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The Standard Model of the Heterostructure for Microwave Devices

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Abstract—A methodology of the selection of the initial materials, architecture and synthesis of heterostructures based on domestic materials and technologies as applied to specific types of microwave components needs to be developed. As the nomenclature expands, the requirements on energy consumption, overall dimensions and weight, frequency range, noise, values of working temperatures, and other characteristics of microwave components have significantly increased. Specific examples of power amplifiers for various applications (wireless communication systems and location systems) are considered. It is shown that in order to implement such developments, it is necessary to apply modern methods of multilevel computer modeling using various methods of optimization and widely use the tested technical solutions. The final result of this development is the creation of a set of basic physical models of the heterostructures, including those based on the solution of optimized problems by choosing the initial material, substrate material, layer composition, their sequences, layer thicknesses, impurity contents, and their distribution by the layer thickness. All this makes it possible to form an acceptable level of mechanical stresses and high values of the electrophysical characteristics in the heterostructure. The initial data set in the form of a library of basic models of the heterostructures will make it possible to significantly accelerate the development of various microwave components and optoelectronic components in the system of instrument and technological design and improve the characteristics of the devices and economic rates.

Keywords: microwave components, heterostructures, standard model, multilevel model, optimization algorithms

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INTRODUCTION

The problem of a rational choice of electronic components remains actual today. This includes their development, ensuring the specified performance characteristics of the electronic systems of hi-tech products, their reliability, and reasonable prices. This problem also applies fully to the electronic components of the microwave range. As the microwave components are widely used in various systems for military and civil purposes, the nomenclature of their production is sufficiently large. Moreover, with the expansion of the field of practical application, the demands for energy consumption, overall dimensions, weight, frequency band, noise, working temperature values, and other characteristics of microwave components are sharply rising. According to [1], the energy consumption and weight-dimensional characteristics of microwave devices for the same functional purpose can differ by three or more orders. Using such systems of instrumental-technological designing (ITD) promotes the successful solution of problems related to the development of new types of microwave devices. The main emphasis of ITD lies in simulating technological processes, heterojunctions, devices based on them, photo detectors, light-emitting diodes, and lasers, as well as the analysis of the spreading of the carriers in the channel.

For performing such developments, various computer-aided design (CAD) systems are used: Microwave Harmonica, Microwave Explorer, Success, Microwave Office (Applied Wave Research), and others [2]. A variety of tools enters into the composition of these systems. For example, the Synopsys TCAD Sentaurus CAD SYSTEM includes the following tools [3]:

—Sentaurus Workbench for creating the model of structures with different thicknesses of the layers, gate length, and depth of gate grooves;

—Sentaurus Structure Editor for creating the geometric models of a transistor;

—Sentaurus Mesh is used for electrophysical modeling, etc.

It should be noted that these systems contain libraries with a large quantity of models of the initial passive and active components (transistors). However, the companies producing microwave components and monolithic integrated circuits as a rule carefully protect their manufacturing methods. This primarily refers to the growth processes and design of the used heteroepitaxial structures, which fundamentally com-

Table 1. Parameters of serially produced powerful microwave transistors

Technology	Frequency range, GHz	Output power range, W	Transistor efficiency, %	Supply voltage, V	Working temperature, °C	Chip output power, W, (evaluation)
Si LDMOS	0–2	5–15	60	28	<200	–
GaAs MESFET	0–14	<14.5	40	8–10	<175	20
GaAs HiFET	0–2.5	1–8	35	14–28	–	–
GaAs HFET	<10.5	<10	50	8	–	20
GaAs pHEMT	0–50	<15	55	8–10	<150	20
GaInP HBT	<10.5	<10	40	9	–	–
SiC MESFET	0–4	<60	40	48	<300	100
GaN HEMT	0–20	<100	60	28–50	<225	200

plicates the direct use of foreign CAD systems [4]. Furthermore, there is a significant gap in such CAD systems connected with the lack of a methodology justifying the used initial materials, the scheme of layer distribution in the structure, the application to specific technologies, etc. In this respect, there is an urgent need to develop the standard models of microwave heterostructures based on domestic materials and technologies, and which are the main initial constructive element in CAD systems.

