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Analytical Modeling of Small Semiconductor Devices Using the Relaxation Time Approximation

J. Sone, T. Kimura, and T. Yamada

Microelectronics Research Laboratories, NEC Corporation
4-1-1 Miyazaki, Miyamae-ku, Kawasaki 213, Japan

A new, analytical model for small FETs is developed, where the two-dimensional field effect and the non-stationary transport effect are considered. A one-dimensional, two-carrier analytical model for bipolar transistors is also presented with the non-stationary transport effect. In these models, the non-stationary transport effects are taken into account using the energy and momentum relaxation times evaluated by Monte-Carlo simulations under uniform fields. These models are applied to submicrometer-gate GaAs FETs and AlGaAs/GaAs HBTs. The non-stationary transport effects and two-dimensional field effects on the device operation and the device noise characteristics are discussed.

I. Introduction

The continuous improvements in performance of semiconductor devices with higher operating frequencies and lower switching delays have been brought about by the reduction in device size. In these small devices, the two-dimensionality in electric fields and the non-stationarity in electron transports such as velocity overshoots and ballistic transports have significant effects on device operations. Because of these effects, device characteristics including noise properties can be considerably modified. As a result, conventional device modelings(1)-(3), where the electron velocity is that appropriate to the local electric field, are no longer satisfactory for these devices.

A lot of computer simulations considering these effects(4)-(7) have been developed. However, they consume a tremendous amount of computing time and hardly allow applications to CAD tools for device parameter optimizations and circuit simulations. Additionally, they can hardly be applied to the device noise analyses greatly important for practical applications in microwave systems.

In this work, a new, analytical model for the small field-effect transistors (FETs) is first presented. Two-dimensional fields and carrier-density distributions are solved, taking into account the non-stationary electron transports with electron energy and momentum relaxation times. One-electron Monte-Carlo transport simulations under uniform electric fields are carried out to evaluate the energy and momentum relaxation times. This analytical model is applied to submicronmeter-gate GaAs FETs to investigate the device operations and the noise characteristics.

Next, a one-dimensional, two-carrier analytical model for bipolar transistors with thin base and collector layers is developed, where the non-stationary electron transports are considered using the energy and momentum relaxation times derived by the Monte-Carlo simulations. The model is applied to an AlGaAs/GaAs hetero-bipolar transistor (HBT) to study the device operations. Finally, conclusions are given.

II. Analytical Model for FETs

A GaAs metal-semiconductor field-effect transistor (MESFET) with highly doped N^+ source and drain contact regions self-aligned to a Schottky-barrier gate is discussed. The device structure of the FET is shown in Fig. 1.

In the analysis, the FET is divided into N sections with a width of Δx along the source to the drain (x-axis). The shape of a depletion layer in the m-th ($1 \leqq m \leqq N$) section counted from the source is approximated by a rectangle with an assumed length a_m (y-axis direction) and a width Δx. The value of Δx is selected such that $a_m >> \Delta x$.

The Poisson equation in the depletion layer in the m-th section is solved as a two-dimensional problem by,

$$V_m(x, y) = V_P \left\{ a_m^2 - \left(a_m - y \right)^2 \right\} + \left\{ A_m \, exp\left(-\frac{\pi x}{2a_m} \right) + B_m \, exp\left(\frac{\pi x}{2a_m} \right) \right\} \, sin\left(\frac{\pi y}{2a_m} \right) .$$

Here, V_m is the electric potential, V_P the pinch-off voltage, and x and y are measured from the source side edge on the gate electrode of the m-th section. A_m and B_m are obtained by connecting the potential $V_m(x, y)$ with that of the preceding (m-1)-th section at their interface.

The current continuity equation and the Poisson equation in the channel give the electric field E_X in the channel. The electron energy and velocity in the section are deduced from the solutions in the preceding section using the energy and momentum relaxation time approximation. The assumed depletion-layer length a_m is determined from the requirement that the electric field E_X in the channel be the same as that in the depletion layer at their interface.

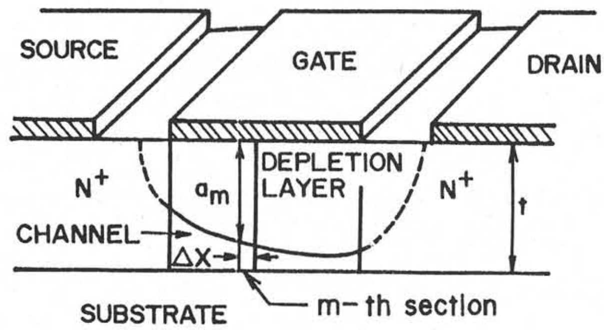

Fig.1. MESFET device structure.

