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AVALANCHE AND TUNNELING BREAKDOWN MECHANISMS IN HEMT'S POWER STRUCTURES

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Résumé - Cet article expose une étude sur le phénomène de claquage dans les HEMTs de puissance AlGaAs/GaAs. Il fait usage, d'une part, de résultats expérimentaux obtenus sur différents composants test et, d'autre part, de modélisations prenant en compte soit l'ionization soit l'effet tunnel. Cette approche apporte une nouvelle compréhension sur les rôles respectifs de ces deux effets dans le déclenchement du claquage et permet de définir des règles de construction.

Abstract - The present paper reports a study on the breakdown phenomenon in AlGaAs/GaAs power HEMT's. It uses, on one hand, experimental results carried out on various test devices and, on the other hand, modeling taking into account either ionization or tunneling effects. Such an approach gives a new understanding on the respective roles of these two effects in the breakdown occurrence and allows to define design rules.

INTRODUCTION

AlGaAs/GaAs High Electron Mobility Transistors (HEMT's) are now able to operate up to 70-80 GHz for small signal amplification. They have also considerable potential in the fields of power amplification provided a high drain current and a high breakdown voltage can be achieved. The first requirement can be satisfied by multiple channel structures [1, 2, 3, 4]. The second one presents much more difficulty. Indeed, high doping level in AlGaAs layers is necessary to get high electron sheet density in the quantum wells, but a great attention must be paid to the design of the structure in order to avoid excessive electric field values in the gate vicinity while keeping an efficient charge control and a good dynamic behaviour under E.H.F. operations.

I - TYPICAL EXPERIMENTAL HEMT BREAKDOWN VOLTAGES

Figure 1a shows typical breakdown voltages V_{BR} of conventional single heterojunction HEMT's. As it can be noted V_{BR} is a decreasing function of the AlGaAs doping level N_D and reaches very low values above 10^{18} cm^{-3} . Measurements carried out on multiquantum well HEMT's have revealed a similar dependance on the layer lying underneath the gate. The design of this layer constitutes a key problem for power HEMT's. Nevertheless, a great improvement is achieved using pulse-doped structures [5] where a thin undoped AlGaAs layer separates the gate from the normally doped AlGaAs layer. As shown in figure 1b, such an arrangement can give a breakdown voltage of about 15V with only a slight dependance on the undoped layer thickness.

II - MODELING OF BREAKDOWN BY IONIZATION

In answer to the question about what determines the above breakdown behaviour, the first idea coming in mind is that of an ionization mechanism. This assumption has been investigated with a numerical model that computes the potential shape and gives the electric field distribution in the transistor under pinchoff conditions. This model solves Poisson's equation and current equation together

$$\begin{aligned} \nabla^2 V(x, y) &= -q/\epsilon [N_D(x, y) - n(x, y)] \\ J_n &= q[-\mu_n n(x, y) \text{grad } V(x, y) + D_n \text{grad } n(x, y)] = 0 \end{aligned}$$

and then computes on every electric field line the ionization integral $\int \alpha dl$, until this one is equal to unity. The ionization coefficient is expressed by $\alpha = A \exp -(B/E) \epsilon$, E being the electric field amplitude

with $A = 1.8 \cdot 10^7 \text{ m}^{-1}$, $B = 5.75 \cdot 10^7 \text{ V/m}$, $C = 1.82$ for GaAs.

and $A = 4.1 \cdot 10^7 \text{ m}^{-1}$, $B = 10^8 \text{ V/m}$, $C = 2$ for AlGaAs ($x = 0.26$).

Neglecting, in a first approach, the gate fringing effect and, therefore, using a one dimensional description along the y axis (normal to the gate), one obtains the results shown in figure 2a, with breakdown voltages of about 35 volt, for a homogeneous AlGaAs layer, whatever the doping concentration and the thickness are. Similar results are given in the case of a pulse-doped AlGaAs

layer, as shown in table 2b. All these results are far from the experimental ones which indicates that this one dimensional approach does not agree with reality. In a second approach, we have then used a true twodimensional description. Figure 3 shows the results obtained for a homogenous AlGaAs layer. A satisfying agreement with experimental data appears for $N_D < 7 \cdot 10^{17} \text{ cm}^{-3}$ but, above this value, there is a discrepancy which is more and more important as N_D increases. Applying the twodimensional treatment to the case of pulse-doped AlGaAs layers, we have found results very similar to those of figure 3, which is somewhat surprising. A detailed analysis has revealed that, despite important variations in the electric field paths under the major part of the gate, the avalanche condition $f_{adl} = 1$ is always realized close to the gate edge where the electric field reaches very high values because of the geometrical singularity and exhibits evolutions that depend only slightly on the layer arrangement. This situation is illustrated with typical examples of field configurations in figure 4.

