A Self-Consistent Charge-Control Model for HEMTs Incorporating Deep Level Effects

Ranjit Singh and Christopher M. Snowden

Microwave and Terahertz Technology Group,
Department of Electrical and Electronic Engineering,
University of Leeds, United Kingdom

Abstract

A new self-consistent charge-control model which includes models for realistic trapping processes is described for a high electron mobility transistor (HEMT). This generalised HEMT model takes into account the effects of deep levels both in semi-insulating GaAs and doped AlGaAs layers. It is shown that conventional charge-control models are insufficient to describe HEMT operation near pinch-off and in the normally-on mode. The model is used to investigate the effects of Fermi-level pinning at the semi-insulating interface on the device performance and is shown to lead to less injection of electrons into substrate.

I. Introduction

An understanding of the trapping mechanism in HEMTs is very important for developing accurate models for HEMT characterisation. Trapping of electrons in doped AlGaAs layer and semi-insulating (SI) GaAs substrate is not only responsible for different anomalies observed at cryogenic temperatures but limit the device performance at 300K as well. Examples include the collapse of I-V characteristics, decrease in both maximum transconductance and in the gate voltage swing, shift in pinch-off voltage, slow transients in switching, and generation-recombination noise. These effects become more pronounced in very short channel HEMTs for millimeter-wave applications. Although trapping phenomena are very important in determining the characteristics of HEMTs and there has been significant amount of research directed towards understanding the basic physics of deep levels in doped AlGaAs layers[1]-[2] and SI substrate [3]-[4], there has been little theoretical effort devoted to incorporating trapping mechanisms in the device models. The influence of Fermi-level pinning at the GaAs substrate on HEMT operation has been discussed by Krantz et al [5] using analytical expressions. Shawki et al [6] have included in their two-dimensional model the trapping process associated with the doped AlGaAs layer by assuming that all donors are electrically active as DX centers. They demonstrated that the DC transconductance can be lowered as much as 60% due to electrons trapped in the doped AlGaAs layer. Japanese work [7] has confirmed that DX centers are also present in n-type GaAs and become the ground state when pressure exceeds 20 K bar. This result provides the strong evidence that DX properties are associated with isolated donors. The measurement work done at IBM Thomas J. Watson Research Center [2] has further shown that there is a strong variation of trapping kinetics with change in alloy composition of $Al_xGa_{1-x}As$. These results strongly suggest that trapping models should include more than one donor level.

In our recent paper [8], we have presented a more realistic three-level trapping model for doped AlGaAs layer. In this paper we present a new self-consistent charge-control model which includes realistic trapping processes in both the doped AlGaAs and SI substrate. The model provides a natural explanation of the published experimental results related to trapping mechanisms and demonstrates the role of deep level states on the operation of single-, multi-channel, inverted and pseudomorphic HEMTs.

II. The Charge-Control Model

In this section a self-consistent charge-control model incorporating deep level effects is developed by modifying the Poisson equation to include trapping effects. Based on the results of a self-consistent quantum mechanical model, which shows that most of the electron reside in first three quantum energy levels, and on the study of Yoshida [9] that a classical model with Fermi-statistics predicts the device performance with good accuracy, a fast and accurate charge-control model is developed. The present model is based on self-consistently solving Poisson and Schrödinger equations for a maximum of up to three quantum energy levels and applying a classical model with Fermi-statistics for the remaining electrons. The self-consistent quantum mechanical model has been described in the literature [9]-[10] and only the broad principle will be described here. The electrostatic potential is related to charge-distribution by Poisson equation

$$\frac{\partial}{\partial x}\left(\epsilon \frac{d}{dx} V(x)\right) + \rho(x) = 0 \tag{1}$$

where ρ is the net local charge density, and the envelope wavefunction Ψ_i for the ith sub-band satisfies the schrodinger equation

$$\frac{\hbar^2}{2}\left[\frac{d}{dx}\left(\frac{1}{m^*}\frac{d\psi_i}{dx}\right)\right] + \left[E_i - V_t(x)\right]\psi_i(x) = 0 \tag{2}$$

where m^* is the effective mass, E_i is the eigen energy for the ith sub-band and V_t is the potential including the local exchange correlation coefficient. The Fermi level is assumed to be constant throughout the semiconducting layers in equilibrium and the self-consistent solution of equations 1 and 2 gives the accurate band profile, sub-band energies and Fermi level.

