

CONFERENCES AND SYMPOSIA

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A scientific session of the Division of General Physics and Astronomy of the Russian Academy of Sciences (RAS) was held at the P L Kapitza Institute for Physical Problems, RAS on 16 December 1998.

Six papers were presented at this session:

(1) **Vorob'ev L E, Firsov D A, Shalygin V A** (St. Petersburg State Technical University, St. Petersburg), **Tulupenko V N** (Donbass State Machine-Building Academy, Kramatorsk, Donbass), **Ledentsov N N, Kop'ev P S, Ustinov V M, Shernyakov Yu M, Alferov Zh I** (A F Ioffe Physico-Technical Institute, RAS, St. Petersburg) "The outlook for the development of radiation sources in the middle-IR range based on the intraband transitions between the energy levels of charge carriers in injection laser heterostructures with quantum dots and wells";

(2) **Aleshkin V Ya, Andronov A A, Gavrilenko V I** (Institute for Physics of Microstructures, RAS, Nizhniĭ Novgorod) "Intraband lasers based on spatial and intervalley transfer of hot electrons in heterostructures with quantum wells";

(3) **Murzin V N, Mityagin Yu A** (P N Lebedev Physics Institute, RAS, Moscow) "Resonance tunneling, electric and optical phenomena in long-period semiconductor superlattices";

(4) **Kulakovskiĭ V D** (Institute of Solid State Physics, Chernogolovka, Moscow region), **Gippius N A, Tikhodeev S G** (General Physics Institute, RAS, Moscow) "Effects of the interaction between light and excitons in microcavities based on heterostructures";

(5) **Ivanov S V, Kop'ev P S, Toropov A A** (A F Ioffe Physico-Technical Institute, RAS, St. Petersburg) "Blue-green lasers based on short-period superlattices in II – VI compounds";

(6) **Kvon Z D, Litvin L V, Tkachenko V A, Aseev A L** (Institute of Semiconductor Physics, Siberian Division, RAS, Novosibirsk) "One-electron transistors based on Coulomb blockade and quantum interference".

Abridged versions of papers 1, 3, 5, and 6 are given below.

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The outlook for the development of radiation sources in the middle-IR range based on the intraband transitions between the energy levels of charge carriers in injection laser heterostructures with quantum dots and wells

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The physical principles of the inversion of the electron population between the size-quantization levels upon injection of the electrons and holes to the *i*-region of a heterostructure with quantum dots or quantum wells allow one to obtain lasing in the middle-IR (MIR) spectral range. Important features of these mechanisms are the simultaneous generation of interband radiation ($h\nu \approx E_g$) in the near-IR (NIR) range and the presence of the 'metastable' level. In quantum dots, such levels appear due to the phonon bottleneck effect. In quantum wells, an energy level can appear due to the weak overlap of the wave functions of electrons at levels in quantum wells of a special shape. Quantum wells are considered in polar semiconductors where scattering of the electrons by optical phonons dominates. Estimates are made of the gain of the MIR radiation upon direct intraband transitions and of the current required for the generation of this radiation in structures with quantum dots and quantum wells. The results of experimental studies of intraband spontaneous MIR radiation occurring simultaneously with the generation of the interband stimulated NIR radiation are presented.

Introduction

Middle-IR semiconductor lasers ($\lambda = 4 - 15$ μm) can find extensive applications in different fields. Nevertheless, the development of normal injection lasers in this spectral range, in which lasing results from radiative recombination of electrons and holes, faces fundamental problems due to an increase in the Auger recombination with the decreasing energy gap E_g. The development of physics and technology of low-dimensional structures opens up new possibilities in the development of MIR lasers.

Many attempts have been made to find structures with quantum wells in which a population inversion (PI) between the size-quantization levels in a quantum well can be produced (the intraband PI). Studies in this field have already resulted in the development of quantum-cascade lasers [1] based on the modified concept suggested in Ref. [2] and in the development of 'fountain' lasers with optical pumping [3]. However, the creation of quantum-cascade lasers represents a complex technological problem, while the necessity of optical pumping in fountain lasers narrows the field of their application.

In this paper, we consider the principles of producing PI in quantum wells (QWs) and quantum dots (QDs) upon injection of electrons into the *i*-region of a heterostructure. Three special features of the appearance of the intraband PI can be noted.

First, intraband PI is achieved both in QDs and QWs upon injection of electron – hole (e – h) pairs by an electric current. Second, a long-lived energy level ('metastable' level) should exist. The third feature is the simultaneous generation in the NIR region. Although below we will consider specific heterostructures, the principles of producing the PI are general and can be also used to create PI in other structures with QDs and QWs.

