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SENSORS ON THE SURFACE ACOUSTIC WAVES FOR INTELLIGENT SYSTEMS

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Summary. *The work is aimed at the study of surface processes on the dynamically deformed adsorbed surface of semiconductors, which will be used as a sensitive substrate in radiometric temperature sensors. The choice of semiconductors with a zinc blende structure is explained by the sensitivity of such electronic subsystem to the deformation of the crystal lattice, which can be caused by the self-consistent redistribution of defects, inconsistency of the parameters of the crystal lattice, or external factors, for example, the influence of mechanical or electric fields. Based on established regularities of the influence of the concentration and type of adsorbed atoms on the spectrum of surface electronic states and the distribution of electron density on the dynamically deformed adsorbed surface of a single crystal, the development of a new class of intelligent sensors with increased accuracy of measuring the concentration of adsorbed atoms and temperature on surface acoustic waves is proposed. Such a new approach is based on the self-consistent effect of the deformation of the crystal lattice on the dispersion law and the spectral width of the phonon mode, the electric charge density, and the energy displacement of the edges of the allowed zones. It is calculated the temperature-concentration coefficient of the resonance frequency of the surface acoustic wave and the regularities of its change depending on the concentration of adsorbed atoms are established. The relevance of this research is determined both by the needs of fundamental research and by applied aspects of development, optimization and cost reduction of the process of designing and creating devices, the functioning of which is carried out on surface acoustic waves.*

Key words: *intelligent sensors, surface acoustic wave, semiconductor, adsorbed atoms, measurement, temperature-concentration coefficient.*

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Statement of the problem. Intelligent systems belong to new scientific and technical achievements that have the prospect of application in almost all areas of human activity and are capable of radically changing the organization and structure of various types of production, testing of biologically and chemically active substances, analysis and control in health care and environmental monitoring systems [1]. Effective operation of intelligent systems is possible only if they are provided with high-quality primary information. This requires the creation of fundamentally new microelectronic sensors based on modern functional materials using the latest physical, chemical, biochemical and biophysical effects, the use of sensor arrays and highly sensitive, accurate and stable measurement channels, the widespread introduction of information networks and high technologies [2]. In this regard, increased requirements are put forward for operational characteristics, such as radiation resistance, fire and explosion safety, an extended range of operating temperatures, long-term stability of characteristics and reliability, etc. It should be noted that the cardinal principles in the creation of sensors of a new generation – intelligent sensors – are connected with the use of new principles of their construction and modern functional materials, including nanostructured ones. At the same time, the development of microelectronics and promising nanoelectronics, methods of automated design, as well as the significantly increased modern capabilities of microprocessor technology and the peculiarities of its use in highly efficient information (intelligent) systems require the implementation of new approaches to the creation of sensors. Therefore, solving such a problem

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requires a comprehensive approach, which consists in the use of new functional materials, structures, ideas, competitive methods and principles of sensor construction.

Intelligent sensors on surface acoustic waves (SAW) are sensor devices used to measure various physical quantities, such as pressure, temperature, humidity, gas concentration, etc. SAW sensors use the surface acoustic waves that are transmitted through a plate of piezoelectric material. When the physical value that needs to be measured changes, the parameter of the piezoelectric material changes, which affects the frequency of the acoustic wave. This change in frequency can be measured and interpreted as a change in physical quantity. Surface wave acoustic sensors focus their energy on the surface, making them typically more sensitive sensors. Intelligent SAW sensors have built-in data processing algorithms and can analyze the data received from them in real time. This allows for quick and accurate monitoring of various environmental parameters online. Surface wave acoustic sensors have a wide range of applications, for example, in medicine, science, industry, transport and other fields. They can be used to measure pressure and temperature in medical devices, to monitor the concentration of gases in industrial processes, to control air quality in transport and buildings, etc. The latest researches in this field are aimed at the development of new materials and methods to improve their sensitivity and efficiency, as well as to expand their capabilities for increased accuracy of measurements of various parameters, such as vapor saturation, gas concentrations, and others.

This work is aimed at the study of surface processes on the dynamically deformed adsorbed surface of a semiconductor, which will be used as a sensitive substrate in temperature sensors. An important role here will be played by the interaction of the surface acoustic wave with atoms adsorbed on the surface of the substrate. The application of surface acoustic waves in electronic devices is presented in many modern works [3–8]. Currently, there are temperature, pressure, humidity SAW sensors, and sensors that can detect any change in the electric field on the surface [5]. However, these studies did not take into account the influence of the mechanism of interaction of adatoms with SAW on the patterns of changes in its characteristics depending on the concentration of adatoms. Also, the mentioned theories do not take into account the peculiarities of the change in the dispersion and width of the acoustic mode of quasi-Rayleigh and electron waves on the adsorbed surface of a solid. In [9] it is stated that the surface acoustic wave can be one of the sources of long-range effects that encourage the formation of nanoclusters outside the laser irradiation zone of the crystal surface. Therefore, the development of the theory of dispersion within the relationship between the quasi-Rayleigh wave and adatoms is relevant and will have practical application in modern opto- and nanoelectronics, in particular, in the development of radiometric SAW sensors for the adatoms concentration and temperature.

