Effect of interface phonons on the functioning of quantum cascade detectors operating in far infrared range

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Introduction

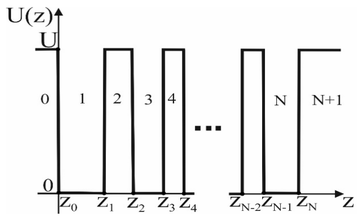
It is well known [1,2], that thanks to the high sensitivity and small noise characteristics, the quantum cascade detectors (QCD) operating in far infrared range can be potentially used in space investigation, medicine, imaging devices, navigation, environment monitoring, etc. To satisfy practical demands, nanodetectors must have rather wide spectral bands, that can be reached by use of two-well active region [3].

Modern quantum cascade detectors can operate at temperatures higher than the room one [1-3], since, the electron-phonon interaction plays not only positive role, being the canal of electron energy relax, but negative too, as a factor causing the renormalizing of their spectral absorption band. Analysis of experimental and theoretical papers shows that investigating the properties of quantum cascade detectors, the golden Fermi rule was usually used for the study of interaction between electrons and confined optical phonons. However, the influence of interface optical phonons was not observed, in spite of their effect can be essential in multi-layered cascades.

In this paper, using the model of position-dependent effective mass and rectangular potentials for the electrons and dielectric continuum model for the interface optical phonons within the method of Green's functions, the electron energy levels renormalized due to interaction with interface phonons are investigated in the cascade of far infrared range quantum cascade detector [4]. The effect of different mechanisms of electron-phonon interaction on the spectral parameters of electron states and absorption band of quantum cascade detector is studied.

The Hamiltonian of the electron-phonon interaction, mass operator

A multilayered semiconductor nanostructure (Fig. 1) is considered as a separate cascade of broad band QCD with known sizes of potential wells and barriers. Models of rectangular potentials and effective masses are used for an electron , taking into account the nonparabolicity of the conduction band.



$$m(E,z)=\begin{cases} m_w(E)=m_w\left(1+\dfrac{E}{E_{gw}}\right), & j=1,3,5,\ldots,N \\ m_b(E)=m_b\left(1-\dfrac{U-E}{E_{gb}}\right), & j=0,2,4,\ldots,N+1 \end{cases} \quad (1)$$

Fig.1 Potential scheme of nanoheterostructure.

The wave functions of electrons are represented as

$$\Psi_{n\vec{k}}(\vec{r})=\frac{e^{i\vec{k}\vec{\rho}}}{\sqrt{S}}\Psi_n(z) \quad (2)$$

where one-dimensional functions $\Psi_n(z)$ are determined from the Schrödinger equation. The energies (E_n) of electron stationary states are obtained by numerical calculations from the system of fitting conditions [5] for the functions $\Psi_n(z)$.

Using quantized wave function

$$\hat{\Psi}(\vec{r})=\sum_{n,\vec{k}}\Psi_{n\vec{k}}(\vec{r})a_{n\vec{k}} \quad (3)$$

we obtain [6] the Hamiltonian of electrons in the representation of their occupation numbers.

$$\hat{H}_e=\sum_{n\vec{k}}E_{n\vec{k}}a^+_{n\vec{k}}a_{n\vec{k}} \quad (4)$$

Within the dielectric continuum model, the spectra and polarization field potentials of interface phonons are determined from the equation.

$$\nabla^2\Phi(\vec{r})=0\ . \quad (5)$$

The solution of this equation is the potential

$$\Phi(\vec{r})\equiv\Phi(\vec{\rho},z)=\sum_{j,\vec{q}}C(\vec{q})\,\varphi_j(\vec{q},z)\,e^{i\vec{q}\vec{\rho}}\ , \quad (6)$$

where

$$\varphi_j(\vec{q},z)=\alpha_j e^{-qz}+\beta_j e^{qz}\ . \quad (7)$$

From the conditions of continuity of the polarization field potential and the electric displacement vector at nanostructure interfaces, the dispersional equation is found. From it, the energy spectrum of I-phonons are calculate.

