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Optimization of barrier thickness for efficient carrier capture in graded-index and separate-confinement multiple quantum well lasers

P. W. M. Blom, J. E. M. Haverkort, and J. H. Wolter
Department of Physics, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands

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We present results from numerical calculations on the carrier capture efficiency in separate-confinement and graded-index separate-confinement multiple quantum well (MQW) lasers. We find that the capture time oscillates as a function of the well width as well as the barrier width between the wells, due to a changing overlap of the barrier wave functions with the bound states in the wells. We show that one order of magnitude improvement in the carrier capture efficiency can be accomplished by properly choosing the dimensions of the layers in the active region of the MQW laser.

Optimization of the operating characteristics of semiconductor multiple quantum well (MQW) lasers with respect to the confinement layers has been performed both experimentally and theoretically. As a result graded-index separate-confinement heterostructure (GRINSCH) lasers are well known to exhibit a lower threshold current density than conventional separate-confinement heterostructure quantum well (SCH-QW) lasers. This performance improvement has partly been attributed to a higher carrier capture efficiency in GRINSCH lasers. Especially in lasers with narrow quantum wells, the carrier capture is expected to influence both the efficiency and the maximum attainable modulation frequency of a quantum well laser. However, no theoretical model exists which predicts the dimensions and composition of the MQW layers in the active region for an optimized carrier capture efficiency and thus for an optimized performance of a MQW laser.

From quantum mechanical calculations on a separate confinement heterostructure single quantum well (SQW), strong resonances (30 ps–1 ns) of the carrier capture time versus well width were already predicted by Bruin and Bastard. In a recent study we expanded and adapted their model to SCH-MQW structures and we demonstrated that the calculated capture time is for the first time in agreement with experimental results. Because of this agreement we are confident that this model can be further exploited to optimize the performance of semiconductor lasers.

In this letter we present the results of a theoretical study on the carrier capture process in a SCH-MQW structure. The conduction band of a SCH-MQW structure with three quantum wells is shown in the inset of Fig. 1. It is demonstrated for the first time that in such a laser structure strong resonances appear not only as a function of well width but also as a function of barrier width $D_b$, of the MQW. Our calculations show that the carrier capture time can be improved by more than one order of magnitude by optimizing the well width, barrier width $D_b$, and composition of the MQW laser structure.

The carrier capture efficiency into the quantum wells was calculated using Fermi's Golden Rule and the Froehlich Hamiltonian for LO-phonon emission. It is assumed that the population of LO-phonon states is negligible, thus there is no escape from the well due to the absorption of a LO phonon. We also assume a constant carrier distribution function up to 36 meV above the barrier band gap for the initial barrier states. For these conditions, we find, in accordance with Ref. 4, that the hole capture rate is one order of magnitude larger than the electron capture rate, because of the larger effective mass; thus the total capture rate is limited by the relative slow capture process of the electrons. In this letter we therefore focus on the electron capture time.

The calculation on a SQW shows that the capture time reaches a minimum for well widths at which a new bound state arises at the top of the well. At these resonant well widths the wave functions of the barrier states have a maximum overlap with the bound states in the well. The capture process is further enhanced by the fact that a new bound state is present below 36 meV of the occupied barrier states. There is, however, a fundamental difference in the capture process of a MQW structure with regard to a SQW. The capture time in a SQW is proportional to the barrier width $L_b$, since a larger barrier reduces the overlap of the barrier wave functions with the bound states in the well. In a MQW this overlap also depends on the barrier thickness $D_b$ between the wells. In Fig. 1 we show the barrier width dependence of the electron capture time for a GaAs/Al$_{0.3}$Ga$_{0.7}$As laser structure with three 50-Å-thick wells. We observe two minima in the capture time at barrier widths $D_b$ of 155 and 280 Å. At these barrier widths the odd and even wave functions have a large overlap with all the wells. For the barrier widths at which the capture time is at a maximum, the barrier wave functions are mainly localized in the confinement layers ($L_c$) of the MQW, so they have a poor overlap with the bound states in the wells.