Analysis of the available investigations. The operating principles of SAW devices are described in [6], where the relationship between sound velocities and temperature frequency coefficients is considered. In the work [7] it was described the procedure for designing and manufacturing of SAW sensors for temperature, pressure and resistance. Using the dependence of the phase velocity of SAW on the thickness of the ZnO film, the authors of [8] considered the dispersion equation of the film SAW waveguide and determined the parameters of the waveguide structures. In work [4], a review of the main researches of Rayleigh wave sensors for the sensing of chemicals in the gaseous phase was carried out. The authors emphasize that the use of new piezoelectric substrates, taking into account the acoustoelectronic effect, is a potential direction of research into chemical SAW sensors. So, all acoustic wave devices are sensors in that they are sensitive to perturbations of many different physical parameters.

However, the above theories describe the processes on the surface of a solid body without taking into account the interaction of adsorbed atoms with SAW and also do not consider the influence of the concentration of adatoms on the surface characteristics. Adsorption on the material surface was considered in works [10–11]. In particular, in [11], the behavior of adsorbed gas molecules was studied and their influence on the electronic properties of the material of gas sensors was investigated. According to theoretical estimates, chemical sensors were developed in experiments, which demonstrate good sensitivity not only to gases, but also to metal ions and humidity.

According to a new global temperature sensor market research report [12], it is predicted that chemical sensors will occupy the largest share of the temperature sensor industry during the forecast period, so the proposed new class of radiometric sensors will be a relevant introduction in modern domestic and global nanoelectronics. Also, gallium arsenide (GaAs) is expected to receive the highest demand in the market during the period 2020–2025 [13].

The growth of the SAW sensor industry in the world is due to the increase in their distribution in modern portable medical equipment, in acoustolocation when determining the topology and morphology of an unknown object, in the field of non-destructive testing, in the automotive sector and home automation systems. Therefore, the proposed new class of intelligent SAW sensors of adatoms concentration and temperature will be a new and relevant introduction to modern domestic and global nano- and acoustoelectronics, medicine and military equipment. The research data can be used in global SAW technologies for the manufacture of wireless, passive and hybrid multifunctional SAW sensors.

The Objective of the work is is the development of a new class of intelligent SAW sensors to increase the accuracy of measuring the concentration of adsorbed atoms and temperature based on the model of self-consistent coupling between the quasi-Rayleigh wave and adsorbed atoms on the surface of a GaAs (CdTe) semiconductor matrix. The object of research is the physical processes that occur on the surface of the dynamically deformed adsorbed semiconductor substrate of the SAW-sensors with increased accuracy of measuring the temperature and concentration of adsorbed atoms. The subject of research is the method of building an intelligent sensor of the concentration of adsorbed atoms and temperature on surface acoustic waves.

Statement of the task. To achieve this purpose, the following main research objectives are identified: improvement of the method of calculating the dispersion relation for the surface acoustic (quasi-Rayleigh) wave and the spectral width of the surface elastic acoustic mode depending on the concentration and type of adatoms, taking into account the non-local elastic interaction of the adsorbed atom with the matrix atoms on the dynamically deformed adsorbed surface of semiconductors with a zinc blende structure; development of a method for calculating the temperature-concentration coefficient of the resonant frequency of a surface acoustic wave based on the developed theory of quasi-Rayleigh wave dispersion on the adsorbed surface of single crystals with a zinc blende structure; determination of the fields of application of PAH sensors with increased accuracy of data processing for measuring the concentration of adsorbed atoms and temperature using the GaAs (CdTe) semiconductor matrix.

Research methods and materials. During the propagation of a surface acoustic wave, electrons on the surface are scattered on its deformation potential inside the volume, as well as on the irregularities created both by the PAH and by the inhomogeneous distribution of adsorbed atoms. By technologically changing the concentration of adatoms, it is possible to change the frequency of the surface acoustic wave and the electronic structure of the near-surface layer of the semiconductor.

