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Miniband Electroconductivity in Superlattices of Cubic Quantum Dots of the InAs/$Ga_xIn_{1-x}As$ Heterosystem

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In this paper, the model of InAs/$Ga_xIn_{1-x}As$ cubic quantum dot superlattices (CQDS) of various dimensionality has been proposed. The energy spectra of electrons and holes of the quantum dot superlattice have been determined in the effective mass approximation and modified Kronig-Penney model. In the frame of this model, the spectra of charges of 3D, 2D and 1D-superlattices can be obtained by changing respective distances between the elements of the superlattice. The energy dependence of the electron and hole subbands (under-the-barrier subbands and over-the-barrier subbands) on the wave vector of the superlattice has been calculated. The number of under-the-barrier subbands is determined by QD size and width of each subband is defined by QD size, distances between superlattice elements and subband numerical index.

The dependences of the Fermi energy and concentration of charge carriers on temperature, concentration of impurities, energy of impurity levels have been obtained and analyzed. We have taken account of the dependence of electron relaxation time on temperature caused by scattering of carriers on both phonons and donor centers. The effect of the impurity system on electroconductivity of the CQDS is investigated. It has been shown that in the presence of deep impurities (-750 meV) the temperature dependence of conductivity of the superlattice has characteristic peaks, which are defined by concentrations of impurities and dimensionality of the superlattice. A different temperature dependence of conductivity has been observed for impurities with the energy of occurrence -150 meV.

Key words: quantum dot, superlattice, electronic states, miniband, electroconductivity.

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Introduction

In recent years the growing interest of researchers, engineers and technologists has been drawn to low-dimensional systems, among which superlattices constitute a special class. The practical significance of such systems for electronics and optoelectronics is justified by increased performance and reduced energy losses. Superlattices, particularly quantum dot (QD) superlattices, are rather important to fundamental science as completely new types of artificial materials with unusual physical properties. Nanostructure engineering [1] of these materials makes it possible to get nanostructures with predetermined physical properties, which are widely used in electronic and optoelectronic devices [2].

Within the approximations of electron effective mass and rectangular potentials, the theory of electronic dynamic conductivity was developed for multibarrier structures (both of plane and cylindrical shape) in [3-5]. The authors in [6] study superlattices of tunnel-connected GaAs QDs, periodically assembled along the elliptic quantum wire, in the matrix $Al_xGa_{1-x}As$. It is shown that the electron energy spectrum in such superlattices is a series of energy minibands, and the position and number of these minibands is determined by the QD size. The width of allowed and forbidden minibands depends on the thickness and height of potential barriers.

Models of three-dimensional superlattices of InAs/GaAs and Ge/Si quantum dots of various geometry (cubic and tetragonal) are considered in [7, 8]. The authors calculated electron and phonon spectra of the superlattices. The dependence of conductivity tensor of the superlattice on its main parameters is studied and shown that properties of the superlattice are more sensitive to interdot distances than to the form of quantum dots.

In [9] in the tight binding approximation the electrical properties of GaAs/$Al_xGa_{1-x}As$ spherical quantum dot superlattices (SQDS) of various dimensionality are studied, depending on the Fermi energy and temperature, concentration of aluminum in

the matrix. For given parameters of the system the calculations were performed to obtain conductivity, containing contributions of the *s*- and three *p*-minibands, with its maximum near the miniband center. The growth of conductivity is observed with decreasing QD radius and aluminum concentrations, and also with increasing SQDS dimensionality. The temperature dependence of conductivity is also examined at various parameters of such systems.

In this paper, the model of InAs/$Ga_xIn_{1-x}As$ cubic quantum dot superlattices (CQDS) of various dimensionality has been proposed. The energy bands spectra of the system have been studied. The temperature dependence of the Fermi energy of the CQDS with impurities has been received and analyzed. We have taken account of the dependence of electron relaxation time on temperature caused by scattering of carriers on both phonons and donor centers. The effect of the impurity system on electroconductivity of the CQDS is investigated.

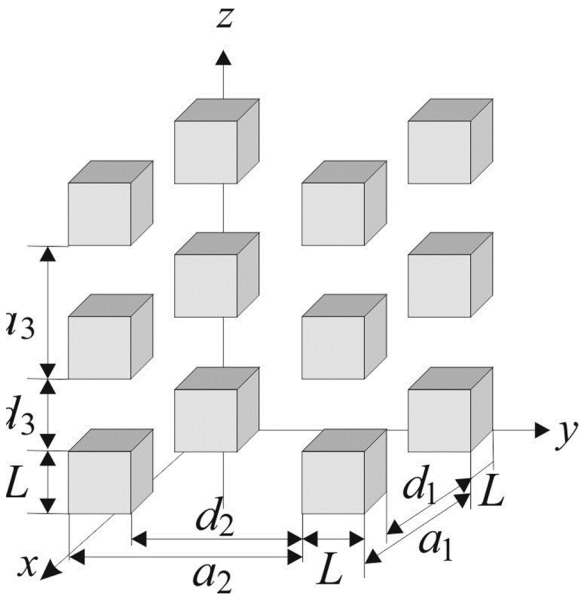

Fig.1. Geometry of the cubic quantum dot superlattice.