PROBLEM STATEMENT

We consider the problem statement by the example of developing microwave components—power amplifiers. Based on the theoretical and experimental research, as well as the accumulated experience producing the components considered to date, sufficiently stable manufacturing domains of powerful microwave transistors based on semiconductor materials of certain types have been formed. The main types of serially produced transistors and their functional characteristics as applied to the raw materials are listed in Table 1 [5]. As it follows from the data of Table 1, each type of device is characterized by certain values of the output power, frequency range, efficiency, etc., which, in turn, depend on a number of fundamental properties of the base materials.

Silicon transistors (Si LDVOS—silicon transistors with lateral diffusion) hold the niche up to 2 GHz. GaAs pHEMT (gallium-arsenide pseudomorphous heterostructural field-effect transistors) are most in demand among devices based on GaAs. These transistors have a high gain, are very efficient, and have high threshold frequencies. The output power of the transistors based on silicon carbide (SiC MESFET—silicon carbide field-effect transistors with homogeneous alloying) in the frequency range up to 2.5 GHz can reach up to 100–150 W and they can operate under difficult conditions. GaN HEMT transistors (gallium-nitride heterostructural field-effect transistors) have quite high performance characteristics. Due to their obvious advantages, gallium-nitride transistors are increasingly being used in a wide range of practical applications. Thus, the brief analysis of the data of Table 1 makes it possible in the first approximation to choose the base material and transistor type depending on the specified frequency boundaries, power, etc. In addition, the growing needs for new components of different fast-developing systems of high-speed wireless data transmission should also be taken into account. Microwave components operating in the frequency range up to 10 GHz and above with extremely small sizes and low power consumption are needed for these systems. They should also have a low price, while being highly reliable. Devices based on silicon, a silicon germanium solid solution, and gallium arsenide best satisfy these demands [6]. For more detailed studies of the rational choice of the raw material, it is necessary to take into account a number of additional typical demands for the microwave power amplifiers, the list of which is presented in Table 2.

Based on the mentioned demands, it is necessary in each particular case to analyze the following types of dependences: the dependence of the frequency on power; the dependence of power on the working temperature; the dependence of the working temperature on the environmental temperature; the dependence of the mechanical stresses on the mismatch of the crystal lattice parameters, thermal expansion coefficients, etc. These dependences make it possible to justifiably select (1) the raw material; (2) the material of the carrier's substrate; (3) the constructive scheme of the heterostructure, in which 2D-gas is generated, and additional layers to ensure the normal operation of the heterostructure as a whole (the sequence, the thicknesses, and the chemical composition of the layers are set), as well as perform the comparative estimation of the expected cost of the heterostructure. To date such research up was mainly carried out based on an engineer's own design experience, by trial and error, using simplified calculation methodologies, etc. All of this has made the design process long and laborious. In order to carry out such work, modern methods of mul-

Table 2. Typical demands for microwave power amplifier

Device type	Operating mode	Functional parameters	Overall dimensions, mm Weight, g	Operating conditions	Reliability	Production cost, rubles
(1) Discrete (2) Small-scale integration circuits (SSIC) (3) Hybrid circuits (SSIC + vacuum)	(1) Pulse (2) Continuous	Frequency range: Decimetric waves 300 MHz–3 GHz Centimetric waves 3–30 GHz Millimetric waves 30–300 GHz Output power, W Up to 1; 10; 20; 40; 100; 200; 1000 Efficiency, % 15–60; >60 Noise factor	(1) Chip sizes (2) Specific output power, W/mm (3) Weight, g	(1) Ambient temperature (2) Mechanical loads (3) Climatic influence (a) on ground (b) in space (4) Radiation exposure	(1) Chip yield, % (2) Failure rate, h^{-1} (3) Operating time between failures, h	Material cost Technology cost

tilevel computer simulation using different optimization techniques need to be applied; and the widespread use of the experience of previous designs is also needed. Let us note that shortening the development terms of new microwave components is a relevant problem. Thus, according to [7], the stages of research and development leading up to industrial production in many cases take nine years or longer. Thus, the lack of the means of solving an intellectual problem by the formation and synthesis of the architecture of the heterostructures complicates the successful implementation of various systems of the ITD of microwave components as a whole. This, ultimately, predetermines the qualitative characteristics of electronic devices, their price and reliability.

