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TITLE: Nanostructures: Physics and Technology International Symposium
[8th] Held in St. Petersburg, Russia on June 19-23, 2000 Proceedings

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The following component part numbers comprise the compilation report:
ADP013002 thru ADP013146
Unipolar semiconductor lasers on asymmetric quantum wells

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Abstract. We propose the original design of an active element of quantum unipolar semiconductor laser both for the optical pumping and current injection modes of operation. The peculiarities of the proposed design are strongly asymmetric barriers surrounding a double-well active element. The suppression of intersubband transitions to the lower working subband can be readily achieved if the transformation point of electronic state dimensionality for the lower subband occurs at small momentum. By this means the population inversion conditions in this system can be easily realized. The results of photoluminescence studies of the individual elements of the proposed structure are presented.

Theory

The double QW structure with asymmetric barriers, which permits to suppress sufficiently the intersubband relaxation, was proposed by us earlier [1]. The design of this structure facilitates the achievement of the intersubband population inversion and consequently the reduction of the threshold pump currents and pumping intensity respectively in the current injection [2] and fountain [3] modes of operation. In this case, the situation of both coherent photonic and electronic subsystems is possible as well as lasing even without the population inversion [4].

The asymmetry of the barriers causes an existence of 2D subband of the corresponding QW only in restricted region of 2D wave vector $0 < |k| < k_c$ because of 2D–3D transformation of electronic state dimensionality. The intersubband relaxation is appreciably suppressed if the distance between the 2D–3D transformation point $k_c$ of the lower subband and bottom of the upper subband exceeds the LO phonon energy $E_{LO}$. We propose here the original design of an active element both for the optical pumping and current injection modes of operation. In Figure 1, the band diagram of the laser structure with optical pumping is shown.

The active element comprises two QW of $h_1$ and $h_2$ width separated by narrow barrier. We use the scheme with pumping between $\varepsilon_1$ and $\varepsilon_3$ subbands and lasing between $\varepsilon_3$ and $\varepsilon_2$ subbands. The peculiarity of the proposed design is the insertion of this active element between the asymmetric barriers $U_0$ and $U_1 (U_1 < U_0)$ where $U_1$ lies close to the $\varepsilon_2$ subband. With such an active element, the transformation of electronic state dimensionality for $\varepsilon_2$ subband allows to increase appreciably the phonon relaxation time $\tau_{32}$ and strengthens the inequality $\tau_{32} \gg \tau_{21}$. The latter is necessary for the population inversion achievement.

Taking into account the finite width $L$ of $U_1$ barrier in the real structure, the active element design was optimized on the basis of calculations of phonon intersubband relaxation times $\tau_{ij}$ and dipole matrix elements $z_{ij}$ ($i, j = 1, 2, 3$). The concrete calculations were performed for the structure on the basis of GaAs/AlGaAs system with a molar fraction of Al in the right barrier $x = 0.35$ and that of $U_1$ barrier $x \sim 0.09$. The QW widths in the active region ($h_1 = 82 \text{ Å}, h_2 = 51 \text{ Å}$) were chosen to obtain the energy gap between
Fig. 1. Band diagram and position of size-quantization levels.

$e_3$ and $e_1$ subbands of the order of 120 meV (for pumping with a CO$_2$ laser), and $e_2-e_1$ separation close to $E_{\text{LO}}$ ($E_{\text{LO}} \approx 36$ meV). In this case, $\tau_{21}$ takes a minimum and reaches 0.5 ps. The width of separating barrier $b_1$ was chosen to optimize a $\eta = (e_3 - e_2)(z_{31}z_{32})^2$ value, which determined the ratio of the gain in the system to the loss [1]. The product $z_{31}z_{32}$ has a maximum at $b_1 \approx 14$ Å.

We have found that the insertion of a narrow barrier $b_2$ of $U_0$ height between $h_2$ QW and $U_1$ barrier allows one to improve the lasing characteristics. This barrier affects $\tau_{32}$ values and permits to control $z_{ij}$ values. The product $z_{31}z_{32}$ increases steadily with $b_2$ and at $b_2 = 20$ Å nearly coincides with that of the structure with symmetric barriers ($U_1 = U_0$).

One has to increase $\tau_{32}$ to obtain the population inversion. In the proposed design this is achieved as a result of the escape of electrons of $e_2$ subband with a finite momentum of longitudinal motion to the region of low barrier $U_1$. This effect occurs at a reasonable large $L$. In this case, a quasi-continuous (QC) spectrum is formed in this region and the additional mechanism of the electron escape from the upper laser subband $e_3$ appears. Moreover, with appropriate choose of $L$ the escape of the electrons from $e_3$ subband to the states of the QC spectrum formed over $U_1$ barrier appears to be suppressed. The described approach allows one to refuse complex injector design in the form of graded Bragg superlattice for quantum cascade laser [3] and simplifies a change-over from the optical pumping to the injection mode of operation.

We carried out numerical calculations of the $b_2$ dependences of the relaxation times $\tau_{31}$ and $\tau_{32}$ for intersubband transitions with a participation of optical phonons, the escape time of electrons from the upper subband to the region of QC spectrum $\tau_{3\text{con}}$, and the total lifetime $\tau_{3\text{tot}}$ for the $e_3$ subband at $L = 400$ Å and $U_1 = 81$ meV. There is a flat maximum of $\tau_{3\text{con}}$ at $b_2 \approx 30$ Å. As this takes place, the total lifetime $\tau_{3\text{tot}}$ is close to its limiting value, and $\tau_{32} \approx 4$ ps being 2.7 times as much as that for the structure with symmetric barriers.

