Physical analysis of the breakdown phenomenon between single or double step gate recess HEMTs

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Abstract — **This paper deals with the avalanche breakdown phenomenon in AlGaAs/GaInAs/GaAs PHEMTs. In order to optimize the structure and to improve the breakdown voltage in this component type, it is necessary to study the influence of the physical parameters on which this phenomenon depends, such as the gate recess topology. The study is based on a two-dimensional hydrodynamic simulation, that takes electrons and holes into account. It is reported that the highest breakdown voltage is obtained for a double step gate recess.**

I. Introduction

The avalanche breakdown phenomenon constitutes one of the main limitations of High Electron Mobility Transistors (HEMTs) for microwave power amplification. The physical understanding of this phenomenon is essential for studying and improving the breakdown voltage. In this work, we propose to analyse the influence of the gate recess topology on this phenomenon. We have used the hydrodynamic model, which has been described by several authors [1,2] because it can provide accurate results with a reasonable computational cost. Thus, it is a good way to optimise a component and to reduce the manufacturing cost point.

This model is obtained from the Boltzmann's transport equation using the method of the momentum. A set of conservation equations for the following macroscopic average quantities is obtained: electrons and holes velocities, carrier density and energy of the electrons.

In section 2, a generalised hydrodynamic model, which includes the avalanche breakdown phenomenon in the channel, is presented. Indeed, the minority carriers and the generation and recombination terms are taken into account in the conservation equations. In section 3, the AlGaAs/GaInAs/GaAs pseudomorphic HEMT with single step gate recess is studied. First, the experimental and theoretical $I_{DS}(V_{DS},V_{GS})$ characteristics are compared. Then the structures with single or double step gate recess are compared.

II. MODEL DESCRIPTION

The numerical model is based on the conservation equations of semiconductors deduced from Boltzmann's equation and coupled with Poisson's equation. The equations used are:

Continuity equations for electrons or holes

$$\frac{\partial n}{\partial t} + \mathrm{div}(n\vec{v}_n) = G - R$$

and

$$\frac{\partial p}{\partial t} + \mathrm{div}(p\vec{v}_p) = G - R$$

where n is the electron concentration and p the hole concentration.

In these equations, the band to band recombination rate R is modelled by using the following expression:

$$R = k\left(np - n_i^2\right)$$

where n_i is the intrinsic carrier concentration and the constant k is $2\ 10^{-16}\ m^3/s$ [3].

The generation rate G is given by:

$$G = \alpha_n n|\vec{v}_n| + \alpha_p p|\vec{v}_p|$$

The ionisation coefficients, α_n for the electrons and α_p for the holes, are defined as the number of electron-hole pairs created by carrier and by unit of length in the direction of the applied electric field. They are given by the following equation [4]:

$$\alpha_{n,p}(E) = \frac{qE}{w_i}\exp\left(A - \sqrt{A^2 + X^2}\right)$$

w_i is the ionisation threshold energy at high field, E is the electric field, A and X are given by the following equations:

$$A = 0.217\left[\frac{w_i}{\langle w_p \rangle}\right]^{1.14} \quad \text{and} \quad X = \frac{w_i}{qE\lambda}$$

with $$\lambda = \lambda_0 \tanh\frac{w_p}{2k_B T_e} \quad \text{and} \quad \langle w_p \rangle = w_p \tanh\frac{w_p}{2k_B T_e}$$

w_p is the energy of the optical phonons, λ_0 is the asymptotic value of the mean free path at high energy and low temperature, k_b is the Boltzmann's constant and T_e is the electronic temperature.

Energy conservation equation:

$$\frac{\partial nw}{\partial t} = -qn\vec{v}\vec{E} - \nabla\vec{S}_n - \frac{n(w - w_0)}{\tau_w} - w.(G - R)$$

S_n is the energy flow for electrons, given by:

$$\vec{S}_n = \vec{Q}_n + [w + k_B T_e(w)]n\vec{v}$$

where the heat flux Q_n is given by the Wiedeman Frantz law [5]:

$$\overrightarrow{Q}_n = -\kappa \overrightarrow{\nabla T_e}$$

and κ is the thermal conductivity of the considered carrier gas, given by:

$$\kappa = (\frac{5}{2} + c)(\frac{k_B}{q})^2 qn\mu T_e$$

The conservation equation for the hole energy is not taken into account in our model because the hole velocity is low. A drift diffusion model is used for these minority carriers.