III - MODELING OF BREAKDOWN BY TUNNELING EFFECT

As seen above, the gate edge is the locus of very high electric field values, so the possibility of tunneling effect at the Schottky contact must be taken into account. Two cases have to be considered. The first one concerns homogeneous doped AlGaAs layers and the second pulse-doped ones.

For the former case the electric field can then be assumed to decrease steeply in the gate vicinity. Therefore the emitter current can be considered as a pure tunneling current (thermionic contribution is negligible) and expressed by the following relation derived from Padovani and Stratton works [6]

$$J_T = (A II W_{oo} / kT) \frac{\exp \left[- \frac{2q \phi_B}{3W_{oo}} \left(\frac{eE_M}{2N_D q \phi_B} \right)^{-1/4} \right]}{\left| \frac{eE_M^2}{2N_D q \phi_B} \right|^{-1/4} \sin \left[\frac{IIkT}{W_{oo}} \left(\frac{eE_M^2}{2N_D q \phi_B} \right)^{-1/4} \right]}$$

where A = Richardson constant in metal

$$W_{oo} = q\hbar/2 (N_D/\epsilon m^*)^{1/2}$$

ϕ_B = Schottky barrier potential

E_M = electric field amplitude at the Schottky contact.

For the latter case the electric field can then be considered almost flat near by the gate. In this case, the tunneling effect results from both thermionic and field emissions and it can be expressed by the relation established by Chivé et al [7] for similar problems.

$$J_T = A \exp \left(- \frac{q \phi_B}{kT} \right) \times \left[\frac{1}{kT} \int_0^{q \phi_B} \exp \left(\frac{u}{kT} - c_o u^{3/2} \right) du + 1 \right]$$

with

$$c_o = \frac{4}{3\hbar q E_M} (2m^*)^{1/2}$$

Figures 5a and 5b show results of computations carried out with the above expressions assuming simply a one dimensional description. The comparison with experimental data gives a satisfying agreement and shows clearly that the tunneling effect is dominant for heavily doped layers underneath the gate. A more complete description would take into account gate fringing effect, space charge reaction and ionization altogether. We are developing such a treatment. Preliminary results indicate that breakdown voltages are probably slightly lower than shown in Figures 5a and 5b.

IV - TEMPERATURE TEST

Heating is the commonly used test that permits to distinguish between breakdown by ionization and/or tunneling effect. Indeed, the variation of the breakdown voltage with temperature is positive for the first case and negative for the second one. We have experimented this method on a lot of HEMTs, all of them having the uppermost AlGaAs layer homogeneous and highly doped. As expected, heating has proved that the involved breakdown mechanism is undoubtedly the tunneling effect. This is shown in Figure 6 with, for comparison, the corresponding behaviour of a typical MESFET (NE 720) indicating that, in this device, ionization is dominant.

CONCLUSION

The above analysis shows clearly that tunneling effect instead of ionization is the dominant mechanism of the breakdown phenomenon in HEMT's when the uppermost AlGaAs layer of these devices is heavily doped ($N_D > 7 \cdot 10^{17} \text{ cm}^{-3}$). Therefore, the achievement of high breakdown voltages requires

that this layer presents a pulse-doped profile with a thin undoped ($\approx 200 \text{ \AA}$) zone underneath the gate. The designer must pay great attention to this requirement when optimizing power HEMT structures.

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Fig. 1 : Experimental Breakdown voltage for conventional HEMTs with an homogeneous AlGaAs layer (a) and for pulse-doped HEMTs (b).

Fig. 2a : Calculated breakdown voltage and maximum electric field of a conventional HEMT as a function of the AlGaAs thickness for two doping concentrations. One dimensional modeling that only considers ionization.

Table. 2b : Calculated breakdown voltage and maximum electric field as a function of the thickness of the undoped AlGaAs layer for a MIS HEMT structure. One dimensional modeling that only considers ionization.