Setting of the problem

Let us consider a system of spatially assembled cubic quantum dots of equal size, which are placed in the matrix, as shown in Fig. 1, i.e., a cubic quantum dot superlattice (CQDS). If $a_1 = a_2 = a_3$, CQDS will be called a 3D superlattice, when $a_3 = a_1 \quad a_2$, a 2D superlattice, and for $a_3 \quad a_1 = a_2$, a 1D superlattice. It is clear that the translation vector of the superlattice

$$\mathbf{r}_n = n_1\mathbf{r}_{a_1} + n_2\mathbf{r}_{a_2} + n_3\mathbf{r}_{a_3},$$

where n_i $(0, \pm1, \pm2, ...)$, $\mathbf{r}_{a_i}$ $(i = 1,2,3)$ are basic translation vectors. Their directions coincide with the axes of the Cartesian coordinate system.

We are interested in nanoscale heterosystems of wide-gap semiconductors. A theoretical study of such systems often involves solving the Schrödinger equation for electrons or holes. The problem can be solved by various methods: using finite elements [10], attached plane waves [11], or pseudopotential [12] etc. We limit ourselves to research CQDSs of small size (2-10 nm) semiconductor quantum dots, which are characterized by size quantization of charged particles. In view of the above, we employ the parabolic band approximation and the effective mass approach to determine the energies and wave functions of not only electrons but also holes (heavy holes).

The Schrödinger equation which describes the motion of a charged particle (electron or hole) in a CQDS can be written as follows:

$$\left[-\frac{\hbar^2}{2}\nabla\frac{1}{m(\mathbf{r})}\nabla + V(\mathbf{r})\right]\psi_v(\mathbf{r}) = E\psi_v(\mathbf{r}). \qquad (1)$$

The periodic potential $V(\mathbf{r})$ which corresponds to an infinite sequence of cubic quantum dots

$$V(\mathbf{r}) = \begin{cases} 0, & \begin{cases} n_1a_1 \le x \le n_1a_1 + L \\ n_2a_2 \le y \le n_2a_2 + L \\ n_3a_3 \le z \le n_3a_3 + L \end{cases} \\ U_0, & \text{in another region of space,} \end{cases} \qquad (2)$$

$m(\mathbf{r})$ is the effective mass of a particle.

Schrödinger equation (1) cannot be solved exactly. We shall simplify expression (2) of the particle potential energy and approximately present $V(\mathbf{r})$ in the form of a sum of three independent periodical coordinate functions *x, y* and *z:*

$$V(\mathbf{r}) = V(x) + V(y) + V(z).$$

It is necessary to solve the Schrödinger equation with a periodical potential to calculate the energy spectra of electrons (holes) in the superlattice

$$V(x_i) = \begin{cases} 0, & n_ia_i \le x_i \le n_ia_i + L \\ U_0, & n_ia_i + L \le x_i \le (n_i+1)a_i \end{cases}, \qquad (3)$$

where $i = 1,2,3$; $x_1 = x$, $x_2 = y$, $x_3 = z$. This choice of the potential allows one to split the motion of a charged particle in three directions. Three-dimensional Schrödinger equation (1) in this case will be written in the form of three identical one-dimensional equations. Then the envelope wave function of equation (1) can be represented as a product of three one-dimensional eigenfunctions

$$\psi_\nu(\mathbf{r}) = \psi_{\nu_1,\nu_2,\nu_3}(x_1, x_2, x_3) = \prod_{i=1}^{3}\varphi_{\nu_i}(x_i), \qquad (4)$$

the energy $E_\nu = E_{\nu_1} + E_{\nu_2} + E_{\nu_3}$. It is necessary to use the following equation to determine E_{ν_i} and φ_{ν_i}:

$$\left[-\frac{\hbar^2}{2}\frac{\partial}{\partial x_i}\frac{1}{m(\mathbf{r})}\frac{\partial}{\partial x_i} + V(x_i)\right]\varphi_{\nu_i}(x_i) = E_{\nu_i}\varphi_{\nu_i}(x_i),\ i = 1,2,3, \qquad (5)$$

Shrödinger equations (5) correspond to the well-known Kronig-Penney model. According to this model, the solution of every equation from (5) is known [13]. The energy of the system is determined from the corresponding dispersion relations in various energy regions of the particle.