DEVELOPMENT OF THE STANDARD HETEROSTRUCTURE MODEL

As mentioned above, the first step in the development system of the standard heterostructure model is to select the raw material and the substrate material. As an example, let us consider the variant of the optimization problem in connection with determining the competitive advantages of low-power microwave devices as applied to the raw materials based on which they are manufactured. Let us note that the market for such devices in a wireless communication system is at present practically unlimited, and the product yield reaches several billion pieces per year. In the case of a discrete device (transistor or other device), we relate the cost, the reliability, the power consumption, the geometric dimensions, the weight, etc., to the competitive indices. In the case of monolithic integrated circuits, we propose replacing their geometric dimensions and weight by the parameter of integration. This replacement is justified by the fact that in most cases, in the current radio-engineering solutions, in addition to discrete devices, the integrated circuits, systems-on-a-chip, and/or system in the body are widely used. Moreover, significant synergism is achieved, with respect to reducing both weight and the geometrical parameters, as well as improving the economic indices of the device as a whole. The example of combining various functional units of a receiving microwave device based on a monolithic integrated circuit is shown in Fig. 1 [8]. According to the data of [1], in this case the weight and overall dimensions could improve by tens or hundreds of times. Thus, the parameter of integration characterizes the possibility of combining the fabrication methods on one chip of a unit of microwave components and of the unit of microwave components with peripheral instruments, ensuring operation in the specified modes of active microwave devices. In addition, the fabrication methods of devices providing the targeted information (e.g., converting an analog signal into a digital signal and vice versa, etc.) is combined. Taking into account that the market of low-power devices is constantly expanding, the problem arises concerning the optimal selection of the raw material from Si–SiGe–GaAs for their production. As the criterion parameters, we propose to use the indices of cost, energy consumption, and integration (the ratio of the weights or volumes of the modules manufactured using discrete components and in the form of monolithic integrated circuits). It is obvious that the cost index is the most significant parameter for mass production. Mathematically, the problem is reduced to finding the optimal value of the integral criterion [9]. The calculations sufficiently correctly suggest that in the case of orientation for mass production, the preference should be given to SiGe. In the case of critical applications when the cost is irrelevant, the devices are more often manufactured based

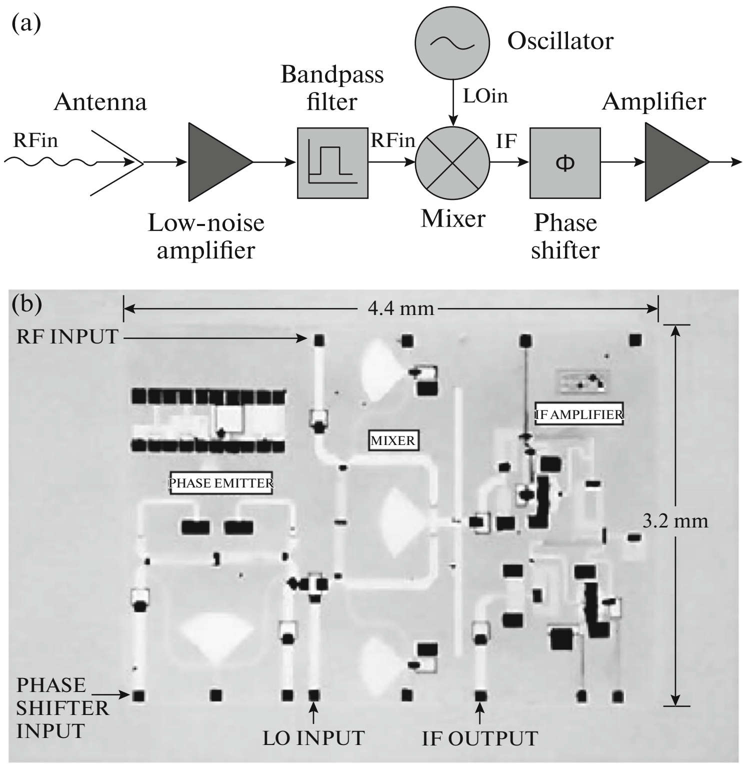

Fig. 1. Functional diagram (a) and design (b) of microwave receiver at 30 GHz [8].