After the quantization of the phonon field [6], the Hamiltonian of interface phonons in the representation of the occupation numbers is obtained.

$$\hat{H}_{ph}=\sum_{\lambda,\vec{q}}\Omega_\lambda(q)(b^+_{\lambda\vec{q}}b_{\lambda\vec{q}}+1/2) \quad (8)$$

The Hamiltonian of electron-phonon interaction is also obtained in the representation of second quantization over all system variables

$$\hat{H}_{e-ph}=\sum_{\lambda,\vec{q}}\sum_{n,n',\vec{k}}F_{n'n}(\lambda,q)a^+_{n'\vec{k}+\vec{q}}a_{n'\vec{k}}\left(b_{\lambda,\vec{q}}+b^+_{\lambda,-\vec{q}}\right) \quad (9)$$

with known binding functions

$$F_{n'n}(\lambda,q)=-\sqrt{\frac{4\pi e^2\hbar}{qL^2N(\lambda,q)}}\sum_{j=0}^{N+1}\int_{d_j}\Psi^{(j)*}_{n'}(z)\varphi_j(q,z)\Psi^{(j)}_n(z)\,dz \quad (10)$$

where N(λ,q) – the normality coefficient.

The Hamiltonian ($\hat{H}=\hat{H}_e+\hat{H}_{ph}+\hat{H}_{e\text{-}ph}$) of the electron-phonon system in the representation of second quantization obtained for the case of weak electron-phonon coupling allows [6] to calculate from the Dyson equation the Fourier images of the electron Green's functions with mass operators (at T = 0K).

$$M_n(\hbar\omega,\vec{k})=\sum_{n'}\sum_{\lambda,\vec{q}}\frac{F^*_{n'n}(\lambda,q)F_{n'n}(\lambda,q)}{\hbar\omega-E_{n'}(\vec{k}-\vec{q})-\Omega_\lambda(q)+i\eta} \quad (11)$$

The real component of M_n determines the shift Δ_n = Re $M_n(E_n, k=0)$, and the imaginary one - the decay $\gamma_n = -2$ Im $M_n(E_n, k=0)$ of the n-th electron state, due to its interaction with all I-phonon modes.

Analysis of the results

Based on the developed theory the spectral characteristics of electrons and interface phonons, as well as the influence of electron-phonon interaction on the spectral characteristics of the electron states in the cascade of broad band far IR range QCD [4] are investigated. The geometrical parameters of the cascade were taken as in the experimental paper [4]: 6.8/**3**/6.8/**5.65**/2/**3.955**/2.3/**3.1**/2.8/**3.1**/3.4/**3.1**/3.8/ **3.1**/4.8 (nm), where bold are the thicknesses of the potential barriers.

In fig.2 the energies (E_n) of all electron states and the probabilities of electron location in QCD cascade, normalized with respect to the energies, are presented. The figure shows that two pairs (low-energy n = 1, 2, and high-energy n = 8, 10) operating electron states with energies E_1, E_2, E_8 and E_{10} are oserved in the two-well active region. Calculations show that quantum transitions between the states of the lower and upper pairs occur with the absorption of far infrared range electromagnetic waves in a wide range of energies [117 meV, 171 meV], which well agrees with the experiments results [5]. The energies ($E_3 \div E_7$) form the so-called phonon ladder in the extractor. It provides tunneling of electrons between the active regions of neighbour cascades in QCD.