When considering a substrate without adsorbed atoms, the temperature SAW sensors are based on the change the quasi-Rayleigh wave frequency depending on the temperature of the substrate. In the case when there are adatoms on the monocrystal surface, the change in resonance frequency occurs not only due to a change in temperature, but also due to the presence of adsorbed atoms. The operation of intelligent sensors of the adsorbed atoms concentration and temperature is based on the measurement of the change in the resonance frequency of the SAW depending on the concentration of adatoms and temperature at a known value of the concentration-temperature coefficient of the resonance frequency of the SAW. The presence of adsorbed atoms and dynamic deformation created by a surface acoustic wave, leads to the renormalization of the spectrum of surface acoustic waves, a change in the spectral width of the phonon mode, and the emergence of localized electronic states near irregularities on the solid surface. The relevance of the construction of such a theory is determined both by the needs of fundamental research and by the applied aspects of the development, optimization and cost reduction of the process of designing and creating devices, the functioning of which is carried out on surface acoustic waves (sensors of temperature and concentration of adatoms, pressure, gas sensors, biosensors, filters, signal processing units, automated executive mechanisms). The choice of semiconductors with a zinc blende structure (GaAs, CdTe) is explained by the sensitivity of such an electronic subsystem to the deformation of the crystal lattice (due to the large values of the deformation potential constants), which can be caused by the self-consistent redistribution of defects, the mismatch of the parameters of the crystal lattice, or external factors, for example, the influence of mechanical or electrical fields. Therefore, the role of the mechanism of interaction of the dynamically deformed adsorbed surface with the electronic subsystem on the formation of electronic states on the surface of semiconductors with a zinc blende structure, depending on the concentration and type of adatoms, is significant and requires a separate study, which makes it possible to develop a new class of intelligent SAW sensors for the concentration of adsorbed atoms and temperature.

The established regularities of the influence of substrate temperature, concentration, and type of adatoms on the formation of surface electronic states will be fundamentally new (since there is no information on the influence of concentration and type of adatoms within the framework of the theory of self-consistent interaction of SAW with adatoms on the formation of surface electronic states in the world literature).

Surface acoustic wave radiometric sensors (SAW radiometers) are a type of SAW sensor used for non-contact measurement of temperature and other physical quantities. They are based on a change in the resonant frequency of the SAW device under the influence of a change in temperature or another parameter. Radiometric SAW sensors are used in various fields such as industry, medicine, science and defense. For example, they can be used for temperature control in reactors, temperature monitoring in gas turbines and other important industrial processes. One of the advantages of radiometric SAW sensors is their non-contact nature, which allows them to be used in difficult environments, such as high temperature, radiation or chemically active areas. They also have high sensitivity and measurement accuracy, which allows them to be used to measure even very small changes in parameters.

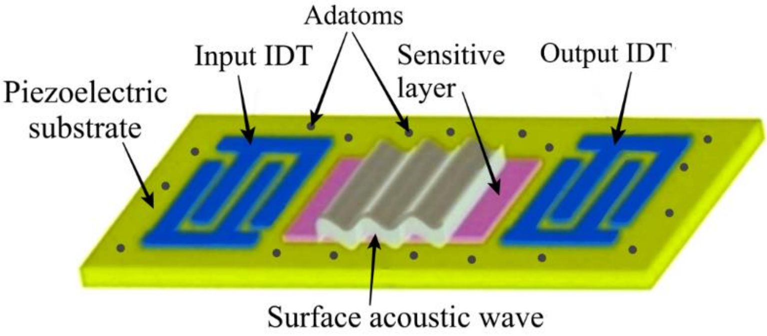

Figure 1. The investigated sensor surface based on SAW with increased accuracy of measuring the concentration of adsorbed atoms and temperature

To build a new class of radiometric sensors of temperature and concentration of adsorbed atoms based on SAW (Figure 1), we will use the theory of dispersion of the quasi-Rayleigh wave and the width of the surface elastic acoustic mode within the self-consistent coupling of the quasi-Rayleigh wave with adsorbed atoms [14]. Virtually all acoustic wave devices and sensors use a piezoelectric material to generate the acoustic wave.

Let consider the near-surface layer of a cubic crystal (GaAs, CdTe (100)) in the process of molecular beam epitaxy or implantation when a stream of atoms with an N_{0d} average concentration acts on it (Figure 2). The defect-enriched layer with adsorbed atoms will be considered as a «film» of thickness d with density ρ and Young's modulus E, rigidly bound to the substrate – the rest of the single crystal.

A surface acoustic wave propagating in the direction of the x axis with $\omega(q, N_{0d})$ frequency, creates dynamic deformation and interacts with adsorbed atoms. The shape of the deformed surface along the x-coordinate depending on time is described by the following function:

$$z_0(x,t) = \tilde{\varsigma}(N_{0d})\cos(qx - \omega(q, N_{0d})t), \tag{1}$$

where $\omega(q, N_{0d}) = \omega'(q, N_{0d}) + i\omega''(q, N_{0d})$ is a renormalized by adatoms dispersion law of quasi-Rayleigh wave; $q = 2\pi / L_x$, L_x – period of roughness (length of SAW) along the x axis (the period of such irregularities at a frequency of 10 GHz is 540 nm).

