ANALYSIS AND OPTIMIZATION OF SINGLE QUANTUM WELL MODFETs

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ABSTRACT

Based on 2D hydrodynamic energy model which features transient simulation of degenerate hot electron transport in submicron MODFETs, we present a detailed analysis of single quantum well (SQW) AlGaAs/GaAs/AlGaAs MODFETs which are proposed to enhance and optimize the device millimetric performance. The structure have been studied for different QW widths as well as different buffer AlGaAs transport parameters. It is demonstrated that hot electron effects set an upper limit on the maximum available gain and maximum oscillation frequency of the structure.

I. INTRODUCTION

The family of FETs based on modulation-doped structures is now holding the world performance records in both digital and microwave (low-noise & power) applications. Yet, there is much to do regarding the optimization of ultrashort-gate MODFETs to achieve millimetric performance especially in the 94 GHz window.

In a conventional $Al_xGa_{1-x}As$/GaAs MODFET structure (**Fig.1**), electrons which are originally introduced into the AlGaAs layer diffuse to the adjacent GaAs layer where they will be confined at the heterointerface in a quasi-triangular quantum well whose width between the conduction band - Fermi level intersection points is about 200 Å. Electrons, thus, form a quasi two dimensional electron gas (2DEG) whose sheet density exceeds 10^{12} cm^{-2}, in an ideal transportation medium, and very close to the gate. Theoretically speaking, this condition yields optimum transconductance g_m and output conductance g_d values. Practically, g_d did not demonstrate the expected low values and records have revealed a saturation performance similar to MESFETs, if not worse. This suggests that in submicron-gate MODFETs, under ordinary bias conditions, carrier release from the 2DEG and, eventually, carrier injection into the deep GaAs bulk is inevitable.

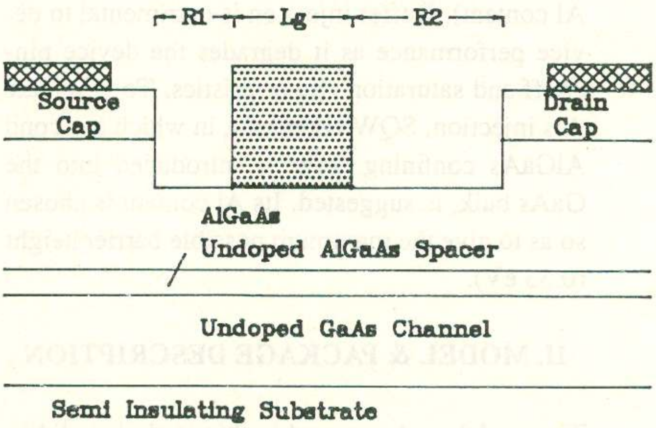

Fig.1 Basic conventional MODFET structure. Fixed parameters for this study are: Lg=0.3u, AlGaAs thickness=360Å, doping=$10^{18}cm^{-3}$ Spacer=40Å and Vds=2.5V.

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Based on 2D hydrodynamic energy modeling of hot electron transport in submicron-gate MODFETs, we have demonstrated that[2] electrons are hot during the main part of their drift under the gate. Furthermore, electrons even in recessed-gate MODFETs, may become hot earlier at the gate entrance of the channel[3]. Consequently, the probability of their scattering to higher quantum subbands and furthermore to the 3D system increases. Electrons which leave the 2DEG are able to move everywhere. In particular they reduce their energy either by diffusing into the GaAs bulk (**buffer injection**) or by transferring to the AlGaAs layer (**back injection and real space transfer RST**) if their average energy exceeds the conduction-band barrier (0.23 eV for a 30% Al content). Buffer injection is detrimental to device performance as it degrades the device pinchoff and saturation characteristics. To eliminate this injection, SQW structures, in which a second AlGaAs confining layer is introduced into the GaAs bulk, is suggested. Its Al content is chosen so as to give the maximum possible barrier height (0.33 eV).

