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structure. The barrier height  $U_1$  is chosen to be close down to the  $\varepsilon_2$  subband minimum in order to destroy the 2D-dimensionality of the BLS above the small quasi-momentum  $k_c$  value. In such a way a phonon relaxation time  $\tau_{32}$  for the intersubband electron transitions from the TLS  $\varepsilon_3$  to the BLS  $\varepsilon_2$  can be increased appreciably compared to the  $\tau_{21}$  relaxation time from the BLS to the reservoir:  $\tau_{32} \gg \tau_{21}$ . The last strength inequality is a indispensable condition for the population inversion. The highest value for the population inversion is

$$I_{\max} = \tau_{32}/\tau_{21}. \quad (1)$$

Unfortunately, a finite width  $L$  of the lower binding barrier  $U_1$  causes an existence of size-quantized quasi-3D states, which are localized beyond the double-well structure, but can serve as intermediate states on the path of electrons from the TLS to the BLS. So we have to take into account quasi-continuous states during the SLAW structure optimization.

The active element of the SLAW has been previously optimized in [ ] from a quantum-mechanical point of view. This tuning was made in the assumption of the optical pumping that allows to simplify the laser structure since neither transport nor cooling of the carriers in the injector region are required. The main requirement is the largest value of a parameter

$$\eta = (\varepsilon_3 - \varepsilon_2)^3 (Z_{31} Z_{32})^2 \quad (2)$$

(where  $Z_{ij}$  are the radiative dipole matrix elements), which defines the ratio of the gain in the system to the loss [ ]. For example, an adjustment of the barrier thickness  $b_1$  allows to increase the value of the  $\eta$  parameter two times. Next the lifetime of electrons in the TLS was maximized. For example, changes of the width  $L$  of the lower binding barrier produce abrupt modulations of the electron lifetimes in the TLS because of a resonant nature of the intersubband transitions.

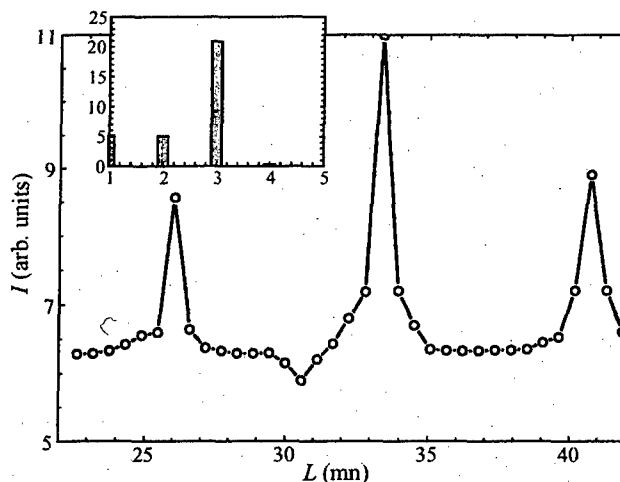
This investigation gives us a rough bottom estimation for the population inversion, i.e. shows the worst case, and allows to get the next parameters of the SLAW: GaAs/ $\text{Al}_x\text{Ga}_{1-x}\text{As}$  structure with molar fractions of aluminium  $x = 0.35$  in the higher barrier  $U_0$  and  $x = 0.09$  in the lower barrier  $U_1$ . The widths of the quantum wells in the active region  $h_1 = 82 \text{ \AA}$  and  $h_2 = 51 \text{ \AA}$  were chosen to obtain an energy gap between the  $\varepsilon_3$  and  $\varepsilon_2$  subbands of about 120 meV for the pumping with a  $\text{CO}_2$  laser and  $\varepsilon_2$  and  $\varepsilon_1$  separation close to the LO phonon energy  $\hbar\omega_{\text{LO}} \approx 36 \text{ meV}$ .

However, to obtain the exact value of the population inversion we must study a BLS population that depends on a rate of electron transitions (also from the quasi-continuous states) to this subband.

## 2. Population inversion in laser on asymmetric quantum wells

The quasi-continuous states are mostly placed exactly between the TLS and BLS. So a situation seems to be desperate. Nevertheless, a feature of this thoroughly designed structure is just the finite width  $L$  of the lower binding barrier. That is why electrons have got only a few intermediate states on their path from the TLS to BLS.

The predominated channel for the nonradiative electron energy dissipation in SLAW is the optical phonon emanation. Due to the fixed energy of the optical phonon, the quasi-continuous states, which are located below the TLS at the distance less than the  $\hbar\omega_{\text{LO}}$ , are inaccessible. Similarly, the BLS is inaccessible from the states which are located nearer than the  $\hbar\omega_{\text{LO}}$  above this state. Thus, only a narrow band  $(\varepsilon_3 - \varepsilon_2) - 2\hbar\omega_{\text{LO}} \sim 15 \text{ meV}$  contains the dangerous intermediate states. It is very important that the width of the *dangerous band* is smaller than the optical phonon energy. So any transitions between



**Fig. 2.** The  $I$  population inversion value as a function of the  $L$  width of the lower binding barrier for the unipolar semiconductor laser. The inset shows the arbitrary population of the quasi-continuous states by the  $L = 33.4$  nm.

the quasi-continuous states inside the dangerous band are impossible and one can consider these states non-interacting.

In fact, there exist following channels for the electron transitions from the TLS to BLS. First, an electron can leap down to the BLS directly. This process is characterized by the  $\tau_{32}$  relaxation time. In any cases this time must be as large as possible in order to increase the  $I_{\max}$  value. Another possibility is the electron transition to a  $j$  quasi-continuous state with the  $\tau_{3j}$  relaxation time. Afterward, there are three ways.

(a) If the host subband hold its minimum in the dangerous band then an electron can go down to the bottom and wait for the transition to the BLS during the  $\tau_{j2}$  time. Only the one subband usually fulfil this condition and this subband can be removed from dangerous band with the appropriate choice of the SLAW structure.

(b) If the host subband hold its minimum outside the dangerous band then an electron can slowly go down through this band due to the intraband relaxation. On this path electron can perform an interband transition to the BLS with the  $\tau_{j2}$  time.

(c) Finally, an electron just can leave the dangerous band due to either the intraband relaxation after the  $\tau_0$  time or the interband transition to the another  $i$  quasi-continuous states during the  $\tau_{ji}$  time. In the both cases there exist only the way to the reservoir.

These facts form the backgrounds of our phenomenological model. This model has an analytical solution and gives us the next expression for the population inversion:

$$I = I_{\max} \left( 1 + \sum_{j \in L} \frac{\tau_{32} \tau_j}{\tau_{3j} \tau_{j2}} \right)^{-1}, \quad \tau_j^{-1} = \tau_{j2}^{-1} + \tau_0^{-1} + \sum_{i \in L} \tau_{ji}^{-1}. \quad (3)$$

It is evident from the (3) that the highest value of the population inversion is the  $I_{\max}$  as before in the (1). The destructive effect of the each  $j$  quasi-continuous state depends on the ratio of the  $\tau_j$  electron lifetime in the dangerous band to the  $\tau_{j2}$  transition time to the BLS. Thus, to decrease the influence of the quasi-continuous states to the population

inversion value we have to accelerate first of all the electron departure from the dangerous band.

Results of numerical calculation the population inversion value for the case of the fast intraband electron relaxation is shown in Fig. 1.

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