Note that earlier [4] it was suggested to use stimulated NIR radiation for producing PI between electronic levels in QWs with two size-quantization levels. The concept suggested in Ref. [4] is interesting, but cannot be realized in a simple rectangular quantum well, because the lifetime of electrons at the upper level is short.

Quantum dots

Intraband population inversion of electrons in quantum dots. Consider the mechanism of population inversion in QDs by the example of the GaAs/AlGaAs layer of QDs with two electronic levels at the central part of the $p^+ - i - n^+$ diode heterostructure (Fig. 1).

After injection from p^+- and n^+-regions into the *i*-region of the diode structure, electrons and holes rapidly reach a wetting layer [5] and then are trapped by the QD states approximately for 10^{-12} s [6]. The lifetime of electrons at level E_2 is long (about 10 ps [6]) because of the *phonon bottleneck effect*. For this reason, in the case of the high injection level (the pump current exceeds the threshold value: $J > J_{\mathrm{th}}$), a PI between levels E_2 and E_1 can be obtained due to rapid depletion of the level E_1 by the intense stimulated interband radiation in the NIR region ($h\nu_{\mathrm{NIR}}^{\mathrm{st}} \approx E_{\mathrm{g}}$).

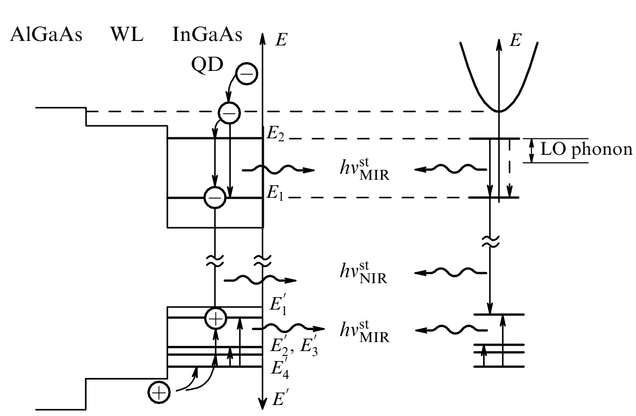

Figure 1. Scheme of electron and hole transitions and level diagram in the QD in the *i*-layer of the $p^+ - i - n^+$ diode heterostructure. WL is a wetting layer. Photon energies $h\nu_{\mathrm{MIR}}^{\mathrm{st}}$ and $h\nu_{\mathrm{NIR}}^{\mathrm{st}}$ correspond to stimulated MIR and NIR radiation, respectively.

Level populations in a structure containing ten QD layers are described, under stationary conditions, by the rate equations

$$10\left[n_2(\tau_{\nu 2}^{\mathrm{sp}})^{-1} + n_2\left(1 - \frac{n_1}{m_1 N}\right)(\tau_{21})^{-1}\right] = \eta J A_2\left(1 - \frac{n_2}{m_2 N}\right), \tag{1}$$

$$10\left[n_1(\tau_{\nu 1}^{\mathrm{sp}})^{-1} + B_1^{\mathrm{st}} N_\nu - n_2\left(1 - \frac{n_1}{m_1 N}\right)(\tau_{21})^{-1}\right] = \eta J A_1\left(1 - \frac{n_1}{m_1 N}\right), \tag{2}$$

where N is the QD density in a layer; n_1 and n_2 are the electron densities at levels E_1 and E_2; m_1 and m_2 are the numbers of states at QD levels; the coefficient η takes into account a decrease in the number of carriers caused by recombination in the *i*th layer outside the QD; τ_{21} is the lifetime of electrons at the level E_2 relative to nonradiative $E_2 \to E_1$ transitions; $\tau_{\nu 2}^{\mathrm{sp}}$ and $\tau_{\nu 1}^{\mathrm{sp}}$ are the times of the interband radiative recombination relative to spontaneous electronic transitions from levels E_2 and E_1, respectively; coefficients A_1 and A_2 are proportional to probabilities of trapping at levels E_1 and E_2 ($A_1 + A_2 \cong 1$). Depopulation of the level E_1 due to stimulated NIR radiation is described by the second term in the left-hand side of Eqn (2). This term dominates when the injection currents J exceed the threshold current J_{th} of generation in the NIR region. It was found experimentally that the photon density $N_\nu \propto (J/J_{\mathrm{th}} - 1)$ for $J > J_{\mathrm{th}}$. By assuming that the coefficient $B_1^{\mathrm{st}} \propto n_1$ [7], one can show from Eqns (1) and (2) that for these currents n_1 is independent of J. Then, n_2 can be easily obtained as a function of the injection current and the threshold current of the PI can be determined.

