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MEASUREMENT OF THE AMBIPOLAR CARRIER CAPTURE TIME IN A GaAs/Al$_x$Ga$_{1-x}$As SEPARATE CONFINEMENT HETEROSTRUCTURE QUANTUM WELL


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The carrier capture in a separate confinement heterostructure quantum well has been studied both experimentally and theoretically. Our calculations show that the electron and hole capture time vary strongly as a function of the excess energy. At an excess energy of 40 meV, both capture times are equal resulting in an ambipolar capture process which allows a direct comparison between theory and experiment. We carried out subpicosecond luminescence spectroscopy experiments and deduce an ambipolar overall capture time of 20 ps, a number which for the first time is in agreement with theoretical predictions. The quantum mechanical overall capture time of 20 ps gives rise to a classical local capture time of 3 ps which is determined from a diffusion model.

Introduction

The capture of photoexcited carriers by a semiconductor quantum well structure is important for the performance of quantum well lasers. However, there seems to be a fundamental problem in the understanding of the carrier capture process by a quantum well according to the large differences between observed and predicted capture times in literature l-3. In a quantum mechanical model, in which the capture process is governed by the emission of optical phonons, strong resonances (30 ps - 1 ns) of the capture times were predicted by Brum and Bastard 1. In recent experiments 2-3 the observed capture times ranged from 0.3 - 3.0 ps and no well width dependence was observed.

In this paper we present both an experimental and theoretical study of the carrier capture process in a 70 Å GaAs/AlGaAs separate confinement heterostructure quantum well (SCHQW).

Theory

We consider a SCHQW as is shown in fig. 1. The transition probability that a carrier in an initial barrier state emits a LO phonon and becomes captured by the well is calculated using Fermi's Golden Rule and the Froehlich Hamiltonian. We assume that there are no LO phonons present, thus there is no thermally activated escape from the well. The calculated capture time \( \tau \) refers to carriers in the whole structure and is therefore called the overall capture time. These calculations were first presented by Brum and Bastard 1. The capture times of the electrons and holes were calculated separately and show strong oscillations as a function of well width. They assumed the carrier distribution for both the holes and the electrons in the initial barrier states to be constant up to 36 meV above the barrier bandgap. Such a constant distribution function of the carriers up to 36 meV is only a good approximation when the carriers are injected at very high excess energies. Most experiments like ours...
Fig. 2: The capture rates of the bandminima of the barrier states in the SCHQW of fig. 1 are shown as a function of the barrier state number nb. The lowest barrier state is labelled as nb=1. Up to 36 meV above the barrier bandgap we have 10 electron and 27 heavy hole states.

However, are carried out at low excess energies. Such a constant distribution function is therefore unrealistic.

In fig. 2 the capture rates for the barrier bandminima are shown for both electrons and holes. The capture rate increases for barrier states at higher energies as a result of an increasing overlap between the barrier states and the bound states in the quantum well. A second feature is that for the lowest barrier states the capture rate of the electrons is larger than the hole capture rate, whereas at high energy levels the electron capture rate is the slowest one. Thus it is evident that not only the capture times are strongly dependent on the distribution of the carriers over the barrier states but it also matters which type of carrier is captured first by the quantum well.

In order to obtain an appropriate distribution function for our experimental conditions, we investigated all possible transitions between the hole and electron barrier states after absorption of a laser photon. By calculating the overlap of the wavefunctions of the hole and electron barrier states, which determines the probability of a transition, we find that each hole state is coupled to only one electron state. This means that the number of barrier states which are occupied after absorption of a laser pulse is equal for both electrons and holes. So in our model the initial states for the capture process are determined by the number of allowed transitions after absorption of a laser pulse. The distribution of the carriers over the barrier states is now dependent on the excess energy of the laser photons with respect to the barrier bandgap, just as the difference in the capture times of the electrons and holes.

Using a carrier distribution which is determined by the allowed transitions between the hole and electron barrier states, our calculations predict an equal capture time for electrons and holes at an excess energy of 40 meV. At this excess energy the capture process is ambipolar and the first 10 barrier states of the electrons and holes are filled. For the electrons this means that the electron barrier states are filled up to 36 meV above the barrier bandgap, whereas the hole states are only filled up to 4.5 meV. The ambipolarity of the capture process at an excess energy of 40 meV allows a direct comparison between theory and experiments, in which only one capture time is measured. In fig. 3 the average electron capture time is shown as a function of well width for a SCHQW with 3 wells. At high excess energies, where a constant distribution function would be applicable, holes will be captured first by the quantum well and will subsequently attract the electrons towards the well. The remaining holes in the barriers will be repelled by the well. In this case a capture model, in which the electrons and holes are treated independently, is clearly not appropriate to describe the experiments.

Results and Discussion.

We report direct measurements of the carrier capture times in a MBE grown GaAs/AlGaAs SCHQW (see fig. 1) by subpicosecond time resolved luminescence spectroscopy using an upconversion lightgate. The time evolution of the quantum well luminescence after direct (below the barrier bandgap) and indirect (above the barrier bandgap) excitation with a subpicosecond laser pulse (0.6 ps) is shown in fig. 4. From these results an overall capture time of 20 ps is obtained which is for the first time in excellent agreement with the calculated ambipolar capture time (see fig. 3).

In a classical point of view the 'overall' capture time still contains a diffusion time in the barrier. Therefore we deduce a 'local' carrier capture time which purely characterizes the scattering processes between 3-dimensional barrier states and 2-dimensional subbands for carriers which are spatially located in the well. The cooling time within the well and the radiative lifetime can be determined by direct excitation, the diffusion constant and the local capture time are then provided by indirect excitation. By applying the classical diffusion model we obtain a diffusion constant of 50 cm²/s, a value which is common for AlGaAs, and a local capture time of 3 ps. We are the first to deduce that the experimentally observed 'overall' capture time of 20 ps gives rise to a 'local' capture time of 3 ps.
energies holes will first be captured by the wells and the electrons will first cool down below 36 meV of the barrier bandgap before being captured. In the reported experiments\textsuperscript{2,3} large excess energies of 700 meV were used.

The second reason is that the capture times are dependent of structure parameters like width of the barrier layers, bandgap energies and number of wells. In order to compare our experimental results with theory, we calculated the capture times using the structure parameters of our sample.

Conclusions

In conclusion we show that the carrier capture in a separate confinement heterostructure quantum well is well described by an ambipolar capture model. The calculated capture times are only comparable with the experiments in case of an ambipolar capture process, which can be achieved by choosing the correct excess energy of the laserlight. From subpicosecond luminescence spectroscopy experiments on a 70 Å quantum well structure an overall capture time of 20 ps is derived, which gives rise to a local capture time of 3 ps.

References