QUASI-2D ANALYSIS OF TRAVELLING GUNN DOMAINS IN MICROWAVE MESFET's

Giorgio Leuzzi[1], Paolo Lugli[1], George Salmer[2], and Franco Giannini[1]

[1] Dipartimento di Ingegneria Elettronica
Università di Roma "Tor Vergata"
Roma, Italia

[2] Centre Hyperfréquences et Semiconducteurs
Université de Science et Techniques de Lille-Flandre-Artois
Villeneuve d'Ascq, France

ABSTRACT

We present a numerical analysis of travelling Gunn domains in GaAs MESFET's based on a quasi-2D hydrodynamical model. The results are shown to be quite accurate in comparison to Monte Carlo simulations, despite the simplicity of the quasi-2D model. A microscopic description of the domain propagation is also given.

Keywords: Gunn domains, MESFET, modelling, simulation

1. INTRODUCTION

The possibility that high electric fields might lead to charge instabilities in III-V semiconductors has been known for a long time (Refs. 1-2). The occurence of stable or travelling charged domains is directly related to the band structure of those semiconductors. Under strong bias conditions, electrons can gain sufficient energy from the electric field to scatter into the upper valleys, where they are characterized by a heavier mass. This causes a negative differential region to appear in the velocity field curve, which in turn might lead to current instabilities for devices operated at high voltages. The oscillatory behavior connected with such instabilities have been exploited for microwave generation in several devices, the prototype of which can be considered the Gunn diode (Ref. 3). In planar field effect transistors, the presence of charge instabilities in the form of propagating charge dipoles is in general undesiderable, as it might disrupt the proper operation of the device and undercut its stability (Ref. 4-5). The presence of travelling domains has been suggested for realistic FET structures on the basis of sophisticated numerical simulations (Refs. 6-9), and has been associated to the observed negative conductance of MESFET's (Ref. 10) and electroluminescence of heterostructure FET's under high bias conditions (Ref. 11).

We will present here a numerical analysis of the nature of travelling Gunn domains in GaAs MESFET's, with a critical discussion of their origin, the condition for their existence, and their effect on the device characteristics. While most of the treatments of stable and unstable Gunn domains in diodes and MESFET's are based on drift-diffusion algorithms, in our analysis we use a simplified quasi-2D approach, which combines a considerable computational speed to a fairly accurate description of the physical processes. In parallel to the quasi-2D model, we have also performed Monte Carlo (MC) simulations, which act as a check for the reliability of the simpler hydrodynamical model, providing at the same time some valuable microscopic information.

2. THE QUASI-2D HYDRODYNAMICAL MODEL

The quasi-2D model is based on the solution of the one-dimensional Boltzmann transport equation (between source and drain), with depletion depth and injection accounted for via an equivalent channel width as described in Ref. 6 (Fig. 1). The equations for particle number, momentum and energy conservation are solved self-consistently with Poisson's equation within a finite-difference scheme. An approximate steady-state solution is used as initial condition, with constant gate-source and gate-drain voltages; the time evolution towards stable or unstable (oscillating) states is then computed. The model accounts for the transport phenomena in the propagation direction in a quite accurate way; approximations are however present in the definition of an equivalent depth of the channel. A further approximation has been introduced in the momentum conservation equation, where the momentum relaxation time has been neglected because much longer than the energy relaxation time. While the microscopic results can present some discrepancies with respect to more exact models based MC or 2D hydrodynamic approaches, especially for charge control in the channel,

the general behaviour of the MESFET turns out to be described quite well. Computational speed on the other hand is much improved, so that standard workstations may be used with reasonable time consumption; no particular programming techniques are required.

Due to the high speed of the simulation, it is possible to use very fine time and space discretisation, which guarantees accuracy and stability of the results. Material related quantities (effective mass, mobility, relaxation times, etc.) have been taken from MC simulations.

