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DEVELOPMENT AND RESEARCH OF W-PARAMETERS OF POTENTIALLY UNSTABLE FOUR-POLES BASED ON THE MATHEMATICAL MODEL OF W-PARAMETERS OF FIELD-EFFECT TRANSISTORS IN THE HIGH-FREQUENCY RANGE

Oleksandr Voznyak, Kateryna Kovalova, Yurii Polievoda, Liudmyla Kolianovska, Svitlana Ovsienko, Alla Solomon

Vinnytsia National Agrarian University, Vinnytsia, Ukraine

Abstract. *The models underlying calculations and research provide the developers with information about the behavior of devices during operation. As modern technologies do not provide high accuracy of measurements, the unstructured models are used, in particular, four-poles, which describe electrical circuits through their external characteristics, without taking into account the internal structure. Four-pole parameters, such as conductivities and impedances, can be measured using special methods, which allows effective analysis of the electrical properties of devices and systems.*

Keywords: structureless models, field-effect transistors, four-poles, W-parameters

OPRACOWANIE I BADANIE PARAMETRÓW W POTENCJALNIE NIESTABILNYCH CZWÓRNIKÓW W OPARCIU O MATEMATYCZNY MODEL POSTACI W TRANZYSTORÓW POLOWYCH W ZAKRESIE WYSOKICH CZĘSTOTLIWOŚCI

Streszczenie. *Modele stanowiące podstawę obliczeń i badań dostarczają projektantom informacji na temat zachowania urządzeń podczas eksploatacji. Ponieważ współczesne technologie nie zapewniają wysokiej dokładności pomiarów, stosuje się modele bezstrukturalne, w szczególności czwórniki, które opisują schematy elektryczne poprzez ich charakterystykę zewnętrzną, bez uwzględnienia struktury wewnętrznej. Parametry czwórników, takie jak przewodność i impedancja, można zmierzyć za pomocą specjalnych metod, co pozwala skutecznie analizować właściwości elektryczne urządzeń i systemów.*

Słowa kluczowe: modele bezstrukturalne, tranzystory polowe, czwórniki, parametry W

Introduction

The main goal of any model that underlies calculations, developments or research is to provide the developers with complete and convenient information about the behavior of the device during its operation. The developers are not interested in the general behavior of circuits or transistors, but rather in the behavior of a specific device or a specific transistor or, at most, the average behavior within a batch. Physical models could provide such information if the parameters of their elements were measured with high accuracy. Unfortunately, modern technologies do not allow such measurements to be made with the required accuracy, so calculations based on the results of imprecise measurements are predominantly qualitative, not quantitative [8].

There are several ways to overcome these difficulties. One of them is to completely abandon physical (structural) models in favor of describing the circuit through its external characteristics. Structureless models are quite accurate, as they are built on the basis of direct measurements of the device parameters, which allows you to automatically take into account all internal relationships. A physical model, no matter how complex it is, always remains only an approximation [6, 7, 13, 14].

1. Formulation of the problem

The problem that arises during the development and research of electrical systems is that modern measurement methods do not allow for high-precision determination of the parameters of device elements, which complicates the accurate modeling of their behavior. This limits the possibility of effective application of physical models for calculations, as they require accurate data on the internal characteristics of the elements [13, 14]. As a result, calculations are based on approximate values, which are often only qualitative, not quantitative. In such conditions, there is a need for effective unstructured models, such as four-poles, which allow more accurate prediction of device behavior, using only external characteristics, collected with measuring instruments [9].

2. Theoretical research

One of the most common unstructured models that generalizes the properties of linear electrical circuits is a four-pole. Any complex electrical circuit can be represented as an object described by the signal ratios on a certain number of pairs of input and output contacts. For example, in the form of a four-pole, elements such as a long line, a transistor, an electrical filter, a transformer, an amplifier, and other devices with two pairs of terminals connecting the source and the consumer of electricity can be modelled. At the same time, when the object of the analysis is only currents and voltages outside the four-pole, its internal structure is not taken into account, and the object itself is considered as a «black box».

The concept of a four-pole arose as a convenient way to generalize the characteristic properties of linear electrical circuits. A four-pole is a device with four terminals (poles), which are divided into two groups – input and output. In this case, the currents in the terminals of the four-pole are pairwise equal and opposite in direction. In the microwave range, the analogue of the quadripole is the so-called two-arm device. This term denotes a closed metal volume with an input and output represented by the segments of a regular transmission line through which only one type of wave can propagate [2–4].

