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Local Diagnostics Of Electrophysical Properties In Semiconductor Nanostructures.

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Annotation. In today's century, the development of information technology has given impetus to the development of the economy. Impact of the development of semiconductor materials and nanoelectronics technologies on innovative processes in the electronic economy. This research examines the concentration and energy levels of charge carriers in modern conditions for the study of electrophysical tools of semiconductor materials and the application of new diagnostic methods. Semiconductor technologies form the basis of modern electronics and information technologies. These technologies are especially important in creating high-speed telecommunication systems. Semiconductor electronic devices are basically the elementary base of micro- and nanoelectronics. Therefore, research and synthesis of new materials, study of their electrophysical properties, production technology were developed in this field.

Key words. Material, structure, diagnostics, concentration profile, energy spectrum, diagram, parameter, local micro- and macro-inhomogeneity, semiconductor structures, deep level relaxation spectroscopy, scanning probe microscopy, capacitance-voltage characteristics, local current relaxation, diagnostics of nanostructures.

Enter.

Scientific and technical progress is associated with the introduction of digital technologies that allow the economy to work with large amounts of data. Economic activity based on digital technologies is called digital economy. It is based on the transition from goods and services in material dimensions to virtual operations in the RAM of computers, in which all types of operations are carried out with units of measurement of the amount of information. 2015 - an exponential trend of data collection was observed. The information age is giving way to the digital age, cloud service, artificial intelligence appeared. For the successful implementation of the digital economy, there is an increasing need to use high-speed digital telecommunications that connect data centers, producers and consumers of services. The development of digital technologies is leading scientific and technical research to increase availability, reduce weight and size indicators, speed and functionality, reduce and optimize energy consumption. Therefore, the design and creation of high-speed telecommunication radioelectronic equipment is required. The production of radioelectronic equipment leads to the creation of an elementary base of micro- and nanoelectronics and solving the problems of improving its quality indicators, as well as conducting a lot of scientific research on semiconductor materials. The search and synthesis of new materials and structures for the improvement of the elementary base, the development and improvement of their production technology, the study of physical processes and phenomena in nanostructures, and the development of the physics of nanosystems have become one of the urgent problems. Based on the understanding of physical processes, constructive and technological recommendations are developed for the production of semiconductor elements and integrated microcircuits.

The emergence of new materials and constructions, the reduction of the active areas of semiconductor devices, the adaptation of the known parameters and properties of their parameters and the development of new methods, the need to improve physical models based on practical research methods. The operation of nanoelectronic devices with quantum wells (QWs), quantum dots (QDs), semiconductor heterostructures containing alternating nanoscale layers of amorphous and crystalline semiconductors in the active region, with size quantization of charge carriers based on related physical phenomena. To study the properties of such structures, using the latest developments in the field of measuring and diagnostic equipment, the most important parameters of semiconductor materials and devices, including electrophysical properties that determine the speed and power consumption of the final radio equipment, are being used.

The electrophysical properties of semiconductor structures are characterized by important parameters such as the concentration of free charge carriers (NC), the energy spectrum of electronic states determined by the configuration of active regions, the composition of solid solutions, the doping profile with the donor or deep energy in the band gap of the semiconductor with an acceptor compound. Capacitance-voltage method is a reliable non-destructive method of measuring the concentration profile at the interfaces between the active layers and the presence of volume structural defects and semiconductor barrier structures [1,2]. The position of the energy levels of volume quantization is influenced by the quality of the heterointerfaces, the size of the gaps in the allowed energy bands at the heterointerface, and the parameters of the electrically active defects that form deep and shallow energy levels.

The listed methods for the study of nanostructures are intended for the study of samples with macroscopic electrical contacts, for which a planar barrier contact model was developed and applied, in which the thickness of the loss layer is the contact will be much lower than the minimum lateral size. The obtained characteristics are averaged over the area of the barrier or ohmic contact, which usually varies 2 10^3-10^4 microns, depending on the sensitivity of the input paths of the measuring devices. It significantly exceeds the characteristic lateral dimensions of quantum dots [3], regions of inhomogeneous thickness and different composition of semiconductor solid solutions, etc. Bu hozirgi va kelajak avlodlarning elektron va integral mikrosxemalari uchun materiallar va konstruksiyalarning parametrlari va xususiyatlarini bir necha yuz nanometrgacha bo'lgan fazoviy o'lchamlari bilan o'rganish va nazorat qilish usullariga shoshilinch ehtiyojni keltirib chiqaradi [4].