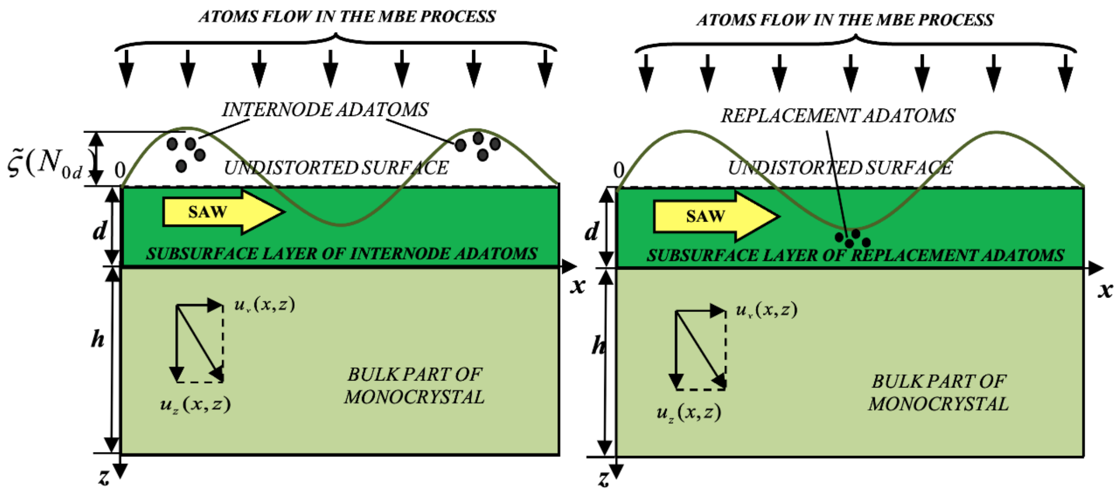

Figure 2. A model of an uneven surface deformed by a surface acoustic wave and adsorbed atoms
a – adatoms are collected in the regions of maximum tensile strain; b – adatoms are collected in the regions of maximum compression deformation

The dispersion equation for a surface acoustic wave that interacts with adsorbed atoms has the form [14]:

$$(q^2 + k_t^2)^2 - 4q^2 k_l k_t = -\frac{2}{\beta}\frac{\omega^2}{c_l^2}\frac{\theta_d N_{d0}}{kT\rho c_l^2} \cdot \frac{D_d q^2}{-i\omega + D_d\left(1 - \frac{2}{3}\frac{1-2\nu}{K(1-\nu)a}\frac{\theta_d^{\,2}}{kT}N_{d0}\right)q^2} \cdot$$
$$\times (1 - l_d^2 q^2) \cdot \left(q^2 k_t \frac{\partial F}{\partial N_{d1}} + (q^2 + k_t^2)\frac{\theta_d}{2a} \right). \tag{2}$$

Substituting into equation (2) $\omega = c_t q \xi$, we obtain:

$$(2-\xi^2)^2 - 4\sqrt{1-\xi^2}\sqrt{1-\frac{c_t^2}{c_l^2}\xi^2} = -\frac{2\xi^2\theta_d N_{d0}}{kT\rho c_l^2}\cdot$$

$$\frac{D_d q(D_d(1-\frac{2}{3}\frac{1-2\nu}{K(1-\nu)a}\frac{\theta_d^{\,2}}{kT}N_{d0})q + ic_t q)}{\left(D_d(1-\frac{2}{3}\frac{1-2\nu}{K(1-\nu)a}\frac{\theta_d^{\,2}}{kT}N_{d0})\right)^2 q^2 + c_t^2\xi^2}(1-l_d^2 q^2)\left(q\sqrt{1-\xi^2}\,\frac{\partial F}{\partial N_{d1}} + (2-\xi^2)\frac{\theta_d}{2a}\right). \qquad (3)$$

The presence of the q multiplier in the numerator (3) allows solving this equation by iterations in the long-wavelength domain $qa << 1$.

The real $\omega'(q, N_{0d}) = \mathrm{Re}(\omega)$ and imaginary $\omega''(q, N_{0d}) = \mathrm{Im}(\omega)$ parts of the expression $\omega(q, N_{0d})$ ultimately determine the correction to the dispersion law of the quasi-Rayleigh wave and its damping, and are determined by relations (4) and (5). We take into account the nonlocal elastic interaction between the implanted impurity and the matrix atoms and the mirror image forces [15].