Let us assume that the generation of NIR radiation begins when 2/3 of states are populated at the level E_1, i.e., $n_1/(m_1 N) = 2/3$. Then, the PI ($n_2 > n_1$) appears when the injection current exceeds $6J_{\mathrm{th}}$ (calculated for $A_1 \ll A_2$; $\tau_{21} \ll \tau_{\nu 2}^{\mathrm{sp}}, \tau_{\nu 1}^{\mathrm{sp}}$; $m_1 = 2$, $m_2 = 4$ [8] and $N = 4 \times 10^{10}$ cm^{-1} [6, 9]).

Generation of stimulated middle-IR radiation in structures with quantum dots. Let us find the current that provides the amplification and generation of MIR radiation upon the $E_2 \to E_1$ electronic transitions. The gain can be written in the form

$$\alpha_{2\to 1} = \sigma_{12}\frac{N}{L}\left[\frac{n_2}{N}\left(1 - \frac{n_1}{m_1 N}\right) - \frac{n_1}{N}\left(1 - \frac{n_2}{m_2 N}\right)\right], \tag{3}$$

where the absorption cross section $\sigma_{12} = 1.6 \times 10^{-15}$ cm^2 [9] and L is the width of the QD layer (we assume that $L = 100$ A). For the condition $n_1/(m_1 N) = 2/3$, it follows from Eqn (3) that the gain $\alpha_{2\to 1} > 0$ for $n_2/m_2 N > 1/2$, which is valid for $J > 25 J_{\mathrm{th}}$.

The generation of MIR radiation in a structure containing a QD can be obtained if the waveguide confinement exists simultaneously on NIR and MIR radiation. A waveguide of such type can be fabricated by growing $Ga_{1-x}Al_xAs$ *i*-layers with variable composition, whose total width corresponds to the wavelength of MIR radiation in the structure. In this case, the optical restriction (Γ) for a structure containing ten QD layers is about 0.1. Then, the condition of NIR generation,

$$\Gamma\alpha_{2\to1} = \frac{1}{l_r}\ln\frac{1}{R}\,, \tag{4}$$

yields the gain $\alpha_{2\to1} = 30\ \text{cm}^{-1}$ for a resonator length $l_r = 1$ mm and reflection coefficient $R = 0.3$. To provide such a gain, an injection current $J \cong 100\,J_{\text{th}}$ is required.

The situation can be considerably improved in QDs with *three electronic levels*. Such QDs can be fabricated, as follows from recently refined calculations of the energy spectrum [10]. To obtain the required gain ($\alpha_{3\to2} = 30\ \text{cm}^{-1}$), an order of magnitude weaker current is sufficient, $J = 6\,J_{\text{th}}$.

Spontaneous middle-IR radiation of InGaAs/AlGaAs structures with quantum dots. The first experimental studies of spontaneous MIR radiation of laser structures with QDs accompanied by the simultaneous generation of NIR radiation were reported in Ref. [11]. Diode structures with vertically coupled QDs were studied. These structures were fabricated to produce generation in the NIR region at a wavelength of 0.9 μm. An active area of these lasers consists of $Al_{0.15}Ga_{0.85}As$ layers containing incorporated self-organized $In_{0.5}Ga_{0.5}As$ QDs. The number of layers is ten. The undoped layers form a waveguide for the operating wavelength. The NIR radiation was detected with a silicon photodiode. The MIR radiation was detected with Ge$\langle$Cu$\rangle$ and Si$\langle$B$\rangle$ photoresistors operating in the range $\lambda = 5-29$ μm. Ge and InSb filters placed in front of photoresistors blocked NIR radiation at $\lambda = 0.9$ μm. The measurements were performed in a pulsed mode at 30 K.

Figure 2a shows the intensities of stimulated NIR and spontaneous MIR radiation as functions of the injection current. Both dependences are of a threshold nature, with close thresholds about 0.33 A. Using a set of optical filters, the MIR radiation was found to cover the spectral range between 10 and 20 μm.

First, a whole set of such samples containing QDs was studied. It was found that the structures that did not show stimulated NIR radiation did not exhibit MIR radiation.

Second, similar studies of laser diode structures with $In_{0.2}Ga_{0.8}As$/GaAs QWs instead of QDs were performed. QWs in these structures had two levels. The threshold current of stimulated radiation was about 0.25 A. Spontaneous MIR radiation was also found in these structures, its intensity being an order of magnitude weaker than that for QDs. The dependence of MIR radiation on the injection current showed no threshold (Fig. 2b).