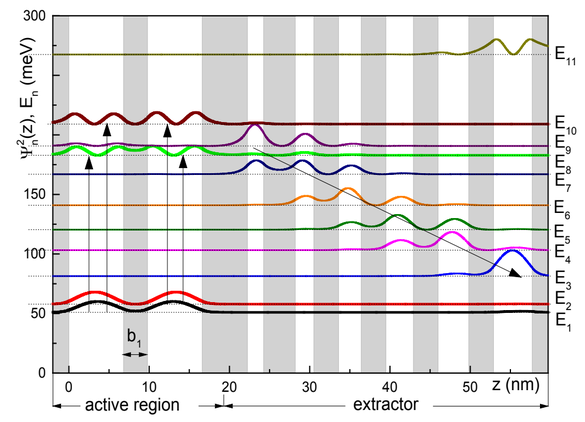


Fig.2 Energies and probability distributions of the electron in the cascade of broad band far IR range QCD.

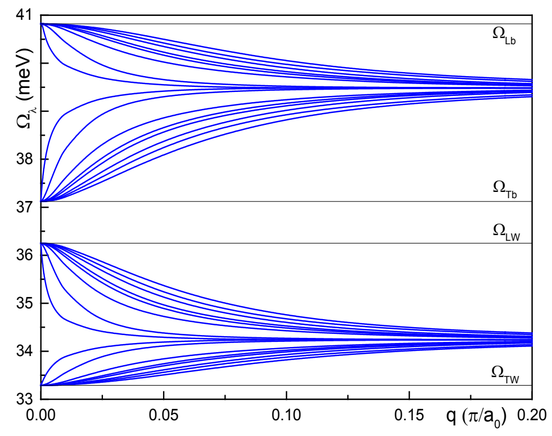


Fig.3 Dependences of all modes of energies of interface phonons on q in QCD cascade.

Figure 3 shows the dependences of all branches of energies (Ω_λ) of interface phonons on the quasi-momentum q in the cascade of QCD. Analysis shows that in the spectrum of I-phonons there are 32 branches that form two sub-bands in the energy intervals [Ω_{Tw}, Ω_{Lw}] and [Ω_{Tb}, Ω_{Lb}], where Ω_L, Ω_T are the energies of longitudinal and transversal phonons, respectively. As the quasi-momentum q increases, the energy modes converge in both sub-bands and their bandwidths decrease. The variation of geometrical parameters of the nano layers of the cascade has a weak effect on the dispersion of I-phonons.

Figure 4 shows the electron energy spectrum and transition energies ($E_n - E_{n'}$) with the absorption of long-range IR radiation as a function of the thickness (b_1) of the potential barrier in the two-well active region. It is clear that the energies of the operating states (n = 1, 2, 8, 10) converge in pairs with increasing b_1, and the width of the absorption band of QCD decreases, according to experiment [4]. The change in b_1 has almost no effect on the energies of the phonon ladder states.

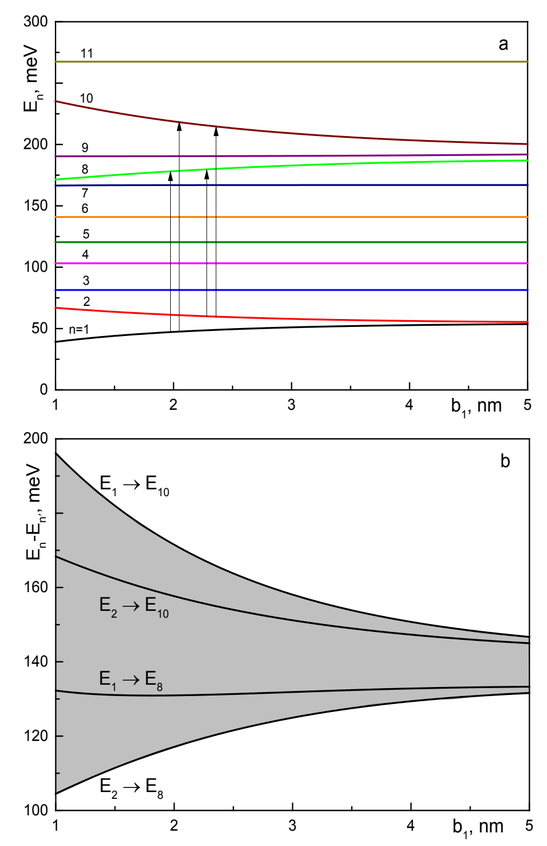


Fig. 4 Energies of electron states as functions of the thickness of the potential barrier in the active region (a) , the position of the absorption peaks of QCD (b).