The parameters of four-poles can be divided into two groups: their own (two-pole) parameters (conductivities, impedances) (e.g. W_{11}, W_{22}) and mutual parameters (W_{12}, W_{21}). These are generalized parameters, depending on the chosen system *Z*-, Y-, *g*- or *h*-parameters, or they are resistance (Ohm) or conductivity (1/Ohm), or a dimensionless quantity.

The parameters of the first group are measured either with specially designed measuring equipment or with standard equipment designed to measure the impedance of bipolar junction transistors.

In order to calculate most electronic circuits, it is sufficient to have a non-standard system of W-parameters of a four-pole circuit, namely: W_{11}, W_{22}, $|W_{12}|$, $|W_{21}|$, $Re(W_{12}W_{21})$, $Im(W_{12}W_{21})$). But in some cases, the calculation requires a complete system of W-parameters, which also includes mutual parameters.

All the methods for measuring parameters of unstructured four-pole models can be divided into standard methods for measuring parameters in short-circuit (*SC*) and idle modes (*IM*), standard methods for measuring parameters at a fixed load Z_0 (Ohm), and non-standard methods for measuring parameters [11, 12].

Immittance parameters, as mentioned above, are usually understood to mean one of four parameter matrices: *Z*-, *Y*-, *g*- or *h*-parameters (known conductance or resistance matrices). To describe a four-pole, any of these matrices can be chosen, each of which has its own advantages and disadvantages compared to the others, but in practice, *Z*- or *Y*-parameters are usually used [4].

2.1. Justification of the equivalent scheme of a field-effect transistor

Models of field-effect transistors used in microelectronics are built on the basis of taking into account the dependence of the drift velocity of charge carriers on the electric field strength in the channel and mainly differ only in the form of approximation of this dependence, therefore the model is built under the following assumptions:

- one-dimensional distribution of charge carrier concentration along the channel thickness;
- a sharp transition between the area of complete depletion
and the conducting part of the channel;
- the diffusion current is much smaller compared to the drift current of the main carriers [1, 5].

Modern *GaAs* transistors are n-type devices operating in the depletion mode. The physical effects in their structure can be described by a system of differential equations that include the continuity equation and Poisson's equation. The characteristics of the starting material, the electrophysical parameters, and the impurity concentration directly enter these equations as parameters. The geometric dimensions and configurations of various areas, including ohmic contacts, are taken into account by boundary conditions. The direct solution of such a system of partial differential equations is associated with significant difficulties and requires a large expenditure of computer time. That's why, the physical equivalent circuits, which include a controlled current source $\dot{S}U_{zv}$ (a complex quantity that has an active and reactive component *Re*, *Im*) and lumped *R*, *L*, *C* (resistance, inductance, capacitance) elements that reflect electrical processes in the structure of the study, are widely used as transistor models [1].

In order to calculate the dynamic characteristics of a transistor, approximate equivalent circuits with lumped parameters that do not depend on frequency are used. As studies of various authors have shown, the use of such models provides sufficient accuracy for engineering calculations and allows to obtain characteristics of real structures in a wide frequency range. The configuration and the number of elements of the equivalent circuit are usually selected taking into account the requirements for achieving the required accuracy.

In order to analyze a field effect transistor as an active four-pole device, an equivalent circuit of a field effect transistor with a Schottky gate is used, which is most widely used in the range of UHF (ultrahigh frequency). In this circuit (Fig. 1) $\dot{S}$ – transistor steepness (steepness of the drain-gate characteristic is the main parameter that characterizes the amplifying properties of the transistor (mA/V); *G* – differential output conductivity of the transistor; C_{DG} and C_{SG} – drain-gate and source-gate capacitances; R_i – differential resistance of the unblocked part of the channel between the source and the gate of the transistor; R_S and R_D – differential resistance of the epitaxial layer, respectively, between the gate and the source and between the gate and the drain, which are not controlled by the gate voltage, including the resistance of the ohmic contacts of the source and drain; R_G – gate metallization resistance; R_{CP} and C_{CP} – spreading resistance and capacitance of the space charge region of the gate contact pads; C_{DS} – drain-source capacitance through a high-resistance pad; L_{Z1}, L_{C1}, L_{B1} – internal inductances of the crystal terminals; L_{Z2}, L_{C2}, L_{B2} – inductances of the terminals outside the transistor case; C_Z, C_C, C_B – capacitances between the terminals and the transistor case.

