Influence of Surface Trapping on Determination of Electron Saturation Velocity in AlGaN/GaN Heterostructures

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Introduction

Investigation of the electron drift and saturation velocity (v_{dr}, v_{sat} respectively) in the AlGaN/GaN high electron mobility transistors (HEMTs) channel is of primary importance. In an *ungated* transfer length method (TLM) test structure, provided that the carrier concentration N is constant along the AlGaN/GaN quantum well (QW) channel and the critical electric field E_{cr} for the electron velocity saturation is not reached (i. e. linear regime), the current I flowing between two TLM contacts can be calculated as:

$$I = e\, N\, W\, \mu\, V / L \qquad (1)$$

where e is the electron charge, W is the channel width, μ is the low field electron mobility, V is the applied voltage and L the TLM contact distance. Monte Carlo simulations [1] have predicted that electrons in GaN at 300 K reach v_{sat} of about 3 x 10^7 cm/s at E_{cr} of about 150 kV/cm. Consequently at high electric fields $E \geq E_{cr} = v_{sat}/\mu$ the current saturates at I_{sat}:

$$I_{sat} = e\, N\, W\, \mu\, E_{cr} = e\, N\, W\, v_{sat} \qquad (2)$$

and v_{sat} can be determined as:

$$v_{sat} = I_{sat} / eNW \qquad (3)$$

Equations (2) and (3) imply that I_{sat} value and v_{sat} determination should be independent on the TLM contacts spacing L. Up to now *I-V* characterization of ungated AlGaN/GaN QW lead to ambiguous results. In this work we analyze mechanisms of current saturation in AlGaN/GaN TLM structures combining DC and pulsed *I-V* characterization with Transient Interferometric Mapping (TIM) optical method [2], [3]. We assume that similarly as suggested by Hasegawa *et al.* [4] for semi-insulating GaAs substrate, a charge injection from contacts and charge trapping on the surface may be present in AlGaN/GaN TLM structures. Consequently, the potential of AlGaN surface is not floating as expected for the ungated structure, and we suggest a different current saturation mechanism resembling the operation of gated structures. We show that TIM results also provide explanation of the current saturation mechanism and directly support conclusions of the *I-V* characterization.

Experimental

AlGaN/GaN structures grown on SiC are used in the experiments. The TLM structure has a width of 100 µm, contact-to-contact distance is L = 2, 4, 8, 16 and 32 µm, and each L is characterized by pulsed (50 ns duration) and DC current-voltage characteristics. In the TIM method the device is scanned from the backside using an infrared laser beam and synchronized with TLP pulses. The phase shift $\Delta\varphi$ of the beam reflected from the top side is caused by a temperature-induced change in the material refractive index n along the beam path and is proportional to dissipated energy in the device [3]. The TIM method allows also to extract the *instantaneous* two-dimensional power density P_{2D} distribution [3]. The P_{2D} map serves to localize the position of the heating source.

Results

Figure 1 shows *I-V* characteristics of the TLM structure under (a) pulsed (t = 50 ns) and (b) DC conditions. DC characteristics show (i) a clear dependence of I_{sat_DC} on L, with the highest I_{sat_DC} values for the shortest L, and (ii) a practically constant V_{sat_DC} ~ 3 V for L = 8 – 32 µm. On the other hand the pulsed characteristics show (iii) higher currents and less pronounced I_{sat_pulse} dependence on L in comparison to DC *I-V*, and (iv) a clear V_{sat_pulse} dependence on L with an almost constant E_{cr} ~5 kV/cm. Provided that (3) is applicable we obtain v_{sat} ~ 1 x 10^7 cm/s at E_{cr} ~10 kV/cm for L = 2 µm in the pulsed regime, down to v_{sat} ~ 1 x 10^6 cm/s at E_{cr} ~ 1 kV/cm for L = 32 µm under DC conditions. Those values are well below values predicted theoretically [1] and observed I_{sat} vs. L dependencies contradict the current saturation mechanism represented by (2) and (3).