3. TRAVELLING GUNN DOMAINS

A typical simulated structure is shown in Fig. 2. The initial condition for the simulation is given by an approximate steady state solution of the quasi-2D model, obtained by setting to zero the time derivatives in the transport equation and by performing a single iteration from source to drain with a simplified finite differences scheme. For a drain current of $180mA$ (corresponding to a gate and drain voltages of $0V$ and $4V$, respectively) a domain is formed at the drain edge of the gate, and begins to propagate towards the drain (Fig. 3). In correspondence to the propagating domain, the electric field reaches values of several tens of kV/cm. Such high field is created by the drop of the applied source-to-drain potential at the edges of a charged dipole created by an accumulation layer (negative) of slow electrons belonging to the satelite valleys preceeded by a positive depletion layer. Outside the domain the field is much lower, reaching values of a few kV/cm under the gate. The dipole travels towards the drain at a speed of about $1.3 \times 10^7 cm^{-1}$. As it moves, the dipole attracts more electrons and the associated field grows. High values of the drain-source voltage and of the channel current are required for the oscillation to be sustained. For lower voltages and currents, the domain dies before reaching the drain, as shown for example in Fig. 4. There the drain current is $120mA$ (corresponding to a gate voltage of $-0.3V$) and the drain voltage is equal to $2V$. For very low drain voltages, a stable domain is formed at the end of the gate.

The I-V characteristics of the MESFET may therefore be divided into three regions (Fig. 5): I - travelling domain; II - partially travelling domain; III - no travelling domain. For very high drain voltages, the domain remains stable at the drain after travelling along the gate-source region. These general conditions of high gate currents and drain voltages indicate that high values of channel doping and thickness favour the domain formation and propagation, together with high drain and gate voltages.

4. COMPARISON WITH MONTE CARLO SIMULATIONS

In order to test the reliability of the quasi-2D model, we have also performed a self consistent MC simulation of the structure shown in Fig. 2. It is well known (Ref. 12) that the MC method provides a very useful tool for the modeling of semiconductor devices, especially when the reduced gate dimensions bring about non local effects such as velocity overshoot. A three valley model of GaAs has been used. Poisson's equation is solved on a 2D grid (within a finite difference scheme) every 10 fs of the simulation.

Figure 6 shows the details of the MC simulation for the same bias conditions as those of Fig. 3, at four arbitrary times during the simulation, 2 ps apart from each other. Electron concentration (a) and electric field (b) have been averaged over the width of the channel. A good qualitative agreement with the quasi-2D model is found. The form of the charged dipole, and therefore the electric field profile seem to be affected by the difficulty of the quasi-2D model to account for the electron penetration into the substrate, which is quite substantial in the simulated device. Improvements of the model are currently being implemented.

The evolution of the domain can be described in the same terms as in the previous section. Here we can see that when the domain reaches the drain contact (solid line in Fig. 5), the electrons forming the dipole accumulation layer exit the device, leading to a sudden current increase. As the dipole discharges, the electric field at the drain-end of the gate increases strongly, causing a large number of channel electrons to be scattered into the satelite valleys. This in turns leads to the nucleation of a new domain, which starts drifting towards the drain (dashed-dotted lines). Such repeated cycle is responsible for an oscillation of the output current with characteristic frquencies in the 50-100 GHz range.

5. DISCUSSION AND CONCLUSIONS

The MC simulation allows a direct look into the microscopic processes that are responsible for the propagation of the travelling domain. In the literature, it is more usual to find analysis of such effect based on drift-diffusion descriptions. There, the condition for nucleation and propagation of Gunn domain is that the electric field in channel access region is above a threshold field, that guarantees a sufficiently high current feeding the domain.

Within the MC simulation, we are able to tag the particles that belong, at any given instant, to the domain, and to trace their evolution forward, and even backward, in time. In Fig. 7a, we follow the evolution of those electrons belonging to the accumulation layer of the domain at a given time ($t = 4ps$ into the simulation). Most of these particles (about 90 percent) occupy the higher valleys. Therefore, as the domain travels, most of the tagged particles fall behind it, becuase of the low speed caused by their heavy mass. At $t = 12ps$, the domain reaches the drain contact, while most of the tagged particles drag along to channel, slowing gaining speed since they have, in the meantime, been scattered back into the Γ valley.