A. The Substrate Trap Model

A high density of both donor- and acceptor-like traps exists in the SI substrate. It is generally accepted that there are up to 4 traps which are important in determining the properties of SI

GaAs [3]-[4] and only these traps are included in the present charge-control model. The first of these is EL2 level deep donor which resides at an energy level 0.8eV below the conduction band edge in concentrations ranging between 10^{20} and 10^{23} m^{-3}. The shallow donor and acceptor traps are generally present in concentration of about 10^{23} m^{-3}. The shallow donor is attributed to silicon introduced from the walls of reactor vessel and shallow acceptor is associated to carbon. Finally, a deep acceptor level is present at an energy level about 0.8 eV above the valence band edge. The local net charge density in SI substrate is given by

$$\rho = q\left[N_D + N_{DTs} + N_{DTd} - N_{ATs} - N_{ATd} - n + p\right] \tag{3}$$

where N_D is the doping density, N_{DTs}, N_{DTd} are the net densities of positive trapped charge in the shallow and deep donor traps and N_{ATs}, N_{ATd} are the net densities of negative trapped charge in shallow and deep acceptors traps respectively.

B. The Doped Channel Trap Model

The doped AlGaAs layer introduces several undesirable effects for HEMT operation. They are mainly related to large number of deep states which become dominant for Al mole fractions $\geq$ 0.22. The doped layer trapping mechanism is incorporated in the present charge-control model based on simple three donor-level model which is described in detail in our recent paper [8]. However, as we will refer to it in this paper, a brief description of it is included here for the sake of completeness. The doped donor atoms can occupy either of the three donor levels, shallow, deep, or DX. The total donor doping density in our model is given by the sum of the densities of the three donor levels. This model is consistent with the models treated theoretically by Morgan [1] and also accounts for experimental results obtained by Mooney et al [2]. The local net charge density in AlGaAs layer is given by

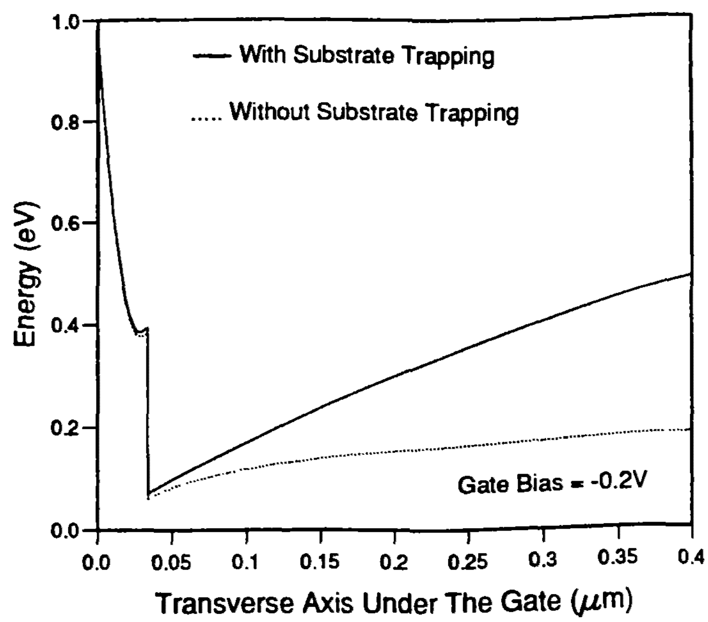

Figure 1. Conduction band energy of a single channel HEMT along the transverse axis under the gate.

$$\rho = q\left[N_D - N_{sT} - N_{dT} - N_{DXT} - n + p\right] \tag{4}$$

where N_{sT}, N_{DT}, N_{DXT} are respectively the net densities of electrons trapped in the shallow, deep and DX levels.

C. The Trap Filling Factor

In HEMTs, the density of mobile carriers depends on the electron trapping in the trap levels. The filling of these trap levels is calculated based on a Shockley-Read-Hall model [11]-[12] for recombination through a single level. The donor traps are positive when empty (i.e. when occupied by holes) and neutral when filled (i.e. when occupied by electrons), and acceptor traps are negative when filled and neutral when empty.

