One-dimensional approximation of Poisson equation for the description of multi-gate conducting channels of FETs and HEMTs

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Abstract. One-dimensional approach for simulation of multi-gate FETs and HEMTS is proposed and validated by comparison with full two-dimensional simulations.

1. Introduction
At the present time, a one-dimensional (1D) approximation for the two-dimensional Poisson equation is extremely useful for the theoretical description of carrier transport and noise in FET/HEMT channels as [1,2]:

$$\varepsilon_c \frac{\partial^2 \varphi}{\partial x^2} + \varepsilon_s \frac{U_g - \varphi(x)}{d'(x)\delta} = e[n(x) - N'_D(x)]$$ (1)

This expression takes into account the influence of the gate potential $U_g$ (second term in l.h.s. of Eq. 1) on the distribution of potential $\varphi(x)$ and electron concentration $n(x)$ along the channel. Here, $d'(x)$ is the local gate-to-channel distance, $\delta$ is the channel width, and $N'_D(x)$ is the effective channel donors density. One of the main advantages of such an approximation is that it recovers, as limiting relations, two representations of the Poisson equation widely used in the theoretical analysis of both $n^+nn^+$ structures and HEMT/FET channels: (i) the limit of an infinitesimally narrow channel ($\delta \to 0$) corresponding to the gradual channel approximation, and (ii) the opposite ungated case ($d'(x) \to \infty$) corresponding to the trivial case of the 1D Poisson equation. The spatial dependences of $d'(x)$ and $N'_D(x)$ in Eq. (1) allow us to describe all reasonable situations such as gated, ungated, $T$-gated channel regions as well as a difference in effective compensated donor concentration in different regions. In essence, Eq. (1) with $U_g = \text{const}$ describes a three-terminal device which includes source, drain and gate. Here we propose an extended interpretation of this equation to the multi-gate case when the gate potential in various channel regions is different, that is $U_g(x)$ in Eq. (1) depends on $x$. 
2. Analytical model

Here, by following ref. [1], we shall briefly discuss main assumptions used to derive Eq. (1). It is supposed that the channel of FET/HEMT structures can be represented as a set of discrete regions (cells) of the length \( \Delta x \) connected sequentially one with another (see Fig. 1). In each cell the total current \( J \) flowing along the channel can undergo the branching between two directions, namely, the longitudinal direction where \( J_c \) flows along the channel and the transverse one where \( J_g \) goes to the gate. In accordance with Kirchhoff law the incoming and outcoming longitudinal currents in the \( n \)-th cell, \( J_c(n-1) \) and \( J_c(n) \), respectively, are related with the leakage current to gate, \( J_g(n) \), by the zero-sum rule:

\[
J_c(n-1) - J_c(n) = J_g(n) \tag{2}
\]

The connection in series of channel cells implies that the longitudinal component of the total current \( J_c(n-1) \) which is outcoming current for the \((n-1)\)-th cell is simultaneously the incoming current for the next \( n \)-th cell. It is evident that such an interpretation of the channel does not take into account the displacement currents which can appear between any two remote cells due to variation in time of the longitudinal component of the electric field in the dielectric surrounding the channel. The equivalent scheme of such a representation is shown in Fig. 1 (right), where the impedances \( Z_c(n) \) and \( Z_g(n) \) which characterize the \( n \)-th cell determine a local branching of the current between the channel and the gate. By separating the total currents \( J_c(n) \) and \( J_g(n) \) into two, namely, drift and displacement components such as: \( J_i(n) = J_{i\,\text{dis}}(n) + J_{i\,\text{cond}}(n) \) where \( i = c, g \), and going to the limit \( \Delta x \to 0 \), in accordance with ref. [1] we shall obtain two quasi-one-dimensional equations which allows us to describe separatively the electrodynamics and the carrier transport along the channel. The electrodynamic part is described by Eq. (1) which is the one-dimensional analogue of two-dimensional Poisson equation and it accounts for the gate influence, while the transport is described by the charge conservation law in the channel:

\[
\frac{\partial}{\partial t} j_c(x) + \frac{\partial}{\partial x} j_{c\,\text{cond}}(x) + \frac{\partial}{\partial x} j_{g\,\text{cond}}(x) = 0 \tag{3}
\]

where \( j_{c\,\text{cond}}(x) \) and \( j_{g\,\text{cond}}(x) \) are densities of the drift component of currents which, respectively, flow along the channel and go into the gate.

