

Monte Carlo Study of the Dynamic Breakdown Effects in HEMT's

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Abstract—We present a theoretical investigation of the near-breakdown scenario in pseudomorphic high electron mobility transistors (HEMT's). We show that the main mechanism for the enhanced drain current is a parasitic bipolar effect due to holes, generated by impact ionization, which accumulate in the channel and in the substrate close to the source contact. The dynamic of this charge accumulation and of the consequent drain current increase is studied by means of a two-dimensional (2-D) Poisson Monte Carlo simulator.

I. INTRODUCTION

BETTER understanding of on-state and off-state breakdown mechanisms of HEMT's has been achieved in recent years [1]–[3]; in particular, experimental and theoretical analysis have shown that one mechanism leading to on-state breakdown is the accumulation, in the channel and in the buffer or donor layers between gate and source, of holes generated by impact-ionization [1], [3]. Accumulation of holes enhances injection of electrons, 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 analyzes have considered high frequency pulsed behavior, which could be more relevant for microwave and millimeter-wave applications of HEMT's. Vashchenko *et al.* [4] have studied drain breakdown of GaAs MESFET's in the ns and sub-ns range and demonstrated that a portion of holes that were generated near the drain is accumulated in the SI buffer near the n^+ source contact, and that device burnout can take place in sub-ns times. David *et al.* [5] estimated the time until breakdown as a function of gate-drain voltage in excess of BV_{GD} in GaAs MESFET's; they calculated typical times in the 20–240 ps range. More recently, Dunn *et al.* [6] carried out a Monte Carlo simulation of impact ionization in 1.2 μm MESFET's and show that

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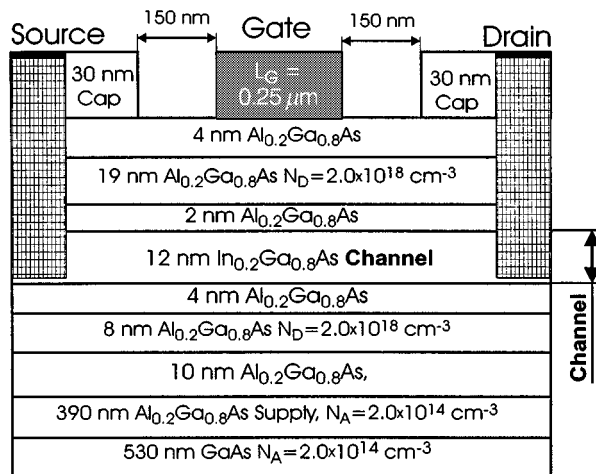


Fig. 1. Schematic cross section of the simulated double heterojunction HEMT (not to scale).

accumulation of holes and electrons can also be correlated with the onset of oscillations with a typical period of 5–10 ps.

In this paper, we describe the dynamical behavior of breakdown effects in 0.25 μm double heterojunction HEMT's by means of a Monte Carlo simulation.

II. SAMPLE DESCRIPTION AND EXPERIMENTAL SETUP

A two-dimensional (2-D) self-consistent Monte Carlo code, accounting for three conduction valleys and three valence bands has been adopted. Poisson equation is solved by applying a multigrid technique [7]. Impact ionization has been described by a modified Kane model [8], with parameters chosen so as to reproduce the experimental ionization coefficients of strained InGaAs measured by David and co-workers [9].

The general-purpose weighted Monte Carlo procedure (100 000 electrons) presented in [8] has been adopted to achieve a correct description of the physics of HEMT breakdown. We simulated a 0.25 μm double heterojunction AlGaAs/InGaAs HEMT's, whose schematic cross section is depicted in Fig. 1. Experimental characteristics have been described in [3]. An n^+ region was introduced under the source and drain metallic contacts (see grid area in Figs. 1 and 3) in order to facilitate electron injection into the channel and to properly reproduce the ohmic portion of the measured current–voltage (I – V) characteristics.

