MODELING OF NEW MICROWAVE DEVICES

G. SALMER

CENTRE HYPERFREQUENCES ET SEMICONDUCTEURS - U.A. CNRS 287
UNIVERSITE DE LILLE I - 59655 VILLENEUVE D'ASCQ CEDEX - FRANCE

ABSTRACT

The main recent evolutions of microwaves devices (MESFET, MODFET, HBT, MISFET, IMPATT diodes and TED) are presented. It appears that many new physical phenomena must be taken into account when we want to describe the behaviour of such devices and to simulate them. These effects occur not only in bulk materials but also in heterostructures. Three different types of models are presented : Monte Carlo simulation, two dimensional and one dimensional resolution of basic equations. Their respective advantages are precised.

INTRODUCTION

During the last few years, important efforts have been done throughout the world to improve the available device simulation models and to develop some new ones. The reason behind this is twofold. First, in well known microwave devices, such as GaAs MESFETs, IMPATT diodes and TED, some important technological improvements have been achieved, namely increasing doping levels with the simultaneous decrease of active zone dimensions, improvement of the transition abruptness between different layers and so on. As a consequence, many physical phenomena that could be neglected for more classical devices receive particular attention and must be taken into consideration. Secondly, new microwave devices have been developed, such as the High Electron Mobility Transistor (HEMT), InP MISFET, Heterojunction Bipolar Tran sistor (HBT) and new kinds of IMPATT devices. In these devices, new structures such as heterojunctions or superlattices for instance are used in which carrier behaviour as well as basic properties may be quite different. New physical phenomena may also occur. The purpose of this paper is to reveal some of the tendencies of microwave devices modeling. Part 1 describes briefly the main technological evolutions of classical microwave devices as well as the fundamental aspects of some new devices. In part II, the main physical phenomena that occur in such devices and that must be taken into account in device simulations are precised. Finally, we shall give some information on the main recent improvements of the various kinds of microwave device models and the main requirements for the near future.

I . MICROWAVE DEVICES : MAIN TENDENCIES

Among the various microwave devices, GaAs MESFET is the most commonly used in low noise or power amplifiers and oscillators. Being used in millimeter frequencies up to 94 GHz, the gate length Lg and the active layer thickness have been dramatically reduced with the consequent increase of doping levels N_D. Typical values are presently Lg = 0.25µm and N_D = 6 10^{17}at/cm^3 (1).

On the other hand, in millimeter wave range, IMPATT and Gunn diodes remain the most popular devices. The active zone thickness decreases as a function of frequency and becomes smaller than 0.7µm for TED and 0.4µm for IMPATT diodes at 140 GHz. In TED, improved output power and efficiency are realized by creating a high field current limiting cathode contact that allows to obtain a near uniform electric field configuration (3,4) leading to an increase of the active zone length by a factor of 2 to 5. In IMPATT diodes, in order to obtain a better confinement of the avalanche zone and then to override their main limitations, new heterostructures based on the very promising properties of GaAs-GaAlAs multilayers(5) have been proposed (6).

Among the new devices, the High Electron Mobility transistor, HEMT, or MODFET seems to be one of the most promising devices for low noise (7) and power (8) applications at frequencies up to 94 GHz. It takes advantage of the enhanced mobility and velocity of electrons in the two dimensional electron gas formed at selectively doped GaAs-/AlGaAs heterojunctions. Very high performance has been achieved ; a noise figure of 2,4 dB at 60 GHz (9) and a gain of 3,6 dB at 94 GHz for 0.25 µm gate length devices. Several new device structures have been proposed and realized in order to improve the device performance. We can cite :

- the inverted HEMT (10) that gives the highest transconductance presently available with FETs.
- the superlattice HEMT for low temperature operations (11)
- the multichannel HEMT for power applications (8)
- the InAlAs/GaInAs HEMT, taking benefit of the superior transport characteristics of GaInAs (12).
- the pseudomorphic InGaAs/AlGaAs MODFET, profiting of the better confinement of the electrons in the quantum well (9).