II. MODEL & PACKAGE DESCRIPTION

The model we have used in this study is valid in the framework of gradual, though large, variation in composition which should occur over a minimum of 10Å for an Al contents of 30%. It is a 2D single equivalent electron gas energy model which features transient simulation of hot electron transport in submicron MODFETs. It simulates a wide variety of governing physical phenomena likeas:

- Nonstationary electron dynamicas and nonisothermal transport which lead to lesser transit times in subhalf-micron gate FETs where velocity overshoots may reach two to threefolds their stationary values. In subquarter micron MODFET structures, the upper values of overshoots are limited in time and space by the temporal and spatial variations of the electron momentum respectively that are also included in the model.
- Carrier degeneracy which is accounted for by an original technique to overcome the shortage of MC results for the material parameters.
- Real space transfer (RST) of hot carriers into the wider band gap material which is detrimental to device performance in the presence of DX-center traps.
- Parasitic MESFET conduction which takes place when the quasi 2DEG density saturates.
- DX-center trapping mechanisms which are responsible for different anomalies especially observed at cryogenic tempeeratures and which also limit the device performance at 300K.
- Carrier injection into the buffer/bulk material which influences the output conductance and maximum available gain dramatically especially as Lg goes shorter than 0.3 μm

The above phenomena are acounted for by four nonlinear partial differential equations (PDEs) which are the continuity eqn, the electron momentum and energy conservation eqs in addition to Poisson's eqn which includes the effect of the donor neutralization due to DX-Centers.

The discretiszation in space is accomplished using finite difference over a 2D nonuniform mesh structure with a mesh size which usually

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[2] T.Shawki, G.Salmer and O.El-Sayed, *"Two dimensional transient simulation of submicron-gate MODFETs"*, Int.Phys.Conf.Ser. n° 91, Chapter 7, pp.749-752, 1988.

[3] T.Shawki, G.Salmer and O.L.El-Sayed, *"MODFET 2D Hydrodynamic Energy Modeling: Optimization of Subquarter-Micron-Gate Structures"*, IEEE Trans. on Electron Devices, vol ED.37, pp.2 -3 , Jan. 1990.

varies between 10 and 300Å depending on the application. The discretization in time is carried out using the fully-implicit first-order backward-Euler formula in order to guarantee numerical stability without the imposition of small time steps.

At each time step, the discretized eqs are linearized by the Newton method which is chosen because of its quadratic convergence and the sequence of eqs is then solved iteratively until self-consistent values of the desired accuracy for all unknown variables are obtained. With a proper adaptive time step refinement which varies between 0.0005 and 0.0025 psec depending on the values of the displacement currents, the results of the first cycle of this iteration is rather close to the exact transient solution. Internal to each cycle, Poisson's eqn is solved using the MDS method which is a variation of the banded Choleski LL^T decomposition especially adapted for dominantly 5-Diagonal systems. The other eqs are solved by the successive overrelaxation (SOR) and Stone's Strongly Implicit (SSI) techniques.

The small signal equivalent circuit of the device is then obtained by taking the Discrete Fourier Transform of the currents recorded during the transient period. The short circuit current gain (SCCG) cutoff frequency f_c and maximum oscillation frequency f_{max} are determined from the zero crossing of the -6dB/decade best-fit lines of the frequency variation of the SCCG and maximum available gain (MAG) respectively.

The performance of the package measured on the IBM 3090 parallelo-vectorial environment, with 4 processors of which three are equiped with the vector facility (VF) modules, records a 70% vectorization rate and up to 30% gain in turn around time (elapsed real time). With these impressive figures, the complete simulation of one point on the dynamic I-V characteristics of a typical submicron MODFET with 4000 mesh points requires ~ 8 minutes of CPU time to accurately simulate a transient period of 3 psec which in most cases is necessary to reach steady state.

III. RESULTS & DISCUSSIONS

Typical distribution of electron-potential isolines (**Fig.2**) illustrates that the potential lines are only perpendicular to the channel axis 300Å away from the buffer interface. Hence, there is always finite transverse electric field components at the gate exit of the channel, where the high energy domain is located (**Fig.3**), which push hot electrons across the buffer interface (RST) for all QW widths.

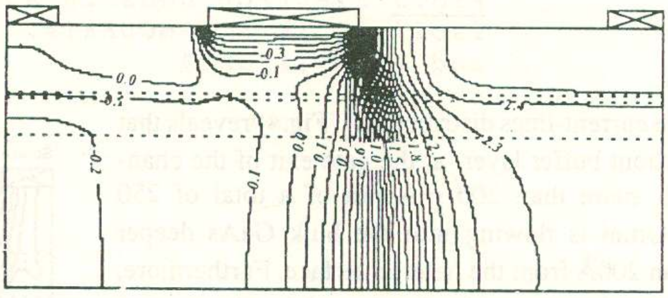

Fig.2 Contours of electrostatic potential. QW width=200Å.