If $0 < E_\nu < U_0$, the dispersion relation has the form

$$\cos(k_i a_{\nu_i}) - \cos(\chi_{\nu_i} L)\,\mathrm{ch}(\xi_{\nu_i} d) + \frac{\left(\chi_{\nu_i} m_2\right)^2 - \left(\xi_{\nu_i} m_1\right)^2}{2\chi_{\nu_i} m_2 \cdot \xi_{\nu_i} m_1} \sin(\chi_{\nu_i} L)\,\mathrm{sh}(\xi_{\nu_i} d) = 0, \quad (6,\ a)$$

In case of $E_\nu > U_0$, it is written

$$\cos(k_i a_{\nu_i}) - \cos(\chi_{\nu_i} L)\cos(\xi_{\nu_i} d_{\nu_i}) + \frac{\left(\chi_{\nu_i} m_2\right)^2 + \left(\xi_{\nu_i} m_1\right)^2}{2\chi_{\nu_i} m_2 \cdot \xi_{\nu_i} m_1} \sin(\chi_{\nu_i} L)\sin(\xi_{\nu_i} d_{\nu_i}) = 0, \quad (6,\ b)$$

where $\chi_{\nu_i} = \sqrt{\dfrac{2m_1\left(U_0 + E_{\nu_i}\right)}{\mathbf{h}^2}}$, $\xi_{\nu_i} = \sqrt{\dfrac{2m_2\left|E_{\nu_i}\right|}{\mathbf{h}^2}}$,

m_1, m_2 are effective masses of a quasiparticle inside and outside the QD. Hence,

$$E_\nu(\vec{k}) = \sum_{i=1}^{3} E_{\nu_i}(k_i),\ \nu = \{\nu_1, \nu_2, \nu_3\}. \quad (7)$$

The dispersion relation of electrons and holes in a CQDS allows one to determine the specific electroconductivity of the system. Let us place this system in a uniform electric field. If the intensity of this field is relatively small, the current density vector is defined by the following general formula [14]:

$$\vec{j} = \frac{e^2}{4\pi^3}\int \tau(T,E)\vec{v}\frac{\partial f}{\partial E}\left(\vec{v}, \vec{\nabla}\Phi\right)d\vec{k}, \quad (8)$$

where f is the electrons distribution function, $\vec{v}$ is their average velosity, $\tau(T)$ is relaxation time; the intensity of the external electrostatic field is expressed through the scalar potential $\left(\vec{E} = -\vec{\nabla}\Phi\right)$. Relation (8) can be written

$$j_i = \sum_i \sigma_{ii'} E_{i'}. \quad (8')$$

For the conductivity tensor of formula (8') the account is taken of contributions of all occupied electronic minibands of the structure, therefore

$$\sigma_{ii'} = \sum_n \sigma_{ii'}^{e,n} + \sum_m \sigma_{ii'}^{h,m}, \quad (9)$$

where $\sigma_{ii'}^{e,n}$, $\sigma_{ii'}^{h,m}$ are components of electron and hole conductivity tensors. In particular, for electron conductivity we have:

$$\sigma_{ii'}^{e,n} = \frac{e^2}{4\pi^3 k_B T}\iiint_{BZ} \tau(T,E) v_i^{e,n}\left(\vec{k}\right) v_j^{e,n}\left(\vec{k}\right) \frac{\exp\left[\dfrac{E_e^n\left(\vec{k}\right) - E_F}{k_B T}\right]}{\left\{\exp\left[\dfrac{E_e^n\left(\vec{k}\right) - E_F}{k_B T}\right] + 1\right\}^2} d\vec{k}, \quad (10)$$

In equation (10) the following notation is introduced: e is the electron charge, k_B is the Boltzmann constant, T is tempetature, E_F is the Fermi energy of the electon system, $v_j^n\left(\vec{k}\right)$ is the i-component of the electron group velocity vector of the n-thsubband.

$$v_i^n(k_1, k_2, k_3) = \frac{1}{\mathbf{h}}\frac{\partial E_e^n(k_1, k_2, k_3)}{\partial k_i}.$$

The integration in (10) is done over the Brillouin quasizone. By analogy the expression of hole conductivity matrix elements can be obtained.

The Fermi energy is found from electroneutrality conditions. We consider the case of doping the matrix by one type of monovalent donor impurity atoms. Then we get the equation to determine the Fermi energy as a function of temperature:

$$\sum_{n,k} \frac{2}{\exp\left(\dfrac{E_e^n(\vec{k}) - E_F}{k_B T}\right) + 1} = \sum_{m,k} \frac{2}{\exp\left(\dfrac{E_F - E_h^m(\vec{k}) +}{k_B T}\right) + 1} + \frac{n_D}{\exp\left(\dfrac{E_F - E_D}{k_B T}\right) + 1}, \quad (11)$$

where n_D is donor concentration, E_D is the energy of occurrence of the donor level, E_F is the Fermi energy of the heterosystem, $E_e^{(\rho)}(\vec{k})$ and $E_h^{(m)}(\vec{k})$ are energies of electron and hole subbands respectively, the energy of occurrence of donor states E_D is counted from the bottom of the conduction band of the semiconductor matrix. The left part of equation (11) specifies concentration of electrons in electronic subbands, the first term in the right part refers to concentration of holes in hole subbands, and the second term of the right part of the equation relates to concentration of holes at the impurity levels.

