# Approximation of MOSFET Transistor Characteristics in Micro- and Nanoelectronics

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***Abstract*** **– The base approach, giving a wide class of functions convenient for engineering practice for the formal description of *I-V* characteristics of the *MOSFET* transistors, is developed. The similarity of *I-V* characteristics of semiconductor devices and the quasi-resonant converter of voltage is an approach basis. The offered functions have certain physical sense that allows modifying purposefully them for the flexibility of their form.**

***Index Terms*** **– approximation, *I-V* characteristic, model, transistor.**

## I. INTRODUCTION

Circuit simulation is an important component by working out and research of semiconductor devices and equipments on their basis. Let us result a number of the problems considered in the book [1].

In connection with transition of semiconductor technology in nanometer area (is more exact, at topological norms less 0,18 μm), a set of new parasitic electric effects has appeared, which were observed earlier only in analog integrated circuits (IC). For this reason, the urgency of exact (SPICE-like) circuit simulation has sharply increased.

Physical processes in the *MOSFET* transistors are described by difficult system of the equations. It is used only for device-technological modeling of semiconductor devices. Therefore, compact models are created by use of the assumptions, which simplify system of the equations to receive the analytical solution, simple enough for use in programs of circuit simulation

Physical compact models are synthesized by analysis of various areas of semiconductor structure for the purpose of a substantiation of simplifying assumptions which would allow receiving the analytical solution of the equations of a continuity, transport and Poisson. Such approach allows to establish physically well-founded assumptions and to establish connection of parameters of model with the geometrical and technological transistor's parameters.

Requirements of simplicity and computing efficiency compel modelers to move on the brink of its reliability. Therefore, the model of transistors is developed for technology of 0,25 μm, is already unsuitable for a 0,18 μm. The model, intended for circuit simulation, should be simple and have simple procedure of the parameter extraction.

The opposite method of synthesis consists that physical processes in the device are not analyzed at all. Instead, the equations of the two-port network are chosen by an expert way, which behave concerning external terminals precisely how the real MOSFET transistors. Such models are called as formal.

Synthesis of the formal models for modeling IC is not considered now perspective, as it does not allow establishing the connection of parameters of model with technical process parameters. But it is possible to notice that formal models are convenient for the analysis of an operating regime of the transistor and the concrete equipment (the amplifier, generator, and modulator) and which can be specified under the problem and transistor passport data.

The limited number of functions is available in an arsenal of modern mathematics, which can be used for construction of compact models. Among them there are no smooth functions which could give the simple and exact description of the transistor in all regimes of its work. Therefore, for smoothness maintenance it is necessary to use
Smoothing functions have no physical sense and can be used only for formal adjustment of model to object.
Here are some examples.

For modeling of area of moderate inversion, the interpolation by smooth function between modes of strong and weak inversion is used. Using smoothing function

$$F(v) = \left[Ln(1+e^{v/2})\right]^2,$$

it is possible to receive uniform expression of the characteristic. But the received equations can not be inverted analytically for obtaining the explicit dependence of currents from voltage as it is required in circuit simulation programs.

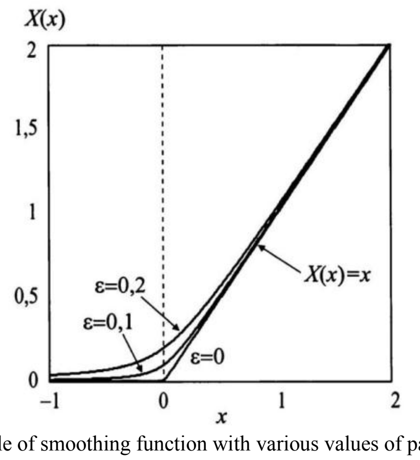


Fig.1. Example of smoothing function with various values of parameter ε of smoothing

For adequate modeling of analog and radio-frequency circuits, the smoothing functions should provide smoothness not only characteristics, but also their derivatives. Smoothing functions of a kind

$$X(x) = 0{,}5\left(x + \sqrt{x^2 + 4\varepsilon^2}\right),$$

are most extended. Where ε is the parameter, defining smoothness of transition from asymptote X(x) = 0 to an asymptote X{x) = χ, as is shown in Fig. 1

For smoothing of linear area with saturation area, the smoothing function is used, as is shown in Fig. 2

$$y(x) = \frac{x x_0}{\sqrt[2m]{x^{2m} + x_0^{2m}}},$$

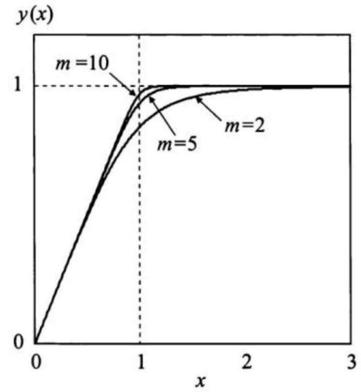


Fig.2. Example of smoothing function with various values of parameter *m* of smoothing

Presence of smoothing functions is one of essential limitations of modern compact models

For radio-frequency circuits, SPICE - like methods of modeling have appeared unsuitable.