The electron-density isolines demonstrate that elctron concentration in the buffer layer exceeds 10^{16} cm^{-3} only around the gate exit of the channel and it records a value greater than $5x10^{16}$ cm^{-3}, which is onehalf the channel density and about one fourth the accumulated charge in the high-energy domain, as the QW width reaches 200Å. This electron injection comes as a result of the presence of a high-energy domain, at the gate exit of the channel, whose average total energy peaks at 0.7eV which is more than twice the channel/buffer conduction band discontinuity (0.23 eV). Now, as the QW width goes from 400Å to 200Å, electrons while keeping their energy distribution, become closer to the buffer heterointerface which explains the increase in the amount of injected electrons.

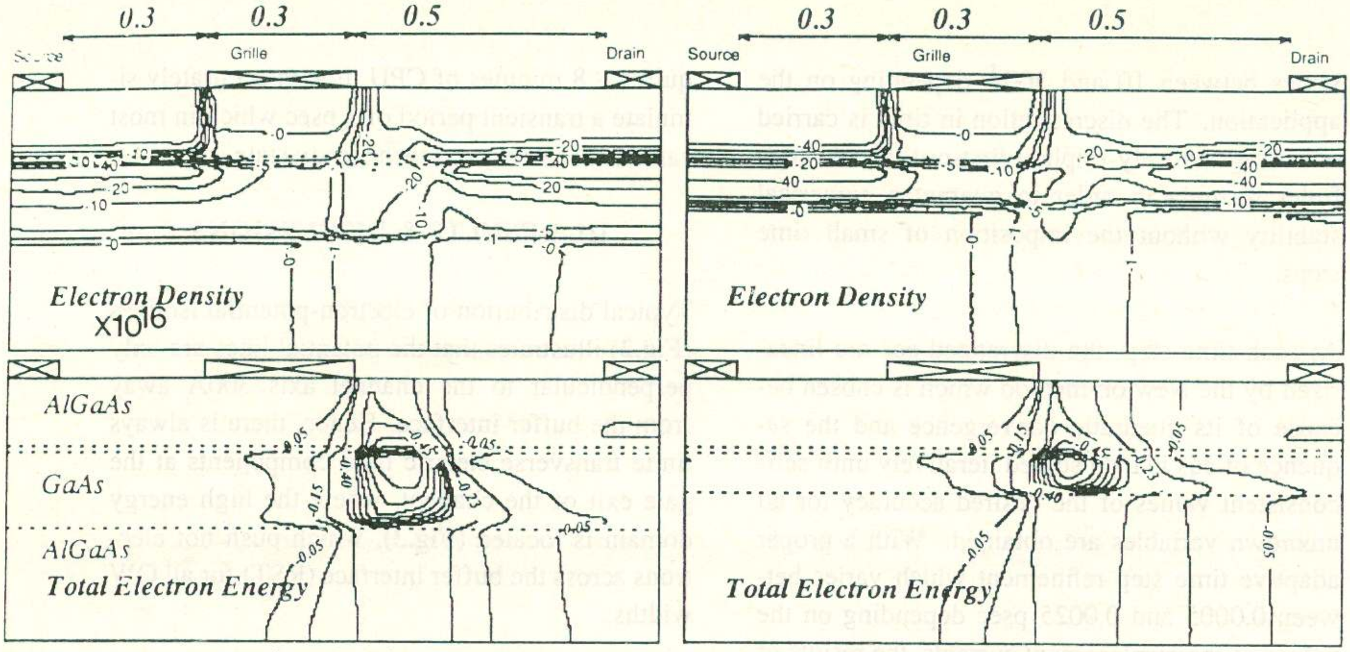

Fig.3 Electron density and total Electron Energy isolines in SQW-MODFETs. Well width= 400Å (left) and 200Å (right)

The current-lines distributions (**Fig.4**) reveals that without buffer layer, at the gate exit of the channel, more than 200 mA/mm of a total of 250 mA/mm is flowing into the bulk GaAs deeper than 200Å from the heterointerface. Furthermore, due to the progressive heating of the electrons as they travel under the gate, carrier injection is not limited to the region around the high energy domain. With the inclusion of the buffer layer, all carriers having energies lower than the barrier height are reflected into the QW. This results in only 40 mA/mm flowing into the buffer layer at the gate exit of the channel.