It is seen from equation (10) that conductivity $\sigma_{ij}^{e,n}$ is determined also by relaxation time $\tau(T,E)$. Most authors assume for simplicity that relaxation time τ is constant and equal to, e.g., $\tau_0 = 10^{-12} s$ [8]. At a first approximation this assumption is substantiated in case of small temperature changes. However, it is known that in

case of most semiconductors [15] there is a significant nonlinear change of relaxation time with temperature. The dependence $\tau = \tau(T, E)$ is caused by scattering of electrons both at phonons and at donor centers. Scattering at acoustic phonons at the expense of the deformation potential allows one to express relaxation time as follows [16]:

$$\tau_a = C_a E^{r_a}, \text{ where } r_a = -\frac{1}{2},$$

$$C_a = \frac{(2\pi)^2 \mathbf{h}^2}{2B_a\sqrt{2m^3}} = \frac{\pi M c_s^2 \mathbf{h}^4}{V_0 kTE_1^2\sqrt{2m^3}}, \qquad (12)$$

c_s $10^{-5}\frac{\tilde{n}\grave{i}}{\tilde{n}}$ is the phase velocity of longitudinal ($s=1$) and transverse ($s=2,3$) sound waves, m is the effective mass of a quasiparticle, V_0 is the volume of an elementary cell.

Whereas scattering at polarization phonons is characterized by the following relaxation time:

$$\tau_p = C_p E^{r_p}, \text{ where } r_p = +\frac{1}{2},$$

$$C_p = \frac{(2\pi)^2 \mathbf{h}^2}{2B_p\sqrt{2m^3}} = \frac{V_0 M_1 M_2 \mathbf{h}^2 \omega_0^2}{4\pi kTe^4 (M_1 + M_2)\sqrt{2m}}. \qquad (13)$$

Taking into account scattering at donor centers

$$\tau_D = C_D E^{r_D}, \text{ where } r_D = +\frac{3}{2},$$

$$C_D = \frac{(2\pi)^2 \mathbf{h}^2}{2B_D\sqrt{2m^3}} \approx \frac{\varepsilon^2 E^{3/2}\sqrt{2m}}{\pi n_D e^4} \ln^{-1}\left(\frac{8mEr_0}{\mathbf{h}^2}\right), \qquad (14)$$

r_0 is the screening radius, n_D is concentration of a donor impurity.

General relaxation time can be derived from the equation $\frac{1}{\tau} = \frac{1}{\tau_a} + \frac{1}{\tau_p} + \frac{1}{\tau_D}$.

Analysis of the results

Specific numerical calculations are carried out for cubic quantum dot superlattices of the InAs/Ga_xIn_{1-x}As with the parameters

$$m_{1e} = 0.023\ m_0,\ m_{2e} = (0.023 + 0.044x)\, m_0,$$

$$V_e = 0.77 \text{ eV}$$

$$m_{1h} = 0.55\ m_0,\ m_{2h} = (0.55 + 0.04x)\, m_0,\ V_h = 0.33 \text{ eV}$$

As seen from (10), it is necessary to determine the Fermi energy of the heterosystem in order to get specific conductivity of the CQDS.

In Fig.2 curves of temperature dependences of the Fermi energy are presented for a 3D InAs/GaAs CQDS (L=96 Å) at different concentrations of donor impurities $n_D = 10^{14}, 10^{16}, 10^{18}\,\text{cm}^{-3}$ and different energies of occurrence of the impurity level $E_D = -150, -450, -750$ meV. We obtained different behavior of dependences of the Fermi energy on temperature at different concentrations n_D. In case of $n_D = 10^{18}\,\text{cm}^{-3}$ the functions $E_F = E_F(T)$ (curves 7,8,9) are monotonic, whereas at certain temperatures there are minima (curves 1-6) at smaller concentrations $n_D = 10^{14}, 10^{16}\,\text{cm}^{-3}$. The change in energy of occurrence of the impurity level significantly changes the energy E_F at the presence of large donor concentrations ($n_D = 10^{18}\,\text{cm}^{-3}$). At small n_D ($n_D = 10^{16}\,\text{cm}^{-3}, 10^{14}\,\text{cm}^{-3}$) the chemical potential slightly depends on E_D and if $T > 600$K, and $n_D = 10^{16}\,\text{cm}^{-3}$, and $T > 100$K, and $n_D = 10^{14}\,\text{cm}^{-3}$, then $E_F \neq E_F(E_D)$.