Figure 7b illustrates the domain feeding mechanism, by tracing backward in time the evolution of those electrons that are found in the dipole at $t = 12ps$. As we see, some electrons which were in front of the domain at an earlier time ($t = 8ps$) have been sucked into it. This is due to the high electric field in the leading edge of the domain, which favours the scattering into the upper valleys of electrons that move in front of the domain at a slightly lower speed than the domain itself. Other electrons are coming from behind, and can reach the drifting domain since they move in regions where the electric field is sufficiently high to give then a high drift velocity, but also sufficiently low to avoid intervalley transitions.

Therefore, the travelling domain is substained by a flux of electrons coming from the channel access region. As soon as those electrons reach the high-field domain region, they are scattered into the upper valley, loosing most of the velocity, and they are left behind, being replaced by new incoming electrons. Such behaviour is possible since the characteristic time for scattering into the upper valleys is much shorter than the one for the reverse transition (typically 100 fs vs 1 ps, respectively, as pointed out in Ref. 13). Additional details will be given in a forthcoming publication.

In conclusion we have presented a quasi-2d simulation of travelling Gunn domains in GaAs MESFET's, which compares well with Monte Carlo simulations, and gives us useful information on the occurence of such process.

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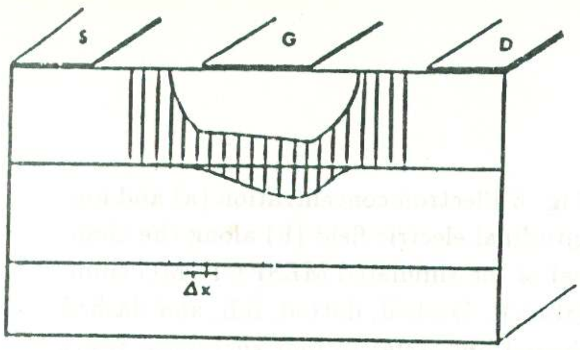

Fig. 1 The quasi-2D model of the MESFET

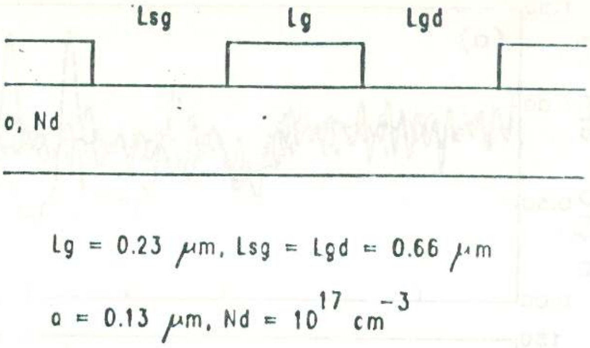

Fig. 2 MESFET's geometry and parameters

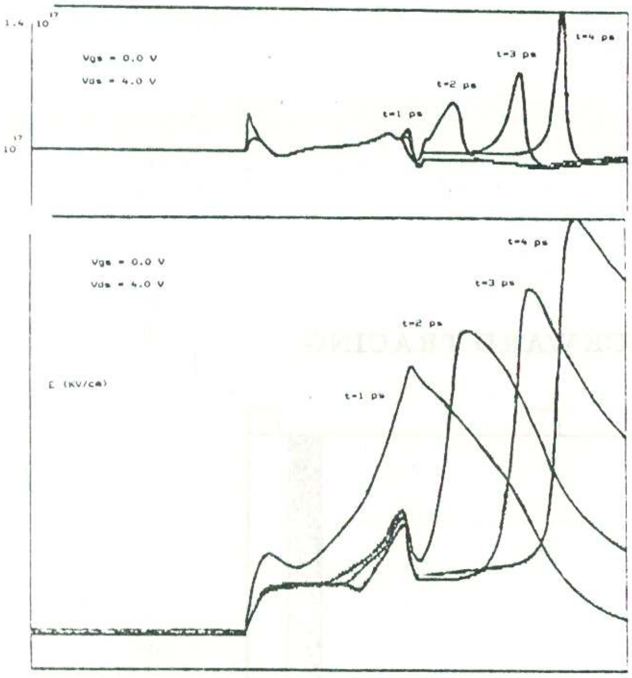

Fig. 3 Electron concentration (a) and longitudinal electric field (b) along the channel of the simulated MESFET (Quasi-2D simulation) for a travelling domain.