Since the local impedances \( Z_c(n) \) and \( Z_g(n) \) can depend on a cell number \( n \), this means that such parameters of the model as the effective channel width \( \delta \), the gate-to-channel distance \( d \),
the donor concentration in the channel $N_d$ can be considered as functions of $x$. As shown in [1-5], this allows us in the framework of Eq. (1) to consider a wide set of tasks which include both gated and ungated channel regions, T-gate, the longitudinal modulation of the channel doping. In essence, all these tasks are reduced to an analysis of three-terminal devices where one of the terminals is the gate which at any point has the same potential $U_g$.

However, both the discrete representation of the channel and the limit at $\Delta x \to 0$ will have no formal changes if one assumes that the gate potential depends on the cell number $n$ that is in Eq. (1) $U_g$ is function of $x$. This allows us to interpret in the framework of Eq. (1) the influence of an inhomogeneous potential at the gate on the carrier transport in the channel as an influence of a sequence of separated gates with different potentials. To avoid unphysical situations in points of gates where the potential has discontinuity, the gate regions with different potentials must be separated by ungated regions where $d(x) \to \infty$. Below we shall present a comparison of results obtained by Monte Carlo simulation performed in the framework of proposed here multi-gate model of FET/HEMT channel and by using full 2D Poisson equation [6].

3. Numerical results

Figure 2. Schematic representation of 2D HEMT of ref. [6] (left) and our simplified 1D model of the same HEMT (right).

Figure 3. Conduction band profile in DG HEMT calculated by MC simulation for 2D (left) and 1D (right) HEMT representations.

The schematic representation of InGaAs HEMT in two-dimensional (2D) case taken from ref. [6] and one-dimensional (1D) approximation used in this work is shown in Fig. 2, left and right, respectively. The gate-to-channel distance $d = 22$ nm, the channel width $\delta = 15$ nm, the gate lengths $G_1 = G_2 = 50$ nm, $N^+ = 2 \times 10^{18} \text{ cm}^{-3}$ (see [6] for more details).
Figure 4. Current-voltage relation for double- and single-gate HEMT calculated by MC approach for 2D [6] (a) and 1D (b) representations.

As an example, Figs. 3 and 4 show results of Monte Carlo simulation of InGaAS HEMT near pinch-off operation at source-to-gate voltages $U_{G1} = -0.2$ V and $U_{G2} = 0.6$ V. The conduction band profiles along the channel are presented in Fig. 3 at increasing values of the applied drain-to-source voltage $U_{DS}$. At $U_{DS} < U_{G2}$ the applied voltage drops mainly at the first gate, while at $U_{DS} > U_{G2}$ the extra voltage drop takes place mainly on the second gate. The drain currents of double- and single gate (DG and SG) InGaAs HEMTs are compared in Fig. 4 for 2D and 1D cases (left and right, respectively). Here, the improvement of the saturation behavior in DG case at $U_{DS} > U_{G2}$ due to action of the second gate is evident. Thus, at the level of electrodynamics (description of potential, see Fig. 3) we find a good quantitative and qualitative agreement of both the approaches. For drift characteristics (see Fig. 4) we get a good qualitative coincidences of results but the quantitative agreement is not so good (probably, due to sufficiently complicate 2D structure (see Fig. 2, left) which cannot be taken into account by simplified 1D model).

4. Conclusions
In conclusion, let us emphasize that one-dimensional approximation given by Eq. (1) with different gate-to-source potential values in different regions of the channel separated by ungated areas provides a good qualitative and reasonable quantitative description of the potential and drift current in the channel of 2D multi-gate FET/HEMT structures. Let us note, that parameters of Eq. (1) such as the channel width $\delta(x)$, the gate-to-channel distance $d(x)$, the ionized donor concentration in the channel $N_D(x)$ must be considered as some “effective parameters” which take into account an influence of the transvers surrounding of the channel on formation of self-consistent distribution of free carriers in the channel. Depending on the task they either can have a simple geometrical meaning or can represent some effective footing parameters.

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5. References
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