Of particular importance is the development of new diagnostic methods that provide a comprehensive study of the material or structure, as a result of which the concentration profile, energy spectrum of charge carriers, parameters of the band diagram, their distributions, local micro- and macro-inhomogeneity, including those in the nanometer range. It is proposed to develop a new technique to ensure the complexity and high localization of studying the electrical properties of semiconductor structures. They are based on the combined use of scanning probe microscopy and capacitance-voltage characteristics, deep-level relaxation spectroscopy, and LF noise spectroscopy [5-6].

The complex application of methods developed for measuring local capacitance-voltage properties, local current relaxation spectroscopy of deep levels, diagnostic methods of semiconductors, micro- and nanostructures allows obtaining additional information and a deeper understanding of physical processes. semiconductors. This contributes to the development of semiconductor physics [7].

The main goal of our research work is that.

1. Analysis of existing methods of studying the energy spectrum, studying electronic states, dipole concentration profiles, defects related to deep energy levels in semiconductor micro- and nanostructures.Nuqtali yarimo'tkazgichli nanostrukturalarning fizik modelini ishlab chiqish elektr potentsial taqsimotining sferik simmetriyasini yaqinlashtirishda to'siq kontaktining konfiguratsiyasini va o'rganilayotgan yarimo'tkazgich mikro yoki nanostrukturasini hisobga oladigan to'siqli kontaktlarni o’tkazuvchanlik tezligini taxlil qilish.
2. Development of a physical model of the formation of a relaxation current during the increase in the rate of energy level charging in a semiconductor structure based on point-barrier contact, which takes into account the spherical symmetry of the electric potential distribution.

3. Development of the fundamentals of semiconductor structures on the basis of joint application, deep-level current relaxation spectroscopy, atomic determination using force microscopy.
4. Research on nickel heterostructures with quantum well depth to improve the model of low-frequency wave generation in semiconductors.
5. Development of a technique for local measurement of voltage characteristics under normal voltage and temperature effects.

The materials selected as the research object of the ongoing scientific research are as follows. Quantum wells (QW) based on heterostructural systems. System based on InGaAs/GaAs, ZnMgSse/ZnSe, ZnCdS/ZnSSe and heterostructures (CT) with self-assembled quantum dots CdSe/ZnSep, surface relief-Si based on advanced semiconductor microstructures, hybrid heterostructures nanoscale layered-Si:H and crystalline Si. Compound-based structures A3IN5 and A2IN6 were selected. Samples are grown using molecular beam epitaxy (MPE) or metal-organic vapor phase epitaxy (PFEMOS) methods [1-4].

The results presented as a result of the scientific research are as follows. Forming a point electrical metal-semiconductor contact to obtain a three-dimensional distribution profile of the concentration of free charge carriers of a semiconductor structure based on the use of a sample scanning probe microscope. Development of measurement-analytical complexes for implementation, developed methods of local measurement of capacitance-voltage characteristics, using low-deep current relaxation spectroscopy, low-frequency wave spectroscopies.

The study of semiconductor nanostructures, advanced structures, the determination of the discontinuities of the allowed energy ranges in nanostructures with quantum wells of different composition and thickness, the distribution of these values along the surface of the sample parallel to the layer forming the quantum wells during dot formation development using research methods that have been studied and developed.

Summarizing the obtained theoretical and experimental results, studying physical processes in semiconductor micro- and nanostructures.

As the content of the main work carried out in scientific research work, a new mathematical model describing the transition period is proposed in a semiconductor dot-to-toe with quantum well depth in contact with the spherical symmetry of the electric potential, taking into account the size filling. The process of current relaxation under the pulsed effect of electric voltage during recharging of size-quantization energy levels in a dense structure has been studied quantization levels. Using the method of local study of the energy spectrum, electronic states in semiconductor structures, that is, in their regions with dimensions in the nanometer range (10–100 nm), are defined as the flow of electric current through the structure under the impulse of an electric voltage. Based on the study of the temperature dependence of the relaxation time, the point barrier formed by the transmission probe of the atomic force microscope (AFM) during external exposures is defined as the boundary region of the metal-dielectric-semiconductor contact. : AFM uses a conductive probe to make an electrical contact, which allows the measurements to be located.

A new technique has been developed to obtain local capacitance-voltage characteristics. Characteristics of the semiconductor barrier structure in the ranges related to the cross-sectional area, which consists of using an atomic force microscope probe system to contact the surface of the semiconductor sample with an electrical point, analyzing the DC component of the current through the sample. It is shown that local capacitance-voltage characteristics can be obtained when a periodic pulsed voltage is applied to it, containing a component proportional to the capacitance of the sample. The calculation of the local profile of contamination concentration in the semiconductor structure was achieved with the point electrical connection of the conducting probe to the surface of the semiconductor sample using a microscope when an external voltage was applied. For example, a Si semiconductor structure with advanced relief, pyramidal surfaces with a base height and side of 3-5 mkm are obtained. becomes easier.

