Experimental and theoretical studies of near-breakdown phenomena in GaAs-based heterostructure FETs

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July 23, 1999

Abstract

We have investigated electrical and optical phenomena related to impact ionization in the near breakdown regime of heterostructure FETs. The experimental analysis is based on electroluminescence spectroscopy correlated to minority carrier gate current measurements. Such experiments are interpreted by means of Monte Carlo simulations.

1 Introduction

Recently, experimental and theoretical analysis have shown that one mechanism leading to on-state breakdown is the accumulation, of holes generated by impact-ionization in the channel and in the buffer or donor layers between gate and source [1, 2, 3].

Accumulation of holes enhances injection of electrons from source to the channel, which induces further impact-ionization. This mechanism may lead to device breakdown and burn-out, and causes an increase in output conductance and kink effects. Most of the above mentioned studies, however, refer to DC conditions, and only a few works [4, 5, 6] have considered high frequency pulsed behavior, which could be more relevant for microwave and millimeter-wave applications of HEMTs.

Spectroscopic analysis of electroluminescence (EL) has been extensively used to characterize hot carrier effects in MESFET's and HEMT's, starting from the works of Zanoni et al. [7], Zappe et al. [8] and R. Ostermeir et al. [9]. Electroluminescence spectra provide useful information in the near breakdown regime[10, 11] as they are related to both hot carrier effects and electron-hole recombination processes.

In this paper we report on the study of near-breakdown effects in 0.25 μm pseudomorphic HEMT's (P-HEMT's). A comparison with AlGaAs/GaAs doped channel HFET's is also given. Electroluminescence spectra are measured and compared with Monte Carlo simulations.

2 Analysis of electroluminescence spectra

A 2D self-consistent Monte Carlo code, accounting for 3 conduction valleys and 3 valence bands has been adopted. Poisson equation is solved by applying a multi-grid technique. Dynamical weighting of the particles which are in sparsely populated phase space regions has been used. Impact ionization has been described by a modified Kane model [12].

This simulator allows us to follow the dynamic evolution of the holes generated by impact ionization in the high field region of the channel.

The simulated device consists of a highly doped GaAs cap layer, a 28 nm $Al_{0.2}Ga_{0.8}As$ upper barrier layer with an active Si doping concentration of $N_D = 10^{17} cm^{-3}$, a 2 nm undoped $Al_{0.2}Ga_{0.8}As$ upper spacer layer, a 130 nm $In_{0.15}Ga_{0.95}As$ undoped channel layer, 550nm $Al_{0.2}Ga_{0.8}As/GaAs$ superlattice, and a tick undoped GaAs layer The $Al_{0.2}Ga_{0.8}As$ barrier layer above the channel contains an delta-doping layer with an active doping concentration of about $5 \cdot 10^{12}\ cm^{-2}$. A symmetric recess for the gate with length $L_g = 0.25\ \mu m$ was adopted.

Biased at high drain voltage, the electrons in the channel become energetic enough to start impact ionization in the high field region of the channel. To analyze the influence of holes onto the drain current, we monitored the hole density in the device as a function of time (Fig.1). We find that the majority of holes generated in the high field region of the channel follow three paths. They either spill over to the barrier layers out the region where they are created, or move along the channel towards the source contact. The holes in the upper barrier layer move directly to the gate contact, where they are collected to form the gate current. The holes moving along the channel towards the source contact first accumulate under the gate contact (~ 10-20 ps). Some of them move further towards the source contact and accumulate in the source sided part of the channel. The rest of the holes move into the substrate.

The presence of electrons and holes in the InGaAs channel open the way for radiative recombination processes leading to band edge electroluminescence. As already discussed above, the holes generated in the drain sided high field region of the channel partially moves towards the gate contact while the rest is swept towards the source contact or moves towards the substrate. The main overlap between cold electrons and holes can be found in the source side of the channel. However, at high V_{DS} holes gain enough energy to move in the cap layer and recombine with electrons. As a first estimate, the emitted light intensity can be considered to be proportional to the product of electron and hole density, as shown in Fig.2. This suggests the following scenario. At short times (20 ps) holes and electron begin to recombine at the source-end of the gate region, due to their accumulation in the gate induced potential valley.