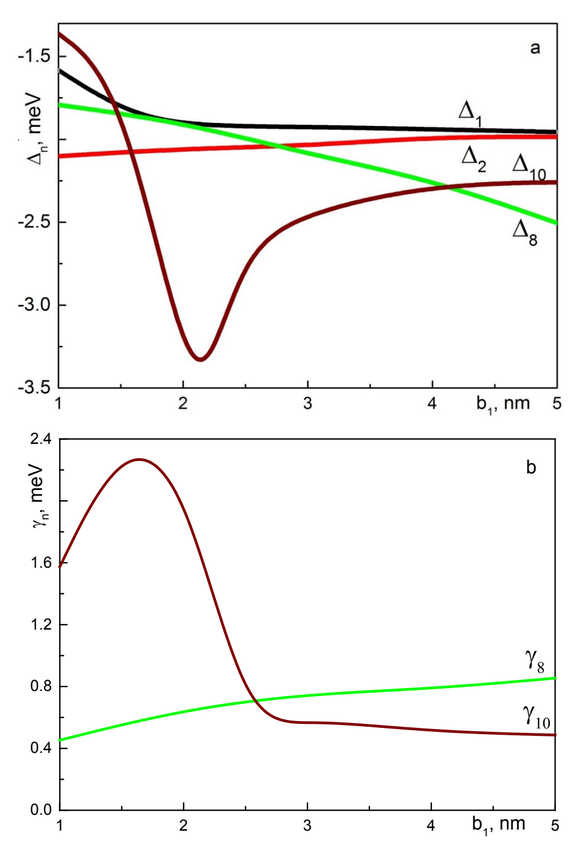


Fig. 5 Dependences of shifts (a) and decay (b) of the electron operating states on the thickness of potential barrier in active region.

Figure 5 shows the shifts (Δ_n) and decay (γ_n) of the electron operating states due to the interaction with all modes of the interface phonons depending on the thickness (b_1) of the potential barrier between the wells of the active region.

We should note that since at cryogenic temperature (T = 0K) the renormalization of the electron spectrum can occur only due to the interaction with the emission of virtual phonons, so the electron-phonon interaction leads to a decrease of the energies of all electron states ($\Delta_n < 0$), regardless of the geometrical parameters of the cascade. Since the magnitudes of decays (γ_n) at T=0K are determined by the condition $E_n > E_{n'}(q) + \Omega_\lambda(q)$, in the selected range of b_1 , the decays of the ground and first excited states are absent ($\gamma_1 = 0$, $\gamma_2 = 0$). Decay of the other two operating states (n = 8, 10) occurs only at the interlevel interaction when the above condition is fulfilled, which causes the nonlinear dependences $\gamma_{10}(b_1)$ and $\Delta_{10}(b_1)$.

Analysis of Fig. 5 shows that the interaction of electrons with interface phonons almost equally renormalizes the energies of all four operating states. Therefore, at cryogenic temperature, the electron-phonon interaction has a weak effect on the position of the absorption band and leads only to its expansion associated with the decay of two upper operating states.

Main results and conclusions

From the first principles the theory of spectral characteristics renormalized by interface phonons in broad band QCD cascade operating in far IR range is developed.

The partial contributions of different mechanisms of electron-phonon interaction in the shifts and decay of electron states in the QCD cascade are investigated. It is established that the intra-level interaction of electrons with all modes of I-phonons prevails over the inter-level ones.

It is shown that at cryogenic temperature, the electron-phonon interaction expands the absorption peak of the broad band far IR range QCD and has a weak effect on its position. Increasing thickness of the potential barrier in the two-well active region, in agreement with the experiment, leads to a narrowing absorption band of QCD due to the convergence of operating energy levels of electron.

References

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