Let us explain qualitatively the phenomena observed. Based on calculations [5] performed for analogous structures with self-organizing QDs, we assumed the presence of two electronic levels in our structure. When electrons are injected into the *i*-layer of the diode structure, they are trapped by a state in a wetting layer for several picoseconds and then transfer to the electronic level of the QD (Fig. 1). Analogous processes take place for holes. Then, electrons and holes can undergo intra- and interband transitions in the QD. The intraband transitions are accompanied by emission of phonons or MIR photons (in this case, $h\nu_{\text{MIR}}^{\text{st}}$ should be replaced by $h\nu_{\text{MIR}}^{\text{sp}}$ in Fig. 1). The lifetime relative to phonon processes in the QD is much longer that in QWs because of the phonon bottleneck effect.

When injection currents are close to the threshold, the ground levels for electrons and holes may be full. So, the optical transitions to these levels from excited ones are impossible.

When the injection current exceeds the threshold, stimulated NIR radiation is emitted and the corresponding interband transitions deplete the ground states. Transitions of the carriers from the excited to ground states cause emission of spontaneous MIR radiation. Its intensity increases with increasing current because electrons occupy the excited states. As the current increases, an increasing number of QDs of different sizes are involved in the generation of NIR radiation, resulting in a superlinear increase in the MIR radiation intensity.

In QWs, in contrast to QDs, the intraband transitions can occur at any current, because the ground subband always has free states. For this reason, the intraband MIR radiation from QWs has no current threshold. Its intensity in QWs is weaker than that in QDs, because the excited-state lifetime in QWs is shorter.

Thus, we have explained qualitatively the basic features of the experimental dependences. The observation of spontaneous MIR radiation represents the first step in the development of the MIR laser operating at transitions between the states of charge carriers in QDs.

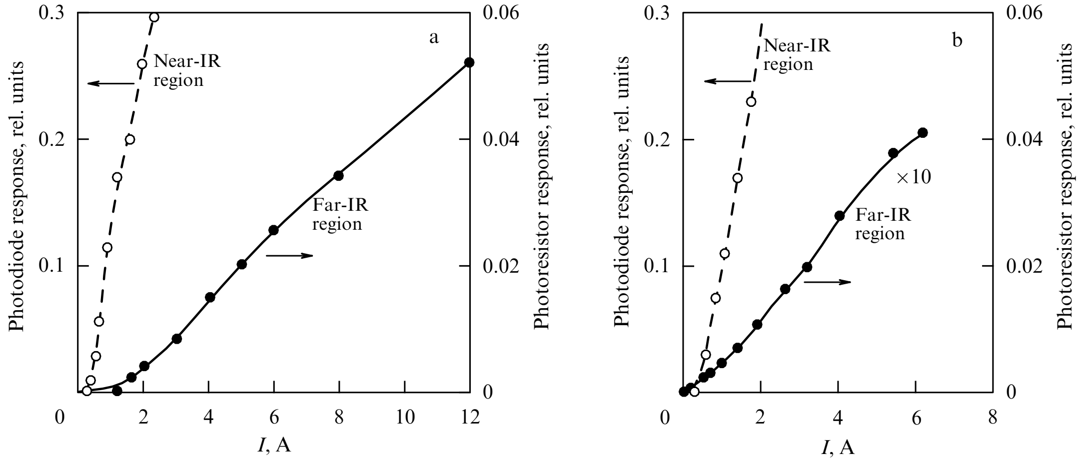

Figure 2. Intensity of near- and middle-IR radiation of structures containing (a) QDs and (b) QWs.