An increase of the number of wells in the laser structure results in an increase of the total number of final bound states. It also gives rise to a decrease in the capture time. Our calculations demonstrate that the capture time is nearly inversely proportional to the number of wells for all the other structure parameters fixed. For example, a change from 1 to 10 wells in a SCH-MQW structure with 70 Å well width gives rise to a decrease of the capture time from 34–2 ps. If the number of wells exceeds about 20, it appears that the capture times are below 1 ps for all well
For the optimization of a laser structure it is important to know how structure parameters like well width $L_w$, barrier width $D_b$, and aluminum fraction in the active layer determine the capture process. For example a change in the aluminum fraction from 0.2 to 0.3 increases the capture efficiency for a structure with 50 Å well width by a factor of 4. A change of the barrier width $D_b$ from 100 to 155 Å gives rise to an increase of the capture rate by a factor of 5. Thus the capture rate can be enhanced by more than one order of magnitude by choosing the optimal combination of the structure parameters. The coupling of a new bound state in the wells, which gives rise to an optimal capture efficiency, is determined by both the well width and the aluminum fraction. In Fig. 2 we plotted as a function of well width the aluminum fraction which gives rise to an optimum in the carrier capture process. Also shown is the wavelength of the electron-heavy hole transitions for these combinations. In Fig. 3 the optimum barrier width $D_b$ is shown as a function of well width for a fixed aluminum fraction of 0.3. The optimum barrier width is small (< 100 Å) just before a new bound state is coupled into the well. After the coupling of a new bound state the optimum barrier width jumps to widths of 150–170 Å. For other aluminum fractions or different compounds, such as InGaAsP or InAlGaP, the bound states are coupled at different well widths, so the curve in Fig. 3 shifts along the x axis. In Fig. 4 we compare the experimentally determined threshold currents, which were reported by Tsang, with the calculated electron capture times as a function of barrier width $D_b$ for four SCH-MQW structures. The shape of both curves confirms the relevance of the carrier capture efficiency with regard to the MQW laser performance.

The carrier capture efficiency in GRINSCH-MQW lasers can also be optimized using our model when we approximate the GRINSCH by a staircase-like barrier with step heights of 36 meV. By choosing the width of the individual steps, the index profile of the staircase-like barrier can be made nearly identical with a true graded-index barrier. As a consequence of the fast carrier cooling due to optical phonons, the carriers relax very efficiently in the staircase-like structure until they are within 36 meV of the barrier band gap. As a result of this cooling, the carriers are approximately confined in a SCHQW type of structure, which is the lowest step in the staircase-like barrier. As an example we calculated the capture time as a function of the well width $L_w$ for a GaAs/Al$_x$Ga$_{1-x}$As SCH-MQW structure. The inset shows the conduction band of the structure with a well width of 50 Å, barrier width $L_b$ of 500 Å, and aluminum fraction of 0.3.

![FIG. 1. Electron capture time vs barrier width $D_b$ for a GaAs/Al$_x$Ga$_{1-x}$As SCH-MQW structure. The inset shows the conduction band of the structure with a well width of 50 Å, barrier width $L_b$ of 500 Å, and aluminum fraction of 0.3.](image1)

![FIG. 2. Aluminum fraction for optimum capture (solid line) vs well width and the corresponding wavelength of the electron-heavy hole transition (dashed line).](image2)

![FIG. 3. Barrier width $D_b$ for optimum capture vs well width at an aluminum fraction of 0.3.](image3)

![FIG. 4. Threshold current density (dashed line) and the electron capture time (solid line) vs barrier width $D_b$ for a GaAs/Al$_x$Ga$_{1-x}$As SCH-MQW structure. The inset shows the conduction band of the structure with five wells and an aluminum fraction of 0.2, the well width ranges from 100 to 150 Å.](image4)
barrier width $D_b$ in a SCH-MQW with $L_b = 100$ Å, which corresponds to a GRINSCH structure with a slope of 0.18 meV/Å, as is shown in Fig. 5. As already stated above the capture time is proportional to the width of the barrier $L_b$. Therefore, in a GRINSCH structure the decrease of the barrier thickness gives rise to a very efficient carrier capture. In comparison with the data for the SCH-MQW in Fig. 1 with $L_b = 500$ Å we now find that the oscillations in the capture time reduce from (0.8–3.5 ps) to (0.1–0.6 ps). On the other hand, our step-like approximation of a GRINSCH does not influence the resonances in well width and barrier width between the wells. The minima in the capture time are still located at barrier widths $D_b$ of 155 and 280 Å, independent of $L_b$. As a result the calculated structure parameters for optimum carrier capture are valid for SCH-MQW structures as well as GRINSCH-MQW structures.

In conclusion, we demonstrated that the carrier capture efficiency in SCH-MQW and GRINSCH-MQW laser structures can be improved by more than one order of magnitude by optimizing the dimensions and composition of the layers in the active region. The predicted capture time for large MQW structures is very short ($< 1$ ps), in agreement with reported experimental results.