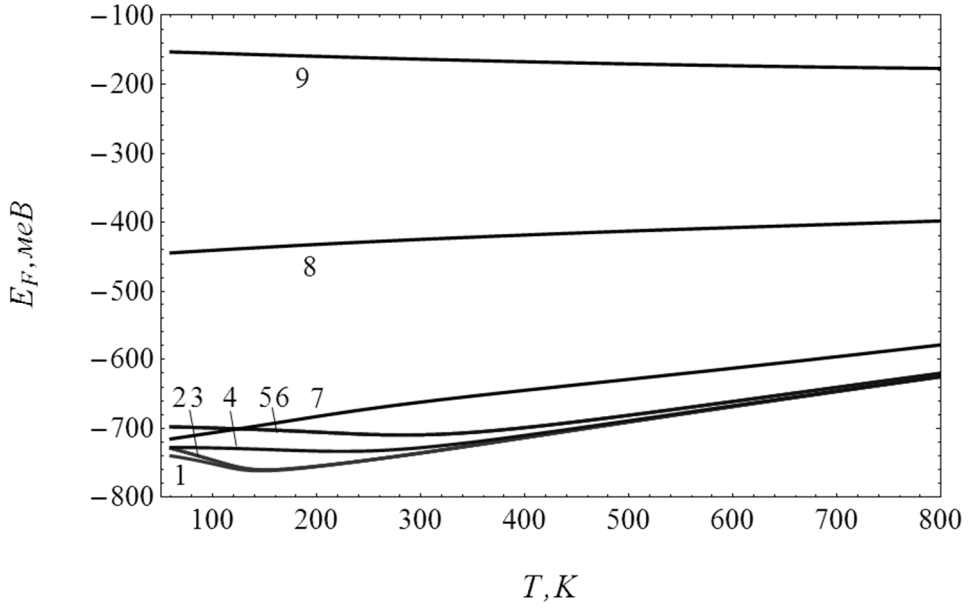

Fig. 2. Temperature dependence of the Fermi energy of the 3D InAs/GaAs CQDS (L=96 Å) at different concentrations of impurities (curves 1,2,3 refer to 10^{14} cm^{-3}; curves 4,5,6 relate to 10^{16} cm^{-3}; curves 7,8,9 refer to 10^{18} cm^{-3}) and energies of occurrence of the impurity level (curves 1,4,7 attribute to -750 meV; curves 2,5,8 refer to -450 meV; curves 3,6,9 relate to -150 meV).

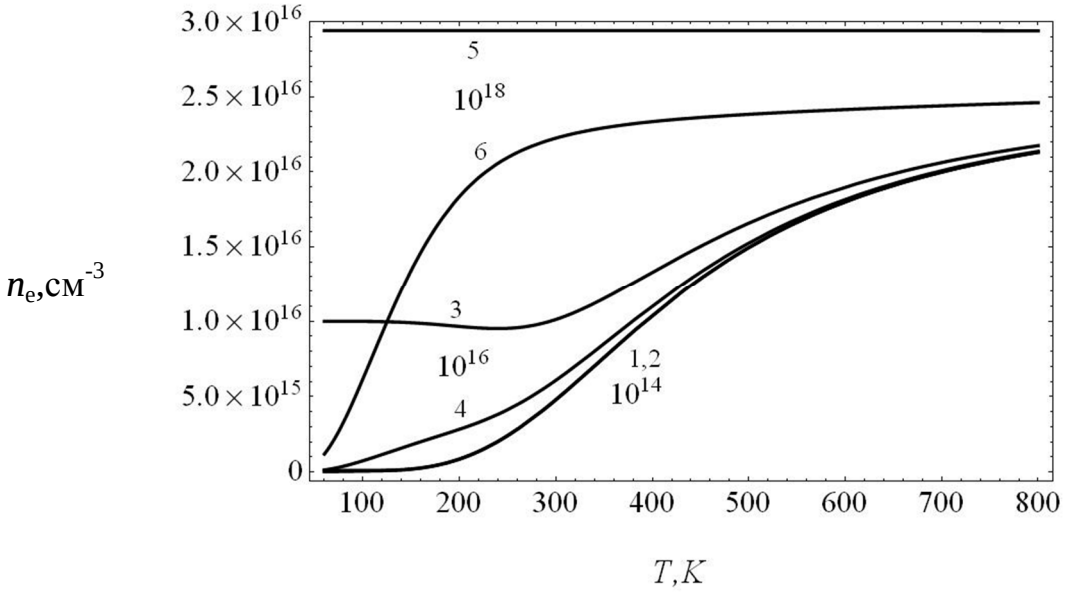

Fig. 3. Temperature dependence of concentration of ground state electrons for the 3D CQDS InAs/$Ga_{0.15}In_{0.85}As$ (L = 96 Å) at different impurity concentrations (curves 1,2 refer to 10^{14} cm^{-3}; curves 3,4 stand for 10^{16} cm^{-3}; curves 5,6 relate to 10^{18} cm^{-3}) and energies of occurrence of the impurity level (curves 1,3,5 refer to -150 meV; curves 2,4,6 stand for -750 meV).