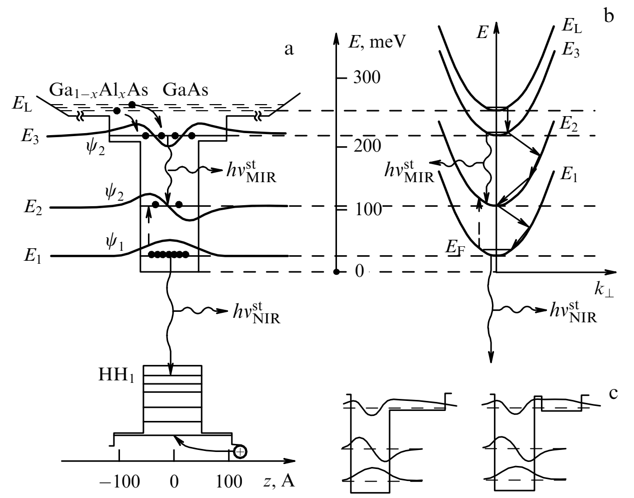

Figure 3. (a) Scheme of electronic transitions in a quantum well in the i-layer of the $\mathrm{p^+}-i-\mathrm{n^+}$ laser, an energy level diagram, and the electron wave functions. The solid arrows denote the electronic transitions accompanied by emission of optical phonons, the wavy arrows show optical transitions in MIR and NIR spectral regions, and the dashed lines show thermal excitations. (b) Scheme of the inter- and intra-subband electronic transitions accompanied by emission of optical phonons. Only basic transitions are shown. The wavy vertical arrows show optical transitions corresponding to stimulated MIR and NIR radiation. (c) Profiles of the QW potential allowing minimization of the overlap of the electron wave functions for the upper and two lower levels.

Quantum wells

Intraband population inversion in quantum wells in the presence of stimulated interband radiation. Consider a $\mathrm{p^+}-i-\mathrm{n^+}$ structure containing a QW in the form of a funnel incorporated into its i-layer (Fig. 3). The narrow central part of the QW is formed by a GaAs layer of thickness 11 nm, with two symmetrically arranged $\mathrm{Al_{0.25}Ga_{0.75}As}$ layers of thickness 5.5 nm each adjacent to it. To the left and right of the QW there are two $\mathrm{Al_{0.3}Ga_{0.7}As}$ layers of total thickness 100 nm, and then, $\mathrm{Al_xGa_{1-x}As}$ layers of a variable composition with x varied from 0.3 to 0.8. The variable composition layers form a waveguide for NIR and MIR radiation in the i-layer.

According to calculations, such a complex QW has three size-quantization levels with energies $E_1 = 28$, $E_2 = 106$, and $E_3 = 206$ meV, the QW being close to the resonance. Note that the energy spectrum in the region of width 100 nm above the barrier is quasi-discrete, with the levels separated by a distance about of 1 meV.

The electrons injected into the i-region occupy the quasi-discrete levels in the region above the barrier and then are trapped at the E_1, E_2, and E_3 levels of QWs due to scattering by optical phonons (estimates show that scattering by acoustic phonons and interface imperfections can be neglected).

Under stationary (but nonequilibrium) conditions, the concentration of electrons at levels can be found from the system of rate equations, which takes into account only basic processes:

$$\eta J A_3 - N_3 W_{23} - N_3 W_{13} - N_3 (\tau^{\mathrm{sp}}_{v3})^{-1} = 0\,, \tag{5}$$

$$\eta J A_2 + N_3 W_{23} - N_2 W_{12} - N_2 (\tau^{\mathrm{sp}}_{v2})^{-1} + \beta_{12} N_1 = 0\,, \tag{6}$$

$$\eta J A_1 + N_3 W_{13} + N_2 W_{12} - N_1 (\tau^{\mathrm{sp}}_{v1})^{-1} - B^{\mathrm{st}}_1 N_v - \beta_{12} N_1 = 0\,, \tag{7}$$

where N_1, N_2, and N_3 are surface electron concentrations at levels 1, 2, and 3; τ^{sp}_{vi} is the lifetime of an electron in the E_i level relative to the radiative recombination during spontaneous emission (an electron is in the conduction band and a hole is in the valence band); N_v is the photon density; and B^{st}_1 is a proportionality coefficient. The last but one term in Eqn (7) describes the depletion of level 1 due to stimulated NIR radiation; for $J > J_{\mathrm{th}}$, it is proportional to $(J/J_{\mathrm{th}} - 1)$.

Terms $\beta_{12} N_1$ describe thermal excitation, where

$$\beta_{12} = W_{12} \exp\left(-\frac{E_2 - E_1}{k_{\mathrm{B}} T}\right).$$

The PI is mainly determined by excitation from the most populated level, i.e., the E_1 level. For this reason, we took into account only this process. The coefficient η takes into account only a fraction of electrons reaching the QW; A_1, A_2, and A_3 are coefficients determined by the probability of electron trapping from the region above the barrier to the QW levels. Finally, W_{ij} are probabilities of nonradiative transitions from the j level to the i level upon the interaction with polar optical (PO) phonons. The interaction with acoustic phonons and interface imperfections is neglected. Estimates show that the interaction with acoustic phonons is an order of magnitude weaker than that with optical phonons. As for the scattering by interface imperfections, it is appreciable in GaAs/AlGaAs QWs only when the size of QWs does not exceed 7 nm [12].

Consider the case of low temperatures, when $k_{\mathrm{B}} T \ll \hbar\omega_0$ ($\hbar\omega_0$ is the PO phonon energy).