on GaAs. The advantages of using silicon–germanium technology in the production of microwave devices for the systems of wireless communication and locations were studied in detail in [1, 6, 10].

Next, we will consider the example of selecting the substrate material in the case of developing and manufacturing a power amplifier based on a gallium nitride heterostructure. For the substrate material based on silicon, silicon carbide, and sapphire, the cost, the heat conductivity, and the integration were chosen as the competitive parameters. For a civil application, the substrate cost is the prevailing factor. For use in space, the heat conductivity is the most important indicator. As a result of the calculations, the correct data on the prospects of silicon substrates for producing gallium-nitride heterostructures intended for mass applications were obtained. Let us note that silicon substrates have clear advantages due to the low cost (lower by factors of 10 and 100 than sapphire and silicon carbide, respectively), the high quality of the working surface, the availability of large-diameter plates (200 mm and larger), and the high degree of integration. Taken together, this makes it possible to significantly reduce the geometrical dimensions and weight of the products and significantly extend their functionality, as well as noticeably lower their cost.

The next step in building the standard model is the choice of the initial heterostructure with the known architecture and parameters based on the experience of previous developments and published information. An example of such a structure is shown in Fig. 2. The problems of using various optimization techniques for creating the computer model of a multilayered semiconductor nanostructure (MSNS) are considered in [11]. The common approach for solving the problem of obtaining promising materials for microwave electronics with predictable properties is presented. The approach can be applied in the development of new technologies for producing a variety of MSNSs. In order to solve the stated problem, an integrated approach based on the predicted computer simulation and comparison of the experimental and theoretical data is used. It assumes the theoretical simulation of the structures and properties of the materials to be created, based on a detailed understanding of their structure at the atomistic level (Fig. 3).

Next, using the mathematical tools shown in Fig. 3, the electrically active part of the initial heterostructure depending on the demands of the technical specifications is optimized. In the model of electrical conductivity, the influence of the dopant content, the stoichiometric composition of AlGaN, and the defects in the bulk and at the boundaries, as well as the thicknesses of the spacer layers and barrier layer, on the concentration and mobility of the charge carriers is studied [12–14]. Note that the optimal electrophysical parameters of GaN heterostructures for some applications are achieved when the molar fraction of Al in a

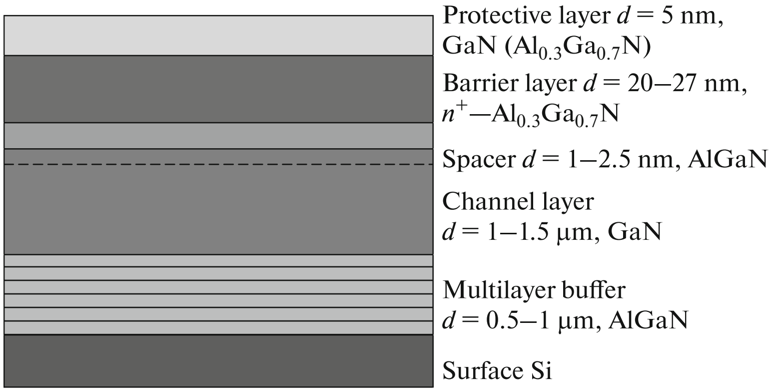

Fig. 2. Scheme of standard model of gallium-nitride heterostructures on silicon substrate.