When the HEMT is biased at high drain voltage ($V_{DS} > 4V$), the strong electric field at the gate-end of the channel heats up

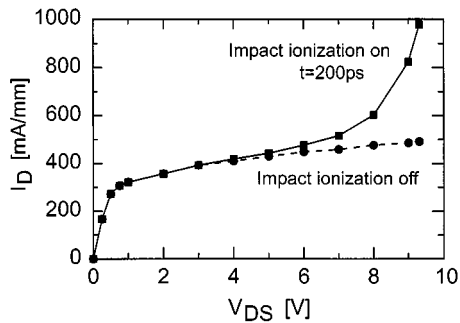


Fig. 2. Simulated output characteristics for $V_{GS} = -0.2$ V with and without impact-ionization.

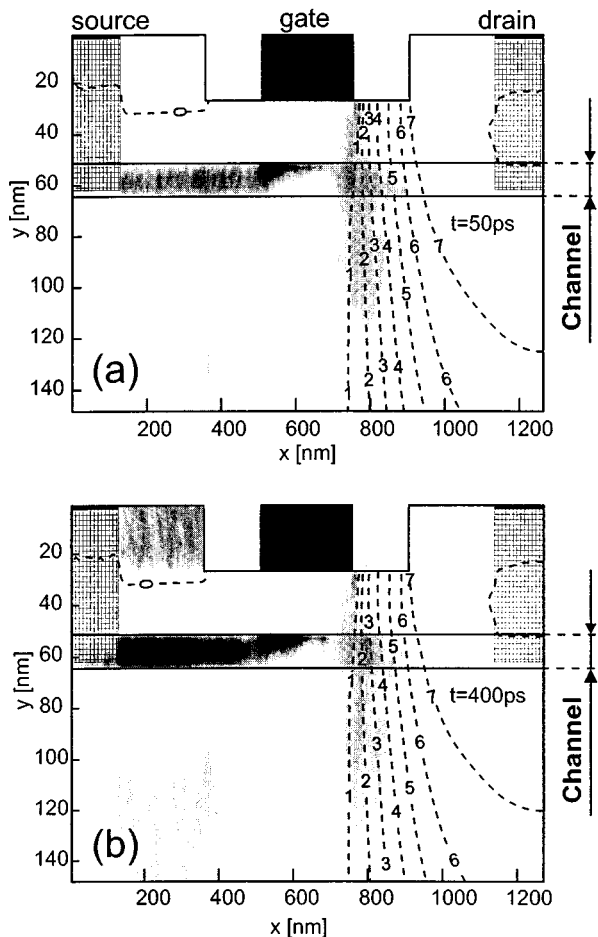


Fig. 3. Hole density at two time values after switching-on of the impact ionization ($V_{DS} = 8$ V, $V_{GS} = -0.2$ V, $T = 300$ K). Isopotential lines (V) are also depicted.

the electrons to energies where they start impact ionizing. Correspondingly, the drain current increases abruptly (solid curve in Fig. 2). A comparison with the dashed curve in Fig. 2, obtained from a simulation where impact ionization is inhibited, demonstrates that such behavior is directly related to ionization processes.

As a result of each impact-ionization process, an electron-hole pair is created. The electron is pushed toward the drain, contributing to the outgoing current. The hole is either attracted by the gate potential, or moves backward toward the

source. The actual hole distribution in the active portion of the device is shown in Fig. 3 for two different times after impact ionization has been switched on. The simulation has been performed as follows: a steady-state condition is first reached without impact ionization (as for the dashed curve of Fig. 2). Then, the impact ionization is turned on ($t = 0$) and both electrons and holes are followed in their dynamics. Fig. 3 also shows the contour lines of the internal potential. The holes are generated by the channel electrons in the high field region at the gate-end of the channel. Some of them (just a few percent) overcome the barrier at the InGaAs/AlGaAs heterointerface and are then collected by the gate contact, contributing a current of a few mA/mm. Around 35% of the generated holes remain confined in the channel and move toward the source contact, while the remaining ones diffuse into the substrate. As time evolves [Fig. 3(b)], a considerable hole concentration builds up at the source-end of the channel and in the substrate, creating a positive space charge region. It has been previously suggested that the accumulation of positive charge near the source contact leads to an increase in output conductance in GaAs MESFET [10], [11], SOI MOSFET's [12], in InP based HEMT's [13] and in InAs/AlSb HFET's [14], [15]. This so-called *parasitic bipolar effect* (PBE) is due to the fact that holes escaping into the substrate of such devices act as a parasitic back gate, which in turn leads to an increase in the electron current flow in the channel.