The potential capabilities of a field-effect transistor are determined by the active region 1 of its crystal, which is characterized by the elements C_{DG}, C_{SG}, R_i, *G* and $\dot{S}U_{zv}$ of the equivalent circuit. The other elements of this circuit worsen most of the parameters of the field-effect transistor and are determined by its design features. So, to simplify the analysis of the active four-pole on a field-effect transistor, we will neglect the influence of the elements *R*, L_{C1}, L_{C2}, C_{CP} and R_{CP}. It is advisable to consider the other elements of the passive part of the crystal and the transistor terminals as external to the four-pole and lead them to the input W_G and output W_L immittances [1].

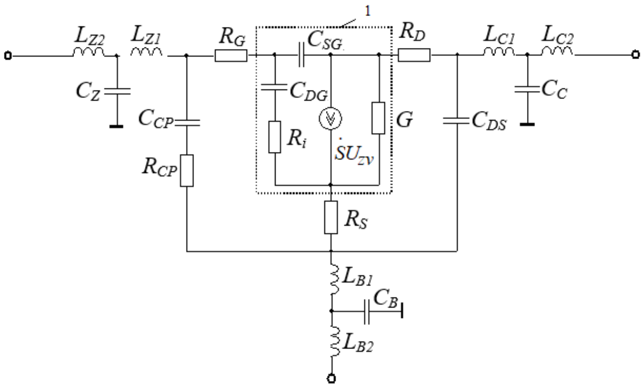

Fig. 1. Equivalent circuit of the field-effect transistor with a common-gate

To simplify the analysis and calculation of the input and output conductance of the four-pole circuit, we will make some assumptions and introduce the notation:

$$\Omega_S = \frac{\omega}{\omega_S},\ \omega_S = \frac{1}{R_i C_{SG}},\ \xi_3 \frac{C_{SG}}{C_{DG}} \tag{1}$$

where ω_S is the cut-off frequency for the steepness of the field-effect transistor, Hz.

Using the single-band approximation for the steepness of the field-effect transistor $S = S/(1+j^{\Omega s})$ and taking into account our assumptions and notations, we write the dependence between the currents I_Z, I_C, I_B and the voltages U_Z, U_C, U_B in the form of an uncertain conductivity matrix of the field-effect transistor crystal:

$$|Y| = \begin{vmatrix} Y_{11} & Y_{12} & Y_{13} \\ Y_{21} & Y_{22} & Y_{23} \\ Y_{31} & Y_{32} & Y_{33} \end{vmatrix} = \tag{2}$$

$$= \begin{vmatrix} \frac{\Omega_S^2}{Ri(1+\Omega_S^2)} + \frac{\Omega_S}{Ri(1+\Omega_S^2)} + j\frac{\Omega_S\ \xi_S}{Ri} & -j\frac{\Omega_S\ \xi_S}{Ri} & \frac{\Omega_S^2 - j\Omega_S}{Ri(1+\Omega_S^2)} \\ \frac{S_0(1-j\Omega_S)}{1+\Omega_S^2} - j\frac{\Omega_S(1-S_0R_i)}{Ri} & G + j\frac{\Omega_S\ \xi_S}{Ri} & -G - \frac{S_0(1-j\Omega_S)}{1+\Omega_S^2} \\ -\frac{\Omega_S^2 + RiS_0 - j\Omega_S(1-S_0R_i)}{Ri(1+\Omega_S^2)} & -G & G + \frac{\Omega_S^2 + RiS_0 + j\Omega_S(1-S_0R_i)}{Ri(1+\Omega_S^2)} \end{vmatrix}$$

which provides the calculation of both standard and non-standard systems of W-parameters of the four-pole.

2.2. Calculation of the parameters of an active four-pole on a field-effect transistor

Let us consider an active four-pole on a field-effect transistor in a specific circuit with a common drain (Fig. 2), which has potential instability up to the frequency $f_{\max}$ (maximum frequency at the transistor's stability limit, Hz).