The better confinement of electrons into the quantum well suggests better pinch off performance (higher K-values) which is reflected in lower terminal currents near pinchoff (**Fig.5**) and better charge control, i.e higher peak transconductance g_m (**Fig.6**). This confinement, in addition, suggests a greater influence on the device

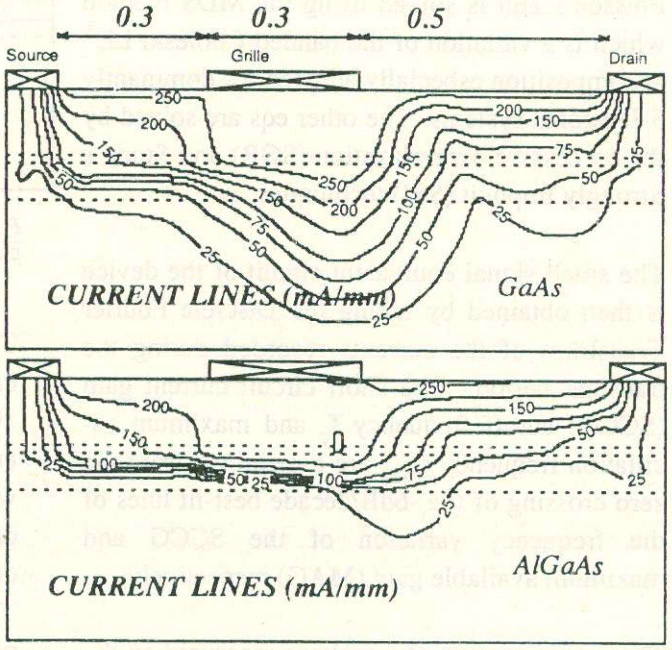

Fig.4 Current lines in conventional (upper curve) and SQW MODFETs. QW width=200Å.

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[4] T.Shawki and G.Salmer, *"Computer-Aided Analysis and Optimization of Subhalf-Micron-Gate MODFET Structures"*, 1990 IEEE MTT-S International Microwave Symposium, Dallas (Texas), May 8-10 1990.

output conductance (g_d) as is depicted in **Fig.6** which demonstrates a nearly 30% improvement in g_d all over the gate voltage swing. Further improvement in g_d could only be obtained by optimizing the recess features[4].

Due to this better confinement, however, the aforementioned enhancements come at the expence of the device capacitances (**Fig.7**) which increase slightly obviously due to the reduction of the effective separation of channel electrons from the gate. This suggests that the buffer AlGaAs layer influences the millimetric performance of the device through the increase in MAG and f_{max} rather than f_c. Buffer confinement is thus one way of increasing f_{max} without the adverse effect of reducing f_c.

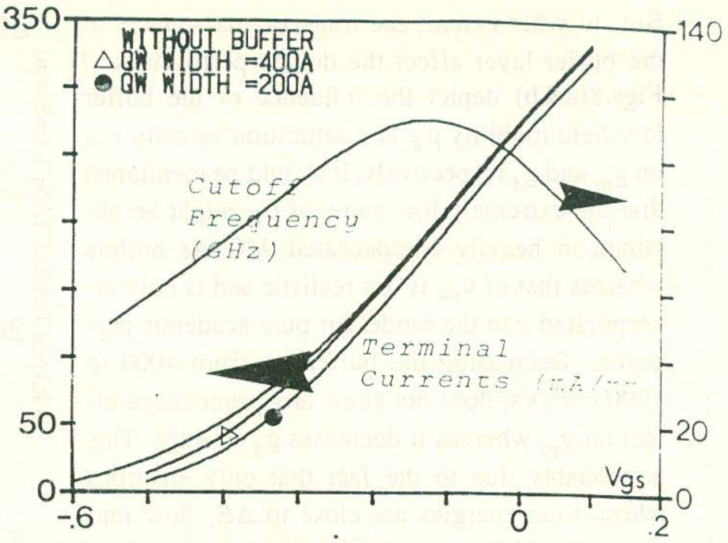

Fig.5 Terminal current and cutoff frequency (F_C) dependence on QW width. F_C is more or less independent of the well width.