$$\omega'(q, N_{0d}) = c_t q \xi_0 \left(1 - \frac{1}{f'(\xi_0)}\frac{2\xi_0\theta_d N_{0d}}{k_B T\rho c_l^2}\cdot\frac{D_d^{\,2} q^2(1-\frac{2}{3}\frac{1-2\sigma}{K(1-\sigma)a}\frac{\theta_d^{\,2}}{k_B T}N_{0d})}{\left(D_d q(1-\frac{2}{3}\frac{1-2\sigma}{K(1-\sigma)a}\frac{\theta_d^{\,2}}{k_B T}N_{0d})\right)^2 + c_t^2\xi_0^{\,2}}\times \right.$$
$$\left. \times(1-l_d^2 q^2)\left(q\sqrt{1-\xi_0^{\,2}}\,\frac{\partial\tilde{F}}{\partial N_{1d}} + (2-\xi_0^{\,2})\frac{\theta_d}{2a}\right)\right); \qquad (4)$$

$$\omega''(q, N_{0d}) = \frac{1}{f'(\xi_0)}\frac{2\beta\xi^3\theta_d N_{0d}}{k_B T\rho}\cdot\frac{D_d q^2}{\left(D_d q(1-\frac{2}{3}\frac{1-2\sigma}{K(1-\sigma)a}\frac{\theta_d^{\,2}}{k_B T}N_{0d})\right)^2 + c_t^2\xi_0^{\,2}}\times$$
$$\times(1-l_d^2 q^2)\left(q\sqrt{1-\xi_0^{\,2}}\,\frac{\partial\tilde{F}}{\partial N_{1d}} + (2-\xi_0^{\,2})\frac{\theta_d}{2a}\right), \qquad (5)$$

where K is the modulus of elasticity; l_d^2 is the average of the square of a characteristic distance of the interaction between the adatom and the matrix atoms; σ is the Poisson coefficient; θ_d is the surface deformation potential; D_d is the diffusion coefficient of the adatom; T is the temperature of a substrate; k_B is the Boltzmann constant; ξ_0 is the solution of equation $f(\xi_0) = 0$, which depends on the ratio between longitudinal c_l and transversal c_t speeds of sound; $\beta = \frac{c_t^2}{c_l^2}$; N_{1d} is the amplitude of periodic disturbance ($N_{1d} << N_{0d}$) [15].

In SAW-based temperature measurement system where the interdigital transducers play an important role, the change of piezoelectric temperature affects on the velocity of the surface acoustic wave propagation. This effect is described by the temperature coefficient of resonance frequency (TCF), which is defined as the relative change in resonance frequency with temperature [6]:

$$\alpha_{TCF}^{0}=\frac{1}{f_0}\frac{\mathrm{d}f_0}{\mathrm{d}T}=\frac{1}{v}\frac{\mathrm{d}v}{\mathrm{d}T}-\frac{1}{\lambda}\frac{\mathrm{d}\lambda}{\mathrm{d}T}, \tag{6}$$

where f_0 is the resonance SAW frequency; v is the velocity propagation of SAW; λ is the SAW length; T is the temperature of SAW device.

The temperature coefficient of frequency characterizes the thermal stability of resonators. During the adsorption process on the substrate surface, it is important to investigate the influence of the adsorbed atoms concentration on the temperature coefficient of the resonant frequency. However, in expression (6) for the temperature coefficient of frequency there is no component that describes the effect of the adatoms concentration on the value of this coefficient. Taking into account this component, the dependence of the coefficient α_{TCF} on temperature and on the concentration of adsorbed atoms will be described by the following functional expression:

$$\alpha_{TCF}=\alpha_{TCF}^{0}+\Delta\alpha_{TCF}(N_{0d}) \tag{7}$$

$$\Delta\alpha_{TCF}(N_{0d})=\frac{1}{v}\frac{d\lambda}{dT}\Delta f(N_{0d})-\frac{\lambda}{v^2}\frac{dv}{dT}\Delta f(N_{0d})+\frac{\lambda}{v}\frac{d\Delta f(N_{0d})}{dT}.$$

Taking into account the ratio $\omega'(q,N_{0d})-\omega'(q,0)=\Delta\omega'(q,N_{0d})=2\pi\Delta f(q,N_{0d})$ we will get:

$$\Delta f(q,N_{0d})=\frac{1}{f'(\xi_0)}\frac{\xi_0\theta_d N_{0d}}{\pi k_B T\rho c_l^2}\cdot\frac{D_d^2q^2\left(1-\frac{2}{3}\frac{1-2\sigma}{K(1-\sigma)a}\frac{\theta_d^2}{k_BT}N_{0d}\right)\left(1-l_d^2q^2\right)}{\left(D_dq\left(1-\frac{2}{3}\frac{1-2\sigma}{K(1-\sigma)a}\frac{\theta_d^2}{k_BT}N_{0d}\right)\right)^2+c_t^2\xi_0^2}\times$$
$$\times\left(q\sqrt{1-\xi_0^2}\,\frac{d\tilde{F}}{dN_{1d}}+(2-\xi_0^2)\frac{\theta_d}{2a}\right). \tag{8}$$

The function that determines the frequency of an acoustic oscillation vibration without adsorbed atoms in the long-wave approximation $qa\ll 1$, has the following form:

$$\tilde{\omega}(q)=\frac{qa}{2}\sqrt{\frac{4E_{ad}Na}{m_1+m_2}},$$

where N is the number of cells; m_1, m_2 – the masses of atoms Ga and As respectively.