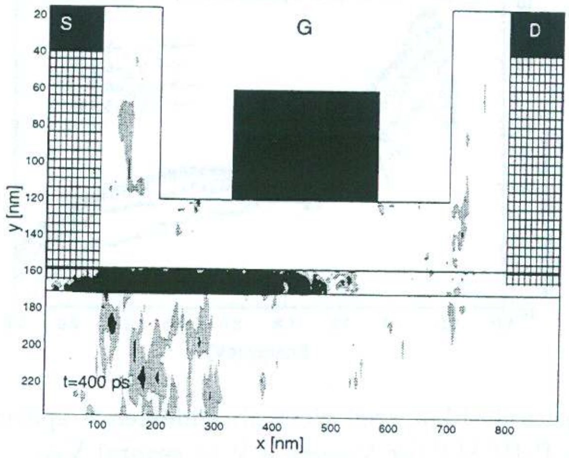

Figure 1: Holes density at 400ps after switching-on the impact ionization in HEMT for V_{DS}=6.5, V_{GS}=-0.6 V

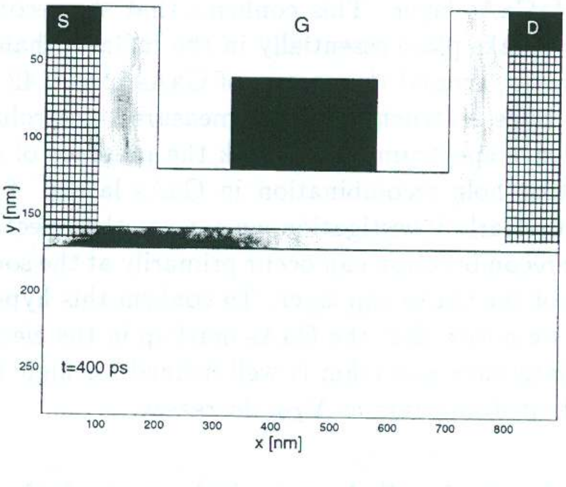

Figure 2: Here we show the $n \cdot p$ product which is proportional to the light emission in the P-HEMT. Light emission occurs in the gate-source region of the HEMT. Here V_{DS}=6.5 and V_{GS}=-0.6 V

On a time scale of ~150ps, however, hole accumulation takes place also in the source region of the channel, which seems to be in an accessible range for direct time resolved measurements.

In order to compare with experimental electroluminescence results we have measured the room tem-

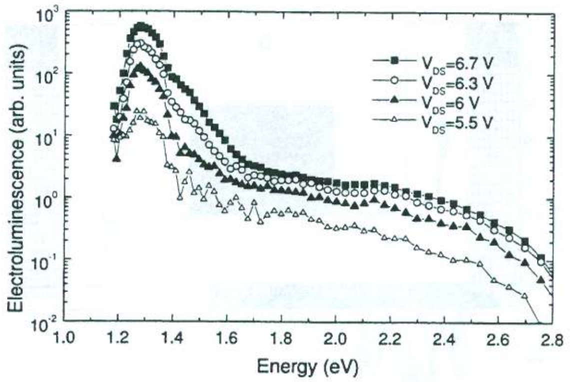

Figure 3: Measured electroluminescence spectra of the P-HEMT for V_{GS}=0.0 V at several V_{DS}

perature electroluminescence spectra of the above P-HEMT by using a cooled Hamamatsu photomultiplier and a monochromator. The measurement have been performed in the Optoelectronic Laboratory at the University of Rome "Tor Vergata". Figure 3 shows the measured electroluminescence spectra of the P-HEMT for V_{GS}=0.0 V at several V_{DS}. The electroluminescence spectra show a maximum around 1.3 eV which is actually the energy gap of the InGaAs layer. This confirms that the recombination take place essentially in the InGaAs channel. However, around the energy of GaAs gap (1.42 eV) we notice a structure in the measured electroluminescence spectrum. This mark the presence of cold electron-hole recombination in GaAs layers. From Monte Carlo investigation we can see that electron-hole recombination can occur primarily at the source side of the GaAs cap layer. To confirm this hypothesis we notice that the GaAs markup in the electroluminescence spectrum is well defined for high V_{DS} while it disappears as V_{DS} decreases.

3 Analysis of electrical characteristics

Figure 4 shows the simulated gate current (I_G)as a function of V_{GS}. The typical 'bell-shaped' behavior of I_G, which is the signature of impact-ionization in HEMT devices is correctly emulated by the simulation program. The simulation allows us to confirm that the behavior of the gate current arises from the interplay between the increase of the number of electrons in the channel and the decrease of their energy by opening the channel.