Figure 2 shows the dependences of the relaxation times on the width $L$ of the region forming a QC spectrum. The maxima $\tau_{31}$ and minima $\tau_{3\text{con}}$, $\tau_{3\text{tot}}$ at $L \approx 340$ and 420 Å are due to the appearance of the level, which is in resonance with $e_3$, in the region of QC spectrum. In this case, the wave function of $e_3$ state penetrates significantly in the region of low barrier $L$, causing the decrease in the overlap with wave functions of $e_1$ and $e_2$ states and the increase in the overlap with states of QC spectrum. The abrupt change of $\tau_{3\text{con}}$ at $L = 350$ Å is associated with the approach of the next level of the QC spectrum to the $e_3$ level by a distance equal to $E_{\text{LO}}$ energy. Thus, the optimal value of $L$ lies in the region of 400 Å.

In order to optimize the laser on the population inversion $I$ parameter, we wrote equations that describe non-equilibrium kinetic processes in the structure under study. It was shown that the dependence $I(L)$ keeps a strong non-monotonous character owing to the
Fig. 2. Dependences of the relaxation times on the width $L$ of the region forming a QC spectrum.

sharp modulation of relaxation rates with $L$ for the various subbands.

The presence of QC subbands decreases the value of population inversion. For example, when a single QC subband $\varepsilon_0$ exists, the population inversion is expressed by the equation

$$I = \frac{\tau_{32}}{\tau_{21}} \left(1 + \frac{\tau_{32}}{\tau_{30} \tau_{02}}\right)^{-1},$$

where $\tau_{ij}$ is the electron relaxation time from $\varepsilon_i$ subband to $\varepsilon_j$ one and $\tau_0$ is a full lifetime in $\varepsilon_0$ subband. Obviously, the top limit of equation (1) is reached, when $\tau_{30} \gg \tau_{32}$ and $\tau_{02} \gg \tau_0$. However, not all the QC subbands participate effectively in electron relaxation from the $\varepsilon_3$ subband to $\varepsilon_2$ one. The transitions to QC subbands separated from $\varepsilon_3$ subband with a gap smaller than $E_{LO}$ are forbidden by the law of energy conservation. If the intersubband relaxation time exceeds the intrasubband time, the electrons are accumulated near the subband edges. In this case, the transitions to the $\varepsilon_2$ subband from the QC subbands separated with a gap smaller than $E_{LO}$ are also prohibited. On these grounds, it is possible to suppress significantly the influence of the QC spectrum on the population inversion.

Experimental results

To study the concurrence of the mechanisms of interband radiative recombination and tunneling through the narrow barrier, the photoluminescence (PL) was measured of single QW with symmetric barriers one of them having the width that was varied in the range $d = 3-10$ nm. The unipolar regime under consideration is realized when the tunneling time appears to be lower than the recombination time. It should be stressed that the tunneling time in its turn determines the intersubband relaxation time. When narrowing barrier the possibility to alter the lifetime of coupled electronic state in a broad range was demonstrated. The variation of lifetime between two limiting cases when it was determined by tunneling from QW through the barrier ($d = 40$ Å) and by radiative recombination time ($d = 80$ Å) was realized. It was found that 80 Å barrier effectively prevents tunneling. The intensity of QW peak drastically decreases for the structure with 60 Å barrier. This is an evidence of the key role of the tunneling through 60 Å barrier in this structure. There is no QW
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contribution in the PL spectrum of the structure with 40 Å barrier and tunneling through the narrow barrier dominates.

The drastic modification of the degree of electronic-wave-function localization in 2D–3D transformation point was demonstrated from comparison of PL spectra of 40 Å GaAs/AlGaAs single QW with strongly asymmetric barriers and of the similar structures but with the additional wider (60 or 80 Å) QW with symmetric barriers coupled with the initial one. The latter structure is a component of the active element of a fountain laser. We have shown that this structure permits one to increase considerably the degree of electronic wave function localization in QW at $k = 0$ that determines the oscillator strength of the working laser transition with only minor variation of the critical value of wave vector of 2D–3D transformation.

The key feature of the proposed scheme is the resonance of the lower subbands in the asymmetric and symmetric QW. This is achieved by the increase of the width of QW with symmetric barriers. For the structure with 60 Å QW the ground subband of this well is sufficiently higher than the ground subband in asymmetric QW and the resonance and thus the transformation point in this subband are absent. Therefore, the transition to this subband from higher states is not suppressed and the ground subband in symmetric QW is highly populated. This is the reason of high intensity of QW peak. For the structure with 80 Å QW the ground state in the symmetric QW appears to be at lower energy and in resonance with the ground subband in asymmetric well. For this reason the ground subband in this structure has the transformation point and the transitions to this subband are suppressed. That is why the intensity of QW peak for this structure is sufficiently weaker. For the structure with single asymmetric QW the discussed effect is weaker due to the lower degree of localization of electronic wave function.

Acknowledgements

This work was supported in part by the Russian Foundation for Basic Research and Federal Programme “Integration” (Project No. A0133).

References