Velocity equations for electrons and holes

$$\overrightarrow{v_n} = \mu_n[-\vec{E} - \frac{1}{n}\vec{\nabla}(nk_B T_e)]$$

and

$$\overrightarrow{v_p} = \mu_p[\vec{E} - \frac{1}{p}\vec{\nabla}(pk_B T_0)]$$

Poisson's equation

$$\nabla(\varepsilon_0 \varepsilon_r \vec{E}) = q(N_d^+ - n + p)$$

The evolutions of $k_B T_e$, μ_n, μ_p and τ_w with energy are obtained from a three valleys Monte-Carlo bulk simulation in stationary regime [6].

The equations are discretised with a finite difference method using a non-uniform mesh where the variables are the potential V, the electron density n, the hole density p and the electron energy w.

This model enables us to obtain the distribution of the physical quantities in the device and the I (V) output characteristics as well as the main elements of the small signal equivalent circuit.

III. SIMULATION RESULTS

Basic structure study

Basic structure is : AlGaAs/InGaAs/GaAs pseudomorphic HEMT with single step gate recess and two delta-doped layers made by United monolithic semiconductor (UMS). The schematic cross section of this structure is shown in figure 1.

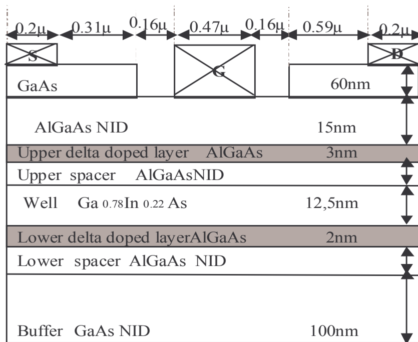


Fig 1: Schematic cross section of AlGaAs/GaInAs/GaAs pseudomorphic HEMT

Comparison with measurements

In order to validate the hydrodynamic model used, it appeared very useful to compare the theoretical predictions with the experimental results.

The comparison between the simulated and experimental drain-current versus drain-source voltage characteristics (figure 2) for the previously described structure, shows that the experimental results fit well agreement with the theoretical results. By comparing the breakdown voltage, the theoretical one is about 6V and the experimental one is 5.5V.

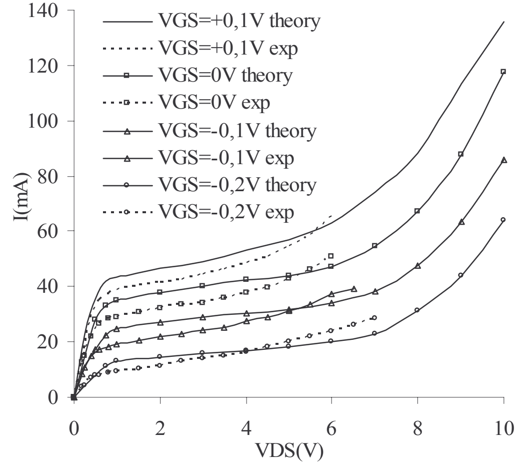


Fig 2: **E**xperimental and calculated $I_{DS}(V_{DS}, V_{GS})$ characteristics

Gate recess influence

With the help of our model, the results obtained with a single or a double step recess topology are compared. The epitaxial layers of double step gate recess structure have the same as the ones of the single step gate recess structure. The length of the narrow gate recess step is 0.16 µm and the length of the wide one is 0.44µm.

The physical quantity distributions (electron and hole concentration, energy of the electrons) and the generation rate of single or double step gate recess structure are shown in figure 3. It can be noted that the maximum energy takes place in the channel at the gate exit for the two structures. The electron energy drops while it moves towards the drain for a double step gate recess structure. The generation is located where the energy is the highest and it is more important in the single step gate recess structure. The hole most part moves towards the source and a small part is collected by the gate.