The total probability of the transition from the state $E_i(\mathbf{k}_{\perp i})$ to the subband E_j is

$$W_{ji}(\mathbf{k}_{\perp i}) = \frac{2\pi}{\hbar} \sum_{k_{\perp j}} \sum_{q_z} |C_q|^2 |J_{ji}(q_z)|^2 \delta_{q_\perp, k_{\perp j} - k_{\perp i}} \times \delta\left[E_i + \frac{\hbar^2 k^2_{\perp i}}{2m_{\mathrm{e}}} - E_j - \frac{\hbar^2 k^2_{\perp j}}{2m_{\mathrm{e}}} - \hbar\omega_0\right], \tag{8}$$

where C_q determines the electron – phonon interaction energy:

$$|C_q|^2 = \frac{2\pi e^2 \hbar\omega_0}{V(q_\perp^2 + q_z^2)\varepsilon^*}\,, \quad \frac{1}{\varepsilon^*} = \frac{1}{\varepsilon_\infty} - \frac{1}{\varepsilon_0}\,; \tag{9}$$

V is the normalization volume; $q_\perp$ and q_z are the components of the phonon wave vector which are perpendicular and parallel to the axes of growth; ε_∞ and ε_0 are the high- and low-frequency dielectric constants of a nonpolar crystal. The integral J_{ji} characterizes the overlap of the electron wave functions for levels i and j:

$$J_{ji}(q_z) = \int \psi^*_j(z) \exp(-\mathrm{i} q_z z) \psi_i(z)\, \mathrm{d}z\,. \tag{10}$$

It follows from Eqn (8) that the probability of scattering from the subband E_j to the subband E_i increases with decreasing $q_\perp$ (i.e., with increasing energy gap between levels i and j) and increasing overlap of the electron wave functions. Calculations yield the following results for our QW: $W_{12} = 2 \times 10^{12}\ \mathrm{s^{-1}}$; $W_{23} = 4 \times 10^{11}\ \mathrm{s^{-1}}$; $W_{13} = 2 \times 10^{11}\ \mathrm{s^{-1}}$; $A_1 = 0.054$; $A_2 = 0.086$; and $A_3 = 0.86$. In addition, the probability W_{ii} of intraband transitions accompanied by emission of a phonon exceeds the probability W_{ji} of transitions between subbands: $W_{ii} \gg W_{ij}$. Thus, W_{13},

$W_{23} \ll W_{12}$ and A_1, $A_2 \ll A_3$, and hence, the E_3 level can be called 'metastable'.

The motion of an electron between levels in the QW can be described in the following way. After emission of a PO phonon, the electron is captured in the level E_3 (Fig. 3). Having emitted the next PO phonon, the electron finds itself in the subband E_2 and rapidly relaxes to the bottom of this subband by emitting two other PO phonons. Then, after rapid emission of the next PO phonon, the electron comes to the first subband and, finally, by emitting the last phonon, it finds itself near the bottom of this subband, in the state near the Fermi quasi-level E_F.

From Eqns (5)–(7) we obtain near the threshold ($J < J_{\text{th}}$): N_3, $N_2 \ll N_1$ and $J_{\text{th}} \cong \eta^{-1} N_{1\text{th}} (\tau_{v1}^{\text{sp}})^{-1}$. Usually, in GaAs/AlGaAs heterolasers at high injection levels near the threshold the radiative recombination dominates ($\tau_{vi}^{\text{sp}} \simeq 10^{-9}$ s), and the threshold current in structures with QWs is approximately $J_{\text{th}} = 200$ A cm^{-2}.

For $J > J_{\text{th}}$, the photon density $N_v \sim (J/J_{\text{th}} - 1)$, and assuming that approximately $B_1^{\text{st}} \sim N_1$ [7], we obtain from Eqns (5)–(7) for sufficiently large injection currents ($J \gg J_{\text{th}}$) that the electron concentration on the level E_1 is independent of the current: $N_1 \cong \text{const} = N_{1\text{th}}$ (for $N_{1\text{th}} = 5.5 \times 10^{11}$ cm^{-2}, the Fermi level $E_F \approx 20$ meV). This fact is well known: after the generation onset, the probability of stimulated emission increases with increasing current due to an increase in N_v; for this reason, the electron concentration remains close to the threshold one despite the increase in the number of injected electron – hole pairs with increasing J. Having solved the system of equations (5)–(7), we obtain

$$N_3 - N_2 = \eta J \left(A_3 \frac{W_{12} - W_{23}}{W_{12}(W_{13} + W_{23})} - A_2 W_{12}^{-1} \right) - N_1 W_{12} \exp\left(-\frac{E_2 - E_1}{k_B T} \right). \qquad (11)$$