Taking advantage of the power capabilities of M.I.S. structures, very promising results have been recently obtained for both of InP and AlGaAs/GaAs devices. Several material properties of InP appear very interesting for that purpose, namely high electron velocities and low values of ionization coefficients. The main problem concerns the physical properties of the isolating layer and mainly its stability. Recent progress have been

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done and very interesting performance has been achieved ; 4,5 W/mm at 9 GHz (13) for instance. GaAs/AlGaAs heterojunction MISFET seems also to be a serious candidate for high-efficiency-high-power-density operation up to millimeter wave range. The main difficulty consists in the realization of a very pure undoped AlGaAs layer that can act as a good gate insulator. Recent results obtained with such a structure (14) appear very promising ; 1 W/mm power density at 18,5 GHz.

Single and Double Heterojunction bipolar transistors (15), based on GaAs/GaAlAs technology may offer very interesting capabilities. This is mainly due to their vertical structure and their very small base thickness. As a consequence, electron ballistic transport can be occured in the base and electron velocity may overshoot in the collector region (16). Due to recent progress in lithography techniques transit frequencies can reach 45 GHz and power capability may attain 2.5 W/mm in the X band (17). The main problem remains the base and emitter access resistances that limit the maximum frequency of oscillation that is close to F_t for such devices. Other kinds of HBT, based on double InP/GaInAs and InAlAs/GaInAs heterostructures have been recently developed (18). They take advantage of the higher values of band discontinuities, carrier mobility and the better capabilities to ballistic transport (19).

II. MAIN PHYSICAL PHENOMENA

As it appears from the previous part, microwave devices behaviour is strongly dependent on some basic properties and physical phenomena that occur in bulk material as well as in hetero or homostructures.

As a matter of fact the electron velocity-field dependance is the main factor that determines the device characteristics (the cut-off frequency for instance) and the respective interest in GaAs, InP or GaInAs material can be related to this dependence. But in the most recent devices, where the basic dimensions are much smaller than 1 µm, carriers are often under non stationnary conditions and the particular effects that then occur must be taken into account ; overshoot phenomena, ballistic transport and so on. A comparison of the typical $I_d = f$ (Vgs) characteristics as shown in fig.1 for a 0,3µm MESFET with and without taking these effects into account demonstrates clearly their importance.

In new submicrometer gate GaAs MESFET's, the doping concentration is often higher than the density of states in the Γ valley of the conduction band ($N_c = 4\ 10^{17}/cm^3$). For these doping densities, the donor level constituting a small band overlaps the conduction band and the Fermi level further lies within it. These phenomena are characteristics of degeneracy and we have to introduce them in the models. In this case, electrons follow Fermi statistics rather than Boltzman's. Moreover, for these carrier concentration levels ($n>n_c$), electron-electron interactions may take a particular importance as they determine the dynamic properties of the carriers. Similar situations can be met in the two dimensional electron gas and AlGaAs layer of MODFET structures. However, it is not evident that the use of the classical assumptions (Boltzmann statistics) may cause significant errors. Moreover, it may be possible to account for the average effect of electron-electron interactions on the equivalent carrier energy relaxation time which is introduced in certain simulations. On the other hand, in the highly doped ($Nd=10^{19}$ at/cm^2) base of a HBT, electrons plasmon interactions may limit carrier velocity overshoot (20).

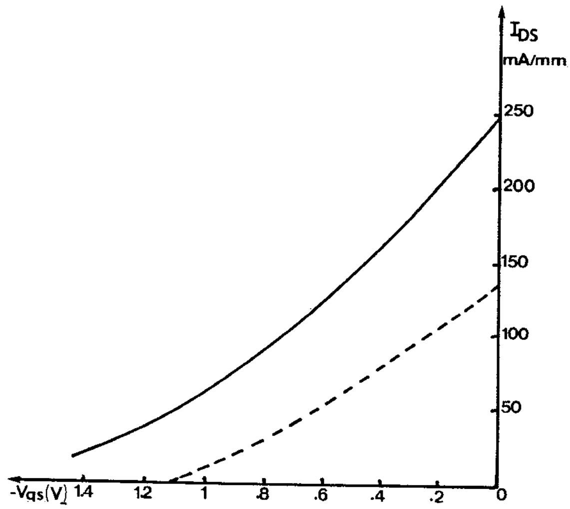

Fig.1 : Id versus Vgs characteristics for a 0.3µm gate MESFET, with (——) and without (– –) taking into account relaxation effects.