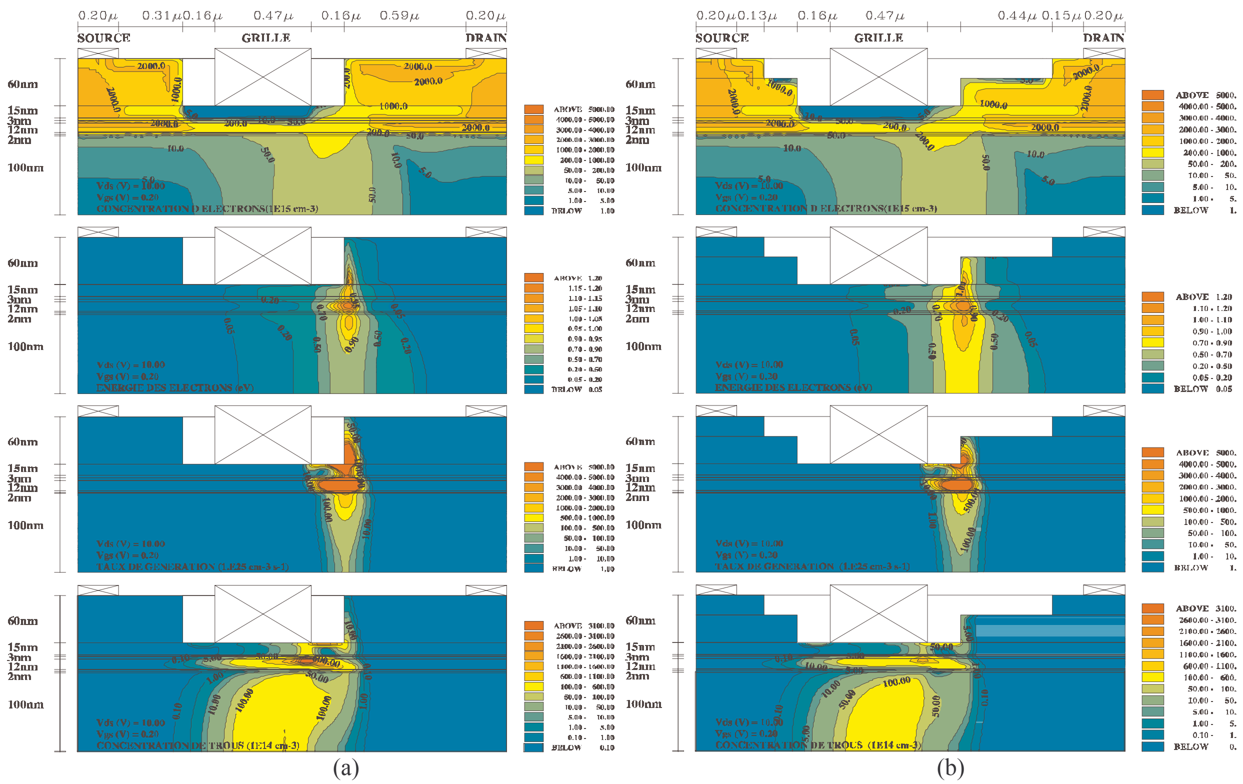


Figure 3: Physical sizes distribution with V_{GS}=+0,2V and V_{DS}=10V for a single (A) and a double (b) step gate recess

The longitudinal evolutions of the carrier energy and the generation rate (fig 4) show that the average energy in the well is more important for the structures with a single step gate recess. In the structure with a double recess, the average energy spreads towards the drain while keeping a maximum located under the first step recess. The generation rate is twice lower in the structure with a double step recess involving a larger breakdown voltage. The carrier evolutions of the two structures (fig 5) show a strong decrease of the carrier concentration (electrons and holes) for the double step gate recess structure.