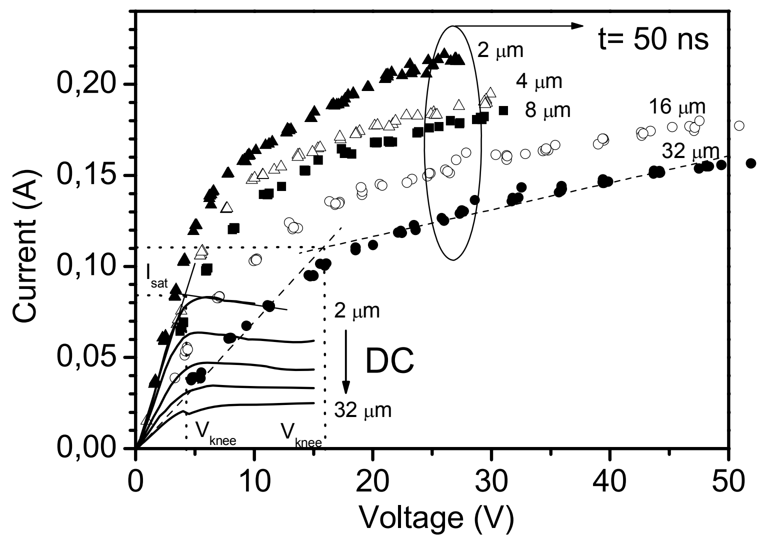

Fig. 1: *I-V* characteristics of the TLM structure with different contact distances in (a) pulsed (t = 50 ns) and (b) DC conditions.

Model

As shown above, none of Equations (1) – (3) describes the current conduction and saturation mechanism in AlGaN/GaN TLM structures properly even if the self-heating effect is considered. We assume that the main reason of that is the wrong assumption of a constant N along the channel. We suggest that the AlGaN surface potential is not floating (i.e. following the channel potential) as expected for the ungated structure, but is biased by a charge injected from contacts. For GaAs it was reported that electrons can be injected from the cathode and subsequently trapped on the surface [4]. Consequently, the potential profile along the semiconductor surface $V_{surface}(x)$ is not linearly increased from the cathode to anode, but is influenced by the presence of the surface charge. If a similar mechanism is assumed for AlGaN/GaN, then $N(x)$ varies along the channel following changes in the channel-to-surface potential difference $V_{channel}(x)$ - $V_{surface}(x)$. This effect is schematically depicted in Fig. 2, where AlGaN/GaN TLM structures with corresponding distributions of $V_{channel}(x)$, $V_{surface}(x)$ and $N(x)$ are given for the case of (a) floating surface potential and (b) charged surface.

