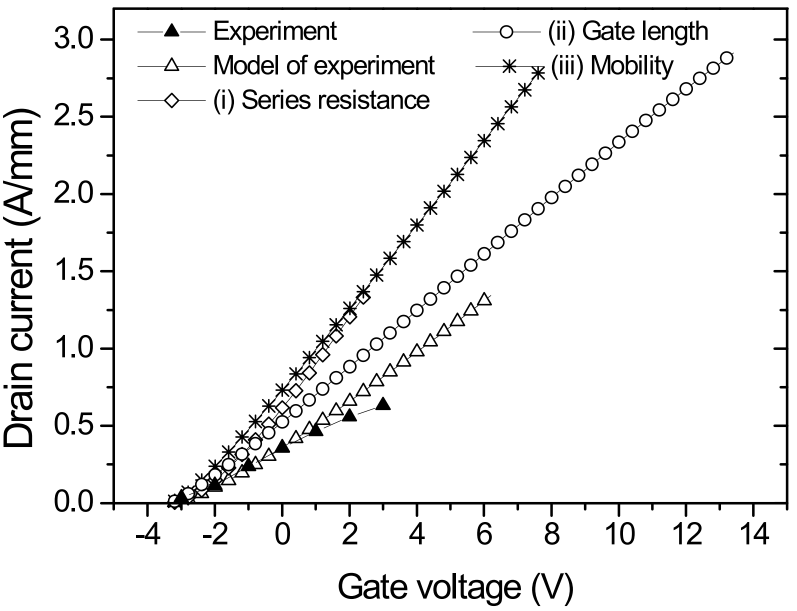

Fig. 2: Experimental and calculated output of InAlN/GaN HEMTs. “Model to experiment” curve is calculated from measured material parameters. Curves (i)-(iii) demonstrate possible enhancement of HEMT characteristics with improvement of (i) series resistance, (ii) gate dimension, and (iii) electron mobility. After ref. [5].

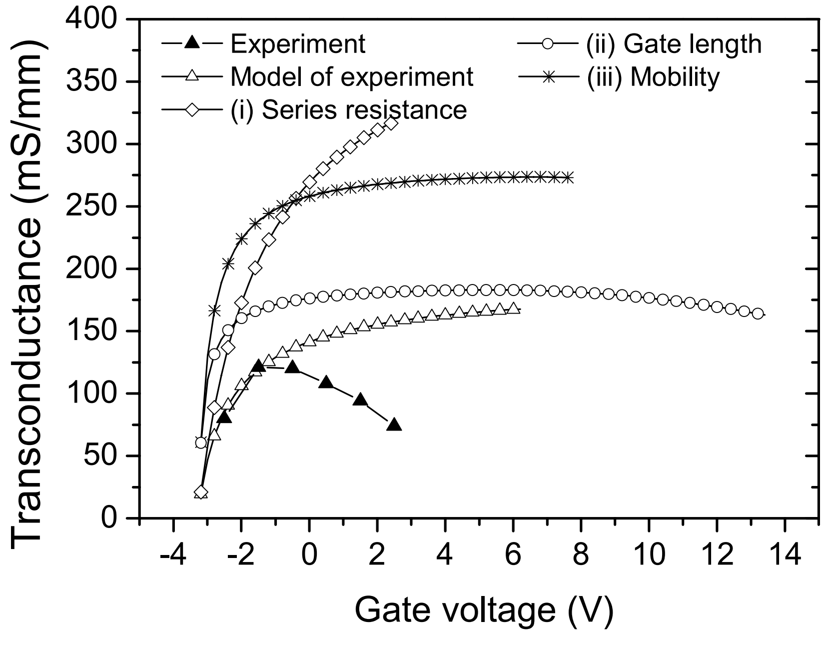

Fig. 3: Experimental and calculated transfer characteristics of InAlN/GaN HEMTs. “Model to experiment” curve is calculated from measured material parameters. Curves (i)-(iii) demonstrate possible enhancement of HEMT characteristics with improvement of (i) series resistance, (ii) gate dimension, and (iii) electron mobility. After ref. [5].

	M. to E.	*(a)*	*(b)*	*(c)*
InAlN thickness (nm)	10			
InAlN permittivity	9.8			
GaN/InAlN cond. band discontinuity (eV)	0.3			
n_S (10^{13} cm^{-2})	2			
φ_{BN}(eV)	0.63			
L_G (µm)	1		0.2	
S-G and G-D distance (µm)	2.5	0.5		
R_C (Ωmm)	1.3	1		
μ (cm^2/Vs)	260			1000
El. saturation velocity v_{sat} (10^5 m/s)	1.2			

Tab. 1 Structural and material parameters used for HEMT modelling. Model of the processed HEMT (Model of experiment) curve was calculated using parameters of the processed HEMT. Improved technological parameters listed in rows (a)-(c) represent changes used for calculating hypothetical devices.

Conclusion

The 1 µm gate-length InAlN/GaN HEMTs exhibited I_{DS} = 0.64 A/mm and g_m = 122 mS/mm. Using an analytical model we demonstrate that the most effective way of improving the state-of-the art InAlN/GaN HEMTs is to enhance the electron mobility in the InAlN/GaN 2DEG channel. Only then the capabilities of InAlN/GaN systems can be fully exploited.

Acknowledgement

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