Methods that allow local measurement of electrical properties (concentration of free NC, resistance, electric potential) of semiconductor micro- and nanostructures. With the decrease in the size of the active regions of the elements, the effect on the physics of micro- and macro-inhomogeneities in the distribution of electrical properties, various structural defects, surface topography and interface properties increases. To detect these microheterogeneities, probe methods are used, which have their own limitations. The physical basis of scanning microwave microscopy and scanning diffuse resist microscopy (SMSR) is reviewed. The main possibilities and limitations of these research methods are discussed.

Based on the review of electrical probe methods for measuring the concentration of free charge carriers in semiconductor materials, the choice of a technique for local measurement of the concentration profile of free charge carriers in semiconductor structures is based. To apply this technique, the electrophysical properties of the dot line - metal-semiconductor structures were taken as an example. A point barrier contact is analyzed in approximation of the spherical symmetry of the electric field and potential distribution in the semiconductor and the sharp boundary of the space charge region (SCR) in the semiconductor. However, when the contact dimensions are proportional to the Debye length, the push of the SCR limit must be considered. The solution of Poisson's equation is described in the spherical coordinates of a metal-semiconductor with a point contact. In the approximation of the absence of charge on the surface, the n-type means:

$$\frac{1}{r^2}\frac{d}{dr}\left(r^2\frac{d\varphi}{dr}\right)=-\frac{eN(1-e^{-e\varphi/k_BT})}{\varepsilon\varepsilon_0}, \qquad (1)$$

Here *e*-elemental charge, T-absolute temperature, e^0-absolute dielectric permittivity, *e*-relative permittivity of the semiconductor, concentration of N-ionized donor impurity (can be but treat the acceptor impurity the same) , *kB*-Boltzmann's constant, *r*- the distance from the geometric center when the metal probe touches the surface of the semiconductor at a point in the main part of the semiconductor.

In this case, the charge on the surface states was not taken into account. As a result of solving the equation, the dependence of the electric potential in the semiconductor (1) is expressed by the expression:

$$\varphi(r,r_0)=-\frac{r_0}{r}(U_K+U_R)exp\left(\frac{r_0-r}{L_D}\right), \qquad (2)$$

Here r_0 is the radius of curvature of the point contact, LD is the Debye length, U*k* is the ion diffusion potential, and UR is the magnitude of the bending stress.

The value of the electrical barrier capacity of a point contact can be calculated as the derivative of the charge of ionized compounds.

$$C(U)=\frac{dQ}{dU}.$$

Contact with the surface of the studied structure is made by a conductive AFM probe. The charge of the surface states was not taken into account in the calculations, and the position of its internal boundary in the semiconductor was satisfied. R > r_0, then the contact can be considered hemispherical in the first approximation degreasing[15-16].

In addition, the value of the barrier capacitance for a hemispherical contact is found by the following formula:

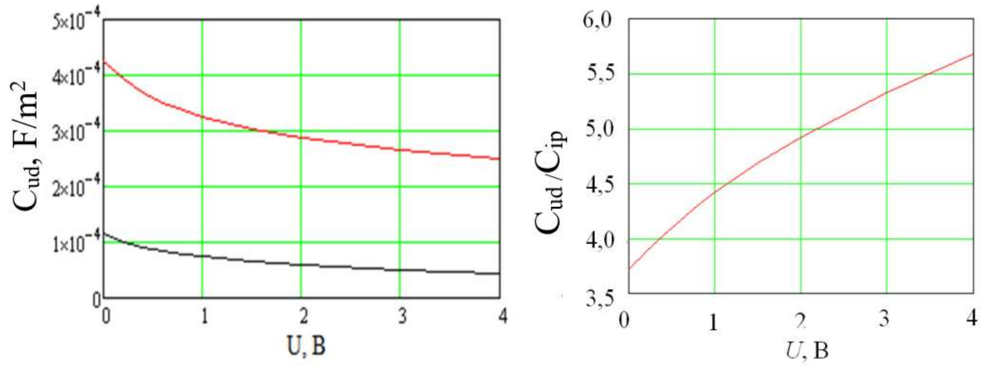
$$C(U)=2\pi e N R^2(U)\left[\frac{dR(U)}{dU}\right], \qquad (3)$$

In Figure 1. The specific capacitance of the point is calculated. It can be seen that the connections are connected to a flat barrier (Fig. 1 a). The ratio of specific capacitance to the specific capacitance of a planar barrier contact (Fig. 1^b). On the other hand, taking into account the contamination of the internal boundary of the SCR at a low concentration of donors, it can be seen that the stress is 10^{15} cm^3 and the radius of contact with the point is 50 nm (n-Si material) [9-10].