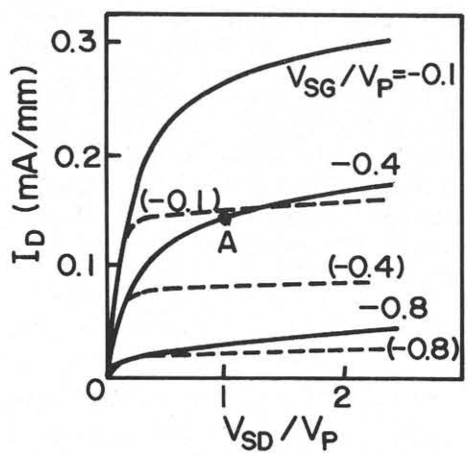

Fig.2. I-V characteristics of the GaAs MESFET. n_d: $1.0 \times 10^{17} cm^{-3}$, t: 0.09μm, Lg: 0.25μm, Vp: 0.5V.
Bias point A: $V_{SD}/V_P = 1.0$, $V_{SG}/V_P = -0.4$.

By connecting the solution for each section from the source to the drain, two-dimensional distributions of the electric field, velocity, and carrier density in the whole FET can be obtained.

This analytical model is applied to a GaAs FET with a gate length of 0.25μm. Figure 2 depicts the I-V characteristics of the device with a pinch-off voltage of 0.5V. For reference, the result of the conventional simulation assuming the electron velocity is determined by the local electric field is plotted by broken lines. The drain current and transconductance (g_m) exhibit about two-times enhancement compared to the conventional result, due to the non-stationary transport effect. As a result, the FET has an excellent performance with g_m

of 660mS/mm and f_T of 180GHz at the bias point A in Fig. 2.

The drain current shows a weak saturation in the small FET. This is because the drain current saturation mechanism resulting from the electron velocity saturation at the high field does not work effectively due to the electron velocity overshoot effect. Instead, the current saturation mechanism resulting from the two-dimensional field effect around the drain edge, so called Shockley mechanism, plays a major role. The latter causes the weak saturation and the drain-conductance enhancement. These characteristics are the same as those obtained by many-particle Monte-Carlo simulations(4).

Figure 3 shows the electron velocity, energy, and density along the channel at the bias point A. The velocity reaches 2.3 times of the steady-state peak velocity. The energy rises up to 440meV around the drain edge. The potential distributions in the FET are plotted in Fig. 4. It can be seen that the reasonable two-dimensional distributions are obtained using the analytical technique.

Since the major noise source in the FETs at microwave frequencies is the thermal noise produced in the conducting channel, the noise characteristics can be expected to be modified considerably due to the hot-electron effects(7). Figure 5 shows the minimum noise figure (NF) of the intrinsic FETs at 10GHz calculated using the equivalent temperature obtained in this model. It can be seen that the 0.25μm-gate FET has NF less than 0.5dB without parasitic resistances.

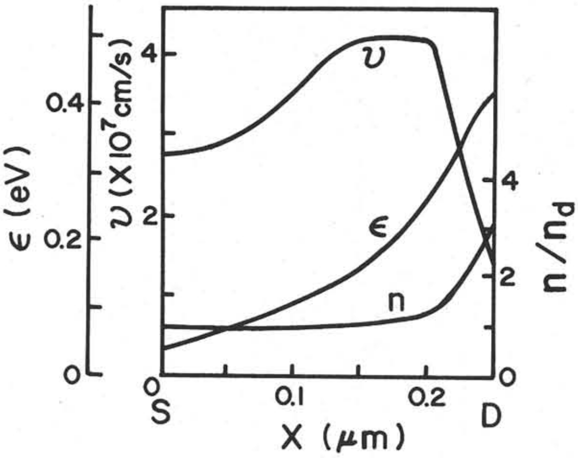

Fig.3. Electron velocity(v), energy(ε), and density(n) of the GaAs MESFET along the channel from the source to the drain. S:Source edge, D:Drain edge.

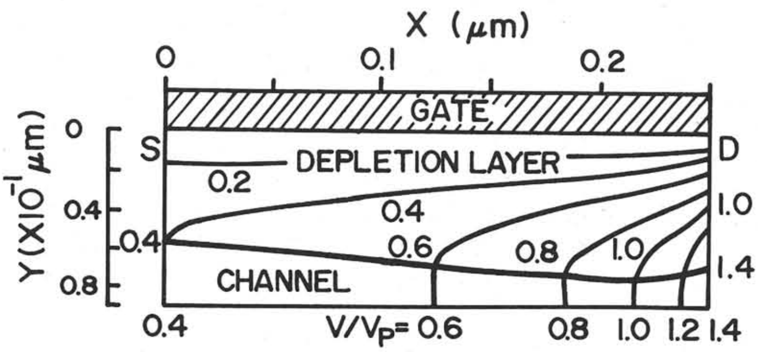

Fig.4. Potential distribution of the GaAs MESFET. The potential of the gate electrode is set to zero. S:Source edge, D:Drain edge.