As was noted above, $W_{12} \gg W_{23}$ and $A_3 \gg A_2$. For $T < 200$ K, the last term in Eqn (11) can be neglected, and we obtain for the PI: $N_3 - N_2 = 6 \times 10^8 J/J_{\text{th}}$ cm^{-2}. Note once more that the important condition for obtaining PI is the generation of NIR radiation. Stimulated NIR radiation removes electrons from the E_1 level and thus maintains the constant concentration of electrons at this level as current J increases. If stimulated NIR radiation was absent, then already at $J/J_{\text{th}} = 10$ the electron concentration would be so high that the interaction between electrons would reduce the PI. In addition, because of the increase in the Fermi level up to $E_F > E_2 - E_1$, electrons would be found in the E_2 band.

In the case of asymmetric QWs (Fig. 3c), the lifetime of electrons on the level E_3 can be increased by further decreasing the overlap of the electron wave functions at levels E_3 and E_2, E_1.

Amplification of middle-IR radiation and lasing in quantum wells. By using [13], we can find the gain upon direct optical transitions between levels 3 and 2:

$$\alpha_{32} = \frac{4\pi e^2 (N_3 - N_2) \cos^2\theta}{cnL_w} \omega_{32} |Z_{32}|^2 \frac{\gamma}{\gamma^2 + (\hbar\omega - \hbar\omega_{32})^2}, \qquad (12)$$

where $Z_{32} = \int \psi_3^* z \psi_2 \, dz$; θ is the angle between the z-axis and the polarization vector $\mathbf{e}_\omega$ of the wave; γ is the broadening; and n is the refractive index. According to calculations, $Z_{32} = 23$ Å.

The condition for observation of stimulated MIR radiation has the form

$$\Gamma \alpha_{32} = \frac{1}{l_r} \ln \frac{1}{R} + \alpha_l, \qquad (13)$$

where l_r is the resonator length, R is the reflection coefficient of mirrors, Γ is the factor of optical restriction for MIR radiation, and α_l is the absorption coefficient for MIR radiation related to free charge carriers in active and passive regions. The factor Γ is approximately equal to the ratio of the QW width to that of the waveguide for MIR radiation. In our case, $\Gamma \cong 10^{-2}$.

If the losses of MIR radiation can be neglected ($\alpha_l \cong 0$) and $l_r = 1$ mm, and $R = 0.3$, condition (13) is satisfied provided $\alpha_{32} = 1200$. According to Eqn (12), this value can be obtained when $\omega = \omega_{32}$ and $\gamma = 2$ meV, if $N_3 - N_2 = 3 \times 10^{10}$ cm^{-2} and the last term in Eqn (11) can be neglected. For the QW parameters chosen, this term can be neglected for $T < 200$ K. Then, the threshold current of generation of MIR radiation is $J_{\text{th}}^{\text{MIR}} = 60\, J_{\text{th}}^{\text{NIR}}$. The situation can be improved by using several QW layers.

Conclusions

Principles for producing population inversion and generation of the middle-IR radiation upon intraband transitions of charge carriers in quantum dots and quantum wells in injection lasers are suggested. Spontaneous far-IR radiation is detected for the first time. This radiation is related to intraband transitions of charge carriers in quantum dots and quantum wells, which are located in the *i*-layer of the injection heterolaser. Calculations are performed which confirm the possibility of producing a population inversion in injection heterolasers and simultaneous lasing in the far- and near-IR spectral ranges.

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Resonance tunneling, electric and optical phenomena in long-period semiconductor superlattices

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Introduction

The development of physical principles of amplification, generation, and conversion of electromagnetic vibrations over a broad IR range and the fabrication of active elements based on these principles remains one of the urgent problems of the physics of semiconductors in solid-state electronics. An important step in this field was the discovery of new mechanisms of amplification of electromagnetic radiation based on dynamic heating of current carriers in strong electric and magnetic fields, resulting in the development of lasers and masers on hot holes — the first solid-state lasers operating in the far-IR and submillimeter spectral ranges [1].

Fundamentally new possibilities in this field are opened up by studies of electronic phenomena in quantum-sized structures, in particular, caused by transitions between the size-quantization states. The energy of intersubband transitions can be varied over a broad range, from near- and middle-IR to the far-IR spectral region [2, 3], by varying the parameters of the structures. Very recently, near-IR lasers of a new type were developed based on the concepts of Kazarinov and Suris about resonance tunneling of electrons in superlattices [4]. Lasing was obtained at the intersubband transitions in a system of quite narrow and strongly coupled quantum wells upon current injection (quantum cascade lasers) [5] and optical pumping (fountain lasers) [6]. Population inversion in both these systems is produced due to the difference of carrier relaxation rates caused by the difference between one-phonon and multiphonon processes of scattering of charge carriers by optical phonons.