For adiabatic Young's modulus E_{ad} and the Poisson coefficient σ_{ad} we have the following relations:

$$E_{ad}=\frac{E}{1-ET\alpha^2/9C_p};\ \sigma_{ad}=\frac{\sigma+ET\alpha^2/9C_p}{1-ET\alpha^2/9C_p},$$

where α is the temperature coefficient of bulk expansion; $C_p\approx\frac{12\pi^4}{5}N_Vk_B\left(\frac{T}{\theta_D}\right)^3$ – the heat capacity at constant pressure per unit volume; θ_D is the Debye temperature; N_V is the number of atoms per unit volume.

The length of the surface acoustic wave we define as $\lambda = \dfrac{2\pi v}{\tilde{\omega}(q)}$. The velocity of SAW is described by the following relation:

$$v \approx c_l = \sqrt{\frac{E_{ad}}{2\rho(1+\sigma_{ad})} \cdot \frac{2(1-\sigma_{ad})}{1-2\sigma_{ad}}}.$$

The numerical calculation was performed for GaAs (100) semiconductor with the following parameter values [15]:

$l_d = 29$ Å; $a = 5{,}65$ Å; $c_l = 4400$ m/s; $c_t = 2475$ m/s; $\rho = 5318$ kg/m^3; $\theta_d = 10$ eV;

$D_d = 5 \cdot 10^{-2}$ cm^2/s; $\dfrac{\partial \tilde{F}}{\partial N_{1d}} = 0{,}1$ eV; T=100 K; $\sigma = 0{,}31$; K = 0,47 eV/Å^3; E=0,54 eV/Å^3;

$\alpha = 17{,}11 \cdot 10^{-6}$ K^{-1}; $N_V = 4{,}42 \cdot 10^{-2}$ Å^{-3}; θ_D=360 K; m_1=69,72 g/mol; m_2=74,92 g/mol.

Research results. Figure 3 shows the graphical dependence of the concentration component of the temperature coefficient of the resonant frequency $\Delta\alpha_{TCF}$ of the surface acoustic wave on the concentration of adsorbed atoms at a substrate temperature 300 K. We see that the functional dependence $\Delta\alpha_{TCF} = f(N_{0d})$ has the non-monotonous character with an attributable maximum at value of adatoms concentration $N_{0d} = 4{,}7 \cdot 10^{13}$ cm^{-2}. In the concentration interval $5{,}1 \cdot 10^{11} < N_{0d} \leq 4{,}7 \cdot 10^{13}$ cm^{-2} there is an increase of $\Delta\alpha_{TCF}(N_{0d})$.

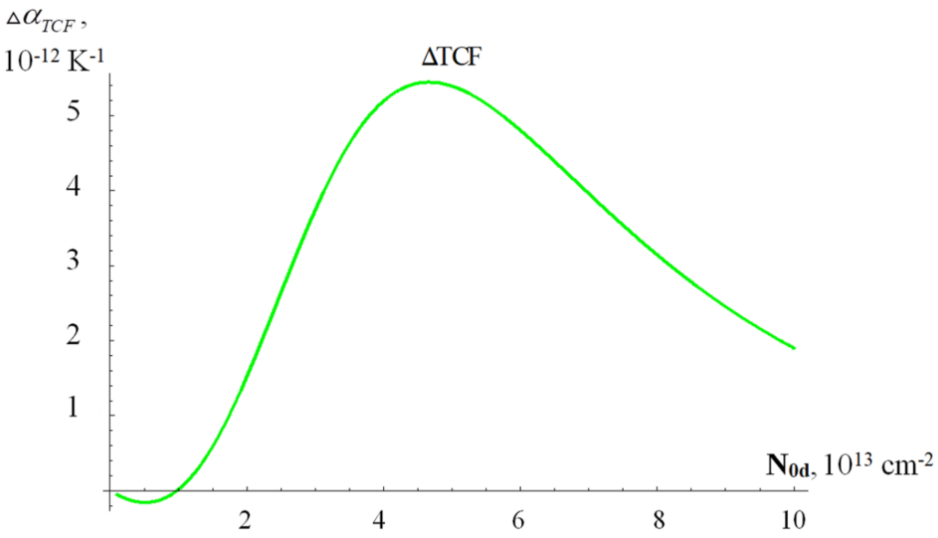

Figure 3. The dependence of the concentration component of the temperature coefficient of the resonant frequency $\Delta\alpha_{TCF}$ of the surface acoustic wave on the concentration of adsorbed atoms at a substrate temperature of 300 K

Figure 4 shows the results of calculating the dependence of the concentration component $\Delta\alpha_{TCF}$ of the temperature coefficient of the resonant frequency of the surface acoustic wave on the temperature of the substrate at three different values of the concentration of adsorbed atoms. The figure shows that with increasing of the concentration of adsorbed atoms the value of the temperature coefficient of the resonant frequency increases. An increase of the substrate temperature results to the decrease of the component $\Delta\alpha_{TCF}$ of the temperature coefficient of the resonant frequency.

