Modelling of Hot Electron Effects in GaN/AlGaN HEMT with AlN Interlayer

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Abstract

Physics-based numerical simulation of an AlGaN/GaN HEMT with additional AlN interlayer (IL) is carried out using both the drift-diffusion (DD) and hydrodynamic (HD) transport models. Assuming that free electrons are supplied by donor-like surface traps (STs) at the top of the AlGaN layer, we show that the AlN IL increases the 2D electron gas density and reduces the ST occupation. The HD model correctly describes ST recharging due to heating of the channel electrons and subsequent thermionic emission into the AlGaN layer. This recharging has a strong effect on channel transport, leading to the creation of a depletion domain, which expands towards the drain with increasing drain bias. The DD model does not include this effect and the depletion region remains unchanged as the drain bias increases.

1 Introduction and Device Model

Gallium Nitride based high electron mobility transistors (HEMTs) have become a focus of interest in efforts to construct gigahertz transistors that can operate at high voltages. It has been found that improvements can be made to the performance of these devices using various techniques, such as by adding a field plate (FP) to the gate, or through the introduction of extra layers. The main effect of the FP [1] is to smooth the electric potential distribution along the channel near the gate edge, due to the presence of the equipotential metal surface, and to decrease the maximum longitudinal electric field in this region for a given drain bias. This allows further increases in the drain bias (and the output power) before the electric field reaches the breakdown threshold value. Furthermore, adding an AlN interlayer (IL) to the AlGaN/GaN HEMT can improve the performance of the device by increasing the density of the 2D electron gas (2DEG) as well as the mobility. This occurs through exclusion of carriers from the AlGaN layer and reduction of the alloy scattering contribution [2]. The AlN IL must be kept as thin as possible in order to reduce its negative effects [3]. A typical thickness of the IL is about 1.5-2 nm. At such small thicknesses the IL will not have a detrimental effect on the transfer of free carriers from the donor-like bandgap states (traps) at the AlGaN top free surface. The surface traps (STs) are at present widely considered to be the main source of the 2DEG electrons in the AlGaN/GaN HEMT channel [3-4]. The STs are characterized by the trap energy E_T=1 eV and the sheet trap density $\sigma_T=3\times10^{13}$ cm^{-2}. The STs, besides being the principal source of the channel electrons, can also influence the HEMT's operation. In particular, they are considered to be one of the possible mechanisms of current collapse in AlGaN/GaN HEMTs via the process of recharging. In addition to current collapse, there are other important physical processes involving STs that can strongly influence the device operation. In this paper we present new results of AlGaN/GaN HEMT simulation using a model which incorporates the STs and an additional AlN IL. The goal of this study is to investigate the effects of the AlN IL on the reoccupation of the STs.

2 Physical Model

In simulation we use both the drift-diffusion (DD) and hydrodynamic (HD) transport models. In the context of HEMT modelling, the use of the energy balance HD model is usually justified by the necessity to tackle the overshoot effect and the spilling of the electrons from the channel into the buffer layer. The main interest here is hot electron effects in the GaN channel and, more importantly, the AlGaN layer. In the DD model high-field effects are only taken into account via the electric field dependence of the carrier mobility, which is sufficient in many cases for an adequate description of the electron transport and device operation. The mean electron energy in the DD model remains at its equilibrium value even at high electric fields. We found that in the case of incorporation of the STs into the HEMT model, only the HD model can be used to correctly account for major effects which are essential to the device operation. The physical reason for this is the exchange of electrons between the channel and the STs. The high electron temperature near the gate edge on the drain side leads to enhanced thermionic emission (TE) of the electrons from the channel into the AlGaN. The escape of electrons results in further depletion of the channel, and considerable subsequent modification of the distributions of the carrier density, the electric field, and electron temperature along the channel. These effects are crucial for device operation and are completely absent in the DD model. The TE escape of the electrons is strongly affected by the AlN IL as a result of the increased barrier height.

3 Simulation and Results

The simulated device structure is similar to that used in [1] with a gate width of 0.35 μm, AlN IL thickness of 1.5 nm, and AlGaN layer thickness of 15 nm. We utilise the commercial device simulator DESSIS [5]. The main parameters used in the simulation are: the saturation velocity in GaN (AlGaN) is 1.4×10^7 cm/s (1.7×10^7 cm/s), the electron mobility is 1100 cm^2/Vs (600 cm^2/Vs). The polarisation field is modelled in the usual way by specifying the sheet polarisation charge density $\sigma_{pl}=-1.5\times10^{13}$ cm^{-2} at the top free surface of AlGaN and at AlGaN/AlN interface (IF) and $\sigma_{pl}=+3.0\times10^{13}$ cm^{-2} at the AlN/GaN IF. The results of the HD model simulation for the electron density n, electron temperature T_n, and longitudinal electric field E_L (in the device with and without AlN IL) are shown in Figs. 1 to 4, respectively. The energy relaxation time of τ_ε=0.1 ps was used in all layers. The AlN IL improves the HEMT's characteris-

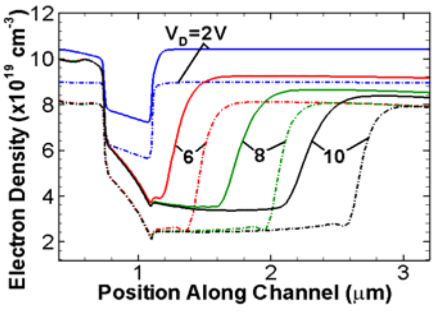

Figure 1: Electron density for HD model with (solid) and without (dashed) AlN IL.