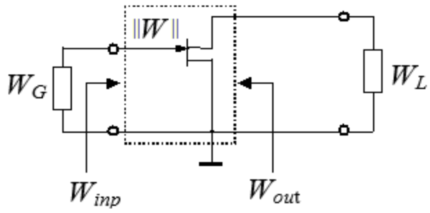

Fig. 2. Active four-pole on a field effect transistor connected in a common drain circuit

Based on the uncertain matrix and taking into account the simplifications, the conductivity matrix for a field effect transistor connected in a common-drain circuit can be written as:

$$|Yc| = \begin{vmatrix} \dfrac{\Omega_S(\Omega_S + j)}{Ri} & -\dfrac{\Omega_S(\Omega_S + j)}{Ri} \\ -\dfrac{\Omega_S^2 + S_0 Ri + j\Omega_S(1 - S_0 Ri)}{Ri} & \dfrac{\Omega_S^2 + S_0 Ri + j\Omega_S(1 - S_0 Ri)}{Ri} \end{vmatrix} \quad (3)$$

Let's find the values for the input Y_{inp} and output Y_{out} conductivities. To do this, we will use the well-known formulas for the dependence of the input and output immittance from the load immittance W_L and the generator W_G.

$$W_{inp} = (\Delta W + W_{11} W_L)/(W_{22} + W_L) \quad (4)$$

$$W_{out} = (\Delta W + W_{22} W_G)/(W_{11} + W_G) \quad (5)$$

where $\Delta W = W_{11} W_{22} - W_{12} W_{21}$.

Substituting the matrix elements into these formulas, after transformations we will find expressions for the imaginary, ImY_{inp} (input) and ImY_{out} (output), and real, ReY_{inp} (input) and ReY_{out} (output), components of the input and output conductances. Similarly, using the indefinite matrix, we obtain expressions for the input and output conductances of the four-poles based on field-effect transistors, connected in circuits with a common channel and gate. The method for determining the parameters of the equivalent circuit of a field-effect transistor is justified in the works and during conducting a numerical experiment [10].

3. Experimental research

A using the method of numerical determination of a non-standard system of the parameters, a numerical experiment was conducted based on a field-effect transistor at a frequency of 0.1–3 GHz, the results of which, together with the theoretical data, are shown in Fig. 3.

From the comparison of the obtained results of the theoretical and experimental studies, it is obvious that the discrepancy does not exceed 15%. This proves the adequacy of the developed methodology for determining non-standard parameters of potentially unstable four-poles [10].

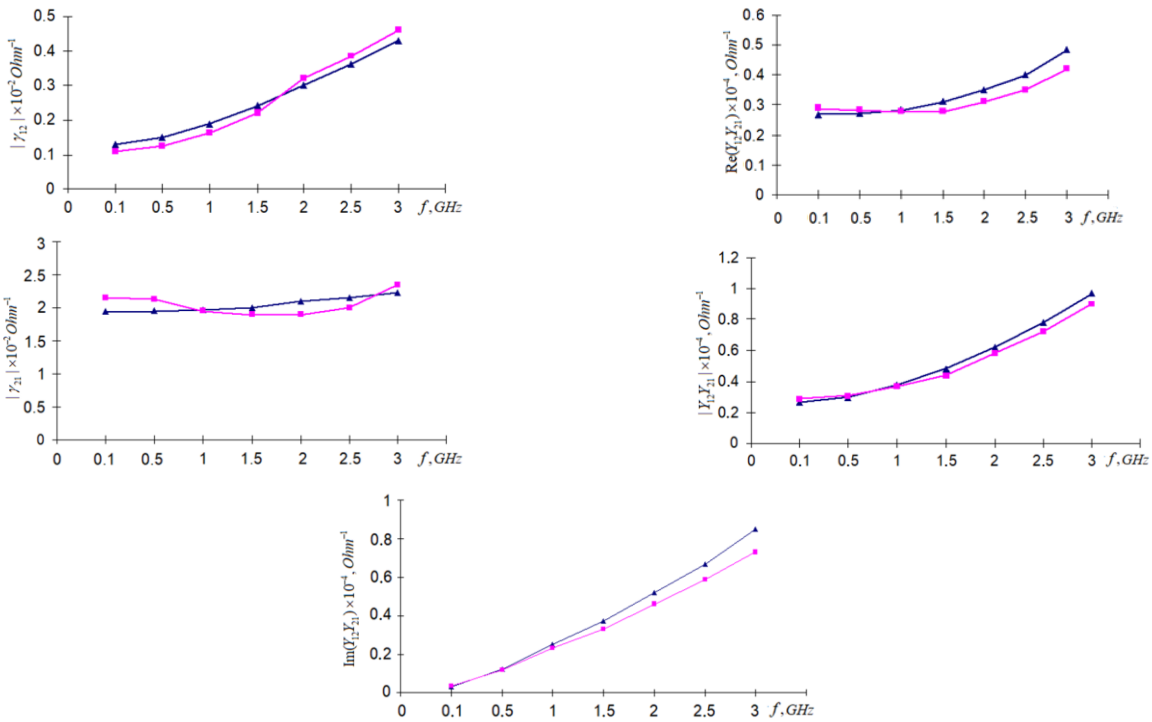

Fig. 3. Frequency dependence of non-standard W-parameters of the 3P321 field-effect transistor connected in a common-gate circuit: □ – theoretical data; ▲ – experimental data