First, at performance of the small-signal analysis SPICE program carries out a linearization of nonlinear elements, and, thus, nonlinear distortions or transformation of spectra of signals at once drop out of area of applicability of such analysis

Second, if for this purpose to use the analysis of transients in a mode of the big signal, the problem becomes almost unrealizable as the integration step should be much less period of carrier frequency, and at the same time the possibility of modeling of the several periods of modelled fluctuations is necessary. Thus, total number of steps of modeling becomes unacceptably large-scale.

Therefore, convenient analytical approximations of the transitive characteristic by one function represent an interest. Models on the basis of the hyperbolic tangent function, focused on the analysis of the intermodulation distortions in radio-frequency circuits, are known. Its feature is absence of necessity for smoothing functions. A shortcoming is that the model is based on empirical dependences and adjusted parameters.

Alternative approaches to modeling, as tabular models, are known also. Their basic appointment is the modeling of electric circuits with devices for which analytical models are not developed yet. For reduction of the size of tables, the templates are used in particular, because it is enough to store parameters of scaling of a template instead of storage of points of the curve. Difference of a template from a formal compact model consists that a template uses only the scaling and shift for adjustment to experimental data and does not contain other parameters. The template is chosen in advance with necessary properties (differentiability, monotony, absence of oscillations of the highest derivatives).

The next function can be a template example:

$$I_D(V_{DS}) = C + M(1 + \lambda V_{DS})\, th(\alpha V_{DS})$$

Four parameters of this equation (C, M, λ, α), are defined by means of a straight extraction technique for each value of voltage $V_{GS}$. Then each of parameters is interpolated by a voltage $V_{GS}$ polynom, factors of which are stored in the table. For example, for a template

$$I_D = I_{pk}(1 + th(\phi))(1 + \lambda V_{DS})\; th(\alpha V_{DS})$$

the equation parameters $\phi, \lambda, \alpha$ are tabular functions from voltage $V_{GS}, V_{DS}$. The $I_{pk}$ is a drain current at which the maximum of transfer conductivity is observed. However, this way does not allow receiving approximation of high accuracy because of insufficient flexibility of a template

In connection with stated, interest represents a finding of functions for construction of compact models as smoothing functions and templates. And, these functions should have certain physical sense that would allow modifying purposefully them for the flexibility of their form. In the present message some results [2] which develop the approach [3, 4] are presented.

## II. РАЗРАБОТКА БАЗОВОГО ПОДХОДА

Similarity of the load characteristics of the quasi-resonant converter of voltage with the characteristics of transistors is used as a basis of the offered approach. The received well-founded expression of characteristics of the quasi-resonant converter, having physical sense, allows describing the symmetric and asymmetrical transitive characteristic of the transistor.

The equivalent generator of the quasi-resonant converter contains the nonlinear internal resistance $R_{i1}$,which dependence corresponds to a straight line 1 is shown in Fig. 3.

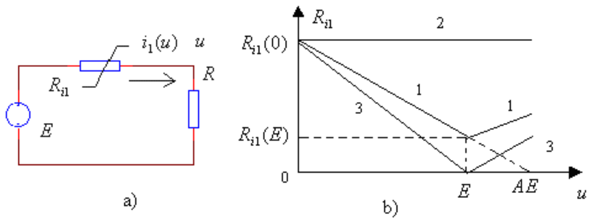


Fig.3. Equivalent generator - a) and dependences of internal resistance of typical energy sources (1- quasi-resonant converter, 2-voltage source, 3-current source-) - b)

Let us receive uniform expression of the characteristic for all area of change of the load voltage. For this purpose, linear dependences in the form of two straight lines 1 for areas are replaced by the hyperbole equation that is shown in Fig 4,a.

In case of hyperbolic dependence $R_{i1}(u_i)$, the equation of the I-V characteristic will become:

$$\frac{i_1(u_i)}{I_1 A} = \frac{u_i / AEr}{\sqrt{1 + (u_i / AEr)^2}}.$$

The plot of this curve has a typical appearance on Fig. 4,b.