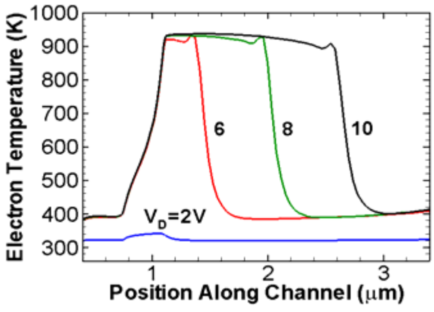

Figure 2: Electron temperature for HD model for a HEMT without AlN layer.

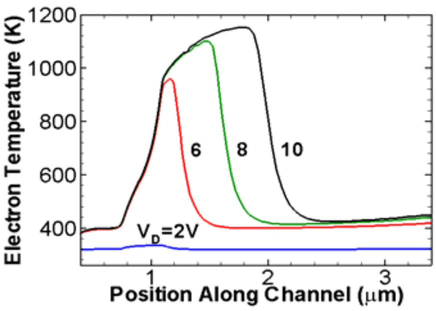

Figure 3: Electron temperature for HD model for a HEMT with AlN IL.

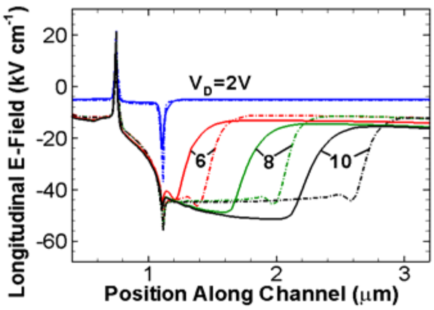

Figure 4: Electric field for HD model with (solid) and without (dashed) AlN IL.

tics due to increased 2DEG density in the channel as a result of the additional polarisation field and higher barrier, which blocks TE carrier emission into the AlGaN layer and reduces the ST reoccupation effect. The most notable effects found relate to the electron density and electric field distributions. These graphs are in contrast with DD model results, shown in Figs. 5 and 6. In the HD model the high electric field domain extends along the channel as the drain bias V_D increases. This is due to additional ele-

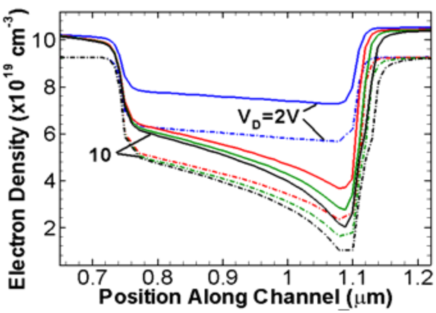

Figure 5: Electron density for DD model with (solid) and without (dashed) AlN IL.

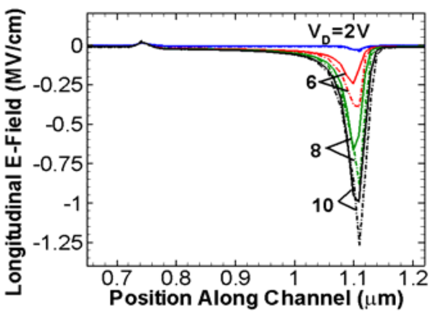

Figure 6: Electric field for DD model with (solid) and without (dashed) AlN IL.

ctron depletion of the channel below the gate edge, as is seen in Fig. 1, which takes place due to electron transfer from the channel to the STs. This escape in turn is stimulated by the hot-electron effect (high T_n) in the high-field region. Since electrons in the DD model remain at room temperature even at high fields, trap repopulation does not occur. As a result, the width of the depletion region varies little above the pinch-off bias. In the HD model the expansion of the hot electron depletion domain also leads to a considerably smaller longitudinal electric field compared to the DD model, as is seen in Figs. 4 and 6. The profiles of n, T_n, and E_L along the channel are strongly influenced by the energy relaxation time in AlGaN layer. Figs. 7 and 8 shows results for τ_ε=0.01 ps. As is seen these distributions are very similar to those from the DD model. The FP effect in the HD model also increases in this case.

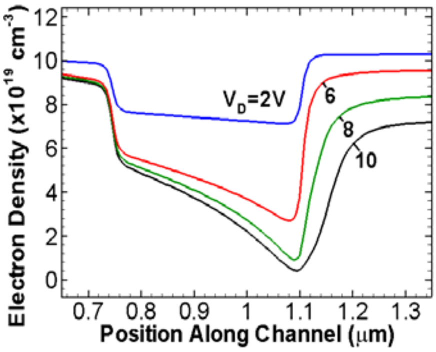

Figure 7: Electron density in HD model with AlN IL and τ_ε=0.01 ps in AlGaN.

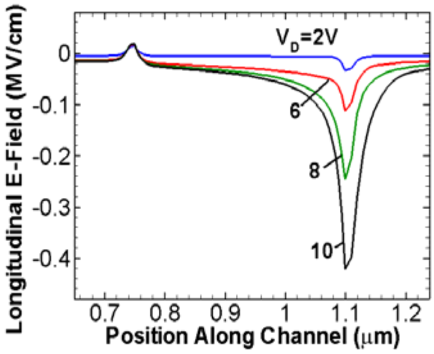

Figure 8: Electric field in HD model with AlN IL and τ_ε=0.01 ps in AlGaN.

4 Conclusions

The DD and HD simulation of HEMT confirmed that the AlN IL increases the 2DEG density and reduces the ST reoccupation. The energy relaxation time in the AlGaN layer has a strong effect on the transport properties of the hot electrons in the channel.

5 References

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