All F.E.T. structures being realized over semi insulating substrates show behaviour and then performance that strongly depends on substrate properties. Mainly, a space charge region is formed between the active or the buffer layer and the substrate. Semi-insulating substrates are obtained by compensating the shallow residual impurities by one or more deep levels. The ionized deep center concentration results from the equilibrium with the free carrier densities and so depends on the bias. These effects occur not only in chromium compensated substrates (chromium is a deep level) but also in "undoped" substrates (EL2 is a deep level). They must be taken into account (21) when devices are modeled under low noise conditions (22) or for logic applications.

Another trapping phenomenon determines the behaviour of MODFET's mainly at low temperatures, where we can expect very interesting performances taking into account the high value of carriers mobility ($\mu > 100.000$ cm^2/Vsec). Of course for small Al mole fractions in $Al_xGa_{1-x}As$ ($x<0,2$), the behaviour is quite similar to GaAs, with shallow donors close to the conduction band. On the contrary for higher Al mole fractions an increasing part of the donor levels become deep with an activation energy of the order of 140 mev (23) leading to a dramatic decrease in the AlGaAs free electron concentration and then consequently in the carrier density of the 2DEG.

The properties and performance of both IMPATT diodes and power FET's are strongly dependent on ionization rates. In classical models, α is taken as only dependent on electric field. In fact, a carrier has to drift over a dark space distance D before it acquires enough kinetic energy to initiate an ionization scattering : that is the concept of non localised avalanche introduced by OKUTO and CROWELL (24). These dark spaces can reach width of 200Å to 300Å that cannot be neglected in view of the dimensions of the active zone. In order to account for these effects, it is possible to postulate that the ionization rates are dependent on the average energy (25,26). Moreover, a microscopic description of ionization events seems necessary to evaluate the expected properties of multilayer structures (5).

Transport properties perpendicular or parallel to the heterojunctions have a decisive influence on microwave devices, such as HEMT, HBT, IMPATT and T.E.D. An accurate evaluation of current perpendicular to the heterojunction must include not only classical drift diffusion but also direct tunneling and thermally assisted tunneling effects. It has to account for the gradual or abrupt character of the heterojunction. Moreover, in specific cases, such as HBT, for instance, only a microscopie simulation can predict accurately the ballistic carrier transport through the base (20).

In MODFET or similar structure, conduction electrons are transferred across the heterointerface, thereby producing a two dimensional electron gas (TEG) of high mobility (fig 2). The width of the potential well formed in this way can be narrow enough for quantum effects to occur.

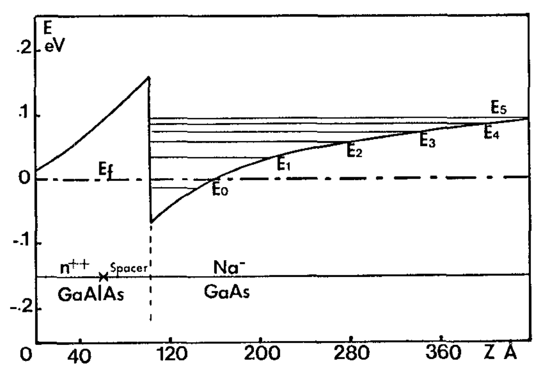

Fig.2 : Subbands structure in ou MODFET heterojunction $n^+AlGaAs(N_D = 10^{18})/\nu AlGaAs/\nu GaAs$.

Electron energies are quantized along the direction perpendicular to the heterojunction (27) ; existence of a subband structure, each with a constant energy state density. This fact involves energy-dependence scattering probabilities different from what is commonly known in three dimensional system, as in bulk material. However, the macroscopic transport properties in the well at high electric fields are not very different than in a pure GaAs material (28) and as the energy spacing between subbands is very small, electrons do not remain in the lowest subbands during the main part of their drift under the gate. As a consequence the necessity of using a specific electron dynamics for the classical devices is not evident. On the other hand, the carrier distribution and then the dynamic properties of superlattice (11) or multichannel (8) MODFET's cannot be described without introducing quantum effects. Moreover, as it is possible to improve the carrier mobility by introducing a spacer layer (undoped AlGaAs) between n^+AlGaAs and undoped GaAs, and as the mobility is dependent on carrier concentration, an accurate model must include screening effects (29).