The effect of temperature on the temperature coefficient of resonant frequency α_{TCF}, which includes two components α^0_{TCF} and $\Delta\alpha_{TCF}(N_{0d})$, is graphically depicted in Figure 5. We see that the absolute value of the temperature coefficient decreases with increasing of temperature.

The results of these studies can be used to create a new class of radiometric sensors on surface acoustic waves (Figure 2) to measure the temperature and concentration of adsorbed atoms on the substrate surface. These studies allow to construct the architecture of these radiometric sensors.

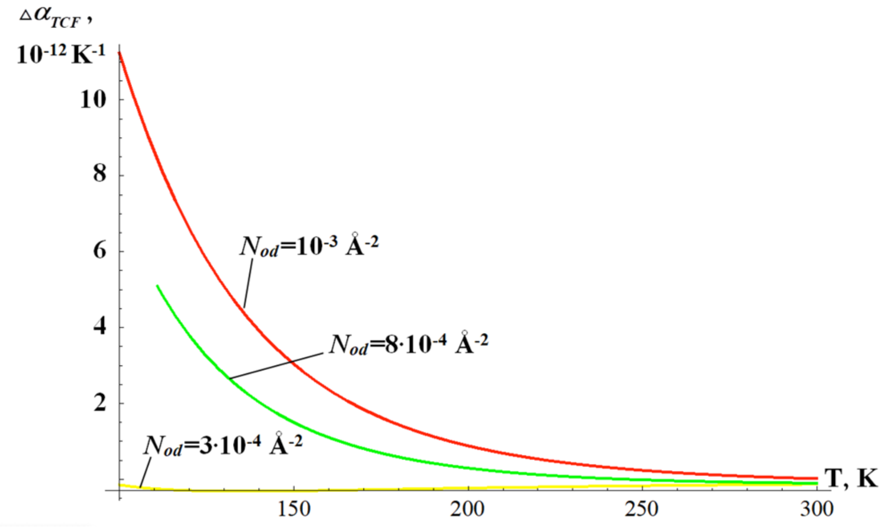

Figure 4. The dependence of the concentration component $\Delta\alpha_{TCF}$ of the temperature coefficient of the resonant frequency of the surface acoustic wave on the piezoelectric temperature

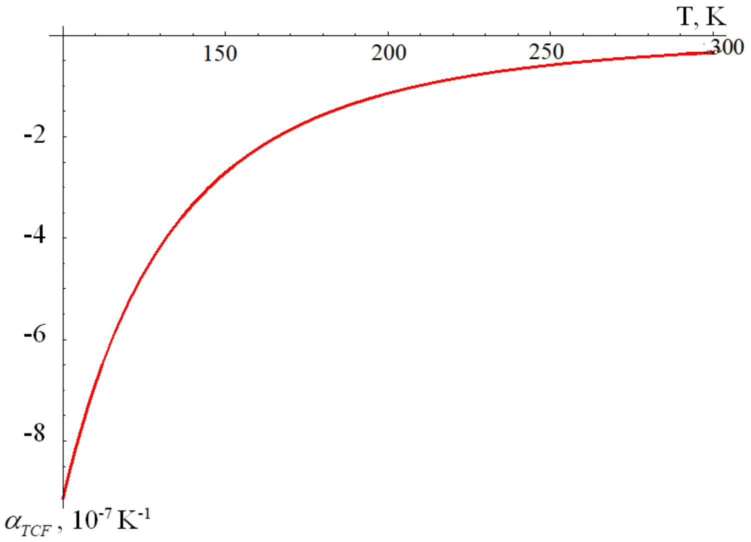

Figure 5. The dependence of the temperature coefficient of the resonant frequency α^0_{TCF} on the substrate temperature

The operation of intelligent sensors of the concentration of adsorbed atoms and temperature will be based on the measurement of the change in the resonance frequency of the SAW depending on the concentration of adatoms and temperature at a known value of the concentration-temperature coefficient of the resonance frequency of the SAW.