4. Conclusions

Based on the developed methodology for determining standard and non-standard W-parameters of potentially unstable four-poles, a detailed mathematical model of W-parameters of field-effect transistors was created, which allows to predict their behavior under high-frequency influences. The main aspects of the study include:

- the optimal equivalent circuits of field-effect transistors for operation in the microwave range have been considered and selected. This selection is based on a thorough analysis of the characteristics of transistors, taking into account the features of their design and operation at high frequencies, which allows for more accurate modeling of their behavior at different frequency regimes;
- equations are obtained that allow to establish the relationship between the physical parameters of the equivalent circuit of a transistor and its W-parameters. These equations take into account the possibility of four-pole instability, which is of key importance for the design of microwave devices, where stability is an important factor for ensuring reliability and performance;
- a detailed algorithm for conducting a numerical experiment to determine the W-parameters of field-effect transistors has been created. This algorithm provides a systematic approach to calculating parameters and allows to obtain the results with high accuracy even under conditions of changing external factors, such as temperature and frequency;

- numerical calculations of both standard and non-standard Y-parameters for bipolar and field-effect transistors were performed. The results obtained were compared with experimental data, which allowed to make a deep analysis of the adequacy of the proposed methodology. The analysis showed that the deviation between the theoretical and experimental results does not exceed 15%, which indicates high accuracy and practical suitability of the methodology for engineering problems.

This development greatly facilitates the design process of microwave devices using field-effect transistors, providing engineers with a convenient tool for predicting the behavior of these elements in difficult conditions, in particular with potential instability of four-poles [1, 10].

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Ph.D. Oleksandr Voznyak
e-mail: alex.voz1966@gmail.com

Candidate of Technical Sciences, associate professor of the Department of Power Engineering, Electrical Engineering and Electromechanics, Vinnytsia National Agrarian University. The author of more than 100 publications, including 5 training manuals, 6 patents for inventions and more than 80 scientific articles in professional publications, including 17 in the scientometric databases Scopus and Web of Science.

https://orcid.org/0000-0002-0986-6869

Ph.D. Liudmyla Kolianovska
e-mail: kolianovska73@gmail.com

Candidate of Technical Sciences, associate professor of the Department of Bioengineering, Bio- and Food Technologies, Vinnytsia National Agrarian University. Research interests: food technologies, vegetable oils, extraction and nutrition science.

https://orcid.org/0000-0002-8645-3515

Ph.D. Kateryna Kovalova
e-mail: katrin.viter@gmail.com

Candidate of Pedagogical Sciences, associate professor of the Department of Ukrainian and Foreign languages, Vinnytsia National Agrarian University. Author of more than 30 publications, including 2 textbooks, more than 20 scientific articles in professional journals, of which 4 are in scientometric databases Scopus and Web of Science.

https://ocid.org/0000-0001-7183-2996

Ph.D. Svitlana Ovsienko
e-mail: ovsiienko@gmail.com

Candidate of Agricultural Sciences, associate professor of the Department of Bioengineering, Bio- and Food Technologies, Vinnytsia National Agrarian University. Scientific interests: innovative methods for increasing the efficiency of food production.

https://orcid.org/0000-0001-5234-4305

Ph.D. Yurii Polievoda
e-mail: vinyura36@gmail.com

Candidate of Technical Sciences, associate professor of the Department of Bioengineering, Bio- and Food Technologies, Vinnytsia National Agrarian University. Author of more than 160 publications, including 3 textbooks, 50 patents for inventions and more than 88 scientific articles in professional journals, of which 19 are in scientometric databases Scopus and Web of Science.

https://orcid.org/0000-0002-2485-0611

Ph.D. Alla Solomon
e-mail: Soloalla78@ukr.net

Candidate of Technical Sciences, associate professor of the Department of Bioengineering, Bio- and Food Technologies, Vinnytsia National Agrarian University. Research interests: production of food products with a combined composition of raw materials.

https://orcid.org/0000-0003-2982-302X