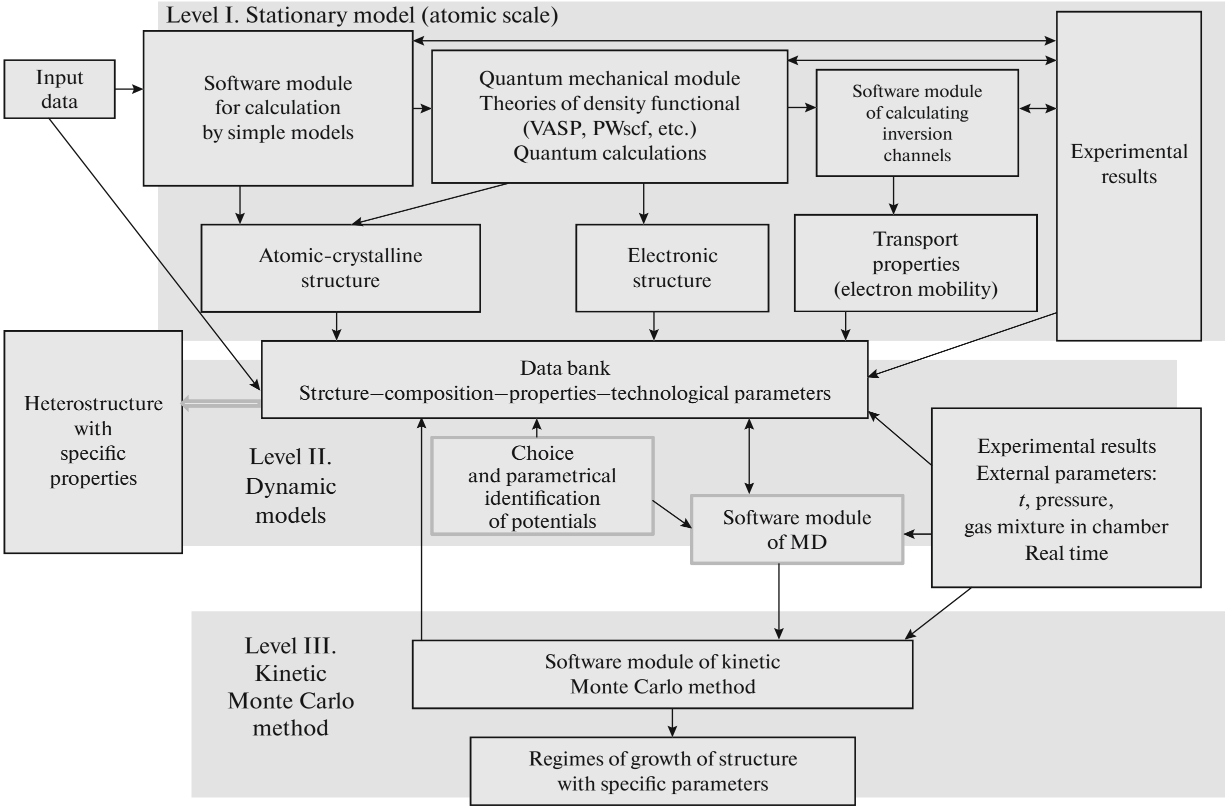

Fig. 3. Scheme of multiscale simulation of semiconducting heterostructures.

layer is at least 0.25, with the thickness of the barrier layer of 6 to 30 nm, with the thickness of the spacer layer of 1 to 2.5 nm, and the doping level by silicon of $(1–5) \times 10^{18}$ cm^{-3}. Depending on the specified frequency interval, reducing the thickness of the barrier layer in the optimal range can be one of the main ways of improving the power parameters of a microwave device [15].