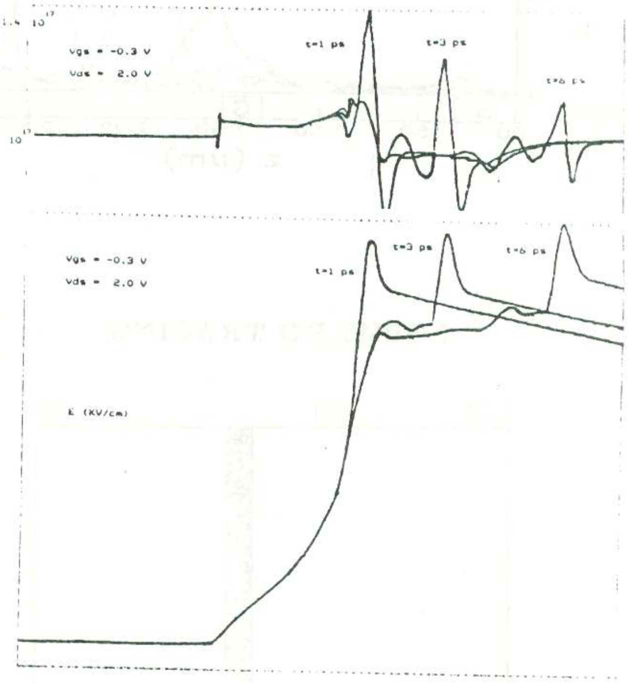

Fig. 4 Electron concentration (a) and longitudinal electric field (b) along the channel of the simulated MESFET (Quasi-2D simulation) for a partially travelling domain.

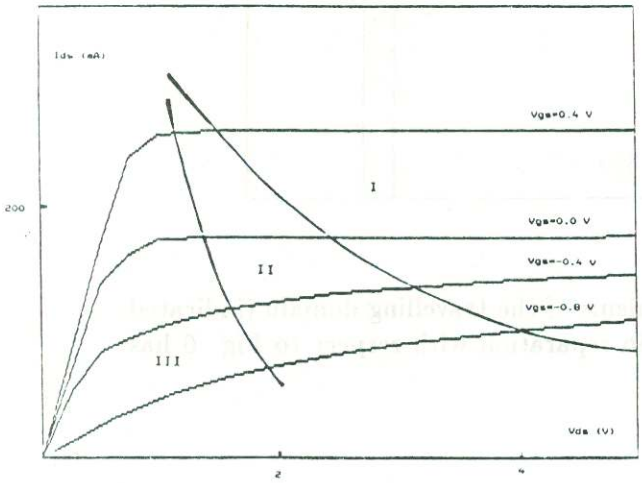

Fig. 5 I-V characteristics of the simulated MESFET showing the three regions of travelling (I), partially travelling (II) and stable (III) domain.