Consistent with the analysis of the hole dynamics made above, we expect that a PBE is responsible for the current increase shown in Fig. 2. As a first check, we have verified that ionization events initiated by secondary carriers are negligible. In order to evaluate the contribution of the impact ionization current (that is the direct effect of the enhancement in the number of carriers when ionization occurs), we have performed a series of computer experiments whose results are presented in Fig. 4. The curves labeled *impact ionization off* and e^-/h^+ *pair generation* refer, respectively, to simulations where impact ionization is always off or is turned on at $t = 0$. The steady state current values correspond to those of Fig. 2 (dashed and solid lines, respectively) for a drain bias of 8 V. The separate electron contribution can be evaluated by artificially allowing only secondary electrons (and not holes) to be created at each ionization process. The current response (curve labeled e^- *generation only*) indicates a minor contribution of the secondary electrons to the drain current. On the contrary, if only secondary holes (and no secondary electrons) are created, the current enhancement is considerable, see curve labeled h^+ *generation only* in Fig. 4. Steady state is reached in this case in a few hundreds of picoseconds, an evidence that hole transport processes do control the dynamical behavior of the device.

A further simulated experiment illustrates the origin of the PBE in our HEMT (see Fig. 5). By selectively removing holes from different regions of the device before solving Poisson equation, it is possible to isolate the space charge contribution from such regions. If, for instance, the substrate holes are not considered, the current reaches a steady value much lower than that obtained both in the "standard" simulation (i.e., when all holes are considered), and if the channel holes are neglected. Such results confirm that the increased drain current of this

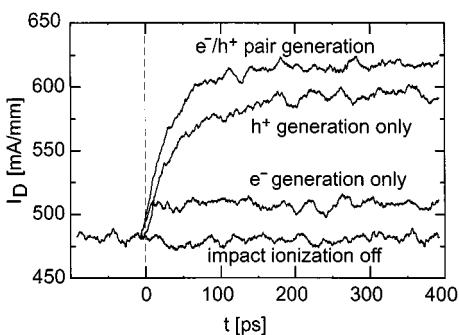


Fig. 4. Time dependence of I_D for several types of simulation, considering or omitting secondary carriers. At $t = 0$ the impact ionization processes are switched-on ($V_{DS} = 8$ V, $V_{GS} = -0, 2$ V, $T = 300$ K).

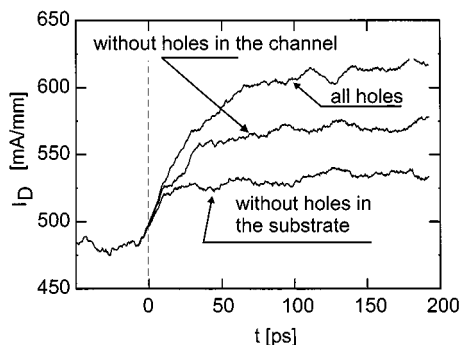


Fig. 5. Simulated time dependence of drain current showing the different contribution due to the hole in the channel and in the substrate. At $t = 0$ the impact ionization processes are switched-on ($V_{DS} = 8$ V, $V_{GS} = -0, 2$ V, $T = 300$ K).

device, biased close to breakdown, originates mainly from the accumulation of holes in the substrate region, and to a minor extent in the channel, which, in turn, gives rise to an enhanced drain current via a parasitic bipolar effect. By inserting a p-type contact that collects the accumulated holes, the parasitic effect almost completely disappears and the simulated on-state breakdown voltage shifts to higher values. A similar finding had been previously presented in relation to the kink characteristics of HEMT's [16], [11].

In conclusion, simulations show that accumulation of holes generated by impact-ionization takes place in the channel and substrate regions. The presence of the positive space charge favors the injection of electrons from the source, thus leading to significant increase in drain current. Such complicated feed-

back, which triggers on-state breakdown in HEMT's, has characteristic times in excess of 100 ps. Thus, the effects of impact-ionization under rf or pulsed drive may be significantly different from those observed in dc.

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