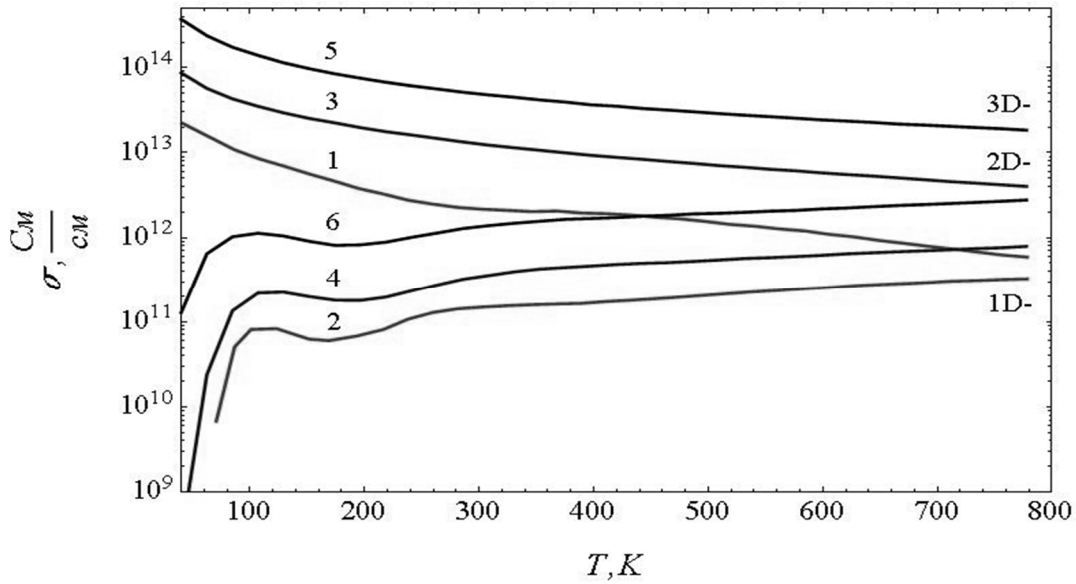

Fig.4. Temperature dependence of electroconductivity of the InAs/$Ga_{0.15}In_{0.85}As$ (L=96 Å) CQDS of various dimensionality (curves 1,2 stand for 1D; curves 3,4 refer to 2D; curves 5,6 relate to 3D), energies of occurrence of the impurity level E_D (curves 1,3,5 refer to -150 meV; curves 2,4,6 stand for -750 meV) at concentration of impurities $10^{18}\,cm^{-3}$.

The next stage of our work was to research the dependence of charge carrier concentration in the subbands on the given parameters.

The calculations of electron concentration n_e in the subbands showed that depending on the energy of occurrence of the donor levels different types of dependences are possible at given concentrations of impurities. At the donor energy $E_D < \min E_{gr}\left(\mathbf{k}\right) = -714$ meV $< \min E_{exc}\left(\mathbf{k}\right) = -609$ meV, e.g., $E_D = -750$ meV, electrons both in the excited and the ground subbands are practically absent and charge carrier concentration n_e monotonously rises with temperature (curves 2,4,6 in Fig.3) for all values n_D (10^{14},10^{16},$10^{18}\,cm^{-3}$ respectively). For donor energies $E_D > \max E_{exc}\left(\mathbf{k}\right) = -340$ meV $> \max E_{gr}\left(\mathbf{k}\right) = -666$ meV, e.g., $E_D = -150$ meV, there are different temperature dependences of concentration n_e. For each n_D there is its own temperature interval within which charge carrier concentration does not depend on temperature. In particular, if $n_D = 10^{16}\,cm^{-3}$, the relevant region is