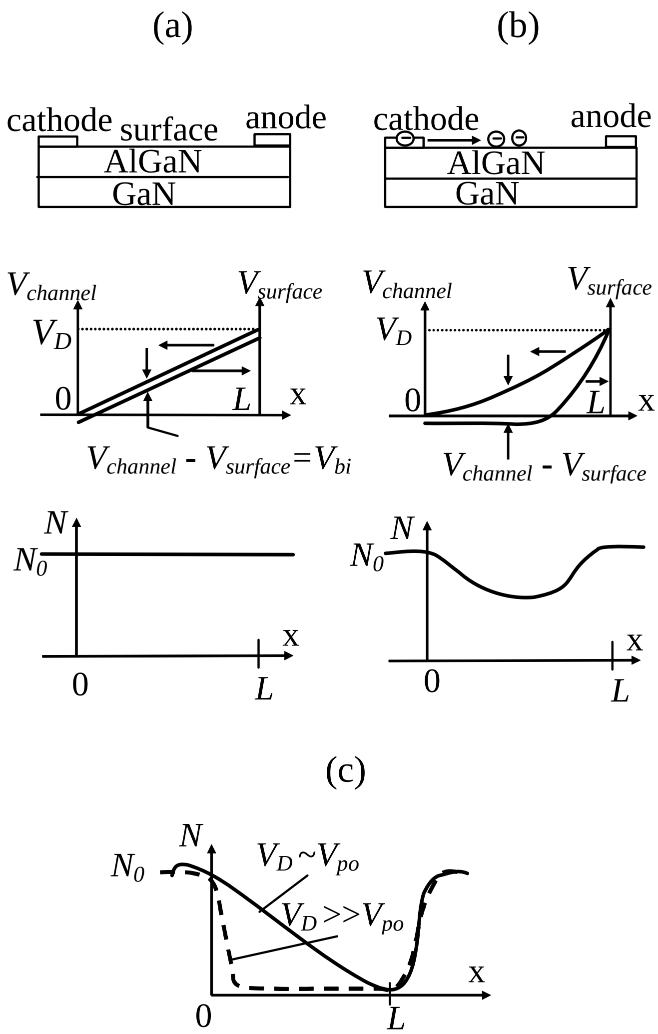

Fig. 2: Model of AlGaN/GaN TLM structures with distributions of $V_{channel}(x)$, $V_{surface}(x)$ and $N(x)$ for (a) floating surface potential, (b) charged surface with a moderate surface depletion and (c) charged surface in the "pinch-off" state. After ref. [5].

As it was shown the surface charge trapping effect seems to be dominant in explaining the differences between the pulsed and DC characteristics, while the thermal effect is marginal. It was reported elsewhere that the time constant of the AlGaN/GaN HEMT thermal transients is in the range of 10^{-7} – 10^{-6} s, while our $I(t)$ transients (not shown) indicate much longer time constants, up to seconds, similarly as reported for the trap-related current collapse.

Figure 3 shows P_{2D} obtained by TIM for structure L = 2 µm, which indicates that the heat is dissipated (and the current flow is located) also below the contacts, i.e. L_H overlaps L by transfer length L_T where the current is crowded. On the other hand, that was not observed by TIM for L = 32 µm. This can be explained by a substantial depletion of the channel in the L = 32 µm structure below the charged free surface, as illustrated by a dash line in Fig. 2(c) and by restoration of N_0 under the contacts. Thus our TIM observations fully support the proposed model.

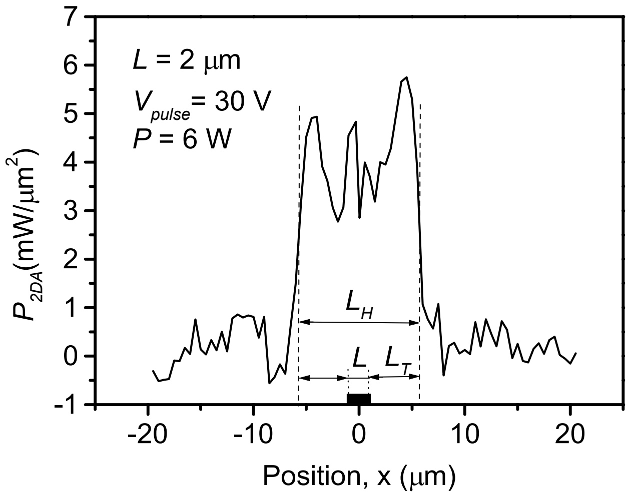

Figure 3 Apparent two-dimensional power density P_{2D} determined by TIM for L = 2 µm. After ref. [5].

Conclusion

We have investigated current conduction and saturation mechanism in AlGaN/GaN ungated TLM structures using electrical and optical mapping methods. We have suggested that the early saturation in TLM *I-V* characteristics and the determined low apparent electron saturation velocity is the consequence of the injection of charges from contacts, surface charging and channel depletion from the side of the surface. A model has been proposed explaining the potential and carrier distribution in the channel and on the AlGaN surface. This model is strongly supported by the TIM measurements, which allow to identify the channel depletion effects.

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