So, intelligent temperature and concentration sensors are sensor devices that are able to read the temperature and concentration of substances in the environment using various technologies, such as thermocouples, thermistors, thermistors, ionization sensors, gas sensors, etc. Intelligent sensors can be connected to the Internet in real time, which allows you to receive data on temperature and concentration of substances online. Such sensors usually have a built-in system of data analysis and transmission, which allows monitoring the state of the environment in which they are used. Intelligent temperature and concentration sensors will have a wide range of applications, for example, in industry, medicine, science, ecology, construction, transport, etc. They can be used to monitor temperature and chemical parameters in production processes, to control air quality in buildings and transport, as well as to monitor the state of the environment.

The proposed method will allow to increase the accuracy of measuring the temperature and concentration of adsorbed atoms, which will allow to expand the working capabilities of the device. Studies of acoustic wave attenuation processes on the defective surface of a single crystal substrate are important for the development of optimal technological modes of nanostructure formation during nanosecond laser irradiation of the single crystal surface, as well as for the construction of devices for reading optical holograms in photorefractive crystals. The proposed new class of intelligent SAW sensors of adatom concentration and temperature will be a relevant introduction in modern domestic and global nano- and acoustoelectronics. The results of studies of the conditions for the formation of surface electronic states can be used for the development of optimal technological regimes for the formation of nanostructures by the methods of molecular beam epitaxy, ion implantation, and nanosecond laser irradiation. The relationship of the concentration of adatoms with the SAW frequency and with the electronic structure of the surface layer can be used in practice to change the reflection coefficients of electromagnetic waves from the separation boundary of media, to change the dispersion law of plasma oscillations, and to diagnose dynamic conductivity, mobility, and concentration of charge carriers on the surface of semiconductors.

Conclusions. The development of a new class of intelligent sensors for the concentration of adsorbed atoms and temperature on surface acoustic waves is described. For the first time, it was used the relationship between the concentration and type of adsorbed atoms with the frequency of the quasi-Rayleigh wave and the influence of this relationship on the spectrum of surface electronic states on the dynamically deformed adsorbed surface of semiconductors with a Zinc blende structure.

The method of calculating the dispersion relation for the surface acoustic (quasi-Rayleigh) wave and the spectral width of the surface elastic acoustic mode depending on the concentration and type of adatoms has been improved, taking into account the non-local elastic interaction of the adsorbed atom with the matrix atoms on the dynamically deformed adsorbed surface of semiconductors with a Zinc blende structure.

A method for calculating the temperature-concentration coefficient of the resonance frequency of a surface acoustic wave has been developed based on the developed theory of quasi-Rayleigh wave dispersion on the adsorbed surface of single crystals with a Zinc blende structure.

It was shown that the functional dependence $\propto_{TCF}= f(N_{0d})$ of the concentration component of the temperature coefficient of resonant frequency has the non-monotonous character with a maximum corresponding to the adatoms concentration of $N_{0d} = 4,7 \cdot 10^{13}$ cm^2, which corresponds to the highest sensitivity of the radiometric sensor.

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СЕНСОРИ НА ПОВЕРХНЕВИХ АКУСТИЧНИХ ХВИЛЯХ ДЛЯ ІНТЕЛЕКТУАЛЬНИХ СИСТЕМ

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Резюме. *Робота спрямована на дослідження поверхневих процесів на динамічно деформованій адсорбованій поверхні напівпровідників, що буде використовуватися в якості чутливої підкладки в радіометричних сенсорах температури. Вибір напівпровідників із структурою цинкової обманки пояснюється чутливістю такої електронної підсистеми до деформації кристалічної ґратки, яка може бути зумовлена самоузгодженим перерозподілом дефектів, невідповідністю параметрів кристалічної ґратки або зовнішніми факторами, наприклад впливом механічних чи електричних полів. На основі встановлених закономірностей впливу концентрації та типу адсорбованих атомів на спектр поверхневих електронних станів і розподіл електронної густини на динамічно деформованій адсорбованій поверхні монокристалу запропоновано розроблення нового* *класу інтелектуальних сенсорів з підвищеною точністю вимірювання концентрації адсорбованих атомів і температури на поверхневих акустичних хвилях. Такий новий підхід ґрунтується на самоузгодженому впливі деформації кристалічної ґратки на закон дисперсії й спектральну ширину фононної моди, густину електричного заряду та енергетичне зміщення країв дозволених зон. Розраховано температурно-концентраційний коефіцієнт резонансної частоти поверхневої акустичної хвилі й встановлено закономірності його зміни залежно від концентрації адсорбованих атомів. Актуальність побудови такої теорії зумовлена як потребами фундаментальних досліджень, так і прикладними аспектами розроблення, оптимізації та здешевлення процесу проектування й створення приладів, функціонування яких здійснюється на поверхневих акустичних хвилях.*

Ключові слова: *інтелектуальні сенсори, поверхнева акустична хвиля, напівпровідник, адсорбовані атоми, вимірювання, температурно-концентраційний коефіцієнт.*

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