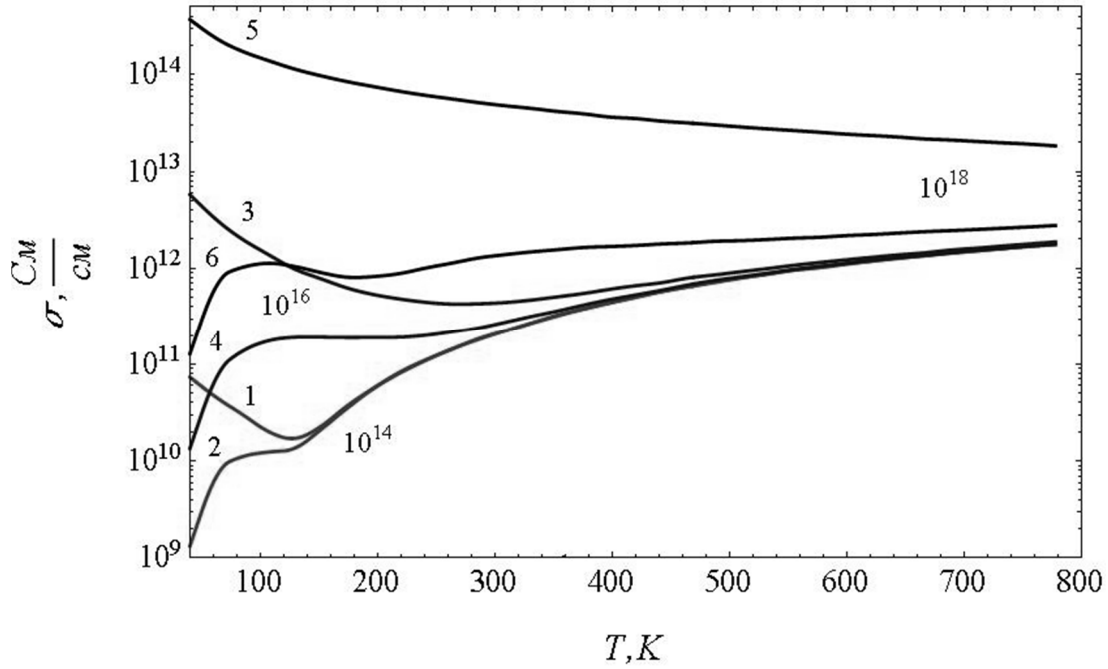

Fig. 5. Temperature dependence of electroconductivity of the 3D InAs/$Ga_{0.15}In_{0.85}As$ (L=96 Å) CQDS at different concentrations of impurities: 10^{14} cm^{-3} (curves 1,2); 10^{16} cm^{-3} (curves 3,4); 10^{18} cm^{-3} (curves 5,6) and energies of occurrence of the impurity level (curves 1,3,5 refer to -150 meV; curves 2,4,6 stand for -750 meV).

$T < 260\text{K}$, and if $n_D = 10^{16}\text{cm}^{-3}$, then $T < 160\text{K}$. If temperature is higher, there is a monotonous increase of n_e with temperature. It should be noted, that at $n_D = 10^{18}\text{cm}^{-3}$ n_e does not change with temperature in the region under consideration $(T \le 800\text{K})$.

Let us place the considered system in the external electric field. We assume that intensity of the electric field is directed along the Oz coordinate axis for superlattices of various dimensionality. In case of a 3D-superlattice of cubic symmetry, conductivity does not depend on the intensity direction, hence σ can be seen as a scalar. And in case of 2D or 1D-superlattice, current density of the CQDS is anisotropic i. e., σ depends on the direction of the vector $\mathbf{r}$ E.

The specific conductivity of the InAs/$Ga_{0.15}In_{0.85}As$ superlattice depends on both concentration and ionization energy of donors, and also on temperature.Fig.4presents the temperature dependence of electroconductivity of systems of various dimensionality (curves 1,2 stand for 1D; curves 3,4 refer to 2D; curves 5,6 relate to 3D) and energies of occurrence of the impurity level E_D (curves 1,3,5 refer to -150 meV; curves 2,4,6 stand for -750 meV) at concentration of impurities $n_D = 10^{18}\text{cm}^{-3}$. We take the following parameters for the systems: QDs size L=96 Å at interdot distance d=12 Å. As seen from the figure, conductivity rises with the increase of dimensionality of the system. The temperature dependence of conductivity is different for different values E_D. When the energy of occurrence of the impurity level $E_D = -150$ meV (curves 1,3,5 in Fig.4), electroconductivity of the CQDS is of "metallic" character as it monotonously decreases with temperature increase. At $E_D = -750$ meV (curves 2,4,6 in Fig.4) electroconductivity rises with the temperature increase. Its nonmonotonous character in the region of low temperatures $(T < 300\text{ K})$, in our view, is explained by the presence of two mutually competing mechanisms: rise of concentration of charge carriers (electrons) and reduction of their relaxation time.