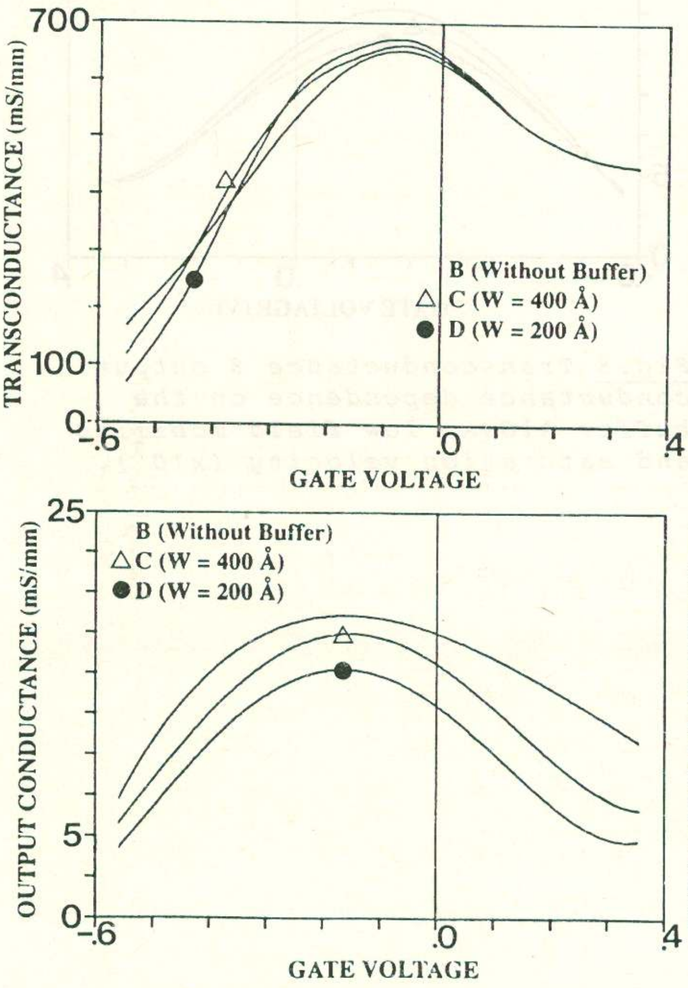

Fig.6 Transconductance and output conductance dependence on QW width.

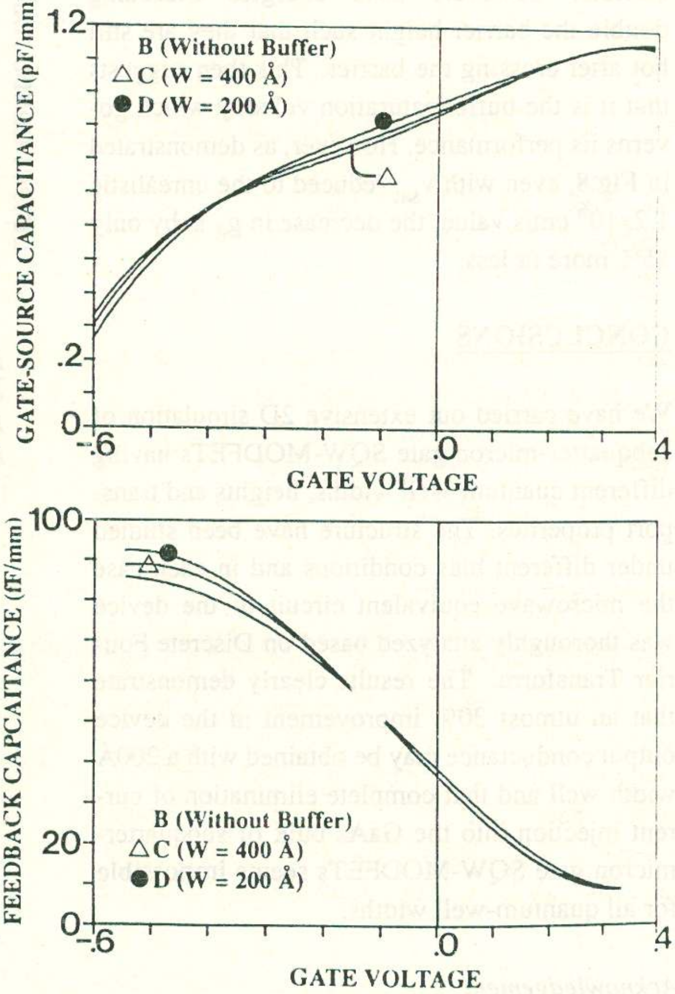

Fig.7 Gate-Source & Feedback capacitances dependence on QW width.