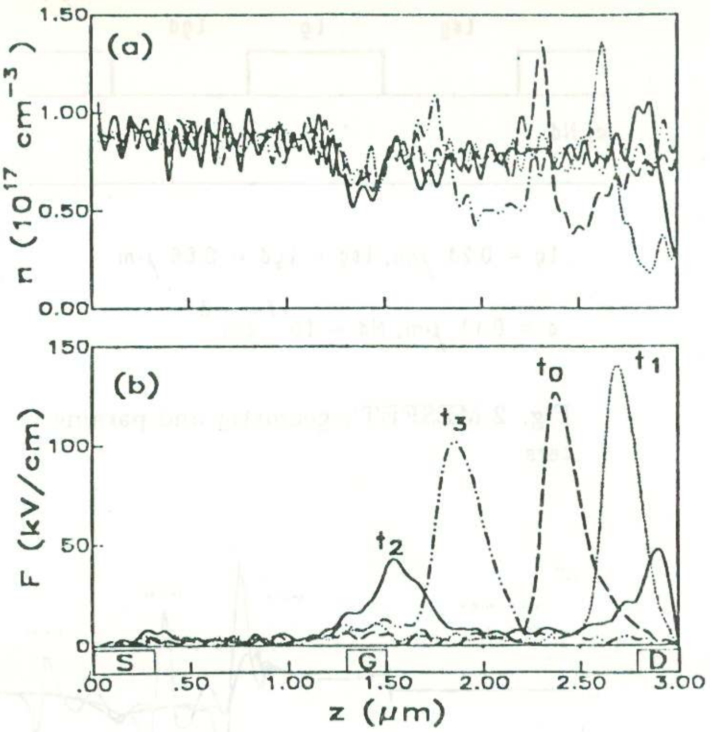

Fig. 6 Electron concentration (a) and longitudinal electric field (b) along the channel of the simulated MESFET (MC simulation) . Dashed, dotted, full, and dashed dotted lines refer to four successive times of the simulation, $2ps$ apart from each other.

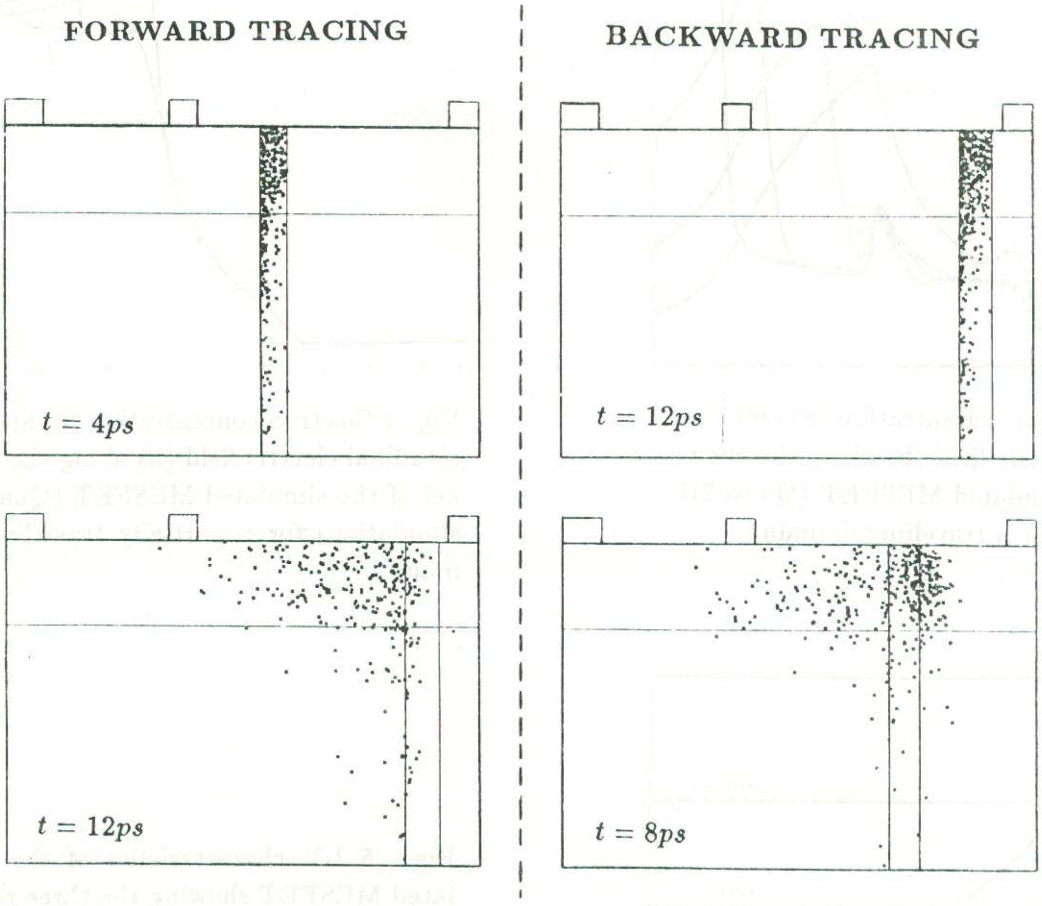

Fig. 7 Schematic representation of the feeding mechanisms of the travelling domain (indicated by the solid vertical lines). Here a longer gate-to-drain separation with respect to Fig. 6 has been used in order to achieve a better description.