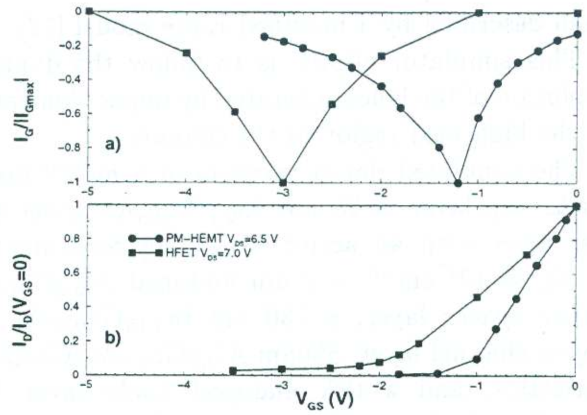

Figure 4: Normalized a)I_G and b)I_D induced by impact ionization

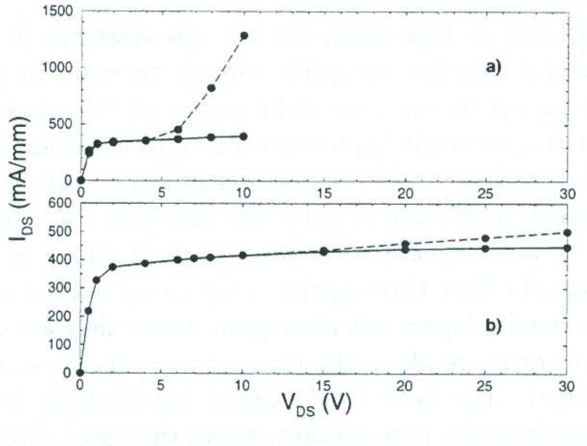

Figure 5: Simulated HEMT characteristics for V_{GS}=0.0. With (continuous line) and without impact-ionization (dashed line): a) P-HEMT, b) HFET

For V_{GS}=0.0 V, breakdown occurs at $V_{DS} \simeq 10$ V, see Fig. 5a, which shows the simulated devices output characteristics with and without impact-ionization. To evaluate the transient behavior of impact-ionization effects, the drain current was simulated, without impact-ionization, until it reached its steady-state value; impact-ionization was then switched on (time t=0 in Fig. 6). The presence of impact-ionization induces a transient in the I_D current, which increases and reaches its new steady-state value in 200 ps, approximately. The observed increase in I_D and output conductance is not simply due to the contribution of generated hole-electron pairs to the device current, but is a consequence of

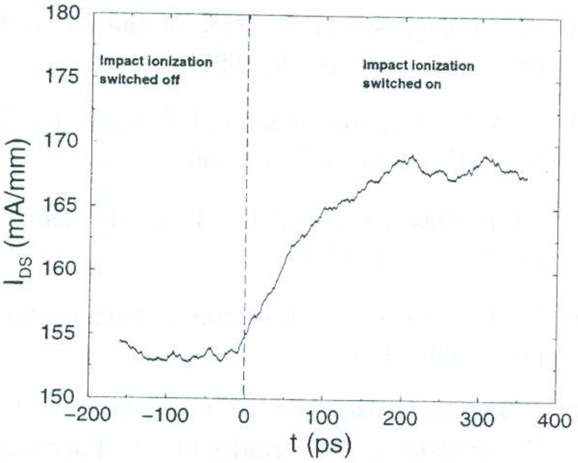

Figure 6: Simulated time dependence of drain current for HEMT obtained at V_{DS}=6.5, V_{GS}=-0.6 V. At t=0 ps the impact ionization process is switched-on

the accumulation of holes in the gate-source channel region and in the substrate, which promotes further electron injection from the source ("parasitic bipolar effect"). The relatively long time required for the observation of breakdown effects due to generated holes may lead to significant differences between DC and rf breakdown characteristics.

4 Comparison with AlGaAs/GaAs HFET

In order to compare the performance of P-HEMT with other heterojunction devices we have simulated an AlGaAs/GaAs HFET. The device layer sequence is the following: undoped GaAs substrate, undoped AlAs/GaAs buffer superlattice, 75 nm $4 \cdot 10^{17}$ cm^{-3} n-doped GaAs, 200 nm $2 \cdot 10^{17}$ cm^{-3} n-doped AlGaAs, and a highly doped GaAs cap layer. The gate length is 0.7 μm. Gate and drain current are shown in Figs 4 and Figs 5 and are compared with equivalent P-HEMT characteristics.