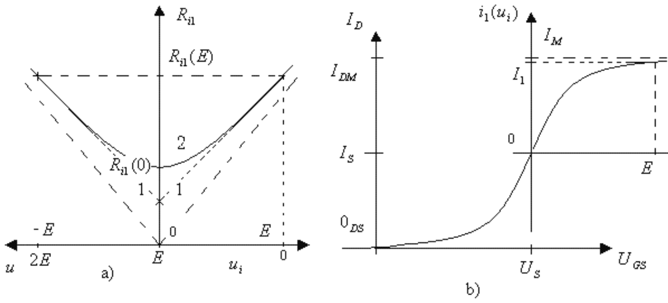

Fig. 4. Dependence of internal resistance as a hyperbole-a) and the symmetric characteristic in all area of change of voltage-b).

The form of the received curve is closed to the typical transfer characteristic $I_D(U_{GS})$ of the field transistor in system of coordinates $I_D 0_{DS} U_{GS}$ . Let us consider the base approach to the description of transistor characteristics. At first, the asymmetrical characteristic in the first and the third quadrantis is considered. In this case, the hyperbole $R_{i1}(u_i)$ will be asymmetrical relative to voltage $u_i$ in Fig.5,a.

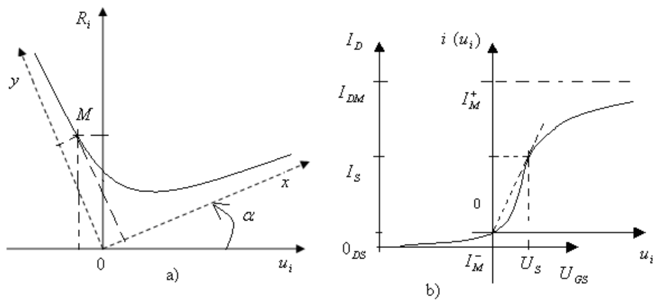

Fig.5. Asymmetrical arrangement of a hyperbole of internal resistance – a) and asymmetrical I-V characteristic in the first and the third quadrantis -b)

Asymptotes $0y, 0x$ form the rectangular system of coordinates turned on a corner $\alpha$ relative to the system of coordinates $R_i \ 0 \ u_i$ .

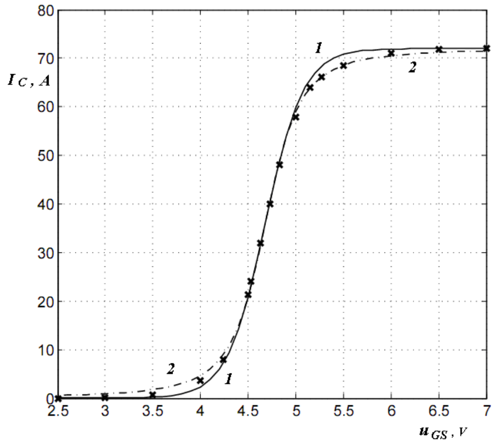

Fig.6. Symmetric approximations:actual values –crosses, hyperbolic tangent - 1,offered approximation – 2

Then the quadratic equation turns out:

$$i^2 + 2\frac{a_{12}u_i^2}{a_{22}u_i^2 + a_{33}} i + \frac{a_{11}u_i^2}{a_{22}u_i^2 + a_{33}} = 0 .$$

Let this asymmetrical curve in Fig.5 would be used for approximation of the transfer characteristic $I_D(U_{GS})$ of the transistor. Then, in initial system of coordinates $I_D 0_{DS} U_{GS}$ whith the actual curve, the system of coordinates $i 0 u_i$ is restored.Example: the transitive characteristic of the transistor $STE26NA90$ is resulted on fig. 6, 7.

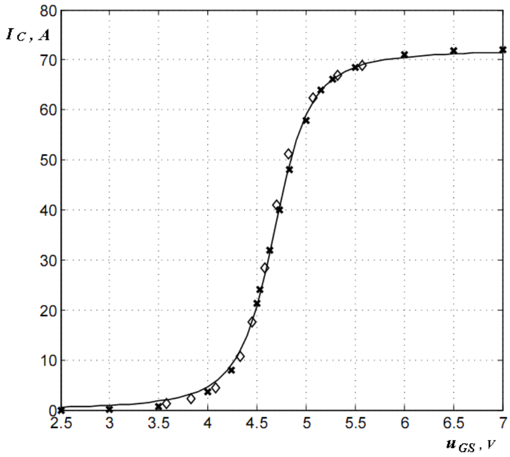

Fig.7. Actual values –crosses,offered symmetric approximation - continuous line,offered asymmetric approximation- rhombuses

## III. CONCLUSION

The carried out analysis of variety of known approximating functions of characteristics of transistors shows that:

- their formal character and absence of physical sense of the entering parameters does not allow to modify them purposefully,

-difficult enough expressions complicate analysis, lead to the solution of the transcendental equations,

The base approach and the whole class of convenient expressions for approximation of characteristics of semi-conductor devices are offered. The presented examples show possibility of direct analytical calculations of operating regimes of transistors.

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