But, to what extent, the transport parameters of the buffer layer affect the device performance ? **Figs.8(a&b)** depict the influence of the buffer low-field mobility μ_{lf} and saturation velocity v_{sat} on g_m and g_d respectively. It should be mentioned that the extremely low value of μ_{lf} might be obtained in heavily compensated AlGaAs buffers whereas that of v_{sat} is not realistic and is only incorporated into the model for pure academic purposes. Decreasing the buffer μ_{lf} from 4000 to 1200 cm^2/Vs, does not show any pronounced effect on g_m whereas it decreases g_d slightly. This is probably due to the fact that only electrons whose total energies are close to ΔE_c flow into the buffer AlGaAs layer with their μ_{lf} after crossing the interface and eventually loosing an amount of energy equal to ΔE_c. The majority of carriers, however, have energies exceeding double the barrier height such that they are still hot after crossing the barrier. This then suggests that it is the buffer saturation velocity which governs its performance. However, as demonstrated in **Fig.8**, even with v_{sat} reduced to the unrealistic 1.2x10^6 cm/s value, the decrease in g_d is by only 15% more or less.

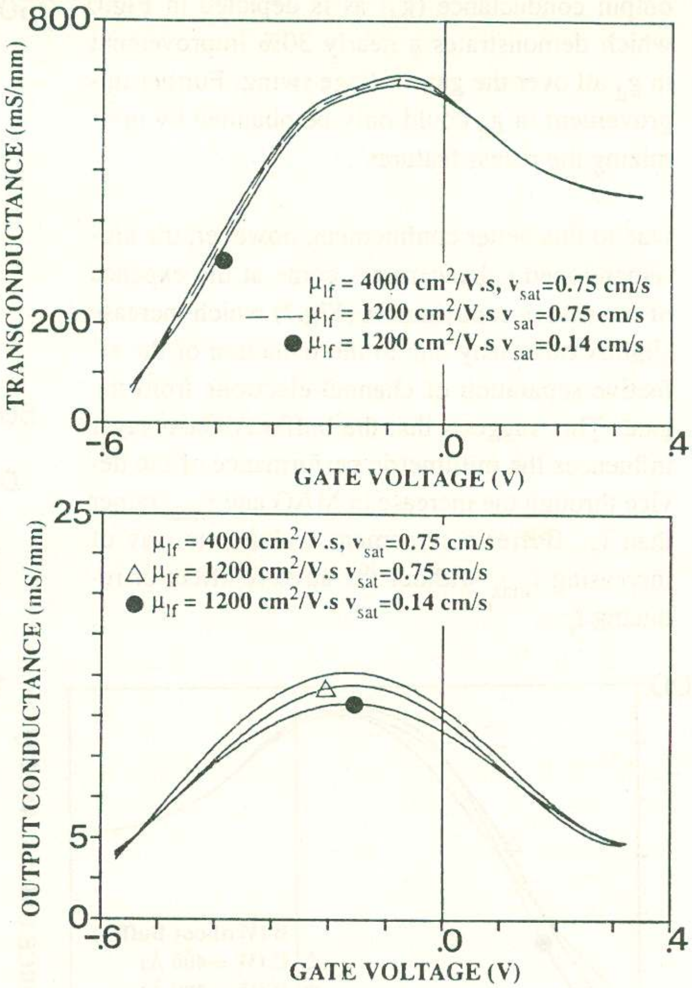

Fig.8 Transconductance & output conductance dependence on the buffer AlGaAs low field mobility and saturation velocity (x10^7).

CONCLUSIONS

We have carried out extensive 2D simulation of subquarter-micron gate SQW-MODFETs having different quantum-well widths, heights and transport properties. The structure have been studied under different bias conditions and in each case the microwave equivalent circuit of the device was thoroughly analyzed based on Discrete Fourier Transform. The results clearly demonstrate that an utmost 30% improvement in the device output conductance may be obtained with a 200Å width well and that complete elimination of current injection into the GaAs bulk of subquarter-micron gate SQW-MODFETs seems **impossible** for all quantum-well widths.

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