Multiphonon capture processes in self-assembled quantum dots

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however, have considered effects of correlations between excitons and unbound electrons or holes when a semiconductor is excited above the band gap. In this paper, we report the observation of a surprising correlation-induced resonance (CIR) that appears in differential transmission (DT) spectra of semiconductor quantum wells (QW) excited above the band gap. The properties of this CIR show that it is not due to bie exciton formation, but instead may arise from correlations between excitons and unbound electrons or holes.

Transient, nondegenerate DT was performed on a 130 Å GaAs multiple QW. The pump pulse is tuned to 25 meV above the exciton resonance, and is spectrally narrowed using a pulse shaper to excite electrons and holes above the band gap with well-defined initial energies. The inset to Fig. 1 shows the absorption spectrum of the sample and the spectral position of the pump. Figure 1(a) contains a reference DT spectrum for resonant excitation of HH excitons, and shows the expected bie exciton-induced absorption resonance for opposite circular polarization (σ±σ−) of pump and probe, but not for the same circular polarization (σ+σ+). In Fig. 1(b), the DT spectrum for nondegenerate pumping also contains an induced absorption resonance; however, the energy position of this CIR is different from the bie exciton and little polarization dependence is observed.

Figure 2 shows the dependence of the CIR on pump-probe delay. As can be seen in Fig. 2(a), the CIR appears almost immediately after the pump pulse, and persists for delays greater than 500 ps. Figure 2(b) shows that the bleaching at the HH exciton resonance (809.0 nm) reaches a maximum just after zero delay, while the magnitude of the CIR (810.6 nm) shows an initial rapid rise near zero delay but does not reach a maximum until nearly 20 ps. The fact that the CIR appears immediately after zero pump-probe delay indicates that it is not due to bie exciton formation, because the initial electron-hole plasma excited by the pump has not had time to form excitons through phonon emission and other relaxation processes.

Another surprising feature of the CIR is shown in Fig. 3, where the DT spectrum is found to be extremely sensitive to the lattice temperature. This behavior is in sharp contrast to the bie exciton resonance for resonant pumping, which shows almost no dependence on lattice temperatures over the same range. We have also investigated the dependence of the CIR on the pump energy. Little effect on the CIR was found for pumping at energies below, at, or above one LO-phonon energy (36 meV) above the HH exciton resonance.

The dependence of the CIR on polarization, pump-probe delay, and lattice temperature clearly indicates that the CIR does not reflect the formation of bie excitons. To explain these surprising results, we suggest that the CIR may arise from correlations between excitons and unbound electrons or holes.

References

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Quantum dot (QD) lasers, with record low-threshold currents, have now been realized in several laboratories. Carriers in such lasers are electrically pumped into barriers around the dots. Thereafter, they are captured into the dots and relax via the QD energy levels to the lower lying lasing levels. The mechanisms for injecting electrons and holes into the QD and the time scale on which these processes occur are not fully known. These will however to a large extent determine the dynamical properties of lasers and other QD-based devices. Two different mechanisms have been proposed: capture via carrier-carrier interaction (Auger processes) and capture via carrier-phonon coupling. In ref. 3, capture of a carrier from the wetting layer (WL) to the first excited state, via emission of one phonon, is found to exhibit strong resonances vs. the dot size. At resonance, the process is shown to be efficient. Furthermore, second-order elastic collisions between carriers and LO-phonons have been shown to give rise to dephasing times of a few hundred femtoseconds in QDs, in accordance with room temperature experiments.

We investigate capture of carriers from states in the continuous part of the energy spectrum into the discrete states of self-assembled InAs/GaAs QDs via emission of one or two phonons. We are not aware of any other investigations of two-phonon mediated capture processes in QDs, but we show that this may be an efficient capture mechanism. The phonons are assumed to be bulk GaAs LO phonons with zero dispersion. The QD was modelled by a finite confinement potential well in the effective-mass approximation.

Fig. 1 shows the capture time (τ) of an electron from a bulk region with carrier density \( N_D = 10^{16} \text{ cm}^{-3} \). From energy conservation requirements, it follows that the capture process is possible for certain intervals of QD radii, that is, there appear radius bands where LO-phonon mediated capture can take place and gaps where it is forbidden. The bands are always larger for the two-
lasing. In that case, two-phonon capture is seen to contribute significantly at realistic bulk densities, well below calculated as a function of \( N_{1D} \). The reason for the cross-over of two-phonon capture times occurring where the single-phonon capture is in the QD for the relatively low density \( N_{1D} = 10^{10} \text{ cm}^{-2} \). The QD is assumed to be a sphere of radius \( a \). The vertical lines indicate local minima within a radius band for the single- and two-phonon capture.

phonon capture, since carriers higher up in the band can be captured. For instance at a radius of \( =10 \text{ nm} \), it is seen that two-phonon capture contributes where the single-phonon capture is in fact not possible. A closer look at the corresponding radius band is given in Fig. 2, where the capture time at the local minima of single- \( (a = 9 \text{ nm}) \) and two-phonon \( (a = 10.4 \text{ nm}) \) capture is calculated as a function of \( N_{1D} \). The reason for the relatively strong density dependence is that only carriers from a narrow energy interval are captured and the occupation probability depends on \( N_{1D} \). The cross-over of two-phonon capture times occurs at high carrier densities where the bulk lasers start to become inverted, and is explained in terms of the Fermi-filling factors. We have also calculated the single-phonon capture time of a WL carrier to all possible states in the QD, for \( N_{1D} = 10^{10} \text{ cm}^{-2} \). It is found to be typically in the range 1–100 ps and becomes even as low as a few hundred femtoseconds.

In conclusion, we have performed, to the best of our knowledge, the first calculations of two-phonon capture in QDs. We find that two-phonon processes may contribute efficiently to carrier injection into QDs, in situations where single-phonon processes are prohibited.

References