An increase of concentration of impurities n_D to the value 10^{18}cm^{-3} by doping of the matrix with a monovalent donor impurity leads to the increase of conductivity by orders of magnitude (curves 5,6 in Fig.5) in comparison with $n_D = 10^{16}\text{cm}^{-3}$ (curves 3,4) and $n_D = 10^{14}\text{cm}^{-3}$ (curves 1,2). In the region of low temperatures $(T < 300\text{ K})$ electroconductivity σ significantly depends on both concentration n_D and energy E_D of donors. As seen from Fig.5, at $n_D = 10^{14}\text{cm}^{-3}$, beginning from $T > 160\text{ K}$, the dependence $\sigma(E_D)$ disappears (for concentration $n_D = 10^{16}\text{cm}^{-3}$ at $T > 560\text{ K}$). Simultaneously, at high temperatures $(T > 500\text{ K})$ conductivity slightly depends also on concentration of impurities n_D. It can be explained by the fact that electron transitions from subbands of the valence band to electronic subbands of the conduction band become essential at such temperatures.

Conclusions

In the paper properties of the system of spatially assembled cubic quantum dots that are embedded in the

matrix (i.e., quantum dot superlattice) have been investigated. We have considered an InAs/$Ga_xIn_{1-x}As$ nanoscale heterostructure. The energy spectra of electrons and holes of the quantum dot superlatticehave been determined in the effective mass approximation and modified Kronig-Penney model. In the frame of this model, the spectra of charges of 3D, 2D and 1D-superlattices can be obtained by changing respective distances between the elements of the superlattice.

The specific calculations have been performed for the CQDS with quantum dots of small size 96 Å for InAs QDs. A detail energy dependence on the wave vector of the electron and hole subbands of the superlattice has been obtained. There are two types of subbands: under-the-barrier subbands with the energy smaller than the energy gap betweeen the conduction band and valence band and over-the-barrier subbands with greater energy. The number of under-the-barrier subbands is determined by QD size and width of each subband is defined by QD size, distances between elements of the superlattice and numerical order of the subband.

In case of the matrix doped by donor impurities, in the presence of impurities of one type we have studied the dependence of the Fermi level, concentration of charge carriers on temperature ($40 \le T \le 800$ K), concentration of impurities (10^{14} cm^{-3}, 10^{16} cm^{-3}, 10^{18} cm^{-3}), energy of impurity levels on the bottom of the conduction band of the semiconductor matrix (-750 meV, -150 meV).

In particular, it has been found that the temperature dependence of concentration of electrons and holes in the subbands of the superlattice is determined by the position of donor levels with respect to the ground electronic subband. When the energy of the impurity levels is lower than the bottom of the ground electron subband, the increase of temperature in the superlattice causes a monotonic rise of concentration of charge carriers. If donor levels are above the top of the subband, there is a monotonously decreasing functional dependence of electron concentration on temperature, which saturates with the rise of temperature.

The comparison of the degree of occupation of the ground and excited subbands shows that occupation of the ground subband is significantly larger than that of excited subbands for the larger region of temperatures ($T \le 500$ K). In particular, for small electric field intensities when the Ohm law is valid, we have calculated the density of conductivity of 3D, 2D, 1D-superlattices. It has been shown that in the presence of deep impurities (-750 meV) the temperature dependence of conductivity of the superlattice has characteristic peaks, which are defined by concentrations of impurities and dimensionality of the superlattice. A different temperature dependence of conductivity has been observed for impurities with the energy of occurrence -150 meV.

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Мінізонна електропровідність у надґратках кубічних квантових точок гетеросистеми $InAs/Ga_xIn_{1-x}As$

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У даній роботі запропоновано модель надґраток кубічних квантових точок (НККТ) різної вимірності $InAs/Ga_xIn_{1-x}As$. Для визначення енергетичного спектру електронів та дірок надґратки квантових точок використано наближення ефективної маси та модифіковану модель Кроніга-Пенні. У рамках цієї моделі зміною відповідних відстаней між елементами НГ отримано спектри зарядів 3D-, 2D- та 1D-нанограток. Обчислено детально залежність енергій від хвильового вектора електронних та діркових надґраткових підзон: підбар'єрних та надбар'єрних. Кількість підбар'єрних підзон визначається розмірами КТ, а ширина кожної підзони задається розміром КТ, відстанями між надґратковими елементами та номером підзони.

Отримано та проаналізовано залежність енергії Фермі та концентрації носіїв струму від температури, концентрації домішок, енергії домішкових рівнів. Враховано залежність часу релаксації електронів від температури, зумовлену розсіюванням носіїв як на фононах, так і на донорних центрах. Досліджено вплив домішкової системи на електропровідність НККТ. Показано, що за наявності глибоких домішок (-750 меВ) температурна залежність провідності $InAs/Ga_xIn_{1-x}As$ НГ має характерні максимуми, які визначаються концентраціями домішок та вимірностями НГ. Для домішок з енергією залягання -150 меВ отримуємо іншу температурну залежність провідності.

Ключові слова: квантова точка, надґратка, електронні стани, мінізона, електрична провідність.