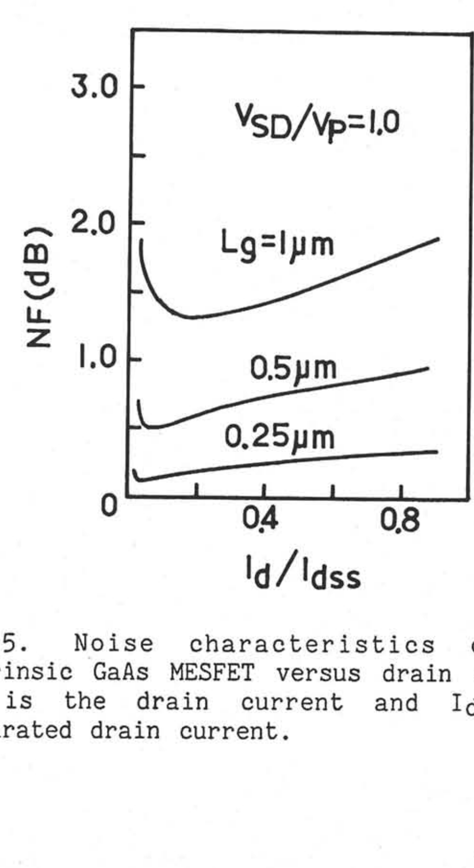

Fig.5. Noise characteristics of the intrinsic GaAs MESFET versus drain current. I_d is the drain current and I_{dss} the saturated drain current.

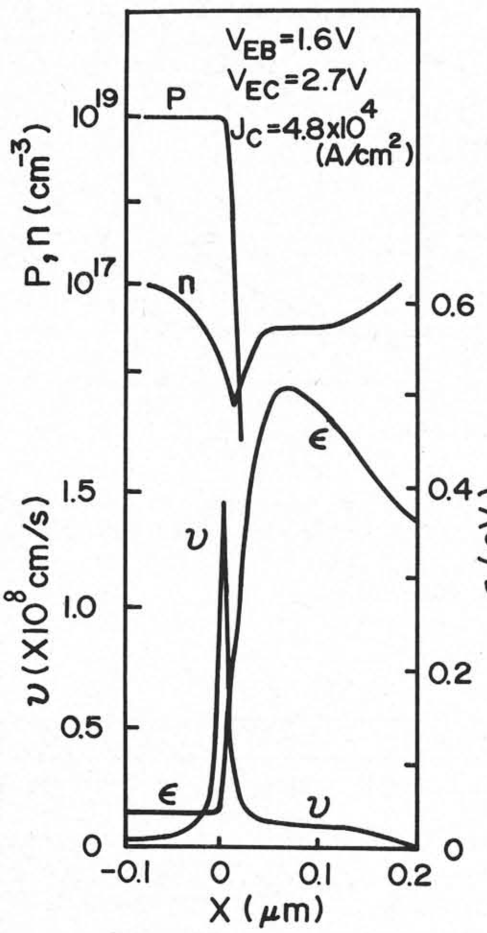

Fig.6. Electron velocity(v), electron energy(ε), and density of electrons(n) and holes(p) in the AlGaAs/GaAs HBT. The base layer:1000Å, $10^{19}cm^{-3}$ (p-type). The collector layer:2000Å, $10^{17}cm^{-3}$ (n-type). An origin of the x-axis is taken at the interface between the base and the collector.

III. Analytical Model for Bipolar Transistors

An analytical model for bipolar transistors is developed, where non-stationary transport effects are considered using the energy and momentum relaxation time approximation. The one-dimensional Poisson equation with electrons and holes is solved iteratively in base and collector layers.

This model is applied to an AlGaAs/GaAs HBT with a 1000Å base layer doped by $10^{19}cm^{-3}$ (p-type) and a 2000Å collector layer doped by $10^{17}cm^{-3}$ (n-type). Figure 6 shows the electron velocity, the electron energy, and the density of electrons and holes in the HBT. It can be seen that a large velocity overshoot exceeding 10^8cm/s occurs at the base-collector interface due to the high field in a reverse-biased p-n junction. The base and collector transit times can be estimated to be 1.6ps and 2.4ps, respectively,

IV. Conclusions

New, analytical models for the small FETs and bipolar transistors have been presented, where non-stationary transport effects have been taken into account using the relaxation time approximations. The models have been applied to submicronmeter-gate GaAs FETs and AlGaAs/GaAs HBTs with thin base and collector layers.

Since analytical methods have been employed in these models, they need not so much computing time, and can be applied to device design tools for device parameter optimizations, for circuit simulations, and for device noise characteristics analyses.

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