Next, let us consider the problem statement of optimizing the construction of a heterostructure, which makes it possible to eliminate (or reduce) the negative influence of mechanical stresses on the magnitude of its deflection and as a result achieve the desired characteristics of the final product. Depending on the specific conditions, various technological methods of solving this problem have been proposed. For example, it was revealed in [16–18] that, even with small differences in the lattice spacing of the AlGaAs/GaAs laser structure ($\sim 1.18 \times 10^{-3}$), mechanical stresses arise, which cause a significant deflection of the plates. It was shown experimentally that the deliberate introduction of a phosphorus impurity in the emitter and waveguide

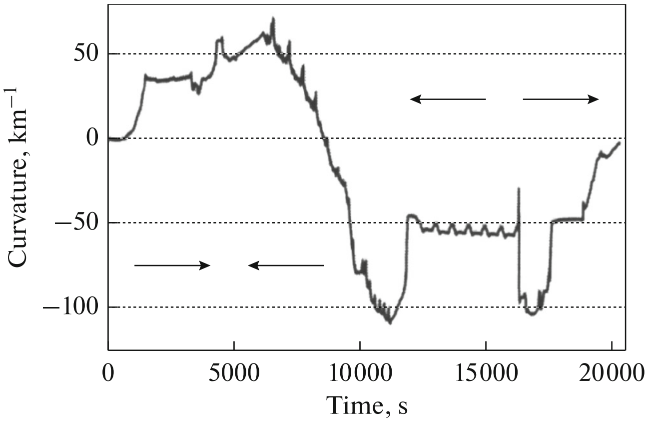

Fig. 4. Behavior of curvature of in-situ structure during deposition of buffer layer, and cooling. Arrows show stresses of tension and compression at different stages of technological process.

layers of AlGaAsP/GaAs heterostructures meant for laser diodes makes it possible to avoid the occurrence of significant mechanical stresses, reduce the amount of deflectionm, and ultimately improve the characteristics of devices. The largest differences in the lattice parameters (17%) and in the thermal expansion coefficients occur in the case of a combination of GaN–Si; for silicon the differences are half those for GaN. When forming the heterostructure due to the significant differences of the these parameters, strong tensile stresses occur, which lead to a significant deflection of the epitaxial structures and possible cracking of the GaN layer with its thickness at least ~1 μm. The original compensation variant for the tension stresses that arose during cooling from the growth of the working temperature to room temperature due to the creation of compressive stresses when preforming the AlGaN buffer and AlN underlayer on a silicon substrate was proposed in [19]. The behavior of the structure's curvature in situ during the buffer layer deposition and with cooling is shown in Fig. 4. The mutual superimposition of stresses of the opposite sign made it possible to notably reduce the amount of deflection and consequently eliminate the cause of the defect and crack formation of the GaN layer. Another solution of the problem of compensating the mechanical stresses in GaN heterostructures is discussed in [7]. The sufficiently low deflection values, close to the initial values, were achieved when forming a multilayer buffer (up to six layers of AlGaN) of a different composition and thickness on a silicon substrate on which the layers of Al and AlN were previously deposited. It should be noted that the improvement of the technology that creates inter alia GaN heterostructures is primarily connected with modeling the processes of the emergence of stresses with the opposite sign and optimizing their distribution (the model of the bending of plates). The influence of the residual stresses on piezoelectric polarization and the mobility of charge carriers (the model of stresses near the interfaces) for correcting the data obtained when optimizing the electrically active part of the heterostructure is also the subject of modeling. Thus, having the standard model of the heterostructure and a certain set of computing tools, we can relatively quickly create the initial architecture of the heterostructure for further ITD. Similarly, we can build a detailed set of standard models of heterostructures for transistors used for different purposes, lasers, light-emitting diodes, and other components manufactured based on gallium nitride, gallium arsenide, silicon carbide, indium phosphide, SiGe, and other materials. Another important factor, which determines the advisability of developing standard models of heterostructures, is the ability to combining the demands of the designers of electronic components with the technological capabilities of manufacturing structures using the standard models. This makes it possible to unify the parameters of the devices and heterostructures in the presence of a large quantity of industrial types of microwave components and devices.

CONCLUSIONS

The problem of forming and synthesizing the architecture of heterostructures based on domestic materials and technologies, which are the main initial constructive element in ITD systems. It is shown that creating a library of standard models of heterostructures makes it possible to significantly accelerate the development of various microwave components, combine the demands of designers on the parameters of the heterostructures with the capabilities of their manufacturing methods, and create unified series of microwave devices.

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