A lot of other physical phenomena or particular effects must be taken into account in microwave device models. Among them, we can cite :
- the behaviour of low height Schottky barrier (TED)
- the thermal dependance of the physical parameters such as mobility, diffusivity, saturation velocity, ionization rates.
- the variations of access impedance with frequency for instance in MODFET.

III. SURVEY OF DEVICE MODELS : DISCUSSION AND RECENT IMPROVEMENTS

We can distinguish three main kinds of theoretical models :

. Monte Carlo or particle model (26, 29, 30, 31): They are the most powerful and accurate methods for modeling. The motion of particles representing the carriers is studied simultaneously in k-r space using Monte Carlo simulation ; all of the scattering phenomena that electrons may encounter in their transport are included. Among the advantages, we can cite :
- these models can be used for all of the microwave devices
- all the physical effects previously described can be introduced
- noise properties can be determined
- accurate useful results can be obtained (30),

Among the disadvantages, we can cite :
- the method requires very long computational time
- it is very difficult to study ac or transient behaviours.

Among the recent progress, we have to point out the introduction of all the physical effects that occur in quantum well devices and mainly the coupling with Schrödinger equation by (32).

. Two dimensional solutions of macroscopic equations (33, 34, 35, 36)

They are based on the two dimensional solution for the semiconductors equations including carrier energy and momentum relaxation effects. The basic assumption is that several quantities are assumed only dependent on the average energy. Among the advantages of these models, we can cite :
- their ability to treat all of the microwave devices with good accuracy.
- they are able to take into account complicated effects such as surface or substrate ones (22).
- their ability to study transient (34) and a.c. regimes (36).

But, from our knowledge, no model presently available takes into account all together the effects that occur in MODFET's or HBT for instance.

. One dimensional solution of the basic equations

- In IMPATT or TED and vertical structures such as HBT, two dimensional effects can be neglected and one dimensional solution (3) of the preceeding equations can be accurate enough. By imposing several assumptions, these models can be used also for MESFETS's (37,25) and MODFET's with their ability to predict noise performance (38).

These models may be simple enough to be performed with small computers and give very accurate results compared with theoretical predictions issued from Monte Carlo simulation and two dimensional model (Fig. 3).

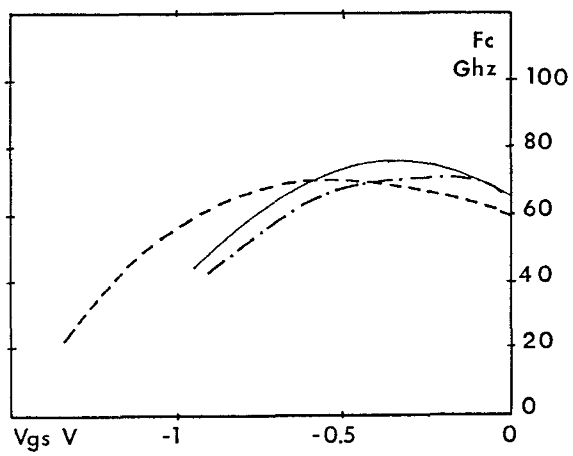

Fig. 3 Cut-off frequency variations versus gate to source voltage for a 0.3µm gate MESFET (37). Different models :—.—.— one dimensional
------ two dimensional
——— Monte Carlo

The main problems concern the difficulties to treat new structures where two dimensional effects or specific physical phenomena (substrate, trapping, doping profile, superlattice...) take a particular importance. The same kind of limitations appears, even for one dimensional structures where sharp discontinuities exist.

It has to be mentioned however that these models allow to study the influence of various technological parameters and to deduce analytical formulations that are accurate, even for sophisticated devices such as HBT (15) and that are used in CAD applications.

CONCLUSION

A lot of sophisticated models of microwave devices are presently available that allow to acount for the main physical phenomena involved. They are indispensable to understand the device behaviour and to give accurate predictions of their performance. Only the most simplified models can be introduced in CAD systems. But their validity must be systematicaly checked by comparison with the most accurate ones in one hand and with experimental results on test elements on the other hand.

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