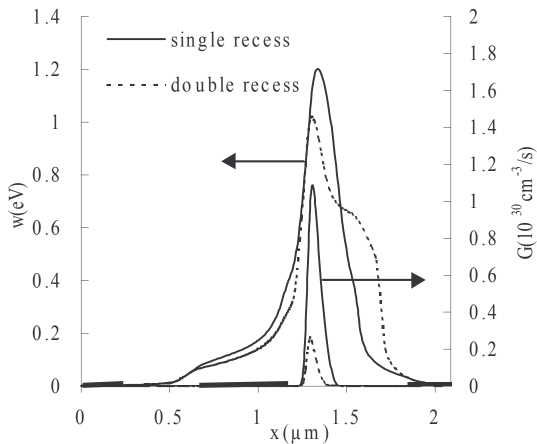


Fig 4: Average electron energy and generation rate in the channel for a single and a double step gate recess (V_{DS}=10V and V_{GS}=+0.5V).

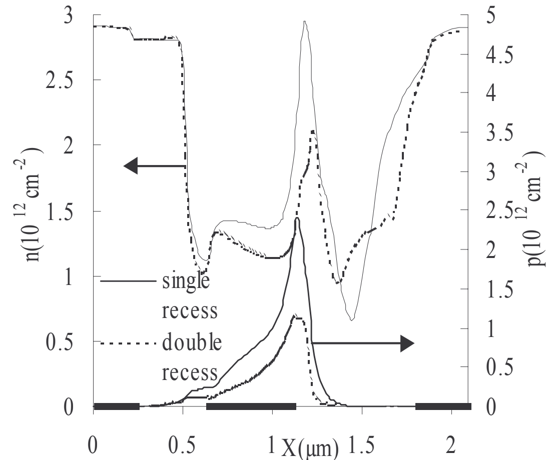
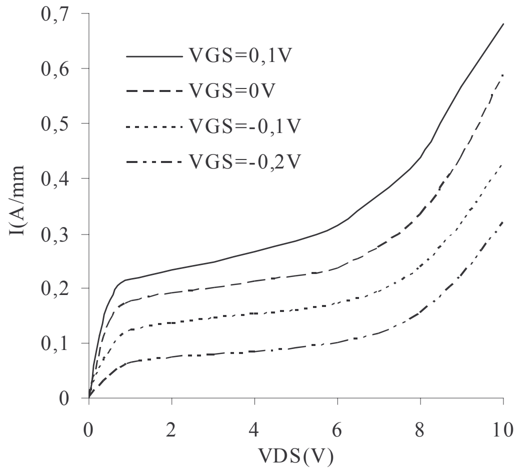
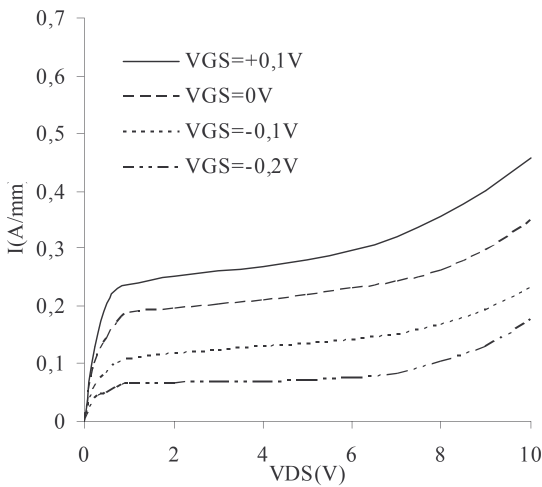


Fig 5: Average electron and hole density in the channel for a single and a double step gate recess (V_{DS}=10V and V_{GS}=+0.5V).

The $I_{DS}(V_{DS}, V_{GS})$ characteristics for the structure with a single or a double step gate recess, (fig 6) clearly show that I_{DS} is slightly smaller in the structure with a double step gate recess. The breakdown voltage is around 6V for the structure with the single step gate recess whereas it is around 8V for the double step recess device.



(a)



(b)

Fig 6: $I_{DS}(V_{DS}, V_{GS})$ characteristics for a single (a) or a double step gate recess (b).

VI. CONCLUSION

The model constitutes a useful tool for the optimisation of the avalanche breakdown voltage taking into account realistic topologies of single or double step gate recess. Because of the significant number of technological parameters and the complexity of the device, such a model constitutes a particularly useful tool for the transistor designer in order to reduce the development costs despite the large computing time due to the model complexity.

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