In this paper devoted to the problem of population inversion in quantum-sized systems, we suggest a fundamentally new approach based on the phenomenon of resonance tunneling in structures with wide quantum wells, in which the difference in energies of the lower size-quantization subbands is less than the energy of an optical phonon. The lifetime of charge carriers in the first excited level in such structures can be determined by comparatively slow relaxation processes, for example, caused by scattering of charge carriers by acoustic phonons. If a sufficiently rapid removal of charge carriers from the lowest state is provided due to resonance tunneling to the neighboring quantum well, one can expect the appearance of strongly nonequilibrium carrier distribution, population inversion and lasing at these transitions.

In reality, the situation is more complicated because of the existence of other relaxation channels (scattering by ionized impurities, interfaces, etc.), which reduce the lifetime of charge carriers in the first excited state and result in the population of the ground state. For this and some other reasons, in particular, the absorption of radiation involving free carriers and phonons, and difficulties of producing an optical confinement in quantum-sized structures at long wavelengths, the problem of resonance tunneling has proved to be one of the most important in this field.

The approach used raises additional problems determined by the special features of systems with wide quantum wells. Of great importance is the degree of overlap of lower subbands in real fabricated structures. Is the resonance tunneling from these states, which would provide the selective removal of charge carriers from one of the subbands, possible? How much are the levels in processes of resonance tunneling matched and how is the resonance structure in an applied electric field changed? In the case of resonance tunneling structures aligned in an electric field, questions arise of regularities of resonance tunneling in such systems, of special features of resonance tunneling and related phenomena taking place in multilayer superlattices with most complicated multiply repeated resonance tunneling element required for increasing optical amplification in quantum-sized structures.

Far-IR resonance tunneling laser operating on intersubband transitions in structures with wide quantum wells

There are several mechanisms of producing a population inversion in lower subbands which can be used for the development of a far-IR resonance tunneling laser operating on intersubband transitions. The concept of optically pumped resonance tunneling lasers operating on intersubband transitions in heterostructures with different compositions of semiconductor compounds in the region of quantum wells is quite promising. Figure 1 shows a scheme of intersubband transitions in the case of resonance tunneling in a transverse electric field. If the structural parameters of a central quantum well are chosen in such a way that the energy distance between the first and second excited states is $\varepsilon_3 - \varepsilon_2 = \hbar\omega_0$ ($\hbar\omega_0$ is the optical phonon energy) and $\varepsilon_2 - \varepsilon_1 < \hbar\omega_0$, then charge carriers appearing due to resonance tunneling from a neighboring quantum well will rapidly relax from the third subband (ε_3) to both lower subbands (ε_2 and ε_1) with times $\tau_{32} \approx \tau_{31} \approx 1$ ps, which are determined by scattering by optical phonons [7]. At the same time, the relaxation of charge carriers upon transitions between two lower subbands ε_2 and ε_1 caused by scattering by acoustic phonons occurs substantially more slowly ($\tau_{21} \approx 200-300$ ps) [7]. In the case of $GaAs/Al_{0.3}Ga_{0.7}As$ structures, this situation corresponds to quantum wells of width $d_w = 250$ A (the energy spectrum is $\varepsilon_1 = 7$, $\varepsilon_2 = 29$,

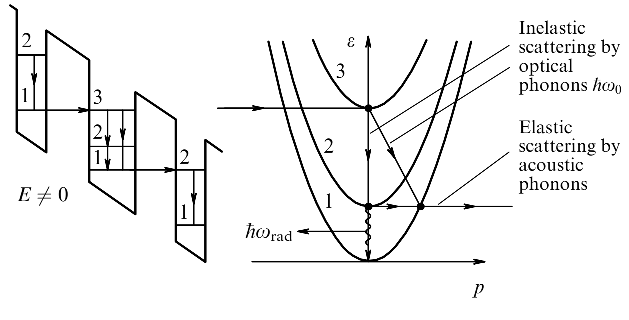

Figure 1. Scheme of intersubband transitions in the laser resonance tunneling structure (the system consists of three $GaAs/Al_{0.3}Ga_{0.7}As$ quantum wells; the central well width is 250 A, $\varepsilon_3 - \varepsilon_2 = 35$ meV, $\varepsilon_2 - \varepsilon_1 = 22$ meV; the optical phonon energy is $\hbar\omega_0 = 36$ meV).