Nazariy hisob-kitoblar natijalaridan C-V xususiyatlari shundan kelib chiqadiki, elektrdagi o'zgarish CVga bog'liq yarimo'tkazgich hususiyatlarini ochib beradi. Kontakt modelini tanlash erkin NS kontsentratsiyasi profilini hisoblashning aniqligiga ta'sir qiladi [16]. Metall yarimo'tkazgichli nuqta to'siqni kontaktining elektr sig'imi ham zaryad tashuvchilarning kontsentratsiyasiga, ham aloqa radiusiga (ishlatiladigan o'tkazgich radiusi) bog'liq. Yarim sharsimon kontaktni yaqinlashtirishda, teskari kuchlanish kuchayishi bilan, planar to'siqli kontaktdan farqli o'laroq, sig'im biroz oshadi. Bu tekis to'siqli kontaktda uning maydoni teskari kuchlanishga bog'liq emasligi bilan izohlanadi, yarim sharsimon modelda esa yarimo'tkazgichdagi SCRning ichki chegarasiga mos keladigan sirt maydoni teskari kuchlanish bilan ortadi. Shuningdek, hisob-kitoblardan kelib chiqadiki, o'ziga xos sferik kontakt sig'imi taxminan, 3,7 - 5,7 marta solishtirma quvvat planar aloqa va bu nisbat ortib borayotgan teskari chiziqli kuchlanish bilan ortadi [11].

Olib borilgan tadqiqot natijalari shuni ko'rsadiki. Mahalliy tok relaksatsiya spektroskopiyasi usuli sinovdan o'tkazilgada chuqur darajalar tok relaksatsiyasi spektroskopiyasi va atom kuchi mikroskopiyasini birgalikda o'rganilayotgan From the results of theoretical calculations, the C-V characteristics are derived from the fact that the change in electric current reveals the semiconductor properties depending on the CV. The choice of the contact model affects the accuracy of the calculation of the free NS concentration profile [16]. The capacitance of a metal-semiconductor point-barrier contact depends on both the concentration of charge carriers and the contact radius (radius of the conductor used). When approaching a hemispherical contact, as the reverse voltage increases, unlike a planar barrier contact, the capacitance increases slightly. This is explained by the fact that its area does not depend on the reverse voltage in the contact with a flat barrier, while in the hemispherical model, the surface area corresponding to the internal boundary of the SCR in the semiconductor increases with the reverse voltage. It is also calculated that the specific spherical contact capacity increases approximately 3.7 - 5.7 times the specific capacity of the planar contact and this ratio increases with the reverse linear voltage [11].

The results of the conducted research showed that. While testing the local current relaxation spectroscopy method, deep levels are being studied together with current relaxation spectroscopy and atomic force microscopy, it was possible to control the distribution of the activation energy of charge carriers along the surface of the semiconductor micro and nanostructure, parallel to the heterointerfaces [13].



(a) **(b)**

Figure 1. a- flat (bottom curve) and the dependence on the specific capacitance of the point (upper curve) contact with reverse voltage barrier;
b - the dependence of the specific capacitances of point and flat barrier contacts on the reverse voltage.

Judging from the scientific work, it can be said that. The boundary dimensions are determined by the diameter of the tip of the conduction probe of the atomic force microscope, and in the values of 10-100 nm in the example of the $Zn_{0.4}Cd_{0.6}S/ZnS_{0.06}Se_{0.94}$ sample structure, the void size of the conduction bands has changed from 391 When obtained up to 431 meV, it was observed that the quality assessment of heterostructures and the distribution of discontinuities in the allowed energy zones along the grown area of epitaxial layers are clearly manifested. It can be seen from this that the possibility of studying micro and macro inhomogeneity has increased. It is shown that several (fewer) emission processes of charge carriers can be studied using the developed method of local RTGS. Power dependence of the relaxation time of the electric current through the CdSe/ZnSe structure with quantum dots, the activation energy of the process of electron emission from quantum dots was experimentally determined to be 620+20 meV [7-17]. Based on the measured local capacitance-voltage characteristic, it is possible to calculate the (visible) distribution profile of the concentration of free electrons with characteristic concentration peaks whose spatial position corresponds to the spatial position of quantum wells in the studied sample created

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