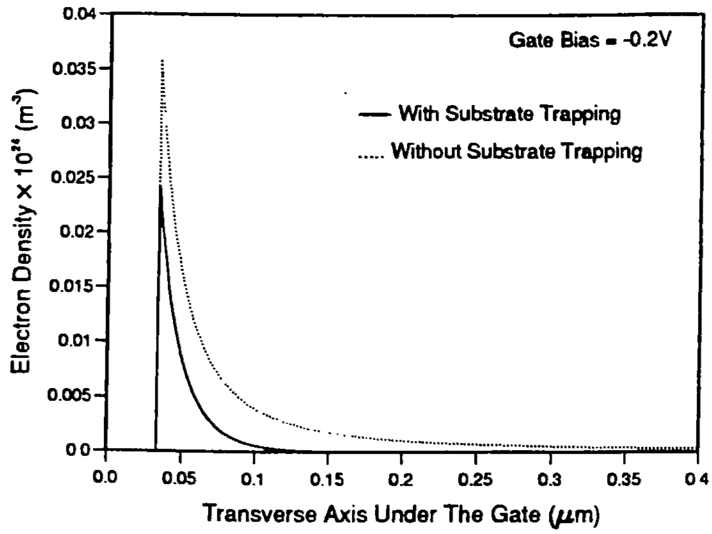

Figure 2. Electron density of a single channel HEMT along the transverse axis under the gate.

III. Results and Discussions

Figures 1 and 2 respectively show the single-channel HEMT's conduction band energy and electron density along the transverse axis under the gate, with and without the SI substrate trapping effect. The simulation results have shown that trapping in the SI substrate have a significant effect near pinch-off. The pinning of the Fermi level at the SI interface makes the conduction band more abrupt and an interface depletion region is formed. This results in decreased electron density near the SI interface due to narrowing of the channel. At the same time this leads to greater confinement of channel electrons and less substrate electron injection. Due to improved carrier confinement with the SI substrate, the device has good pinch-off characteristics.

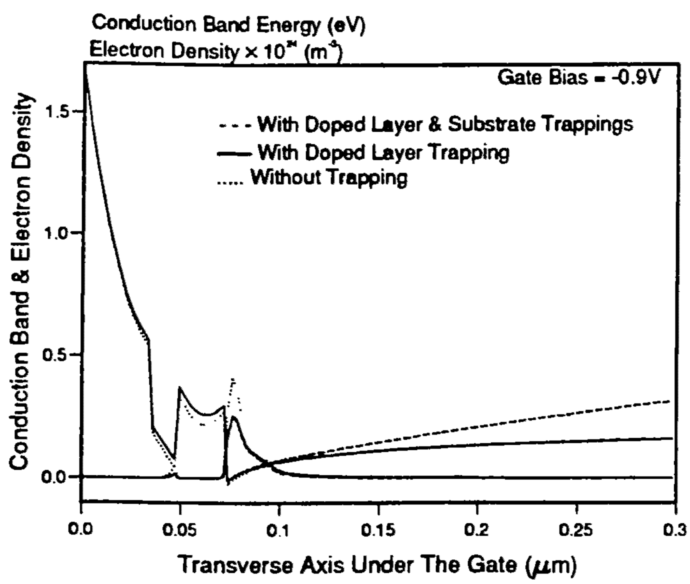

Figure 3. Conduction band energy and electron density of a two channel HEMT along the transverse axis under the gate.

The simulation results have shown that doped layer trapping effects become more important as the gate-source voltage is made more positive. This is due to the increase in parallel current in doped AlGaAs layer and saturation of two-dimensional electron gas which no longer responds to variation in gate voltages. This demonstrates the decrease in maximum trans-conductance and collapse of IV characteristics at high gate voltages. Figure 3 shows the charge-control results of a two-channel AlGaAs/GaAs HEMT and demonstrates that doped layer trapping effect is dominant for all the gate-biases. In multi-channel HEMTs, the effect of trapping is more pronounced in the second doped layer because parallel current in it flows for almost all the gate-bias voltages. In pseudomorphic HEMTs, the effect of the SI substrate is less pronounced.

IV. Conclusions

We have developed a new self-consistent charge-control model for HEMTs that includes trapping effects in the SI GaAs substrate and doped AlGaAs layer and provides a physical understanding of short channel HEMT operation. It is expected that the present charge-control model will be useful in developing more realistic and accurate models for HEMTs.

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