The GaAs/AlGaAs HFETs, exhibit a similar behavior of the gate current vs gate-to-source voltage, however, the maximum of the curve is shifted with respect to the P-HEMTs to lower V_{GS} voltage. This has also been experimentally observed[13] and it is related to the pinch-off condition. Indeed, the maximum of the gate current always occur in correspondence of the near pinch-off bias which is in absolute value higher for the HFET than for the P-HEMT. In the simulated HFET device the breakdown occur at larger values of V_{DS} if compared with the simulated P-HEMT. Figure 5b shows, indeed, that differences in the I_{DS} vs. V_{DS} HFET characteristic with and without impact ionization is observable only for $V_{DS} > 20$ V while for the P-HEMT breakdown is reached already for $V_{DS} \simeq 10$ V. Figure 7 shows the I_{DS} vs V_{DS} characteristic of the HFET for several V_{GS} with and without impact ionization processes. For near pinch-off condition, the breakdown occurs at lower V_{DS} with respect to open channel conditions.

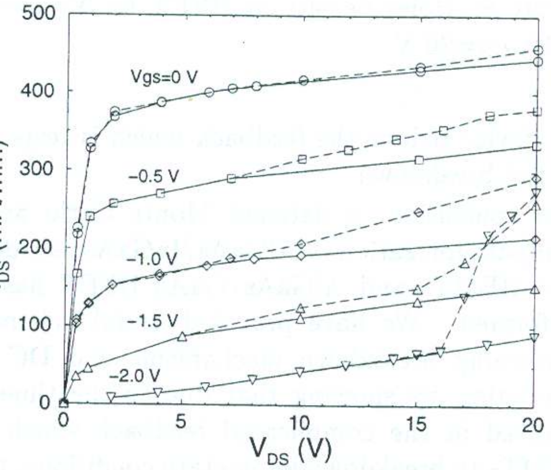

Figure 7: Simulated electrical characteristic of HFET device. With (continuous line) and without impact-ionization (dashed line)

The higher breakdown voltage of the HFET with respect to the P-HEMT cannot be attributed to the higher band gap of GaAs with respect to the InGaAs. On the contrary, GaAs has a higher impact ionization coefficient with respect to the strained InGaAs[14]. The reason for the P-HEMT prebreakdown behavior seems to be related to several factors, among with the peak electric field and hole confinement. In fact in the P-HEMT holes are confined in the channel and are able to produce both bipolar effect and secondary electrons which in turn will impact ionize to produce the breakdown condition. In the HFET holes are less confined in the channel and leave the active region of the device moving both in the gate and in the substrate (see Fig. 8). The absence of holes in the active part of

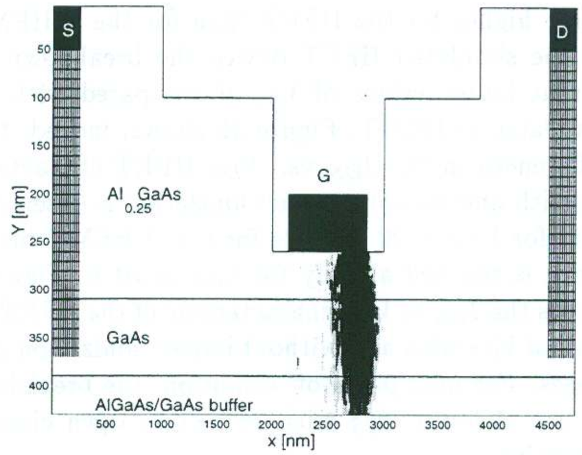

Figure 8: Holes density in HFET for V_{GS}=-1.5 V and V_{DS}=20 V

the device reduce the feedback which is responsible for the breakdown.

In conclusion, a detailed Monte Carlo analysis of impact-ionization in AlGaAs/InGaAs pseudomorphic HEMTs and AlGaAs/GaAs HFET has been performed. We have provided useful information concerning breakdown mechanisms and DC characteristics, by showing that due to the timescales involved in the complicated feedback which leads HEMTs to breakdown in on-state conditions, the effects of impact-ionization under rf drive may be significantly different from those observed in DC. The results show that impact ionization effects are reduced in HFET's with respect to HEMT's. Thus, simple heterostructure HFET's represent a good compromise for obtaining good rf performance at the high end of microwave frequency range.

The work was partially supported by the INFM-PAIS project.

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